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Battery electric trucks in nighttime delivery - the future of city logistics?

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Summary

Especially in urban areas, a large proportion of air pollution can be attributed to road transportation. Thus, in many cities banning diesel engines driven vehicles from inner cities is discussed. Those diesel bans pose a severe threat to logistic service providers (LSP) active in city logistics, since their fleets are based on diesel engine powered vehicles. A solution for LSPs would be the implementation of battery electric heavy-duty trucks (HDTs). In order to compensate their high investments, high mileage is required to be able to benefit from the low operating costs. This could be achieved by implementing nighttime delivery. In this study, we use data from a German LSP in food logistics and a system dynamics model, integrating a total cost of ownership calculation and two discrete choice models to determine for the LSP whether from an economic perspective, nighttime delivery with battery HDTs is beneficial and how it might diffuse. We find that nighttime delivery with battery HDTs is immediately profitable and that diffusion in the fleet and on the customer side only takes a little more than one HDT's lifetime.

Keywords: truck, BEV (battery electric vehicle), off-peak, modeling

1 Introduction

Air pollution causes more than 300,000 premature deaths in Europe per year [1]. Large proportions of the total emissions of main air pollutants can be attributed to road transport, such as nitrogen oxide (NOX: 30%), carbon monoxide (CO: 20%), very small particulate matter (PM2.5: 11%) or non-methane volatile organic compound (NMVOC: 7%) [2]. Especially in urban areas, freight and passenger traffic and therefore transportation-induced air pollution is heavily concentrated, hence, posing a huge risk to health of local residents. In order to reduce those emissions and thus, to improve health of human beings, emission regulations are put in place on different legislative levels and regulatory limits for air pollutant emissions were enforced [3]. Many cities, though, are struggling to meet those regulatory limits, forcing them to implement further measures. In this context, access regulations banning diesel engine-powered vehicles from inner cities are currently discussed widely, particularly in Germany [4]. Such regulations, however, heavily threat operations of logistic service providers (LSP) that are active in city logistics (e.g. retail logistics service providers for food, clothes, furniture, electronics etc.) since their fleets are based on, often quite old, diesel heavy-duty trucks (HDTs) only meeting low emission standards. In case of an enforcement of strict diesel engine bans for urban areas, most LSPs would have to substitute their entire vehicle fleet overnight.

Switching to vehicles with alternative powertrains is the preferable option to bypass diesel bans. Especially battery electric HDTs are discussed as an alternative to diesel HDTs [5] but besides their technical restrictions such as limited range and payload and the limited availability of electric HDTs on the market, most of all high investments are a barrier for their implementation, particularly in a cost-competitive business such as logistics. As opposed to higher investments, variable costs of battery HDTs are much lower compared to diesel HDTs, resulting in high annual mileage being beneficial for battery HDTs. A way to increase annual mileage of HDTs in a city logistics context is the extension of delivery hours by implementing off-hour or even nighttime delivery [6, 7, 8]. Due to local noise restrictions over night, this is only possible with battery HDT. Consequently, the number of trips that a single HDT can drive per day and therefore the daily mileage increases through nighttime delivery. That also leads to an increased daily delivery capacity of a single HDT and in consequence reduces the total number of vehicles required.

In this study, we explore whether battery HDTs can be an alternative to diesel HDTs in city logistics from an economic point of view. Therefore, we answer two questions:

1. Are battery HDTs able to compete with diesel HDTs in a cost-based comparison from the perspective of a LSP, assuming that only battery HDTs are able to carry out nighttime delivery?
2. How might battery HDTs diffuse in the LSP's fleet and how might nighttime delivery diffuse among the LSP's customers, i.e. retail stores?

The outline is as follows. In section 2, we present the methodology and data used for the analysis and we provide the results in section 3. We conclude with a discussion and conclusions in section 4.

2 Methods and Data

2.1 Methods

In order to answer the two research questions presented above, we integrated a total cost of ownership (TCO) calculation and two discrete choice models (DCM), a supplier DCM and a customer DCM, in a system dynamics (SD) model (see Figure 1). We apply that model to a German LSP in foods logistics.

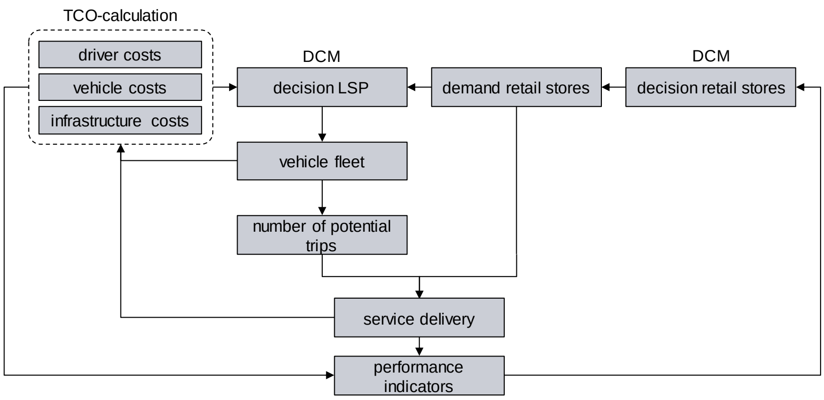

Figure 1: Basic model structure

First, we develop a *TCO-model* for the transportation operations of the LSP, including costs for drivers, vehicle costs as well as costs for charging infrastructure at the warehouse (only relevant for battery HDTs). TCO-models are widely applied for economic analyses of different vehicle technologies [9, 10, 11]. The TCO for vehicle type r (different types see Table 1) can be calculated according to equation 1. The costs for drivers (C_r^{driv}) and vehicle costs (C_r^{veh}) depend on the vehicle type, whereas costs for charging points (C^{infra}) are independent from the vehicle type. Further, we assume that one fast charging point is sufficient for four HDT.

$$TCO_r = C_r^{driv} + C_r^{veh} + \frac{1}{4} \cdot C^{infra} \qquad (1)$$

Driver costs can be calculated by multiplying the hourly driver wage ($w^{day/night}$), which differs between daytime and nighttime due to night allowances, with the number of daily trips and the duration of the respective trips. The duration of trips ($dur_r^{day/night}$) varies on the one hand between daytime and nighttime since less traffic during nighttime allows higher average speeds and thus, reduces trip duration and on the other hand according to the HDT type. Different payloads of HDTs lead to different numbers of stores that can be supplied per trip, which influences trip duration and as a consequence the number of daily trips ($tr_r^{day/night}$) varies as well. Beyond that, it is assumed that only battery HDTs are able to carry out nighttime delivery. This can be justified by the much higher noise emissions of diesel HDTs that are not able to meet strict noise protection regulations, such as in Germany for example. That is why night trips are not relevant for diesel HDT. The result is multiplied with the number of days per year the vehicle is in use (diu_r). Those costs can be reduced by the company's tax rate (ctr) since they are tax-deductible. As a result, the actual annual driver costs are retrieved, which can be converted into the present value of the total driver costs over the HDT's lifetime by a multiplication with the annuity present value factor (APV) [12, 13].

$$C_r^{driv} = (w^{day} \cdot tr_r^{day} \cdot dur_r^{day} + w^{night} \cdot tr^{night} \cdot dur^{night}) \cdot diu_r \cdot (1 - ctr) \cdot APV \quad (2)$$

The APV corresponds to the reciprocal value of the annuity factor, where n is the operating life of HDTs and i the common interest rate (see equation 3).

$$APV = \frac{(1+i)^n - 1}{(1+i)^n \cdot i} \quad (3)$$

For the calculation of the vehicle costs we apply the net present value method with resale value and tax payment on gains realized by sale [gnann, blohm] in combination with APV calculations (see equation 4). According to our assumptions, operating life is equal to depreciation period. The vehicle's investment costs comprise the list price of the vehicle in year $t\,(LP(t)_r^{veh})$, the sales price in year t ($SP(t)_r^{veh}$), as well as taxes on the respective gains realized by sale and additionally tax-reducing depreciation over the HDT's operating life, which is converted into its present value. The variable vehicle costs include fuel consumption of the vehicle (fc_r), fuel price (fp_r), maintenance and repair costs (m_r), costs for tyres (ty_r), toll costs (tl_r) and the vehicle's annual kilometres traveled (VKT). Furthermore, fixed vehicle costs have to be considered such as taxes (tx_r) and insurance costs (ins_r). Finally, variable as well as fixed vehicle costs are tax-deductible.

$$C_r^{veh} = LP(t)_r^{veh} - \frac{SP(t)_r^{veh} \cdot (1-ctr)}{(1+i)^n} - \frac{LP(t)_r^{veh}}{n} \cdot ctr \cdot APV + ((fc_r \cdot fp_r + m_r + ty_r + tl_r) \cdot VKT + tx_r + ins_r)(1 - ctr) \cdot APV \quad (4)$$

Infrastructure costs comprise the list price of fast charging points at time t ($LP(t)^{infra}$) and maintenance and repair costs (m^{infra}). Since the operating life of charging infrastructure l is a lot higher than the assumed HDT's operating life, the list price is reduced by the share the operating life of the infrastructure exceeds the HDT's operating life (see equation 5). Furthermore, depreciation of the charging infrastructure as well as maintenance costs are tax-deductible.

$$C^{infra} = LP(t)^{infra} - \frac{LP(t)^{infra}}{n} \cdot ctr \cdot APV - \frac{LP(t)^{infra} \cdot (l-n)}{l \cdot (1+i)^n} + m^{infra} \cdot (1 - ctr) \cdot APV \quad (5)$$

Further on, it is assumed that a certain share of the fleet is replaced each year and the TCO are one of the criteria the LSP bases its buying decisions on (choosing between diesel and battery HDTs), which is operationalized in a *supplier DCM* (see 14, 15, 16, 17 for details on DCM). The other criterion we included in the buying decision is the expected customer demand (from retail stores) split in regular daytime and nighttime delivery demand. While the former can be fulfilled by diesel or battery HDTs, the latter, due to noise emission restrictions, by battery HDTs only.

We expect total demand to grow at a constant rate (using current delivery demand at the LSP's warehouse as starting value), whereas demand for nighttime delivery, being a subset of total demand, depends on customer decisions (starting at zero demand). We use a *customer DCM* to represent the customer's decision on whether to retrofit its store and to prepare it for nighttime delivery or not. Four different types of retail stores are modeled, accounting for three different retrofitting efforts, while the last store type is not able to implement retrofits at all. Furthermore, we assume that three decision criteria are relevant for the customers: expected improvements in delivery quality (higher promptness of delivery through nighttime delivery), changes in transportation costs (diesel vs. battery HDTs) and risk reduction (maintaining the opportunity of being supplied also case of access regulations). Stores, that decide to implement retrofits are considered as customers for nighttime-delivery and represent customer demand.

In order to account for the dynamics and complexity inherent in a supplier-customer-relationship and to be able to include changes in environmental conditions and potential feedback loops, we integrated the TCO-model and the two DCM in a *SD model*. The buying decision of the LSP has impact on the vehicle fleet, which defines the number of potential delivery trips. Supply and demand are matched in the SD model and furthermore, actual service delivery is modeled. Based on the operations' TCO and on actual service delivery several performance indicators can be measured which influence the customer's decision and thus close the model's loop. Further, by means of the SD model the potential diffusion of battery HDTs and nighttime delivery can be explored.

2.2 Data and Assumptions

Four different HDTs types (see Table 1) representing the truck types used in a fleet, operating from a specific warehouse of a German LSP, are included in the calculations. For the diesel HDTs, we could rely on real-life figures, whereas the prices for battery HDTs are based on assumptions.

Table 1: Net list price for HDTs in 2018 and share in LSP's fleet

Truck type	Diesel HDTs [EUR]	Battery HDTs [EUR]	Share in LSP's fleet [%]
Straight truck (max. GVW 18t)	120,000	227,000	5
Straight truck (max. GVW 26t)	145,000	256,000	55
Semi-trailer truck	175,000	291,000	20
Straight truck with full trailer	200,000	320,000	20

GVW = gross vehicle weight; price for truck and trailer, including cooling units; each battery HDTs with 180 km range; battery price on system level: 467 EUR/kWh [18], price diesel HDTs [19], component costs battery HDTs [20]. All prices in EUR_{2018}.

Table 2: Logistics parameters

Parameter	Unit	Value
Total number of retail stores	#	670
Share of retail stores type I	%	20
Share of retail stores type II	%	10
Share of retail stores type III	%	11
Share of retail stores type IV	%	59
Weekly retail store demand	TU/(w·store)	115
Weekly stops per store	Stopp/(w·store	9.4
Annual demand increase	%	0.5
Duration of stop	h	1
thereof usable for charging	h	1
Duration of warehouse stop	h	1,6
thereof usable for charging	h	1,3
Share of trip in town	%	20
Share of trip out of town	%	20
Share of trip on highway	%	60
Average speed daytime in town	km/h	30
Average speed daytime out of town	km/h	50
Average speed daytime on highway	km/h	70
Average speed nighttime in town	km/h	40
Average speed nighttime out of town	km/h	60
Average speed nighttime on highway	km/h	80
Capacity straight truck (max. GVW 18t)	TU/trip	28
Capacity straight truck (max. GVW 26t)	TU/trip	29
Capacity semi-trailer truck	TU/trip	44
Capacity straight truck with full trailer	TU/trip	58

We obtained data on the current fleet, demand and delivery trips from a specific warehouse of the LSP, which we supplemented with further assumptions (see

Table 2). In that context, we assume that diesel HDTs are operating between 6 a.m. and 10 p.m., while battery HDTs operate 24 hours a day. Furthermore, it is assumed that a battery range of around 180 km is sufficient, which according to the average trip length of 120km is suitable and no battery change is required during the HDT's operating life. Average driving speed tends to be around 30% higher during nighttime delivery. Parameters on environmental conditions, such as battery prices [18] and fuel prices [19, 21] are drawn from various sources and techno-economical parameters were mostly retrieved from [19, 22].

As an example, we present the parameters for a 26t HDT in 2018, which is the truck mostly used in the fleet of the LSP, in Table 3. All assumptions are for Germany and prices are net and in EUR_{2018}.

Table 3: Techno-economical parameters for 26t HDT in 2018

Parameter	Abbreviation	Unit	Diesel HDT	Battery HDT
Driver wage daytime	w^{day}	EUR/h	25	
Driver wage nighttime	w^{night}	EUR/h	28.8	
Number of trips daytime	tr^{day}	#/d	2.8	2.8
Number of trips nighttime	tr^{night}	#/d	-	1.5
Trip duration daytime	dur^{day}	h	5.7	
Trip duration nighttime	dur^{night}	h	5.4	
Days in use per year	diu	d/y	306	
Company tax rate	ctr	%	30	
Operating life	n	y	9	
Common interest rate	i	%	6.5	
Annuity present value factor	APV	-	6.7	
Vehicle list price	$LP(t)^{veh}$	EUR	145,000	256,000
Vehicle sales price	$SP(t)^{veh}$	EUR	11,100	18,700
Fuel consumption	fc	l/km or kWh/km	0.28	1.26
Fuel price	fp	EUR/l EUR/kWh	1.01	0.17
Maintenance and repair costs	m	EUR/km	0.09	0.05
Tyre costs	ty	EUR/km	0.04	
Toll costs	tl	EUR/km	0.09	0.08
Vehicle kilometres traveled	VKT	km/y	100,000	138,000
Tax	tx	EUR/y	506	
Insurance costs	ins	EUR/y	6,729	
List price fast charging point	$LP(t)^{infra}$	EUR	-	79,500
Maintenance and repair costs Infrastructure	m^{infra}	EUR/y	-	2,500
Operating life infrastructure	l	y	-	15

We calculated the model with two different scenarios, which mainly differ in terms of battery prices and fuel prices. In the first scenario, which is called "moderate energy transition" (ME), we assume that a moderate transition towards renewable energy sources takes place. That results in decreasing battery prices and slowly increasing electricity prices. In the "expensive sustainability" (ES) scenario battery prices decrease slower, electricity prices, however, increase quite fast.

3 Results

3.1 TCO

Regarding the TCO, we make a detailed comparison of diesel and battery HDT with and without the consideration of nighttime delivery. Furthermore, we present the development of transportation costs of battery and diesel HDTs over time and the delivery capacity improvements through nighttime delivery.

A comparison of the TCO of a new diesel and battery 26t HDT in 2018 in daytime delivery only, which represents the current state in logistics operations, shows that diesel HDTs are slightly cheaper (Figure 2). This is mainly due to the much lower vehicle costs, which for a diesel HDT are only 12% of total TCO in comparison to 19% for a battery HDT. Fuel costs, however, are lower for battery HDT (10%) than for diesel HDT (14%). In addition, maintenance costs and toll costs are a little bit higher for diesel HDT. Further, fast charging infrastructure costs make up around 2% of battery HDTs TCO, whereas diesel HDTs, of course, don’t require charging infrastructure. What stands out further is the high share of driver costs (around 60%) which dominates all other costs.

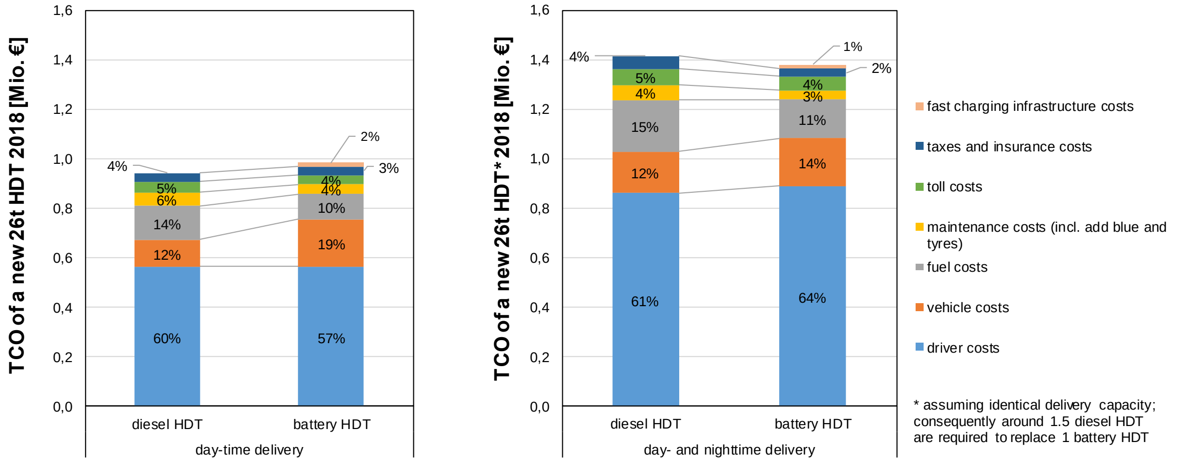

Figure 2: Absolute and relative TCO of a new 26t truck in 2018 for day-time and day- as well as night-time delivery

When considering day- as well as nighttime delivery, where the latter only applies for battery HDTs, battery HDTs are cheaper than diesel HDTs. Although driver costs, on an absolute as well as relative basis, increase for battery HDTs because of the night allowances, battery HDTs are beneficial from a TCO perspective. It has to be pointed out, that in the day- and nighttime delivery calculation same delivery capacity for both HDT types is set, resulting in one battery HDT replacing around 1.5 diesel HDTs. Only battery HDTs are able to carry out nighttime delivery, which increases their daily delivery capacity. Furthermore, in the day- and nighttime delivery calculation daily vehicle kilometers driven increase, which allows the battery HDT to benefit from its relatively low operating costs. In summary, this shows that nighttime delivery is the decisive factor for improving the profitability of battery HDTs and thus, from an economic and ecological point of view, battery HDTs in nighttime delivery seem to be the preferable option for city logistics.

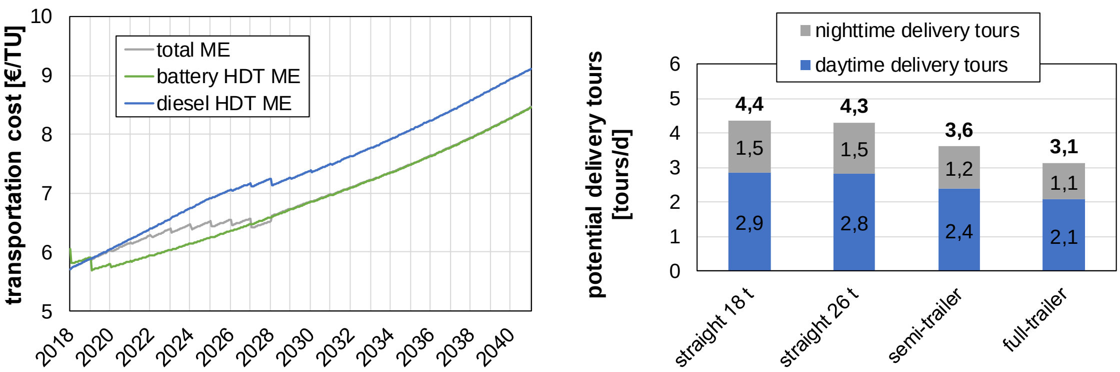

Figure 3: Development of transportation costs of pure battery and diesel HDTs fleets in comparison to calculated fleet mix (total) over time and potential of daily delivery tours for different truck types during daytime and nighttime.

Figure 3 shows how transportation costs in Euro per transportation unit might develop in future. Transportation costs are a lot higher for diesel HDTs than for battery HDTs in the ME scenario. Further, the spread in transportation costs increases in the first years and in the further course, it stays stable. The main reason for the steadily increasing transportation costs can be found in the environmental conditions: personnel costs are expected to increase continuously, which also applies to diesel and electricity prices. Moreover, we explored why battery HDTs are that much cheaper than diesel HDTs: in the first years, this is mostly because battery HDTs can carry out up to 50% more delivery tours, depending on the HDT type, than diesel HDTs (see Figure 3).

3.2 Diffusion

Regarding the diffusion of battery HDTs in the LSP's fleet, the results can be seen in Figure 4. To consider different potential developments of the environment, we calculate two scenarios, ME and ES.

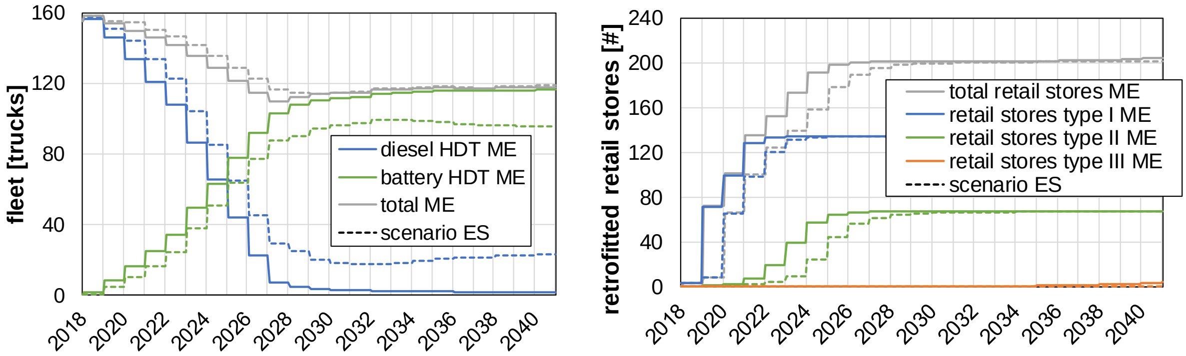

Figure 4: Diffusion of battery HDTs in the LSP's fleet over time in two different scenarios and development of demand for nighttime delivery over time

In both scenarios, battery HDTs diffuse quickly in the LSP's fleet, replacing diesel HDTs almost entirely after a bit more than one decade. This is interesting, especially in the light of the assumed operating life of 9 years for HDTs. It seems that operating lifetime of HDTs has a major impact on the duration of the diffusion process. Another interesting development is the decreasing total number of HDTs required to fulfil slightly increasing demand. Because of the higher delivery capacity of battery HDTs with their increasing share in the fleet, in total less HDTs are required. The fast diffusion can be attributed to the low transportation costs of battery HDTs.

On the customer side, demand of retail stores of type I and II (no and little retrofitting effort) for night-time delivery increases very quickly and reaches its full potential after some more than a decade, which is similar to the battery HDTs diffusion. Retail stores of type III, however, show almost no demand, which is due to the high retrofitting effort. Accordingly, supply and demand of nighttime delivery with battery HDTs increase very quickly and almost in parallel.

4 Discussion and Conclusions

Our results come with some uncertainty. Firstly, techno-economic parameters for battery HDTs mostly rely on assumptions, since almost no battery HDTs are available on the market. Secondly, our assumptions regarding future developments of vehicles prices and battery prices as well as diesel and electricity prices on the one hand have high impact on the results and on the other hand, they are highly uncertain. Besides the techno-economical parameter assumptions, we assumed that suitable battery HDTs are available on the market and that regulation clearly allows silent battery HDTs to delivery during nighttime. Both are not the case until now.

We could show, that diesel HDTs in daytime delivery in food logistics have slightly lower TCO than electric HDTs. This is because of their lower investment costs. Nighttime delivery, however, turns battery HDTs into the most beneficial option in terms of TCO. Lower operating costs and first of all a higher delivery capacity are advantages of battery HDTs in that context. Furthermore, the transportation cost benefits stay stable also in future. The reason for that is the higher delivery capacity - a battery HDT can carry out up to 50% more daily trips than a diesel HDT. The diffusion of nighttime delivery with battery HDT is very fast, on the LSP's side, as well as on the customer's side. It only takes around one operating life of HDTs until almost the entire fleet is shifted to battery HDTs, which is due to the much lower transportation costs of battery HDTs.

Customers with little or medium retrofit effort in order to make their retail stores nighttime delivery ready also adopt quite fast, while customers with high retrofit effort show almost no interest.

In summary, we can conclude that battery HDTs are not much more expensive than diesel HDTs are in food retail logistics. Furthermore, when implementing nighttime delivery they are even beneficial from the economic perspective and diffuse quickly on the LSP's as well as on the retail store's side. Besides the mainly cost-based advantages of nighttime delivery with battery HDTs found in the analyses, many more advantages do exist - from an ecological perspective as well as from a social perspective. Battery HDTs being powered by electricity from renewable energy sources cause almost no CO_2-emissions and for technical reasons their noise emissions are very low compared to diesel HDTs. Furthermore, congestion during daytime can be reduced, if transportation operations are shifted into the night. On the other hand, it also has to be mentioned that up to date the availability of suitable battery HDTs is very low and in many countries, regulations on noise emissions prevent nighttime delivery. If those mentioned barriers could be cleared out, however, nighttime delivery with battery HDTs is a highly promising way for more sustainable city logistics.

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