

Walking on sunshine: Pairing electric vehicles with solar energy for sustainable informal public transport in sub-Saharan Africa

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Abstract

Minibus taxi public transport is a seemingly chaotic phenomenon in the developing cities of the Global South with unique mobility and operational characteristics. Eventually this wide-spread fleet of minibus taxis will have to transition to electric vehicles. This paper examines the impact of this inevitable evolution on a city-wide scale in Kampala, Uganda. We present a generic simulation environment to assess the grid impact and charging opportunities, given the unique paratransit mobility patterns. We used floating car data to assess the energy requirements of electric minibus taxis, which will have a knock-on effect on the region's already fragile electrical grid. We used spatio-temporal and solar photovoltaic analyses to assess the informal and formal stops that would be needed for the taxis to recharge from solar PV in the region's abundant sunshine. The results showed energy demand from a median of 224 kWh/d to a maximum of 491 kWh/d, with a median charging potential (stationary time) across taxis of 8 h/d to 12 h/d. The potential for charging from solar PV was 0.24 kWh/m² to 0.52 kWh/m². Our simulator and results will allow traffic planners and grid operators to assess and plan for looming electric vehicle roll-outs to the most-used mode of transport in Africa.

Keywords: Electric vehicle; Paratransit; Minibus taxi; Demand management; Renewable energy.

1. Introduction

“Urgent action is needed to identify sustainable pathways for the decarbonization of transport in SSA, in line with the United Nations (UN) Sustainable Development Goals (SDGs) and the Paris Agreement. . . . Shifting to EVs [electric vehicles] could be eased by carefully co-locating additional local electricity generation with charging infrastructure, likely in the form of PV [photovoltaics]. Investment into this infrastructure needs to happen concurrently with EV adoption. Yet, at present, . . . this investment is hindered in part by the inability to accurately forecast the likely EV demand for electricity, resulting in uncertain returns on investment.”—Collett and Hirmer (2021) in Nature Sustainability

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Paratransit plays a vital role as the primary form of transport in sub-Saharan Africa’s public transit system. It transports more than 70% of the daily commuters and is a source of livelihood for many families (Behrens et al., 2015). Paratransit in the region takes various forms, such as minibus taxis, motorcycle taxis and bicycle taxis (Ehebrecht et al., 2018), with minibus taxis carrying the largest daily share of passengers (Behrens et al., 2017). Powered by internal combustion engines, the taxis contribute greatly to the emission of greenhouse gases and a general decline of air quality in African cities (Collett and Hirmer, 2021).

The term “paratransit” means something wholly different in Africa’s developing countries from the meaning used in developed countries; from its inception to its vehicle types to its operations. In developed countries, paratransit usually means a point-to-point flexible demand-responsive transport service customised with special requirements for the elderly and the disabled (Behrens et al., 2017; Askari et al., 2021). For Africa’s developing countries, paratransit “*refers to demand-driven, unscheduled public transport provided by small operators, typically in mini- to medium-sized buses*” (Jennings and Behrens, 2017). Paratransit is a system which has evolved independently of the government, and is often considered informal. It operates somewhere between private passenger transport and conventional public transport in terms of cost, scheduling and route flexibility (Ndibatya and Booysen, 2021; Neumann and Joubert, 2016; Falchetta et al., 2021). Besides minibuses, paratransit can also consist of single-passenger motorcycle taxis (“boda bodas”) such as those in Kampala, or the tricycle taxis (“tuk-tuks”) in Nairobi (Mutiso and Behrens, 2011; Booysen et al., 2013; Diaz Olvera et al., 2019). Travel by paratransit accounts for approximately 70%, 90%, 91%, and 98% of the road-based passenger trips in Johannesburg, Lagos, Kampala and Dar es Salaam, respectively (Behrens et al., 2015; Evans et al., 2018). Of these paratransit trips, 83% are by minibus taxi (Dorothy et al., 2016; KCCA, 2016; Evans et al., 2018). These minibus taxis are mostly old, second-hand imports from developed countries. For example, in Nigeria, the average age of light commercial vehicles (such as minibus taxis) is 24 years (Cervigni et al., 2013, p. 348). The age and ubiquity of minibus taxis cause a serious environmental concern.

Furthermore, high levels of congestion can be found in cities of developing countries, due to high rates of urban migration. This congestion further exacerbates the carbon footprint of the transport sector, as vehicles sit idling in traffic for long periods of time.

For example, as a result of high congestion, Uganda’s transportation system emits 2 Mt of CO₂ per year, which is 38 % of Uganda’s total carbon emissions (Crippa et al., 2019). The World Health Organisation classifies exposure to ambient air pollution (AAP) as a major threat to human health in sub-Saharan Africa, linking it to the increase in cardiovascular and cardiopulmonary diseases and lung cancer and respiratory infections (Dalal et al., 2011; Amegah and Agyei-Mensah, 2017).

Developing countries typically have a very high urban population density, and urgent action is required to

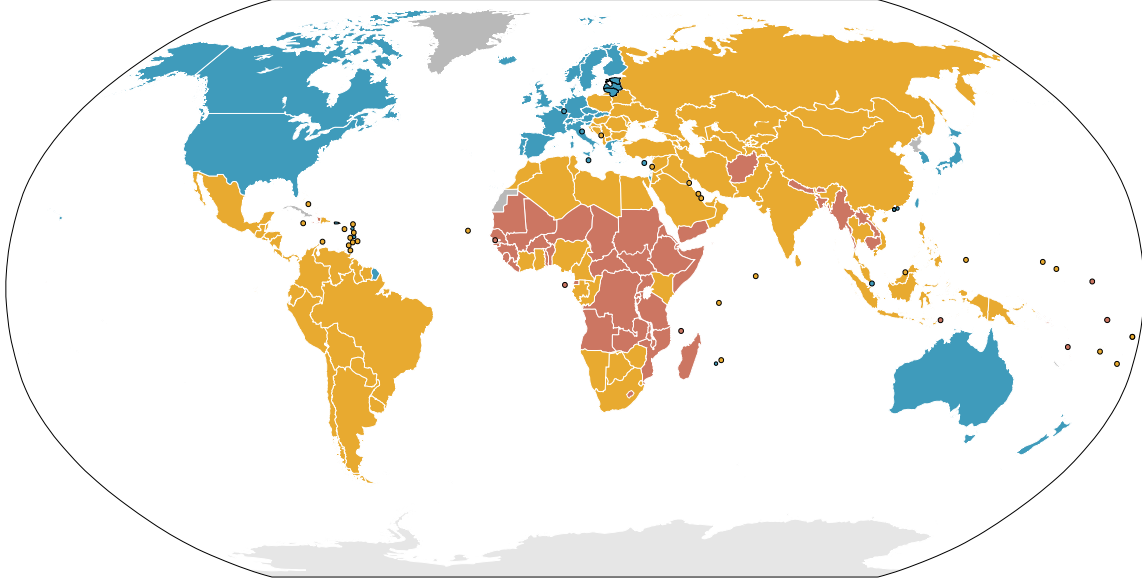


Figure 1: World map with countries classified by level of development. ■ Least developed countries; ■ Developing countries; ■ Developed countries. Source: Wikimedia Contributors (2021)

save lives and improve living conditions to an acceptable standard. The developing world consists of 86 % of the global population and its vastness is shown in the map in Figure 1. This paper will contribute an approach to forecast the energy consumption of future electric public transport in developing countries.

1.1. Perspectives on sub-Saharan Africa's paratransit

In sub-Saharan Africa, the public transport industry experienced two fundamental organic changes in the last quarter of the nineteenth century. The first was the shift of transport services proprietorship, from public to private, most often sole proprietorship, as a result of the World Bank's structural adjustment policies of the 1990s that restricted financing to state-owned entities, leading to their eventual collapse (Kumar, 2011; Ajay Mahapatra Kumar et al., 2008; Cervero and Golub, 2007). The second was the gradual introduction of low-capacity (five- to twenty-seater) passenger-carrying vehicles to fill the public transport vacuum (Diaz Olvera et al., 2019; Mutiso and Behrens, 2011; Behrens et al., 2015; Jennings and Behrens, 2017).

Originating simply as a complementary transport service, the minibuses have become a way of life for the urban poor in several African cities.

Two competing views have broadly shaped discourse on the minibuses as part of the paratransit system in Africa. The predominant view is that minibuses and paratransit in general are the most extreme example of public transport failure in the developing world (Lucas et al., 2019). To support this view, terms such as “chaotic”, “unsustainable”, “unsafe” and “pollutants” are common in the literature in reference to the minibuses (Venter et al., 2019; Pojani and Stead, 2017, 2018; Agbibo, 2016). Consequently, proponents

of this view advocate for a total overhaul of the minibus taxi industry and its replacement with western ideas of orderly transport, such as bus rapid transit (BRT) and light rail transit (LRT). Practically, however, this approach has faced massive resistance by existing paratransit operators, who have often used illegal means to cripple development of such systems. Besides that, the financial feasibility of BRT/LRT is disputed, as they require massive amounts of capital investment, which is often lost to corruption and mismanagement. Jennings and Behrens (2017)

Proponents of the second view advocate for a hybrid future, with paratransit complementary to the scheduled BRT/LRT (Ndibatya and Booysen, 2020a). However, the adoption of this view is very slow and also facing resistance from paratransit operators. Although several benefits would accrue to them (such as job security for the drivers, proper regulation, and government subsidies), they would lose their autonomy and the elements of self-organisation that formed the core of the original paratransit in Africa.

An alternative third view is emerging, which imagines Africa’s paratransit system as a complex adaptive system, composed of many interdependent components that interact non-linearly, often operating between “chaotic” and semi-orderly states (Behrens et al., 2015; Goodfellow, 2017). This view acknowledges the coping mechanisms and innovative forms of self-organisation exhibited by paratransit and how the system adapts to serve the population’s mobility needs with little or no centralised control. Actually paratransit “chaos” reveals to some degree the hidden order described by Hecht (2007) as the “invisible governance ... that maintains competing agendas and aspirations in some kind of functional and parallel existence” (Hecht, 2007).

The minibus taxi paratransit came into being to suit the mobile lifestyle of the urban poor in sub-Saharan Africa. It is unlikely that paratransit will be phased out of Africa’s cities any time soon. They are ubiquitous and will continue for many reasons: their schedule flexibility, the urban sprawl, the irregular commuter movement patterns in urban spaces due to informal employment and the socio-cultural lifestyles of the urban poor in developing cities. However, the environmental cost of running these old internal combustion engine vehicles is worrying. It has triggered discussions about the possibility of transitioning to electric minibus taxis as part of the global electrification and sustainability agenda (Collett and Hirmer, 2021).

1.2. The transition to electric vehicles and the electric minibus taxi

The development of low-carbon transport in cities is crucial to the global agenda to combat climate change’s various effects sustainably. The Intergovernmental Panel on Climate Change (IPCC) estimates that the transport sector generates 23% of the global energy-related greenhouse emissions. In sub-Saharan Africa the deteriorating air quality resulting from ambient air pollution and a high concentration of particulate matter (PM_{2.5}) is partly attributed to vehicle emissions (Lozano Gracia et al., 2021; Singh et al., 2020; Rajé et al., 2018). Electric vehicles would have almost zero local carbon emissions, greatly improving the air quality

in the highly congested urban cities of developing countries. Furthermore, the WHO estimated that 712,000 deaths in Africa in 2012 were due to air pollution, though the figure may be higher than reported because air pollution epidemiological data is limited (Cohen Aaron J et al., 2017). Akumu estimates the cost of air pollution in African cities to be as high as 2.7% of GDP (Akumu, 2014). Three of the seventeen United Nations Sustainable Development Goals, one, eleven and thirteen, are clean energy, sustainable cities and climate action (Zinkernagel et al., 2018).

Consequently, electrification is promoted as a low-carbon transport strategy to reduce combustion emissions and slow down the possibly damaging effects of climate change. In the same spirit, the transition to electric vehicles is gradually picking up in developing countries to the extent that some vehicle manufacturers are planning to phase out internal combustion engines. Sub-Saharan Africa is seeing a few isolated pilot electric vehicle projects, mainly focusing on micro-mobility (as motorcycles and tricycles), as well as buses and private cars (Black et al., 2018; Biryabarema, 2021; Kavuma, 2020). At present, there is no known electric vehicle transition initiative targeting the paratransit industry, let alone the minibus taxis that are responsible for more than 80% of the public transport trips in the region.

This paper builds a foundation for evaluating the eventual impact of the transition to electric minibus taxis on cities' electrical grids, localised pollution, carbon footprint and taxi owners' profitability. Specific attention is given to the energy requirements of these vehicles, the potential distribution of charging stations and the potential electricity generation capacity from renewable sources.

1.3. Overview of earlier studies and approaches

Initiatives to achieve sustainable urban mobility often follow a three-pronged transport decarbonisation approach, the “Avoid-Shift-Improve” paradigm (Galuszka et al., 2021; Lah, 2017). This approach aims to reduce trips, shift towards sustainable forms of transport (public transport, non-motorised modes and electric vehicles) and improve the transport-system's efficiency through infrastructure (Le and Trinh, 2016; Osei et al., 2021). In sub-Saharan Africa, the avoid and shift approaches have not been intensively studied (Krüger et al., 2021). The focus has been primarily on improvements: urban traffic management strategies such as widening roads, optimising road signalling and tightening law-enforcement (Sietchiping et al., 2012; Shams and Zlatkovic, 2020; Krüger et al., 2021; Venter et al., 2018). Ironically, evidence from other world cities suggests that building freeways and roads around cities only increases car dependence and thus intensifies congestion and pollution (Sietchiping et al., 2012). Shifting to alternative, sustainable technologies, particularly by introducing electric vehicles in public transport and paratransit, is an approach that has been neglected. The literature on paratransit in sub-Saharan Africa focuses on aspects of sector governance (Goodfellow, 2017) and regulation and reforms (Jennings and Behrens, 2017; Lucas et al., 2019), but seldom on operations (Ndibatya

and Booysen, 2020b), mobility characteristics (Ndibatya and Booysen, 2021) and the prospects of electric mobility integration (Galuszka et al., 2021).

Research from outside the region shows that electric vehicles are three times more efficient than internal combustion engine vehicles and twice as efficient as hybrid vehicles (Du et al., 2017; Weiss et al., 2020). This efficiency is achieved partly by the efficient braking systems and elimination of idling losses and the consequent saving of energy for the vehicle’s actual movement (Weiss et al., 2020). Although debate continues on the economic and environmental trade-offs associated with electric vehicles (Li et al., 2016), there is evidence of sustainable electric vehicle deployment. Some researchers argue that deploying electric vehicles shifts gasoline usage to coal-fired power generation, which exacerbates CO₂ emissions by the power systems (Li et al., 2016). However, electric vehicle proponents counter-argue that, on a macro-scale, these vehicles’ impact in terms of CO₂ emissions depends mainly on the charging strategy and that the emissions can be reduced by optimising the use of renewable energy sources such as solar power (Schücking et al., 2017; Buresh et al., 2020). In one of the scarce and isolated publications on electric vehicles in sub-Saharan Africa, Buresh et al. (2020) note that South Africa (like many countries in the region) has high levels of insolation (the measure of solar energy at a place over a specified time), from between 4.5 and 6.5 kWh/m² per day, with annual sunshine averaging more than 2500 hours. This implies that the region has an excellent chance of harnessing solar and other (existing) renewable energy sources to power electric vehicles. Indeed, projects researching alternative renewable energy have taken shape in the region (Jadhav et al., 2017), though not targeting electric vehicles for public transport services.

Two main research gaps remain in the literature on sub-Saharan Africa’s transition to electric minibus taxis. One is the mobility characteristics of minibus taxis. As Quirós-Tortós et al. (2018) observe, to estimate the charging requirements and vehicle performance of an electric vehicle we need to know its mobility patterns, such as distance, travelling time and idle time (or stopping time and duration). In other words, the vehicle’s mobility has spatio-temporal dimensions. Apart from the findings of isolated studies on minibus taxi mobility, such as those by Ndibatya and Booysen (2021), the general mobility dynamics of paratransit in sub-Saharan Africa are unknown. The other is the region’s potential for renewable energy from different sources such as solar PV, wind and bio-fuel as part of this transition (Sawadogo et al., 2020; Jadhav et al., 2017; Soares et al., 2019).

From the sparseness of the work, it is clear that we lack information on the mobility of minibus taxis in sub-Saharan Africa and specifically the requirements of these minibus taxi fleets if they are converted to electric vehicles (Collett and Hirmer, 2021).

1.4. Contribution

In order to address the research gap found in the preceding section, we contribute our reproducible method for determining paratransit mobility and projecting estimates of electrical energy demand and the potential for renewable energy to meet that demand. This paper will apply the method to a specific case-study in Kampala, Uganda. Using floating car data obtained from eight taxis over a period of around ten months, the electrical energy demand of these taxis will be assessed. Kampala is chosen as a case-study due to the fact that it is one of the cities that would benefit the most from electric paratransit.

Firstly, it has a large proportion of minibus-taxi travellers Behrens et al. (2015), and has extremely poor air quality, attributed to high congestion and grid-lock on a daily basis (Matagi, 2002). High congestion and high minibus-taxi ridership are hallmarks of urban cities in Africa. Other developing countries across the world may not use minibus-taxis, but the other forms of paratransit that they use can benefit from the approach taken in this paper to characterise their paratransit system’s mobility. Once the movement patterns and stopping patterns are identified, subsequent steps of the methodology can be used to explore charging opportunities.

Secondly, like Kampala, most countries in sub-Saharan Africa are subject to high solar irradiance. Hence, Kampala’s placement near the equator makes it a good representative of how solar energy can be used to help satisfy the energy demands of public transport electrification. For countries outside of Africa, in regions with less solar irradiance, the tools used in this methodology can be used to evaluate the potential of other renewable energy sources.

Lastly, since Uganda’s energy grid is already 90 % powered by renewable resources USAID (2019), it is in a good position to electrify vehicles if the grid is able to support them without having to revert to fossil fuels for electricity production. Hence, it is important to evaluate if existing renewable energy sources will be able to support the additional demand of mass vehicle electrification. This is even more important for other developing countries, such as South Africa and Nigeria, who rely on fossil-fuels extensively for electricity production, but still suffer frequent black-outs, due to being unable to meet pre-existing energy demand.

Our custom-built software, which we call *eMBT-Sim*, is used to perform analyses of vehicle mobility, solar PV models and electric vehicle models. We publish the software for free use and modification, subject to the terms of the GPLv3 license. Using the results obtained from this software, we estimate the impact on the Ugandan grid of converting all the minibus taxis in Kampala to electric vehicles, with and without solar augmentation.

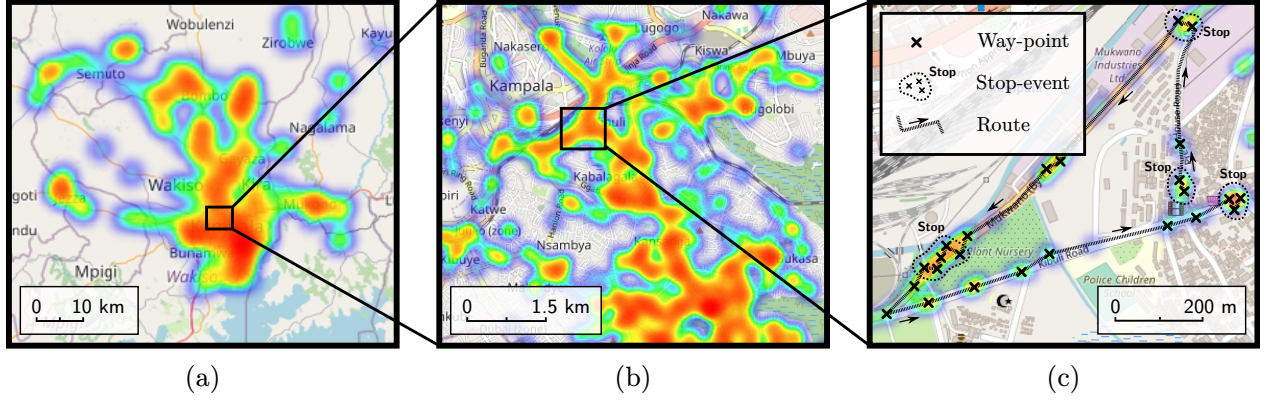


Figure 2: (a) Heat map showing the variation (by density) of floating car data; (b) Density of floating car data within the city of Kampala; (c) Illustration of *way points*, *stop-events* and route generation process.

2. Method

This section describes the dataset and the three models used for the research: the minibus taxi (MBT) mobility model, the photovoltaic (PV) model and the electric minibus taxi (eMBT) electric vehicle (EV) model. It describes the pre-experimental collection and analysis of the floating car data from a fleet of eight internal combustion engine minibus taxis. Inter-town MBT mobility modelling involved spatial clustering of floating car data to identify stopping events and generate routes between stops in preparation for PV and eMBT modelling. We present two model simulation setups for the EV and PV models and discuss their application to our urban paratransit context. The PV model was based on the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (Blair et al., 2014). We ran the PV and the EV models independently in a micro-transport simulator (SUMO) (Lopez et al., 2018; Kurczveil et al., 2014), then recorded and analysed the eMBT energy and PV requirements for each simulated context.

A custom simulation software was written in Python to automate the steps in this methodology. The software is publicly available at: <https://gitlab.com/eputs/embt-sim/>

2.1. Mobility

The dataset consisted of floating car data obtained by tracking urban minibus taxis operating on routes in Kampala, Uganda. The area under study is defined by a box with coordinates (0.170202, 32.181182) and (0.794505, 32.852554). The area of study is shown in Figure 2a. The data was obtained using GPS tracking devices (viz.: Maestro MicroTracker MT-01), which were installed on a fleet of 8 MBTs for a period of 10 months. The data consisted of timestamped geographical-coordinates, altitude, speed and direction, logged at approximately one-minute intervals.

Due to errors in the data-capture, some MBTs in the fleet had fewer than 10 months of data. Furthermore, irrelevant data was removed from the dataset, viz. public holidays and weekends, as well as dates when the

MBT left the area of study. After this, there was an average of 150 days of data per MBT.

2.1.1. Identifying minibus taxi stops

To generate the mobility patterns and establish the potential for charging at stops, it was necessary to identify stop-events from the GPS traces. Additional temporal analysis was required to determine the stop arrival-times and stop durations. We therefore categorised each datapoint as being either a *way-point* or part of a *stop-event*.

A stop-event in our work is closely related to the “stay point” defined by Zheng et al. (2009) and Damiani et al. (2014) and refers to a series of consecutive datapoints during which the MBT is considered stopped. Way-points are datapoints which define the route that the MBT must take when travelling between stops.

A stop-event begins when the taxi’s velocity is below a threshold of 1 km/h, and ends when the taxi has either exceeded a velocity of 10 km/h or drifted 25 km from the initial datapoint of the stop-event. The arrival-time of the stop-event is the timestamp of the initial datapoint in the series, and the duration of the stop-event is the difference between the timestamps of the first and last datapoints in the series. The result of this process is illustrated in Figure 2c. All the datapoints which do not belong to a stop-event are considered way-points, and will be used for generating routes for the EV model.

2.1.2. Generating routes

To simulate the mobility of MBTs and subsequently study their energy requirements, we generated *routes* linking the identified stops and the waypoints in the sequence recorded by the GPS tracker. A route is defined as a series of *edges* connecting the way-points and stops, while also specifying the times until which the eMBT should stop at each of the stops. The simulated eMBT follows these routes in order to simulate its mobility.

We used the stop-events and waypoints identified in Section 2.1.1, as well as the road-network, and SUMO’s shortest path Dijkstra algorithm to generate the routes. The underlying road-network was imported from OpenStreetMap (OSM) (OpenStreetMap contributors, 2017), which included the road-segments (a.k.a. edges), intersections, speed limits, and traffic lights information.

For each taxi, each day’s route was generated by traversing through the taxi’s datapoints for that day. For each datapoint, the nearest edge on the road-network from the datapoint’s coordinates would be found, and the shortest path from the edge of the previous datapoint to the current edge would be calculated. This path would be appended to the route being built. If the datapoint is part of a stop-event, the route would also specify that the eMBT should stop at the current edge until the timestamp of the current datapoint. This process is illustrated in Algorithm 1.

The paths between the sources and destinations of interest were computed using SUMO’s implementation of the Dijkstra algorithm (Lopez et al., 2018). This algorithm searches for the route with the least *cost* (Lewis,

```

foreach MBT do
  foreach day of data do
    Initialise the route as an empty list;
    foreach datapoint do
      current_edge := Find the nearest edge to the datapoint's coordinates;
      Calculate the shortest path from previous_edge to current_edge;
      Append this path to the route;
      if datapoint is part of a stop-event then
        Append datapoint's timestamp to the route. It will be the time until which to stop at the current edge;
      end
      /* Store the current edge for the next iteration. */
      previous_edge := current_edge;
    end
    Save the route;
  end
end

```

Algorithm 1: Routing algorithm.

2020), where the *cost* can be the distance, time, or projected-electricity-consumption required to traverse from source to destination. In this study, we defined the cost as the *distance*, as it was the simplest cost to calculate.

2.2. The eMBT EV model

We set up a simulation model using a custom SUMO electric vehicle simulation model, to measure the temporal variation of power and energy usage and the relationships between power consumption and eMBT speed. The model's parameters were specified to match the prevailing MBT used in sub-Saharan Africa, the Toyota Quantum. The weight and front surface area were measured from a Toyota Quantum minibus taxi. We approximated the rest of the parameters according to the recommendations by Fridlund and Wilen (2020). These parameters include: height 2.3 m, width 1.9 m, front-facing surface area 4 m², weight 2900 kg, constant power intake 100 W, propulsion efficiency 0.8, recuperation efficiency 0.5, roll drag coefficient 0.01 and radial drag coefficient 0.5. The simulation program initialised the eMBT model for each date that was simulated. The eMBT model was applied to the generated routes. For every second of simulation time, the simulator outputted the energy consumption and speed of the eMBT as it progressed along its route.

With an average of 150 routes per taxi, the volume of output data from the model was huge. Our goal was to obtain useful metrics that would summarise this data. The first metric we considered was the average power usage profile of the whole eMBT fleet. Such a profile would indicate how much power the eMBTs used at various points in time. This profile would be indispensable, for example, for testing the hypothesis that there would be a good charging opportunity during the day. It would also show what order of magnitude the motor size should be. We calculated the profile by obtaining the power-vs-time profile for each day, averaging this across all days for each eMBT, and then averaging that across all eMBTs in the fleet. The profile was plotted with respect to time.

2.3. PV model simulation setup

We set up the SAM-based PV model to calculate the energy available from photovoltaic sources and to study the daily charging potential for each eMBT in a synthetic fleet of eight eMBTs. The model generates the plane-of-array solar irradiance profile based on radiometric data, solar azimuth angle, and photovoltaic panel tilt angle. We used radiometric data for a year sampled every 15 minutes from the National Solar Radiation Database (Sengupta et al., 2018). The tilt angle was set to 3° , South facing, which is the optimum tilt angle suggested by Jacobson and Jadhav (2018).

To get the output power profile of the PV array, a 16 % system efficiency was applied to the irradiance profile, i.e., 20 % and 80 % were used for the solar panel and balance of the system (including the inverter), respectively. We used the stop-event analysis from Section 2.1.1 to further analyse the battery charging potential from solar PV by evaluating the times at which the stop-events occurred and their durations. We first applied thresholds to filter out stop-events with durations above 8 hours or below 20 minutes. This was to ensure that stop-events irrelevant to our study did not skew the results. These stop-events were grouped according to the spatial cluster in which they occurred, and temporal clustering was done within each spatial cluster to obtain spatio-temporal clusters.

Based on the stop-events detected during the spatio-temporal clustering, we computed the potential energy sourced from PV per day. For each eMBT stop-event, the PV output-power-profile was integrated from the beginning to the end of the stop-event in order to calculate the total energy that could be charged from PV during that stop-event. The PV energy of each stop-event was summed to get the total energy that could be charged from PV for that day as a function of the area of the PV array. These “daily PV charging potentials” were aggregated for each taxi and plotted as box plots. This metric allowed us to approximate the size of the PV array required to provide a certain percentage of an eMBT’s energy demands.

3. Results and discussion

This section describes the results obtained from applying our three models to the floating car data of Kampala and its surrounds. The results obtained refer specifically to the MBT mobility, the eMBT’s power requirements and the potential charging opportunities. The charging opportunities are separated into stop times for the purpose of source-ambivalent charging, and potential charging from PV.

The MBT mobility modelling provides the identified stop-events that serve as input to the PV modelling while generating routes used to determine the power requirements of the individual eMBT and the fleet of eMBTs.

3.1. Mobility analysis

The movement patterns of a minibus taxi is a key factor in deciding the taxi's suitability for electrification. The first step in this analysis was to identify the stopping patterns of the minibus taxis. The stops identified from this step are shown in Figure 3. The plots show the arrival time and duration of all stops encountered by each of the taxis. Stops shorter than 20 minutes were filtered out from these plots, since they are unsuitable for charging, as well as stops longer than 8 hours, since they do not constitute normal taxi behaviour.

The scatter-plot displays seemingly chaotic patterns, so box-plots of the stop-duration are overlaid for each hour of the day. The box plots reveal that, for all the taxis except T13, 50% of their stops are less than one hour long. Some taxis also indicate that they stop longer at certain times of the day than others. For example, T14 has a larger stop-duration at around 8–11 am and likewise for T24 at around 12–14 am. This could indicate that these are the times that the taxis wait for their passengers to board. Also, some taxis, such as T13, have a very high variance in their stop-duration, which could indicate that they serviced a different route, or that the taxi needed to wait longer for it to fill up with passengers.

The stops identified in this step were also aggregated into a box-plot which shows the total *daily* stop-duration for each of the taxis. This is shown in Figure 5b. Although the scatterplots indicated that most taxis stopped for short durations for each of their stop-events, the box-plots indicated that *overall*, the taxis spent a large proportion of their day stopped. The box-plots showed that the mean stop duration is 9.7 hours per day (40% of the day). We see, for example, that taxis T06 and T08 stop for the longest time (around 12 hours per day), while Figures 3b and 3c indicate that their stop-events are relatively short (less than 1 hour each). This reveals that the taxis stop frequently, for relatively short periods.

3.2. Energy analysis

The output of the EV simulation is shown in Figure 4. The mean instantaneous power demand versus time of a working weekday is shown in Figure 4a. A clear typical temporal profile is apparent for the minibus taxis, closely matching the expected peak traffic hours.

There is a morning peak demand period from 7 am to 9 am, with a peak value of 15 kW. A diminished demand with a mean of around 10 kW is observed from 11 am to 4 pm, constituting a period of reduced activity and demonstrates the potential for solar charging. A gradual increase to another pronounced peak value of 17 kW between 7 pm and 9 pm follows, and this flatter evening demand profile slowly declines to return to less than 3 kW by midnight. Complete inactivity is observed from midnight to 5 am. This indicates that there is around 5 hours for charging during night-time hours. It is clear that the taxis are active for a very long period of the day. This corresponds to the qualitative study done by Spooner et al. (2020, p. 29) which showed that some taxi drivers in Kampala worked for more than 15 hours per day.

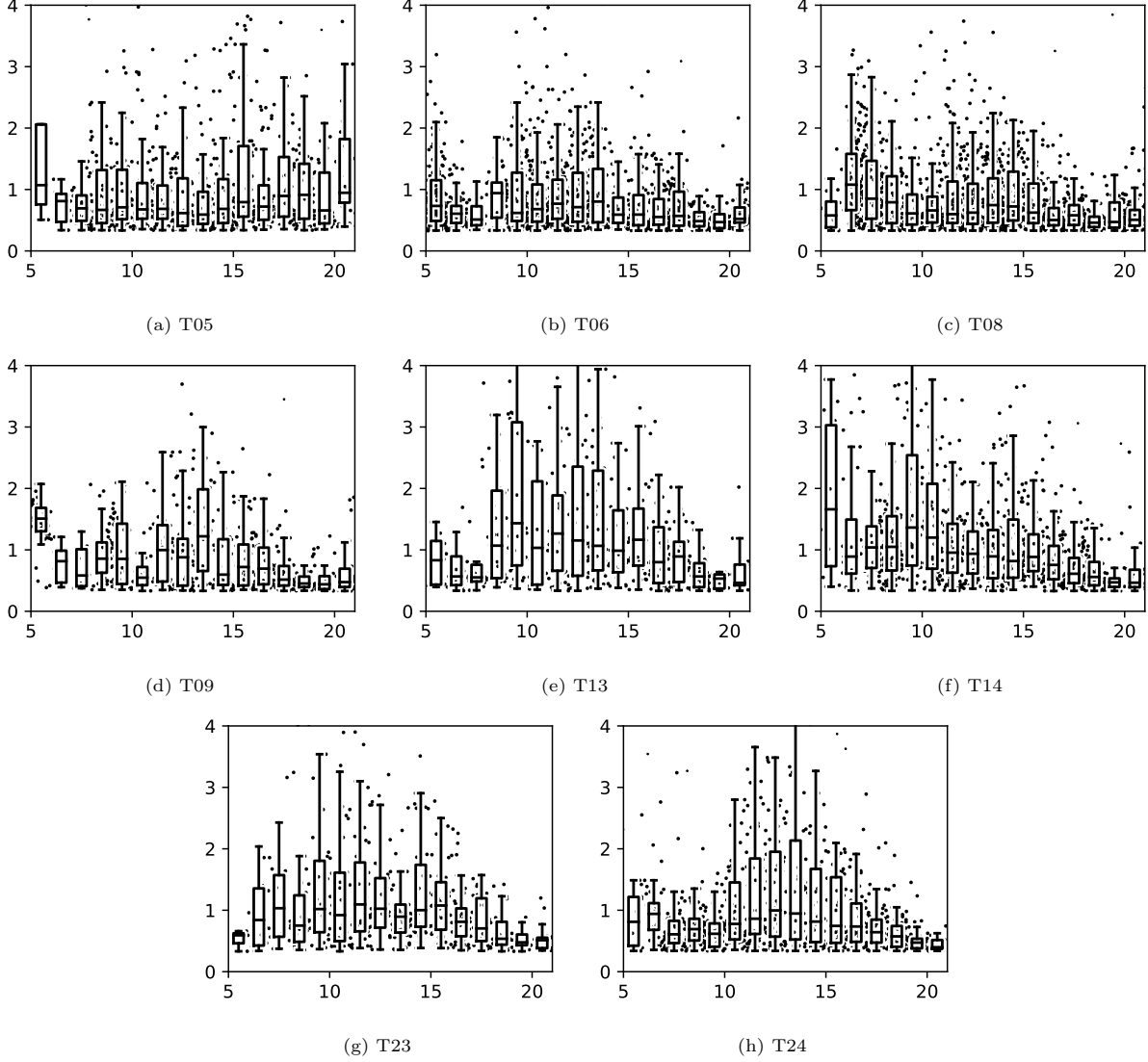


Figure 3: Scatter plot of stop-events. The duration of each stop (in hours) is plotted on the vertical axis and the arrival time (hour of day) of the stop is given on the horizontal axis. Box plots of stop-duration for each hour of the day are overlaid on the scatter plot.

This temporal profile indicates the energy demand requirements of the eMBTs, and already hints at some charging potential during the evening—probably from grid power—and some during the middle of the day—preferably from solar power.

The distribution of power profiles across the eight taxis is shown by the shaded area, labelled *Power Distribution*. The distribution shows that most of the taxis follow the trend of using more power during the morning and the evening.

Figure 4b shows the mean instantaneous speed of the MBTs versus time of the day. The similarity of this plot to the power profile highlights the substantial impact of speed on power draw. The energy required was close to linearly proportional to the distance travelled, which demonstrates that a simpler distance-based

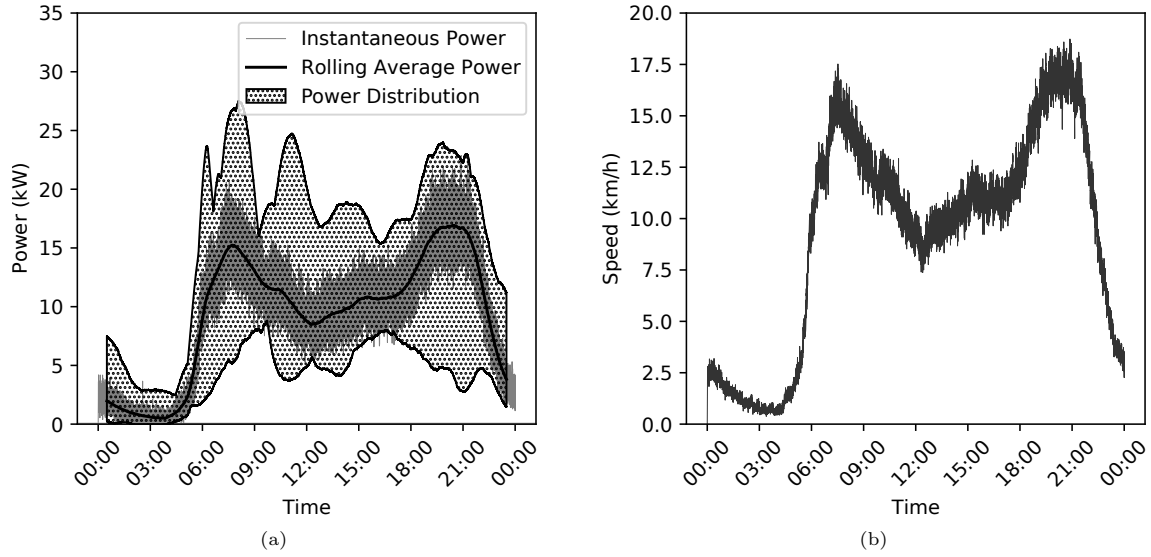


Figure 4: Summary of electrical requirements for all the simulated eMBTs (a) Daily power (instantaneous and rolling average) sampled per second; (b) Speed vs time

model would have provided good estimations and required substantially less processing power. The mean energy required per day was 220 kWh, and the mean distance was 224 km (obtained by integrating the power and speed profiles respectively).

The distribution of energy usage per day, is shown in Figure 5a for each of the eight taxis. The taxis' energy usage is similar, with the median energy per taxi per day across all taxis ranging from 108 kWh to 335 kWh, with the mean of the medians equal to 224 kWh. For seven of the eight taxis, there is a 75 % probability that the taxi will use less than 314 kWh on a given day. For the eighth taxi, the 75th percentile energy-usage is 375 kWh. However, up to 491 kWh would be needed to meet the energy demand of *all* (non-outlier) days for all the taxis.

The results show that a maximum battery capacity of 491 kWh may be needed for urban travel, if charging is limited to the stationary period before the day's first trip, but for 75% reliability, a 375 kWh battery would be sufficient.

3.3. Charging potential

A sizable eMBT fleet could place a substantial burden on the local electrical network and power generation capacity of countries in sub-Saharan Africa. The strain on the local utility could cause infrastructure and electrical supply problems, so we investigated the opportunities for charging these vehicles from solar PV systems. To discover the eMBTs' opportunities and requirements if they are to charge during stationary periods, we did a 24-hour analysis of the start times and the durations of stop-events. The analysis shows what the average charger capacity should be if a vehicle is charged using only power from the local electrical

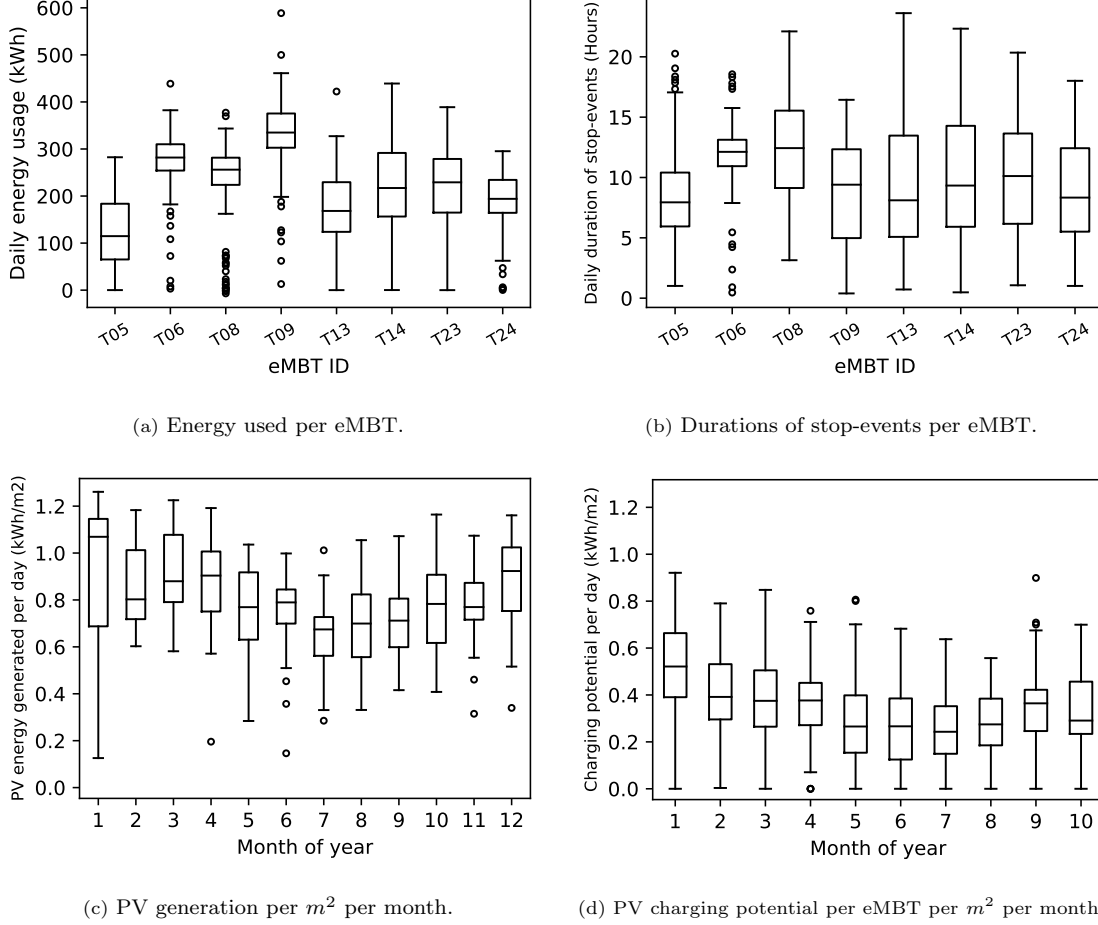


Figure 5: Summary of mobility, energy requirements, and charging potentials.

utility. We applied a minimum stop duration of 20 minutes and a maximum stop duration of 8 hours per event to ensure that only valid operational stops would be identified and that drop or pick up and go events were not included as charging opportunities. We chose the maximum of 8 hours because a taxi in normal service would not stop for longer than that on a week day.

3.3.1. Charging from the grid

Figure 5b shows the distribution of stop-events across days, with the minimum and maximum stop duration thresholds applied. The figure shows that the MBTs' cumulative stop duration times vary considerably, with the median duration per day ranging from a minimum of 8 h for taxi T05 to a maximum of 12 h for taxi T08.

To calculate the charger capacity we used a relatively high energy demand and a relatively short charging time for an averagely demanding situation. We used the averages of the 75th percentile of the energy usage (Figure 5a) and the 25th percentile of the 24-hour stop duration times (Figure 5b) as 273 kWh and 6.7 h respectively to calculate a charger capacity of 40.6 kW. This assumes a constant charging profile of 40.6 kW

for 6.7 h to fully recharge a vehicle.

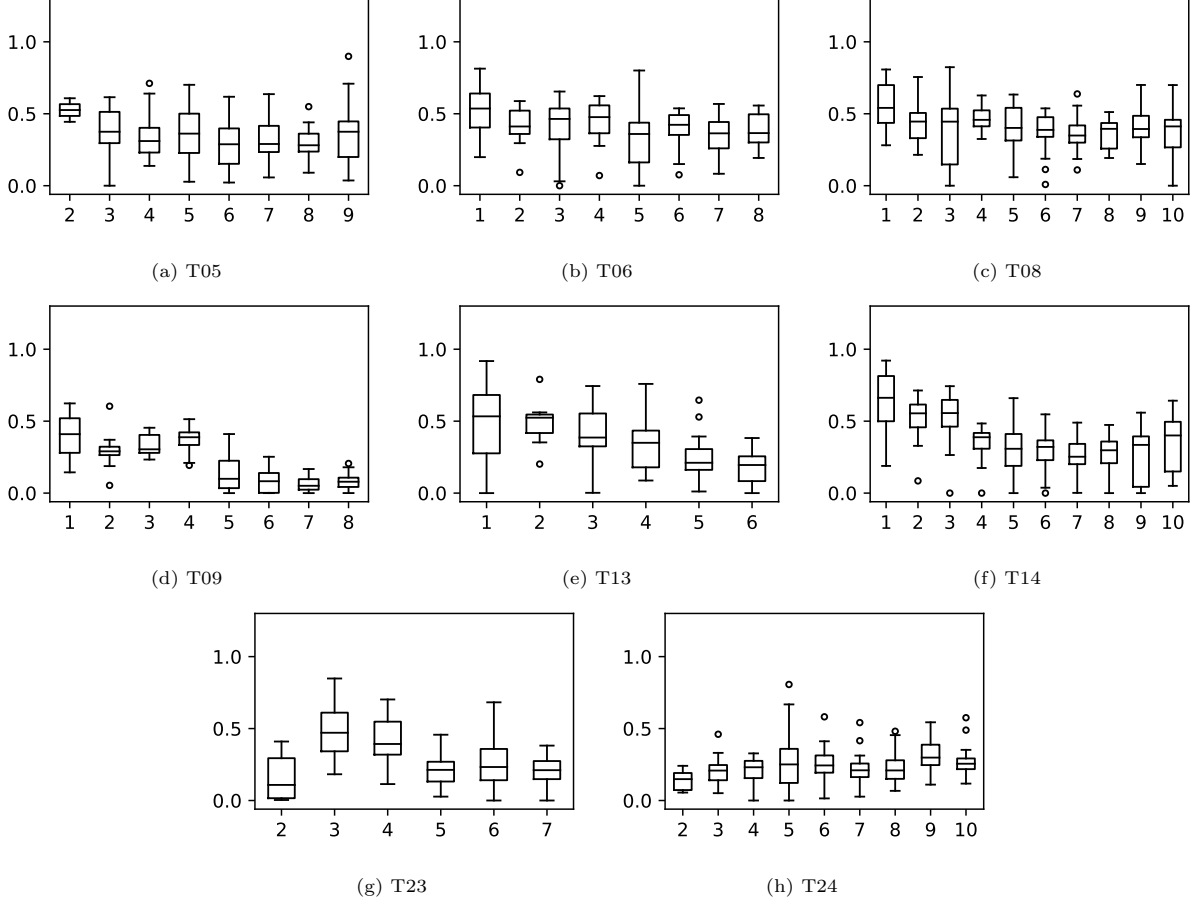


Figure 6: Disaggregated charging potential (in kWh/m²) per eMBT for each month of the year.

3.3.2. Charging from solar PV

We evaluated the potential for charging the eMBTs from solar PV, both to reduce the load on the electrical grid and to reduce the size of the battery installed in the eMBT. The energy generated per surface area is shown in Figure 5c for each month of the year, representing an upper bound of charging potential during stationary periods.

The aggregate charging potential per square metre of solar panel, for the fleet, is shown in Figure 5d, indicating that a large amount of the generated energy could be used during stops. The disaggregated distribution of charging potential for each taxi, per square metre of solar panel, is shown in Figure 6.^{*1} Despite the fact that the taxis followed slightly different stopping patterns, as discussed in Section 3.1, this figure indicates that the variation of charging potential between taxis is low, and that they would thus require similar

^{*1}Some of the taxis have less than 10 months of data due to errors in data-collection.

charging infrastructure. Assuming that the PV installations were sized to exploit the median stop potential per taxi, the mean potential would be 0.34 kWh/m^2 and would vary from a minimum of 0.24 kWh/m^2 to a maximum of 0.52 kWh/m^2 during the year. The results show that a solar installation of approximately 660 m^2 would be required per taxi to ensure that the taxis' daily energy requirements would be met on an average day.^{*2} In other words, a PV installation the size of a football (soccer) field would be enough to meet the energy requirements of ten taxis 50 % of the time.

Given the estimated 25,000 MBTs in Kampala (Kamuhanda and Schmidt, 2009; Spooner et al., 2020), our analysis indicates that to charge all the minibus taxis from the national grid will require 19% (5.6 GWh/d) of the current daily national energy generation capacity (USAID, 2019).

4. Conclusion

Concern about the possible effects of climate change has driven an energy revolution from internal combustion engines to electric vehicles in the Global North. Pushed by market forces and supplier preferences from beyond its own borders, this wave will eventually break over the Global South and its organically evolved and notoriously chaotic paratransit systems and fragile electrical grids. Sub-Saharan Africa has many specific characteristics, challenges, and opportunities that will eventually determine its response.

This paper focuses on paratransit in the region, which transports more than 70% of the region's commuters. One of the unanswered questions is how the dissimilar mobility characteristics of the minibus taxis, the mainstay of the region's paratransit system, will translate into electrical requirements. Since these taxis park spontaneously at tacitly known stops of the drivers' choosing, for durations determined by passenger demand, the capacity of charging infrastructure at these stops is unknown. Further, the extent to which these charging stations can be powered by the region's abundant sunshine remains unclear.

This paper therefore investigated these three unknowns for minibus taxis, using an urban scenario in Kampala, Uganda, as a case-study.

Firstly, the results showed that the taxis we studied would mostly have a similar energy demand with a nominal 224 kWh required per median day if no additional charging capacity was provided. This would increase to 375 kWh when accommodating all days, except for two taxis, which required up to 491 kWh.

Secondly, evaluating the charging potential showed that the median stops per day ranged from 8 h to 12 h. As expected, the taxis with the shorter stop periods, and hence less time for charging, are also the ones that would need more energy because they are more mobile. Nevertheless, a nominal 41 kW charger will suffice if

^{*2}The PV area to meet the taxis' daily energy requirements on an average day was calculated by dividing the mean 50th percentile of energy demand by the mean 50th percentile of charging potential.

charging from a fully operational grid.

Finally, evaluating the solar irradiation for the stop times and durations, showed that the mean charging potential per median day ranged from 0.24 kWh/m² to 0.52 kWh/m². This implied that around 660 m² (half of an Olympic swimming pool) of PV would be required to meet the taxi's energy demand on an average day.

Although the paper's results focus on specific case-study, for the first time, a rough estimate of the of the energy requirements of SSA's minibus taxis has been found. Firstly, it is clear that a substantial amount of energy is needed to support the mobility requirements of minibus taxis. This can be an obstacle for developing countries with energy insecurities. Regardless, renewable sources of energy should be found to offset this energy demand and to ascertain a sustainable transition to electric vehicles. We see that, conflicting to this need, a substantial investment would be needed to ensure that sufficient renewable energy generation capacity is installed.

The instructive approach of this article should provide traffic planners and grid operators with a methodology to evaluate the impact of electric vehicle roll-outs in other regions of the world. The methodology can be adapted to suit mass roll-outs in developing countries, as well as roll-outs in small, privately owned fleets such as courier vans in a developed country.

Some further work is envisaged. Firstly, seasonal variation of the results may need to be taken into account. In Winter months, heating may increase energy usage, and solar irradiation would be less. This effect was not seen in this paper, due to Kampala being on the equator. Secondly, a structured approach to calculate the optimum battery size of the taxis would help for approximating the vehicle cost and feasibility. The duration of stops and energy consumed between stops would need to be taken into account when determining the battery size.

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