Environmental and Social Impact Assessment of Electric Motorcycle Taxis in Kampala, Uganda

Final Report

University of Michigan Master's Project Team

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This study was about the impact of electric motorcycles on *boda boda* drivers, and it would not have been possible without them. Our gratitude in particular goes to Geofrey Ndhogezi, who clued us into many of the dynamics of the *boda boda* industry throughout the course of this study. Geofrey also led the maintenance study, along with Ssenyonjo John Bosco and Constant Kizito.

We would also like to thank the twenty-one key informants we interviewed from across the industry, civil society, academic and journalistic realms who provided key insights into the rapidly evolving *boda boda* industry. Additionally, our gratitude goes to Moses Owori Jr, who led the general survey, and we thank him and his team for surveying over 200 *boda boda* drivers throughout Greater Kampala in a time of great uncertainty.

This study was significantly complicated by the COVID-19 lockdown, which devastated drivers' livelihoods and led to a rash of police violence against them. To be a *boda boda* driver in Kampala is to deal with significant barriers at every turn. Over the course of this study we have found that the adoption of electric motorcycles can lead to an improvement in drivers' livelihoods, and it is our hope that it can be one of many solutions to *boda boda* drivers' obstacles.

1. Key Findings

In Kampala, Uganda, motorcycle taxis - *boda bodas* - play a critical role in moving people and goods across the city. This informal industry is a significant source of income for an estimated 150,000 people within Kampala and a million across the country. Yet, *boda boda* is considered a low-profit business, the drivers are marginalized, and they are at risk of extortion, accidents, and hostility. The motorcycles running on internal combustion engines (ICE) also contribute to both local air pollution and global greenhouse gas emissions.

Zembo is a Kampala-based company that produces electric motorcycles targeting the *boda boda* market. While electric vehicles are generally thought to have positive social and environmental impact compared to ICE vehicles, the literature is scarce regarding the impact on electric motorcycles in urban environments with high degrees of poverty and informality such as Kampala City. We engaged in this research to better understand the degree of impact that electric motorcycles have in both social and environmental dimensions.

We hypothesized that electric motorcycles would benefit the *boda boda* drivers by improving their net income and social well-being; and emit significantly less local air pollutants and greenhouse gases compared to the conventional motorcycles currently in use. The following is a summary of key findings from the research:

<u>Social Well-being</u>

We found a positive change in perceived individual well-being and social status of drivers who ride electric motorcycles (Zembo drivers). Electric motorcycles improve the social acceptance of *boda boda* drivers with peer *boda boda* drivers, government and police authorities, passengers, and other stakeholder groups. However, driving an electric motorcycle was not a strong indicator of drivers' job satisfaction. More in-depth analysis of other contributing factors to job satisfaction is needed.

<u>Net Income</u>

Our study, conducted in October 2020, found that *boda boda* drivers overall were earning significantly less income during the period of the study due to the impact of the COVID-19 lockdown and curfew in Uganda. We estimate a nearly 1/3 reduction in revenue for *boda boda* drivers compared to recent literature that estimated the drivers' income at pre-COVID level (Recovery and Reform). Zembo drivers were more successful during this time, earning $21 USD[i] more than conventional drivers in weekly revenue. This difference can be partly explained by the higher proportion of Zembo drivers who use ride-hailing applications than that of conventional drivers. The difference in revenue between Zembo and conventional drivers that do not use ride-hailing applications decreases slightly to $19 per week.

Zembo drivers on average also paid significantly less than conventional drivers on fuel and maintenance costs. We estimated that the weekly battery cost of an average Zembo motorcycle is $15 USD, 68% of the weekly fuel cost of an average conventional motorcycle. Likewise, weekly maintenance cost of an average Zembo motorcycle was estimated at $0.4 USD, a 90% reduction compared to the maintenance cost of an average conventional motorcycle. However,

[i] All survey data was collected and processed in 1,000 UGX and converted to USD based on the current currency exchange rate of 1 UGX to 0.00027 USD.

the cost savings is likely overestimated because of the significantly lower average age of electric motorcycles and term-limited subsidies provided by Zembo. Accounting for expiration of warranties after two years, we estimate that electric motorcycles will provide 55% reduction in maintenance costs compared to a similarly aged conventional motorcycle.

Environmental Impact

Two distinct models which used annualized and modeled hourly electricity generation profiles for Uganda came to strikingly similar conclusions indicating significant reductions in local air pollutant and greenhouse gas emissions. These models indicate Zembo motorcycles represent a ~97% reduction in CO2 and over 90% reduction in local air pollutants PM2.5, CO and NO2 compared to the most common conventional motorcycle the Bajaj Boxer. Integrating estimates for emissions from Zembo battery production indicates only a slight decrease in CO2 reductions, but it does indicate that switching to electric motorcycles increases lifecycle emissions of SOx.

2. Project Introduction

In Kampala, motorcycle taxis - *boda bodas* - rule the streets. Cheaper than ride-hailing taxis, faster and more direct than minibuses and more maneuverable than anything else on the road, *boda bodas* also play a critical role in moving goods for small businesses and making deliveries while providing employment for an estimated 150,000 people throughout the city and a million across the country.

Yet *boda bodas* are not without their downsides. They are a low-profit business, where at least half of a driver's income goes into fuel, leasing, and maintenance costs. Drivers are marginalized by authority figures, vehicles and passengers and are at risk of extortion, accidents, and personal hostility. Conventional motorcycles also burn fossil fuels which contribute to both local air pollution and global greenhouse gases.

A well-known solution to heavily polluting vehicles is replacing them with electric vehicles charging on a clean electric grid. Electric vehicles also have significantly fewer parts than conventional vehicles and can result in savings for drivers, though battery cost often drives the prices of electric vehicles past those of conventional vehicles with comparable range per energy refill. Additionally, joining more professional outfits and using new technologies has been shown to improve drivers' perceptions of their social standing.[1] The introduction of affordable electric motorcycles in East Africa could thus be a fitting solution.

The Social Status of Boda Boda Drivers

Boda boda drivers are socially marginalized by their work, and are often considered uneducated, suspect and even criminal.[2] These negative stereotypes are used by police and other authority figures to exploit *boda boda* drivers. Drivers are financially extorted and pushed to the margins, where they are at higher physical risk.

Daily expenses for *boda boda* drivers are significant. Drivers typically buy around four liters of gasoline a day, costing around $4. Maintenance costs are highly variable and include bi-weekly oil changes costing around $5, commonly replaced items like headlights and clutch, and less common items such as engine components that incurs significant costs. Drivers also typically pay rent or lease for the motorcycles costing around $2.8 a day.

The Environmental Implication of Boda bodas

Boda boda motorcycles also have negative environmental impacts. The global transit sector accounts for approximately 23% of direct global GHG emissions and roughly half of it can be attributed to vehicle transport.[3] An estimated 7.0 Gt of CO_2 was emitted by vehicle transport in 2010 and the amount is increasing faster than any other sector. The Intergovernmental Panel on Climate Change (IPCC) asserts that to avoid the worst effects of climate change, the planet will have to reach global net zero CO_2 emissions by 2050.[4] While developed countries account for most of both current and legacy emissions,[5] developing countries are likely to experience large increase in emission rates due to rapid increases in passenger vehicle ownership fueled by demographic and economic growth.

Gasoline combustion in transportation also emits local air pollutants commonly thought to have adverse health consequences. PM 2.5, PM10, SOx, and NOx have been linked with increased morbidity.[6] Reducing air pollutant emissions can potentially improve life expectancy and quality of life for those living and working in close proximity to roadways. Gasoline-burning engines and fluctuating maintenance regimes are contributing to some of the most polluted air in Africa. Particulate matter (PM) levels have grown by an estimated 162% since the 1970s.[7] PM2.5 is known to cause sickness and death. It is estimated to cause 26 deaths per 100,000 in Uganda.[8]

Social and Environmental Impact of Electric Boda bodas

Zembo is a Kampala-based company that produces electric motorcycles and provides battery charging and swapping services for *boda boda* drivers. We have engaged in a research in partnership with Zembo to better understand the degree of impact that electric motorcycles have in both social and environmental dimensions.

We hypothesized that electric motorcycles would benefit the *boda boda* drivers by improving their net income and social well-being; and emit significantly less local air pollutants and greenhouse gases compared to the conventional motorcycles currently in use.

To test these hypotheses, we conducted interviews with more than 20 key informants in the sector, surveyed 200 *boda boda* drivers, and developed a model of energy use and pollution based on *boda boda* trip and emissions data.

3. Social Impact

3.1. Boda Bodas in Ugandan Society

The *boda boda* industry in Uganda began as bicycle-taxis on the border with Kenya in the 1960s.[9] In the 1990s the government of Uganda lowered import restrictions, leading to second-hand Japanese motorcycles entering the market en masse.[10] By the early 2000s, cheap Indian-manufactured motorcycles began dominating the market, with the Bajaj Boxer arising to become the most popular brand today with an estimated 94% market share of *boda bodas*.[11]

Today, *boda bodas* play a critical role in Ugandan economy, providing hundreds of thousands of jobs, providing rapid, door-to-door transportation, and sustaining local businesses with delivery and logistics services. While estimates for the total number of *boda bodas* operating in Kampala vary widely, many estimates average around 150,000. Most *boda boda* drivers support families, so that we may estimate around one million people around Kampala are indirectly supported by the *boda boda* industry. Local businesses also make significant use of *boda bodas* for stocking shops and for making deliveries.[12]

The role of *boda bodas* in delivery services was highlighted during the COVID-19 lockdown in 2020, when *boda bodas* were banned from carrying passengers for four months but allowed to carry packages. Yet this was estimated to only provide 10% of the regular work, and passengers and drivers took to desperate measures, including carrying passengers in boxes to move them around the city.[13]

It should also be noted that the *boda boda* industry is heavily male-dominated - less than 0.1% of drivers are women. This means a significant source of employment is kept permanently out of women's hands and worsens economic outcomes for already disadvantaged women. However, women benefit from using *boda bodas* to move small goods to shops and marketplaces, to deliver goods, to take children to school, and for access to healthcare.[14]

<u>Boda boda Economics</u>

Boda boda work generally provides low profits for drivers. Capital required for a new Bajaj Boxer, the most common motorcycle brand in Kampala, is around $1,500 USD. Used motorcycles typically cost around half of what a new motorcycle of the same model would cost. Drivers finance the motorcycles by buying them on lease to own schemes, borrowing from microfinance institutions, or renting someone else's motorcycle on daily fees. We found that 80% of *boda boda* drivers either own or are on a path to owning their motorcycles. About half of their daily income was used to pay for fuel, maintenance, and lease on the motorcycles.

<u>Position and Risk</u>

Boda boda drivers are also socially marginalized by the nature of their work and are often at risk of being hit by larger vehicles, extorted by policemen, and insulted by passengers. Motorcycles are small and without an exterior, and *boda boda* drivers almost always come off worse in collisions with passenger cars, minibuses, or trucks. Corruption among the police is rife in Kampala. Policemen are known to demand bribes for common infractions of the law, as well as locking up motorcycles when drivers are unable to pay. Finally, drivers deal with passengers and the public who often look down on them as uncivilized, uneducated and/or unhygienic.

3.2. <u>Methods</u>

To test our hypotheses on the social impact of electric *boda bodas*, we conducted a survey of 200 *boda boda* drivers including both conventional and electric motorcycles, operating in the Great Kampala Metropolitan Area. Additionally, we conducted a second survey of 122 conventional and electric *boda boda* drivers focusing on the maintenance cost and drivers' maintenance behavior. This section describes the methodology used in each survey.

3.2.1. General Survey

<u>Sample Selection</u>

At the time of the survey in October 2020, 20 *boda boda* drivers operated Zembo Storm electric motorcycles. All 20 drivers (Zembo drivers) were selected for the survey. Three additional electric motorcycles were owned by Zembo for internal use and were not included in the survey.

We used a stratified sampling method to select 180 *boda boda* drivers who operated ICE motorcycles (conventional drivers). The conventional drivers were selected based on the location of the stages that they operated on. Within the Greater Kampala Metropolitan Area (Kampala, Mukono, and Wakiso districts), we categorized *boda boda* stages by the neighborhood type: commercial, industrial, and residential. The number of stages selected for each neighborhood type is intended to be representative of the types of economic environments in which *boda boda* stages are located (*Table 1*).

Table 1 – Boda boda Stages Selected by District and Neighborhood Type, count

	District			
	Kampala	Mukono	Wakiso	Grand Total
Commercial	23	6	29	**58**
Industrial	7	2	11	**20**
Residential	32	2	30	**64**
Grand Total	**62**	**10**	**67**	**139**

<u>Survey Design</u>

The survey consisted of 73 questions that asked the drivers to provide information on the demographic characteristics including information about the motorcycle and the stage, daily income, expense amount and frequency, job satisfaction and future aspirations. In addition, Zembo drivers were asked about their reasons to choose electric motorcycles and perceived changes after switching to electric motorcycles including the level of social respect from various stakeholder groups. Pre-screening questions were used to exclude drivers who are less than 18 years old, those for whom *boda boda* is not the main source of income and those who operate outside of Greater Kampala Metropolitan Area.

<u>Survey Execution</u>

A Makerere professor and experienced researcher was the lead surveyor for this survey and recruited five enumerators locally in Kampala to carry out the survey. He trained the five enumerators and oversaw the survey operations. The enumerators approached each of the selected stages and surveyed on average 1~2 drivers at each location. The survey was conducted verbally, and the enumerators used digital tablets to record the responses online. The survey took on average 22 minutes per person. Both Zembo and conventional drivers were paid 10,000 UGX ($2.75 USD) for responding, similar to what they could be earning from a ride of the same length of time.

<u>Data Analysis</u>

Upon receiving the survey results, we manually reviewed the data for missing or erroneous information. Mistakes in data entry such as typographical errors and currency unit errors were fixed by hand after confirming with the surveyors. Any unresolved error in the data was dropped from the analysis.

We asked respondents to rate their overall job satisfaction in a 5-point Likert scale measure between very dissatisfied and very satisfied. We then codified the responses into incremental numeric values from 0 to 4 for analysis.

For Zembo drivers, we also asked whether their perceived social respect from different stakeholder groups has changed after switching to the electric motorcycle. The average perceived change in social respect was calculated by measuring the percentage of respondents who reported an increase in social respect for each stakeholder group.

Estimates for daily income was collected by asking the survey respondents how much money they made yesterday or on the last day they worked. Drivers' weekly revenue was calculated by multiplying the daily income by the number of workdays per week that the driver worked. The formula is as follows:

$$Weekly\ Driver\ Revenue = Previous\ Day's\ Income \times Weekly\ Work\ Days$$

We divided the expense items of *boda boda* drivers into three categories: recurring costs that are highly variable depending on the distance traveled of *boda boda* such as fuel cost; fixed recurring costs such as regular payment on motorcycles and maintenance costs; and non-recurring costs such as down payment on motorcycles and entry fee to join a stage. We categorized the maintenance cost as fixed cost based on the short-term nature of income recognition of *boda boda* drivers. It would be difficult for a *boda boda* driver who typically calculate earnings on a daily basis to attribute maintenance expenses that are incurred on a much longer cycle toward the length of their operations. Please refer to *Table 2* below for a breakdown of expense items.

Table 2 – Expense items by cost category

Recurring		Non-Recurring
Variable	Fixed	
Fuel/Battery	Motorcycle Payment	Motorcycle Down Payment
Airtime	Maintenance	Driving Permit Fee
	Engine Oil	Stage Join Fee
	Police Fee	PSV Fee
	Stage Fee	Boda Group Join Fee
	Insurance	

Weekly expenses for each recurring cost item were calculated by multiplying the expense amount by the number of payment cycles in a 7-day week. The formula is as follows:

$$Weekly\ Expense = Expense\ Amount \times \frac{7}{Payment\ Cycle\ in\ Days}$$

The average weekly expense amounts for each recurring cost item were calculated by dividing the total weekly expenses of the cost item by the number of respondents.

Finally, we calculated two types of income indicators. The operating income of *boda boda* drivers was calculated by subtracting the variable recurring costs from the revenue. The operating income represents the earnings of *boda boda* drivers associated with the distance they traveled on motorcycles. The net income of drivers incorporates the fixed recurring costs that may be incurred independent of whether the driver operates the *boda boda* or not. In calculating the operating income and net income estimates, we assumed that drivers who did not respond to particular cost items incurred $0 USD on that item.

3.2.2. Motorcycle Maintenance Survey

To supplement the data collected from the general survey on maintenance expenses of conventional and electric *boda boda* drivers, we conducted a separate survey focusing on the maintenance cost and frequency of various motorcycle parts.

<u>Sample Selection</u>

17 Zembo drivers were selected for this survey, all of whom were also included in the general survey. Three Zembo drivers were excluded from the maintenance survey as we recruited them as the enumerators of this survey.

A different set of conventional drivers were selected for the maintenance survey than those who were selected for the general survey. The sample selection process was done similarly based on the location of the stages. Stages were selected evenly across the five divisions of Kampala city. A total of 105 conventional drivers responded to the survey.

<u>Survey Design</u>

In consultation with *boda boda* drivers, we created a list of 38 commonly maintained items for conventional motorcycles. For electric motorcycles, the list consisted of 21 items accounting for parts that are unique to each power system. Three additional spaces were given in the survey to name other maintenance items if needed. For each of the items listed, we collected information on when the item was last repaired, and at what cost. A comment space was provided to indicate when two or more items were paid for together in order to prevent double counting. Given the regularity and high cost of engine oil changes, the survey question asked for frequency of oil change rather than the last repairs for this item.

<u>Survey Execution</u>

We recruited three of the Zembo drivers as enumerators of the maintenance survey. The three drivers were excluded from answering the survey questions to avoid conflict of interest. The enumerators were trained by us over video call sessions to carry out the survey. They were also trained using the University of Michigan COVID-19 research guidelines to ensure low risk research. The survey was conducted for 10 days in July 2020. For Zembo drivers, the survey was scheduled individually based on their availability. For conventional drivers, the enumerators approached the drivers at selected stages and asked for participation. All surveys were conducted verbally with the enumerators writing down the answers on the survey sheet on behalf of the respondents. The survey took on average 17 minutes per person. Both Zembo and conventional drivers were paid 7,500 UGX ($2 USD) for responding, similar to what they could be earning from a ride of the same length of time.

<u>Data Analysis</u>

To calculate the average maintenance cost of each component, we assumed that the drivers were at a halfway point of their maintenance cycle for the component at the moment of the survey. We used the following formula:

$$Average\ Maintenance\ Cost = \frac{365\ days/yr}{Days\ since\ Repair \times 2} \times Average\ Cost\ of\ Repair\ \times \%\ of\ Respondents\ Reporting\ Repairs$$

The total annual maintenance cost of motorcycles was then calculated by aggregating the average annual maintenance costs of each component.

The young age of Zembo motorcycles and the company's replacement policies and time-limited warranties complicated calculation of maintenance costs for electric motorcycles. We took Zembo's warranty policies at face value to assess the potential increases in costs as warranties end.

Post-survey Follow-up

We followed up with semi-structured interviews with five Zembo riders in March 2021 who had participated in the original maintenance surveys, to probe further their experiences with maintaining their electric motorcycles.

3.3. Summary of Findings

From our survey of conventional and electric motorcycles, we investigated:

- The demographic composition of conventional and electric *boda boda* drivers.
- Changes in well-being of *boda boda* drivers after switching from conventional to electric motorcycles.
- Changes in take-home income of *boda boda* drivers after switching from conventional to electric motorcycle.

3.3.1. Demographic composition

All of the survey respondents are male, and the majority of drivers were in the age range 25 to 39 for both conventional and Zembo drivers. Most of the drivers had fewer than 10 years of experience in the industry, while Zembo drivers on average appeared to be more experienced than conventional drivers (*Figure 1*and *Figure 2*).

Figure 1 – Age Group by Motorcycle Type, percent

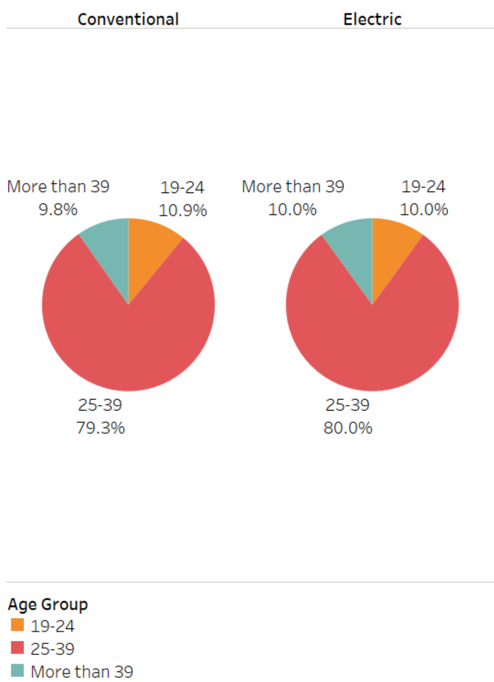
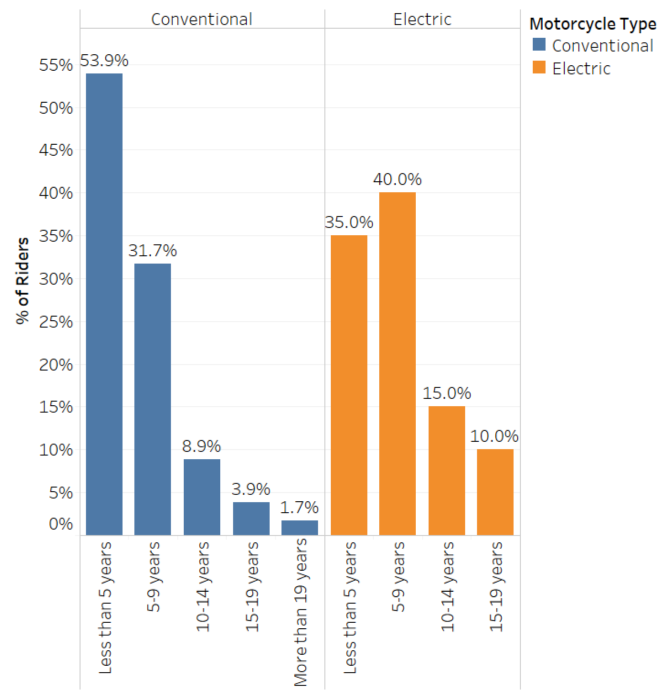
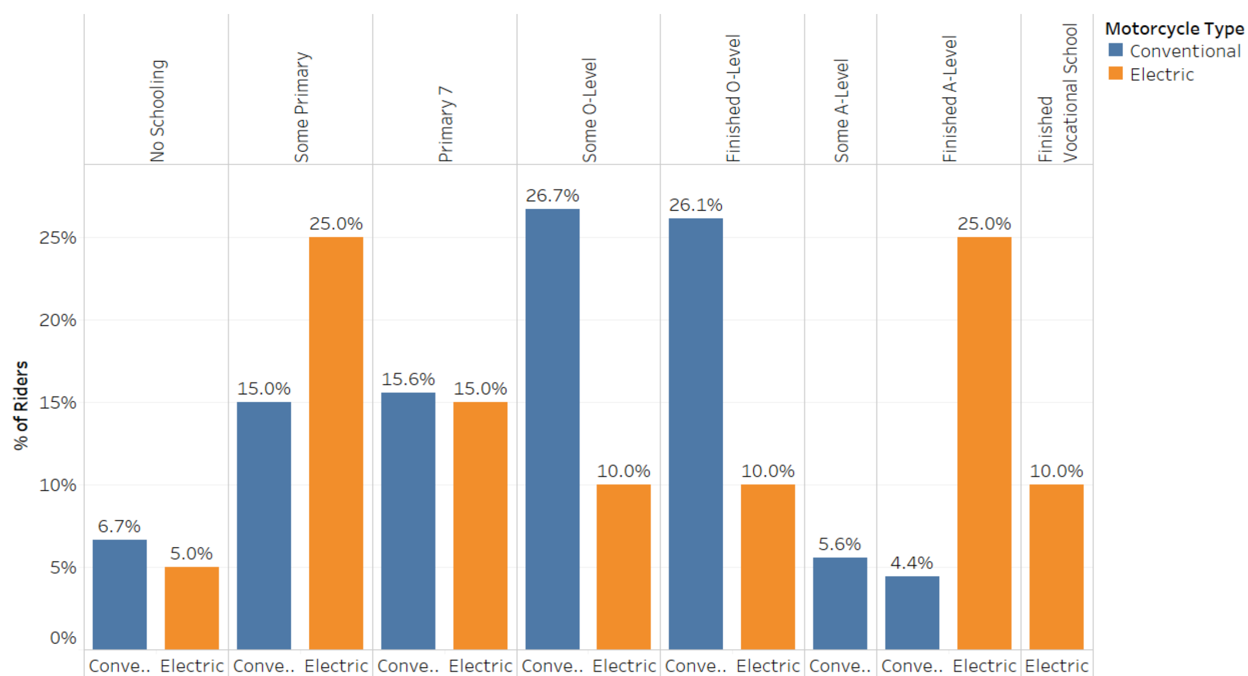


Figure 2 – Experience by Motorcycle Type, years



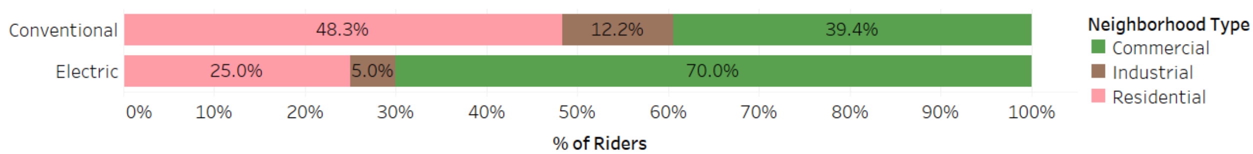
The distribution of drivers' level of education showed differences between conventional and Zembo drivers. The majority of conventional drivers either finished or received O-level education. Zembo drivers were divided between those who completed or received primary education and those who finished A-level education or above (*Figure 3*).

Figure 3 – Level of Education by Motorcycle Type, percent



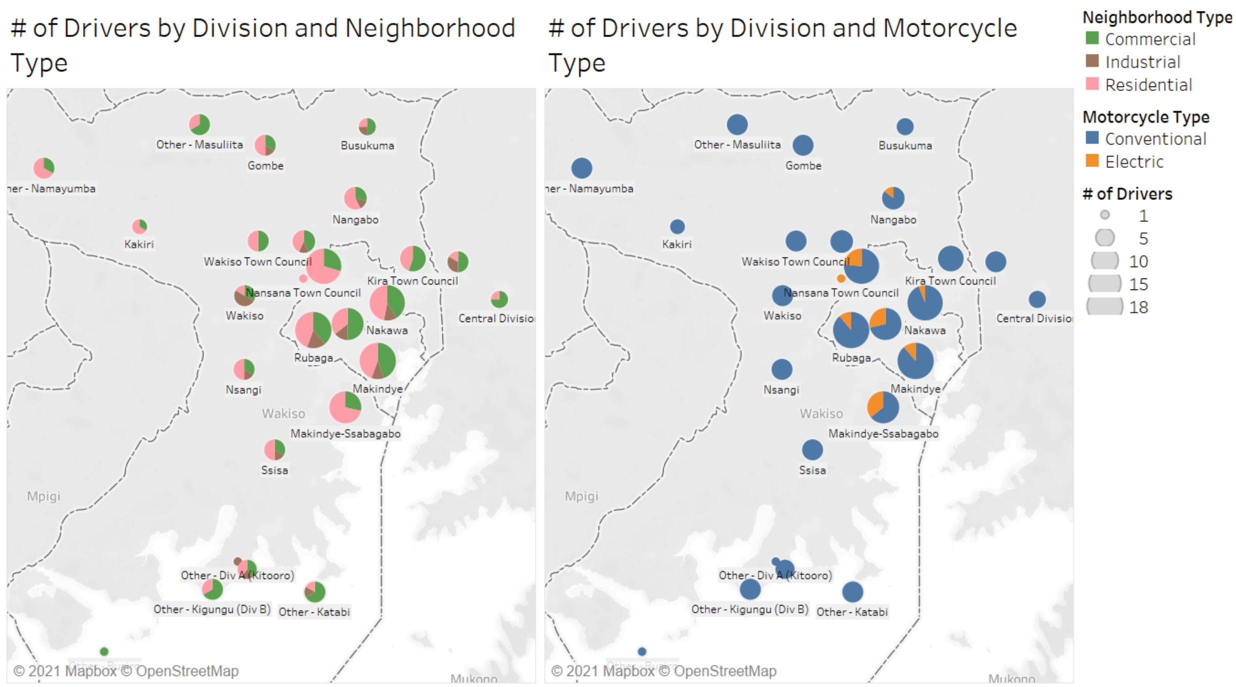
We reviewed the location of stages where conventional and Zembo drivers operate, and the types of neighborhoods where the stages are located. Overall, a higher share of Zembo drivers operated in commercial areas compared to conventional drivers who were more likely to be located in residential areas (*Figure 4*).

Figure 4 – Conventional and Zembo Drivers by Neighborhood Type, percent



All Zembo drivers were operating within the city of Kampala and the neighboring divisions of Makindye-Ssabagabo and Nangabo, as expected due to the availability of charging stations in the city (*Figure 5*).

Figure 5 – Number of Drivers by Location and Neighborhood / Motorcycle Type

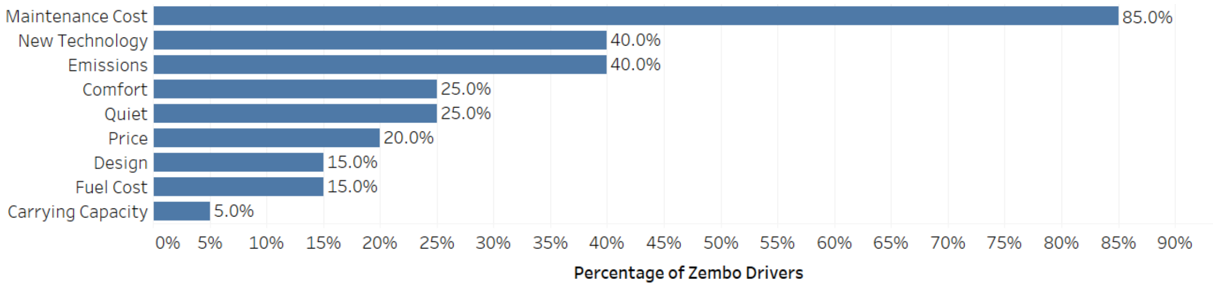


3.3.2. Changes in Social Well-being Perceived by Zembo Drivers

To measure the changes in social well-being associated with driving an electric (vs. conventional) *boda boda*, we asked the Zembo drivers about their reasons for choosing Zembo motorcycles. We also asked them to compare their social interaction with a list of stakeholder groups and general well-being before and after switching to Zembo motorcycles.

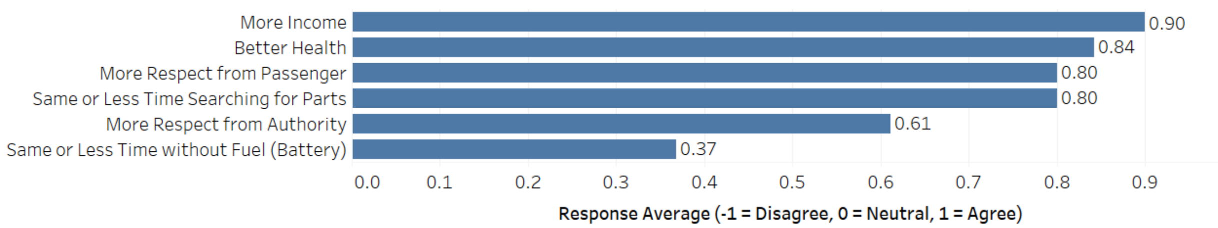
85% of Zembo drivers cited low maintenance costs as one of their considerations in choosing to drive Zembo motorcycles. Low emissions and appeal of new technology were also popular factors for 40% of respondents (*Figure 6*).

Figure 6 –Drivers' Reason to Switch to Zembo (Multiple Select), percent



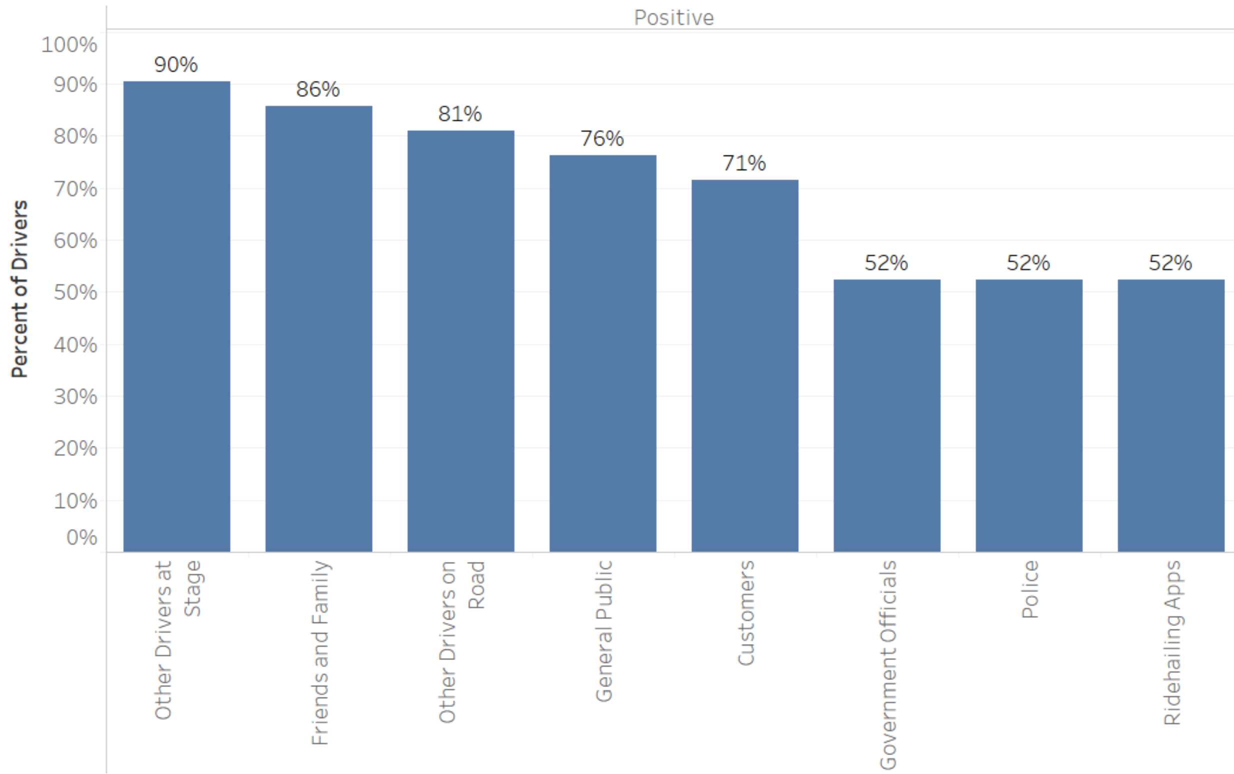
We asked Zembo drivers to indicate their agreement with a number of statements describing changes expected to occur after switching to drive Zembo motorcycles. We assigned numerical values to the responses – -1 for disagreement, 0 for neutral, and 1 for agreement – and averaged the responses on a scale from -1 to 1. Zembo drivers commonly indicated that they earn more income, feel healthier, and are more respected after switching to Zembo motorcycles. Expected concerns around battery depletion and the availability of repair parts were not commonly indicated by drivers (*Figure 7*).

Figure 7 – Driver Response to Expected Change after Driving Zembo Motorcycles



Similarly, we asked Zembo drivers to indicate in what direction the perceived social respect from different stakeholder groups has changed after driving Zembo motorcycles. Zembo drivers commonly indicated that they feel more respected in their interaction with all types of social groups (e.g., other *boda boda* drivers, friends and family, and passengers). The perceived impact was greater among those in close social circles with other drivers in the same stage and friends and family members. Fewer Zembo drivers responded that they feel more respected by government officials and police after driving Zembo motorcycles (*Figure 8*).

Figure 8 – Driver Perceived Improvement in Social Standing per Stakeholder, percent



Limitations

The study on social well-being of electric *boda boda* drivers is limited by the small sample of Zembo drivers (N=20). As a result, our observations are largely descriptive. Further, Zembo drivers may respond favorably about their current situation since they already made the investment to drive Zembo electric motorcycles, implying the potential for confirmation bias.

Despite these limitations, the survey results provide preliminary insights into the role of electric motorcycles in promoting the self-esteem of *boda boda* drivers and social standing from those who interact with the drivers. Elevation in perceived social status associated with driving an electric motorcycle could contribute to legitimization of motorcycle taxi driving as a respectable occupation and de-stigmatize the job, which is currently often considered dangerous, unruly, and only undertaken by people from low socio-economic background. A larger quantitative study, qualitative research, or a mixed-methods study on the Zembo drivers would contextualize the social changes they perceive in driving electric motorcycles.

Job Satisfaction

Another indicator of drivers' well-being is perceived job satisfaction. We asked respondents to rate their overall job satisfaction in a 5-point Likert scale measure between very dissatisfied and very satisfied. We then codified the responses into incremental numeric values from 0 to 4 for analysis. While the average level of job satisfaction of Zembo drivers was 3.0, slightly higher than the 2.88 average of conventional drivers, we found no statistical significance in the difference (*Table 2*).

Table 3 – Two Sample t-Test for Job Satisfaction and Motorcycle Type

	Conventional	*Electric*
Mean	2.883333333	3
Variance	0.751675978	0.842105263
Observations	180	20
Hypothesized Mean Difference	0	
df	23	
t Stat	-0.542305854	
P(T<=t) one-tail	0.296411997	
t Critical one-tail	1.713871528	
P(T<=t) two-tail	0.592823994	
t Critical two-tail	2.06865761	

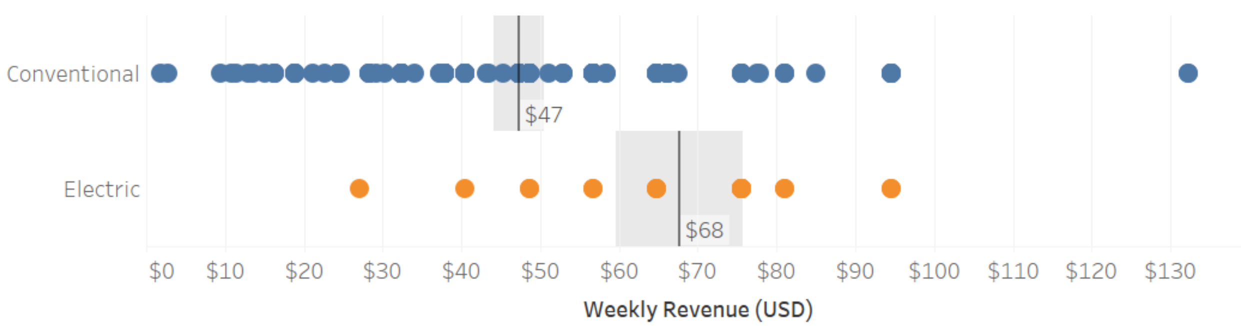
The lack of statistical significance in the difference in job satisfaction between the conventional and Zembo drivers may be attributable to other factors such as daily profit, time in traffic, customer interaction, etc.

3.3.3. Driver Net Income

Weekly Revenue

We estimated weekly revenue of *boda boda* drivers by asking their yesterday's income and multiplying the figure by the number of days worked per week. On average, Zembo drivers earned $68 (± $8) USD in weekly sales revenue while conventional drivers earned $47 (± $3) USD at 95% confidence intervals. This result leads to an average $21 USD difference in weekly revenues earned between Zembo and conventional drivers (*Figure 9*).

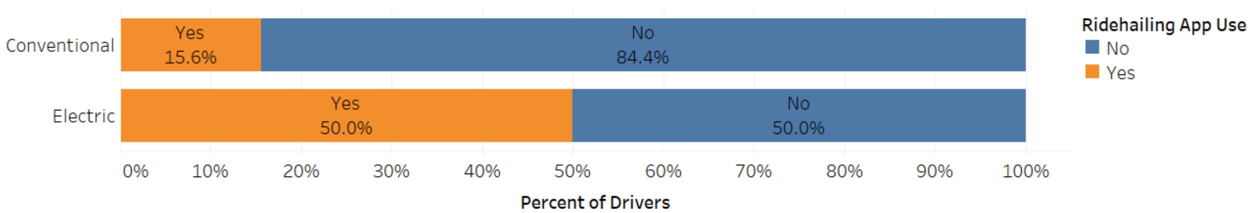
Figure 9 – Drivers' Weekly Revenue by Motorcycle Type, USD



The revenue estimates for both conventional and Zembo drivers, however, is likely underestimated due to the impact of COVID-19 pandemic. By the time of this survey in October 2020, nation-wide lockdowns and curfews significantly limited the drivers' ability to secure customers and generate income, and the economic downturn pushed more people into the *boda boda* industry, further driving down individual revenue. A comparable study in April 2020 that estimated daily earnings of *boda boda* drivers in pre-COVID settings reported that the drivers earn 38,000 UGX per day, an equivalent of $72 USD in weekly revenue.[15] This figure is $25 USD higher than the average weekly revenue estimate of conventional drivers in our survey.

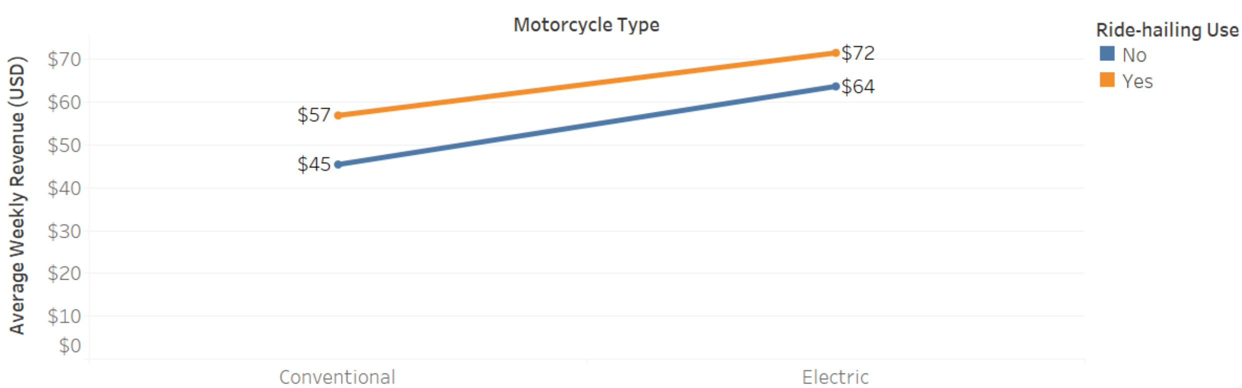
The downward impact of COVID-19 on revenue generation of conventional drivers was likely greater than that of Zembo drivers, due to the higher proportion of Zembo drivers using ride-hailing applications and Zembo's financial support of its riders during the worst of lockdown. About half of the Zembo drivers reported that they use one or more types of ride-hailing applications such as SafeBoda, while only 15% of the conventional drivers said that they use any ride-hailing application (*Figure 10*). Use of ride-hailing application could alleviate the negative impact of COVID-19 on income by providing alternative sources of income such as delivery services as well as helping drivers to expand their customer base through the application.

Figure 10 – Drivers Using Ride-hailing Applications by Motorcycle Type, percent



Despite the impact of COVID-19 and use of ride-hailing application on drivers' revenue, a significant portion of the revenue difference between conventional and Zembo drivers can be attributed to the use of electric motorcycles. In both groups drivers who use ride-hailing applications and those who do not, Zembo drivers earned significantly more revenue per week than conventional drivers did (*Figure 11*).

Figure 11 – Weekly Revenue by Motorcycle Type and Ride-hailing Application Use, USD

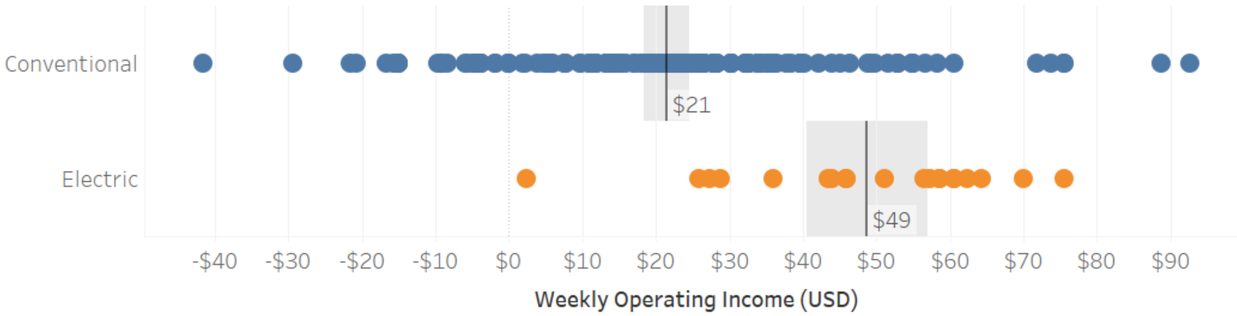


There are other probable factors behind Zembo drivers improved earnings that could not be sufficiently quantified during this study. First and foremost, electric motorcycle reduced maintenance needs should result in reduced downtime for electric *boda boda* drivers, increasing working hours, which is supported by informal driver interviews. Second, the "newness" or symbolism of modernity that electric motorcycles represent can result in increased passenger interest and thus more revenue. Finally, Zembo itself suspended drivers lease payments during the COVID-19 lockdown from mid-March to late July and supported drivers with food aid, which helped.

<u>Expenses</u>

To understand the operating income of conventional and Zembo drivers, we first subtracted the variable expenses – fuel/battery and airtime costs – from the weekly revenues. The average weekly operating income of Zembo drivers was $49 (± $8) USD and that of conventional drivers was $21 (± $4) at 95% confidence intervals (*Figure 12*).

Figure 12 – Drivers' Weekly Operating Income by Motorcycle Type, USD



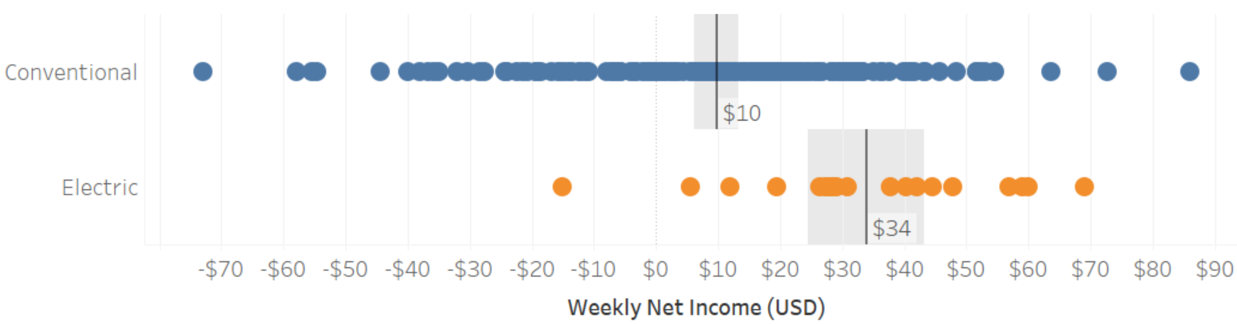
The average difference in weekly operating income between conventional and Zembo drivers was $28 USD, wider from the $21 USD difference in weekly revenues. All of the added $7 USD difference is derived from cost savings on battery swapping versus petrol fueling (*Table 4*).

Table 4 – Weekly Recurring Expenses by Motorcycle Type, USD

	Motorcycle Type	
	Conventional	Electric
Fuel/Battery	21.75	14.65
Airtime	4.20	4.25
Motorcycle Payment	17.34	16.37
Engine Oil	2.42	
Maintenance (Excl. Engine Oil)	1.61	0.35
Insurance	0.26	0.32
Police Fee (Bribe)	1.80	2.69

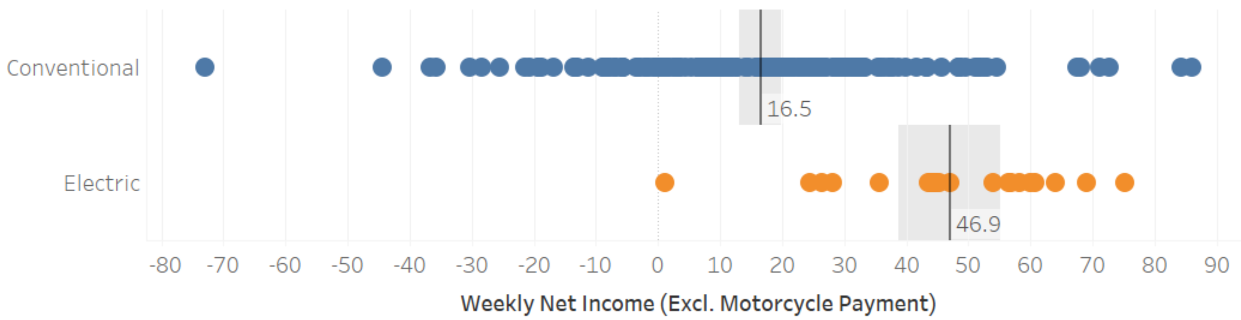
Accounting for other fixed expenses such as maintenance costs and payments on motorcycles, the average weekly net income of Zembo drivers was $34 (± $9) USD and that of conventional drivers was $10 (± $3) at 95% confidence intervals (*Figure 13*). The average difference in weekly net income between conventional and Zembo drivers was $24 USD, narrower from the $28 USD difference in weekly operating income.

Figure 13 – Drivers' Weekly Net Income by Motorcycle Type, USD



The closing in the gap between the weekly operating and net income of conventional and Zembo drivers can be attributed to the lower proportion of conventional drivers who are making regular payments toward their motorcycles. While Zembo drivers on average pay slightly less than conventional drivers on motorcycle payments (*Table 4*), only 39% of conventional drivers surveyed were making regular payments toward their motorcycles compared to 100% of Zembo drivers who were on such payment schemes. Excluding the motorcycle payments from the equation results in more than $30 USD difference in weekly net income between conventional and Zembo drivers (*Figure 14*), reflective of the added savings on maintenance and engine oil costs (*Table 4*). We expect that the relative impact of recurring motorcycle payments on net income of Zembo drivers will be offset in the future as more drivers start to fully pay off their lease on the motorcycles.

Figure 14 – Drivers' Weekly Net Income (Excl. Motorcycle Payment) by Motorcycle Type, USD

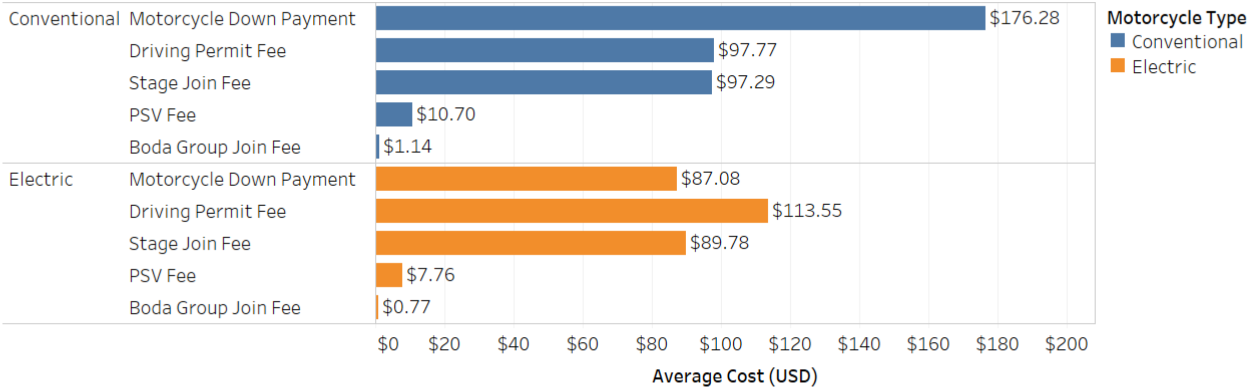


It is worth noting that a significant portion of conventional drivers appear to be operating at a net loss when taking fixed recurring costs into consideration at the time of this survey. This is likely due to the impact of COVID-19 on the revenue stream of *boda boda* drivers. While most of the drivers are still earning positive operating income to cover for variable costs such as fuel and airtime, they inevitably accrue expenses such as motorcycle payments, maintenance and engine oil costs that typically are incurred independent of the distances covered by the drivers in operation. However, we expect this effect to be temporary in nature as most drivers will turn back to positive net income assuming the average weekly revenue to return to the pre-COVID figures around $72 USD.[16]

Additionally, we analyzed the non-recurring expenses that *boda boda* drivers pay. The most significant difference between conventional and Zembo drivers on non-recurring fixed expenses was the down payment on their motorcycles. On average, conventional drivers paid twice as much as what Zembo drivers paid upfront to obtain their motorcycles. The difference is likely due to the financing structure of the motorcycles as the average total cost of Zembo motorcycles is estimated to be $1,715 USD while comparable new conventional motorcycles are priced at around $1,525 USD. Critically, nearly half of all conventional motorcycles are bought used, which further brings the average total cost for conventional motorcycles down drastically to $1,050 USD.

Meanwhile, Zembo drivers appear to be paying more to obtain their driving permit than the conventional drivers. This is likely because most of the Zembo drivers operate within the city of Kampala whereas a high proportion of conventional drivers surveyed operate in municipalities outside the city center (*Figure 15*).

Figure 15 – Fixed Expenses by Motorcycle Type, USD



3.3.4. Maintenance Cost Breakdown

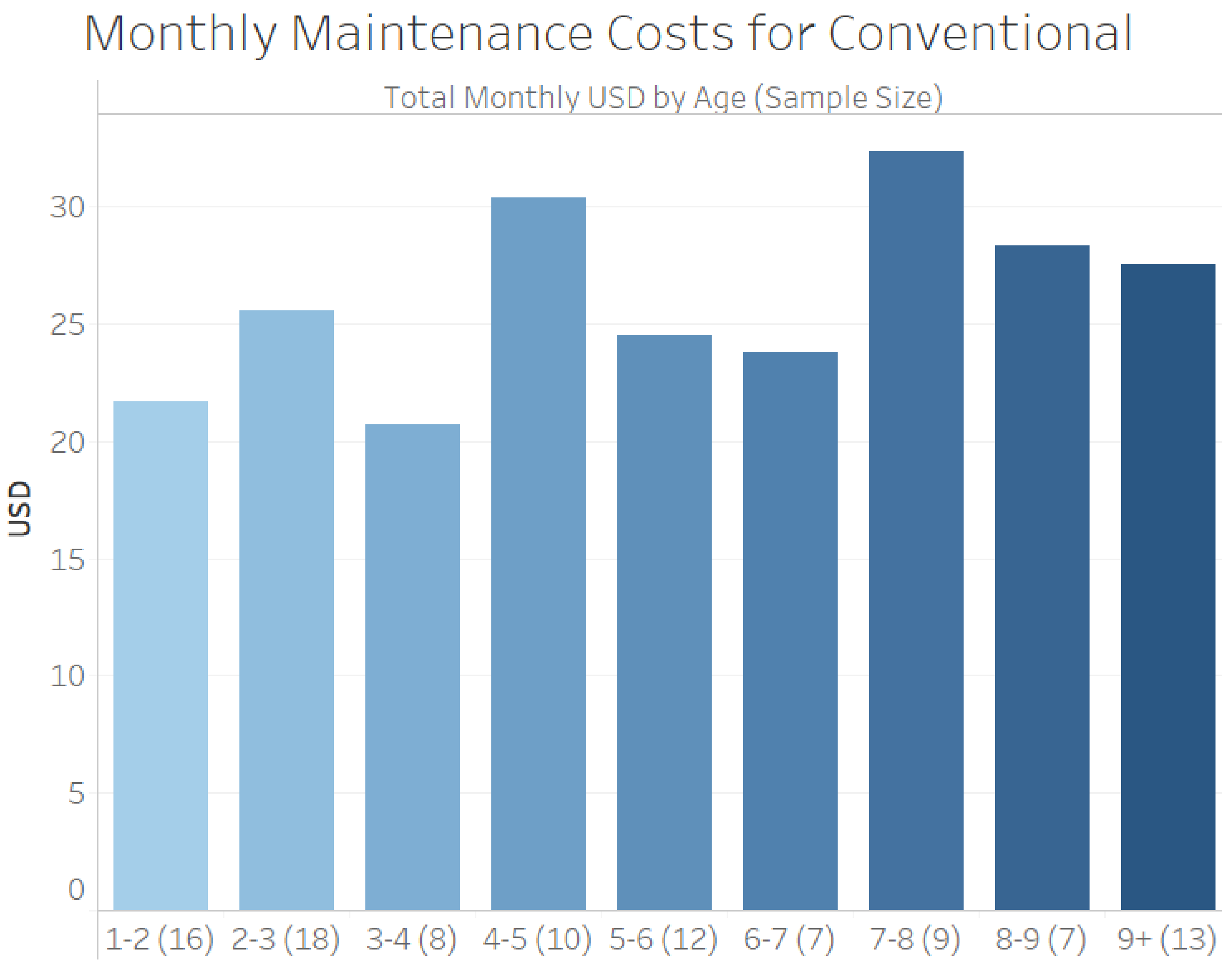
While maintenance costs account for a significant portion of cost savings realized for Zembo drivers, we anticipate that the cost estimate can be highly variable depending on the age of the motorcycle and the drivers' driving and maintenance behaviors. To supplement the data collected from the general survey on maintenance expenses of conventional and Zembo *boda boda* drivers, we conducted a separate survey focusing on the maintenance cost and frequency of various motorcycle parts.

Motorcycles that are estimated to be older than nine years were excluded from the analysis as it was not possible to verify their exact age. Similarly, motorcycles under the age of one year old were also excluded due to small sample size likely caused by the COVID-19 related slowdown in the *boda boda* industry.

<u>Conventional Motorcycle Maintenance Habits</u>

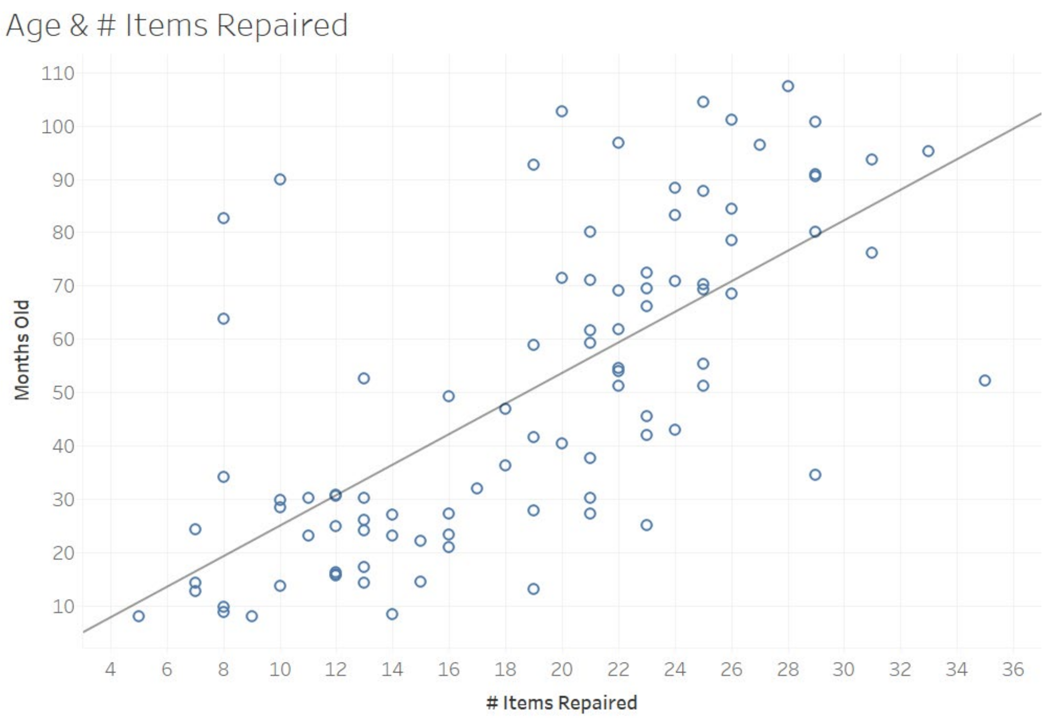
Based on the survey results, we estimated the average maintenance costs of conventional motorcycles by the motorcycle age. There was only slight rise in maintenance cost recorded as the age of motorcycles increase (*Figure 16*).

Figure 16 – Conventional Motorcycle Monthly Maintenance Cost by Motorcycle Age, USD



On the other hand, a strong correlation was identified between the age of the motorcycle and the number of parts repaired per motorcycle (*Figure 17*). The results may indicate a decrease in cost per item or a shift in maintenance behavior from replacing parts to merely mending as the motorcycles age. The difference in driving behavior may also manifest in maintenance costs assuming drivers are segmented between those who spend more on maintenance and sell off their motorcycles at a younger age and those who spend minimally per repair and keep their motorcycles going for longer.

Figure 17 – Conventional Motorcycle Parts Repaired by Motorcycle Age



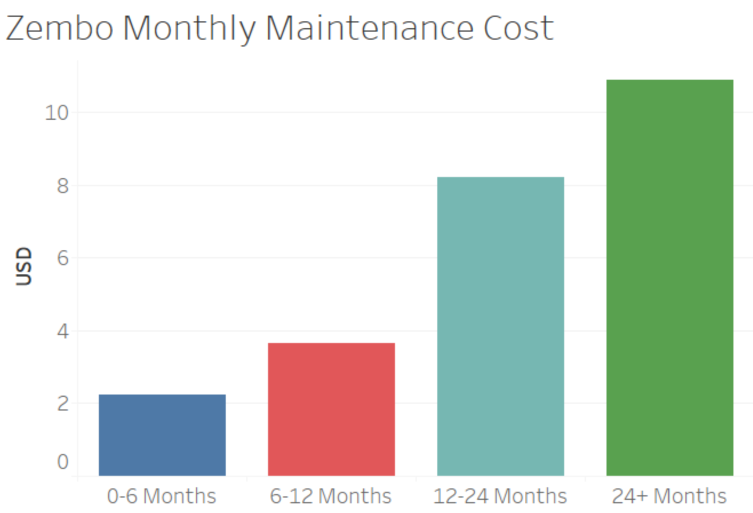
<u>Zembo Motorcycle Maintenance Habits</u>

Estimating maintenance costs for Zembo motorcycles were complicated by several factors. At the point of this study, the majority of Zembo motorcycles were under the age of 8 months. Only few items had recorded history of maintenance and the costs of maintenance were unknown as they were covered under warranty provided by Zembo. We also identified inconsistencies in warranty policy provided by Zembo that further complicated the reported cost of maintenance.

The general survey results estimated 90% reduction in maintenance cost of Zembo motorcycles compared to that of conventional motorcycles. To better understand the impact of Zembo's warranty policy on the maintenance cost over time, we obtained warranty and price data from Zembo.

Incorporating price lists and warranty conditions for spare parts, we estimated that the monthly maintenance cost for Zembo motorcycles would rise to about $11 USD at two-year mark when the warranties expire (*Figure 18*). The estimated reduction in maintenance cost was still significant at 45% level compared to that of conventional motorcycles. Semi-formal post-survey interviews with Zembo drivers found general satisfaction with the low maintenance needs of their vehicles.

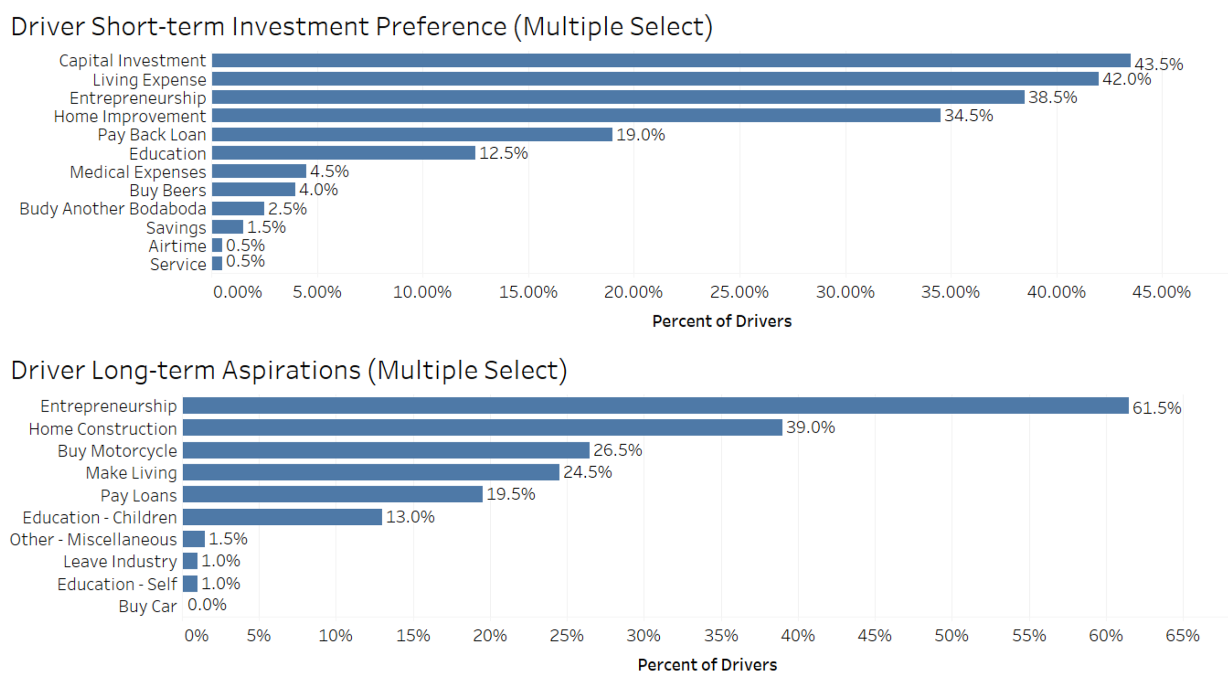
Figure 18 – Zembo Motorcycle Monthly Maintenance Cost by Motorcycle Age, USD



3.3.5. Long-term and Value Chain Impact

To understand the potential benefit of higher income for *boda boda* drivers, we asked the drivers about their plans for short-term investment of higher earnings and long-term aspirations. In both short- and long-term, drivers expressed a preference for investment in *boda bodas* or other types of businesses as well as improvements in their residential housing (*Figure 19*).

Figure 19 – Short- and Long-term Driver Aspirations (Multiple Select), percent



At current stage, it is impossible to accurately estimate quantitatively the long-term social impacts of electric *boda bodas* due to the young age, and limited market penetration of electric motorcycles. Yet, given the increased take-home income of Zembo drivers and their long-term aspirations in entrepreneurship and home improvement, we can reasonably infer opportunities for long-term economic development of Ugandan society enabled by electric motorcycle operations.

The positive environmental impact of electric motorcycles, especially in displacing local air pollutants such as PM2.5 can potentially lead to improved public health outcomes when electric *boda boda* operations achieve a significant scale.

Electric *boda bodas* can also have long-term implications for both upstream and downstream value chains. Most noticeably, extraction of raw materials required to manufacture lithium-ion batteries including lithium, cobalt, graphite, and manganese are frequently associated with corruption and human rights violations.[17] For lithium-ion phosphate (LFP) battery that Zembo uses for its motorcycles, lithium is the most critical mineral susceptible for potential human rights implications as many countries in Africa including Zimbabwe, Namibia, and South Africa are producing the mineral at an increasing scale.[18]

On downstream value chain, a significant number of industries are associated with *boda boda* work including fuel stations, mechanics, and small restaurateurs. While we expect that electrification of *boda bodas* will have minimal impact on the employment of fuel station attendants and restaurateurs, the informal maintenance industry is expected to undergo significant changes.

Electric motorcycles typically require less maintenance than conventional motorcycles as they have less components that require regular maintenance. Heyen-Perschon estimated that there exists about one to two mechanics per 40-60 *boda bodas*.[19] Estimating for the number of *boda bodas* in Kampala, the industry supports about 5,000 informal mechanics. It is likely that the demand for mechanic work would be significantly reduced for a similarly sized fleet of electric motorcycles.

4. Environmental Impact

4.1. Introduction

The impact of fossil fuel-burning vehicles on global climate change is well known, and transportation now makes up nearly a quarter of global greenhouse gases. Additionally, gasoline engines contribute significantly to local air pollution, which causes an estimated 155 age-standardized deaths per 100,000 in Kampala in 2018.[20]

This study focuses on transportation solutions as advances in technology have made electric transportation options more comparable to widely adopted ICE options in terms of cost and performance. This increase in parity potentially offers a way to displace current transportation behaviors and disrupt the pattern of growing emissions. Encouraging studies have already shown that when paired with low-carbon electricity generation, electrified transportation can reduce CO2eq, PM 2.5, and NOx in some Sub-Saharan Africa settings.[21] This study seeks to expand upon this research by examining Zembo's electric *boda boda* use case in Kampala, Uganda.

With an estimated 150,000 *boda bodas* in Kampala, conversion of even small percentages of the overall population could drive meaningful change. Based on our literature review, we predict that the use phase emissions of conventional *boda bodas* will surpass the levels of the electric *boda bodas*, so much so that they would justify the creation of the electric *boda bodas* lithium-ion batteries. We further predict that given the current grid composition, over time the displaced emissions from electric *boda bodas* would reduce without further investment in on-site solar PV.

4.2. <u>Methods</u>

To test our hypotheses, our team aggregated data inputs and assembled a computational model that could be leveraged to compare emissions from a Zembo electric *boda boda* to a modeled conventional *boda boda*. In this section we detail the inputs and describe the models. We first built a simple model using average generator emissions from 2018 UEGCL statistics, before creating an advanced model that took into account time-of-day and seasonal generation variation. For higher accuracy, we used the advanced model to draw our conclusions. We found similar conclusions across the two models.

4.2.1. The Simple Model - Inputs

The Simple Model compares electric and conventional motorcycles assuming both are moving 149.7 km / day, a statistic taken from Zembo's pre-COVID-19 Swapies data. The Simple Model uses an annual average of generation, smoothing over seasonal and hourly variations in generation on the Ugandan grid (*Table 5*). Critically, the Simple Model focuses exclusively on use phase, and thus hydropower generation and solar are treated as entirely non-polluting (*Table 6*).

Table 5 – Electricity Generation Statistics by Generator Type

Statistics by Source (2018 only)			
	Generation	Capacity	Capacity
	% of annual	MW	% of total
Bagasse	5.1%	77.5	9%
Large Hydro	78.5%	630	72%
Small Hydro	10.7%	102.5	12%
Solar	0.8%	20	2%
Thermal	4.9%	50	6%

Table 6 – Emissions Factor by Generator Type

Emissions Factor by Generator Type					
	CO2 Factor	NOx Factor	CO Factor	Sox Factor	PM2.5
	kg/MWh	kg/MWh	kg/MWh	kg/MWh	kg/MWh
Bagasse	443.00*	0.34*	7.87*	0.64*	0.00006**
Thermal	788.00***	1.89***	0.17***	8.64***	0.41***

* (Shah et al, 2016)
** (Meza-Pelacios et al, 2019)
*** (Farquharson, 2019, from EEA, 2016)

<u>Electric Motorcycles</u>

The Simple Model used 2018 statistics of electricity consumption by Umeme, the national electricity company, disaggregated by generator. Generation by quarter and by peak/off-peak/shoulder was aggregated for an annual generation number, while new generation that came on that year was weighted for the number of quarters that generator participated in. For

Emissions factors for the four types of generation – hydroelectric, solar PV, heavy fuel oil, and bagasse – were then calculated using existing literature to find emissions for CO2, NOx, SOx, CO, PM10, PM2.5 and HC.[22] Not all pollutant emissions statistics were available for all forms of generation. For hydroelectric generation, all save one plant are run-of-the-river, and the single dammed hydroelectric plant is at the mouth of Lake Victoria, so we did not include emissions from anaerobic decomposition that happens at typical hydroelectric dams.

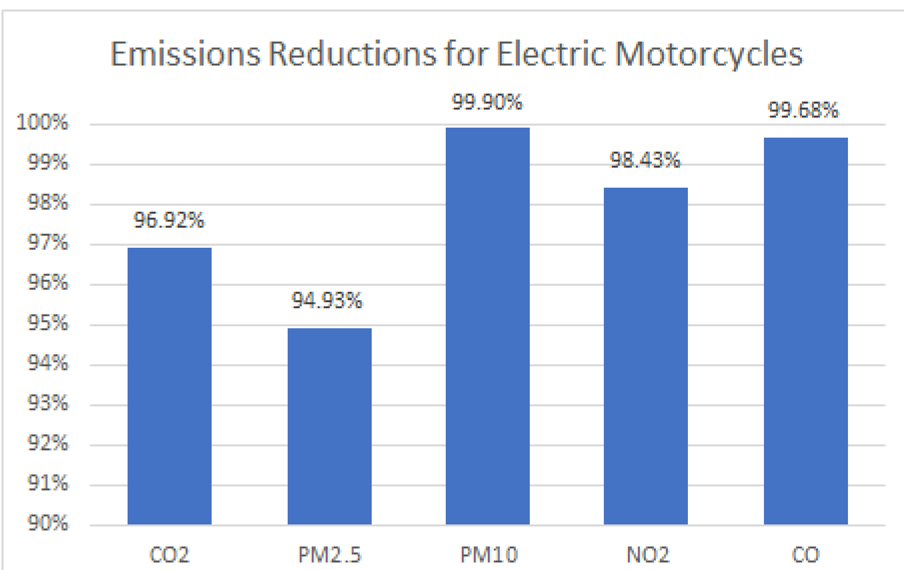
Conventional Motorcycles

For understanding emissions from conventional fossil fuel motorcycles, we used data from Tsai et al's 2017 study of comparable four-stroke motorcycles for PM10, NO2 and CO. We used Cueller et al's 2016 study to find PM2.5 data, and multiple sources pointed us towards CO2 emissions data. We did not have data for SOx and HC, and these were stricken from our estimates.

4.2.2. Simple Model - Results

We found drastic reductions in use phase emissions, largely due to the dominance of hydroelectricity on the Ugandan grid – 89.2% of generation in 2018 was from hydroelectricity, and more hydroelectric plants have been added since. CO2 emissions are 97% lower, and all other local air pollutants reduce by at least 90% except for sulfur oxides, which rise from minimal to 760 g / year / motorcycle (*Figure 20*).

Figure 20 - Reductions in Emissions from Simple model, on a 90-100% scale

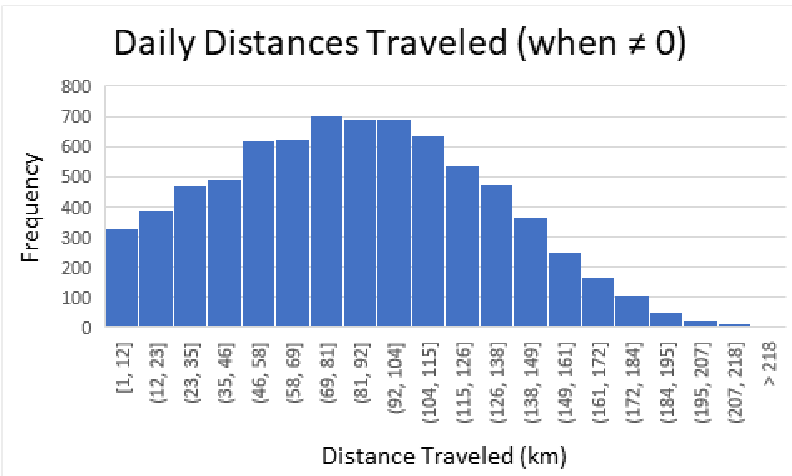


4.2.3. Advanced Model - Inputs

Driving Data

Location data collected on 81 Zembo Storm electric *boda bodas* laid the foundation for this analysis. Each Zembo-operated *boda boda* was equipped with a GPS transponder, which transmitted the *boda boda*'s latitude, longitude, and speed approximately every 10 seconds while the bike was active during the period of July 11, 2020 through December 31, 2020. In total, the dataset accounts for 649,034 km traveled. Drivers averaged 70 km per day with a standard deviation of 51.49 km (*Figure 21*).

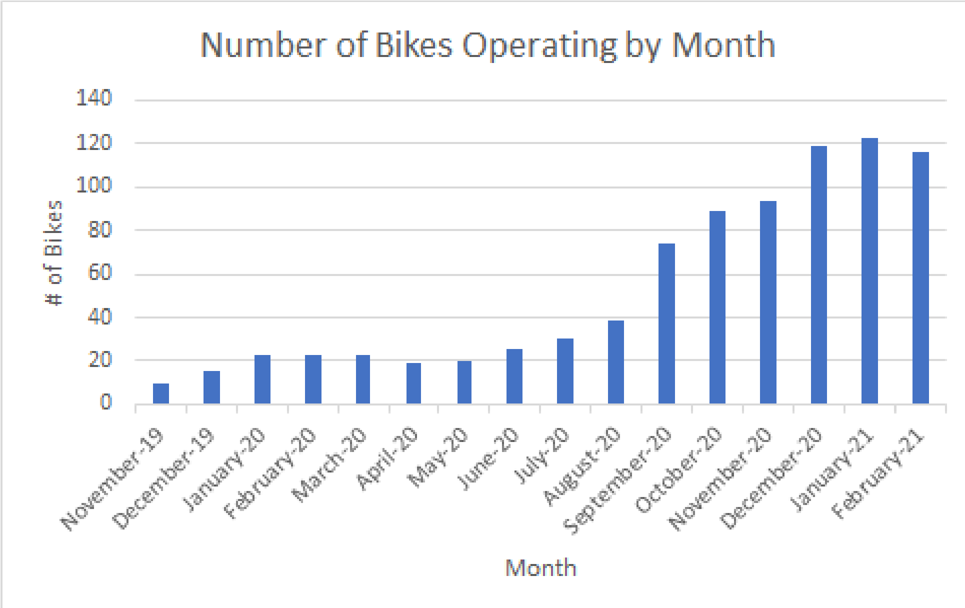
Figure 21 – Distribution of Daily Distances Traveled, count



During the analysis window, several notable events occurred. Foremost, starting on March 25, 2020, Kampala began observing strict driving curfews due to the emerging COVID-19 pandemic, banning all public means of transportation. *Boda bodas* were allowed to conduct deliveries between 6 AM and 2 PM daily, but these trips comprised only approximately 10% of drivers' typical trip load.[23] A month later, the *boda boda* ban was extended to 5 PM, yet passenger travel remained banned until July 27.[24] Even with the passenger ban lifted, a curfew for *boda bodas* remains as of April 2021.

Additionally, Zembo scaled their operations considerably over the course of the analysis window. In January, 23 bikes Zembo were in operation, but this number grew to 119 bikes by December 31 (*Figure 22*). Despite these complicating factors, the breadth of data both in number of drivers and duration gives us confidence our sample is reasonably representative of typical driving behavior and useful for forward looking projections.

Figure 22 – Zembo Motorcycles in Operation by Month, count



It was also determined that it was necessary to cluster the collected GPS data points into discrete trips. Initially, the researchers considered using the pre-clustered trips provided by the GPS transponder provider, however, it was quickly evident that the values purported were outside rational bounds. It was not uncommon to find total distance values purported in excess of 250km between swaps which, not only exceeded observed limits of the technology, but also did not align with driver interviews.

Additionally, clustering GPS data points into trips was necessary for the conventional *boda boda* modeling efforts. In the case of the conventional *boda boda*, engine operating conditions and idle time were critically important to consider and could only be calculated provided with clearly defined trips.[25]

This was accomplished by isolating groups of valid GPS data points with speeds above 0 km/h and were offset by periods when the vehicle remained stationary for 60 seconds or greater. 60 seconds of stationary positioning was determined to be the optimal criterion for delineating trips through a sensitivity analysis, which sought to best match a manually recorded set of trips that occurred on January 12, 2021.

Once segmented into discrete trips, distance traveled between the GPS points within the trip, denoted as D_n, were determined by summing the distance between reported coordinates in a trip (D_n) using the haversine formula (see the below equation) where D_n represents the distance between any two consecutive points within a trip.

$$D_n = cos^{-1}\left(\sin\left(\frac{lat_1 * \pi}{180}\right)\sin\left(\frac{lat_2 * \pi}{180}\right) + \cos\left(\frac{lat_1 * \pi}{180}\right)\cos\left(\frac{lat_2 * \pi}{180}\right)\cos\left(\frac{long_2 * \pi}{180 - \left(\frac{long_1 * \pi}{180}\right)}\right)\right) * 6378.1$$

To account for the non-linear nature of driving in a city, this formula was exercised between all consecutively reported coordinates in the trip and then summed to a total trip distance (see the below equation).

$$Distance_{Trip} = \sum_{i=0}^{n} D_i$$

Electricity Generation

Generation data for the electricity used by Zembo in the charging of their electric *boda bodas* is composed of two sources: grid and on-site solar. Grid generation data was sourced from the Uganda Electricity Regulatory Authority, “Electricity Supply Industry Performance Report for the Year 2018.”

In 2018, Uganda had 930 MW of nameplate generation capacity, which was predominantly (82.4%) composed of small and large hydroelectric plants, followed by Bagasse (9.2%), and subsequently Thermal (6.0%) and Grid Scale Solar (2.4%). Average generator utilization equaled 47% in XX, with most (89%) of electricity generation coming from small- and large-scale hydroelectric plants. *Table 7* outlines these details more fully.

Local firms suffered around 6.3 outages per month according to the World Bank.[26] This is attributable to the local distribution grid, which is based on outdated infrastructure and is subject to high compensation costs for acquiring land for infrastructure. Additionally, having excess supply on the grid drives up the cost of electricity, as the power generating assets were paid for with loans that must be paid back.[27]

Table 7 – Uganda Electricity Generation by Plant

Statistics by Source (2018 only)					
	Generation	Generation	Capacity	Capacity	Annual Capacity Factor
	MWh	% of annual	MW	% of total	%
Bagasse	206,457.03	5.1%	77.5	9%	30%
Large Hydro	3,180,164.24	78.5%	630	72%	58%
Small Hydro	435,673.53	10.7%	102.5	12%	49%
Solar	31,987.59	0.8%	20	2%	18%
Thermal	198,806.80	4.9%	50	6%	45%

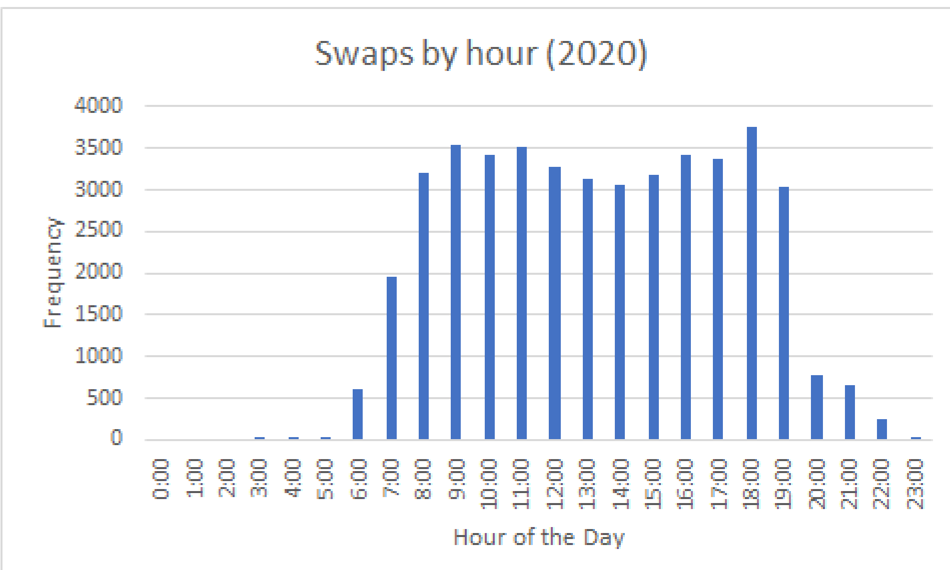
The data retrieved from the Uganda Electricity Regulatory Authority is limited in temporal granularity to quarterly intervals that are subdivided into “Peak”, “Off-Peak”, and “Shoulder”. As such, understanding the true effect of charging at different hours was not possible. To overcome this hurdle, we collected the usable capacity of each generator accounting for T&D limits, and fuel source, using and observed generation sales prices as primary guides for the hourly generation model that was later assembled.

Additionally, we modeled Zembo’s four roof-top solar installations it utilizes to supplement their charging network. This was completed by using the system parameters of each site and a resource profile obtained from the National Renewable Energy Laboratory (NREL) 2019 solar resource dataset as inputs to NREL’s PVWatts® calculator.

Demand Data (including Charging Data)

Two sources of electricity demand data were used in the final models. The first dataset was provided by Zembo, and detailed key attributes relating to the battery swapping operation. In particular, the dataset included a log of the arrival times and states of charge of all batteries swapped during the year 2020 (*Figure 23*). These attributes, when paired with the parameters of the charging equipment utilized by Zembo, enabled the creation of a comprehensive charging schedule, which approximated when charging took place and the total energy delivered to each battery.

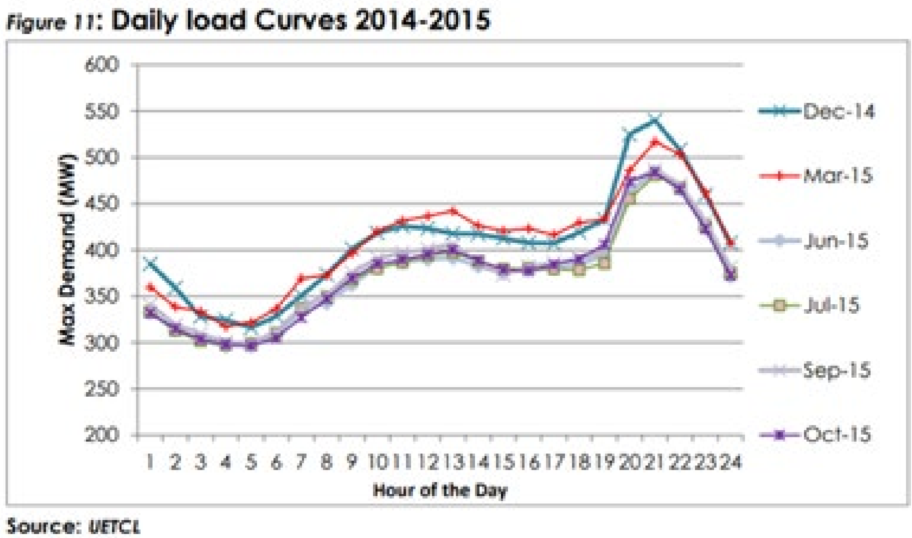
Figure 23 – Battery Swap Frequency by Hours of the Day, count



Additionally, to model the impact of increasing amounts of bikes on the road, an hourly demand dataset was retrieved from the Uganda Electricity Regulatory Authority’s “The Least Cost Generation Plan” which detailed energy sales for the year of 2015 (*Figure 24*).[28] This demand schedule was then scaled to account for increases in demand observed for Uganda in the U.S. Energy Information Administration’s “Annual Electricity Consumption” report. The authors could find no clear reporting on transportation and distribution losses for Uganda; however, all demand data was increased by 15% to conservatively account for T&D losses. This is based on all neighboring countries stated efficiencies, which range between 5.7% (South Sudan) to the

21.43% (Democratic Republic of Congo).[29]

Figure 24- Daily Electricity Load Curves by Hour of the Day, MW



Motorcycle Characteristics

Environmental performance of the Zembo Storm motorcycle was compared to the modeled performance of the Bajaj Boxer 100cc. Based on our collected sample, the Bajaj Boxer represents more than 90% of the motorcycles used as *boda bodas* operated in Uganda. From interviews, the Bajaj Boxer is dominant because of its power, affordability, and the wide availability of spare parts.[30] As evidenced by *Table 8*, the two models of motorcycles are highly comparable. Both vehicles weigh approximately the same (13 kg difference), are capable of achieving highway speeds, and run identical tire specifications. The Bajaj Boxer 100cc is specified for higher power, a high max speed, and greater range, yet given the application as *boda boda* within the city of Uganda, elevated performance in these categories is unlikely to materially alter the comparison.

Table 8 – Zembo and Bajaj Motorcycle Technical Specifications

Motorcycle Technical Specifications		
	Zembo	Bajaj
	Storm	Boxer 100cc
Motor Power	3000 W	6030 W
Max Speed	65 km/h	95 km/h
Range	60 km	511.5 km
Weight	96 kg	109 kg
Battery / Fuel Tank Size	72V 30Ah LFP	9.3 L
Tire	2.75-17/3.0-17	2.75-17/3.0-17

4.2.4. Conventional Boda Boda Emissions Model

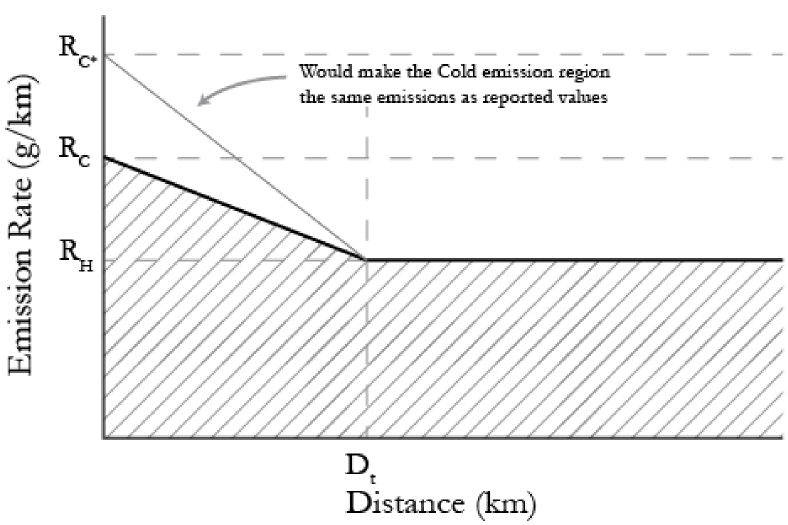
To determine the environmental performance of the Bajaj Boxer 100cc conventional *boda boda* (CBB), driving data from the Zembo fleet was used to model driving behavior of an analogous CBB fleet. We then quantified the associated emissions of this fleet by accounting for three critical attributes of conventional use phase emissions: engine operating conditions, idling time, and distance traveled. Equation X details this function below.

$$Emissions_{CBB} = f(engine\ operating\ conditions, time\ spent\ idling, distance\ traveled)$$

<u>Moving Emissions</u>

With the coordinates grouped into trips, the time between trips was calculated and paired with the distance traveled to calculate the emissions for the period of time when the *boda boda* was moving. It was assumed based on findings in Yao et al 2012, that if the time between any two trips was greater than two hours the engine could be asserted to be a cold start, whereas anything less than two hours was determined to be a hot start. If the vehicle was started "cold", a linear function progressed the emissions rate of the *boda boda*, denoted as R_{moving} (given in [g/km]), towards normal operating emissions (*Figure 25*).[31]

Figure 25 – Motorcycle Emission Rate by Distance, g/km



The second element, Distance traveled was sourced from the trip distance. The differential distance traveled denoted as Distance was then integrated with the R_{moving} to produce the total trip emissions associated with the period when the *boda boda* was moving.

$$Emissions_{moving} = \int_{0}^{Distance_{Trip}} R_{moving}\, dDistance$$

Idling Emissions

An additional product of grouping GPS data points into trips, was the ability to sum any remaining stationary intervals less than 60 seconds within the trips bounds to find the approximate total idle time observed during the trip. The time spent idling was then multiplied by emission rates (R_{idling}, given in [g/sec]) for the seven types of emissions we quantify, which were obtained from a previous study.[32] In Tsai et al 2017, emission factors were collected for a comparable motorcycle with a 100cc carbureted engine. The following equation shows this.

$$Emissions_{Idling} = R_{idling} * Idle\ Time$$

Ultimately the sum of the incremental start-up emissions, idle emissions, and emissions associated with distance were then summed to produce a discrete trip total of the 7 category emissions (described in the equation below).

$$Emissions_{CBB} = Emissions_{moving} + Emissions_{Idling}$$

Forward Looking Projections

To validate whether or not any achieved environmental advantage of the electric *boda boda* could scale, it was critical to incorporate a future state modeling element. This was conducted through a Monte Carlo simulation. The simulation operated by sampling random a day from the observed population 365 times to construct a modeled year for one *boda boda*. Moreover, this process could be repeated for varying numbers of additional bikes. The Monte Carlo simulation ultimately was run for 250 *boda bodas* (approximately double current operations), 1,000 *boda bodas* (mid-case), and 10,000 (aspirational case).

4.2.5. Electric Boda Boda Emissions Model

Given the lack of tailpipe emissions, estimates of the emissions created by electric *boda bodas* (EBB) were determined for the Zembo fleet by accounting for two critical contributors to use phase emissions: the quantity of electricity consumed by the vehicles and when the battery charging was conducted.

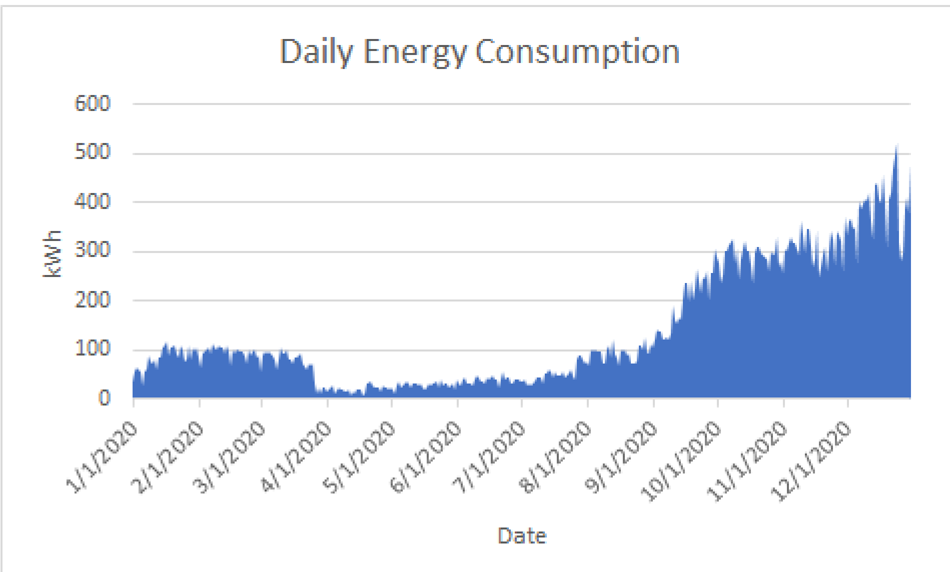
$$Emissions_{EBB} = f(Quantity\ of\ Energy\ Consumed, Time\ of\ Charging)$$

Quantity of Energy Consumed

The quantity of energy consumed by a given EBB was determined by examining consecutive swaps. By taking the difference between the outgoing battery's state of charge and the incoming battery's state of charge (both given as a percentage of the battery's capacity) and then multiplying by the battery's capacity the total energy consumed over the swap interval is calculated. To account for charging inefficiencies this value was divided by a charging efficiency value assumed to be 0.9 (see the equation below) a total energy for the interval was constructed. All batteries were assumed to conform to the stated capacity of 2.16 kWh. *Figure 26* shows the distribution of energy demanded on a daily basis from January 1, 2020 to December 31, 2020.

$$Energy\ Consumed = \frac{(Battery\ State\ of\ Charge_{outgoing} - Battery\ State\ of\ Charge_{incoming}) * Battery\ Capacity}{Charging\ Efficiency} - Onsite\ Solar\ Consumed$$

Figure 26 – Distribution of Daily Energy Demand, kWh



<u>Time of charging</u>

Time of charging was assumed to start immediately after the swap and end once the battery recovered to a full charge. The charge rate, which was determined based on the system parameters of each charging cabinet (220V-5A or 1100w). For Zembo's standard 2.16 kWh battery this equates to approximately 1 hour and 58 minutes for full charge recovery.

<u>Allocation of Charging</u>

Given the varying battery swap times and varying states of charge the amount of energy consumed allocated to each hour was constructed through a multi-step approach.
First, the total time to charge was calculated by dividing the energy consumed (defined above) by the charge rate. Next, the allocation factor for the first hour was calculated by taking the time remaining in the hour of delivery (T_0) and dividing by the total calculated charge time (T_{total}). This factor multiplied against the total energy consumed represented the allocated energy for the first hour.

To determine possible allocations for subsequent hours, a similar process was followed, however, instead of calculating the allocation factor based on the time remaining in the hour, an "if" statement was leveraged.

If the remaining charge time was less than 60 minutes (T_{total} - T_n< 60), then the difference of T_{total} and T_n would be divided by (T_{total}) to determine that hour's allocation factor. If the remaining charge time exceeded 60 minutes (T_{total} - T_n >60), 60 minutes would be divided by the total time for the allocation of that hour and would be repeated until (T_{total} - T_n < 60).

On-site PV Energy Consumed

We assumed that 100% of the modeled generation that occurred during a period of known battery charging displaced what would be corresponding demand from the grid. This was based on two key facts. First the average energy demand was significantly larger to the relative to the average generation potential of Zembo's on-site solar assets. Second, Zembo's direct ties the solar PV installations to the battery charging infrastructure, making it clear that the energy will not suffer from significant transmission and distribution or other material losses en route to charging. As such, we subtracted the hourly generation from PV sites from the hourly demand schedule devised in sections prior. For 2020, this amounted to 12.16 MWh across the 3 sites.

Dispatch Model

To calculate the emissions attributable to charging batteries, a dispatch model was created that could be run at varying levels of energy demand. In this way each incremental demand case would be subtracted from the base case to show the relative impacts.

The base case was constructed with aforementioned grid generation parameters, scaled hourly grid demand data, and sales price data. Using python program, the program sought to fulfill all energy demands for any given hour at the lowest cost. Once a given generator's practical capacity was fully allocated the next most expensive generator would be selected until all demanded energy was delivered.

Once the optimal schedule was achieved, the corresponding energy generated by each generator over the course of one year was multiplied by the associated emission factors for the respective fuel type collected from Tsai et al 2014.

Forward Looking Projections

As in the case of the conventional *boda bodas*, a simulation ultimately was run for 250 *boda bodas* (approximately double current operations), 1,000 *boda bodas* (mid-case), and 10,000 (aspirational case).

In the projected cases, values of demand were generated through a similar sampling procedure to that of the conventional models. Each modeled EBB would consist of a sample of trips for each of the 365 days of the year. Based on the number of trips sampled for a given day, the simulation would then sample among that population of days with a corresponding number of trips to generate a daily demand. The daily demand would then be appended to the distribution model to determine total emissions. Finally incremental emissions would be calculated by subtracting the modeled emissions from the base case.

4.3. Results

4.3.1. Emissions Comparison

Base Case

The below *Table 9* details the emissions estimates on an annual basis for the seven pollutants examined (CO2, PM2.5, SO2, NOx, and HC) for the year 2020. The results indicate that across 6 of the 7 pollutants, the conventional *boda boda* emits higher levels than the Zembo Storm motorcycle. The base case scenario found a 97.52% reduction in CO2 emissions, 98%+ reductions in CO, PM2.5 and NOx, and an 80.5% reduction in SOx.

Table 9 – Yearly Emissions (2020)

Yearly Fleet Emissions (2020)				
	Conventional (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	38,725.32	960.57	37,764.75	-97.52%
CO	1,512.12	17.06	1,495.05	-98.87%
PM2.5	8.09	0.00	8.09	-100.00%
NOx	77.58	0.74	76.84	-99.05%
SOx	7.12	1.39	5.73	-80.51%

Doubling Case, Mid-Case, and Aspirational Case

Table 10 – Yearly Fleet Emissions Doubling Case (250 Bikes)

Yearly **Fleet** Emissions (250 *Boda bodas*)				
	Conventional (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	342,173.66	23,220.80	318,952.86	-93.21%
CO	13,361.46	412.52	12,948.93	-96.91%
PM2.5	71.48	0.00	71.48	-100.00%
NOx	685.36	17.82	667.54	-97.40%
SOx	62.92	33.55	29.38	-46.68%

Yearly **Bike** Emissions (250 *Boda bodas*)				
	Petrol (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	1,368.69	92.88	1,275.81	-93.2%
CO	53.45	1.65	51.80	-96.9%
PM2.5				-100.0%

	0.29	0.00	0.29	
NOx	2.74	0.07	2.67	-97.4%
SOx	0.25	0.13	0.12	-46.7%

Table 11 – Yearly Fleet Emissions – 1,000 Bikes (Mid-Case)

Yearly **Fleet** Emissions (1,000 *Boda bodas*)				
	Conventional (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	1,365,171.00	111,451.15	1,253,719.85	-91.84%
CO	53,308.39	1,979.96	51,328.44	-96.29%
PM2.5	285.21	0.02	285.19	-99.99%
NOx	2,733.42	85.54	2,647.88	-96.87%
SOx	251.05	161.01	90.04	-35.87%

Yearly **Bike** Emissions (1,000 *Boda bodas*)				
	Petrol (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	1,365.17	111.45	1,253.72	-91.8%
CO	53.31	1.98	51.33	-96.3%
PM2.5	0.29	0.00	0.29	-100.0%
NOx	2.73	0.09	2.65	-96.9%
SOx	0.25	0.16	0.09	-35.9%

Table 12 – Yearly Fleet Emissions - 10,000 Bikes (Aspirational-Case)

Yearly **Fleet** Emissions (10,000 *Boda bodas*)				
	Conventional (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	13,643,264.28	1,170,164.48	12,473,099.80	-91.42%
CO	532,749.87	20,788.25	511,961.62	-96.10%
PM2.5	97,884.29	0.17	97,884.12	-100.00%
NOx	27,322.11	898.09	26,424.01	-96.71%
SOx				-32.62%

	2,508.91	1,690.53	818.38	

Yearly **Bike** Emissions (10,000 *Boda bodas*)				
	Petrol (kg)	Electric (kg)	Displaced (kg)	% Change
CO2	1,364.33	117.02	1,247.31	-91.4%
CO	53.27	2.08	51.20	-96.1%
PM2.5	9.79	0.00	9.79	-100.0%
NOx	2.73	0.09	2.64	-96.7%
SOx	0.25	0.17	0.08	-32.6%

4.4. Comparing the Simple and Advanced Models

The Simple and Advanced Models Base Case have strongly similar findings. The differences arise from the Advanced Models usage of hourly generation, which finds less generation from heavy fuel oil (*Table 13*).

Table 13 – Motorcycle Emissions Model Comparison

Bike Emissions (2020)			
	Simple Model	Advanced Model Base Case	Advanced Model Aspirational Case
CO2	-96.92%	-97.52%	-91.42%
CO	-99.68%	-98.87%	-96.10%
PM2.5	-94.93%	-100.00%	-100%
NOx	-98.43%	-99.05%	-96.71%

4.5. Analysis / Discussion

Environmental Advantages of Electric Boda bodas

As evidenced by the results, it is clear that our hypothesis that the use phase emissions of conventional *boda bodas* will surpass the levels of the electric *boda bodas* is plausible for 6 of the 7 evaluated emissions. Given the operating conditions currently observed the results from this study indicate there to be a distinct use-phase advantage in terms of for the Zembo Storm when compared to a conventional motorcycle on the basis of CO2, CO, PM2.5, PM10, HC, and NOx. The results do indicate that one pollutant is likely to increase SOx with any displacement of conventional motorcycles with electric motorcycles. The increases in SOx are likely to be seen in proximity to the Bagasse generators.

Lithium-Iron Phosphate Batteries (LIPB)

In acknowledging one of the major critiques of the environmental sustainability of electric mobility,[33] we examined some of the life cycle impacts of that can be imputed to the 72V 30Ah LFP battery, which Zembo utilizes in their battery swapping program. LIPB batteries have been recognized as potentially having lower life-cycle impacts,[34] yet the manufacturing process and material inputs are not wholly devoid of impact. Wang et al 2017 delves into these impacts more specifically through a cradle-to-gate life-cycle analysis for a 1kWh LIBP battery.[35] We used the results from this study to compare to the modeled results above.

To account for the larger capacity of the Zembo batteries impacts were scaled linearly. Likewise, to account for the average operating inventory of 1.7 batteries per *boda boda*, emissions were scaled to reflect the observed operating conditions (*Table 14*).

Table 14 – LFP Battery Manufacturing Emissions

LFP Battery Manufacturing Emissions (adapted from Wang et al 2017)		
	per bike (kg)	**per battery (kg)**
CO2eq	118.24	69.55
SO2eq	0.88	0.52
PM10eq	0.38	0.22

We then mapped these values to emissions reductions observed in each of the modeled use case scenarios. Taking into account the purported average lifespan of the EBBs, the results indicate in the following table that the of emissions attributable the battery manufacturing do not negate the reduction of emissions generated in the use phase in any of the three cases (*Table 15*).

Table 15 – Motorcycle Emissions Displaced During Use Phase vs. Battery Manufacturing

Bike Emissions Displaced During Use Phase vs. Battery Manufacturing Emissions (200 Case)				
	Use Phase Displaced (kg)	Battery Manufacturing (kg)	Total Displaced (kg)	% Change
CO2	1,275.81	59.12	1,216.69	-95.68%
SOx	0.12	0.44	(0.32)	75.07%

Scaling solar

The solar installations are displacing a material amount of energy from the grid, but due to the highly clean energy grid, this likely does not offer a short-term solution for rapidly improving the environmental performance of the Zembo Motorcycle. Each MWh is currently only reducing the SOx emission by 125g (*Table 16*).

Table 16 – Emissions Displaced by Solar Installations

	2020 Displacement (kg)	Future Displacement (kg)
CO2	599.11	6144.95
CO	10.64	109.17
PM2.5	0.00	0.00
NOx	0.46	4.72
SOx	0.87	8.88

Impact of SOx

Given the projected increase in SOx emissions from operating Zembo electric boda bodas, it is important to recognize, what effects might be observed as a result. There are 3 primary effects of sulfur oxides on human health and ecosystems.[36] First, sulfur oxides are heavier than air, which can cause suffocation above certain atmospheric concentrations. [37] Second, sulfur oxides can comprise a significant proportion of the particulate matter and have been linked to increased asthma attacks, heart and lung disease and respiratory problems in susceptible population groups.[38] Finally, sulfur oxides can be converted to acids by aqueous phase reactions in the atmosphere. These acidic aerosols are eventually precipitated as acid rain, snow, sleet, or fog but only when they encounter the right meteorological conditions.[39]

Each of the three possible effects are linked to the point sources of the sulfur oxide emissions. In the case of Zembo motorcycles this would happen in proximity to the Ugandan electricity generators that emit sulfur oxides, and in proximity of the Chinese electricity generators that emit sulfur oxides in generating electricity for the construction of the electric battery. Since, modeling of the emission trajectories associated with each point source of sulfur oxide emissions was not within the scope of this project only observed values from literature are presented.

At concentrations of approximately 500 parts per billion (ppb) sulfur dioxide can cause suffocation that can be fatal. The normal atmospheric background concentration of SO2 is generally less than 10 ppb. At 20 ppb or lower there should be no ill effects to a healthy person.[40]

Uganda does not currently have published ambient air quality standards, as such reference values from United States Clean Air Act, which was last amended in 1990, is offered for context. The current primary limits, which provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly is 0.197 mg/m3 of SO2 over a 1-hour period. The current secondary limits, which provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings, is 1.310 mg/m3 of SO2 over a 3-hour period.[41]

5. Conclusion

5.1. Driver Annual Statistics

Social Impacts

- A pre-COVID study found a driver typically earns $10.26, of which he takes home $4.93

- We found that Zembo drivers pay 32% less for battery-swapping than conventional drivers pay for fuel, saving drivers ~$1 a day
- Controlling for drivers usage of ride-hailing applications, we found that Zembo drivers made around $3.15 more per day at the time of our study

Environmental Impacts
- Pre-COVID, drivers were moving on average 150 km around the city.
- Yearly, this represents 46,928 km
- For a fuel bike, our simple model estimated this would cause 3,305 kg of CO2, 0.65 kg of PM2.5, 53.5 kg of PM10, 11.6 kg of NO2 and 210 kg of CO.
- Switching to electric will reduce the emissions to 102 kg of CO2, 0.03 kg of PM2.5, 0.053 of PM10, 0.18 kg of NO2 and 0.68 kg of CO
- This represents an avoided emission of 3.2 t of CO2, 0.62 kg of PM2.5, 53.49 kg of PM10, 11.46 kg of NO2, and 209.68 kg of CO on average per driver per year

5.2. Understanding our Findings

Though it is still early days, electric motorcycles are clearly delivering significant benefits in improving driver income and social standing while reducing air pollution and greenhouse gases. While this study was affected by the COVID-19 lockdown and economic turmoil, Zembo motorcycles are clearly benefitting their drivers in improved social respect, reduced costs, improved revenues, and benefitting society at large with reduced local air pollutant and greenhouse gas emissions. However, potential negative impacts from the manufacturing value chain and on the local maintenance industry remain to be tackled.

5.3. Moving Forward

The *boda boda* industry is in a state of flux, as government crackdowns, the COVID-19 pandemic and ride-hailing all significantly impact drivers fortunes and passengers' experiences. Electric mobility is bringing its own disruptions, but there is reason to believe that it will be more successful in taking over the industry, especially within dense urban areas.

Drivers and industry insiders make clear that cost-saving is one of the most critical factors of adoption success in the *boda boda* industry - as long as Zembo or competitors continue to prove that point to drivers, we can expect numbers of electric motorcycles to continue to rise. With that rise, new opportunities and issues may rise to the surface in efforts to improve Zembo's environmental and social impact. Three clear opportunities are in improving battery swapping network density and range, creating a professional, geographically dispersed maintenance network, and finding responsible end-of-life uses for Zembo's electric batteries.

Opening new battery-swapping stations has huge potential to further improve efficiency and reduce environmental impacts, while simultaneously making better use of driving time and increasing take-home pay for drivers.[42] Zembo drivers' abilities to earn are currently limited by the battery-swapping network. We expect Zembo will continue to increase battery-swapping stations as more drivers are onboarded in Kampala and that they will accrue significant benefits in efficiency and driver satisfaction.

Questions remain about the potential impact of moving away from conventional motorcycles on the local maintenance industry. The informality and entrepreneurship of the Ugandan economy means that unless Zembo has a strong plan for retaining rights to maintenance, mechanics are likely to teach themselves to repair electric motorcycles. Zembo could work to retain control over the spare parts import market and open its own maintenance branches, it could train and / or verify mechanic shops for maintaining the motorcycles, or it could leave it to Kampala's vibrant informal economy. These would all have different impacts on the number and benefits of jobs available, as well as the reputation of Zembo motorcycles, but the second option likely best balances expansion of maintenance services while minimizing investment risk for Zembo.

Finally, Zembo currently plans to retire the LFP batteries at two years old, when they are likely to still have 80-90% depth-of-discharge capacity. There are currently no recycling facilities in Uganda for these batteries, but a potential solution could be using the batteries in Zembo's solar installations or selling them on to other solar PV construction companies. There is currently low penetration of lithium batteries in Uganda due to lack of market familiarity and high costs, both of which could be solved by Zembo's used but still highly functional batteries.

As a market leader in Uganda and the region, Zembo is laying the groundwork for the electric mobility transition. Following through on these recommendations can help not only Zembo but the wider industry improve its environmental and social impact on *boda boda* drivers' livelihoods, passenger experiences, and the health and wellbeing of Kampala residents.

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