A WEB OF FACTORS AND DEPENDENCIES TO CONSIDER IN THE ELECTRIFICATION OF SOUTH AFRICA'S MINIBUS TAXI INDUSTRY

A JAHURA[1]*, MJWA VANDERSCHUREN[1] and MJ BOOYSEN[2]**

[1]Centre for Transport Studies, Department of Civil Engineering, University of Cape Town,
Private Bag X3, Rondebosch 7701, South Africa;
*Tel: 078 260 3361; Email: jhrane001@myuct.ac.za
**Email: marianne.vanderschuren@uct.ac.za
[2]Department of Electrical and Electronic Engineering, Stellenbosch University,
Private Bag X1, 7602; Email: mjbooysen@sun.ac.za

ABSTRACT

South Africa's minibus taxis operate fundamentally differently to formalised and structured public transport. The informal, demand-driven industry has grown into the constraints of passenger demand, accessibility, and affordability of the lower-income group it tends to serve, and it has become the main mode of transport for millions of South Africans.

The slow adoption of electric vehicles into South Africa's automotive industry presents environmental and economic concerns. The transport industry emits high amounts of carbon, and the automotive industry is completely reliant on producing internal combustion engine vehicles which will eventually be phased out by the country's biggest international customers.

Efforts towards electrification must prioritise minibus taxis due to their importance to local paratransit. However, this is a complex endeavour. Electrification will inevitably introduce many challenges through a complex web of factors and dependencies, ranging from mobility and charging operations to environmental impacts and vehicle characteristics.

This paper identifies and analyses these factors and dependencies and describes some of the key considerations required to ensure a successful paratransit transition to electric mobility. The paper concludes that although the complexity of economic, environmental, and energy-based aspects is unpacked, there are additional factors such as road safety and other social considerations that are required for more holistic electric mobility planning. All these factors must be considered as parts of a larger ecosystem of electrification instead of as individual problems.

1. INTRODUCTION

1.1 Background

South Africa's minibus taxi industry is the main mode of transport for approximately 10.7 million South Africans (Statistics South Africa, 2020). Presently, there are approximately 250,000 to 300,000 minibus taxis in the country belonging to an estimated 20,000 owners and 1,200 taxi associations nationally (Booysen et al., 2022; Human & Morrison, 2023). As explained in Vegter's 2020 report, the industry gained prominence during the Apartheid era (in the 1980s) from the need of marginalised ethnic groups to travel from their homes to seek economic opportunities. These citizens' homes were predominantly located in townships and informal settlements far from central business districts and other popular locations of work, and the state-funded public transport systems did not adequately transport citizens to and from these communities (Vegter, 2020).

The organic growth of the industry was led mostly by 16-seater minibus taxis (Govender & Allopi, 2006). As described in Ingle's 2009 historical review of the industry, minibus taxi operations were based on the drivers' knowledge of popular routes and peak travel times, unlike the structured and timetabled public transport services in developed countries. Despite its relative informality, this modus operandi gave marginalised ethnic groups access to relatively affordable and accessible transport which also provided a form of economic empowerment for minibus taxi owners. However, it led to an industry that was loosely regulated, presenting issues such as poor working conditions for drivers due to minibus taxi owners flouting labour laws; difficulties for the government in enforcing vehicle and traffic laws due to a lack of strict regulation of the industry; and a lack of safety for passengers due to unroadworthy vehicles and dangerous driving patterns (Ingle, 2009). Furthermore, the industry has been incessantly plagued with strife, much of it in the form of mafia-like violence in disputes for routes and power (Geldenhuys, 2022).

1.2 Contextual Analysis

Currently, all the minibus taxis on South Africa's roads are internal combustion engine (ICE) vehicles that run on petrol or diesel. In 2022, 14% of all new cars sold worldwide were electric (Global EV Outlook, 2023). In South Africa, however, only 0.1% of vehicles sold in the same period were electric (FAnews, 2023). This is an issue from an **environmental** and an **economic** standpoint. The transport industry is responsible for 20% of total carbon emissions and it is the third-highest contributor to air pollution in the country (Showers & Raji, 2021). Thus, the relatively slow adoption of potentially greener options such as electric vehicles (EVs) is of great environmental concern. Additionally, the country's biggest purchasers of vehicles manufactured locally – the European Union and the United Kingdom – have placed tight restrictions on sales of new ICE vehicles from 2035 (Birel et al., 2024; Castle & Hendry, 2024). Since most vehicles manufactured locally are ICE vehicles, approximately R157 billion of export revenue (Parker, 2023) is at risk if South Africa does not electrify its automotive industry.

1.3 Problem Statement

South Africa is lagging behind in terms of electric vehicle adoption, and stronger efforts are required to ensure the country's automotive industry transitions to electric mobility to minimise the environmental and economic consequences of the continued dominance of ICE vehicles. Considering the importance of minibus taxis to South African paratransit, the country's EV transition must prioritise minibus taxi electrification. However, as illustrated in *Figure 1*, there are many cascading factors and dependencies which role players must consider. All must be carefully analysed and synthesised to formulate practical, actionable plans for electrification.

1.4 Aim of Paper

This paper aims to identify and connect the main factors of importance involved in the potential ecosystem of electric minibus taxis in South Africa, and the dependencies influencing them. It also aims to provide role players of electric mobility in South Africa (and Sub-Saharan Africa as a whole) with an overarching view of the different aspects that must be considered when analysing each factor and its dependencies, especially in an environmental and economic context.

The approach is to use a combination of existing literature on the electrification of fleet (from developed and developing countries) and experience from local efforts in the last five years to plan for the electrification of paratransit.

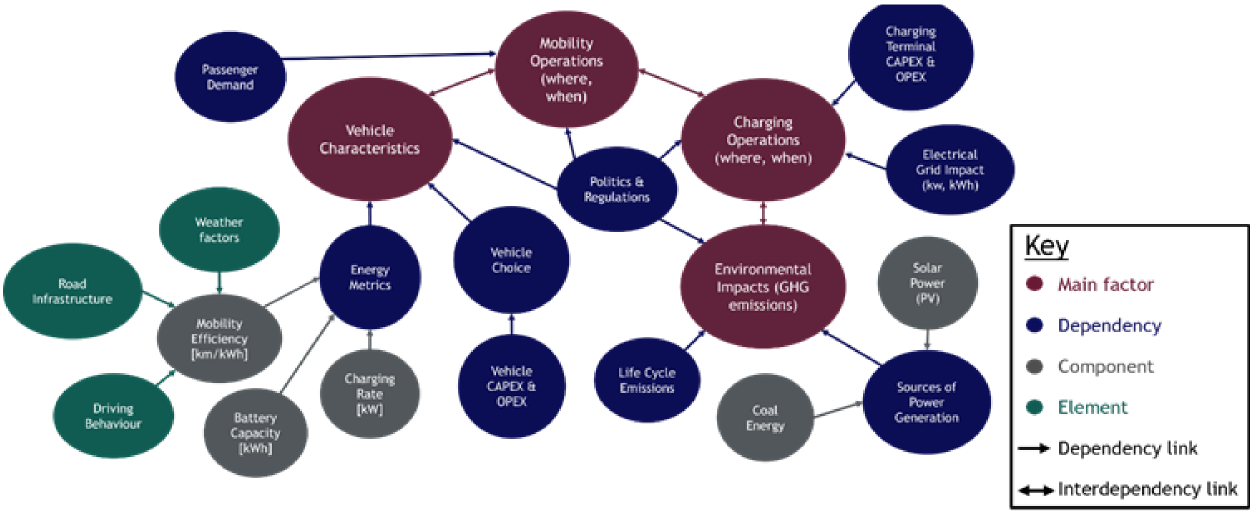

Figure 1: A web of factors and dependencies to consider in the electrification of South Africa's minibus taxi industry. Elements influence components, and these components influence dependencies, which ultimately influence the main factors

2. ANALYSIS OF FACTORS AND DEPENDENCIES

2.1 Mobility Operations

Mobility operations are the crux of the minibus taxi industry, as they determine where and when taxis operate. Currently, minibus taxi travel is loosely scheduled and timetabled. Taxis with licenses for specific routes have certain trips that they generally aim to complete at certain parts of the day. Day-to-day operations, however, are dependent on passenger demand. Taxis wait for passengers at taxi ranks or known hotspots throughout the day and once the taxi is full, they depart for the destination. There is flexibility in this regard as drivers have the prerogative to pick up or drop off some passengers at certain sub-destinations depending on their needs on the day. This form of pseudo-scheduling where drivers use experience and perceived daily demand works well enough currently for ICE taxis, but for electric vehicles where ranges and charging locations will likely be limited, more formal schedules and timetables will likely be required. A concerted effort will have to be made by taxi owners and associations alike as well as technical experts to decide how taxis will complete trips throughout the day. This will also need to include charging schedules to determine where and when taxis will charge and how this will fit in with their scheduled daily trips. Although the current flexible nature of minibus taxi transit might be able to be preserved in some sense, is highly likely that more formal operational plans will need to be put in place in order for electric mobility operations to be successful.

When analysing mobility operations as business processes, three general levels of planning are suggested for consideration when implementing electric mobility for public transport: strategic planning, tactical planning, and operational planning (Olsen & Kliewer, 2022). In the context of electric minibus taxis in South Africa, strategic planning must begin with a thorough demand analysis to determine which locations have sufficient passenger demand to serve. This must then be used to identify a list of locations for each vehicle fleet to service, and the locations of charging stations must thereafter be decided based on trip locations and vehicle characteristics.

Trip timetables should then be drafted as part of the tactical planning process to determine which times of the day minibus taxis must serve specific locations as per demand (e.g., trips from location A to location B from 12:50 to 13:20) and how many minibus taxis must be allocated to each route per time period. Maintenance schedules must also be drafted in the tactical planning phase to ensure that the minibus taxis remain roadworthy.

Operational planning will use the tactical plans to implement the schedules and specify the day-to-day activities, including assigning vehicles to trips (e.g., assigning minibus taxi 12 to trip C from time A to time B) as well as assigning drivers to vehicles. For local trips, each taxi will likely be paired with one permanent driver, but for long-distance trips where it is not uncommon to have two drivers taking turns to share the driving load, these driver swaps must be scheduled. Figure 2 illustrates the three general levels of planning suggested and the activities involved in each level.

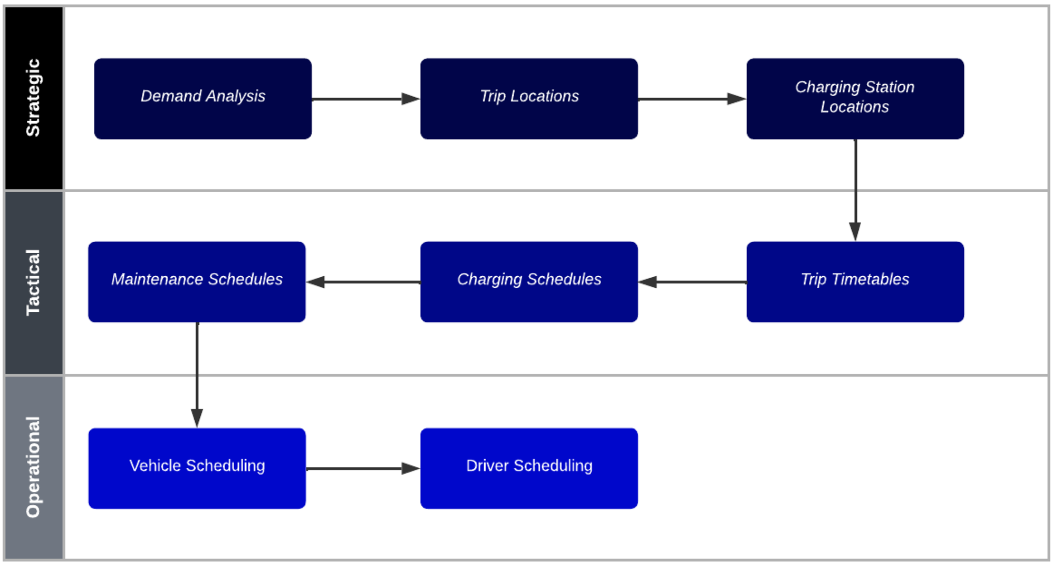

Figure 2: The three general levels of planning suggested to plan for the mobility of electric minibus taxis in South Africa

In addition to technical planning considerations, government laws and regulations will also influence how electric mobility is allowed to operate. Local politics will play a continuous role, as the incessant battle for routes and power within taxi associations will likely affect the potential implementation of any plans for electric mobility operations. Thus, operational planners will need to engage continuously with taxi associations to ensure that mobility operations are executed peacefully.

2.2 Charging Operations

As mentioned in the previous section, carefully planned charging operations are essential to successful electric mobility operations. As of September 2023, there were more than 2,200 registered electric vehicles and approximately 435 total charging stations in South Africa (Labuschagne, 2023), with these numbers set to increase year-on-year as South Africa's EV industry grows and private investment increases. Although South Africa has a relatively slow rate of EV adoption, it has a good ratio of vehicles to chargers with 5.06 vehicles per charging station (Labuschagne, 2023). To accommodate the country's entire network of minibus taxis, however, a significantly greater number of stations would be required, and the ratio of vehicles to chargers would likely be much larger.

2.2.1 Charging Terminal Expenditure

A key consideration for EV charging operations would be how funds will be raised for charging stations to be built and operated. Currently, all of the charging infrastructure in the country is funded by the private sector, with private companies investing millions to develop the national charging network year on year (Labuschagne, 2023). In the context of the minibus taxi industry, the amount of capital expenditure (CAPEX) required would almost certainly be out of reach of the private sector alone. Therefore, government and/or international funding agencies must become involved to help invest in costly charging infrastructure if the business case for electric minibus taxis can be proven. Additionally, some form of coordination between different taxi owners and associations is required to form agreements on how charging infrastructure will be shared between multiple taxis.

2.2.2 Electrical Grid Impact

A key concern for the electrification of transport in South Africa is the country’s prevailing electrical energy crisis, which leads to rolling blackouts. A primary concern is whether the limited electricity supply will impair electric mobility. A secondary concern is whether electric mobility’s eventual dependence on electricity will further hamper an already erratic electricity supply. Moreover, constrained electricity distribution infrastructure may not be able to service the high additional demand of electric vehicles. This is especially true at and around minibus taxi ranks, which tend to serve lower-income areas.

A tool for simulating the charging of electric vehicle fleets in sub-Saharan Africa was developed by Giliomee & Booysen (2023). They found that to electrify the country’s entire minibus taxi industry using the existing national grid is currently infeasible, as a fleet of 250,000 electric taxis with an average peak load of 12 kW/taxi would require additional generation capacity of up to 3 GW, i.e., an 11.3% increase in available generation capacity nationwide. However, when using various “load-shifting” approaches which limit the concurrent charging of a set number of taxis at given times to reduce peak loads (supported by external batteries and solar charging stations), a 66% reduction in the average peak power draw and a 58% reduction in energy drawn from the grid were simulated. Thus, with the right combination of energy sources and efficient planning for charging operations, it would be feasible to electrify the industry successfully. However, this would also require a coordinated effort from taxi owners and associations nationwide. This could present political challenges, but there is a good chance of cooperation from taxi owners and associations if they can be convinced that electrifying the industry is in their best economic interests. Therefore, incentivising cooperation is essential.

2.2.3 Behavioural Considerations When Charging

One consequence of the transition to electric mobility in the minibus taxi sector is the way in which current fast fuelling with an abundance of fuel stations will be replaced by behaviour around charging that takes a long time and leads to lost revenue, combined with competition for the limited number of charging stations. For example, given the opportunity cost of charging, the “first in, first out” nature of charging stations, and the transient nature of demand, there is a high likelihood of opportunistic and erratic charging behaviour (Pretroius et al., 2024). This behaviour, which will have substantial impacts on operations, mobility, the national grid, and revenues, could potentially be modelled with agent-based modelling.

2.3 Environmental Impacts

2.3.1 Sources of Power Generation

One of the main advantages of switching to EVs is the environmental benefit. EVs have no tailpipe emissions – which is highly advantageous when compared to ICE vehicles – but they are not necessarily free of carbon emissions. The emission potential of each EV depends on the emissions released before and during its manufacture, as well as the emissions released through charging operations in the form of power generation emissions. As detailed in Eskom’s integrated report (2023), the state-owned entity generated 215,318 GWh of energy which was available for distribution – approximately 90% of the country’s energy. Of this energy, 171,131 GWh (or 79%) was generated from coal-fired power stations. This means that in tandem with other carbon reduction initiatives, electric minibus taxis would have to charge using cleaner sources of energy to help achieve sustainability goals.

2.3.2 Life Cycle Emissions

The sourcing and manufacturing of EV battery cells have often been points of concern due to the carbon emissions associated with these activities. As addressed by Dunn et al. (2014), the mining and refining of the raw materials used in the manufacturing of these cells (i.e., lithium, cobalt, and nickel) emit large amounts of greenhouse gases. Battery cell manufacturing, however, is the largest contributor, accounting for 45% of total emissions in the value chain (Kim et al., 2016). Despite these emissions, EVs still have substantially lower life cycle emissions than their ICE counterparts **if a clean energy mix is used** in their charging operations. This was confirmed by Jessika Trancik from the Massachusetts Institute of Technology (MIT), who compared the life cycle carbon dioxide emissions of EVs and ICE vehicles of similar sizes and weights (Petersen, 2022). This was done assuming an energy generation mix of 60% fossil fuels and 40% renewable energy for EV charging operations. As illustrated in Figure 3*,* she found that the emissions of an EV were typically approximately 30% lower than that of a comparable ICE vehicle, even when taking manufacturing emissions into account (assuming that other life cycle emissions such as transport emissions are equal). Thus, if South Africa can invest in renewable sources of energy generation such as solar power, then the minibus taxi industry will be able to benefit from the environmental advantages of electrifying its vehicles.

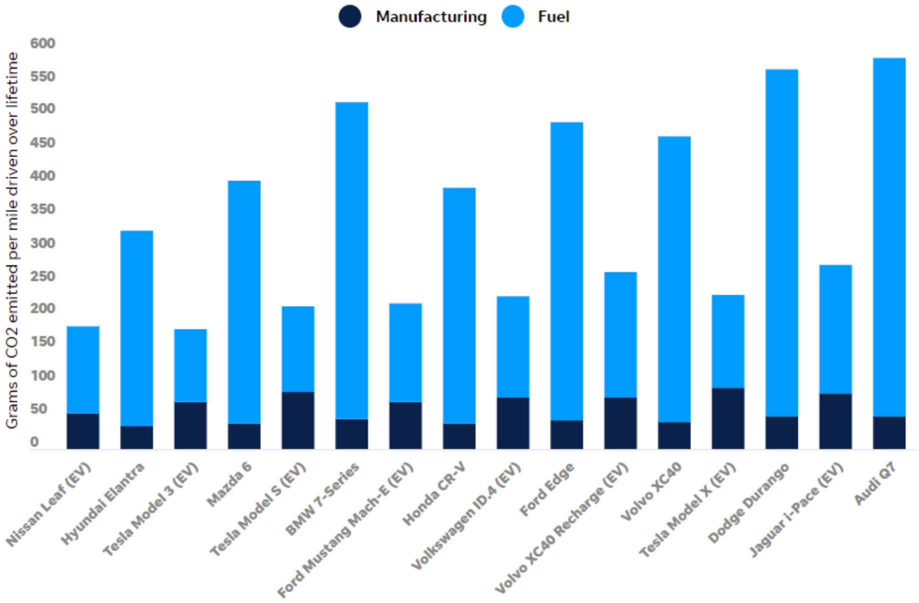

Figure 3: Life cycle carbon dioxide emissions per mile driven for pairs of electric vehicles and comparable internal combustion engine vehicles (Petersen, 2022)

2.4 Vehicle Characteristics

Various technical characteristics of minibus taxis will be key factors in determining how mobility operations must be planned and executed, as well as where and when each minibus taxi must be charged. Politics in the form of regulations, taxes and other fiscal policies will have an influence on each input.

2.4.1 Vehicle Choice and Expenditure

The capital budgets that minibus taxi owners and associations have available will determine which types of taxis they may purchase and/or order to be manufactured. Often to a lesser extent, purchasing decisions are based on expected operating expenses.

A new Toyota Hiace Ses'fikile 2.5D 16-seater petrol minibus taxi currently costs approximately R543,900 directly from Toyota. As for its electric counterpart, the World Bank report focusing on the decarbonisation of paratransit in South Africa (2022) estimates that an electric minibus taxi would cost $45,000 (approx. R830,000) without considering shipping and import duties, an increase of $15,520 (R286,350) compared to petrol-fueled minibus taxis. This figure will increase when shipping costs and import duties are added, which currently stands at 25% of the retail value of EVs, compared to just 18% for imported ICE vehicles (Dannhauser, 2023). Therefore, South Africa's minibus taxi industry must investigate options for producing electric taxis locally to minimise capital costs.

As investigated by Lacock et al. (2023), retrofitting existing ICE minibus taxis with an electric battery, motor, and other necessary components to electrify them is a practical method of reducing the capital costs involved with electrifying vehicle fleets. If this practice can be adopted nationwide, it could make the capital costs more financially feasible for minibus taxi owners.

Minibus taxi owners could potentially offset high capital costs with operational savings, especially when considering that many minibus taxi owners finance their vehicles and can thus spread out the capital cost (plus interest) over the repayment period whilst benefitting from reduced operational costs, making the vehicle more affordable.

Golden Arrow – the largest bus transport provider in Cape Town – is currently testing the economic benefits of electrifying its fleet of 1,100 ICE buses. It began by integrating the imported BYD K9 bus into its fleet in 2021, with great financial success. The company has stated that the operational expenditure (OPEX) for their new electric buses is approximately 70% less than for their ICE buses, and they estimated further savings of 50% on spare parts and 30% on labour due to fewer moving parts (Crouth, 2023). It expects these savings to break even with the capital costs within eight years.

Although electric minibus taxis will have different specific cost figures than electric buses, Golden Arrow has shown that it could be financially feasible to electrify minibus taxi fleets if owners and associations can offset the capital costs by maximising operational savings. The overall savings could be even higher if the taxis are produced locally or retrofitted from existing ICE taxis.

Despite the promising case of Golden Arrow, there is also a recent example of EV fleets proving not to be financially viable. Hertz – a car rental company in Florida, USA – recently announced that it will sell one-third of its EV fleet and replace it with ICE vehicles (CNN, 2024). The company cited EV market price declines, increased depreciation, and expensive maintenance and repair costs as the reasons for its decision. This highlights the importance of ensuring electric minibus taxis are designed and manufactured in a manner that makes them easy to maintain and repair, which will allow owners to minimise maintenance costs. It should also be noted that unlike ICE vehicles which benefit from decades of research and development as well as established spare parts networks, EV maintenance regimes and networks are still in their infancy.

2.4.2 Energy Metrics

Battery capacity and the associated range achievable on a single charge have been some of the key limitations of electric vehicles. Still, EV technology is advancing yearly and EVs are becoming increasingly capable of achieving longer ranges on a single charge. Most comparable commercial electric vans that can currently be purchased have useable battery capacities ranging anywhere from 40 to more than 100 kWh, the latter of which is more expensive to produce and less efficient to carry onboard. Optimal operational planning and trip optimisation (i.e., mobility operations planning) will be required to maximise the number of trips electric minibus taxis can complete without recharging. In light of peak times of the day when passengers often have to wait for taxis, integrated battery swopping can also be utilised at charging stations. This will enable vehicles which run out of battery to continue operating almost seamlessly, whilst helping to avoid overloading the grid during peak charging times.

The rate at which an EV battery is charged is another key energy metric contributing to vehicle characteristics and thus to mobility and charging operations. The charge rate is inextricably linked to the battery capacity, the battery technology, and the charger capability. This could present issues if the charging infrastructure and the minibus taxi batteries on which it is used are not sufficient to provide an acceptable rate of charge. This would reduce the number of trips taxis can complete daily, thereby increasing opportunity costs and decreasing profits.

In South Africa, the national EV charging network has been growing year on year, and despite the slow growth of the private EV market, charging station manufacturers have been showing consistent interest in increasing the size of South Africa’s charging network. The fastest charging rate achievable with AC power is 22 kW (World Bank, 2022), and this is the most common rate currently found at charging stations. If faster rates were to be used at local charging stations, a shift to DC power would be required, resulting in increased strain on the national grid. Capital and operational costs would also increase, as DC charging has been shown to be substantially more expensive to install and operate than AC charging (Lim et al., 2022).

Mobility efficiency is perhaps the most important energy metric, as it is a direct measure of how much utility a driver can get out of the vehicle in terms of km/kWh. There are few studies focusing on estimating the energy efficiency of electric minibus taxis in the sub-Saharan region. However, a consolidating paper by Abraham et al. (2023) concluded that the battery expenditure of electric minibus taxis in sub-Saharan Africa is estimated to be between 0.49 – 0.51 kWh/km. This means that for a battery with 70 kWh of useable energy, a theoretical range of 140 km will be achievable on a full charge assuming an average mobility efficiency of 0.5 kWh/km, i.e., 2 km/kWh. Even with a more optimistic assumption of a 100 kWh battery, this results in 200 km of theoretical range – far below current ICE minibus taxis which have more than 500 km of range on a full tank. This highlights the need to ensure that ranges achieved by electric minibus taxis are maximised to ensure they can complete all daily trips without fail.

Donkers et al. (2020) conducted a comprehensive study on the effect of driving conditions on EV mobility efficiency in Utrecht, the Netherlands. They found that driving behaviour, weather factors, and road infrastructure directly affect the mobility efficiency of electric vehicles. Driving behaviour is of particular importance in the South African context as taxi drivers often drive aggressively in order to meet daily fare quotas and make profits. The studies – which were validated using 30 on-road driving tests – showed that aggressive driving consumes more energy than conservative driving styles at higher speeds. As illustrated in Figure 4, the reduction in efficiency becomes more pronounced at speeds exceeding 60 km/h and even more pronounced at speeds exceeding 80 km/h, which is a point of note as South African taxi drivers have been shown to regularly flout speed limits (Imaniranzi, 2015). Driving speed oscillations were also found to influence mobility efficiency negatively, with aggressive driving using 22% more energy at an oscillation of 0.2 m/s^2, whilst conservative or "eco-driving" used just 1% more energy.

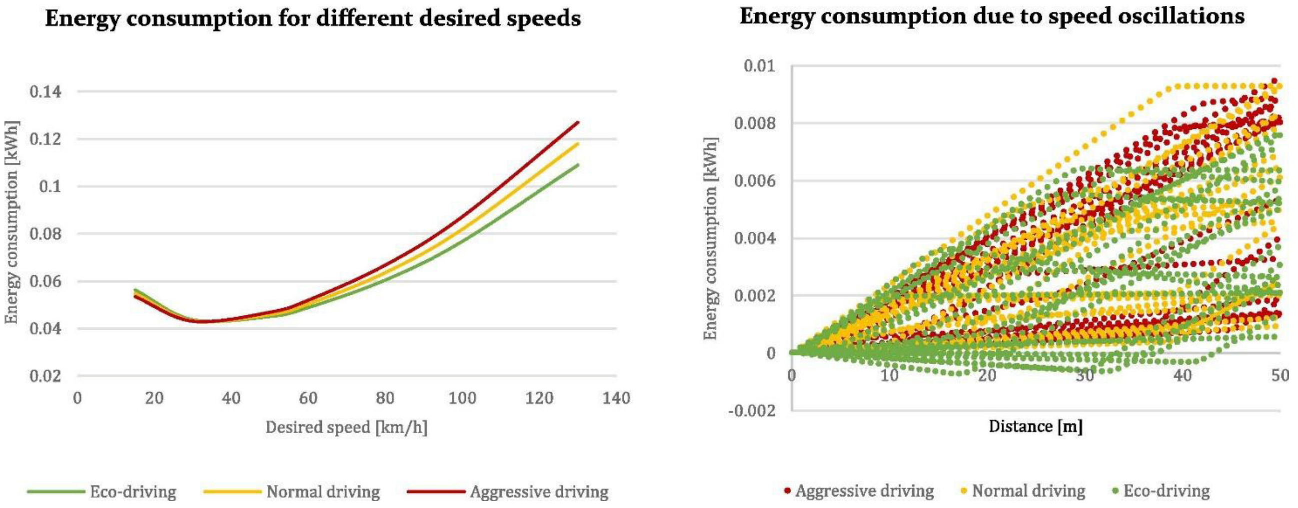

Figure 4: Effects of different driving styles and speed oscillations on energy consumption (Donkers et al., 2020)

Regarding road infrastructure, Hull et al. (2023) found that a change in elevation is the characteristic that has the largest impact on mobility efficiency. As expected, uphill roads had the worst mobility efficiency of 0.47 kWh/km, followed by intercity roads (0.40 kWh/km), then by urban roads (0.37 kWh/km), and finally by downhill roads which had the best efficiency of 0.33 kWh/km. Although these figures were found to be inaccurate in follow-up studies, they still provide a good relative measure of the effect of road infrastructure on mobility efficiency. In addition to these results, it must be noted that as with other types of vehicles, the regular maintenance of road infrastructure is essential to maximise both the comfort and mobility efficiency of electric minibus taxis.

There is limited research on the effects of South African climate and weather conditions on electric mobility efficiency. Regardless, the study done by Donkers et al. (2020) provides a good baseline for general weather conditions. They found that when driving at low speeds of 30 km/h, mobility efficiency improves in a somewhat linear fashion from approximately 0.07 kWh at 0°C ambient temperature to approximately 0.03 kWh at 20°C. The influence of ambient temperature was found to be significantly lower at high speeds of 130 km/h. The influence of wind on mobility efficiency was found to be independent of driving style at lower speeds. Still, at strong headwinds of 100 km/h, aggressive drivers used approximately 11% more energy than conservative "eco-drivers". This underscores the importance of responsible driving behaviour to maximise mobility efficiency.

3. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper identifies and analyses the factors and dependencies involved in electrifying the minibus taxi industry in South Africa, as illustrated in Figure 1. Aspects such as passenger demand requirements, CAPEX investment affordability, and charging station distribution and timing (to name a few) all need to be considered holistically. This paper illustrates the complexity of this web of factors and dependencies.

Operations for both mobility and charging are intricately linked as they are interdependent and essential for the scheduling and management of electric minibus taxis. Charging operations are likely to be costly and require well-structured funding and shared usage agreements, and the impact of charging operations on the grid must also be continuously monitored. The environmental impacts of electrifying minibus taxis depend on the sources of power generation, as a cleaner energy mix would be better for the environment. Lastly, the energy metrics of charging rate, battery capacity, and mobility efficiency are vehicle characteristics which are determined by the choice of vehicle that taxi owners and associations can afford to source and/or order for manufacture.

In this paper, the complexity of economic, environmental, and energy-based aspects is unpacked. Not included in the paper are considerations such as social aspects, changes in road safety risks, and the impacts on the job market. Adding the social dimension will grow the web of dependencies, increasing the complexity. According to the authors, further research into social aspects of the electrification of the minibus taxi industry, amongst others, is required in addition to the aspects mentioned in this paper. It is also noted that the environmental impacts of electric vehicles will be influenced by local laws and policy regulations, and government agencies must ensure that the laws and regulations regarding electric vehicles are conducive to the successful growth of the industry.

The authors recommend that role players and researchers use the factors identified and discussed in this paper as guiding tools for more detailed planning and analysis of each individual factor. It is also recommended that these factors and their dependencies are treated as cogs in one big wheel of electrification instead of individual problems that must be solved independently.

4. ACKNOWLEDGEMENTS

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