An Energy Efficiency Comparison of Electric Vehicles for Rural–Urban Logistics

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Abstract In many small and medium-sized businesses in rural–urban areas, delivery services to and from customers, suppliers, and distributed locations are required regularly. In contrast to purely urban commercial centres, the distances here are larger. The aim of this paper is to identify opportunities for substituting combustion-engine logistics with lightweight electric commercial vehicles and the limitations thereto, describing an energy efficiency comparison and improvement process for a defined logistics application. Thus, the area of Heilbronn-Franconia and its transport conditions are presented as examples to compare the use case to standard driving cycles. Then the logistic requirements of Heilbronn UAS (*University of Applied Science*) locations and the available vehicles as well as further electric vehicle options are depicted. Options are discussed for the additional external payload in search of transport volume optimisation without increasing the vehicle floor space. To this end, simulation models are developed for the aerodynamic examination of the enlarged vehicle body and for determining energy consumption. Consumption and range calculation lead to vehicle concept recommendations. These research activities can contribute to the transformation of commercial electro mobility in rural and urban areas in many parts of Germany and Europe.

Keywords Small electric commercial vehicle · Rural–urban logistics · Computational fluid dynamics · Transport volume optimisation

1 Introduction

When considering future transportation options, heavy-duty vehicles and their alternative drives come to mind, although a commercial approach is lacking. Both opportunities and challenges seem immense, although available technologies enable

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change towards more sustainable transport for the vast majority (76%, [1]) of commercial vehicles in Europe. The sub-3500 kg-N1-class of commercial vehicles defined by EU regulations [2] does not cover long-distance freight shipping and only handles local to rural individual end-customer supply. This class with payloads comparable to passenger cars still lacks alternative powertrains (<2% [1]), despite the continuously rising share of electric passenger car production (12% of the German Car Industry by April 2020, [3]). Road logistics powertrain electrification has slowly been growing [4]; particularly on shorter tracks, electric commercial vehicles have come into mass use [5], due to stricter emission limits. Moreover, battery electric vehicles (BEV) hold the potential of logistics cost reduction [6].

The possibility of concept transfer from passenger BEVs to rural transporters and application of the ecological imperatives begs the question of how to select the most appropriate vehicle for the particular application, which is answered in the following paragraphs.

1.1 Developments in Rural BEV Application

In the field of inner-city delivery traffic with light commercial vehicles [7, 8], as also for heavy commercial vehicles on the "last mile" in urban distribution traffic [9, 10], there have already been numerous developments, investigations, and studies. Delivery services are increasingly employing electric vehicles in cities [11, 12].

The range of electrically powered commercial vehicles limits their use initially to urban areas. Hardly any scientific publications have investigated the potential of commercial BEVs in rural–urban areas. The "*eMiniVanH*" project established by the Ministry of Economic Affairs Baden-Wuerttemberg aims to fill this gap.

Important features of vehicles used in rural–urban areas are longer distances and higher driving speeds. Daberkow and Häussler [13] describe the usability of light electric passenger cars in this rural–urban area, as a first investigation. They range in variety from specially developed research vehicles [14, 15] to models already available on the market from well-known vehicle manufacturers. A collection of some small electrical vehicles is given by Brost et al. [16].

The application of such vehicles in courier and parcel delivery services creates a demand for a daily range of 30–800 km [17, p. 171]. By limiting these driving profiles to more task-related parcel services, the range requirement shrinks to 30–360 km, with average speeds up to 60 kmh^{-1}, soon to be covered by common BEVs.

N1 light-duty BEVs try to enter a most competitive market segment, which eliminated several small companies and small series of large OEMs. Therefore, the following legally highway-suitable vehicles are all considered, and chosen as representative types for further discussion because they differ significantly in size and load volume: the *Renault Kangoo Zero Emission* (2013–2017), an electrified high roof station wagon; the *Streetscooter Work Box* (2015–2020), solely battery electric, developed for *Deutsche Post AG*; the *Volkswagen e-up! load-up!* (2013–

2016), an electric light-duty variant of a mini car; and finally, the *Volkswagen e-up!* (since 2020), with its extended range facelift. From these types, a vehicle is chosen matching the use case, which can replace a combustion vehicle most efficiently.

1.2 Facility Test Environment in Heilbronn-Franconia Region

The "eMiniVanH" project deals exemplarily with freight traffic between the Heilbronn UAS locations. The state of Baden-Wuerttemberg lies along the French border and is located in the southwest of Germany. The Heilbronn-Franconia region, see Fig. 1, covers an area of 4765 km^2 with a population of roughly 0.9 million, and its administrative seat is Heilbronn (population 130,000), see [18].

Heilbronn-Franconia is an important economic region. Large manufacturers like *AUDI AG* as well as large suppliers like *Robert Bosch GmbH* contribute to the economic wealth of the region.

Individual mobility and public transportation are key aspects of the region. UAS has purchased and operates a *VW e-up! load-up!* model as representative of a small electric commercial vehicle, see Fig. 2 left and middle.

This special vehicle has a continuous cargo area instead of the rear row of seats. With 60 kW drive power and an installed battery capacity of 18.7 kWh, this compact vehicle (length 3540 mm according to VW AG [20]) is eminently suited to urban as well as rural areas. The initial tests were made for parcel and mail transport substitution (see Fig. 2 on the right). As the standard freight consists of a few post

Fig. 1 Heilbronn landscape [19] and rural–urban location of Heilbronn-Franconia region [18]

Fig. 2 Volkswagen *e-up! load-up!* with cargo compartment (left and middle) and a typical example of parcel and mail transport with an internal combustion-engine-powered transporter (right)

boxes, replacing the combustion-engine-powered transporter is easily possible. About 960 kg of the payload is to be transported, per week. However, further expansion of the loading volume is desirable for additional applications, and the effects on the range must be investigated.

2 Digital Prototypes and Simulated Driving Cycles

Prior to prototype manufacturing and road test execution, a preceding digital part development supported by simulations must prepare design decisions. As with many car and truck bodybuilders, digital data of the base vehicle, for example, CAD-3D or Digital Mock-Up (DMU) data for the *VW e-up! load-up!* are not available. The following Sect. 2.1 describes the reverse engineering of a digital prototype for further investigations. In Sect. 2.2, this DMU is assessed aerodynamically, as the air drag is mainly of relevance for energy consumption simulations. Section 2.3 describes energy consumption simulations for the use case, a facility management trip between all four locations, and other scenarios comparing several competing vehicle variants.

2.1 *Creating a Digital Mock-up*

The DMU also provides the opportunity to design extra volumes for transport and load carrier fixation systems for the specific case. The digital representation does not require all details and parts of the vehicle. Only exterior surfaces and interior geometry of the cargo bay are of relevance. Manual Laser imaging, detection and ranging (LIDAR) scanning produces STL-Files of the payload compartment and the exterior surfaces, as shown in Fig. 3. Some errors occur while matching several scans together automatically. Redesigned post and pharma boxes complete the DMU.

Fig. 3 LIDAR-Scan of the *VW e-up! load-up!*; left: exterior; centre: cargo compartment; right: pharmaceutical cargo containers, "*Postbehälter Typ 2*" and VDA/Euronorm

2.2 CFD Based Roof Extension Development

The roof of the *VW e-up! load-up!* is also used for the generation of storage space, in addition to the interior space. The design of potential roof box variants is based on computational fluid dynamics (CFD) simulations. The models of the *VW e-up! load-up!* and its roof extension variants are shown in Fig. 4. Four post boxes stored in either container extend the storage volume by 100 l, as the roof load is restricted to 50 kg, equalling four times the mass capacity of a post box.

The Reynolds-Averaged Navier-Stokes K-Ω model and a steady-coupled implicit flow solver were used to simulate the turbulent flow of the incompressible air with 20 ms^{-1} (72 kmh^{-1}) and 35 ms^{-1} (126 kmh^{-1}) for comparison. As the model contains ten prism layers geometrically growing with a growth factor of 1.73 over 8 mm total thickness, all the wall-y+ values lie below 3 as required by the applied turbulence model. The wheels rotate at matching angular velocity, their separate rim mesh region consisting of a moving reference frame. The vehicle geometry is simplified by a closed radiator grille and a smooth vehicle undertray and neglects suspension components. Tire treads, mirrors, and wheel front flicks are considered. Exploiting symmetry properties reduces the cell count to 16 million by using a half model in an open road setup [21].

Different roof extension designs are compared to the scanned reference model using the CFD results drag coefficient c_d and the normal area in the driving direction A_x. The objective is a minimized additional air resistance for the predefined load volume gain.

2.3 Driving Cycles for the Rural–Urban Use Case

Today, a vehicle's energy consumption is compared utilising standardised test procedures, the New European Driving Cycle (NEDC) and the Worldwide Harmonised Light Vehicles Test Procedure Class 3b (WLTP) driving cycles predefined by UN-laws UN ECE/324 and UN GTR15. The WLTP Class 3b driving cycle provides a good basis for vehicle comparison in a rural–urban use case.

These predefined cycles may not necessarily represent the specific requirements of arbitrary delivery services in rural–urban areas. Here, a further unique Use Case

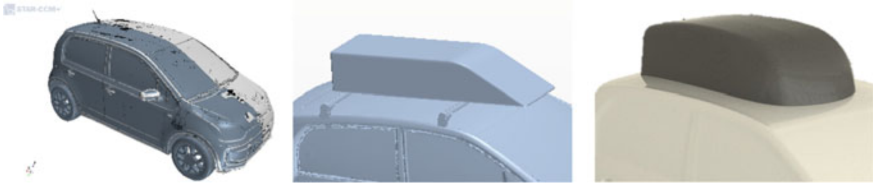

Fig. 4 e-up! *load-up!*, removable roof box (middle), fixed high roof compartment (right)

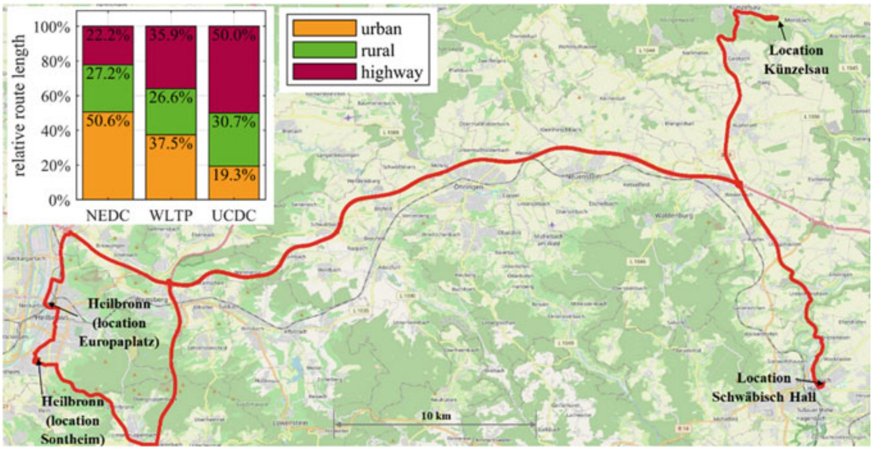

Fig. 5 Driving route between the UAS Heilbronn campus [own illustration with map material from © 2020 GeoCzech, Inc.] and chart with street and traffic type characteristics (top left)

Driving Cycle (UCDC) for the Heilbronn UAS testbed completes the assessment as a third cycle. This route as shown in Fig. 5 connects the different campuses of the UAS.

The UAS has two campuses in Heilbronn, one in Künzelsau and the other in Schwäbisch Hall. The route with 145 km total length contains city traffic, rural roads, and highways. Its sections represent a real use case with street and traffic types as in Table 1.

NEDC consists of two parts (urban and non-urban), and WLTP Class 3b distinguishes four different speed sections. Figure 5 shows that the UCDC lacks city tracks but has a larger share of highway track length compared to the WLTP. This partial route with a top speed of 100 kmh^{-1} contributes to a smoother but faster cycle on average with an average absolute acceleration $\overline{|a|} = 0.230\ \text{ms}^{-2}$ (WLTP: $\overline{|a|} = 0.358\ \text{ms}^{-2}$) and an average velocity $\bar{v} = 64.8\ \text{kmh}^{-1}$ (WLTP: $\bar{v} = 46.5\ \text{kmh}^{-1}$). Consumption and range calculation determine transferability of WLTP results for the UCDC.

Table 1 Characteristics of different street and traffic types [22]

Street type	Characteristics
City streets with urban traffic	Driving speed up to 60 kmh^{-1}, frequent stop-and-go, intermittent acceleration necessary
Country roads	Driving speed between 60 and 90 kmh^{-1}, no stops, certain acceleration necessary
Highway	Driving speed up to 130 kmh^{-1}, constant driving, hardly any acceleration necessary

2.4 Simulation Model for Vehicle Drive Cycles

To compare the energy consumption stated at the accumulators of different vehicles, a *MATLAB®* program evaluates the velocity profile of the three driving cycles. Dry mass, payload, acceleration, and velocity contribute to the driving resistance forces' drag, tire friction, and inertia and their corresponding powers [23]. The non-constant altitudes of the UCDC are included. Due to restricted public access, several parameters were estimated and used equally for all assessed vehicles, as Table 2 shows.

The *VW e-up! load-up!* (2013) has a payload capacity of 286 kg, which shall be the payload in the presented use case. Technical data of each vehicle provides their dry mass and dimensions, but no information about drag coefficients' projected frontal area is published. For an engineering estimation, a cross-sectional CAD-sketch delivers well-approximated values. Drag coefficients' estimations are listed in Table 3.

In addition, technical data deliver values for battery capacity used for range calculation and at least one driving-cycle-based consumption value. The *VW e-up! load-up!* OEM data shows 11.7 kWh/100 km NEDC energy consumption, whereas the simulation without payload shows 11.8 kWh/100 km. The *Kangoo Z.E.* OEM data shows 15.2 kWh/100 km NEDC energy consumption, while the simulation of the empty vehicle shows 15.1 kWh/100 km. These sufficiently matching results qualify the simulation very well for further concept comparisons and thus indicate verifiable results.

Table 2 Substitute parameters used equally for all assessed vehicles

Parameter	Abb.	Value	Source
Tire friction coefficient	f_{R}	$0.01 + \frac{v}{10^4}\frac{s}{m} + \frac{v^4}{2\cdot 10^7}\frac{s^4}{m^4}$	[23, p. 50]
Powertrain efficiency coefficient	η	0.78	[24, p. 124]
Recuperation efficiency coefficient	η_{recu}	$0.741 = 0.95\eta$	[25, p. 19]
Mass surcharge factor for the moment of inertia	k	1.25	[26, p. 82]

Table 3 Aerodynamic parameters of compared vehicles

Vehicle	A_{x} (m^2)	c_{d}	Source
VW e-up! load-up! (2013)	2.07	0.311	LIDAR Scan and CFD
Renault Kangoo Z.E.	2.5	0.35	Estimation [27, pp. 66 + 643]
Streetscooter Work Box	3.5	0.45	Estimation [27, p. 643]
VW e-up! (2020)	2.1	0.30	Estimation based on 2013 model

3 Result Evaluation for Designs and Energy Consumption

The first section of this chapter summarises the space gained by enlarging the interior and the roof box. Section 3.2 describes the conceptual decision for the roof box, determined by CFD simulations. Based on this, Sects. 3.3 and 3.4 comprise the simulation results with the consequences for the different vehicle types.

3.1 Enlargement of the Interior Space

There are some design options to enlarge the interior loading capacity to individual requirements [28]. All-purpose solutions or individual custom-made designs are offered by various manufacturers [29].

Especially with small vehicles, optimisation of the already limited loading volume is of critical importance. The simplest way to optimise the loading opportunities is to enlarge the loading floor to the front area by removing the front passenger seat. Furthermore, it must be ensured that the driver's view is not inadmissibly restricted and that the driver is not endangered by the payload [30]. For the universal requirements of the load compartment, a flat loading platform is suitable.

3.2 CFD Simulation Results

The velocity profiles of the simulated flows are shown in Fig. 6.

The acute angle at the beginning of the removable roof box results in a relatively low stagnation point (1). A high loss of velocity occurs in the gap between the roof box and the vehicle roof, which negatively affects the calculated c_d-value (2). Based on the absence of any space between the car roof and the high roof compartment,

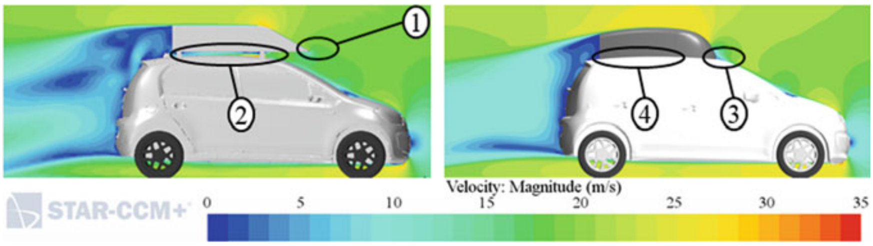

Fig. 6 Simulated flow velocity profiles for roof concepts from Fig. 5. Driving route between the UAS Heilbronn campus [own illustration with map material from © 2020 GeoCzech, Inc.] and chart with street and traffic type characteristics (top left) Fig. 4

Table 4 Comparison of the calculated values

	VW e-up! load-up!	+ roof box	+ high roof variant
Drag coefficient c_d	0.311	0.44	0.343
Reference area A_x (m^2)	2.07	2.30	2.31
$c_d \cdot A_x$ (m^2)	0.646	1.014	0.791
Drag force (20 ms^{-1}) (N)	**152**	**239**	**186**

the drag forces in this area are significantly lower than for the removable roof box (4). In addition, the high roof is in contact with the vehicle body, thereby making for optimal deflection at the beginning of the high roof. Moreover, no direct stagnation point is created at the top of the high roof (3). Table 4 compares simulation results for the roof extensions to the *VW e-up! load-up!* model equipped as standard.

The published drag coefficient of 0.308 [20] for *the VW e-up! load-up!* is slightly below the CFD simulation result of 0.311 (see Table 4). In comparison, the high roof compartment delivers far better results than the removable roof box. This happens because the high roof variant has no gap between vehicle body and high roof and therefore does not lead to unfavourable flow conditions.

3.3 Results of the Simulated Drive Cycles

Despite the differences between the real-driven UCDC and the standardised test-bench cycle WLTP, both lead to the same consumption, as Fig. 5 shows, differing less than 2%. Despite the significant differences outlined in Sect. 2.3, the WLTP represents this use case adequately. The NEDC results in 13–21% less electric energy usage, depending on the assessed vehicle. In conclusion, the simulated WLTP provides an appropriate prognosis for small and light commercial BEV energy consumption.

The *VW e-up! load-up!* stands out regarding consumption, even fully loaded. Additional extensions like the examined roof compartment increase aerodynamic resistance to such an extent that a high roof station wagon type becomes the recommended vehicle concept, as it offers around 400% more cargo space with approximately the same air resistance. Neither consumption nor range qualifies the *Streetscooter* or comparable vehicle types for operation in this use case, as their design for solely urban terrain is reflected in aerodynamic weakness, as Fig. 7 shows.

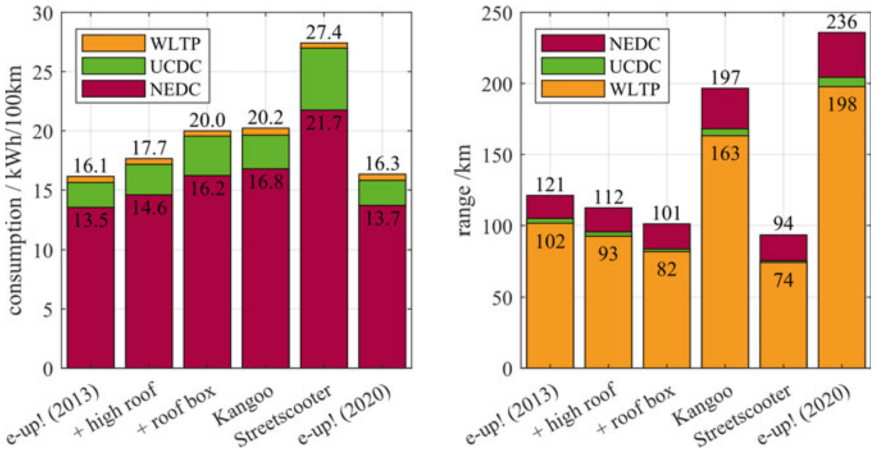

Fig. 7 Energy consumption and range calculation results

4 Conclusion

The standard variant of the *VW e-up! load-up!* vehicle type can carry 12 post containers, resulting in 300 l cargo volume. Due to the proposed interior design change of the *VW e-up! load-up!*, 20 post containers of 500 l in total are available. This is 67% more cargo volume than the reference model. This approach goes beyond solutions with roof extensions, due to the absence of aerodynamic deterioration. The *VW e-up! load-up!* high roof variant together with the new interior design, see Fig. 6, is designed for four additional post containers with a total of 600 l. Compared to the standard variant, this yields 100% more containers, although it leads to an increase in energy consumption by 20%. The range with a high roof thus decreases from 102 to 82 km, see Fig. 7. Before adding roof storage to a light-duty mini car, deciding on the *Kangoo* is thus more energetically reasonable.

The developed cargo load concept and the energy consumption investigations show that the *VW e-up! load-up!* vehicle types are a good option close to small and light electric commercial vehicle concepts for the rural–urban region with larger distances. Even at higher speeds, acceptable distances and payloads can be covered without stopping for charging. Thus, the *VW e-up!* (2020) including an enlarged, interior payload compartment becomes the ideal choice for the presented use case.

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