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Substitution of Conventional Vehicles in Municipal Mobility

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Abstract: Among the economic sectors, mobility is showing significant environmental impacts, especially in the use phase of vehicles. By substituting fossil-fuelled propelling systems, environmental impacts such as the Global Warming Potential (GWP) can be reduced. The use of properly designed light electric vehicles (LEVs) significantly reduces further environmental impacts, as well as maintenance costs, which are relevant for a circular economy. For example, the use of low-voltage (42 V) propelling systems enables the maintenance of LEVs in a broader range of existing bicycle workshops. Regarding the environmental impacts, the described LCA results indicate the advantage of LEVs compared with EVs and ICVs, e.g., vehicle weight is found to be a main factor related to environmental impact for each type of vehicle. This implies a reduced need for battery capacity and lower emissions of particulate matter from tire and break abrasion. This study aims to present the application potential of LEVs and the related reduction in environmental impacts. Anonymised inventory lists of municipal vehicle fleets are analysed for quantifying the substitution potential of LEVs in specific use cases. For this purpose, the use phase of vehicles is analysed with a focus on product design for repair and recycling and supplemented by the results of a comparative environmental impact assessment of internal combustion engine vehicles (ICEVs), electric vehicles (EVs), and LEVs. The comparison is made on the premise of similar application requirements. These specifications are the ability of each of the vehicles to transport a maximum of three persons (driver included) or one driver and 250 kg of cargo in 3 m^3 over a daily distance of 100 km in urban areas. On this basis, the municipal environmental benefits derived from substituting small vehicles in the form of ICEVs and EVs with LEVs are assessed. The results show that in the field of municipal mobility, a relevant number of conventional small vehicles can be substituted with LEVs. The environmental impacts in categories of the highest robustness level, RL I, that is, Global Warming Potential, fine dust emissions, and Ozone Depletion Potential, can be reduced by LEVs by 50% compared with EVs and by over 50% compared with ICEVs. The strong influence of vehicle weight on the abrasive conditions of tires and brakes is considerable, as shown by reduced fine dust emissions.

Keywords: product design for repair or recycling; reduction in raw material consumption; value chains in the circular economy

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1. Introduction

Germany has failed to reach its emission reduction targets set for the traffic sector. Additionally, in 2015, around 13,000 premature deaths were related to particulates and ozone stemming from the transport sector, which is a third of all indicated 43,000 premature deaths related to ozone and particulates in the near-ground level of the atmosphere [1]. Ongoing political efforts are made, therefore, to reduce the emissions related to the mobility sector. Among these measures, multiple programs for supporting sustainable vehicle types and mobility services have been implemented [2].

The production and sales of (battery) electric vehicles (EVs) are increasing worldwide, with the user choice in Germany falling predominantly on sports utility vehicles and midrange vehicles [3,4]. Due to their design, EVs require less maintenance and repair than internal combustion engine vehicles (ICEVs), although additional training in handling high-voltage systems for maintenance personnel is necessary [5–7]. EVs reduce the greenhouse gas potential in the use phase. The traction batteries used in EVs account for a high proportion of the environmental impact of EVs over their lifespans. Due to their lower total weight, light electric vehicles (LEVs) allow for the use of smaller traction batteries while retaining range and usability comparable to EVs. The legal definition as to what constitutes an LEV can be found in European and German law [8]. In brief, an LEV in EU class L6e-B is described as a maximum 6 kW powered four-wheeler with a 45 km/h maximum speed. Due to this and other effects, LEVs show a significant reduction in all environmental lifecycle impact categories [9,10], even if battery recycling or repurposing and the remanufacturing of retired batteries is included [11]. Thus, LEVs are a sustainable alternative to conventional ICEVs and EVs in many fields of application [12]. As Germany has failed to meet its emission reduction targets in the traffic sector, additional political measures are needed to reduce transport-related emissions (https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2024/03/20240315-germany-on-track-for-2030-climate-targets-for-the-first-time.html (accessed on 15 June 2024)). Moreover, there is a strict legislation to reduce local emissions particularly in large cities (https://www.umweltbundesamt.de/sites/default/files/medien/pdfs/umweltzonen.pdf (accessed on 15 June 2024)). Fostering the use of LEVs is one measure to help support the transformation of the traffic sector [13].

However, in the private customer sector, purchasing decisions for automobiles are often influenced by a series of rational and emotional factors [14]. Compared with EVs and ICEVs, LEVs differ in a broad range of technical and soft characteristics, such as design, driving experience, range, travel speed, charging infrastructure, traffic space requirements, ergonomics, usage variants, reparability, comfort, and passive safety [15]. Although LEVs show superiority over traditional EVs and ICEVs regarding many relevant vehicle characteristics, LEVs lack practical presence in everyday life, particularly in Europe [16]. To foster customer acceptance and market entry, the usability of LEVs in real-world applications can be illustrated by using LEVs for everyday services such as parcel delivery [15,17–19], transportation [20], or taxiing services [21]. As in commercial use cases, emotional aspects tend to be less important for investment decisions (compared with private customer decisions); it is more likely to convince fleet managers of commercial fleets of the advantages of LEVs, particularly with regard to operational cost and increased sustainability. Therefore, the customer's readiness to adopt innovative vehicle designs can be considerably increased by proposing LEVs which have been implemented and tested by practitioners in real-world experiences [20,22].

Following this rationale, this study analyses the substitution potential of LEVs in municipal vehicle fleets. The study and its conclusions are based on LCA results and qualitative assessment of the substitution potential of conventional cars with LEVs in municipal fleets. As municipal vehicle fleets are visible to inhabitants of cities to a large extent, the user's familiarisation with LEVs and their assimilation increases. Thereby, positive emotions for LEVs and, indirectly, acceptance of LEVs can be fostered. To convince managers of municipal fleets, a multi-purpose LEV was designed and implemented as a prototype. Municipal service fleets are used to fulfil a wide range of service tasks (like surveillance, taxiing, transportation, or garbage collection [13,17]). Thus, multi-purpose LEVs that can easily be reconfigured offer many benefits, such as less complicated operation management, decreased operational costs, and higher (vehicle) sustainability/longevity. These vehicles are more flexible to fit requirements of various service tasks [16,21], which enables them to be smaller in size without sacrificing levels of readiness. This manuscript illustrates the substitution potential by presenting results of an LCA comparing environmental benefits of the proposed multi-purpose LEV with ICEVs and EVs for typical applications in municipal fleets. Additionally, a qualitative analysis of the substitution potential of LEVs is presented by using a fuzzy variable approach based on interviews with fleet managers from two municipalities in Germany.

To do so, this study is organised in the following way: Section 2 presents the multi-purpose vehicle concept used to evaluate the substitution potential of LEVs in municipal vehicle fleets. The multi-purpose LEV design is focused on flexibility and circularity, making it easily adaptable to different use cases. Section 3 provides a comparative LCA of the multi-purpose LEV concept objectifying environmentally related advantages over traditional ICEVs and EVs over the vehicles' life cycles. Section 4 analyses the substitution potential of the multi-purpose LEV concept in municipal vehicle fleets in Germany. The analysis is based on two qualitative case studies for Germany. The manuscript closes with a conclusion in Section 5.

2. LEV Concept

2.1. General Design Approach

In the first step, possible fields of application for LEVs were identified considering the restrictions implied by the legal definition of EU vehicle class L7e. The multi-purpose LEV conception and design were developed from expert discussions, which allowed us to derive variants of the base construction of multi-purpose LEVs, adjusted for/depending on different uses. The basic objective was to design an LEV that can be used as a transporter for up to three persons or, alternatively, a transporter of goods and equipment of up to 250 kg in a closed volume of 3 m^3. Additionally, the vehicle design is based on the paradigm of Refuse, Rethink, Reduce, Repair, Refurbish, and Remanufacture from the 9R Framework [18], which is a popular strategy to support circular economy in mobility. Following the "R paradigm" will help to create circular value chains in production, i.e., the use and reuse of products and services, like LEVs and their related business cases.

The multi-purpose LEV concept is called Cargo Cruiser III (CC III) and is based on the LEV prototype Cargo Cruiser II (CC II) with an ergonomic muscle-electric powertrain system and mixed-material construction [21]. The CC III concept uses a fibre composite structure facilitating adaptability and flexibility needs derived from various application scenarios in and beyond municipal fleets. By using CATIA VR 6R2022 and ANSYS 2019 R3 software, the state-of-the-art fibre composite design was modified for modular vehicle construction. The primary objectives are to ensure the following:

- Carriage of two EUR-pallets or up to three persons;
- Vehicle width of 1.30 m;
- Travel speed up to maximum of 50 km/h in urban traffic areas.

Focussing on repairability and recyclability, a vehicle design was developed to allow for easy maintenance and repair by regional bicycle workshops. A low-voltage system of 42 volts was chosen for the powertrain system, which is comparable to already established e-bikes. All relevant design decisions were based on the French repair index [22] and the Ecodesign Directive [23]. The CC III in full-fibre composite was re-designed from CC II to reduce maintenance requirements even further. Therefore, glass-fibre composite leaf springs were used, enabling a significantly longer service life compared with conventional spring systems [24]. The construction parts of the vehicle were limited to a composite chassis as well as attachments and aggregates that are needed by regulations relative to EU L7e. A structural health monitoring system was integrated into the fibre-composite-based vehicle structure to indicate mechanical overloads to the user, preventing repairs due to the mishandling of the vehicle.

In essence, five core aspects of EVs, LEVs, and ICEVs were used to assess their suitability for the circular economy:

- Maintenance costs;
- Product lifetime;
- Resource consumption;
- Potential for combined use and retrofitting at the end of the product's life.

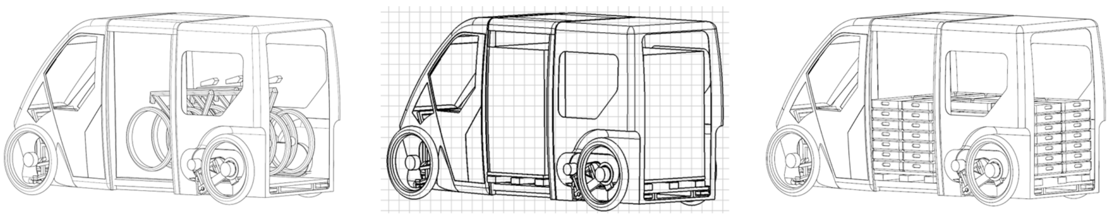
The use of a 42 V low voltage in the powertrain system enables maintenance and repair by personnel experienced in the bicycle and pedal-electric-bicycle sector. Complex training, as required for the handling of high-voltage systems or for the maintenance of conventional EVs, is not necessary in this case. Test drives were carried out under real practice conditions, with a payload of 212 kg and one driver in the seat cruising the urban area of Berlin Friedrichshain. Test drives were conducted over a distance of 33.6 km, including 45 to 67 start and stop procedures, under continental climate conditions, i.e., between 3 °C (winter) and 13 °C (spring). The average velocity on the test track was 20 km/h, with a maximum velocity of 44 km/h. Under full payload and winter conditions, an energy consumption of 24.2 kWh per 100 km was measured, while 14.2 kWh per 100 km was consumed under summer conditions with only one driver on board.

Based on the concept of modular construction, the vehicle demonstrates a high level of reparability due to good accessibility to all technical components. Technical elements and add-on parts are deliberately not linked to manufacturers, but only to performance characteristics.

Thanks to the comparatively small traction battery needed to power CC III, a low-voltage system was implemented as the basis for ease of maintenance, which makes special training in handling high-voltage systems obsolete and can be recharged without special charging technology. Due to the ergonomic arrangement of all functional elements, the vehicle design supports business models based on the "product as a service" or "leasing for retrofit" approach, as well as conventional ownership and operating models.

2.2. Flexibility of Multi-Purpose LEV

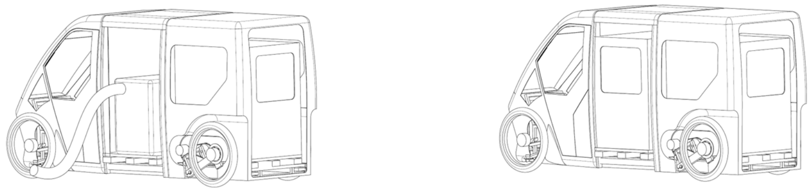
To enable closed-loop value chains while producing LEVs under European market conditions, a modularised vehicle concept was developed that allows for uncomplicated switching among different types of uses. The modular concept is based on grid dimensions for storing two regular transport EUR-pallets within the 1.30 m width of the vehicle. This technically challenging concept enables a cargo mode for the transport of bicycles and e-scooters, as well as two commissioned transport EUR-pallets for meal delivery services to elderly people (Figure 1).



(**a**) (**b**) (**c**)

Figure 1. The vehicle cargo variant for transport of goods can be used for bulky items. (**a**) Transport of up to 6 rental bicycles. (**b**) Lockable large-load carriers placed on EUR-pallets, e.g., tool trolleys. (**c**) Transport of stacked carriers, e.g., meal delivery for communal facilities.

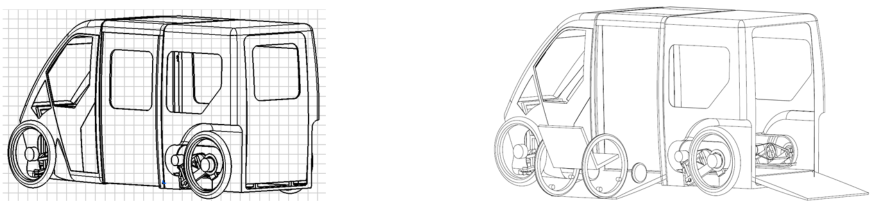
Principles for loading equipment similar to air freight were adapted. Two floor supports were inserted into the Cargo Cruiser to lock via force-fit and form-fit connection transport EUR-pallets to the vehicle structure. In the variant as a service vehicle, LEV CC III can have specific technical items inserted. Compared with known LEVs, the volume of over 3 m^3 with flat and low floor is unique and enables a large variety of use cases, from tram switch servicing, management of public parks, or other public cleaning services (Figure 2).



(**a**) (**b**)

Figure 2. Vehicle variant that can be converted for use in the field of urban cleaning. (**a**) High-pressure cleaner for tram switches reversibly inserted into the vehicle. (**b**) Reversibly inserted large-load carrier with opening for collecting waste from small public bins.

The easy-to-mount vehicle doors on the side and at the back of the rear case body are pivotal to using CC III for taxi services. A two-seater can be inserted above the rear axle and locked to the vehicle structure easily. The low floor without steps inside the LEV enables access for wheelchair users in an ergonomic manner (Figure 3).



(**a**) (**b**)

Figure 3. Vehicle variant for transport of persons and personal goods. (**a**) Closed van for the transport of persons and (**b**) ramp for the entry of wheelchairs.

The found construction of the CC III enables high flexibility of use cases and can be seen as novelty concept in vehicle class of LEVs.

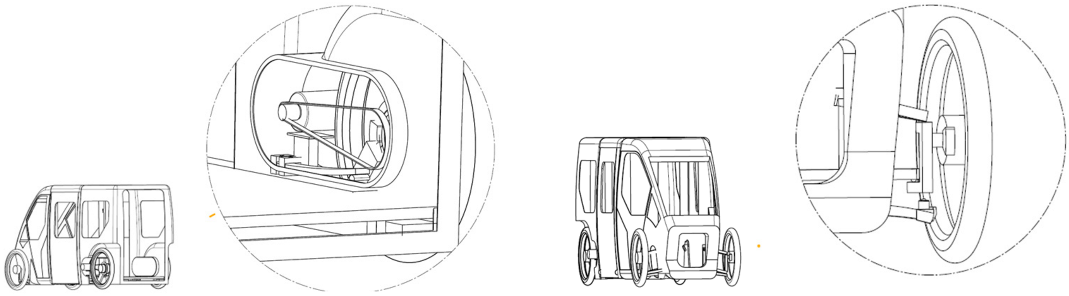
2.3. Product Design for Repair or Recycling

Aiming at a high level of repairability and recyclability, functionalised design solutions were developed for CC III, and systemic decisions were made to reach high maintainability:

- Low-voltage (42 V) drive system;
- No technical links that limit the supply of parts to specific suppliers;
- Maintenance-free attachments (e.g., glass-fibre-reinforced leaf springs);
- Good accessibility to wearing parts for maximum ergonomics in maintenance;
- Structural health monitoring (SHM) system for structural control.

To harvest the lightweight construction potential in road vehicle construction, an SHM system, which signals the mechanical overload (overload due to loading or road damage) of the load-bearing fibre composite components, was tested on the LEV. Mechanical overload stresses caused by misuse can be successfully detected by a strain sensor and can be displayed directly to the driver or evaluated via remote data transmission. This SHM system facilitates fault diagnosis by mechanically monitoring the integrity of the load-bearing fibre composite components.

Wear that cannot be completely prevented, such as abrasion of tyres and brakes, is comparatively easy to remedy, thanks to good accessibility to the rear and front axles, compared with conventional passenger cars. The vehicle structure of CC III is improved by industrial design for better ergonomic accessibility to wearing parts. The LEV can be maintained by conventionally equipped workshops for two-wheelers, like bicycle or motorcycles, due to the chosen 42 V powertrain system. The powertrain system can be found at the rear axle. Thanks to the demountable cover, this unit is directly accessible from inside the vehicle (Figure 4a) for maintenance and repair. Maintenance-free glass-fibre composite leaf springs are used at the front and rear, showing sufficient damping characteristics. The brake system and mechanical drive for steering are accessible when demounting the mudguards from the front wheels (Figure 4b).



(**a**) (**b**)

Figure 4. Maintenance and repair-friendly vehicle structure shown here for the drive system. (**a**) The drive system close to the wheel and the maintenance-free GRP leaf spring are located under an easily removable cover, and (**b**) the front axle with the steering mechanism is freely accessible and equipped with a maintenance-free GRP leaf spring.

In order to improve crash safety in case of side impacts, a battery tunnel is located under the driver seat transversely to the driving direction. The battery is housed in the transverse tunnel, which allows for a low floor in the passenger/cargo compartment. Access to the battery is given by a removable cover inside the rear compartment. By opening the battery compartment, the battery components are accessible ergonomically and in dry condition.

3. Comparative Environmental Impact Assessment of LEVs, EVs, and ICEVs

The comparative environmental impact assessment of all three types of vehicles is made on the premise of similar application requirements for all vehicles. These specifications are daily transport within a 100 km range in an urban area of (a) three persons (driver included) or (b) 250 kg of cargo. The comparison is made on existing life cycle inventory (LCI) databases for EVs and ICEVs, which rely on real vehicle data (e.g., conventional cars with transport capacity of four persons and 250 kg of cargo). For LEVs, a specific LCI was created based on the technical specifications (and, thus, materials) used to build the prototype of the LEV in a German facility for producing fibre composites.

Identifying hot spots of environmental impacts provides arguments to municipal fleet managers for advocating the substitution of conventional EVs and ICEVs with LEVs. The beneficial characteristics of multi-purpose LEVs, here described considering CC III, should be understood as a tailor-made solution for specific uses in municipal fleets. Flexibility inherent to conventional EVs and IECVs from Original Equipment Manufacturers differs from the intended flexibility of the multi-purpose LEV described in this work; the possible driving speed is regimented to 45 km/h for CC III, which links the use of such vehicles to the geographical context of cities.

3.1. Functional Unit

For a comparative environmental impact assessment, it is required to define a functional unit (FU). Aiming at a comparison of EVs, ICEVs, and LEVs without predetermining or restricting the assessment of the substitution potential, i.e., the second aspect of the work presented in Section 4, the unit of comparison is defined in as simple a manner as possible. The FU should cover the aspects described as follows.

Vehicle operation in urban traffic of a 1 km journey, without specification of the transport loads but with potential capacity for minimum two persons and 80 kg of personal equipment or one person and 250 kg of cargo.

This choice was made because this functional unit can be used in the second part of the work to narrow down the patterns of use in evaluating the substitution potential in Section 4. The unit one-kilometre travel distance is a commonly used performance measure in fleet management.

3.2. General Assumptions for Comparative Environmental Impact Assessment

To enable a robust comparability of vehicle categories with a focus on weight and propelling, the data representing the infrastructure and other upstream processes have to represent the same time and region, ensuring a frame near to a real-world scenario for the further planned assessment of the substitution potential in municipal fleets. The geographical region of interest chosen is Germany, which was also set for the environmental impact assessment.

The following assumptions were made in order to compare the environmental impact of LEVs, EVs, and ICEVs:

- Energy mix in Germany from the secondary literature;
- Utilisation of transport infrastructure from the secondary literature;
- An LEV can be modelled as the equivalent of two electric motor bikes;
- The PEF method provides a tool for the planned assessment of environmental impacts.

As no Product Environmental Footprint Category Rules (PEFCRs) are available for road operating vehicles, current data sets from the secondary literature for the European operating area are assumed to be suitable for a comparative assessment in the context of this study.

3.3. Methodology for Environmental Impact Assessment

The environmental impact assessment was carried out in line with the method of Product Environmental Footprint (PEF), which is increasingly being used in the European Union. This method is based on life cycle analyses in accordance with DIN EN ISO 14040 [25].

The aim of this part of the study is the comparative assessment of the environmental impacts of operating vehicles in the categories of LEVs, EVs, and ICEVs. In order to avoid possible shifts between the life cycle stages of the three different vehicle categories, the scope of the assessment was considered to be the entire life cycle, "cradle to grave", including maintenance costs, uses of infrastructure, and the production of traction batteries in case of EVs and LEVs. It is expressly pointed out that no comparative LCA of specific products was carried out here, but only an orientating evaluation of vehicle types based on statistical data from the secondary literature. Therefore, the highly integrated inventory data for vehicle categories, the use of transport infrastructure, and the energy sources used were taken from the publicly accessible Ecoinvent 3.8 database with geographical reference Germany and the current time frame [26]. The modelling of the vehicle categories reflects the state of the art in 2023.

All of the 16 environmental impact categories used in Environmental Footprint 3.1 (EF) were selected for the environmental impact assessment to enable a holistic comparative analysis of the three vehicle categories. In addition to the different environmental impacts resulting from electric motor vs. combustion engine propelling, meaningful results on the influence of the vehicle weight can thus be expected from the comparison of EVs and LEVs. As the impact categories of EF 3.1 are related to three different robustness levels in aspects of scientific reliability, this categorisation in three robustness levels was used to weight the results for interpretation. To ensure the comparability of the vehicle, the categories were given by defining a functional unit that represents the smallest common multiple of all possible types of vehicle utilisation.

The functional unit to be comparatively assessed was defined as vehicle operation in an urban traffic "1 km journey", without specification of the transport loads.

The application of secondary data sourced from Ecoinvent 3.8 [26] for the use phase of all three vehicle categories, known as the most influencing part of the vehicle life cycle [27], ensured the statistical relevance of the inventory data. In general, it is often not possible to determine the uncertainties of selected data sets and parameters by using mathematically sound statistical methods. Nevertheless, in order to define the significance of differences in results and to ensure a robust distinction, a significance threshold of 10% was chosen, as commonly used for LCAs.

3.4. Results of Comparative Environmental Impact Assessment and Interpretation

To enable a comparative environmental impact assessment of light and regular vehicles with different powertrain systems, the normalisation of the values of environmental impacts related to the case of EVs was carried out. Normalised to EVs, the influences of the used powertrain on one side and the vehicle weight become clear. Using this, the influence of a powertrain's energy type can be compared to similar conventional EVs and ICEVs. Moreover, the environmental impacts related to the weight of the vehicles can be clearly assessed, as LEVs and EVs use the same type of energy. The different environmental impact categories of EF 3.1 are grouped in three robustness levels (RLs), I to III, for characterisation to lay the foundations for establishing scientific models of the assessed impact categories. Such RLs indicate the specific reliability of the results of assessing environmental impacts. Hereby, RL I signals the most robust assessing model, the results of RL II are to be interpreted carefully, and RL III should be used only as a guideline.

A considerable reduction in environmental impacts can be observed for EVs compared with conventional ICEVs (Figure 5).

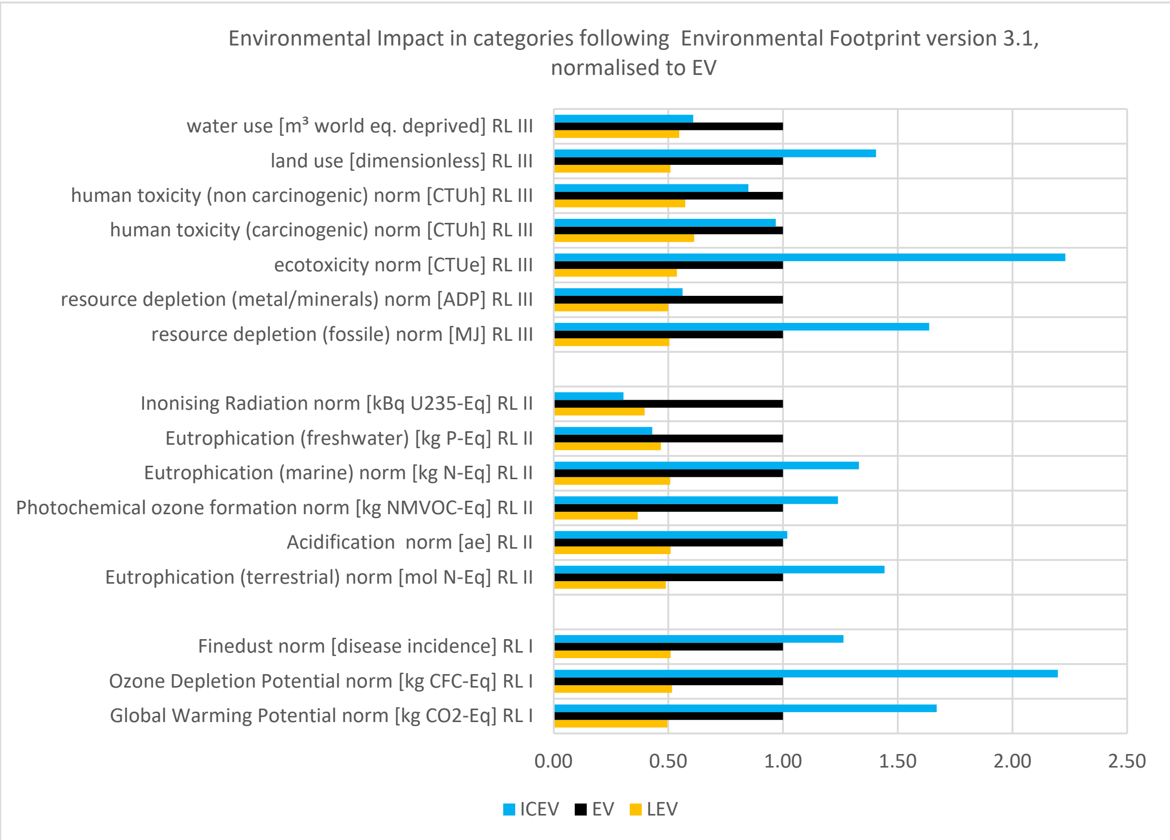


Figure 5. Significantly reduced environmental impacts of EVs and LEVs compared with ICEVs based on the environmental indicators of Environmental Footprint 3.1 normalised to the environmental impact of EVs. In addition, the robustness levels of the environmental indicators are used for sorting indicators from RL I for indicators with high robustness to RL III for indicators with low robustness, given as indicative guidelines.

This correlates to actual findings [27]. Considering ICEVs and EVs vehicles in comparable classes differing in the powertrain system, all environmental impacts related to indicators of RL I are substantially lower for EVs. The environmental impact of EVs of RL II is reduced by 50% in the case of the Ozone Depletion Potential (ODP), by 30% for the Global Warming Potential (GWP), and by 10% for fine dust emissions in the form of particulate matter (PM). For LEVs, the three indicators ODP, GWP, and PM are even 50% lower compared with EVs.

Compared with EVs, ICEVs show marginally reduced environmental impacts in two environmental impact categories of RL II and in four environmental impact categories of RL III. In relation to LEVs, ICEVs show a lower environmental impact for two categories of RL II. However, the difference is below 10%, which is commonly considered below the significance threshold in LCAs.

Based on the significant differences in the environmental categories of RL I and II, the results indicate that a 50% decrease in environmental impacts can be achieved by substituting conventional vehicles with LEVs, specifically for particulate matter pollution, damage to the ozone layer, and Global Warming Potential. Due to the shutdown of German nuclear power, the impact category Ionising Radiation for the vehicle use phase in Germany is lower than under the assumed global electricity mix for electric vehicle operation. Thus, LEVs also substantially reduce the environmental impacts of RL II. LEVs also represent a reliable solution to improve air quality in cities by reducing ozone formation and particulate emissions, which in turn positively affects living quality and (hidden) health costs for the city's inhabitants.

4. Assessing Substitution Potential in Municipal Vehicle Fleets

4.1. General Assumptions in Assessment of Substitution Potential

To determine the substitution potential of CC III in typical municipal vehicle fleets, the following assumptions were made:

- Municipal staff are open to use new types of vehicles and are able to handle and maintain CC III.
- Municipal fleet management are free to decide on financing as well as business and operating models for new types of vehicles.
- LEV CC III can be operated in usual business modes.
- Municipal fleets are operated to fulfil a set of typical mobility and logistics tasks for which a wide variety of different vehicles is used.
- Typically, all vehicles are either EVs or ICEVs. Introducing LEVs in municipal fleets allows fleet managers to improve fleet operations by reducing maintenance cost due to easy repair procedures.
- Lower fuel cost due to vehicle weight reduction.
- Reduction in fleet size, as CC III has a flexible design and thus can be converted easily into different variants such that changing mobility and logistics demands can be addressed quickly and easily.

To analyse the substitution potential, the municipal vehicle fleets from a German city of about 150,000 inhabitants are reviewed. The fleets are operated by the municipal administration and a municipal energy provider. The vehicles are used in the following mobility and logistics tasks:

- Garbage collection;
- Urban staff mobility;
- Public surveillance and monitoring;
- Municipal infrastructure maintenance (e.g., road, light rail, water, electricity, etc.);
- Maintenance of energy infrastructure and municipally owned power plant;
- Miscellaneous mobility and transport processes.

The vehicle fleets of the case study municipality and municipally owned energy provider consists of 83 and 93 vehicles in total. The vehicle fleets can be categorised by vehicle class and task assignment. In the following, Table 1 summarises the vehicle counts.

Table 1. Fleets of vehicles of municipal administration and municipal energy provider of a German city of about 150,000 inhabitants categorised by type.

Vehicle Category	Municipal Service	Energy Provider	Total
Lorry	0	4	4
Tractor	3	1	4
Van/light-duty vehicle/miscellaneous	27	71	98
Car	53	17	70
Total	83	93	176

4.2. Methodology for Assessing Substitution Potential of LEVs

To assess the substitution potential of LEVs in municipal vehicle fleets, a fuzzy variable approach [28] was used. This approach parametrises a profile matching between vehicle characteristics and task requirements. The list of vehicle characteristics considers all technical specifications relevant to the application scenarios (like payload, battery capacity, air conditioning, etc.). Task requirements describe vehicle-specific dimensions which are relevant when vehicles are assigned to a specific task (e.g., payload, range, comfort, etc.). To assess the relevance of a vehicle characteristic i to a task requirement dimension j, a loading is defined by r_{ij}, with $0 \leq r_{ij} \leq 1$. Let $r_{ij} = 1$ indicate high relevance of vehicle characteristic i to task dimension j, while a value of 0 is interpreted as no relevance. Table 2 shows the relevance scores r_{ij} estimated from expert consultations with fleet planners of the municipality under investigation.

Table 2. Relevance scores of vehicle characteristics for task requirements.

Vehicle Characteristic \ Task Dimension	Flexibility Requirement	Range Requirements	Payload Requirements
Battery/fuel capacity	0.50	1.00	0.50
Payload capacity	0.125	0.00	1.00
Comfort	0.75	0.00	0.00
Adaptability	1.00	0.00	0.00

To assess the compatibility of a vehicle type with the task requirements, the relative performances of different vehicle types are assessed regarding the vehicle characteristics. Let c_{ki} indicate the relative performance of vehicle type k regarding vehicle characteristic i. For convenience, it is assumed that $0 \leq c_{ki} \leq 1$, where 0 and 1 indicate the worst and best relative performance, respectively. Then, $s_{kj} = \sum_i c_{ki} \cdot r_{ij}$ indicates the relative suitability of vehicle type k regarding task dimension j. Table 3 shows the relative suitability scores of the vehicle types for the selected set of characteristics.

Table 3. Assumed relative performance scores of considered vehicle types and vehicle characteristics.

Type \ Characteristic	Battery/Fuel Capacity	Payload Capacity	Comfort	Adaptability
ICEV	1.00	1.00	1.00	0.25
EV	0.75	0.40	1.00	0.10
LEV	0.50	0.30	0.25	1.00

Finally, let w_{jt} indicate the importance of task dimension j for task t with $0 \leq w_{jt} \leq 1$. Table 4 summarises the importance scores of the considered tasks in all task dimensions.

Table 4. Importance scores of considered tasks for all dimensions.

Task \ Task Dimension	Flexibility Requirement	Range Requirements	Payload Requirements
Garbage collection	0.125	0.50	0.75
Staff mobility	0.75	0.25	0.00
Public monitoring	0.50	0.50	0.00
Infrastructure maintenance	0.125	0.50	0.25
Miscellaneous service tasks	0.75	0.50	0.125

Tables 2–4 summarise the scores obtained from interviews with fleet management experts of the municipality under study. Although the score assessment is the result of a qualitative interview process with only a limited number of participants, it reflects the opinion of relevant decision makers in municipal service agencies and illustrates the procedure for suitability assessment. Note that for assessing relative vehicle performance scores as well as relevance and performance scores based on a larger sample, comparative assessment methods like the AHP might be applied.

To quantify the substitution potential of two vehicle types, we define overall and relative suitability scores as follows: Let overall suitability be defined by $\bar{s}_{kt} = \sum_j s_{kj} \cdot w_{jt}$ for vehicle type k and task t. Relative suitability scores $\tilde{s}_{kt}$ are computed for each task by normalising the overall suitability scores to the highest suitability scores obtained by a vehicle type for each task, i.e., $\tilde{s}_{kt} = \frac{\bar{s}_{kt}}{\max_k \bar{s}_{kt}}$. The higher the scores, the higher the perceived suitability of vehicle type k for task t.

The closer the suitability scores of two vehicle types, the more similar the vehicles are regarding the requirements of a certain task t. The closer to 1 a relative suitability score is, the better the vehicle type matches the best vehicle type regarding a particular task. Finally, comparing the suitability scores with scores of economic and environmental performances allows for the recommendation of beneficial substitutions.

4.3. Case Study Result: Substitution Potential of LEVs

The suitability scores of LEVs, EVs, and ICEVs for the tasks outlined in Section 4.2 and based on the scores summarised in Tables 2–4 are summarised in Table 5.

Table 5. Overall and relative suitability scores for all considered vehicle types and tasks (overall score/relative score).

Task \ Vehicle Type	ICEVs	EVs	LEVs
Garbage collection	1.83/1.00	1.12/0.61	0.85/0.46
Staff mobility	1.74/1.00	1.14/0.78	1.23/0.84
Public monitoring	1.31/1.00	1.01/0.77	0.99/0.75
Infrastructure maintenance	1.08/1.00	0.73/0.68	0.57/0.53
Miscellaneous service tasks	1.91/1.00	1.43/0.75	1.43/0.75

It appears that ICEVs show the highest suitability scores for all tasks. As ICEVs are currently standard vehicles for all tasks and show highest variability in models, this result was expected. Nonetheless, EVs and LEVs show similar suitability scores, particularly for the staff mobility, public regulatory, and miscellaneous service tasks. Regarding LEVs, in particular, the adaptability to varying demand scenarios is an advantage compared with conventional vehicle types like ICEVs and EVs. For public monitoring, comfort requirements hinder a better suitability score for LEVs. For payload-intensive tasks like garbage collection and infrastructure maintenance, ICEVs are still best suited. Nonetheless, the suitability analysis indicates that LEVs have a considerable substitution potential for certain typical municipal tasks, like staff mobility and public monitoring.

To assess the substitution potential in terms of vehicle counts, the shares of vehicles dedicated to the tasks with high substitution potential have to be estimated. In the following, we assume that vehicles used for the staff mobility, public monitoring, and miscellaneous service tasks can be substituted with LEVs. Based on the fleet composition shown in Table 2 and expert consultations, we discarded lorries and tractors, as these vehicles are designated for special purposes. The remaining vehicles can be roughly categorised as passenger cars and light-duty vehicles. For these vehicles, substitutability with LEVs is assessed in expert consultations. Light-duty vehicles and passenger cars are categorised as substitutable or non-substitutable by reviewing task assignments and vehicle characteristics. The results are summarised in Table 6.

Table 6. Relevance scores of vehicles characteristics for LEV substitution in two identified relevant vehicle fleets.

	Municipal Service		**Energy Provider**	
	Subst.	**Non-Subst.**	**Subst.**	**Non-Subst.**
Van/light-duty vehicle (N1)	1	26	7	64
Car (M1)	20	33	16	1
Total	21	59	23	65

Many light-duty vehicles are equipped for specific tasks, like garbage collection, road cleaning, etc. During expert interviews, it became clear that LEVs are not considered substitutes for specialised vehicles. Indeed, those tasks are mandatory municipal services, and potential vehicle failures cannot be compensated for, since vehicle budgets are limited and fleet sizes are calculated carefully. Thus, in pilot phases with experimental vehicles, vehicles with standard configuration shall primarily be substituted, aiming at minimising the risk for service task disruptions due to LEV failures.

An additional implicit aspect relevant to assessing the suitability of LEVs is the planning reliability of vehicle usage. Due to the comparatively limited range of LEVs, tasks which involve predetermined paths, which change to a limited extent, are preferred candidates for LEV substitution. Thus, the so-called planning reliability of vehicle paths is a further criterion for substitutability. According to this, journeys that are planned and carried out mostly in the urban area and in direct connection with duty rosters are robust and reliable in terms of planning. Well-plannable paths are typical, e.g., for inspection and surveillance tasks.

Based on the results of the case study, it can be concluded that the substation potential of LEVs in municipal fleets ranges between 20 and 30%. Although the sample was small, the results indicate that the identified substitution potential is valid and relevant, especially for fleets of medium-sized German cities.

5. Conclusions

The study shows a relevant potential for the substitution of conventional personal cars, EVs, and ICEVs with LEVs in vehicle class EU L6e. The significant reduction in environmental impacts in terms of greenhouse gas emissions and fine dust in the form of PM 2.5 and PM 10 is a key argument for this substitution potential. Using LEVs for passenger transport in urban traffic halves the environmental impacts of Robustness Level I compared with the operation of ICEVs and EVs. In all other environmental impact categories, LEVs also show relevant reductions in environmental impact, compared with EVs and ICEVs. Thus, LEVs can help to substantially reduce traffic-induced environmental burdens. However, the reluctance to adopt new vehicle concepts is substantial, particularly among decision makers in the private sector. Thus, using LEVs in municipal service applications is a viable option to increase presence and assimilation of LEVs.

The conducted case study indicates that LEVs for passenger transport can substitute up to 20–30% of the vehicles in municipal fleets in medium-sized German cities. As shown in this study, a share of up to 10% of conventional cars in municipal vehicle fleets appears to be safely substitutable with LEVs, leading to significant reductions in environmental impacts stemming from vehicle fleets that are operated by municipalities. A possible multiplier effect of increased visibility of LEVs in municipal services cannot be assessed at present.

Besides municipal fleets, the described multi-purpose LEV Cargo Cruiser III demonstrates relevant potential for diverse applications in urban environments. These include last-mile parcel delivery, the sustainable taxiing of persons, and LEV sharing programs. Such possible applications of LEVs will contribute to mitigating urban congestion and pollution while enhancing the efficiency and sustainability of urban transportation systems. As cities are aching with increasing challenges related to environmental sustainability and mobility, the versatile nature of multi-purpose LEVs offers promising solutions for addressing these issues.

For a deeper understanding and to quantify the potential of the proposed multi-purpose LEV, more comprehensive case studies are required, particularly in other types of communities (large cities as well as rural communities). Presumably, the estimated substitution potential is even larger in bigger cities. Further research should also study other operational and strategic challenges, such as range and recharging restrictions, as well as effects of unfavourable weather conditions.

A variety of elements for optimisation are not considered here, such as grid-serving and/or bidirectional charging, grid-autonomous operation under use of urban photovoltaics for LEV power supply, and the minimised need for traffic space, which leads us to expect a further reduction in environmental impacts and an increase in social benefits by using LEVs. These optimisation options should be explored in further research. In summary, larger data sets and more diverse case studies on the potential of multi-purpose LEVs are required to validate the broad substitution potential of these vehicles. Additionally, usage tests of LEVs under real-world conditions are necessary to evaluate their performance, reliability, and user satisfaction, thereby informing further improvements and ensuring their practical viability in urban environments. Investigations of user acceptance in rural areas, for instance, to enhance the mobility of elderly populations in rural areas, are planned to be carried out in an interdisciplinary approach.

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