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Viability of electric vehicles in combined day and night delivery: a total cost of ownership example in Germany

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A review of the body of literature yields general indications that electric freight vehicles can improve emissions and costs in off-hour delivery schemes. However, the literature fails to quantify the savings potential in a combined day and off-hours double-shift usage. Hence, this article qualitatively clusters the advantages of electric vehicles in off-hours delivery schemes and provides quantitative exemplary model calculations on the total costs of ownership in single- and double- shift usage. Surprisingly, the calculations contradict the hypothesis that is commonly deduced in the literature that with a higher utilisation, electric vehicles generally become more competitive compared to their conventional siblings. This study finds that electric medium-duty vehicles are only financially competitive at higher mileages, if the savings achieved by lower operational costs are greater than the costs for battery replacements. These become more frequent at higher mileages; hence a long battery warranty is essential when planning to operate EVs in double-shifts. An elasticity analysis finds that further important parameters influencing the competitiveness of medium-duty electric vehicle compared to conventional diesel models are the discount rate, purchase prices, and the cost of diesel fuel. In conclusion, financial subsidies for purchasing freight EVs might lead to higher numbers of these vehicles. However, increasing the per-kilometre cost advantage of electric freight vehicles would support their utilisation, i.e. in combined day and night shifts, and hence would further mitigate the road freight transport emissions in cities.

Keywords: electric vehicles, off-hour delivery, double-shift, urban freight transport, total cost of ownership.

1. Introduction

The European Commission (2011) proposes the use of freight electric vehicles (EVs) to reduce greenhouse gas and air pollutants in urban last mile transport. In their "Transport White Paper 2011" the commission envisions the more silent electric motor technology to enable shifting a certain volume of urban freight transport into the night-time, in order to reduce the congestion in metropolitan areas.

While off-hour delivery (OHD) schemes have been demonstrated in projects throughout several cities during the past decade (Bestufs, 2003) and further projects were tested more recently in New York City, Dublin, Barcelona or Paris (TRB, 2013), examples of OHD with battery electric vehicles are still rare. The most important barrier for companies to deploy freight EVs are the high purchase costs (Amburg and Pitkanen, 2012; Ball and Wietschel, 2009). Macharis et al. (2013) conducted total a cost of ownership calculation (TCO) for conventional and electric logistics vehicles. They conclude that light commercial electric vehicles and quadricycles can be competitive over conventional vehicles in their calculation model. The same study finds that trucks with a payload

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of over one ton (or 3.5 tons gross weight) are not competitive, due to the large and expensive batteries, and thus high purchase price. However, vehicle utilised in night-time logistics are often larger vehicles (Silas et al., 2012; Holguín-Veras et al., 2013). Hence, an uncompetitive TCO can be seen as one of the major reasons for the generally low market demand, and with it, the small choice of available freight EV models. This again leads to a low economy of scales and thus high costs for the vehicles.

TCO calculations are carried out to understand the life time costs of electric compared to conventional freight vehicles (Feng and Figliozzi, 2013; Davis and Figliozzi, 2013; Lee et al., 2013; Lebeau et al., 2015b). All of those authors conclude that freight EVs can only become competitive in scenarios with a high utilisation. A case study using qualitative and comparing 57 freight initiatives which utilise electric freight vehicles underlines this conclusion: in ten of the cases, companies extend the range of the freight EVs by intermediate charging, in order to achieve a more profitable operation (Taefi et al., 2015). This implies that companies expected that the competitiveness of freight EVs to increased, when raising their daily mileage beyond the range possible with one battery charge.

Based on this knowledge, the presented paper proposes and explores the hypothesis that EVs which are deployed in a combined day and night shift for urban freight delivery are more likely to be competitive, compared to conventional diesel vehicles. In case this hypothesis is true, a combined day and night delivery with EVs presents a valuable opportunity for transport companies in reducing the TCO of their delivery vehicles, as well as for cities to mitigate the negative impact of freight transport, such as congestion, air pollutant- and noise emissions.

The document proceeds as follows: a literature review is carried out in Section 2, in order to explore if, and to what extent, EVs are recommended in OHD schemes. The scientific literature on this topic was found to be scarce; hence the potential impact of EVs on advantages and drawbacks of OHD schemes is clustered from the existing literature in Section 2.1. Furthermore, a quantitative evaluation of the cost-effectiveness of EVs in double-shift usage is lacking. Thus, Section 3 describes the methodology of the total cost of ownership calculation applied. In Section 4 the hypothesis of whether EVs in a combined day and night shift are more likely to be competitive is tested, by providing exemplary model TCO calculations in order to quantify the costs. Section 5 discusses the results of this research by evaluating several scenarios. Section 6 concludes with recommendations to policymakers and proposals on research opportunities, in order to further advance the field of electric urban freight transport and to abate freight transport-induced emissions.

2. Literature

Since the past decade, the literature on OHD has taken a steady rise, while research on EVs in city logistics surged in the current decade. However, studies regarding these two aspects in combination, in order to improve the urban transportation system, are scarce. The existing body of knowledge is reviewed in order to achieve an overview on the state-of-the-art and to determine if, and to what extent, EVs have been proposed in OHD schemes. The following five databases and catalogues are chosen for the search, based on their accessibility and relevance: ScienceDirect (a full text scientific database); Emerald Insight (database of Emerald Resources); GVK PLUS (the common union database of seven federal states of northern Germany including online contents); WISO (a large database of German national and international journal articles from economics and the social sciences); Google Scholar (free search engine for scholarly literature). After testing keywords, the searched string results in: *("off-hour delivery" OR "off-peak delivery" OR "night delivery" OR "off-hour distribution" OR "night distribution") AND "electric vehicle"*.

The period for the search is limited to articles which were published from the beginning of 2010 to April 2015. 2010 is chosen as a start date, since the year 2010 is considered as the start of

modern EV production (Trigg, 2012) and marks the start of many large EV initiatives in Europe, such as "Plugged-in Places" in the UK, "Electric Mobility Pilot Regions" ("Modellregionen Elektromobiltät") in Germany or "Model City Electric Driving" ("Proeftuin electrisch rijden") in the Nether- lands. The searches in the five databases yield a total of 55 results. Of these, the following results are removed: two redundant publications, 17 non-reviewed research reports of projects, presentations, or articles in practitioner's journals, nine articles, where the contents do not match the searched topic (such as papers discussing hybrid vehicles or the energy grid). This reduces the number of reviewed publications with contents related to EVs and OHD schemes to 29 papers.

The findings of the relevant literature are aggregated in a concept matrix based on Webster and Watson (2002). Table 1 clusters if, and to what extent, EVs are recommended, in order to improve advantages and drawbacks of OHD (papers may contribute to more than one statement).

Table 1. Number of papers and types of advantages of EVs discussed in OHD schemes

Adressed topics	#
No connection between EVs and OHD in article	19
EVs are a general option in OHD schemes	4
EVs in OHD schemes can be more silent in comparison to diesel vehicles	5
EVs can be more profitable, if utilised in a day shift and a night shift	4

The topics "EVs" and "OHD" schemes are discussed as separate items in the majority of the identified papers (i.e. 19 papers). Both measures – exchanging conventional freight vehicles with EVs, or shifting deliveries to off-hours – are addressed as possible, but not interlinked, options in order to improve the sustainability of urban freight transport.

The authors of the remaining ten papers relate to EVs as a vehicle technology which is, or could potentially be, utilised in OHD schemes. Four publications briefly acknowledge EVs as a complimentary option to increase the sustainability of city logistics approaches, such as night delivery, mirco-consolidation centers or intermodal networks (Roumboutsos et al., 2014; Macharis and Milan, 2014; Macharis et al., 2013; Lebeau et al., 2013). Five papers discuss the EV advantage of a more silent transportation in OHD: Cavar et al. (2011) find that truck arrivals have 62% of the most important noise source in night delivery. Salama et al. (2014) examine the potential of green loading zones for New York City, USA. They conclude that the benefits of EVs – such as reduced noise and dependency on imported energy, as well as economic development opportunities – are significant and outweigh the effort of overcoming the barriers to installing green loading zones. Lützenberger et al. (2014) and Lützenberger et al. (2015) derive a combined model of intelligent energy and mobility services, by aggregating results of smart grid and electric mobility projects. In one of the reviewed projects – "Multi-shift operation and night delivery with electric commercial vehicles" (NANU) ("Mehrschichtbetrieb und Nachtbelieferung mit elektrischen Nutzfahrzeugen") – they report that medium-duty freight EVs are valuable when operated in residential areas, especially in multi-shift usage, due to the quieter electric motor. Moreover, the combined day and night shift doubles the utilisation of EVs and thus may result in a more efficient delivery performance. Taefi et al. (2013) carried out a multi-case research in order to generate an overview of freight EV-use cases in Germany. One of the cases refers to the NANU project: apart from the more silent delivery at night, here there are plans to deploy EVs in three shifts per day and they are thus expected to operate with a profitability. In a later publication, Taefi et al. (2015) aggregate 57 cases of freight delivery with EVs in the North Sea Region of Europe. They find that in two cases, companies deploy their EVs in multi-shift delivery or during the night-time. This enables the companies to exploit new business opportunities and to extend the range of the EVs, in order to operate the EVs profitably, compared to conventional trucks.

As a result, this review of the literature finds that none of the papers gives a full overview on the advantages or disadvantages of utilising EVs in OHD schemes, and none of them has proven

the assumed comparably lower costs, to date. This underlines the need to perform a total cost of ownership analysis for deploying EVs in double-shift. Further, in the following subsection the impacts of EVs in OHD schemes are clustered. Therefore, related results from the literature on either urban freight delivery with EVs, or off-hour delivery are considered, in order to position the results of the literature review performed above in a broader perspective.

2.1 The impact of electric freight vehicles on off-hours delivery schemes
Various stakeholder groups and their interests are affected by OHD schemes. These are clustered in Figure 1 in grey boxes.
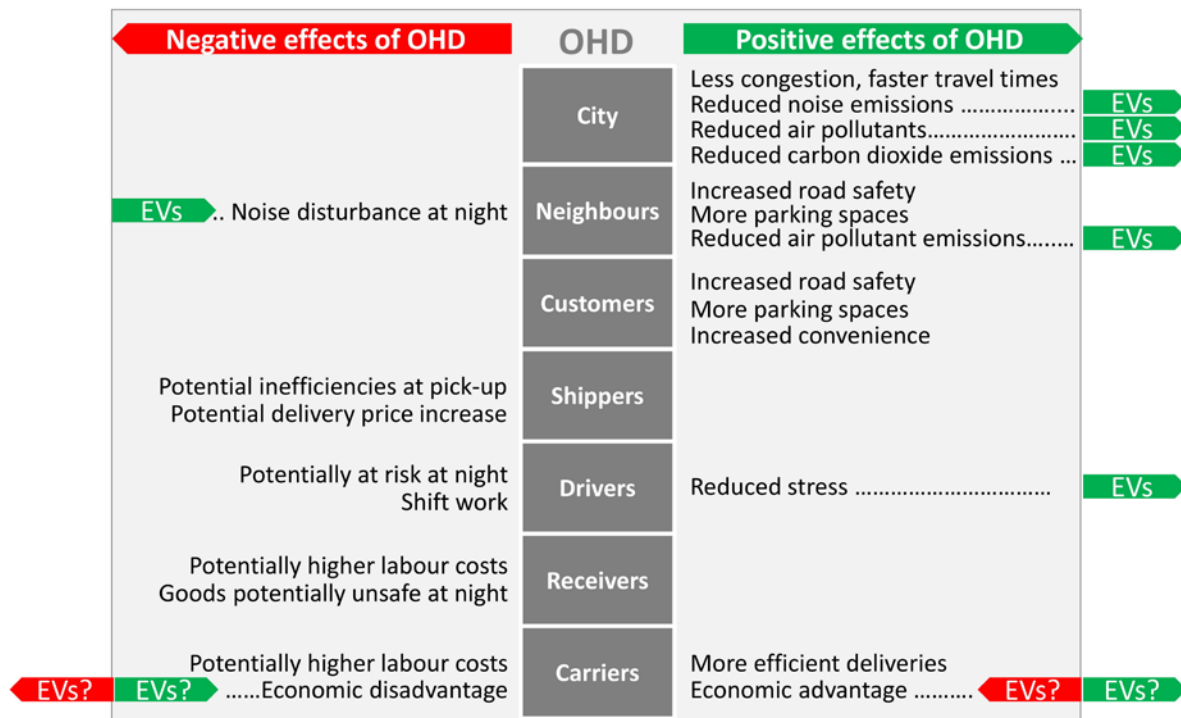

Figure 1. The impact of electric vehicles on stakeholder effects of off-hour delivery schemes

City dwellers benefit more from a fluid traffic and thus from overall and lower noise, CO_2 and air pollutant emissions (Balm et al., 2014; Cavar et al., 2011; Geroliminis and Daganzo, 2005; Roumboutsos et al., 2014; Silas et al., 2012). The objection of neighbours to potentially higher noise emissions at night is problematic (Balm et al., 2014; Cavar et al., 2011; Russo and Comi, 2010; Suksri et al., 2012). Noise might be reduced by implementing a certified silent delivery chain (Dizian, 2012) which includes more silent EVs (Lützenberger et al., 2015; Wang et al., 2013). Neighbours and customers benefit from enhanced road safety; since traffic of heavy delivery vehicles and second- row parking is reduced, passengers can cross the streets more safely (Cavar et al., 2011; Silas et al., 2012). Additionally, the shopping convenience for customers can increase, since the shop staff have more time for the customer requests in daytime, and goods are not stored in the aisles and refilled during the daytime (Cavar et al., 2011; Silas et al., 2012). For shippers the time of the delivery has no impact, as long as the product reaches its destination on time, unless they experience delivery price increases and inefficiencies during the pick-up process leading to higher costs (Holguín-Veras et al., 2005). Drivers, on the one hand, feel less stressed due to the predictable times of arrival, closer parking to the receiver, reduced probability of fines, and generally lower traffic level in New York City (Holguín-Veras et al., 2013). On the other hand, their safety, as well as the safety of the goods, is problematic in some delivery areas (Balm et al., 2014; Cavar et al., 2011; Holguín-Veras et al., 2005). Furthermore, the negative effects of shift-work on

humans are well researched. For carriers, OHD can be financially attractive (Cavar et al., 2011; Holguín-Veras et al., 2005; Holguín-Veras, 2010, 2011; Silas et al., 2012). Night delivery can increase the efficiency of the delivery vehicles, due to the shorter time per delivery in the less-dense traffic, the faster and easier possibility to find a space for loading and unloading of goods, and reduce the costs for parking ticket violations (Holguín-Veras et al., 2005). However, the additional costs for off-hours labour or increased insurance and security costs can reduce or even outweigh the advantages of a more fluent delivery (Cavar et al., 2011; Holguín-Veras et al., 2005). While off-hour delivery schemes can be attractive for carriers, receivers often perceive an economic loss due to the need for additional staff to receive the freight at night (Cavar et al., 2011; Dizian, 2012; Holguín-Veras et al., 2005; Suksri et al., 2012). This financial disadvantage often cannot be compensated by soft advantages, such as increased customer convenience (Holguín-Veras et al., 2005). In order to reduce costs for the receiver, staff-less handover of the goods is tested in various projects. Examples are the German project "Urban Retail Logistics", where a mobile freight container was developed and tested, which can be deposited at the customer premises; in New York City, similar delivery lockers or containers were tested, in other cases the drivers received the key to access the stores, or secured area for delivering (Holguín-Veras et al., 2012, 2013; Wojtowicz et al., 2015). A complementary option is to subsidise the receivers, financed by the main beneficiaries of OHD schemes; the city or municipality (Holguín-Veras et al., 2005; Holguín-Veras, 2010, 2011; Holguín-Veras et al., 2013; Silas et al., 2012).

The impacts of EV usage are extracted from the literature by means of a qualitative analysis. The findings are inserted into the compilation of the effects of OHD schemes of Figure 1 by red and green arrows, indicating respectively the impairment or improvement of the scheme. Deploying EVs in OHD schemes has positive effects for city dwellers and neighbours close to the area where the goods are delivered to. It is commonly understood that EVs are free of tailpipe emissions, thus reduce CO_2 and air pollutant emission during off-hours delivery. For trucks up to 20 tons, the noise emission from the drivetrain is dominant over the tyre noises up to 50 km/h (Steven, 2011). (Steven, 2011). Hence, electric delivery trucks up to 20 tons with a more silent electric motor reduce noise emissions during night-time delivery (Salama et al., 2014), especially when approaching, or departing from, residential areas (Cavar et al., 2011; Ltzenberger et al., 2015). However, other important noise sources in the delivery chain, i.e., generated by the drivers, or by loading or unloading goods (Holguín-Veras et al., 2005), are not reduced. The absence of vibrations and the lower noise of the electric trucks can additionally reduce the stress level of drivers (Taefi et al., 2016). With regard to the other listed aspects of OHD schemes it is irrelevant if an EV or conventional vehicle is utilised to deliver goods during off-hours. Whether EVs present an additional cost factor in a combined day and night shift, or whether they reduce the transportation costs for the carriers, is analysed in the next section with exemplary TCO calculations.

2.2 Total cost of ownership calculations

TCO calculations are a common method within the transport industry to calculate vehicle costs during the vehicle life cycle, from purchasing to selling or scrapping. Various TCO calculations that have been performed before are described within the literature, in order to compare the overall costs of electric commercial vehicles to conventional (diesel), or hybrid and gas vehicles. This paper researches the effect of a higher mileage on the TCO of medium-duty freight vehicles, since vehicles utilised in night delivery are usually medium- or even heavy-duty vehicles. For this reason, TCO comparisons on passenger vehicles, as for example carried out by Gass et al. (2014) and van Vliet et al. (2010) are not considered in the following review.

Macharis et al. (2013) compare the TCO of eight battery electric vehicles, five diesel vehicles and two petrol vehicles utilised for commercial transport purposes. They conclude that all of the compared electric quadricycles and two of the three light commercial electric vehicles have a lower TCO than the vehicles with combustion engines. However, they found that both of the medium-duty EVs are more expensive in comparison. Their sensitivity analysis shows that a 50% reduction of the battery

price would have the largest effect for those EVs, which have large batteries or require frequent battery changes. A similar paper was presented with a different order of authors in Lebeau et al. (2013). Due to the similarities, the latter paper is not considered further. In a more recent work, Lebeau et al. (2015b) exclude the medium-duty EVs from the TCO and focus only on light electric freight vehicles. They conclude that the tested light commercial EVs are competitive against petrol vehicles, but not against diesel vehicles. However, in a sensitivity analysis the authors find that with an increased utilisation, the EVs break even with the diesel vehicles at between 16,000 and 25,000 km per year. Furthermore, the authors conclude that the EVs should be sold right before a necessary battery replacement, in order to decrease the TCO. In a further publication, Lebeau et al. (2015a) implement the TCO approach into a fleet size and mix vehicle routing problem with time windows for EVs. They indicate that large electric vans need to cover a very high mileage before becoming cost-competitive. Lee et al. (2013) compare medium-duty diesel and electric delivery trucks with regards to their life cycle energy consumption, greenhouse gas emissions and TCO in the USA. They calculate the TCO for two freight EV types in several drive cycles. They conclude that only for urban drive cycles with frequent stops and low average speeds – such as the New York City Drive Cycle – the median of the EVs' TCO is, on average competitive over an array of possible conditions. On the New York City Drive Cycle the vehicles become more cost-effective when the achievable lifetime vehicle kilometres travelled are high, and when at the same time no battery change is necessary. Feng and Figliozzi (2013) carried out a TCO calculation in order to compare the TCO of an electric and a conventional medium-duty freight vehicle for a fleet replacement model in the US market. They point out that freight EVs can only become competitive in scenarios with a high utilisation, especially if a battery replacement is required. Davis and Figliozzi (2013) combine four models i) a TCO calculation, ii) a model to calculate the power consumption and hence the range of the EVs, iii) a model for including routing constraints and iv) a model to describe the real-world travel speed profiles, in order to examine the competitiveness of medium-duty freight EVs. They conclude that the EVs become more competitive in scenarios where a combustion engine performs inefficiently (frequent stops with idling motor during deliveries or in congested urban traffic) and the vehicle utilisation is maximised (high daily mileage and long planning horizon).

A general conclusion of existing TCO calculations for freight vehicles is that light electric commercial vehicles can already be competitive against conventional models, under certain prerequisites. Medium-duty vehicles often utilise large and costly batteries, hence they need to drive a higher daily mileage in order to amortise. Authors researching the TCO of freight EVs note the importance of a high vehicle utilisation in achieving a cost-efficient operation, on the one hand. On the other hand, they describe the diminishing effects of a battery replacement on the TCO. So far, the technical prerequisites for, and economic effects of, a very high usage, such as a combined day and night shift, have not been researched.

3. Methodology

The TCO is calculated with equation 1, based on the net present value methodology utilised in Lee et al. (2013); Lebeau et al. (2013, 2015b); Macharis et al. (2013) and Gass et al. (2014):

$$TCO = \sum_{t=0}^{N} (1 - R + c_t)(1 + r) \tag{1}$$

From equation 1 it can be seen in the TCO at a certain point in time is a sum of three components: The residual value R, discounted by the discount factor r is deducted from the discounted purchase price of vehicle and replacement batteries I in year t. The discounted costs for operation and maintenance of the vehicle c_t are added annually for the number of years N, until the vehicle is scrapped or sold.

The TCO calculations in this paper are carried out in order to test if a medium-duty electric truck

can be more competitive in double-shift utilisation than in singe shift. Thus, the difference between the costs of the TCO of an electric and a diesel vehicle is calculated for single- and double-shift utilisation according to equation 2:

$$\Delta TCO = TCO_{EV} - TCO_{Diesel} \tag{2}$$

Mass produced medium-duty electric vehicles do not exist yet. The models in the market are converted from existing conventional vehicle models. For this reason, the medium-duty EVs tested in this calculation can be directly compared to an existing conventional "sibling", which has similar technical characteristics, except for the drivetrain. In an exemplary calculation the 7.5-ton Toyota Dyna 200 diesel model is compared to a conversion by Emoss named Dyna EV200; and a 5-ton Mercedes Sprinter is compared to a conversion by German E-cars called "Plantos" Hence, two sets of calculations are carried out for each two-vehicle pair, comparing the costs in single- and in double-shift usage (see Table 2).

Table 2. Tested TCO calculations

Tested scenarios	Singe-shift	Double-shift
5 t EV vs. 5 t diesel	Δ TCO 1	Δ TCO 2
7.5 t EV vs. 7.5 t diesel	Δ TCO 3	Δ TCO 4

The EV manufacturers (Emoss and German E-Cars) and the general European importer of the Toyota Dyna provided recent information about the prices and technical details of the vehicles from a datasheet (German E-Cars, 2015) via email and telephone communications. With the Mercedes Online-configurator, a Mercedes Sprinter panel van was chosen. The criteria were set to configure a vehicle with internal combustion engine (ICEV) that was as similar as possible to the Plantos. The vehicle selected is a Sprinter 513 CDI with a long wheelbase, very high roof and 95 kW Euro VI motor without BlueEfficiency packet and with automatic gear shift. Further information on the Sprinter was retrieved from the datasheet of Mercedes-Benz (2015).

4. Results of the TCO calculation

The vehicle parameters which are set as input parameters for the TCO calculation, such as the purchase price, fuel consumption and battery parameters are listed in Table 3.

Table 3. Details on the compared vehicle characteristics

Vehicle parameters	Sprinter ICEV	Sprinter EV	Dyna ICEV	Dyna EV
Fuel consumption [l/km] for diesel models / Energy consumption [kWh/km] for EVs				
Vehicle model	Sprinter 513	Plantos	Dyna 200	Dyna EV 200
Manufacturer	Mercedes	German E-Cars	Toyota	Emoss
Gross vehicle weight [t]	5.0	5.0	7.49	7.49
Purchase price[a] [€]	48,518	95,000	31,765	110,000
Fuel consumption [l/km] for diesel models / Energy consumption [kWh/km] for EVs				
NEDC	0,0853[b]	0,32	0.099[b]	0,75
Assumed realistic	0,153	0,464	0,173	1,088
Battery parameters				
Battery energy [kWh]	n.a.	38,6	n.a.	120
Battery type	n.a.	Lithium ion	n.a.	Lithium iron phosph.
Range [km]	n.a.	120	n.a.	160
Battery warranty	n.a.	2,000 cycles	n.a.	100,000 km or 3 years
Duration full charge [h]	n.a.	14 (230V/16A)	n.a.	n.a.
	n.a.	2.5 (400V/32A)	n.a.	8 (380V/32A)

[a]Excluding VAT
[b]Fuel consumptions for the standard platform model (Toyota Dyna), standard model (Mercedes Sprinter)

As base country for all parameters, Germany is chosen. In order to compare the costs of the vehicles

only, neither purchase price subsidies for EVs, nor the one-time investments in charging infrastructure for the EVs, are included in the comparison. In Germany, purchase price subsidies are only available in certain regional pilot projects in the year 2015. While the charging infrastructure can be a relevant cost factor (Lee et al., 2013), investing in new charging infrastructure might not be a necessity for every company. Hence, the additional costs for the charging infrastructure are excluded, similar to the TCO calculation of Lebeau et al. (2015b). In order to discuss the effects of subsidies and charging infrastructure costs, these factors are discussed in a scenario analysis. With 6.7%, the weighted average cost of capital of the transport and leisure industry was very low (KPMG, 2015), while with -0.83% the base interest rate was even negative in the year 2015 in Germany (Bundesbank, 2016). Hence, the opportunity costs of the capital, reflected in the discount rate, are rather low. Thus, the discount rate is set to 5% and varied in the elasticity analysis in Section 4.4.

The calculation model foresees a high annual mileage and a long usage period of eight years (cf. Section 4.3). Thus, it can be assumed that the residual values of the vehicles (not the EVs batteries, see below) are zero and the vehicles are scrapped at the end of their life. Since the goal of the TCO calculation is to identify cost differences, the costs which are similar for both vehicles such as the vehicle bodies, in case of the Dyna pair, or costs for scrapping can be neglected and are not discussed further. This is possible, since the TCOs compare technically identical vehicles – with the exception of the drivetrain and battery, the latter being calculated separately.

The manufacturer indicated that the Emoss Dyna EV consumes 0.75 kWh/km. However, the energy consumption of a vehicle depends on many factors, such as the payload, the ambient temperature, the topography, the traffic's velocity, or the driver's behaviour. In a real-world drive cycle, a fleet of medium-duty EVs consuming 0.8 kWh "in good conditions" – according to the manufacturer – consumed 1.15 kWh/km, or +44% on average in practice (Prohaska et al., 2015). A standard test procedure, such as the UN ECE-R101, is utilized for passenger vehicles and based on the NEDC drive profile, leads to more comparable results. De Cauwer et al. (2015) find that the realistic energy consumption of the small electric delivery van Renault Kangoo ZE, is 48% higher than measured according to the NEDC. For commercially-used conventional passenger vehicles, Mock et al. (2014) reported a similar difference of 45% between the measured fuel consumption according to the NEDC and real world data in Europe for the year 2013. Hence, the current study assumes that the data for the energy and fuel consumption have to be corrected on average by +45% for both technologies, in order to reflect a realistic consumption.

For the diesel models additional corrections have to be included: The standard platform model of the conventional Toyota Dyna 200 consumes 9.9 litres per hundred kilometres in combined driving, according to manufacturer. An additional two litres are added, to factor-in the increased wind resistance when the vehicle is fitted with a box. Corrected by the factor of +45% the vehicle is assumed to realistically consume 17.3 litres of diesel per 100 km when driving in a city. Similarly, 2 litres per hundred kilometres are added to the consumption of the Mercedes Sprinter, to factor in the higher drag for a high roof and long wheelbase panel van version. The realistic fuel consumption of the Mercedes Sprinter, corrected by the factor +45%, amounts to 15.3 litres per 100 km. Due to the uncertainties of these assumptions, the energy and fuel efficiency of all vehicles are included in the elasticity analysis in Section 4.4.

The batteries of electric vehicles degrade over time and when being discharged and recharged (Conti et al., 2015). Vehicle manufacturers define that batteries reach their end-of-life when their remaining energy, which is equivalent to the capacity, reaches 80% of the initial value (Conti et al., 2015; Narula et al., 2011). This TCO calculation applies the pessimistic assumption that the EV batteries need to be replaced once the warranty expires. Further, used EV batteries can be utilised in stationary applications at the end of their vehicle battery life (Neubauer and Pesaran, 2011; Narula et al., 2011). The calculation model assumes that the used EV battery with 80% capacity can be sold at 50% of the current price of a new battery on the second-hand market, based on the study on used

EV batteries by Narula et al. (2011).

4.1 Costs for operation and maintenance

Operational costs are either to be paid annually (insurance, circulation tax or road worthiness and emission testing); or are dependent on the driven mileage (energy or diesel consumption, service and maintenance). These costs differ in different European countries. The costs for the road worthiness testing and insurance are assumed to be similar for the compared vehicle pairs, thus are neglected in the calculation. The costs utilised in this TCO calculation are summarised in Tables 4 and 5.

The circulation tax is waived for EVs in Germany for ten years, when purchasing an EV before the end of 2015, which is the case with this model. The tax for the conventional vehicles is calculated based on an Online calculator provided by the German Federal Ministry of Finance. An emission testing is not necessary for EVs, since they are free of tailpipe emissions. A comparative case study of freight initiatives in six European countries summarises that companies report lower values for the costs of servicing and maintenance of their EVs; for example, due to less movable parts, but the study does not quantify the reductions (Taefi et al., 2016). Due to the unavailability of data, this study bases the costs for service and maintenance for the diesel vehicles on Feng and Figliozzi (2013). They assume in their baseline scenario that the maintenance costs of an EV are US$ 0.02 per mile per year (€0.187), which is equivalent to 50% of a conventional vehicle.

Table 4. Details of the costs for operation and maintenance

Operational and maintenance costs p.a.	Sprinter ICEV	Sprinter EV	Dyna ICEV	Dyna EV
Circulation tax [€]	173 / n.a.	285	n.a.	
Emission test [€]	10	n.a.	10	n.a.
Service and maintenance [€/km]	0.043	0.022	0.043	0.022

Table 5. Yearly estimations for energy, fuel, and battery price

Parameter	2016	2017	2018	2019	2020	2021	2022	2023	2024
Battery [€/kWh]	284	244	210	193	178	163	150	138	127
Diesel [€/l]	1.183	1.190	1.197	1.203	1.210	1.213	1.217	1.220	n.a
Electricity [€/kWh]	0.141	0.146	0.150	0.155	0.159	0.163	0.166	0.170	n.a.

The recent and projected costs for EV batteries are researched in a study by Nykvist and Nilsson (2015), who performed a comprehensive research of 85 cost estimates of EV battery prices and learning rates. The learning rate indicates the price decline per cumulative doubling of production in percent (Weiss et al., 2012). Nykvist and Nilsson (2015) report an average price of US$ 410 (€385) per kWh in 2014, and also that the prices will fall to US$ 230 (€216) in period 2017 to 2018 with an average learning rate of 14%±6%. The cost for market-leading manufacturers was at $ 300 per kWh in 2014 and the cost declines with a learning rate of 8%±8%. The costs for the whole industry and the market leaders will converge when prices reach US$ 230 per kWh, which will be in period 2017 to 2018. However, the authors acknowledge that there is still a high uncertainty in their projections due to "sparse data". For this reason, the elasticity of the battery prices is tested in Section 4.4.

Long-term prognoses for the energy and diesel price development are naturally subject to uncertainties. The prognosis for the energy price in this TCO calculation is based on the energy prognosis developed in a comprehensive study for the Federal Ministry of Economic Affairs and Energy (Schlesinger et al., 2014, pp. 225-227). According to the study, the wholesale prices of energy will fall until 2020, due to an increasing share of renewable energies. However, in summary the energy prices are projected to rise, as a consequence of the costs for expanding the grid infrastructure for the renewable sources. The study projects that the costs for industry customers will increase from €0.119 per kWh in 2011, to €0.159 per kWh in 2020, and further to €0.177 per kWh in 2025 (excluding VAT).

The utilised prognosis for the development of the diesel price is taken from Brokate et al. (2013). Those authors developed a scenario analysis for the passenger car market up to 2040 and based their projections of the diesel price on information from the International Energy Agency. Their study assumes that the price for diesel will rise from €1.14 per litre in 2010 to €1.21 per litre in 2020 and to €1.24 per litre in 2030 (excluding VAT).

The feasibility of the projections is tested by comparing the interpolated value for the year 2014 with the realistic average values in Germany in year 2014. The average diesel price for consumers was €1.13 per litre, the average price of electrical energy for companies consuming between 2,000 MWh to under 20,000MWh was €0.135 per kWh (both without 19% VAT) (Statistisches Bundesamt, 2015). Assuming linear price increases, the interpolated values from the diesel price prognoses for 2014 are €1.17 per litre diesel and €0,135 per kWh electrical energy. With errors between 2 and 3%, both prognoses can be accepted as sufficient for the basic TCO calculation; however, the prices will be included in the elasticity analysis and the currently lower diesel prices will additionally be discussed in the scenario analysis.

4.2 Parameters of the calculation model

This manuscript tests the hypothesis that electric vehicles can be more cost efficient than their conventional sibling at a high annual mileage in double-shift usage. As parameters for the calculation model, a mileage of 100 kilometres per shift and an utilisation of eight years are set. The model assumes that the vehicles are purchased in the last days of December 2015 and are deployed from the beginning of 2016, onwards. Assuming 250 working days per year, the annual mileage amounts to 25,000 kilometres and 250 battery cycles (one shift per day) or 50,000 kilometres and 500 battery cycles (two shifts per day). Only the full battery recharge between the shifts is counted as a cycle, and the necessary small battery boosts during loading or unloading of the freight (see below) are neglected. This seems feasible, as recent research indicates that recharging smaller levels at a low battery state of charge does not reduce the battery lifetime significantly (Conti et al., 2015). According to this driving and charging pattern, the batteries of the EVs reach the end of their warranted kilometres or cycles at the following times:

- Dyna EV in single-shift usage: at the beginning of year five; in double-shift usage: at the beginning of years three, five and seven. In both scenarios the battery reaches the end of its life in the last shift of year eight and is sold at the beginning of year nine.

- For the Sprinter EV the battery does not need to be replaced in single-shift usage, but it is at the end of its life at the end of year eight, and can be sold on the second-hand market at the beginning of year nine. In double-shift usage a new battery is needed at the beginning of year fife. This battery can then be sold at the beginning of year nine.

The daily maximal range of an electric vehicle is limited by the size of the battery, the energy consumption and the time necessary for recharging the vehicle. Thus, an evaluation is needed if the EVs utilized in this model firstly can realistically cover the desired distance of 100 kilometres of a single shift even in the worst-case scenario at the batteries end of life. Secondly, the duration of fully recharging the batteries has to be considered, in order to understand whether the EVs can be utilised in a double shift scenario. Based on the assumed realistic energy consumption, the Sprinter EV has a realistic range of 83 km with a fresh battery and a range of 67 kilometres at the end of the battery life. Hence, enough energy to cover the remaining 33 kilometres needs to be added by recharging during the shift in the worst-case scenario. The battery of the Sprinter EV is fully charged within 2.5 hours. This means that the vehicle needs to be charged for 73 minutes during the shift, assuming a linear charging time, in order to be able to cover the remaining 33 kilometres. This is a feasible time, since the charging can take place i.e. during the drivers breaks or when loading and unloading of goods. Fully recharging the battery before the start of the next shift is also possible with the Sprinter EV.

The Dyna EV has a specified range of 160 kilometres per battery charge, based on the NEDC

profile. When considering the more realistic energy consumption according to Table 3, the vehicle has a maximal range of 110 kilometres with a fresh battery and 88 kilometres if the battery is at the end of its life. In the latter case, the Dyna EV will need to recharge energy to cover the remaining 12 kilometres distance during each shift. Charging electrical energy to cover 88 kilometres takes 8 hours. Assuming linear charging characteristics, the vehicle will need to be charged for 65 minutes per shift, to be able to attain a range of 100 kilometres per shift. Similar to the Sprinter EV this is a feasible time. Meeting the second constraint to recharge the batteries between the day and the night shift is more problematic with the Dyna EV. The vehicle needs 8 hours to recharge its batteries to 100%, thus, needs to charge for a total of 16 hours per day, while at the same time being deployed in two shifts. This is only theoretically possible when the EV is charged for about four additional hours per shift, i.e., 30 minutes per hour, during breaks and whenever freight is loaded or unloaded. A study with data from real-world delivery with medium-duty electric vehicles indicates that during a delivery shift, at least a similar time to driving is spent on being parked, for loading or unloading the vehicle (Prohaska et al., 2015). The assumed double-shift schedule leaves three hours per shift to travel the distance of 100 kilometres between the destinations for loading and unloading. At a minimal speed of 33 kilometres per hour, this seems possible for regional or urban deliveries, especially during off-hours. However, the constraint in this theoretical setup considerably limits the usability of the Dyna EV in a realistic setting.

4.3 TCO calculation and implications

Figure 2 shows the comparison of the costs of the 5-ton electric Plantos and a comparable Mercedes Sprinter ICEV when deployed in single-shift (left) or double-shift (right). The bar graphs indicate the costs each year, excluding certain costs which are similar to both compared vehicles, such as insurance, road worthiness testing or costs for scrapping, as described in Sections 4.1 and 4.2. At the end of year zero (2015) the vehicles are purchased and afterwards operated for eight years (2016 2023). At the beginning of year nine the vehicles are scrapped and the battery of the EV sold to the second-hand market. Furthermore, the black line in Figure 2 shows the cumulated TCO differences according to equation 2.
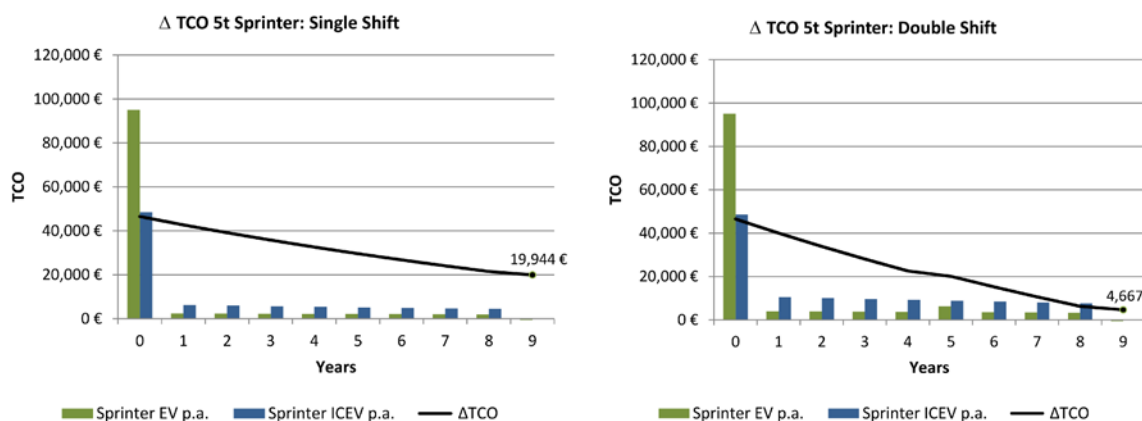

Figure 2. TCO difference of the conventional 5 ton Mercedes Sprinter and Plantos EV

From the bar graphs it can be seen that the Sprinter EV's battery does not need to be replaced in single-shift usage. The replacement in double-shift usage at the beginning of year five is not very expensive, since the EV only has a relatively small battery of 38.6 kWh and battery prices will have fallen to €178 per kWh in year 2020. Notwithstanding, in both scenarios, the EV is more expensive than the diesel vehicle, but the cost difference decreases with every year of operation.

This result is consistent with the findings in earlier TCO studies, as described in Section 2.2. A further observation is that the TCO gap of the Sprinter EV is smaller when operated in double-shift. The discounted per kilometre cost difference decreases by 7.64% in double-shift, compared to

single-shift usage. This supports the hypothesis that a double-shift operation of EVs can be more competitive. In this scenario, the Sprinter EV would break-even in the tenth year of operation, hence it would have a lower TCO than the Sprinter ICEV when operated for at least ten years in double-shift. Figure 3 displays the results for the comparison of the electric and conventional 7.5 ton Dyna 200.

In both scenarios – single- and double-shift – the electric Dyna is clearly more expensive that its conventional sibling. The purchase prices of the new 120 kWh large battery at the beginning of year five in single-shift, and at the beginning of years three, five and seven in double-shift increase the TCO gap significantly. Only in single-shift operation the lower operational costs can offset the necessary investment for the replacement battery at the end of year eight. In double-shift usage, the frequent replacements lead to a scenario, where the TCO of the Dyna EV becomes less favourable than in single-shift operation. Operating the Dyna EV in double-shift increases the discounted cost difference per kilometre by 5.5%. In conclusion, for this vehicle the assumption generally found in the literature, that a higher utilisation automatically leads to a reduced TCO is not true. Similarly, for this vehicle, the hypothesis that EVs in double-shift usage are more competitive than in single-shift usage, must be rejected.
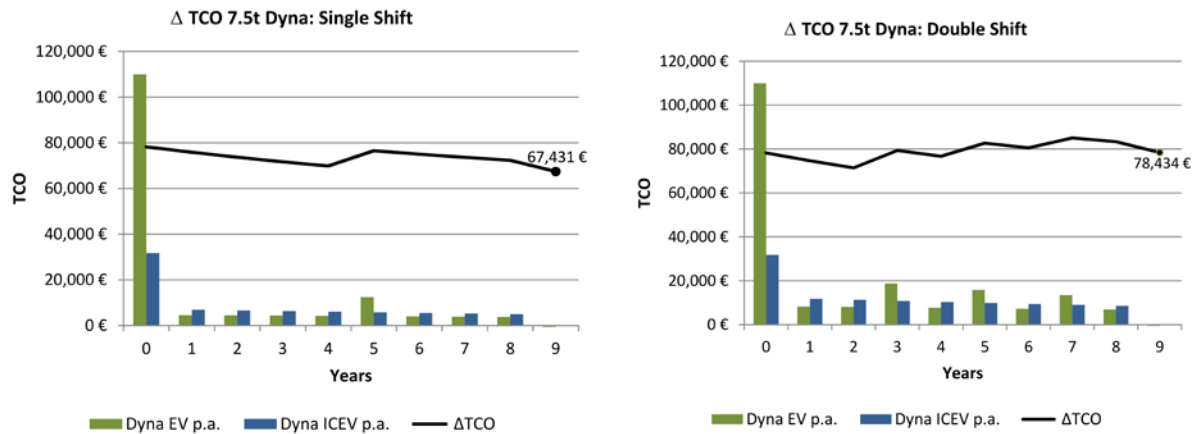

Figure 3. TCO difference of the conventional 7.5 ton Dyna 200 and Dyna EV 200

4.4 Elasticity analysis

An elasticity analysis is performed in order to understand which factors lead to the differences in the TCOs, apart from the need for battery replacement and higher kilometres travelled. The elasticity η_x^c is computed in a similar manner to Feng and Figliozzi (2013), by assuming a range for parameter x and computing the cost differences of the per kilometre delta costs c with equation 3.

$$\eta_x^c = \frac{(x_1 + x_2)}{(c_1 + c_2)} \cdot \frac{(c_2 - c_1)}{(x_2 - x_1)} \tag{3}$$

The factor with the highest absolute elasticity has the largest influence on the costs, as compared in Table 6. This is the case for the discount rate in Δ TCO 2 (35.81). This value means that if the discount rate is increased by 1%, the discounted cost difference rises from ¤0.01 per kilometre by 35%. The Sprinter EV in Δ TCO 2 has nearly similar overall costs as the compared Sprinter diesel vehicle. For this reason, increased investments, reflected in a higher discount rate or increased EV, lead to a relatively high increase in the price gap. Any price increase of 1% for factors in Δ TCO 3 and 4, on the contrary, have a relatively lower impact on the elasticity results, since the price gap of the EV compared to the Dyna ICEV is large.

The alternating sign of the elasticity of the battery price and size can be easily explained: Increasing the battery prices or sizes by 1% reduces the TCO gap in the $\Delta TCO1$ calculation, but increases the gap in the calculation of Δ TCO 2 to 4. The purchase price of the EVs is fixed, but the battery

in $\Delta TCO1$ does not need to be replaced and fetches a higher resale value at the end of the TCO calculation period, whereas the batteries in the other TCO calculations need to be replaced at higher costs.

Table 6. Per kilometre discounted cost elasticity factors

Parameter	Δ TCO 1	Δ TCO 2	Δ TCO 3	Δ TCO 4
Vehicle technical factors				
EVs purchase price	4.76	20.36	1.63	1.40
Diesel vehicles - fuel consumption	- 1.48	-12.68	- 0.50	- 0.86
Diesel vehicles - purchase price	- 2.43	-10.40	- 0.47	- 0.40
EVs energy consumption	0.58	4.98	0.40	0.96
Diesel vehicles - maintenance costs	- 0.61	- 2.59	- 0.18	- 0.15
EVs maintenance costs	0.30	1.29	0.09	0.08
Price projections				
Discount rate	5.51	35.81	0.81	0.06
Diesel fuel price	- 1.48	-12.68	- 0.50	- 0.86
Electric energy price	0.58	4.98	0.40	0.69
Battery price or size	- 0.08	0.24	0.05	0.26
Battery resale price	- 0.16	- 1.83	- 0.39	- 0.78

Overall, the fuel consumption and prices of the diesel vehicles show the largest elasticity, after the discount rate and the purchase prices. Other factors are lower than the influence of operating the EV in single- or double-shift. Thus, this analysis supports the finding of Feng and Figliozzi (2013), that the discount value has the largest impact on the TCO calculation. However, the current study finds that a longer planning horizon, such as suggested by Feng and Figliozzi (2013), does not automatically lead to a higher competitiveness for every EV. A longer planning horizon only leads to more competitive results for the EV, if the investment for the new battery can be offset by the lower operational costs. Furthermore, Lebeau et al. (2015b) suggest selling the EV only at the end of the battery lifetime. The calculation in this paper supports this finding, but moreover suggests that EVs have individual optimal daily mileages (influencing the need for battery replacements) at which they could be operated, in order to maximise their TCOs.

5. Discussion

The calculations suggest that the TCOs of both exemplary calculated EVs are not competitive compared to a similar ICEV within an eight years operational period in Germany. The comparison of the distance travelled (100 vs. 200 km/day) indicates that the daily average mileage is an important influencing factor for the TCO. Further, the elasticity analysis finds that the largest influencing factors of the TCOs are the discount rate and the EV purchase price, followed by the cost of diesel fuel and the diesel consumption. Despite their impact, potential EV purchase price subsidies, as offered in some European countries, as well as the potential costs for the additional (quick-) charging infrastructure when purchasing an EV, have not been included in the TCO calculation. Furthermore, an estimation of realistic fuel consumption was included in the TCO calculation; but the recent oil price decline is not reflected in the utilised price projection, which led to diesel prices of below €1.00 at filling stations at the end of 2015 in Germany.

A scenario analysis is carried out, in order to analyse the impact of these factors and to discuss the potential effects of selected fiscal subsidies on the utilisation of EVs in a combined day and night double-shift delivery. In a practical application, the long recharging time of the Dyna EV battery limits the double-shift usage, as discussed in Section 4.2. Hence, the scenario analysis is limited to the re-calculation of the Δ TCOs for the 5 ton Sprinter EV and ICEV in the following scenarios:

- The costs for the set-up of quick-charging infrastructure depend upon the circumstances, technology utilised and the number of vehicles between which the costs can be

distributed (Lee et al., 2013). This paper tests a scenario in which the cost of the required quick-charging infrastructure for one Sprinter EV is €10,000.

- The impact of two purchase price subsidies are studied: a) a €3,000 price subsidy, currently discussed for commercially utilised vehicles in Germany; b) a 36% environmental investment allowance, which equals €34,200 in the case of the Sprinter EV, is offered in the Netherlands (Netherlands Enterprise Agency, 2015).

- The diesel price provided in the projection is decreased by 20% over the calculation period, which leads to a currently realistic price of €0.99 per litre (including VAT) in 2016.

- The final scenario regards raising the tax on diesel fuel by €0.184 (excluding VAT), in order to match the rate of taxation on petrol in Germany.

The results of the calculation are summarized in Table 7.

Table 7. ΔTCO of the 5 t Sprinter vehicles in different scenarios

Scenario	Baseline	Infrastructure €10,000	Purchase price subsidy		Diesel price adjustment	
			€1,000	36%	-20%	+18.4%
Single-shift [€]	19,944	29,944	16,944	14,256	27,874	11,956
Double-shift[€]	4,667	14,667	1,667	29,533	20,527	11,309

Unsurprisingly, an inclusion of quick-charging infrastructure costs linearly increases the cost gap between the ICEV and the EV (€29,944 in single-shift / €14,667 in double-shift), while purchase price subsidies have the opposite effect. Since the Sprinter EV becomes more competitive as the kilometres that are driven increase, the TCO of the EV is nearly similar to the ICEV in double-shift operation with a low purchase price subsidy of €3,000 (€1,677). If a high subsidy such as in the Netherlands would be offered, the EV would be more profitable regardless of the driven mileage (€-14,256 / €-29,533). Hence, supporting the investment into electric vehicles or charging infrastructure could help companies to overcome the cost gap of medium-duty EVs, although it would not encourage them to deploy the EVs in a combined day and night double-shift.

If the diesel price stays at 20% below the applied projections, then the operation of EVs becomes generally less attractive, since the cost gap between ICEVs and EVs grows. Furthermore, due to the increased operational costs of EVs in this scenario, the difference between higher- and lower-mileage operations would decrease (€27,874 / €20,533). On the contrary, a higher mileage scenario becomes more attractive if the per kilometre costs of ICEVs are penalised by raising the diesel tax to a similar level as the petrol tax (€11,956 / €-11,309). A similar effect could be achieved by implementing a city toll for freight vehicles, for example.

6. Conclusion

This manuscript researches the viability of EVs in OHD and finds that, thus far, EVs and OHD have mostly been perceived as two possible, but non-interlinked measures to mitigate the negative effects of urban road freight transport. Hence, this paper presents a compilation of an overview on the state-of-the-art with respect to how utilising EVs can amplify the advantages of OHD schemes. Utilising EVs in OHD schemes further decreases the noise, air pollutant and CO_2 emissions, which would be already mitigated when implementing an OHD. Especially, during the vehicle's approach and departure at night-time, EVs can significantly lower the noise level and hence raise their acceptance by residents. However, shippers have to ensure that the complete OHD chain is below a certain noise level.

This paper further contributes to the scientific body of knowledge by exemplarily exploring the financial viability of medium-duty EVs in high mileage scenarios. The hypothesis is tested that EVs that are deployed in combined day and night shifts – double-shifts – are more likely to be competitive, compared to conventional diesel vehicles. The results of exemplary model calculations quantify potential savings but show that the hypothesis only can be accepted if

certain conditions apply. A model calculation showed that increasing the mileage leads to more frequent battery replacements due to battery aging. In the case where the battery is not safeguarded by a long warranty, its expensive replacements can overcompensate the economic advantage of the operational costs of EVs. This can especially be the case if the energy efficiency of EVs is low, while the compared ICEV is rather fuel efficient, or if the costs of diesel are low. This is a novel contribution, since all TCO calculations for freight EVs in the literature have concluded that EVs become more competitive with increasing utilisation.

6.1 Implications for policymakers and practitioners

For practitioners who aim to introduce freight EVs in a combined day and night delivery, the above finding is essential. It suggests that before purchasing a specific EV, the cost-optimal mileage of the vehicle should be calculated, in order to understand whether the vehicle characteristics comply with the desired tour-lengths, or whether it is possible to adapt the tour planning. In the applied scenario, the EVs may only become competitive with a comparable diesel vehicle when they are deployed on cost-optimal tour lengths; and only then they might be utilised in larger quantities, in order to enhance the benefits of OHD, such as reducing congestion and emissions.

The elasticity analysis showed that, besides the high purchase prices, the current low oil price is a major obstacle to the adoption of freight EVs. To policymakers, the results of the scenario analysis imply that a purchase price subsidy could support the uptake of freight EVs. However, in the current period of low diesel fuel prices, a very high purchase subsidy would be necessary to compensate for the lower operational cost advantage of EVs. The scenario analysis examines an increase of the per-kilometre costs of diesel freight vehicles as an alternative policy option. As an example, abolishing the tax advantages of diesel fuel compared to petrol, would lead to a scenario in which the examined freight EV would become competitive in a higher utilisation combined day and night delivery scenario.

In order to overcome the largest barrier for companies engaging in OHD schemes, Holguín-Veras et al. (2012) suggest motivating receivers by using financial incentives, i.e. for the participation in OHD or the installation of necessary security equipment. The combination of a minor city-toll and targeted incentives was recommended by Holguín-Veras and Aros-Vera (2015) as an efficient policy option, in order to support the uptake of OHD schemes in the City of New York.

Consequently, both the uptake of OHD and freight EVs need policy support. As a combined policy measure supporting both schemes, this paper suggests raising the per-kilometre costs of freight ICEVs by implementing a daytime city-toll or kilometre surcharge, for which freight EVs would be exempted. Simultaneously, receivers could be financially incentivised to accept OHDs, while the shippers receive financial incentives if they deploy freight EVs. The level of the latter subsidy, i.e. a tax incentive, could depend on the mileage driven by the freight EVs, in order to maximise the utilisation of the vehicles. Although an exemption of EVs from the daytime surcharge partly cannibalises the shift towards the night-time utilisation, it offers shippers that cannot shift their delivery times into the night-time an option to avoid the city-toll, while it supports environmentally friendly freight delivery at the same time. Further research is suggested, in order to identify the necessary magnitude, type and duration of these financial incentives.

A further option is to start the uptake of OHD by subsidising the purchase of EVs that are utilised for the transport of goods on an own-account basis. Here, the shipper, carrier and receiver are identical. This means that the two key stakeholder groups involved in off-hours deliveries, as defined by Holguín-Veras et al. (2005), belong to the same company. This eliminates handover issues, as the driver could have access to the warehouse. Furthermore, the productivity benefits of OHD are internalised: potential savings of transport costs can offset increased costs for receiving freight during off-hours.

6.2 Limitations and suggestions for further research

The input data utilised in the TCO calculations are based on data that are available in the literature. However, not all necessary input information was available for medium-duty EVs. Therefore, some findings were transferred from passenger EVs research, although they might not be valid for medium-duty freight EVs. For example, the calculation assumes that the realistic energy consumption of medium-duty electric freight vehicles is about 45% higher than stated by manufacturers, in accordance with findings from studies on the energy efficiency of passenger EVs. Quantitative real-world tests with medium-duty EVs and comparable ICEVs are necessary in order to generate input data of TCO calculations. Further data which could be drawn from real-world tests are, for example, the costs for service and maintenance, costs for the insurance of EVs and the resale prices of batteries. Moreover, the reduction of noise, air pollutant and greenhouse gas emissions of EVs in OHD, which is only qualitatively discussed in this paper, could be quantified by way of practical measurements.

The possibility for quick-charging EV batteries is relatively recent. The effects of intermediate charging on battery degradation are disputed in the scientific literature (Lacey et al., 2013). This TCO calculation assumed that a partial recharge of the battery at lower state-of-charge levels does not impact on the batterys state of health, in accordance with Conti et al. (2015). Future research could examine the effects of intermediate quick-charging on EV batteries in the real-world.

Although this study is based in Germany, its main findings can be generalised: when calculated for other European countries, input settings of the delta TCO calculation would certainly need to be adapted, such as for local EV subsidies and taxes, the price and projections for energy, diesel or battery costs, or the discount factor. However, the general methodology stays similar. Furthermore, the finding that a medium-duty freight EV does not necessarily become more competitive at higher mileages is new and transferable. However, this study only tested two different mileages for the TCOs kilometre dependency. Since the calculation of the kilometre-dependent TCO is complex and non-linear, due to the effects of the battery replacement, further research is suggested in order to derive a more general model to reflect the impact of different mileages on the TCO of EVs.

Acknowledgments

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