Electrification of Urban Three-Wheeler Taxis in Tanzania: Combining the User's Perspective and Technical Feasibility Challenges

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Abstract This study assesses the feasibility of electric three-wheelers as moto-taxis in Dar es Salaam, Tanzania from a socioeconomic and technical point of view. The analysis is based on three pillars: (i) the acceptance of users (the moto-taxi drivers) for adoption, (ii) the vehicle specifications incl. battery type and size, and (iii) the role of the charging infrastructure. Findings are based on data from empirical field-work; methods used are qualitative and quantitative data analysis and modelling. Main findings include that moto-taxi drivers, who we see as most important adopters, are open towards electric mobility. They request however that vehicles should have similar driving characteristics than their current fuel-vehicles. As the market is very price sensitive, keeping the vehicle cost is of high importance. A high potential to lower these costs is seen by offering opportunity charging spots around the city. If such an infrastructure is being implemented the combination with suitable, cost competitive vehicles makes the transformation of the vehicle market towards electrification possible.

Keywords E-mobility · Charging infrastructure · Opportunity charging · Informal transport · Moto-taxi

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1 Introduction

Two- and three-wheeled motorcycle-taxis (moto-taxis) have a significant and increasing modal share in rural and urban areas of developing countries, especially in Sub-Saharan Africa [1–3]. In urban areas, the popularity of the moto-taxis is linked to their ability to fill supply gaps in transport systems that are a result from fast urban growth and sprawl, insufficient urban and transport planning, and the overall deterioration of public transport in recent decades [4–6]. However, besides improving the mobility of citizens and providing job opportunities, combustion fuelled two- and three-wheelers increasingly contribute to air pollution and other negative externalities such as noise, traffic congestion and safety issues [2, 7–9].

In Dar es Salaam, largest city of Tanzania, the number of two- and three-wheelers has steadily grown in the last decade, and today they have become commonly visible in the streetscapes. Back in 2014, over 50,000 three wheelers were registered in Tanzania, and for 2018 WHO reported a total of 1,282,503 two- and three-wheelers in the country, 59% of the nation's registered vehicles [8]. In Dar es Salaam, moto-taxis form a *de facto* public transport system. They connect the main trunk roads with residential areas as well as feeding the public transport system [9, 10], often in areas where no other publicly available transport modes exist. Drivers of moto-taxis are commonly organized in groups, who wait at designated moto-taxi stands for their clients. Usually, drivers are only active at one or a small number of stands. Cruising is uncommon and drivers usually return to their stand after each ride. In 2010, the city administration legalized the operation of moto-taxis, but at the same time, restricted the access to the city-centre due to safety reasons and increased traffic congestion. Another argument was the need to improve air-quality.[1] Today, the city-centre lacks a public transport system for shorter distances to complement the bus rapid transit (BRT) that is designed to feed in commuters from the peri-urban areas. Along the BRT routes, especially the three-wheelers connect passengers to the BRT system (Fig. 1).

Being locally emission free, the electrification of the three-wheeler taxi-fleet represents a possible solution to face the sustainability challenges that could ultimately also allow moto-taxis to access the city centre again. It could also be a sustainable transport solution for other parts of the city. This study will evaluate the feasibility of electric vehicles as replacement for combustion-engine-driven moto-taxis in Dar es Salaam. The analysis is based on three pillars: (i) the acceptance of users (the moto-taxi drivers) for adoption, also with respect to the market conditions and business models and an assessment of the technical feasibility, with (ii) respect to the vehicle specifications such as battery type and size, and (iii) the role of the charging infrastructure. Our research is based on empirical field-work, data analysis, and modelling.

[1]Group discussion with public officials from "Surface and Marine Transport Regulatory Authority, (SUMATRA) during a stakeholder workshop at the University of Dar es Salaam in March 2018.

Fig. 1 Moto-taxi in Dar es Salaam. Photo taken during field trip Feb. 2019 © DLR/Benedikt Hanke

In result, we find a high level of acceptance of electric mobility amongst moto-taxi drivers, who currently own the vast majority of three-wheelers in Dar es Salaam. These findings however only hold if the electric vehicles fulfil the following criteria: driving characteristics (top-speed, passenger capacity) that are similar to the combustion fuelled three-wheelers, a sufficient range and cost competitiveness. To date, no such vehicles exist on the international three-wheeler market, and if, they would be too costly, mainly due to the battery cost that increase with capacity. This is an obstacle for a quick adoption. We therefore continue to analyse how battery sizing can be interlinked with charging infrastructure: If opportunity charging spots are installed at dedicated moto-taxi stands, the currently existing adoption barriers could be reduced. This could ultimately help to fasten adoption of electric three-wheelers in Dar es Salaam.

2 Methods and Data Collection

The study builds on a mixed methods approach that relies on empirical field work for data collection, modelling of the vehicle and power train as well as the battery storage and charging infrastructure.

2.1 Data Collection

Four methods for data collection were applied during two field stays in Dar es Salaam (November to December 2018, February 2019): (1) A paper-pencil survey among a total of 105 drivers at four different moto-taxi stands, located in the subwards of Mikocheni, Sinza and Mbezi was carried out. Questionnaire items included socioeconomic profiles of drivers, vehicle data, information on vehicle ownership, income and operation costs, as well as service characteristics such as the estimated number of trips per working day and regular operating hours. (2) Group discussions with representatives of two out of the four moto-taxi associations were conducted. The exchange served to assess the drivers' acceptance of E-mobility and to unveil potential benefits as well as obstacles linked to an implementation of electric three-wheelers in the city. (3) Explorative, open interviews with key stakeholders from public authorities, research institutions and private companies were conducted to assess regulatory frameworks and technical feasibility of implementing E-mobility in Dar es Salaam and to inquire about battery recycling capacities and the local vehicle market. (4) A GPS tracking campaign, over a period of one full week in each case, was carried out among three-wheeler taxi operators at the four different moto-taxi stands in order to gather vehicle driving profiles. The tracking was conducted with 1 s resolution in time using the DLR Moving Lab.[2] The drivers were asked to take notes for clarification of measurement artefacts and for additional information (passengers carried per trip, refuelling). During the measurement campaign 65 individual vehicle profiles, each representing one week of driving activity, with over 18 million individual data points covering 33,637 km were collected (see Fig. 2).

2.2 Modelling of Vehicle and Power Train

The design of the power train for an electric three-wheeler followed a multi-step approach and included the following steps:

1. Internet-based market research of available electric three-wheelers (carried out in January 2019) on a global scale, to understand what vehicles are available and asses if they are suitable to be used for the use-case as moto-taxi in Dar es Salaam.
2. A workshop with moto-taxi drivers (February 2019, c.f. 2.1) with the aim to identify needs, expectations and barriers about using electric three-wheelers.
3. Development of a power train concept reflecting the inputs from step 2.
4. Set up of a simulation model for three-wheelers with the power train concept developed in step 3 that simulates the energy demand.

[2] https://movinglab.dlr.de/en/.

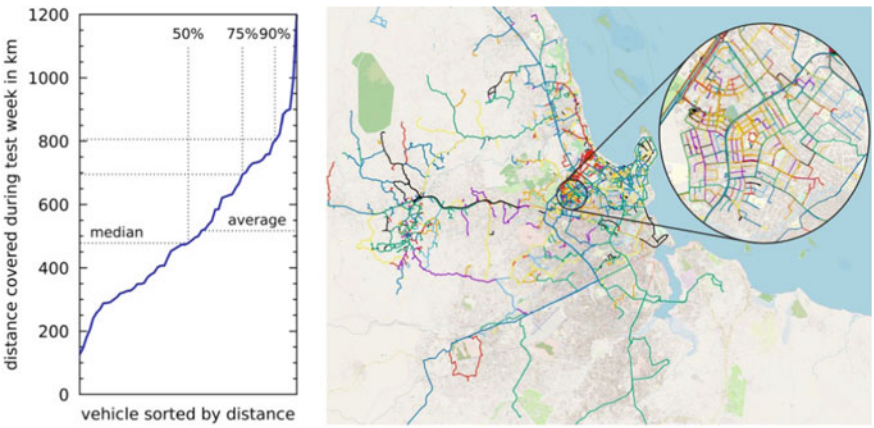

Fig. 2 Kilometres covered per vehicle during the test sorted by distance covered (left). Map of Dar es Salaam's city centre and it's outskirts with tracks of the GPS measurement campaign (right, figure uses map data from "© OpenStreetMap contributors, CC-BY-SA, www.openstreetmap.org/copyright")

Regarding the overall development of the vehicle, special attention was given to the need to keep the vehicle cost low (c.f. 3.1). The development steps therefore focused on the power train, which jointly with the battery is the main cost driver. In this step, two battery technologies were considered: lead acid and lithium ion batteries. Lead acid batteries are widely available in Tanzania as 12 V starter batteries. Therefore, choosing an intermediate circuit level of 48 V is reasonable. For lithium ion batteries, an intermediate circuit level of 48 V or 400 V can be considered, with 400 V being widely-used in electric vehicles, giving some advantage in the overall efficiency of the power train. Given that the authors rate safety a high issue, especially in developing countries, a 48 V intermediate circuit level is favoured.

The selection of the inverter technology depends on the intermediate circuit level: a MOSFET (metal-oxide-semiconductor field-effect transistor) inverter in case of 48 V, an IGBT (insulated-gate bipolar transistor) inverter in case of 400 V. Motor technologies can be rated under various aspects. Based on the findings of step 2 (c.f. above) low cost, longevity and easy maintenance were rated highest, while efficiency and power density were given lower priority. Consequently, we consider an asynchronous motor to be the best option, alongside to a gear box with a fixed ratio that allows for a smaller and cheaper overall system [11].

To calculate the vehicles energy demand, we set up a simulation model which uses efficiency maps or fixed efficiency values for the chosen power train components. Additionally, a drive cycle is needed like the Worldwide harmonized Light Duty Test Cycle (WLTC). However, after riding three-wheeler moto-taxis in Dar es Salaam during a field trip ourselves, we agreed that the real usage of those vehicles does not come close to the velocity profiles of standard drive cycles. Hence using them would lead to a falsified simulated energy demand. We therefore developed our own representative drive cycle for Dar es Salaam, using the GPS data from our empirical work (c.f. 2.1), partly following the approach of Eghtessad [12].

2.3 Modelling of Battery Storage and Charging Point Interdependency

In this step, we analyse the interdependence of a minimum required vehicle battery capacity, to fulfil the individual driving needs at minimal vehicle cost, and the availability of charging infrastructure at the dedicated moto-taxi stands. Our approach aims at describing a solution for a one-to-one replacement of combustion engine based vehicles (with current driving profiles) with battery electric vehicles. Based on the driver's interviews (c.f. 2.1), cost neutral solutions will have the highest acceptance for adoption. Based on the driving behaviours extracted from the GPS tracks of the tracking campaign, relevant charging locations at the moto-taxi stands were selected. Based on the availability of this charging network, we calculated the minimal required battery capacity for the individual vehicle.

We identified main moto-taxi stands of the drivers using a histogram methodology, creating a heat map of all measured vehicle locations. The identified stands matched with the findings from the driver interviews. Six public spots were identified as suitable public or semi-public charging locations to conduct so called opportunity charging. Opportunity charging in this study is defined as charging while waiting for customers during normal business hours at the point of business (here, specifically at the location of the dedicated moto-taxi stands mostly frequented).

The number of vehicles during a specific week of GPS tracking (c.f. 2.1) and the maximum number of vehicles at any station at the same time during that week is shown in Table 1. The coincidence factor is between 67 and 93%. If all vehicles need access to a charging point whenever they are at the station, up to one charging point per vehicle would be required. In the recorded data, most of the time, at least one vehicle is available at the main station of the driver group, with very few exceptions. Highest availability of vehicles is recorded around noon. Vehicle availability is higher during the day than during the night.

Table 1 Vehicles under test (VUT) and coincidence factor of moto-taxis at the stations

Week	# VUT	Max.	# VUT at station (%)
1	10	8	80
2	14	13	93
3	21	14	67
4	20	16	80

For the charging of the three-wheelers, we assumed that every parking event longer than 3 h is used to charge the vehicle, independent of the location. Introducing a technology change would incentivize drivers to select long term parking spots that would allow them to recharge the vehicles during longer breaks, where the vehicle is out of business. If a parking event takes place within 300 m of an opportunity charging station at the moto-taxi stands for more than 17 min, opportunity charging was conducted in the model. 12 min of the time at the stand are deducted for arriving, connecting and unplugging the vehicle. Taking these model assumptions into account, the shortest charging event lasts at least 5 min. Two charging scenarios with typical household currents of 7 A (1.6 kW) and 16 A (3.7 kW) and two SOC-target scenarios (80 and 100%) were considered.

During charging, an energy loss of 5% from grid to battery was taken into account. The technical battery capacity was assumed to be utilizable from 20 to 90%. The corresponding battery weight was included in the energy demand model of the vehicle (c.f. 2.2). The state of charge (SOC) was defined based on the effectively available (useable) battery capacity as 70% of the technical battery capacity. We applied a simplified battery model to account for the increased charging time demand above 80% SOC and conservative assumptions on the maximum charging rate where taken (see Eq. (1)).

$$C = \begin{cases} 0.5 & \forall \mathrm{SOC} < 80\% \\ 0.2 & \forall \mathrm{SOC} \geq 80\% \wedge \mathrm{SOC} < 90\% \\ 0.1 & \forall \mathrm{SOC} \geq 90\% \end{cases} \quad (1)$$

We conducted ensemble simulations considering different charging currents and vehicle loads to identify the range of energy storage demand in the vehicle battery with focus on the identification of the effectiveness of the availability of opportunity charging stations at the central moto-taxi stands and the robustness of the solution.

Further assumptions and thoughts: The economic and social framework in Dar es Salaam does not yet allow for higher-priced solutions like DC fast charging, battery swapping or inductive charging, as these solutions increase the upfront investment demand per operated vehicle. These technologies were not considered in this study. Technologically pragmatic and cheap to install charging opportunities at the central gathering points of the drivers could create job opportunities and reduce the battery storage demand for the vehicles, while significantly cutting the vehicle cost.

3 Results

3.1 Economic Feasibility and Drivers' Acceptance of E-Mobility

The socioeconomic survey we carried out among 105 three-wheeler taxi drivers was designed to assess economic feasibility of implementing electric three-wheeler taxis in the local context. In this regard, the results of the survey provide information on current service characteristics, vehicles and maintenance, vehicle ownership, costs and revenues, and socioeconomic data (Table 2).

The results show that the moto-taxi operators have long-time experience in the transport sector, working on average for 5.8 years as a taxi driver. Working times are long with drivers spending 6.4 days per week and 13.4 h per day on the job. The reason for long working hours is relatively high operating costs and the need to carry out as many passenger trips per day as possible in order to gain sufficient daily revenues that also allow supporting family dependents (avg. of 5 persons). A majority of 61% of interviewed drivers carries out more than 15 passenger trips per working day, while 15% attain over 25 passenger trips. Operating costs result not only from vehicle maintenance (avg. of 54,889 TZS/month, ~24 US$) and fuel consumption (avg. of 11,822 TZS/working day, ~5 US$), but mainly from the fact that a majority of drivers work on vehicle rent contracts (58%) or pay for a hire-purchase contract (6%). On average they spent 18,265 TZS (~8 US$) each day on vehicle rent, independent from their working days, hours and revenues. As the gross income per working day amounts to 42,990 TZS (~19 US$), it can be derived that most drivers gain relatively small net incomes.

Moreover, survey results indicate that drivers face social insecurities resulting from the threat of road accidents and necessary vehicle repairs, such as major engine failures (16.5% of vehicles affected). These incidents not only involve social and financial costs but can also lead to loss of income. Another aspect in regard of job insecurity is the seemingly high fluctuation in vehicle access: 63% of interviewed drivers gained access to their current vehicle only in 2018 or 2017, while most of them have been working in the sector for much longer than that. It is unclear if this high vehicle turnover results from frequently occurring terminations of rent contracts by vehicle owners or from unreliable or worn-out vehicles that need replacement: in this regard, results show that by the end of 2018 only a small share had a vehicle age of more than five years. In any case, buying or renting a new vehicle involves monetary and transaction costs that can put an extra burden on the drivers. The results consequently show that the moto-taxi sector is highly cost-sensitive—a fact that needs strong consideration when implementing E-mobility by replacing or retrofitting the existing vehicle fleet.

The aspect of cost sensitivity was also reflected in the group discussions with two moto-taxi stand associations: the drivers agreed that an E-mobility solution for three-wheeler taxis must not come with additional costs compared to current combustion fueled vehicles (which cost from 2800 to 3500 US$ according to local

Table 2 Summary of survey results among moto-taxi drivers (n = 105)

Socioeconomic data	
On average drivers are 34.6 years old	A driver's income supports 5 dependents
Drivers have been working as moto-taxi operators for 5.8 years (median = 5)	

Working days and hours	
Drivers work 6.4 days/week	Drivers work 13.4 hours/day

Number of passenger trips per day						
1–5	*6–10*	*11–15*	*16–20*	*21–25*	*26–30*	*>30*
4%	17%	18%	29%	17%	7%	8%

Year of vehicle production							
Unknown	*2012 or earlier*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
19%	13%	11%	13%	11%	11%	11%	11%

Year of vehicle access					
2013 or earlier	*2014*	*2015*	*2016*	*2017*	*2018*
6%	8%	15%	8%	14%	49%

Vehicle ownership		
36% owner drivers	58% renters	6% hire-purchasers

Costs and revenue	
Drivers spend 18,265 TZS/day on vehicle rent (median = 20,000)	Drivers spend 11,822 TZS/working day on fuel (median = 12,000)
Drivers spend 54,889 TZS/month on **maintenance (median = 50,000)**	Drivers earn a gross income of 42,990 TZS/working day (median = 45,000)

Repairs and accidents	
16.5% of vehicles had a major engine failure	21.8% of vehicles needed major repairs
11% of vehicles have been involved in one or more road accidents	

Opportunities for night charging
99% of night parking areas have electricity access
66% of vehicles parked on protected private parking area

stakeholders). Slightly higher vehicle costs would be acceptable, given that maintenance and energy costs turn out to be lower over the vehicle lifetime. Further preconditions are efficient vehicle charging times and easy access to charging stations or other charging opportunities. Additionally, sufficient travel speed (up to 90 km/h), a motor with higher power (current three wheelers with combustion engine offer 5.5–7.6 kW) and the ability to cover sufficient distances are important requirements for the drivers.

As part of the group discussions, the drivers also produced a list of potential benefits but also challenges they associate with an implementation of electric three-wheeler taxis in the local context: In addition to technical improvements and higher comfort of the service vehicles (e.g. less vehicle vibration, reduced noise, reduced need for spare parts), the drivers see potentials of higher incomes due to the symbolic value of modern technology attached to electric vehicles and its likely attractiveness to their customers. Stated disadvantages encompass low vehicle range that could limit opportunities to carry out passenger trips into peri-urban areas, lack of knowledge regarding electric vehicle maintenance, unclear availability of spare

Table 3 Results of the market analysis of three-wheeled vehicles (as of January 2019)

	Seats			Top speed in km/h			Battery tech.			Voltage level			
	3	4	5	25	45	<60	Pb	Li	n/a	48 V	60 V	72 V	n/a
Number of vehicles	4	2	7	8	2	3	7	3	3	9	1	2	1

parts in the country, higher vehicle purchasing costs, and a potential danger of increased accidents due to the low noise emission of electric vehicles. Another major concern was that the electric system could turn out to be unreliable during the rainy season. These insights are highly valuable as they indicate important criteria for drivers' acceptability of E-mobility and thus provide inputs for identifying sustainable technical solutions.

Looking at the electric three wheelers being currently available for purchase first thing to mention is their rapidly growing number in the recent years with manufacturers being mainly located in China and India. Since technical data is often hardly available, only a total of 13 vehicles could be investigated in this study (see Table 3).

Most of the vehicles are designed to carry five people (driver + 4 passengers) and offer a top speed of 25 km/h. They use mostly lead acid batteries and an intermediate circuit voltage level of 48 V. Battery capacity is often around 5 kWh, which results in a stated range of up to 100 km. This consequently relative low energy consumption is related to the low top speed of the vehicles. Motor power is mainly below 5 kW, mostly even below 2 kW with one exception at 7 kW.

Taking 6.4 working days per week into account, we found that 50% of the vehicles travel less than 75 km per working day and 75% of all vehicles travel less than 109 km. On average 81 km are covered during a working day (see Fig. 2, left). The available vehicles seem to cover a wide range of driving demands, though at an insufficient top speed.

Vehicles being offered in the European Union can cost from around 3360 US$[3] up to 16,800 US$, while vehicles offered in India are in a price range of 1904 US$ up to 4760 US$. However, since for most of the vehicles prices were not available and the market is assumed to change quickly, these prices can only give a rough indication.

3.2 Drive Cycle

The generated drive cycle uses the GPS tracking data as input, Fig. 3 shows the result. The length has been set to 1000 s to make it easily comparable to the WLTC.

[3]2019 yearly average exchange rates were used. 1.12 US$/€ and 2307.06 TZS/US$ [13, 17].

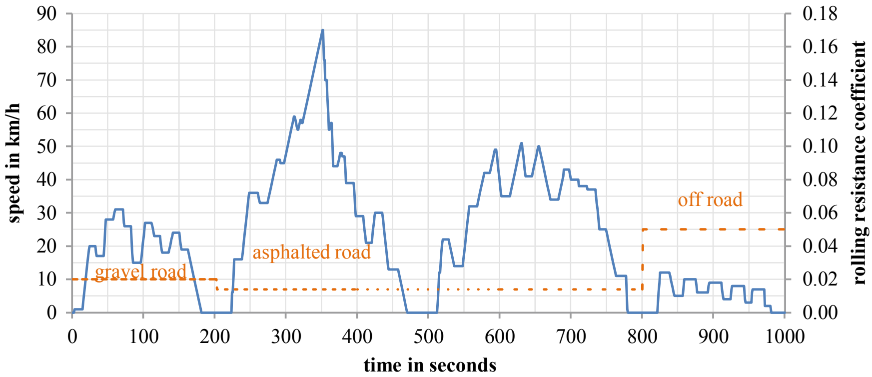

Fig. 3 Generated Dar es Salaam-drive cycle

It has been purposely separated into four sections which represent typical driving situations. To reflect the different road conditions, the rolling resistance coefficient is varied depending on the intended driving scenario of a section.

The first section represents a trip from a residential area to a main road, for example to feed the BRT system. The roads in residential areas are mainly small and gravel roads, which results in a maximum speed of 31 km/h. The second section is a trip on an asphalted main road from the suburbs to the city centre. Here, higher speeds up to 86 km/h can be reached. Despite having a very small portion in the measured trips, this maximum speed has been added on drivers' demand that wish for a fast vehicle and was the highest measured speed in the GPS data. The third section is a trip inside the city centre with a limited maximum speed of 52 km/h on asphalted roads. The last section is a trip through a residential area with a very bumpy dirt road. To model the higher energy demand for that kind of road, the rolling resistance coefficient has been significantly increased.

3.3 Energy Demand

Figure 4 shows the results for a simulated vehicle with full load (300 kg, equals approx. one driver plus three passengers) or half load (150 kg, one driver plus one passenger) performing the generated drive cycle (see Fig. 3). The simulation has been conducted for a vehicle using lead acid or lithium ion batteries which leads to a different overall weight of the vehicle. Battery size was varied in steps of 2 kWh in a range from 4 to 16 kWh.[4]

[4]This is not the technical but the usable battery capacity. To calculate battery weight, the energy density has been multiplied with 1.5 (lithium ion) or 1.1 (lead acid) to cover the additional weight of housing, cooling etc.

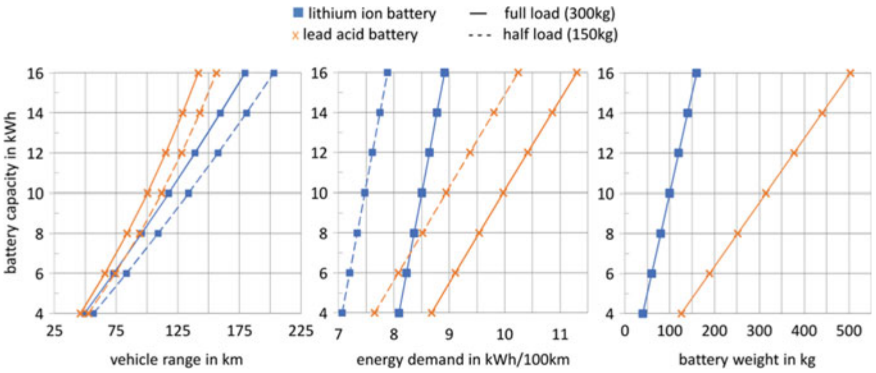

Fig. 4 Simulation results: range, energy demand, and battery weight for the generated drive cycle

Energy demand and vehicle range only differ slightly with increasing battery weight for the two variants which can be explained by the vehicles recuperation capability while braking. Though, the difference in battery weight widens strongly with increasing capacity.[5]

3.4 Battery and Opportunity Charging Point Demand

The battery demand of the vehicles to fulfil the mobility needs of the tested individual vehicles with and without opportunity charging is shown in Fig. 5 (left). Only lithium ion battery systems are shown, as we excluded lead acid batteries from the charging point analysis. We only assessed lithium ion batteries at this stage, due to the excess weight and negative environmental effects of lead acid batteries [14] and the expectation for a further price deduction of lithium ion batteries in the next years in.

The battery capacity demand distributions are fully separable for the cases with and without opportunity charging. To reduce the battery capacity demand of electric moto-taxis, the availability of opportunity charging stations at the moto-taxi stands is a viable measure. To serve 75% of the tested individual cases, the maximum calculated effective vehicle battery storage capacity is reduced from 22 to 12 kWh by introducing opportunity charging. Taking 2019 battery pack prices into account [15], a 12 kWh battery pack contributes at least 2016–4032 US$ to the vehicle price, while a 22 kWh battery contributes 3696–7392 US$—exceeding price expectancy ranges of the drivers and operators by far.

[5]For the lead acid variant, a stronger chassis would be needed, at least above a certain battery weight. This effect has not been included in the model and would widen the gap even more.

According to a distributor of three-wheelers (source: interview, c.f. Sect. 2.1), life times of three-wheelers in Dar es Salaam range between 3.5 and 6 years, driving 30,000 km per year and 100–200 km per day. If we assume a life time distance of 180,000 km, a battery capacity sufficient for 100 km requires 1800 full battery cycles, while 50 km require 3600 full battery cycles. Currently, lithium ion batteries reach 1500–2000 cycles, with 3000 cycles expected in 2030 [15]. The vehicle life of a battery electric three-wheeler with 50 km travel distance could therefore reach 150,000 km in 2030. Current studies suggest that a halving of today's prices until 2030 is likely to occur, with a vehicle life time of 150,000 km and prices between 84 US$/kWh [15] and 94 US$/kWh [16]. In this case, the price of a battery pack for a three-wheeler with 12 kWh technical battery demand would be between 1008 and 1128 $US while a 22 kWh battery would contribute 1848–2068 US$ to the vehicle price.

The charging point utilization at the defined stations per VUT is depicted in Fig. 5 (right) and maximum numbers are given in Table 4. The number of vehicles waiting at a station surpasses the number of vehicles actively charging most of the time. A full service availability scenario requires 0.43–0.80 charging points per vehicle, but only 0.29–0.70 charging points are utilized more than 1% (1 h 41 min) during the test week. As the batteries are charging faster from 0 to 80% SOC, the charging infrastructure requirements can be reduced by only charging the vehicle batteries to 80% SOC at the opportunity charging stations. This reduces the number of required charging points to 0.43–0.7 in a full service availability scenario, at the cost of a slightly higher battery demand (compare Fig. 5, left). The reduction of charging points and its effect on waiting time and moto-taxi service quality needs to be further studied in a field test, as the available data based on the behaviour of combustion engine driven vehicles is not suited to answer this question.

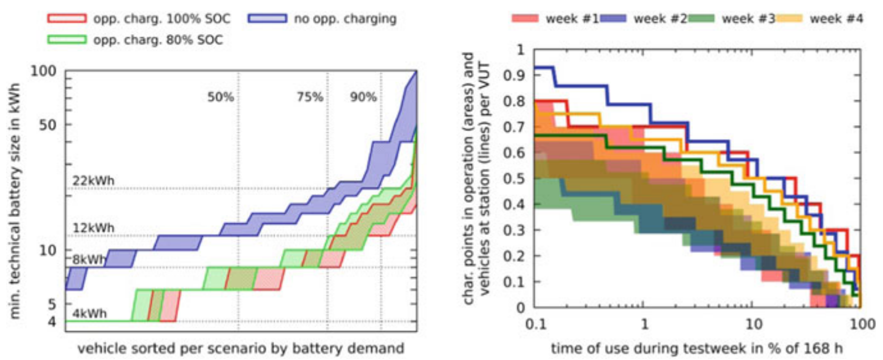

Fig. 5 Battery demand for battery electric vehicles with lithium ion batteries of the different scenarios with and without opportunity charging (left). Utilization of charging points as well as number of vehicles at stations normalized to the vehicles under test in a given test week (right)

Table 4 Vehicles under test (VUT) and charging points required for minimal battery size

Week	# VUT	# Charging points 100% SOC		# Charging points 80% SOC		# Charging points > 1% utilization	
1	10	7–8	70–80%	7	70%	4–7	40–70%
2	14	8–10	57–71%	8–9	57–64%	4–7	29–50%
3	21	9–14	43–67%	9–11	43–52%	6–11	29–52%
4	20	11–16	55–80%	11–13	55–65%	8–12	40–60%

4 Conclusions

The results of our study show that the electrification of three-wheeled moto-taxis in Dar es Salaam is possible, but subject to several constrains and barriers. Drivers show a high willingness to adopt electric vehicles; however, they require them to (a) at least deliver the same income than fossil-fuelled vehicles and (b) have similar driving characteristics. Besides, they expect electric three-wheelers to have a positive effect on the driving comfort for themselves and for their passengers.

From a socio-technological point of view, our analysis shows that currently available electric three-wheelers cannot be used as a one-to-one replacement. This is mainly due to the limited capability of the drive train, that limits the top speed and range that is requested by the drivers. Also, the current prices are not competitive.

Regarding technical specifications, safety issues lead us to recommend 48 V intermediate circuit voltage that is less likely to cause harm in case of maintenance and accidents. Lead acid batteries would be able to serve a capacity of up to 8 kWh, but due to the negative long-term environmental implications as a result from improper handling and disposal, lead-acid cannot be recommended. Above 8 kWh, due to their higher energy density, lithium ion batteries should be favoured.

Availability of infrastructure for opportunity charging reduces the demand for vehicle battery capacity. Charging infrastructure can therefore support the early adoption of electric moto-taxi by reducing overall vehicle cost. Charging points with household typical currents are sufficient to achieve this goal, with 0.43–0.7 charging points per vehicle being required.

Economic factors play an important role for the adoption of electric mobility, especially in the very cost sensitive Tanzanian vehicle market. Current lithium ion battery prices are too high for a wide adoption, but a price decrease is expected in the next 10 years. We therefore conclude that the combination of suitable, cost competitive vehicles and available opportunity charging infrastructure can make a transformation of the vehicle market towards electrification possible. In the future, policy makers should carefully reflect that changes to the structure of the informal moto-taxi market could require their interventions: In a market where driver organizations prevail, it can be assumed that these organizations will set up charging infrastructure, because this can help them reduce their cost and maintain the control to the access to the market. However, if technologies such as e-hailing (Uber, Bolt, SafeBoda) continue to take over market shares of the moto-taxi market [18], this may lead to a reduced amount of drivers who organize themselves in organizations and at designated stations. A publicly available charging infrastructure would then become more relevant for drivers who seek to buy electric vehicles, which policy makers should reflect when they want to speed up the adoption process.

The results we present here were generated for the city of Dar es Salaam. However, similar conditions, in which moto-taxis fill gaps of urban transport, exist in many cities of Sub-Sahara-Africa. Especially under similar driving patterns, our results are transferable to other places. We would expect that this is the case in cities where drivers are organized in organizations with designated stations and where morning and afternoon peak demand exists, allowing for opportunity charging with similar frequencies. Furthermore, the distances vehicles drive should be similar, which we expect to be the case when similar conditions related to land use and transport infrastructure are in place.

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