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Climate footprint of light-duty trucks:
Evaluation of gathered trip data from the German funding program "Electromobility on Site"

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Summary

This paper aims to analyze the climate impact of electric light-duty trucks (e-LDT) in commercial and municipal use compared to conventional LDT (diesel). Mainly focuses on the use phase by harnessing trip data of 133 LDT gathered from 2012 to 2019. Accompanying research is conducted by *NOW GmbH*, an organization that coordinates the funding program "Electromobility on Site" on behalf of the *German Federal Ministry of Transport and Digital Infrastructure*. The funding program is divided into the R&D-project phase, which helped to develop efficiency and climate-friendly e-LDT to step into the purchase phase.

Keywords: truck, fleet, LCA (Life Cycle Assessment), government, vehicle performance

1 Introduction

1.1 The transport sector challenge

The German Federal Government agreed on the target to reduce the greenhouse gas (GHG) emissions of the transport sector by 42 % from 1990 till 2030. The achievement will be attained when the transport sector produces 95 instead of 163 million tons of CO_2-eq. [1]. Germanys vehicle fleet consist of about 63.7 million, of which 14 % are light-duty trucks (LDT) used to transport goods or passengers. In Germany 91 to 98 % of all LDT are running with a diesel engine [2].

1.2 Funding program "Electromobility on Site"

NOW GmbH (National Organisation Hydrogen and Fuel Cell Technology) manages the funding program "Electromobility on Site" on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI) [3]. The program aims to support the market development of battery-electric (BE) mobility based on three pillars: 1. Supporting the purchase of BEVs and charging infrastructure in all segments for municipal and commercial fleets, 2. Supporting the design and roll-out of municipal electromobility concepts, 3. Funding for collaborative research and development (R&D) projects targeting the development of market-ready offerings. In addition to supporting these activities, NOW GmbH conducts accompanying research by drawing insights from R&D projects and cross-pollinating through networking activities and linking stakeholders from research, industry, government and users. Since 2012, funded vehicles have been fitted with data loggers from *NOW GmbH* to collect data for research purposes.

1.3 Purpose

To achieve the goal of GHG reduction, an assessment of the climate impact of electric light-duty trucks (e-LDT) compared to conventional LDT is necessary. Therefore, this study is focusing on the climate impact through the whole life cycle of commercial and municipal used LDT. The comparative carbon footprint between conventional and electric LDT refers to the European vehicle category N1. This applies to all trucks up to a gross vehicle weight of 3.5 tons. Internal combustion vehicles (ICEV) with diesel engine are considered as an appropriate benchmark. While data availability is given the usage is examined more closely. The database includes trip data mainly collected from 2012 to 2019. There are two observation periods based on the available database. The first funding phase assesses the climate footprint of a LDT with commissioning in 2012 and end-of-life in 2026. For that a lifetime of 15 years for any powertrain is assumed. The second observation period refers to a LDT with commissioning in 2018 and end-of-life in 2032. This work is intended to complement LCA studies by giving a bigger picture of the use phase for commercial and municipal applications in urban and rural public transportation. Some of the interesting questions in this context are:

- Does an electric light-duty truck cause fewer GHG-emissions over the entire life than a conventional counterpart?
- Will the GHG-footprint change in a development period from 2012 to 2018?
- How does the user profile of electric light-duty trucks change in the context of municipal and commercial applications in the "Electromobility on Site" funding program?
- Which recommendations can be given to municipal and commercial users for the ecological use of their vehicles?

2 Methodology and database

This study is a quantitative analysis and applies primary as well as secondary data. The primary data mainly consists of the "Central Data Monitoring" of BMVI's "Electromobility on Site" funding program, accompanied by NOW GmbH. Further primary data is obtained by querying various vehicle producers and expert opinions. Additional secondary data within the scope of literature review is collected.

2.1 Life cycle assessment

Climate footprints are a component of life cycle assessments and are characterized by considering the impact category GHG-emissions. Increased GHG emissions cause a warming of the earth's atmosphere. Consequently, the polar ice caps going to melt and the sea level rises. The GHG effect is calculated according to *IPCC* guidelines. GHG includes besides CO_2, also methane (CH_4), nitrogen oxide (N_2O) and various fluorinated gases. The GHG can be converted to CO_2 equivalents (CO_2-eq.) using GHG factors [4].

2.2 Tool for climate footprint assessment

The LCA tool *GEMIS* 5.0 (September 2019) and the database *ProBas* of the *German Federal Environment Agency* is used to determine the climate footprint. *GEMIS* (Global Emissions Model of Integrated Systems) is an open-source software for modeling life cycle and material flow analyses with an integrated database for energy, material and transport systems [5]. The data collected in this database is mainly entered and evaluated by the *International Institute for Sustainability Analysis and Strategies (IINAS)*.

2.3 Database of the use phase

Hereafter, the descriptive evaluation of the “Central Data Monitoring” is subdivided in more detail. The evaluation includes ten LDT models which comprise a total of 133 LDTs with 170,140 journeys, approx. 800,000 kilometers driven and energy consumption of around 172,000 kWh. The data collection is carried out over a period from 2012 to 2019. The data is based on two phases from the BMVI "Electromobility on Site" funding program. In the research phase from 2012 to 2017, trip data from 12 different R&D projects are collected. In the procurement phase from 2018 to 2019, trip data from 14 projects are collected:

- First funding phase (2012): generation of vehicles built between 2010-2013
- Second funding phase (2018): generation of vehicles built between 2017-2018

The ten vehicle models differ in terms of manufacturers, vehicle weight, maximal payload, battery capacities or consumption data. To standardize the data the vehicle models are specified in two LDT types hereinafter named as first and second funding phase. For data protection reasons, no further information is available.

Table 1: Technical details of the light-duty truck types

Light-duty truck types	Sample		Weight	Payload	Battery capacity	NEDC-consumption	WLTP-consumption[1]	Range
	Trips	Number of LDT	[kg]	[kg]	[kWh]	[kWh/100km]		[km]
First funding phase	129,678	83	1,780	750	24	19	28	160
Second funding phase	40,462	50	1,560	700	33	15	23	186
sum/ mean	170,140	133	1,662	724	30	18	23	174

In the following, the individual columns of the table are described in more detail. The **sample** of the first funding phase includes 83 e-LDTs and 129,678 trips. 350 annual trips per vehicle are calculated for the first funding phase. This corresponds to a frequency of less than one trip per day. The data collection took place over a period of 4.4 years. In the second funding phase 40,462 trips from 50 vehicles are collected. Therefore, data was collected for 17 months or over 1.4 years. Based on the total number of trips, it can be concluded that there are approximately 570 annual trips per vehicle. This means commercial and municipal users make about 1.6 trips per day, and hence represents an increase in the number of journeys per vehicle and year of about 60%. Fig. 1 visualizes the annual breakdown of trips and number of LDTs.

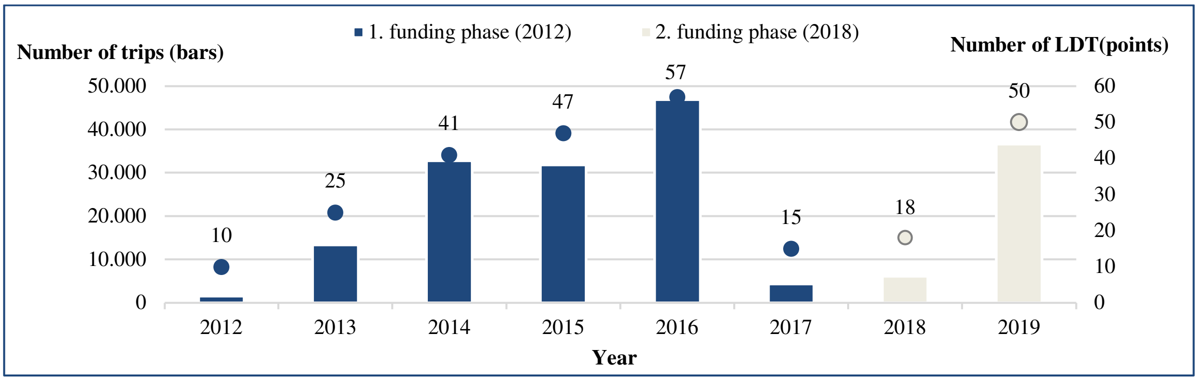


Figure 1: Sample of the "Central Data Monitoring"

The vehicle **weight** of the models ranges from 1,400 to 2,200 kg. If the payload is added, the vehicles reach a total weight of 1,980 to 3,200 t. The **battery capacity** of the vehicle models from the first funding phase ranges from 20 to 40 kWh with a mean of 24.66 kWh and a median of 22 kWh. In the second funding phase the range of battery capacity is identical, but with a mean of 33.92 kWh and a median of 33 kWh. The mean and median battery capacity increases by about 10 kWh from the first to the second funding phase. For the evaluation, a battery capacity of 24 kWh for the first funding phase and 33 kWh for the second funding phase is set. WLTP-**consumptions** for e-LDT are partly provided by the manufacturers. In lack of information a conversion factor of 1.5 from NEDC to WLTP is calculated.[1] In principle this value is not relevant for this work as the real energy consumption can be determined. The values are only an indication of the plausibility of the data. In this context, the consumption of diesel LDT can be crystallized. A conversion factor of 1.21 is being used to calculate the consumption of internal combustion vehicles from NEDC to WLTP [6]. WLTP-consumption of 6.4 liter/100 km for the first and 5.9 liter/100 km for the second funding phase is further used to figure out the climate impact. The conventional LDTs are selected according to similarities to e-LDT. Vehicles registered as Euro 5 (from 2009) serve as comparison vehicles for the first funding phase and vehicles registered as Euro6d Temp (from 2017) serve as comparison vehicles for the second funding phase [7]. Seven substitution models were found. The GHG emissions of 152 kg CO_2-eq/km for the first and 137 kg CO_2-eq/km for the second funding phase are modeled according to the procedures of the LCA tool *GEMIS*.

[1] A conversion factor of 1.5 is being used in the absence of manufacturer data on WLTP consumption. The factor was determined using available manufacturer data.

3 Life-cycle parameters

Further the impacts to develop a climate assessment are described. Those parameters of each life cycle phase are as follows. For the **production phase** parameters as battery cell chemistry, battery weight, energy density, vehicle weight, vehicle components and battery production country are needed. Further the **use phase with** country-specific electricity mix, lifetime mileage, utilization, energy or fuel consumption and charging losses shall be examined closely. In closing the **end-of-life phase with** recycling approach and assumptions on greenhouse gas emissions shall be parameterized.

3.1 Parameter of production phase

Set parameters refer to extraction and production of the individual vehicle parts and raw materials. Vehicle manufacturing takes place in Germany, while the battery production is in China. The weight based model *GREET* with a database from 2019 is used to model the material input [8]. *PEFCR* model, which is based on standardized life cycle assessment, is being used to model the battery [9]. In the transition from a conventional to an electric vehicle, the internal combustion engine and fuel tank are mainly replaced by an electric motor and battery. The components take up considerably less volume but weigh more than those of an ICEV. Electric powertrains have a much simpler structure. Furthermore, the maintenance effort is reduced, for example, by eliminating oil changes or gentler braking process due to recuperation. However, electric vehicles have a higher degree of an inbuilt control system and must be equipped with more electronics [10]. Chassis, body and starter battery are modeled the same way for both. For modeling with *GREET* it is necessary to associate the vehicle weights. Market vehicle models with electric and diesel powertrains were compared. The average weight of the diesel-powered vehicles in the first funding phase is 1,650 kg. Without the starter battery of assumed 20 kg the LDT body + powertrain weighs 1,630 kg. Averagely 1,410 kg for ICEV in the second funding phase is determined. The weight of the starter battery remains the same. **Lithium-ion batteries** are used in electric vehicles. Those can consist of different cell chemistries like NMC (nickel-manganese-cobalt oxide), NCA (nickel-cobalt-aluminum oxide) or LMO (lithium-manganese-oxide). The choice is crucial for achieving high energy densities. NMC is the most common chemistry in the vehicle models and can also be found in the VW e-Golf or Nissan Leaf [11, 12]. For this work, therefore, NMC is selected. Another important factor is the choice of the battery lifetime. It is differentiated according to calendar and cycle aging [13]. In reviewed studies it is usually assumed that the batteries will last the entire vehicle life of 12 to 15 years and a cycle life of 1,000 cycles [14–16]. Therefore, it is assumed that one battery will last the entire vehicle life of 15 years. It is necessary to model the battery by weight differences. In the first funding phase a 300 kg battery with a capacity of 24 kWh is assumed which represents an energy density of 80 Wh/kg. For the second funding phase a battery capacity of 33 kWh with a weight of 250 kg is assumed, representing an energy density of 132 Wh/kg.

3.2 Parameter of the use phase

The use phase includes the entire well-to-wheel emissions, thus subdivided into well-to-tank and tank-to-wheel. Well-to-tank refers to the path of electricity or fuel supply, including raw material extraction and processing, due to energy distribution into the vehicle. Tank-to-wheel refers to the local emissions that are emitted from the vehicle during driving [18]. This section also develops figures by evaluating the database "Central Data Monitoring" for mapping electric vehicle journeys.

3.2.1 Electricity and fuel supply

It is essential to adapt the right GHG emission factors for the electricity and fuel supply of LDTs. The majority of prior research has applied electricity supply by using country-specific electricity mixes [16, 19, 15]. Germany has a share of 46 % renewable energies in 2019. Some scenarios believe in an 80 % decarbonization till 2050 which allows to reduce the emission factor from 474 g CO_2-eq./kWh in 2018 to 52 g CO_2-eq./kWh in 2050 [20–22]. Those emission factors are interpolated and averaged for the funding phases. As a result, 457 g CO_2-eq./kWh for the period from 2012 till 2026 and 366 g CO_2-eq./kWh from 2018 till 2032 is applied. Best case scenario shall be an energy supply by photovoltaic (PV) systems for e-LDT. An emission factor of 32 g CO_2-eq/kWh from 2012 to 2026 and 23 g CO_2-eq/kWh from 2018 to 2032 is figured [23, 24, 20, 25]. A closer look into the German fuel mix from diesel LDT shows an average of 10 % or 12.7 % biofuel for the first or second funding phase [26–29]. An average emission factor of 48 g CO_2-eq./kWh for the period from 2012 to 2026 and 42 g CO_2-eq./kWh for 2018 till 2032 is interpolated and averaged [30–32].

3.2.2 Real energy consumption

In this section, the energy consumption [kWh] per 100 kilometers of the two funding phases is determined. The result will serve as a parameter for the use phase of the carbon footprint. According to Fetene et al. [33], the driving energy consumption is calculated by dividing energy consumption [kWh] by trip distance [km].

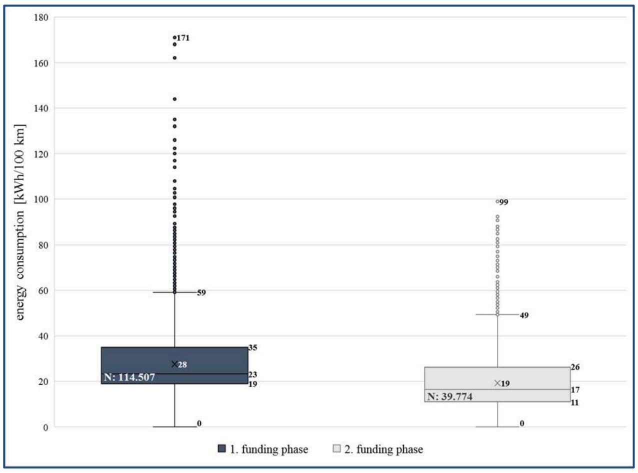


Figure 2: Real energy consumption [kWh/100km] measured with trip data

Even though upfront data cleaning was preceded the boxplot evaluation in Fig. 2 still shows outliers. The outliers are up to 171 kWh/100 km in the first funding phase and up to 99 kWh/100 km in the second funding phase. In the first funding phase the upper and lower limit of the 1.5-fold interquartile range (IQR) reach from 0 to 59 kWh/100 km, the median is 23 kWh/100 km and the **mean is 28 kWh/100 km**. The first quartile (25 % of the lower values) is 19 kWh/100 km and the third quartile (75 % of the upper values) is 35 kWh/100 km. For the sensitivity analysis, the first quartile is evaluated as low consumption and the third quartile is considered as energy-intensive driving. For the second funding phase the evaluation shows a 1.5-fold IQR between 0 and 49 kWh/ 100 km. The median is 17 kWh/ 100 km and the **mean is 19 kWh/ 100 km**. A low consumption is 11 kWh/100 km and a high consumption is 26 kWh/ 100 km. During the charging process electrical energy is converted into chemical energy. During this physical conversion process energy is needed [34]. Various parameters, like the length of the charging cable, charging capacity and temperature influence the amount of charging losses [35]. To determine the real charging losses, trip data from the vehicles are compared to charging infrastructure data. In most cases the charging stations are users-/company-owned. This allows an assignment between vehicle and charging station. To calculate charging losses the state of charge (SoC) at the end of a charging process is compared to the SoC at the start of a journey. The difference of those numbers should be understood as charging losses. In the first funding phase data of 68 e-LDT were collected and in the second funding phase of 50 e-LDT. The results show an average loss for both phases of approx. 17.3%. In the first funding phase the median is identical to the mean value. In the second funding phase the median is 16 %. The dispersion of the first and third quartile ranges from 10 to 25 % in the first funding phase and from 7 to 24 % in the second funding phase. A comparison of these values with the literature review shows a plausibility of the calculations. The study *Agora Verkehrswende* [15] assumes a decrease in charging losses from 15 to 10 % till 2030. *Wietschel et al*. [19] assume charging losses between 9 to 14 % depending on charging current. Consistently **17 % charging losses** are added to the energy consumption for each funding phase. It is assumed that low energy consumption correlates with low charging losses. The same applies to medium and high charging losses. An overview is given in Tab. 2.

Table 2: Real energy consumption plus charging losses

Energy consumption + charging losses	First funding phase (2012)	Second funding phase (2018)
Lower consumption	20.90 kWh/100 km	11.77 kWh/100 km
Mean consumption	32.76 kWh/100 km	22.23 kWh/100 km
Higher consumption	43.75 kWh/100 km	32.24 kWh/100 km

3.2.3 Real annual mileage

The annual mileage is calculated by determining the reporting days of the individual vehicles. The reporting days are defined from the first day of available data by data logger until the removal. The calculation of the annual mileage of a vehicle is carried out by multiply 365 days by total mileage per vehicle [km] and dividend the result by total reporting days. After determining the annual mileage of all 133 LDTs Figure 3 presents the annual mileage [km/a] as a whisker-boxplot analysis per funding phase.

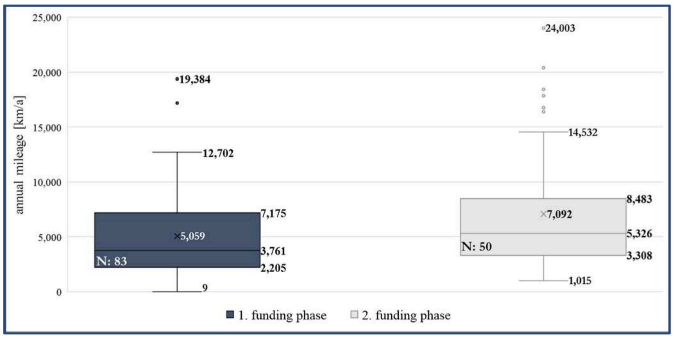


Figure 3: Real annual mileage [km] measured with vehicle data

It is shown that in the first funding phase relatively just a few outliers lie above the whiskers of approx. 12,700 km/a. The highest mileage is 19,384 km/a. The quartiles of the boxplot range from 2,205 km/a up to 7,175 km/a. The median is 3,761 km/a and is far below the **mean of 5,059 km/a**. The mean is used to calculate the climate impact. In the second funding phase more outliers above the upper whisker of about 14,530 km/a can be seen here. The highest annual mileage is achieved by a vehicle with about 24,000 km/a and thus maps a common profile of commercial traffic with approx. 20,700 km/a [36]. The median is 5,326 km/a and the **mean** is slightly higher at **7,092 km/a**. The third quartile is 8,483 km/a and represents a higher driving profile in the sensitivity analysis. The first quartile shows an annual mileage of 3,308 km/a.

3.3 Parameter of end-of-life phase

When the end-of-life is reached a dismantling and recycling of the vehicle is needed. For the vehicle body CO_2 emissions can be modified on a weight basis using secondary studies. It is assumed to be 0.53 kg CO_2-eq/kg ICEV and 0.48 kg CO_2-eq/kg e-LDT [15]. The cut-off approach is applied, whereby materials such as copper and aluminum are fed into the process as secondary materials. However, the situation becomes more complex in the case of lithium-ion batteries. After the battery packs have been removed from the vehicle the battery modules contain of individual battery cells. These are fed into a special blast furnace process. This pyrometallurgical process produces a metallic alloy containing nickel, cobalt, copper and lithium concentrate. Then metal salts are recovered from the intermediate products in the so-called hydrometallurgical process [37]. The battery recycling process emits a GHG potential of 0.874 kg CO_2-eq./kg [15].

3.4 Parameter overview

As mentioned, there are important parameters for the assessment of a climate impact. These parameters are defined per life cycle phase. Tab. 3 gives an overview about the different parameters for each funding phase.

Table 3: Life phase parameter differences for each funding phase

Life cycle phase	Parameters	First funding phase (2012)	Second funding phase (2018)
Production	Production year	2010	2015
	Battery weight	300 kg	250 kg
	Battery capacity	24 kWh	33 kWh
	LDT weight ICEV	1,650 kg	1,410 kg
	LDT weight electric	1,780 kg	1,560 kg

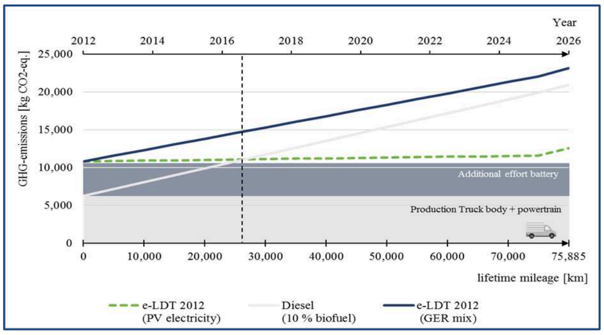
Use	Observation time	2012-2026	2018-2032
	Annual mileage	5,059 km/a	7,092 km/a
	Ø GER energy mix	457 g CO_2-eq./kWh	366 g CO_2-eq./kWh
	Energy consumption incl. charging losses	32.76 kWh/ 100 km	22.23 kWh/100km
	Ø GER fuel mix	48 g CO_2-eq./kWh	42 g CO_2-eq./kWh
	Diesel consumption	6.4 l/100 km	5.9 l/100 km
End-of-Life	Life mileage	75,885 km	106,380 km

4 Results

Further the results of the two funding phases are explained separately. As well as a comparison between both funding phases is made to show the changes caused by improved modeling parameters, such as higher annual mileage, lower battery weight and lower emission factor of the electricity mix. For better comparability, the same usage profile is assumed which means the annual mileage is the same for diesel and electric vehicles.

4.1 Climate footprint of first funding phase (2012)

In the first funding phase the vehicle achieves a lifetime mileage of 75,885 km in 15 years. The left Fig. 4 shows how the GHG potential of the vehicle models changes after production over the entire life up to the end-of-life. The GHG emissions of the end-of-life phase appear in this diagram by an upward bend at the end of the line. The upper horizontal x-axis runs from the first time of travel in 2012 to the end-of-life in 2026. The lower x-axis shows the lifetime mileage. The dotted line in between both x-axes represents the ecological break-even point. The right Fig. 4 gives an overview of the GHG emissions of each life cycle phase.



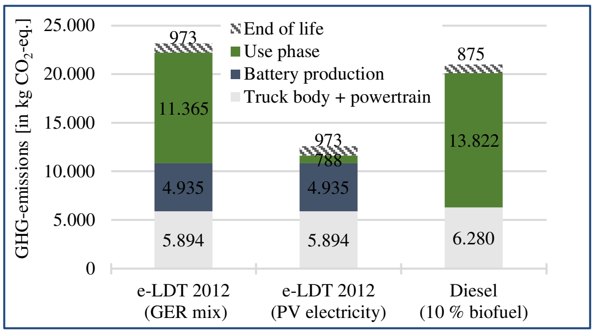


Figure 4: Climate footprint of the first funding phase per year, mileage (left side) and per life cycle phase (right side)

Diesel vehicles carry a smaller climate footprint at the beginning, after which the usage line rises steeply. The production of diesel vehicles has a GHG potential of 6,280 kg CO_2-eq. The largest share of the climate impact from internal combustion LDT is accounted to the use phase. Issued by direct and indirect emissions which are produced during the fuel supply and combustion in the vehicles. Due to its high consumption, the diesel vehicle has a climate impact of 13,822 kg CO_2-eq. during the use phase. A direct comparison of the use phase of diesel and electric vehicles shows a 20 % higher GHG impact. In contrast, the e-LDT has to bear a high emission effect from the production phase especially due to the 300 kg battery. CO_2-emissions of 10,829 kg CO_2-eq. from the production process are twice as high as for internal combustion vehicles. The electric vehicle which uses electricity from PV-systems shows a relatively flat gradient. The use phase only has a minor impact on the climate. The e-LDT (PV electricity) is more climate-friendly after around 27,000 km or five years compared to the diesel LDT. With the modeling parameters applied here the electric vehicle with German electricity mix cannot fall below the GHG emissions of the diesel vehicle within the 75,885 km lifetime mileage. The usage of the e-LDT (GER mix) has the highest proportion of carbon footprint with 11,365 kg CO_2-eq. This is influenced by energy consumption, charging losses and annual mileage. For both powertrain variants the end-of-life only has a small share in the GHG impact.

4.2 Climate footprint of second funding phase (2012)

The LDT in the second funding phase achieve a lifetime mileage of 106,380 km within 15 years. Fig. 5 gives an overview of the GHG potential of the LDT. The upper horizontal x-axis runs from 2018 to 2032.

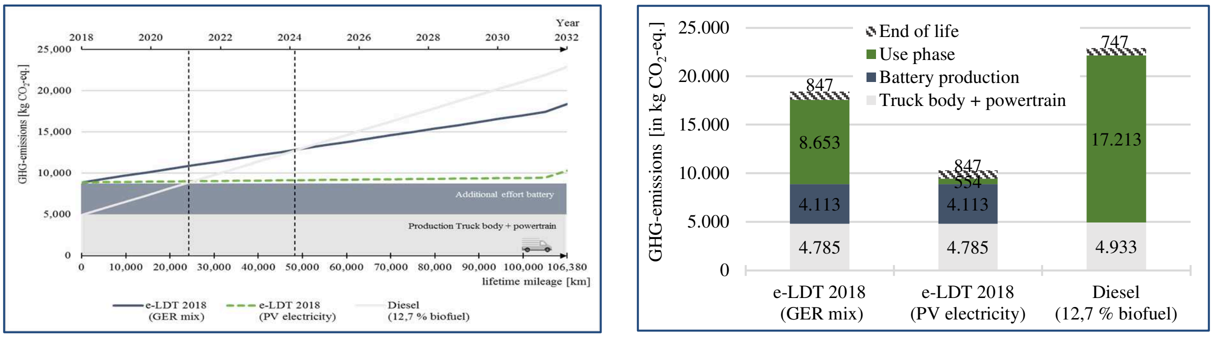


Figure 5: Climate footprint of the second funding phase shown over the lifetime per year and mileage (left side) and per life cycle phase (right side)

The climate footprint of diesel vehicles has been reduced compared to the first funding phase. On the one hand this can be attributed to new materials used and on the other hand to a lighter vehicle weight of 1,410 kg. Nevertheless, GHG emissions rise steeply during usage. The production of diesel LDT emits GHG of 4,933 kg CO_2-eq. In contrast, the e-LDT has to bear a high emission impact from the production phase especially due to the 250 kg battery. The emissions of 8,898 kg CO_2-eq. from the production are almost twice as high as those from internal combustion vehicles. During the use phase the electric vehicle with an average German electricity mix emits 8,653 kg CO_2-eq. The use phase of diesel LDT with direct and indirect emissions accounts for the largest share of the climate impact of ICEV. The diesel vehicle has GHG of 17,213 kg CO_2-eq. in the use phase. If the use phase of the diesel LDT is compared directly with the e-LDT the emissions of the diesel vehicle are 50 % higher. However, it is more climate-friendly after almost 50,000 km or seven years. The e-LDT powered by electricity from PV systems has a lower climate impact during its use phase. It is therefore used in a more climate-friendly way than the diesel vehicle after about 25,000 km or 3.5 years. This makes the use phase more climate-friendly than the production phase of the modeled e-LDT. The end-of-life has a small share in the climate impact due to the limited data available and conservative assumptions.

4.3 Comparison of both funding phases

A brief comparison of the electric light-duty trucks between the two funding phases is made.

Production phase: The carbon footprint of the production phase of the vehicle body + powertrain decreased from 5,894 to 4,785 kg CO_2-eq. (first to second funding phase). GHG emissions were improved by 19 %. This development particularly dependents on vehicle weight reductions (from 1,460 to 1,290 kg) and changes in the year of manufacture (from 2010 to 2015). The climate impact of material input is reduced through more efficient production processes or CO_2-reduced electricity supply. The climate impact of battery production decreased from 4,936 to 4,113 kg CO_2-eq. This reduction is solely due to the reduction in battery weight from 300 to 250 kg. There were no material adjustments or other changes in the modeling.

Use phase: GHG emissions changed from 11,365 to 8,653 kg CO_2-eq. which corresponds to a reduction of 24 %. Relevant parameters for this reduction are improvements in the average German electricity mix (from 457 g CO_2-eq./kWh to 366 g CO_2-eq./kWh) and reduction of energy consumption (from 32.76 kWh/100 km to 22.23 kWh/100 km). The increase in annual mileage harms the final result of the carbon footprint. In terms of GHG emissions per kilometer [in g/km], however, these can help to compensate for the climate impact of the production phase more quickly.

End-of-life phase: The change in recycling emissions is due to changes in the weight of the battery and vehicle.

4.4 Sensitivity analysis

The environmental impact of vehicles is presented by showing a single result. For that reason, the carbon footprint can only be interpreted for this one vehicle with the selected parameters. The complexity, uncertainties and variants of carbon footprints are not sufficiently illustrated by a single result. Therefore, it is relevant to examine the influencing factors more closely and to vary them. The stability of the result of the conducted carbon footprint can thus be checked by changing individual parameters, such as annual mileage, driving energy consumption or battery size. An interpretation and recommendations for action can only be crystallized when the parameters with a high influence are clear [16]. The possible influencing factors with the highest leverage associated during the work are investigated in the sensitivity analysis. Evaluations can only be carried out individually for each funding phase. While one parameter is changed, all others remain the same. To focus on the change of e-LDT, the combustion vehicle (diesel) has remained the same within the calculation. The following graphs show the GHG emissions in grams of CO_2-eq. per kilometer.

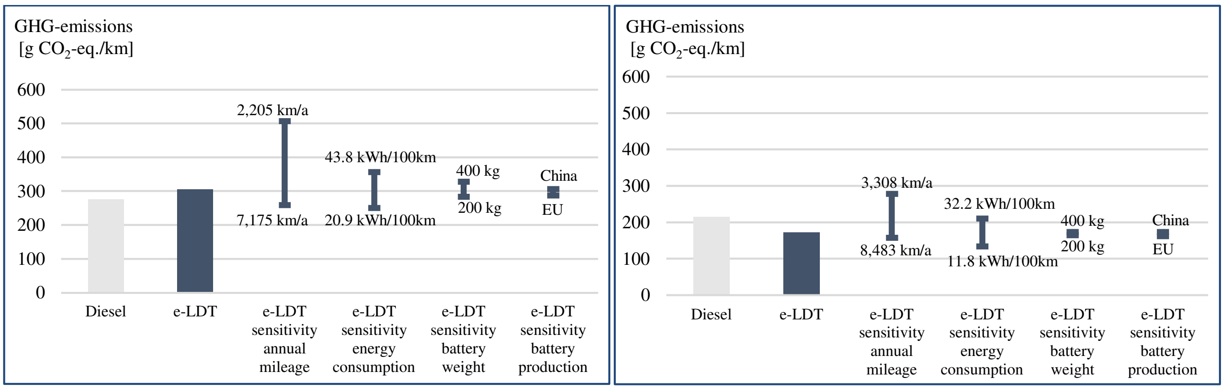


Figure 6: Sensitivity analysis of the first funding phase (left) and second funding phase (right)

In the first funding phase a significant improvement is shown by increasing annual mileage. It has the greatest influence on the result. With a lower annual mileage the use of an e-LDT becomes unecological compared to the diesel LDT. Furthermore, the driving energy consumption influences the climate impact. If the vehicle is driven with lower consumption it can achieve a better climate impact per kilometer than the diesel LDT. The battery size and the country of production of the battery seems to have less influence. For battery production in China CO_2 emissions of approx. 798 g CO_2-eq/kWh and for Europe approx. 349 g CO_2-eq/kWh are determined. Although the variation of the battery production country has little influence on a single vehicle, it would make sense to manufacture in a climate-reducing continent or country when it comes to higher scaling production. An improvement in the results of the sensitivity analysis of the second funding phase is shown by increasing the annual mileage to about 8,500 km/a the climate impact of the e-LDT can be improved. This applies to the modeling parameters used and the assumed lifetime of 15 years. Further increases in annual mileage distribute to decreasing CO_2 emissions over the vehicle kilometer. Driving energy consumption also has a major influence on climate assessment. With a driving energy consumption of 11.8 kWh/100 km the greenhouse balance can improve to approximately 130 g CO_2-eq/km. The battery size and the country of manufacture of the battery have less influence compared to the other parameters.

5 Conclusion

In order to classify the results, the research questions posed at the beginning are taken and answered.

Does an electric light-duty truck cause fewer GHG-emissions over the entire life than a conventional counterpart?

Yes and no, it depends strongly on the modeling parameters. The first funding phase shows that e-LDT which uses the average GER electricity mix in the period 2012 to 2026 is not climate-friendlier than diesel LDT. However, if those were 42 % better utilized (increased annual mileage to 7,175 km/a instead of 5,059 km/a) e-LDT could be more climate-friendly. The assumption of a more fuel-efficient driving style of about 21 kWh/100 km instead of 33 kWh/100 km (incl. charging losses) can also improve the climate impact. Considering the current technology of e-LDT in a commercial and municipal context the results show that they are climate-friendlier after around 7 years or 50,000 km. Also, in this case, e-LDT can reach the break-even point much earlier if they are better utilized. Relevant for this modeling is the underlying electricity mix. Any effort to increase renewable energy sources can have a positive climate effect. Electricity from PV systems is examined as an alternative power supply which produces the best possible climate impact result in both funding phases. In the first phase e-LDT can operate in a more climate-friendly way after only five years or 27,000 km. In the second phase, even after 3.5 years or 25,000 km. Other parameters such as vehicle and battery efficiency, vehicle weight and material input also play a role in this result.

Will the GHG-footprint change in a development period from 2012 to 2018?

Yes, the CO_2 footprint changes positively with the modeling parameters applied. It turns out that funding within the research phase of new technologies brought a learning effect. The vehicle models have become comparatively more efficient. Despite higher battery capacities of around 10 kWh the vehicles in the second funding phase (from 2018) consume almost 10 kWh/100 km less. Further levers for climate improvement between the two funding phases are a higher degree of utilization, expansion of renewable energy sources, improvement of the production flow and material input as well as vehicle and battery weight reduction.

How does the user profile of electric light-duty trucks change in the context of municipal and commercial applications in the "Electromobility on Site" funding program?

The mean annual mileage increased by 40 % from 5,059 to 7,092 km/a between the first and second funding phase. The higher usage profile argues for a better acceptance of electric vehicles. Potentially the vehicles are better utilized by integrating those into real fleet operations. With the funding lever of procurement investments, the "Electromobility on Site" funding program offers an important advantage for the ecological use and real integration of e-LDT in the daily application context of municipal and commercial users.

Which recommendations can be given to municipal and commercial users for the ecological use of their vehicles?

A major impact can be made by changing the energy supply to climate-friendly solutions. If users ensure their own electricity generation using photovoltaic system they will generally reach an ecological break-even point more quickly than users of the German electricity mix. It is therefore important to feed the self-generated regenerative electricity into the charging points and thus into electric vehicles. The variance of the annual mileage has a very high influence on the results. In the commercial and municipal context the results show a low mileage, especially in comparison to internal combustion vehicles. It is therefore highly relevant to increase the utilization of the vehicles. The potential use of e-LDT should be expanded by improved fleet management. For example, by reducing the fleet-size and introducing a better-timed sequence. Further, new mobility concepts offer opportunities for fleet sharing. In a commercial context, cross-company sharing of LDT can also take place. For example, as in the R&D project "Smart eFleets" which is funded by the "Electromobility on Site" funding program [38]. A similar possibility for municipal fleets can be developed.

Which political levers can be applied to the ecological use of vehicles?

Users should be informed about usage options, an increase of the degree of utilization and climate friendliness of e-LDT. This can be intensified through campaigns, action guidelines or municipal workshops. If the degree of utilization is increased through higher annual mileage, the climate impact of battery production can be compensated as quickly as possible. Further development of renewable energy sources should be progressed and funded. Possibly the funding program can be adapted by connecting financial support of charging stations in combination with self-generated regenerative electricity. Also, there are addressable research needs within the federal program. The database for evaluating the recycling process of lithium-ion batteries is limited. Metadata in cooperation with recycling and research institutes could be collected and interpreted. The evaluation of charging losses in the first and second funding phase show minor improvements. For a holistic increase in efficiency, research incentives should be provided to reduce charging losses.

5.1 Limitations

Although LCA methods are standardized the results of the studies differ. Therefore, this study cannot show a representative picture of all LDT in commercial and municipal contexts. Each application case is different, and therefore brings different climate assessment results. This study does not consider other environmental impact categories, such as acidification or eutrophication which could play a significant role in shifting the environmental problem. The data evaluation may contain measuring errors or transmission errors. The usage profile between electric and internal combustion vehicles are put on an equal footing, but it should be noted that these may differ in the real world. For better comparability it is recommended to collect data from combustion vehicles in the same application context. The open-source LCA tool *GEMIS* does not consider the energy supply for the assembly process of the vehicles. For this purpose, assumptions have been made which may not be totally applicable to the modeling of the *GEMIS* evaluations.

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References

[1] BMU, *Klimaschutz in Zahlen: Der Sektor Verkehr,* 2019. accessed on 2020-03-04.

[2] Shell and DLR, SHELL Commercial Vehicle Study, 2016. accessed on 2020-03-20.

[3] NOW GmbH, *Website,* https://now-gmbh.de/de. accessed on 2019-10-16.

[4] IPCC, *AR5 Climate Change 2013: The Physical Science Basis,* https://www.ipcc.ch/report/ar5/wg1/. accessed on 2020-02-26.

[5] IINAS, *GEMIS. Model and database,* 2019.

[6] ICCT, *CO2 emissions from new passenger cars in the European Union: Car manufacturers' performance in 2018,* Aug, 2019.

[7] German Bundestag, *Einzelfragen zu CO2-Grenzwerten bei Fahrzeugen,* Jun, 2018.

[8] Greet 2, *Argonne GREET Model,* https://greet.es.anl.gov/, 2019. accessed on 2020-02-26.

[9] Recharge, *PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications,* Februar /2018.

[10] A. Karle, *Elektromobilität. Grundlagen und Praxis.* München. Carl Hanser Verlag, 2018.

[11] electrive.net, *Nissan setzt beim 62-kWh-Leaf weiter auf AESC-Zellen,* https://www.electrive.net/2019/01/10/nissan-setzt-beim-62-kwh-leaf-weiter-auf-aesc-zellen/, 2019. accessed on 2020-03-04.

[12] L. A.-W. Ellingsen, LCA of Li-ion batteries: current state and prospects, 2017.

[13] P. Keil, *Aging of Lithium-Ion Batteries in Electric Vehicles,* 2017.

[14] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack *Journal of Industrial Ecology*, vol. 18, pp. 113–124, 2014.

[15] Agora Verkehrswende, *Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial.* Berlin, May, 2019.

[16] M. Messagie, *Life Cycle Analysis of the Climate Impact of Electric Vehicles,* 2017.

[17] Envision AESC, *Product System,* https://www.envision-aesc.com/en/product.html, 2020. accessed on 2020-03-03.

[18] H. Helms, J. Jöhrens, C. Kämper, J. Giegrich, and A. Liebich, *Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen,* Apr, 2016.

[19] M. Wietschel, M. Kühnbach, and D. Rüdiger, Die aktuelle Treibhausgasemissionsbilanz von Die Die aktuelle Treibhausgasemissionsbilanz von Elektrofahrzeugen in Deutschland *Working Paper Sustainability and Innovation*, No. S, Feb, 2019.

[20] IINAS, *Der nichterneuerbare kumulierte Energieverbrauch und THG-Emissionen des deutschen Strommix im Jahr 2018 sowie Ausblicke auf 2020 bis 2050. Bericht für die HEA - Fachgemeinschaft für effiziente Energieanwendung e.V.* Darmstadt, 2019.

[21] Öko-Institut and F. ISI, Klimaschutzszenario 2050 – 2. Endbericht. On behalf of Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2015. accessed on 2020-03-05.

[22] UBA, *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 - 2018,* https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-10_cc_10-2019_strommix_2019.pdf, 2019. accessed on 2020-02-26.

[23] Öko-Institut, *Ökobilanzdaten für Erneuerbare Energien im Bereich Treibhausgase und Luftschadstoffe, 2012.* accessed on 2020-03-05.

[24] SmartGreenScans, Carbon- and environmental footprinting of photovoltaic modules, 2012. accessed on 2020-03-05.

[25] ÖKOBAU.DAT, *Database,* https://oekobaudat.de/datenbank/browser-oekobaudat.html, 2015. accessed on 2020-03-05.

[26] Öko-Institut and DLR, *RENEWBILITY „Stoffstromanalyse nachhaltige Mobilität im Kontext erneuerbarer Energien bis 2030“.* On behalf of Federal Ministry for the Environment, Nature Conservation and Nuclear Safety *(BMU),* Dezember/2009.

[27] UBA, *Weiterentwicklung des Analyseinstruments Renewbility - Renewbility II - Szenario für einen anspruchsvollen Klimaschutzbeitrag des Verkehrs.* Berlin, 2012.

[28] ifeu, *CO2-neutrale Wege zukünftiger Mobilität durch Biokraftstoffe. Eine Bestandsaufnahme,* 2004.

[29] DGMK, *Ansatzpunkte und Potentiale zur Minderung des Treibhauseffektes aus Sicht der fosilen Energieträger.* Hamburg, 1992.

[30] UBA, *Erneuerbare Energien in Deutschland. Daten zur Entwicklung im Jahr 2017.*

[31] IINAS, *GEMIS. Datenbank,* 2011.

[32] BMWi, *Energiedaten: Gesamtausgabe,* https://www.bmwi.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html, 2017. accessed on 2020-03-05.

[33] G. M. Fetene, C. G. Prato, S. Kaplan, S. L. Mabit, and A. F. Jensen, *Harnessing Big-Data for Estimating the Energy Consumption and Driving 2 Range of Electric Vehicles. Paper presented at Transportation Research Board (TRB) 95th Annual Meeting , Washington, D.C, United States,* 2016.

[34] R. Pfeil, *Methodischer Ansatz zur Optimierung von Energieladestrategien für elektrisch angetriebene Fahrzeuge*. Springer Fachmedien Wiesbaden, 2019.

[35] R. Graf, D. Wehner, M. Held, S. Eckert, M. Faltenbacher, and S. Weidner, et al., *Bewertung der Praxistauglichkeit und Umweltwirkungen von Elektrofahrzeugen - Zwischenbericht.* Berlin, 2015.

[36] M. Bäumer, H. Hautzinger, M. Pfeiffer, W. Stock, B. Lenz, and T. Kuhnimhof, et al., *Fahrleistungserhebung 2014 - Inländerfahrleistung.* Bremen. Fachverlag NW, Aug, 2017.

[37] C. Hagelücke, Recycling of lithium-ion battery. Mail accessed on 2019-10-30.

[38] Smart eFleets, *Forschungsprojekt im Elektrofuhrpark,* https://www.smartefleets.berlin/, 2019. accessed on 2020-03-08.

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