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Life Cycle Analysis of an On-the-Road Modular Vehicle Concept

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Abstract: In order to reduce the environmental impacts caused by the transport sector, autonomous and electrified on-the-road modular vehicles (otrm) could be a solution. By separating the drive unit from the transport unit, they enable use cases for various transport tasks and reduce individual and motorized transport and its generated emissions. Therefore, the goal of this study is to assess the environmental impacts from cradle to grave by applying the LCA methodology for a defined otrm—the U-Shift—vehicle fleet considering a specific use case relative to a reference vehicle fleet. The results indicate that the U-Shift fleet reduces the life cycle environmental impacts in a range of 3–28% for all of the seven impact categories, which are analyzed in detail. While emissions from the use phase are similar, U-Shift has an environmental benefit in the production phase due to a low amount of resource-intensive driveboards. Considering the early development stage of U-Shift, several measures are discussed, addressing the material and configuration aspects of the vehicles as well as optimized use case applications, which promise further impact-reduction potential.

Keywords: LCA; on-the-road modularity; passenger and cargo transportation; environmental impact; battery electric vehicle; driverless vehicle

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1. Introduction

The transport sector accounted for 22% of greenhouse gas emissions in the EU28 countries in 2019 [1–3]. Despite technological advances, CO_2 emissions decreased only marginally between 1990 and 2014 [4], as transport demand increased at the same time. In recent years, the demand for passenger and cargo transport has increased even further [5–7]. Technical, logistical and organizational concepts are needed to increase transport efficiency in order to limit the environmental impacts induced by traffic. One specific measure of the EU meant to help achieve its "Green Deal" targets is "rolling out cleaner, cheaper and healthier forms of private and public transport" [8]. Various technology trends can be observed in different modes of transportation that correspond to this and other measures: electrification and automation are taking place in aviation (e.g., Volocopter [9]), as well as on rail (e.g., Parallel Systems [10]), water (e.g., Rolls-Royce [11]), and road. In the case of road vehicles, another trend is to increase the modularization strategy within vehicle design. Modularization is already a well-known and successful strategy in the production of vehicles; however, during operation, conventionally built vehicles remain integral, i.e., fixed [12–14]. People Mover [15–18] and Cargo Mover [15,18,19] are examples of in-production modular vehicles.

The modularization strategy is extended even further by on-the-road modular vehicles (otrm), which separate the driveboard from the transport unit. This allows the driveboard to be used for different purposes by picking up specific transport units during operation [20,21]. The German Aerospace Center and partners developed the U-Shift vehicle concept, which is a standalone otr-modular vehicle concept consisting of an autonomous and electric driveboard and various application-optimized transport capsules for people and cargo transport [20,22]. Other concepts exist as well, such as the Rinspeed Snap (standalone otrm, as well) [23] or the

Rinspeed microSNAP [24], which is an infrastructure-based otrm vehicle, i.e., a crane-like infrastructure is needed to swap the transport units [14].

U-Shift, as an exemplary vehicle of the otrm-standalone vehicle class, has already been examined from an operational [14] and economic point of view [25], with promising results. Further, an energy consumption simulation [26] has been conducted and its technological feasibility was examined [20,22]. For a holistic assessment of the otrm-vehicle compared to the status quo, an analysis of the environmental impacts is essential. One key idea underpinning otrm-vehicles is the substitution, and therefore the reduction, of motorized individual transport. A literature review conducted by Neef et al. (2018) shows that numerous LCA studies reached the conclusion that using mobility services rather than individually owned cars is advantageous regarding greenhouse gas emissions [27]. The analyzed studies often mention a decrease in the number of private cars where on-demand mobility services are offered. The number of private vehicles replaced by a shared vehicle differs between the studies and goes up to 12 replaced cars [28]. A reduction of vehicles may lead to a reduction of parking space, resulting in a gain of space, as parking lots comprise up to 15% of the urban area in industrialized countries [29].

In some of the studies, transport services were not the only focus; the effects of automated vehicles were investigated as well. The combination of both suggests a high potential for saving CO_2-emissions in comparison to conventional vehicles today. Some studies predict a reduction of up to 80% [30,31]. The use of automated vehicles also leads to a reduction in the number of accidents, as 88% of road accidents are caused by human error [32].

The implementation of additional systems for automated driving causes an increase in life cycle greenhouse gas emissions. However, the direct effects of automation during the use phase will ensure a reduction in greenhouse gas emissions. The decreasing effect is greater than the increase caused by installing the systems and leads to an overall reduction in greenhouse gas emissions [33].

As the subject of the study is an electric vehicle, a closer look is taken at the LCA of electric vehicles. A study comparing different LCAs of electric vehicles shows a high variety of results. The research demands a uniform approach [34]. Particularly regarding the production and recycling of the traction batteries, the charging infrastructure and the environmental impact of the different charging strategies, the results are often inconsistent due to a lack of data [34]. In most cases, primary data regarding the whole life cycle of an electric vehicle are not available [35]. Statistically, primary data are collected for only one in ten LCA studies. Most of the other studies use data from four LCA studies conducted in the time period 2010 to 2014. That raises the question of whether these data are still up to date [36].

One of the main components of an electric vehicle is the traction battery. It is responsible for a high percentage of the environmental impacts, especially regarding the extraction of raw materials and the production phases. The electricity mix (the share of different sources in electricity generation), maintenance, traffic flow, driver behavior and choice of functional unit are further factors that can significantly influence the environmental impacts of an electric vehicle [36–41]. The end-of-life phase of an electric vehicle plays a subordinate role in the overall result [37].

Future electric vehicles might reduce greenhouse gas emissions by 45–78% compared to today. The reasons for this are lower emissions concerning the battery production and a higher share of renewable resources in the energy supply. The main influencing factors are the carbon intensity of the (charging) current and the vehicle's lifetime mileage [42]. Due to an engine design with fewer moving parts and lower maintenance intensity, electromobility offers more potential for lifetime extension than internal combustion engine vehicles. In order to keep the design and technology up to date over a long period of use, an otrm vehicle concept offers the additional advantage of being able to combine passenger and goods transport [14,42]. While the environmental effects of sharing, electrification and automation of vehicles have been studied to some extent, neither a comprehensive investigation of all of these aspects nor the influence of vehicle modularization on the environmental impacts have been covered by the literature yet. This work is intended to begin closing this gap with the following goals in mind:

- Assessing the environmental impacts of a defined on-the-road modular vehicle fleet from cradle to grave, considering a specific use case.
- Comparing the environmental impacts of the defined otrm vehicle fleet with a reference vehicle fleet for the same use case.
- Identifying the main causes of the environmental impacts.
- Interpreting and communicating the key findings.

Furthermore, a substantial focus of the work regards the development of an appropriate methodology and key methodological findings, since modular vehicles differ fundamentally from their integral counterparts, and thus, existing life cycle assessment models must be adapted; not only does the examined vehicle change, but also its operational scenario, i.e., the logistical processes. The results are relevant for the LCA research field as well as for the future development of otrm vehicles.

The remaining sections of the paper are organized as follows: First, the materials and methods for the LCA are described, including the vehicles under investigation, the selected use case, as well as the methodology and the scope of the LCA. Then, LCA results are shown for relevant impact categories, followed by a discussion. A conclusion completes the work.

2. Materials and Methods

2.1. Compared Vehicles: On-the-Road-Modular U-Shift and Electrified, Automated Reference Fleet

The on-the-road modular (otrm) vehicle U-Shift consists of a standardized, electric and driverless drive unit (the driveboard) and application-optimized transport units (the capsules). As shown in Figure 1, the driveboard can independently pick up and change capsules during operation.

Figure 1. U-Shift vehicle concept. Source: own visualization with images from DLR, CC BY-NC-ND 3.0.

Only a standardized interface is required, as the lifting unit is located in the driveboard. Thus, the driveboard can be used almost 24/7 for changing purposes: e.g., public transport, parcel delivery, and retail logistics. The capsules can be designed cost-effectively and with low complexity, so that they can be individually tailored to the application. Cargo capsules can carry 3 pallets (in the case of the short capsule variant), while the passenger capsule has a maximum capacity of 19 persons (standing and seated). The passenger capsule has lateral, height-flexible access, while the cargo capsule can be loaded and unloaded from the rear at ground level [22,43].

U-Shift is to be compared with a reference vehicle fleet in the LCA. To ensure that the results correlate as closely as possible with the modularization, the reference vehicle needs to represent the same vehicle segment and technological features in terms of powertrain and automation as the U-Shift configuration. An electric Mercedes-Benz Sprinter [44], which is produced in the standard variant for both passenger and freight transport, is used as an example. The automated, generic adaption is called RoboVan in this paper.

The approach for the acquisition of data includes different sources: the ecoinvent database, a manufacturer survey, an expert survey and a literature review.

Ecoinvent is a non-profit organization which was founded in 2000 by several Swiss institutes. The aim of the organization is to provide consistent and standardized life-cycle inventory data to simplify the conduction of LCA and make the data more transparent and comparable [45]. This increases the credibility and acceptance of the method. The database is regularly expanded and updated. The third version of the database, which has been available since 2013, extends the geographical scope from the former European focus to a more global view. Many different economic sectors are covered, and different methods for the life cycle impact assessment (LCIA) are available.

The base of the data acquisition is a bill of materials of each of the fleet (U-Shift or reference) units. The data for U-Shift is based on the development status as of 2020. To obtain data for the manufacturing phase, a survey was conducted among 71 companies. All components for which a suitable data set was available in the ecoinvent database were removed from the list for the survey. Where data could not be obtained from the manufacturer survey or were incomplete, literature references were used as a basis, or data and assessments by experts were referred to.

2.2. Use Case: Combined Transport of Cargo and Persons

In discussions with the Stuttgart City Council and the Stuttgart Chamber of Commerce and Industry, the Stuttgart-Vaihingen district was identified as a neighborhood in which U-Shift could be usefully deployed under the characteristics modular, electric and driverless. First, areas of application are identified in workshops with associations from passenger and freight transport, which are relevant for the segment addressed by U-Shift (e.g., no heavy cargo transport or mass transport). For the defined use case, retail freight transports, parcel deliveries to areas of high population density, and on-demand ridepooling transports are selected. This results in the applications shown in Figure 2. For these areas, the demand structure is derived by GIS analysis (geographic information system) and traffic demand matrices. This results in the total demand in the form of a transportation matrix (refer to [46] for more details).

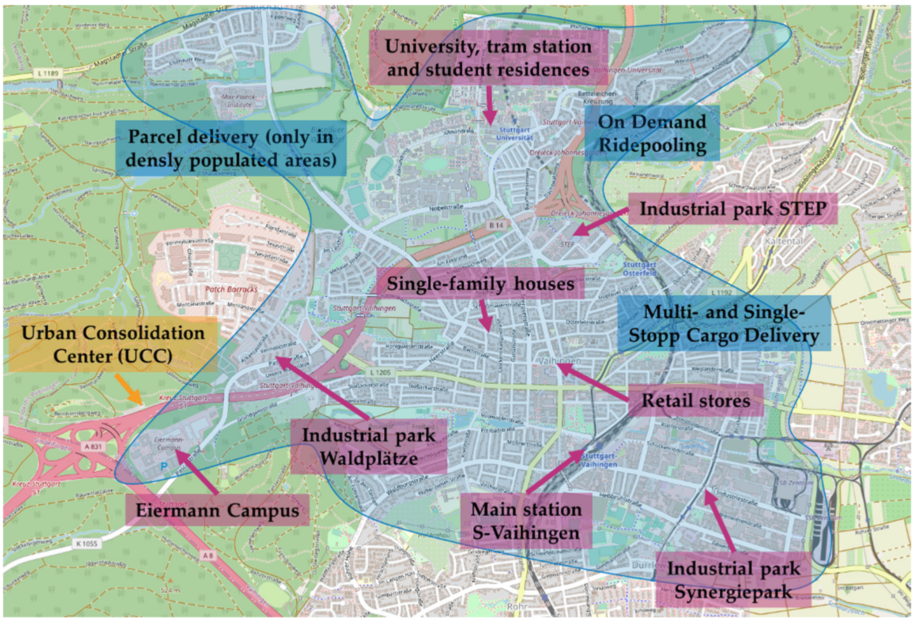

Figure 2. The use case area (in) S-Vaihingen with highlighted applications (blue). Source: own visualization with map from OpenStreetMap.

For the comparison of the vehicle alternatives, the current transport tasks are abstracted and a consolidation center on the outskirts of the city is introduced, from which the goods are transferred from long-distance transport to local transport (last mile). The analyzed vehicles operate only in local traffic.

The premises of the application are: logistics concepts are changed and operate smoothly, driverless as well as electric driving are established and status quo infrastructure is considered. This means that, for example, the cargo loading docks for the delivery of goods to shops are not changed to suit the conditions of the new vehicle.

We call the combination of vehicles and use case an application scenario. This is based on how the vehicle type (reference vs. U-Shift) performs the application tasks. By a disposition of vehicles and, if necessary, capsules, the fleet size is determined [46]. In addition, the LCA-relevant transport KPI fleet km travelled is calculated: Table 1.

Table 1. Use case specific data for U-Shift and the reference (Abbreviations: PT—passenger transport, CT—cargo transport).

Parameter	RoboVan (Reference)	U-Shift
Vehicle fleet	PT: 21 CT: 18	21 driveboards
Capsule fleet	n. a.	PT: 21 CT: 159
Annual mileage of 1 vehicle/driveboard	PT: 28,000 km CT: 24,000 km	47,000 km

2.3. Methodology of Life Cycle Assessment

The LCA methodology is defined in the ISO Guidelines DIN EN ISO 14040 and 14044. While DIN EN ISO 14040 describes the principles and the framework, DIN EN ISO 14044 defines the requirements for an LCA study and provides guidance for the implementation. An LCA is divided into four phases: The definition of the goal and scope of the study, the life cycle inventory, the LCIA and the evaluation of the findings [47]. In the first phase, the goal of the study and its scope, including all basic assumptions, are defined. This includes not only the temporal and geographical framework, but also the description of the product systems, the functional unit, the system boundaries and the allocation procedure. Further, the methods used for the LCIA, evaluation, assumptions, data and their quality and any identified limitations should be explained [48]. Based on the definitions of the scope, all relevant data for the processes within the system boundaries are collected in the lifecycle inventory phase. All input and output flows of the processes in the product system are scaled to the reference flow, which is defined depending on the functional unit [49]. The reference flow describes the amount of product that is needed to fulfill the functional unit, the central reference value of the LCA. It has to be measurable and clearly defined, but can be set individually. The data for the several process modules can be measured, calculated or estimated and serve for the quantification of the inputs and outputs of those modules [48]. The LCIA is based on the functional unit and is therefore a relative approach with a scientific basis. In this phase, the material flows of the life-cycle inventory are translated into potential environmental impacts. This step is often performed via a software tool. In the phase of evaluation, conclusions are drawn from the life cycle inventory data and the LCIA by identifying the significant parameters. They are interpreted regarding the goal definition of the LCA and recommendations and restrictions are formulated. Finally, a sensitivity analysis can be conducted to identify the impact of changes in the data.

2.4. Scope of the Study

The considered location for the LCA is Germany. If no data for Germany are available, data for European circumstances are used. The use case for this study assumes future technological conditions, especially regarding the availability of automated vehicles, and a higher share of renewables in the electricity mix. A cradle-to-grave consideration is chosen, as there is no LCA available for a comparable vehicle concept and to avoid distortion by leaving out individual parts. The functional unit is defined as the transport of 2.6 million persons, 0.9 million parcels and goods on 0.1 million euro pallets during one operation year within the defined use case. The required fleet mileage to fulfill the functional unit (over an average year for the defined use case) is chosen as the reference flow. The following further assumptions and system boundaries supplement the scope of the study:

- The cut-off method is considered for data from the ecoinvent database. This corresponds to the European waste hierarchy and favors the use of recycled materials [50].
- The cut-off criterion according to DIN EN ISO 14040 is set at 1% of the mass.
- Traction batteries have a considerable influence on the life cycle assessment [37,51]. Since their life expectancy can differ (usually being lower) from that of the vehicle [52,53], it is assumed that the traction batteries are replaced during operation.
- Road building activities and supplementary infrastructure (automation and charging) are assumed to be similar for all vehicle alternatives and are thus neglected.
- Maintenance of the vehicles is left out, because there are no reliable data for the maintenance of autonomous cars available at the current time.

While cargo transport is mostly quantified in ton-km, passenger transport is mostly given in passenger-km. The use case includes both cargo and passenger transport. Therefore, vehicle-km are chosen as a neutral unit. The life-cycle assessment includes the raw materials extraction, the manufacturing of the vehicles as well as the use phase and the end-of-life phase. The product system is depicted in Figure 3.

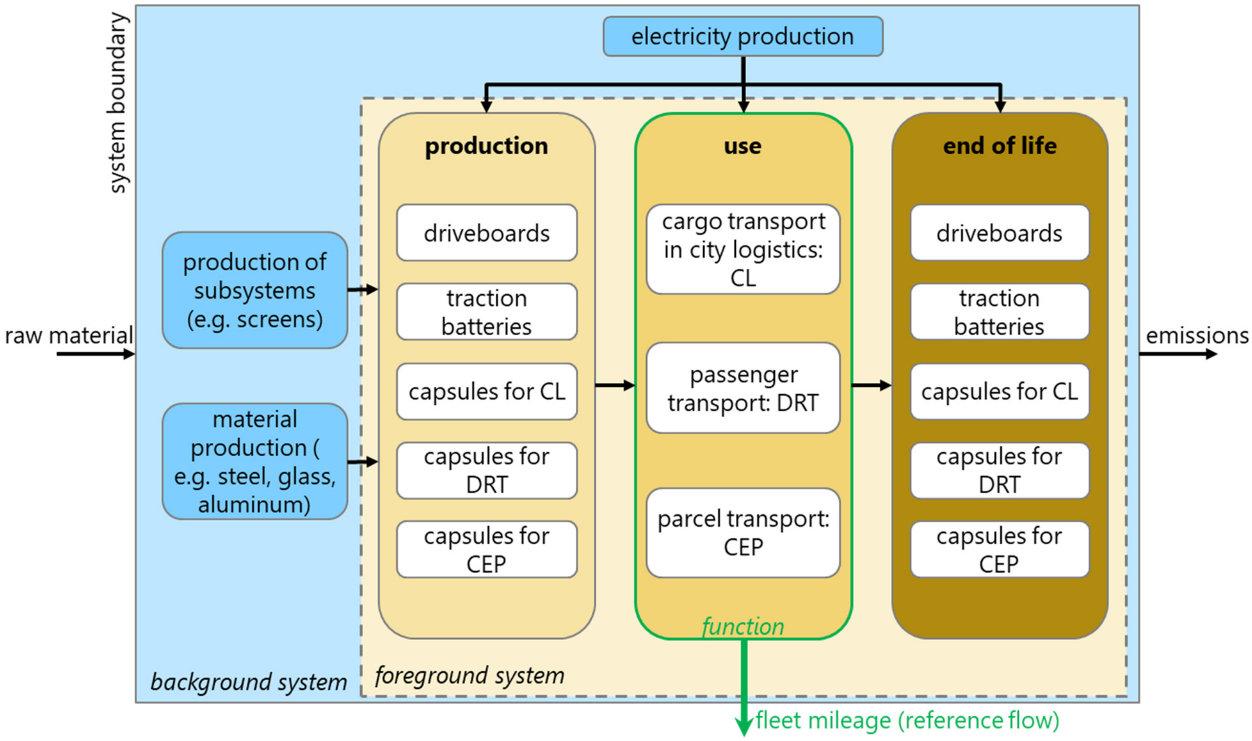

Figure 3. Product system of the U-Shift vehicle fleet for the defined use case (CL—city logistics; CEP—parcel delivery services consisting of courier, express, parcel delivery; DRT—demand responsive transport for public transport).

The LCA is based on the following key parameters, derived from literature, state-of-the-art vehicles and the U-Shift developer team (Table 2).

Table 2. LCA-relevant data for U-Shift and the reference (Abbreviations: PT—passenger transport, CT—cargo transport).

Parameter	RoboVan (Reference)	U-Shift
Vehicle fleet	39	21 driveboards 180 capsules
Lifetime mileage	325,000 km (results in 11 (PT) and 14 (CT) years)	325,000 km (results in 7 years)
Capsule lifetime	n. a.	PT: 17 years CT: 23 years
Traction battery	PT: 60 kWh CT: 80 kWh	Driveboard: 65 kWh PT-capsule: 35 kWh (for air condition, infotainment and traction support)
Battery lifetime	200,000 km or 8 years	200,000 km or 8 years
Annual fleet mileage	PT: 594,000 km CT: 426,000 km	PT: 594,000 km CT: 394,000 km
Electricity mix	70% renewables	70% renewables
Reference flow (mileage p.a.)	1.02 million km	0.99 million km

The lifetime mileage of U-Shift driveboards is assumed to be similar to that of RoboVan vehicles; however, as U-Shift is not a mass-production vehicle, empirical values are missing. This parameter and some others are varied in a sensitivity scenario.

The model of the U-Shift vehicle fleet is created with the Umberto® LCA+ software by using already existing process data from ecoinvent and by creating new process modules. Some of the existing process data aremodified to fulfill the special efforts needed to model the new vehicle concept. The transport of the passengers and the goods are modeled separately, as they require different capsules. The central transportation processes are designed in a modular manner, comparable to the transportation process modelling of the ecoinvent database [54,55]. The production and the end-of-life of the respective capsules and the driveboards are included proportionately in the model. This proportion is calculated from the lifetime mileage of the modules. The lower life expectancy of the batteries in comparison to the other modules is also considered. The non-exhaust emissions of the U-Shift vehicles are also integrated into the model. They can be estimated dependent on the vehicle mass. The model is divided into three sections to simplify the interpretation of the results. These are the production, the transport of passengers and cargo (use) and the end-of-life (disposal).

Input and output values are parameterized respectively calculated in the modeled material flows. Table 3 shows the input/output balance for the example of the "passenger transport" process. Table 4 shows the corresponding process for the RoboVan-model.

Table 3. Main in- and outputs for U-Shift during the passenger transport process (values in 1000; referring to the reference flow).

Input Material	Quantity	Output Material	Quantity
Battery (capsule)	0.28 kg	Brake abrasion	0.002 kg
Capsule	2.06 kg	Road wear	0.02 kg
Driveboard	1.93 kg	Tire abrasion	0.10 kg
Electricity	290.91 kWh	Passenger transport	593.69 km
Traction battery (Driveboard)	0.55 kg		

Table 4. Main in- and outputs for RoboVan during the passenger transport process (values in 1000; referring to the reference flow).

Input Material	Quantity	Output Material	Quantity
Electricity	308.72 kWh	Brake abrasion	0.002 kg
Traction battery	0.87 kg	Road wear	0.02 kg
Vehicle	5.52 kg	Tire abrasion	0.11 kg
		Passenger transport	593.69 km

All impact categories from the ReCiPe2008 LCIA method [56] are regarded in the evaluation (Table 5).

Table 5. Impact categories of the ReCiPe 2008 method (impact categories marked with * are analyzed in detail); source: aggregated from [56].

Impact Category	Indicator	Unit
climate change (CC) *	global warming potential (GWP)	kg CO_2-eq
ozone depletion (OD)	ozone depletion potential (ODP)	kg CFC-11-eq
terrestrial acidification (TA) *	terrestrial acidification potential (TAP) *	kg SO_2-eq
freshwater eutrophication (FE)	freshwater eutrophication potential (FEP)	kg P-eq
marine eutrophication (ME)	marine eutrophication potential (MEP)	kg N-eq
human toxicity (HT) *	human toxicity potential (HTP)	kg 1,4-DCB-eq
photochemical oxidant formation (POF) *	photochemical oxidant formation potential (POFP)	kg NMVOC-eq
particulate matter formation (PMF) *	particulate matter formation potential (PMFP)	kg PM_{10}-eq
terrestrial ecotoxicity (TET)	terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-eq
freshwater ecotoxicity (FET)	freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-eq
marine ecotoxicity (MET)	marine ecotoxicity potential (METP)	kg 1,4-DCB-eq
ionizing radiation (IR)	ionizing radiation potential (IRP)	kg U^{235}-eq
agricultural land occupation (ALO)	agricultural land occupation potential (ALOP)	m^2 p. a.
urban land occupation (ULO)	urban land occupation potential (ULOP)	m^2 p. a.
natural land transformation (NLT)	natural land transformation potential (NLTP)	m^2
water depletion (WD) *	water depletion potential (WDP)	m^3 water-eq
mineral resource depletion (MRD) *	mineral depletion potential (MDP)	kg Fe-eq
fossil resource depletion (FD)	fossil depletion potential (FDP)	kg oil-eq

Detailed analyses are made for the following categories, based on a selection by Hill et al. (2020) [57] and a literature overview of the most frequently used impact categories in LCA studies on electric vehicles [58]:

- climate change,
- terrestrial acidification,
- human toxicity,
- photochemical oxidant formation,
- particulate matter formation,
- water depletion,
- mineral resource depletion.

3. Results

The tabular view in Figure 4 gives a qualitative overview of the comparison of the two fleet alternatives (U-Shift and the generic, driverless status quo (RoboVan)) for all impacts covered by the ReCiPe2008 LCIA method, including both the total life cycle and single life cycle phases.

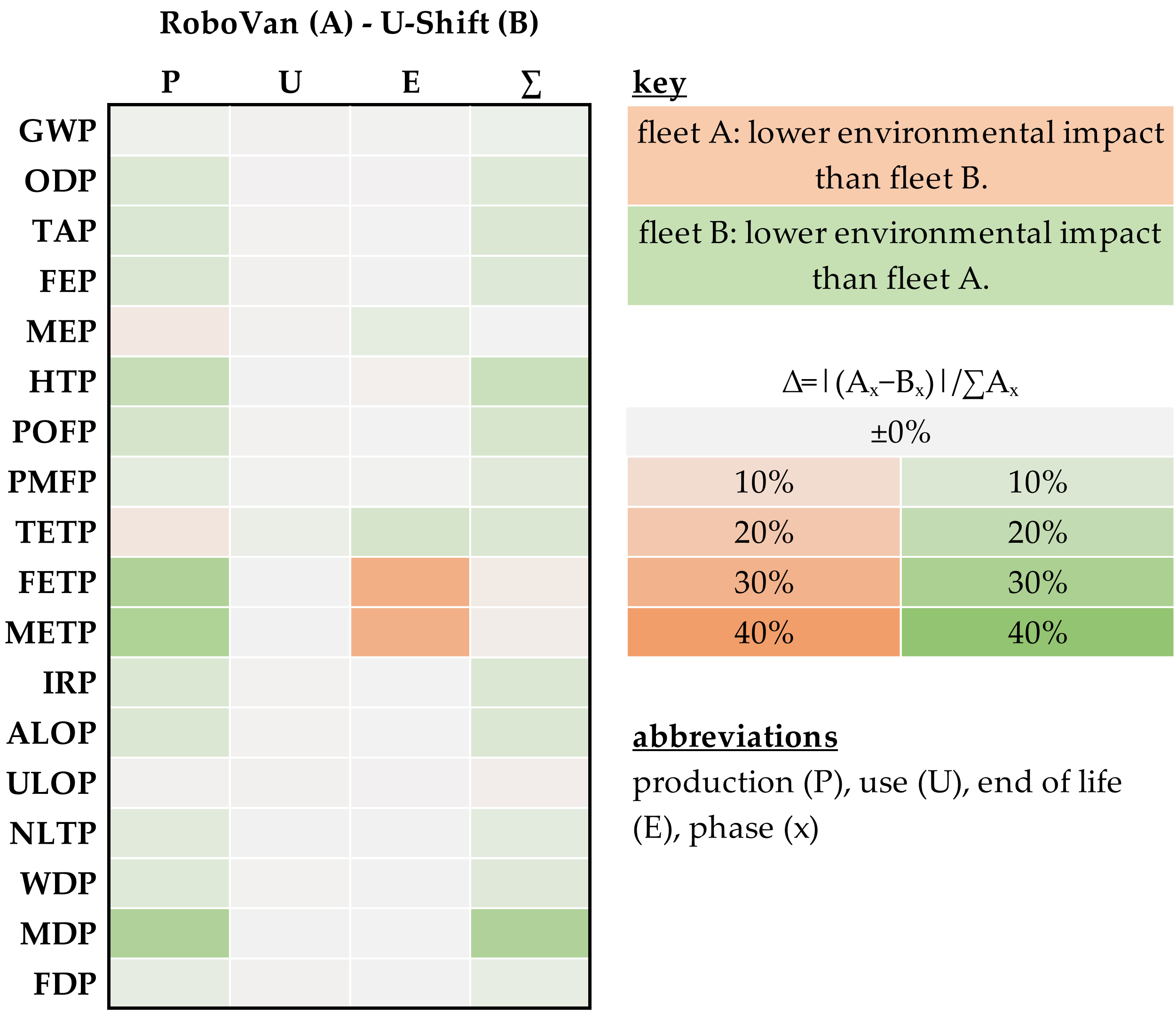

Figure 4. Results for all ReCiPe2008 impact categories, represented by their indicators (abbreviations and description of impact categories in Table 5).

On average over all impact categories, the U-Shift solution has an almost 10% lower environmental impact for the S-Vaihingen application than the RoboVan fleet, when analyzing the total of all life cycle phases. For 12 of the 18 impact categories, the environmental impact of the U-Shift fleet is at least 5% lower. Especially in the production phase, higher distinctions can be observed. Only for marine eutrophication, terrestrial ecotoxicity and urban land occupation, RoboVan causes lower emissions than U-Shift in the production phase; in the end-of-life phase, especially for freshwater ecotoxicity and marine ecotoxicity.

An almost identical mileage of the U-Shift and RoboVan fleet (Δ3%) results in a similar environmental impact in the use phase. The U-Shift system has a lower or higher energy consumption than a RoboVan vehicle, depending on the coupled capsule; the differences are equalized for most of the impact categories. Due to the lower number of driveboards compared to the RoboVan fleet, the U-Shift fleet has lower environmental impacts in the production phase in 15 impact categories.

Since U-Shift vehicles require significantly fewer driveboards than the amount of RoboVan vehicles, a comparison per vehicle would distort the result strongly to the disadvantage of U-Shift. The advantage of the modular concept—the efficient use of a small number of driveboards—would thus not be considered.

As the U-Shift driveboards have high annual mileages (Table 1), they are replaced in shorter cycles with new driveboards, as in the reference fleet's case. Thus, improved and potentially more efficient technology can by deployed faster.

Figure 5 presents a detailed analysis of the environmental impacts, giving the absolute and relative contributions of each life cycle phase for the U-Shift and the RoboVan vehicle fleets.

Figure 5. Detailed analysis of selected impact categories comparing the RoboVan and the U-Shift fleet.

The detailed analyses show that for GWP, TAP, POFP, PMFP and WDP, the disposal phase has a low impact (0–4%) for both alternatives. This is consistent with findings from the literature on life cycle assessments of battery electric vehicles [37]. The use phase includes emissions from use (non-exhaust emissions) as well as emissions generated during the generation of the electricity required in use. The share of the use phase in GWP is 61–64%, and thus corresponds to literature values for battery electric [59] as well as additionally automated vehicles [33]. Equivalent shares for POFP and PMFP are also in line [59].

The shares of the production phase of U-Shift are lower than those of the RoboVan for all impact categories, since the smaller number of driveboards and the durable capsules cause proportionally lower emissions. Using the example of vehicles for DRT operation (passenger transport), the main emitters were identified for the production phase. For U-Shift, the sum of the driveboard and the passenger transport capsule was calculated for this purpose. The results are compared with an LCA performed by Vilaça et al. (2022) for driverless vehicles in ridepooling (similar use case). For the GWP, Vilaça et al. (2022) determine shares of CO_2-eq emissions of about 20% each due to the traction battery and the automation components [60]. The values determined for U-Shift (battery: 25%; automation: 20%) and RoboVan (battery: 20%; automation: 25%) correspond very well to this.

In the following, sensitivities are shown in parameter variations. The electricity generation and the traction battery production, among other parameters, have been identified as critical influencing parameters by other works, as described in the introduction.

For this work, the electricity mix is changed into a scenario with lower and one with higher shares of renewable energies, compared to the base case. The electricity mixes are based on the energy reference forecasts for the German Federal Ministry of Economics and Technology [61].

The traction battery is considered indirectly by varying the energy consumption with the assumption that increased energy consumption results in a proportionate rise in the capacity of the traction batteries in order to keep the predefined range requirement. The energy consumption of U-Shift was derived from a simulation conducted in Dymola by Schall, Sigle and Ulrich (2021) [26]. The values for RoboVan were determined on the basis of real battery-electric commercial vehicles of the same category, supplemented by additional consumption for the automation, which is based on findings from the literature [33,60,62,63].

In addition, the lifetime is varied for several components: for the driveboards and the traction batteries, the lifetime mileage is adjusted, and for the transport units of the U-Shift, the calendrical lifetime is altered accordingly.

Figure 6 illustrates the effects of parameter variation for each vehicle fleet, showing that the parameter variations change the results of the fleets in a similar way. Thus, the comparison in Figure 3 remains stable, as long as the parameters for the fleets are changed in the same direction.

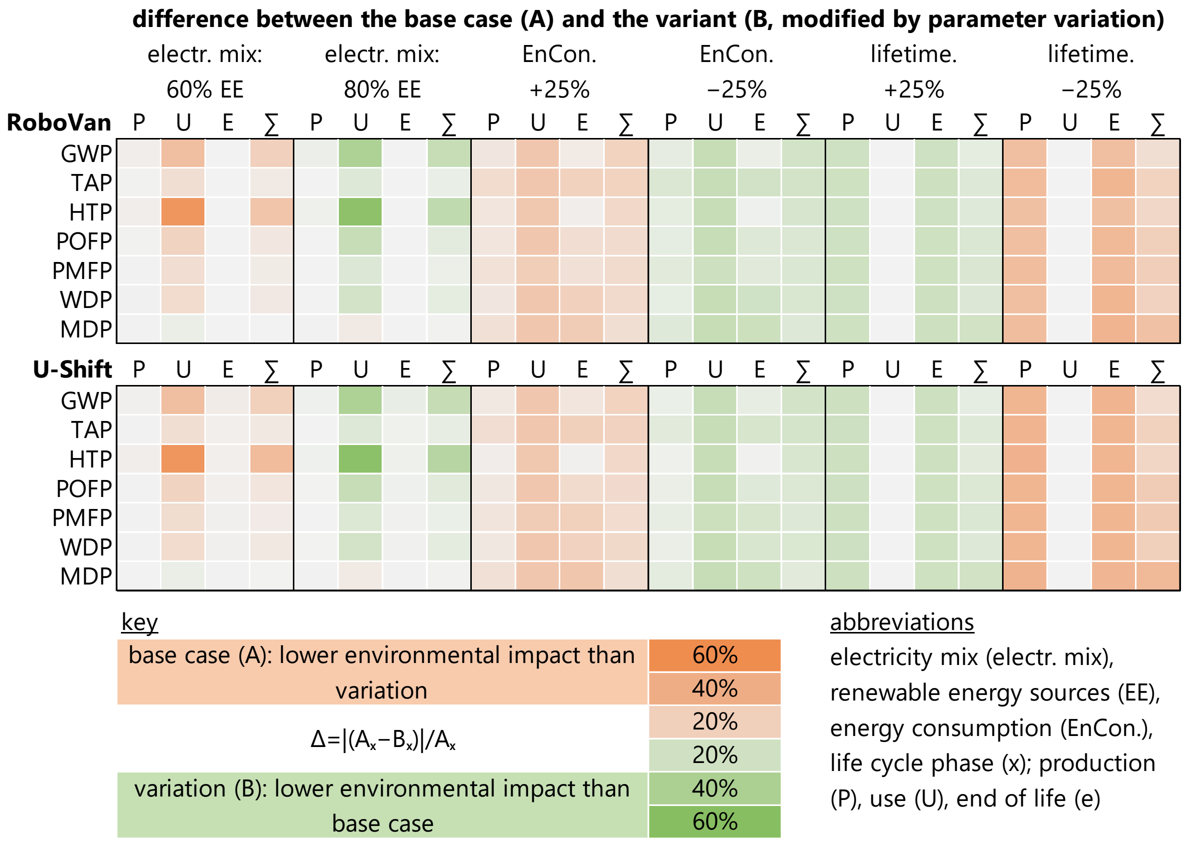

Figure 6. Vehicle-specific sensitivity analyses by varying different parameters (impact categories are defined in Table 5).

As expected, an increased share of renewable energy sources in electricity generation, reduced energy consumption and a longer lifetime reduce the environmental impacts. The opposite parameter variations in each case increase the environmental impacts to a similar extent.

Electricity mix and energy consumption primarily affect the use phase. When the electricity mix is changed, mineral depletion (MDP) behaves contrary to the other impact categories. An increased share of renewable energy sources reduces the environmental impacts for most impact categories; however, more resources relevant for MDP, such as gold and copper in electronic components [64], are required for electricity generation from renewable energy sources. Therefore, Fe-eq emissions increase with an increment of renewable energies.

The lifetime has an effect on the production and disposal phases, since a longer lifetime means that a vehicle's emissions are proportionately less considered.

4. Discussion

In the following, the results are interpreted and the circumstances under which U-Shift could further reduce its environmental impact are discussed. In addition, possible further research activities are outlined.

In most of the 18 analyzed impact categories, U-Shift already has lower environmental impacts than the driverless reference vehicle fleet. Even though the results are close, the findings do not change much when sensitivity analyses are conducted. U-Shift is currently in an early development phase. Therefore, there are no comparable LCAs or data from production vehicles. The data are based on primary data from current U-Shift prototypes under development, assuming technological advances to volume vehicles. In contrast, the comparison vehicles are based on production vehicles, and thus have already been optimized for many years. It can therefore be assumed that the results would be even more in favor of U-Shift if data were available for field-proven production U-Shift-vehicles.

4.1. Deployment Scenarios

The large number of capsules used by U-Shift and the additional weight due to modularization must be compensated for by efficient deployment. In the current application scenario, this is achieved by the significantly lower total of driveboards (vehicles) compared to the number of reference vehicles (RoboVan). Thus, the reduction of the fleet size along with the maximization of the utilization grade of the vehicle units through improved application scenarios exhibit high savings potential. If the disposition of the fleet is optimized in operations research (OR) simulations in future works, a significantly more efficient U-Shift deployment can be expected. Early work towards this is in progress [21,65]. Both a reduction in the capsule-to-driveboard ratio and a reduction in the entire fleet size regarding the number of driveboards as well as capsules promises a lower environmental impact.

Furthermore, a deployment scenario optimized by simulations potentially reduces mileage and thus, environmental impacts. This applies not only to the U-Shift application scenario but also to the RoboVan fleet. However, the reduction is potentially higher for U-Shift due to the additional transport units.

4.2. Use Phase and Lifetime

Increased lifetime allows for improved results, as observed in the sensitivity analysis; especially for capsules and traction batteries. The modularization strategy of U-Shift involves complex driveboards, yet simple capsules. A lower complexity could result in a longer lifetime. In addition, the capsules could be produced in the future in a more resource-efficient way than is currently assumed.

The use phase accounts for the highest share of emissions for most impact categories for both vehicle alternatives, with emissions correlating with energy consumption and mileage. Advances in vehicle development can primarily reduce energy demand, e.g., in the case of U-Shift through lightweight capsules, especially for the heavy capsules used for passenger transport. However, efficiency gains in the utilization phase through lightweight materials shift emissions to the manufacturing phase [66] (pp. 739–741). The respective optimum must therefore be identified for each case.

On average, the U-Shift driveboards have an annual mileage of 47 thousand km, which is about 80% higher than for RoboVan vehicles. This is why they are replaced by new units in shorter cycles. Increasing and improving maintenance could counteract this fact and potentially extend the lifetime of U-Shift driveboards. The potential to enhance the lifetimes of driveboards by increased maintenance has not yet been evaluated or considered by this LCA model; however, such maintenance does offer the potential to further reduce environmental impacts. Prolonging the lifetime and therefore the use phase of the driveboards should also be critically assessed in regard to the increase of non-exhaust emissions.

5. Conclusions

An LCA approach was developed that can be applied to novel, on-the-road modular vehicle concepts such as U-Shift. When comparing U-Shift to a conventionally integral vehicle, it is important to consider the entire fleet in a use case to account for the systemic changes caused by modularization. To investigate the modularization-induced effects, the reference vehicle was automated as well. An LCA model was implemented with which the integral reference vehicle fleet and the on-the-road modular U-Shift fleet can be compared in a consistent manner. The high number of capsules within the U-Shift fleet has to be compensated for through a lower number of complex driveboards and an efficient use phase. In particular, the lower number of U-Shift driveboards compared to vehicles in the reference fleet is beneficial. As the energy consumption and lifetime of the vehicle components have a significant effect on the environment impacts, future development of driveboards and capsules should focus on designing capsules for a long use phase and driveboards for efficient energy management, thus reducing the required battery capacities in driveboards and selected capsules.

In future work, the LCA model should be enhanced to include, amongst others, an LCA on social indicators [67] and an investigation of the circularity [68] of the product systems. Since the selected use case has a significant influence on the result, the established LCA method for on-the-road modular vehicles should be applied to future use cases. Furthermore, a comprehensive consideration including economic aspects is important, with future work investigating the economic use in differently structured and developed regions worldwide.

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