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PILOTING AN OPEN-SOURCE TRANSPORT JUSTICE TOOL FOR SOUTHERN AFRICA

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DEDICATION

In the hopes that this work may in some way contribute to the development of my beloved Africa, this is dedicated to the bright and eager minds that may use my work in present and future transport planning for African cities and beyond.

To my incredible husband, Kapil, and our daughter, Lia, you were and will always be my guiding light and purpose.

Thank you to the family and friends that encouraged, motivated and supported me. I am truly blessed and grateful.

To my supervisors, Dr Obiora Nnene and Prof. Mark Zuidgeest for their continued guidance, support and encouragement; we finally did it!

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ABSTRACT

Traditional transport planning methods largely promote transport-related social exclusion in favour of existing travel patterns. The monetary valuation of travel time savings (biased towards projects that serve higher income earners), thus generates more overall benefits and focus of alleviating network congestion.

Typically, the general distributive principle of goods is equality; however, this can't easily be extrapolated in the context of transportation. Accessibility, in the transport context, can be defined as how well the transport network connects people with activities. Mobility refers to the variety of transportation options and how well they provide access to transit-connected opportunities and services. Mobility and accessibility are jointly crucial to enabling everyone to enter the economy and live better.

Transport Justice, a term coined by Karel Martens (2017), develops a new paradigm for transportation planning based on principles of justice focusing on marginalised and poorer communities or groups of people. It is based on social justice philosophies centred on the concept of equality of resources. To enhance the process of regional transport planning, these principles of justice can be applied to and quantified in the evaluation of urban transportation systems. This method challenges transportation experts to conduct systematic studies of the degree of accessibility and mobility experienced by various demographic groups rather than continuing to concentrate narrowly on specific aspects of the greater transportation system.

The objective of this study was to determine to what extent and how the approach and underlying analytical methods can be applied by developing an open-source analytical tool for transport planning based on principles of transport justice (mobility and accessibility). The research intended to firstly, review a suitable open-source software to determine if it could be the platform of choice for developing a robust, scalable and easy to use transport justice analysis toolkit for southern Africa; and then apply/case-test the chosen software in the cities of Kigali, Rwanda and Nairobi, Kenya. This research formed part of a larger Volvo Research and Educational Foundations (VREF) project that the University of Cape Town was involved in regarding transport planning based on the principles of justice in Africa (piloting a proof of concept in Kigali and Blantyre Malawi).

The open-source analytical tool developed in this study (using r5r) showed true potential, robustness and replicability to be able to compute all the relevant and potential statistics and parameters as required to evaluate the transport justice indicators of any region. Thus, the r5r model demonstrated the robustness and scalability of the code underlying the transport justice analysis tool in this study with minimal input data set requirements.

The accessibility levels and potential mobility levels for each population group per mode were determined using three accessibility measures (cumulative, inverse and exponential power accessibility measures) and the Potential Mobility Index (PMI-score). Assessment of accessibility patterns vary and change in time and space. To capture the changes in accessibility levels using simple accessibility measures that differentiate between multiple accessibility measures, differences between persons and identify population groups that are entitled to accessibility

improvements are most representative. Furthermore, the interpretability and communicability of the results become easier.

The groups were then assigned under 50%, 30%, and 10% accessibility thresholds based on their respective accessibility levels. The study considered only the 30% threshold and under this threshold, groups that contributed the most to the unfairness of the transportation system were identified and ranked based on their respective Accessibility Fairness Index scores (AFI) using the cumulative accessibility measure.

The study findings revealed that the majority of public transportation reliant population groups contributed to the unfairness of the transportation system. Even with limited and inferred data for the cities, the application of transport justice principles in the open-source analytical tool developed in this study revealed stark disparities in job accessibility between car owners and public transportation users.

Traditional transport modelling inputs essentially requires demographic and socio-economic data sets segregated in certain administrative level zones overlaid with its relevant road network information. This in turn provides indicators for the transport demand requirements of the transport system in each zone. It also provides a basis for comparisons of this demand with respect to transport supply by comparing the road network and transit facilities available or being tested. Framing a transport modelling exercise using the theories of transport justice requires almost all the traditional transport modelling with a few additional and relatively easily computed / derived inputs. However, for developing African countries (like Rwanda and Kenya), the availability and digitisation of these basic data sets is still limited. The following points briefly highlight the issues and considerations this study had to contemplate in terms of data requirements:

1. Population data set

   Population data sets that were available were outdated and only available at a district level and therefore had to be projected proportionally for each of the regions based on their respective area proportion. Updated data at a regional level will greatly improve and increase the reliability in the results. However, for this study it is limited to projected statistics to demonstrate the design and replicability of the open-source transport justice analysis tool being developed in this study.

2. Socio-economic data set

   Similarly, the employment data was also only available at a district level and had to be projected proportionally for each of the regions based on their respective area proportion.

3. Road network data

   The OpenStreetMap platform was utilised, however, despite this open-source map platform being free of charge to use it is important to note that it is created from contributions from volunteers and may have some discrepancies/errors. It would be more appropriate to calibrate and validate the road network data set from more reliable data sets or results, should they be available.

4. GTFS transit data set

   The GTFS data set only had limited data for transit services (e.g., in Kigali only KBS-I data was listed). Furthermore, it showed formatting / compatibility issues within the GTFS data set. This issue may have arisen due to weak formatting of the GTFS data or due to coding compatibility issues. Nevertheless, the existing GTFS data was used to demonstrate the design and replicability of the open-source transport justice analysis tool being developed in this study. This was further tested using the Nairobi GTFS data, which although also limited in terms of listed transit services, presented no formatting or compatibility issues within the GTFS data set.

Finally, the insight from this study has shown that the theory and principles of transport justice might be utilised when there are significant mobility and accessibility disparities. The use of the open-source analytical tool developed in this study can be extremely useful in the African context where data is limited or basic in nature, but could still be beneficial and give rich and insightful outputs that steer transport planning, forecasting and investment prioritisation in the right direction.

Keywords:

Accessibility; Mobility, Transport Justice, Transport Equity, Transport Poverty, Public Transport, Transport Planning, Social Inclusion, Social Exclusion, Open-source transport planning tools, Inequality, Kigali, Rwanda, Nairobi, Kenya, Southern Africa, Africa.

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ACRONYMS AND ABBREVIATIONS

AFC	Automated fare collection
AfDB	African Development Bank
AFI	Accessibility Fairness index
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
AIIB	Asian Infrastructure Investment Bank
BRT	Bus Rapid Transit
CBA	Cost-benefit analysis
CBD	Central Business District
CFI	Corporate Finance Institute
CUM	Cumulative Gravity
DART	Dar es Salaam Rapid Transit
EDPRS 2	Economic development and Poverty reduction Strategy 2 of 2013-2018
EXP	Exponential Gravity Power
FFS	Free Flow Speed
FONERWA	Rwanda's Fund for the Environment and Climate Change
GIS	Geographical Information System
GIZ	Deutsche Gesellschaft fur Internationale Zusammenarbeit
GTFS	General Transit Feed Specification
IGC	International Growth Centre
INTALInC	International Network for Transport and Accessibility in Low-income Communities
INV	Inverse Gravity Power
IPEA	Institute for Applied Economic Research (Brazil)
IRPTN	Integrated Rapid Public Transport Network
ITDP	The Institute for Transportation and Development Policy
JICA	Japan International Cooperation Agency

KARA	The Kenyan Alliance of Resident Associations
KBS	Kenya Bus Services
KeNHA	Kenya National Highways Authority
KRB	Kenya Roads Board
KNBS	Kenya national Bureau of Statistics
KURA	Kenya Urban Road Authority
MBT	Mini-bus Taxi
MININFRA	Ministry of Infrastructure (Rwanda)
MINIRENA	Ministry of Environment (Rwanda)
MINECOFIN	Ministry of Finance and Economic Planning (Rwanda)
MINALOC	Ministry of Local Government (Rwanda)
MCG	Mombasa County Government (Kenya)
NEMA	National Environment Management Authority (Kenya)
NCC	Nairobi City County Government
NaMATA	Nairobi Metropolitan Area Transport Authority
NaMATA	Nairobi Metropolitan Area Transport Authority
NDoT	National Department of Transport (South Africa)
NISR	National Institute of Statistics
NMT	Non-motorised transport
NTSA	National Transport and Safety Authority (Kenya)
ODF	Official Development Finance
OSM	OpenStreetMap Street
OTP	OpenTripPlanner
PMI	Potential Mobility Index
PT	Public Transportation
RECs	Regional economic communities
RALGA	Rwanda Association of Local Government Authorities
REMA	Rwanda Environment Management Authority

RFTC	Rwanda Federation of Transport Cooperatives
RHA	Rwanda Housing Authority
RITCO Ltd	Rwanda Inter-Link Transport Company
RNP	Rwanda National Police
RTDA	Rwanda Transport Development Authority
RURA	Rwanda Utilities Regulatory Authority
SACCOS	Savings and Credit Cooperative Organizations
SDG	Sustainable Development Goal
SSATP	Africa Transport Policy Program
SSM	Soft Systems Methodology
STASSA	South Africa-specific Sustainable Transport Assessment Tool STASSA
TAZ	Transport Analysis Zone
TLAB	Transport Licensing Appeals Board (Kenya)
TOD	Transit Oriented development
UN	United Nations
UN-HABITAT	United Nations Human Sentiment Program
UNDP	United Nations Development Program
UNEP	United Nations Environment
USAID	United States Agency for International Development
VREF	Volvo Research and Educational Foundations
WHO	World Health Organisation

1 INTRODUCTION

1.1 BACKGROUND

An online article in India's Economic Times (What Is Transport Planning? 2014) defines transport planning as "*planning required in the operation, provision and management of facilities and services for the modes of transport to achieve safer, faster, comfortable, convenient, economical and environment-friendly movement of people and goods.*" It predicts future travel demand and plans for all the facilities and services needed to achieve it. Transportation planners and engineers optimize people and cargo transportation throughout cities, regions, countries, etc. Planning for transportation is essential for defining cities, enabling economic activity, fostering community interaction, and improving quality of life. Additionally, it is crucial for sustainable growth and guaranteeing that the community has safe access to transport at different levels. Different practices, such as urban development, urban transport policies, legislative activities, funding bodies and project management all come together under the auspices of transportation planning.

Transport planning methods are typically based on a series of mathematical equations, factors, weighting and heuristics that are used to develop models which predict and represent how people travel in transport networks. The most famous and commonly used being the aggregated four-stage computerized transport model (of predict and provide). These methods and models have been around for decades and are long standing in the field however, they have also highlighted many concerns and critiques such as:

- questioning its theoretical foundations and intrinsic underpinnings (assumptions within the model and future forecasting)
- 'predict-and-provide' principles favour existing patterns of travelling with limited forecasting applicability and relying on the peak hour information to provide enough insight to inform decisions on transportation system improvements
- little focus on the wider needs of people and vulnerable sections of the populations who use it
- non-motorised transport (NMT) modes are largely not adequately modelled and the focus mainly becomes biased to an increase in mobility for car users

Traditional transport planning methods largely promote transport-related social exclusion in favour of existing travel patterns, the monetary valuation of travel time savings from the reliance of cost-benefit-analyses (biased towards projects that serve higher income earners), thus generating more overall benefits and focus of alleviating network congestion. For example, road congestion has been seen as the main transport problem rather than focussing on investments to ease congestion as the proper solution. These methods, which neglected the mobility and accessibility issues faced by various sections within a population, has in effect encouraged transportation-related social exclusion.

Equality and equity in social systems are comparable yet distinct. Equality is equal opportunities and support distributed equally to everyone. However, equity goes a step further by providing different degrees of help depending on need to attain more equitable outcomes. Typically, the general distributive principle of goods is equality; however, this can't easily be extrapolated in the context of transportation. Accessibility, in the transport context, can be defined as how well the transport network connects people with activities. The effectiveness of the transportation system and the level of accessibility in a city are related; the degree to which these two criteria are interconnected impacts how many opportunities city people can access (Quiros, Kerhners, & Avner, 2019).

Mobility refers to the variety of transportation options and how well they provide access to transit-connected opportunities and services. Mobility and accessibility are jointly crucial to enabling everyone to enter the economy and live better. Authors like Levine & Garb (2002) state that the difference between mobility and accessibility is "*A mobility improvement is a reaction in the generalised (i.e., time-plus-money) cost of travel per kilometre; and an accessibility improvement is a reduction in the generalized cost per destination".*

Transport Justice, a term coined by Karel Martens (2017), develops a new paradigm for transportation planning based on principles of justice focusing on marginalised and poorer communities or groups of people. It is based on social justice philosophies centred on the concept of equality of resources. To enhance the process of regional transport planning, these principles of justice can be applied to and quantified in the evaluation of urban transportation systems. This method challenges transportation experts to conduct systematic studies of the degree of accessibility and mobility experienced by various demographic groups rather than continuing to concentrate on the transportation system. The principles of transport justice primarily seeks to amplify a person's mobility and accessibility. Transportation equity or justice is the fairness with which the effects of transportation (benefits and expenses) are distributed (Litman, 2014).

The objective of this research project is to determine to what extent and how the approach and underlying analytical methods can be applied by using an open-source analytical tool for transport planning based on principles of transport justice.

1.2 CONTEXT

Rapid and frequently unplanned urban growth is occurring in both large and middle-sized African cities as the continent urbanises at an extremely fast rate. As such, the planning, growth, and management of cities are consequently fraught with difficulties for policy- and decision-makers. Sustainable urban development prioritises mobility and accessibility; however, when compared to the needs of their residents, the majority of African cities exhibit inadequate levels of mobility and accessibility. Sub-Saharan Africa specifically is the most rapidly urbanising region in Africa and globally, with an urban population nearing 500 million. This number is anticipated to double within the next two decades. In 2000, one in three Africans resided in urban areas; by 2030, this proportion will be one in two (PPIAF, 2018).

Poor urban design, ineffective delivery of essential services, poor infrastructure, inadequate transportation options, often unregulated traffic, rising congestion and pollution, and a lack of technical, institutional, and financial resources are common problems in African cities. Furthermore, few policy- and decision-makers have yet to acknowledge how fundamentally distinct urban mobility needs are from intercity transportation needs. This hinders their ability to appropriately address the problems created by insufficient urban transportation infrastructure.

Rwanda and Kenya are two rapidly developing cities in East Africa and serve as case studies for piloting an open-source analytical tool for transport planning based on principles of transport justice.

Rwanda has one of the highest population densities in Africa, with 414 individuals per square kilometre. By 2032, the population in Rwanda is expected to reach 16,9 million. Kigali, Rwanda's capital, is located in the country's geographic and economic centre. This draws national and local traffic into the city, creating infrastructure, environmental, and safety issues with local impacts (SSATP, 2015).

From a national standpoint, Rwanda has clearly shown a trend toward greater motorisation. Between 2011 and 2016, the total number of motorised vehicles, excluding motorcycles, increased from roughly 106,000 to 184,000. During this time, the fleet's average annual growth rate was 11,8%. The size of the nation's motorbike fleet, which is currently believed to be over 80,000, has also increased dramatically. In terms of traffic safety, 3,815 people died in road traffic accidents in Rwanda in 2017, accounting for 6% of all fatalities that year. In addition to strong penalties for drunk driving, since 2007, the government has set and enforced severe speed limits in urban areas and on intercity roadways. Public transportation and commercial vehicles must be equipped with speed governors, and the legal maximum speed is 60 km/h. Motorcycle riders and their passengers are required to wear helmets, and this rule is actively enforced. The nation's transportation infrastructure has made tremendous strides since 2010, especially with the development of one-stop border posts and the expansion of the paved road network. Paved national roads measured 1,355 km as of 2016, up from 1,279 km in 2015.

Across the nation, air pollution is becoming a bigger problem. Metropolitan air pollution is mostly caused by the transportation sector, and since Kigali is the largest urban area, the problem is most severe there. The 2014 Strategy for Reduction of Traffic Congestion and Air Pollution in the City of Kigali highlights that the recommended World Health Organisation (WHO) permissible limit for suspended particulate matter (PM10) (50 g/m^3) has already been severely exceeded. This demonstrates that the bulk of the time Kigali residents are outdoors, particularly in the evening when PM10 concentrations are highest, they are exposed to unhealthy levels of the gas.

The policy and strategy paper by the Africa Transport Policy Programme (SSATP) on for Sustainable Accessibility and Mobility in Cities of Rwanda (SSATP, 2018a) summarises how major mobility and transportation advancements in Kigali over the past few years have focused on things like:

- converting informal services to scheduled bus operations
- roll out of an automated fare collection (AFC) system

- focus on alleviating general traffic congestion (specifically with motorcycle taxis)
- inclusion and prioritisation of non-motorised transport (NMT) infrastructure into key projects
- developing a bus rapid transit (BRT) system
- moving the international airport to Bugesera

Key advancements and difficulties in Rwanda's secondary cities have centred on:

- extension of paved roads and establishment of NMT infrastructure
- creation and enhancement of public transportation hubs
- limitations in intercity connectivity and transport services, and
- traffic congestion due to the rise and prevalence of motorcycle taxis.

Kigali have been proactive in ensuring and implementing many measures to address urban mobility issues; however, and despite these efforts, the current public transport system is still far from optimal. The Strategic Transportation Master Plan (2013) and Kigali City Master Plan (2013 & 2020) highlight that concerted plans are in place to strategically guide Kigali's development through optimal land use and facilitating rapid economic growth. To alleviate traffic congestion in Kigali, NMT and synchronized transport and traffic management systems are targeted. (SSATP, 2018)

The Republic of Kenya has a population of 47,5 million people and is a 580,000 km2 country located in the Southern East Africa region (2019 Kenya Population and Housing Census). Kenya's population density is 94 individuals per square kilometre. Kenya's urban population is estimated at 14 million and by 2030 this is projected to reach 22 million people (World Bank, 2016).

With 50% of the official labour market and 50% of the country's GDP concentrated in its metropolitan region, Nairobi, Kenya, is the nation's principal economic engine. Despite averaging 5,400 persons per km^2, the Nairobi's' population density varies widely. Consistent with national trends, the city is expanding rapidly, and by 2030 it is predicted to be home to 6 million people (World Bank, 2016).

Important national frameworks for enhancing urban mobility and accessibility in Kenya include the country's Integrated National Transport Plan and its National Urban Development Plan. The primary aim of urban transportation planning (in the context of these frameworks) is to increase citizens' opportunities for social interaction with one another and with the built environment as a whole (SSATP, 2018b).

The rate of motorization in Kenya is still low on a national scale. Currently, there are between 26 and 28 automobiles per 1,000 people, depending on the source. According to estimates, Kenya's entire vehicle fleet was roughly 1,3 million units in 2014, with about 80% of those being used cars. Despite Kenya's motorization rate being significantly lower than Rwanda, the motorization rate is growing. The Kenya National Bureau of Statistics (KNBS) reports that between 2003 and 2012, the number of imported automobiles surged by nearly 300%, from 33,000 units to 110,474 units. There were 112,536 automobiles registered in total in 2015, including both newly registered and re-registered vehicles. Although walking is the primary mode of transit in the city, there are poor safety conditions for pedestrians in Nairobi's metropolitan districts due to the presence of aggressive, hasty, and large volumes of motorized traffic. High rates of automobile accidents affect pedestrians. According to data from road accidents between 2010 and 2013, out of 700 deaths annually, nearly two thirds were pedestrians.

In Kenyan cities, air pollution is a significant cause of respiratory illnesses, with particle matter (PM) concentrations frequently surpassing acceptable limits by a significant margin. For instance, research on PM 2,5 in Nairobi (Kinney et al., 2011) indicated that inhabitants are frequently exposed to high amounts of fine particle air pollution, which might have detrimental long-term effects on health.

The policy and strategy paper by the Africa Transport Policy Programme (SSATP) on for Sustainable Accessibility and Mobility in Cities of Kenya (SSATP, 2018b) summarises that at the urban scale, key mobility and transport developments in Nairobi in recent years aim to include:

- Nairobi (and Mombasa) plan for the introduction of Mass Rapid Transit systems.
- Ongoing expansion of commuter rail capacity and stations in Nairobi and Mombasa
- Infrastructure fast tracking due to current mass rapid transit projects
- Focus on NMT users (latent demand) by increasing the capacity and efficiency of the public transport network/system
- Plan/establish a truly multi-modal public transport system embracing and incorporating all modes e.g., boda boda. Matatu's, etc.).

Key advancements and difficulties in Nairobi's secondary cities have centred on:

- Developing and promoting matatus and bus services as more important modes of public transport
- Projects to Improve the connectivity of Mombasa Island to the southern mainland

As in the case of Kigali, Nairobi's public transport system is far from optimal although one commendable strength is Kenya's on-going devolution process. Counties are geared to have the responsibility of the transport planning function. Although challenges in the sharing of roles and responsibilities between national and local government are apparent.

Van Zyl et al (2014) highlights the planning and conceptual design process for a public transportation system for Kigali City, with an emphasis on aspects of the then-current and proposed public transportation system, were included in the study, along with key findings. It was reported that the planning process was thorough and took guidance from international best practise by encompassing all the planning components of a conventional full feasibility study. The early planning and design of a public transport system for Kigali City barely mentions accessibility and mobility characteristics. It states that the *"status quo assessment covered the current land use and city structure, travel characteristics, public transport services and their usage, traffic conditions and public transport infrastructure."* Van Zyl et al (2014).

The fundamental aim of this research will endeavour to no longer focus on the transport system in its traditional sense, but rather and instead to systematically analyse the ease of movement and level of accessibility experienced by the population groups in each city. With the focus being the equality to resources and how these concepts of justice can be extended to, and quantified in, the assessment of each city's transport system.

1.3 PROBLEM STATEMENT

As previously noted, most African countries have very high levels of spatial and social inequality; against this background, the injustices in the domain of transportation hardly ever attract attention. It is commonly known and accepted that mobility and more importantly access to safe, reliable and affordable transportation is fundamental to advancement and growth of the human race. It links us to employment opportunities, health care and education facilities as well as social and recreational activities to name a few. Preserving this fundamental is key, but should also look to address the high levels of spatial inequality by exploring and expanding transport planning objectives.

Recent theoretical and empirical research have shown that people are starting to pay more attention to the social and economic implications of transportation, but this is mostly happening in first-world nations with less focus in Africa. Transport is essential for distributing socio-economic advantages (or losses) caused by diverse modes of transportation or simply by transportation itself; and this is what makes it important in the discussion of social justice. Beyazit (2011) explains the various consequences that transportation has in relation to the degrees or types of equity in the distribution in her paper, "Evaluating Social Justice in Transport." Transport is in a unique position where it can on the one hand aide in advancing social fairness or on the other hand exacerbate disparities between or within populations or regions. To put it differently, for the system to work appropriately, the distribution must be equitable for all stakeholders. How a need is defined or justified presents the biggest obstacle to addressing transportation requirements in an equitable manner. (Vasconcellos, 2012).

The literature review section of this study highlights and reveals the broad concern with the scarcity of accurate and dependable tools to monitor and evaluate the non-transport benefits and consequences of transportation efforts in Africa specifically. Understanding the measurement of social inclusion or exclusion is not a common transportation research analysis framework within the context of Africa. For the most part from a spatial perspective, Africa's transportation issues are typically characterised as ones of inequality, marginalisation or poverty. (Jennings et al 2018).

Nashilongo and Zuidgeest (2020) concluded a study in Windhoek, Namibia which aimed to test the application of rules of transportation planning based on principles of transport justice (as developed by Karel Martens). The study identified and ranked population groups experiencing the least accessibility to employment opportunities by evaluating the fairness of the Windhoek transportation system and its associated transportation modes using accessibility and mobility indicators. However, these were calculated and evaluated using ArcGIS, which is expensive software requiring licenses and skilled operators (and not open-source. Microsoft Excel, which is relatively easy and inexpensive to obtain, was also used in the tabulation and evaluation, although again, not entirely open source.

There are not that many quantitative studies that actually measure transport justice, let alone studies that use open-source software packages making this form of transport planning and evaluation accessible to all key stakeholders and transport policymakers. The aim of this study is therefore to investigate an open-source software tool using basic and limited data and replicable relatively easily to other data scarce African cities. Using open-source software allows universal, free use thereby circumventing the typical cost barriers associated with licensed transport modelling software and the skills required to operate these software tools (which are sometimes quite complex).

1.4 TRANSPORT JUSTICE EXPLAINED

Seeking transport justice thus requires a radical shift away from the traditional transport planning process. In his 2017 book 'Transport Justice – Designing Fair Transportation Systems' Karel Martens develops an alternative set of rules for transport planning, rules that are based on social justice philosophies from Walzer to Rawls and Dworkins' notion of equality of resources. His proposed method takes population groups as its starting points and assesses to what extent groups, differing in terms of income, transport mode availability, and residential location amongst others, are served by the transport and land use systems. By doing so, the approach identifies the population groups that suffer most from the unfairness embedded in those systems (and by extension the unfairness embedded in the analytical tools used to plan these transport systems). His proposed approach makes it possible to single out the population groups that are particularly affected by sub-standard levels of accessibility. Furthermore, the method assists in identifying the causes of such sub-standard levels of accessibility, the generation of solutions and the assessment of the costs and benefits of these solutions.

A key feature of the proposed transport planning based on justice method is a quadrant system that summarises population groups' current, modelled, levels of so-called potential mobility and potential accessibility. These indicators ae then visualised on a set of axes, as shown in **Figure 1**.

Both axes reflect a range of levels from low to high and create a coordinate system in which population groups can be positioned. The average level of potential mobility and at the average level of accessibility is where the axes intersect. This simple coordinate system enables the placement of population groups (depicted as dots in the diagram) vis-à-vis both axes, based on the measurement of a group's potential mobility and accessibility. It also enables the introduction of a sufficiency threshold of accessibility (the dashed lines), which would most likely be positioned anywhere below the origin of the coordinate system by the real-life agents involved in the process of setting the sufficiency standard.

In quadrant one (bottom-left), a population with low mobility and accessibility is recognized. Because of its transportation issues, it should receive accessibility upgrades first. The second quadrant has insufficient mobility but sufficient accessibility, the third quadrant has sufficient mobility and accessibility, and the fourth quadrant has insufficient accessibility and but sufficient mobility.

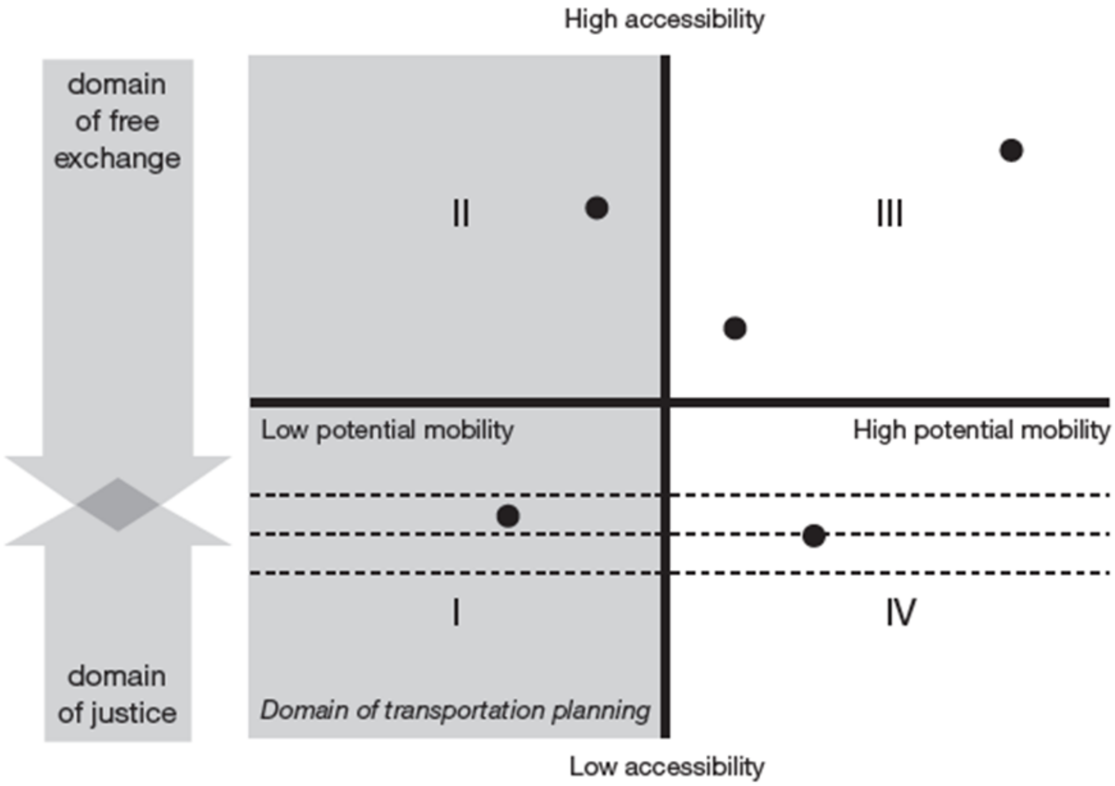


Figure 1: Coordinate system of potential mobility (horizontal axis), potential accessibility (vertical axis) and sufficiency threshold/s of accessibility

The notion of potential mobility here relates to the transport system's contribution to the potential people have to move around. Its indicator represents both the speed, as well as the structure of the mobility options available (and affordable) to the population group in an area. This doesn't necessarily relate to the revealed use of the available (and affordable) mobility options.

The second indicator is an accessibility indicator that measures the opportunities a population group can reach within a reasonable time and money budget, taking into account the spatial structure of the city, its transport network as well as the location of each population group and the mobility options available to them.

Martens then adds a third feature, the so-called accessibility-sufficiency threshold (a minimum level of accessibility required, as represented by the dashed lines in

Figure 1, which allows the identification of population groups that experience accessibility shortfalls and the level of severity thereof. In this 'domain of justice', interventions are required that aim to uplift these population groups to above the sufficiency threshold(s). Such measures could range from (increased) fare subsidies, new public transport routes, bicycle lanes, to land use developments. The traditional modelling tools could still be used to analyse impacts of such accessibility shortfalls, but not perhaps the level of severity.

Martens' methodology diverges from other exemplified studies in that it encourages the establishment of accessibility standards after consultation with relevant society's residents and specialists. Despite the accessibility measurements utilizing already established calculation techniques (such as the gravity measure), this is supplemented by the measure of potential mobility, which shows how the transportation system affects the accessibility of different demographic groups (Martens, 2017). Furthermore, the Accessibility Fairness index (AFI) is also introduced in Martens approach (and subsequently has been improved in many later papers). It is based on the population impacted by the accessibility levels, and is used to rank the seriousness of accessibility deficits.

1.5 AIM AND OBJECTIVES

Apart from traditional transport planning methods largely aimed at increasing car mobility, it also favours first world/developed countries in terms of the rich outputs / results that can be derived from these tools. Data availability in these countries that inputs into these methods is typically expansive and multi-modal in nature. Applying "tried and tested" methods from other countries and cities without understanding, appreciating and acknowledging the context in which you wish to apply these methods are problematic. Africa, in general, has unique and often grass root challenges that developed countries either don't encounter or appreciate as a factor to be considered at higher levels. This holds true for transport planning and its typical approaches, as has been seen and experienced over the years. This is why the concept of transport justice and its perceived benefits are so intriguing in the context of African transport planning.

Most of Africa's public transport is informal and unscheduled and arguable haphazard in nature. Data availability is scarce and data collection is mostly ad-hoc and irregular. When it comes to transport planning, forecasting and investment prioritisation this makes it a challenging case. African cities could benefit from transport planning tools that require modest levels of data but could give rich and insightful outputs that steer transport planning, forecasting and investment prioritisation in the right direction. Data requirements for transport justice planning are modest in nature. Calculating the potential mobility and accessibility levels for all population groups requires a powerful database model developed in a statistical computing environment, combined with Geographical Information System software (GIS) to analyse and map areas of injustice based on a set of sufficiency thresholds.

The objective of this project is to test the capabilities of an open-source analytical tool; using a simple, user-friendly and rapid open-source routing engine to test the key aspects of transport justice viz. potential mobility, potential accessibility and accessibility fairness index in the context of Kigali, Rwanda and Nairobi, Kenya.

The key question is how can a new approach of transportation planning (with transport justice at the forefront) be adapted and integrated in the existing practice of transportation planning, using case study areas of Kigali and Nairobi?

The specific objectives of this study are:

1. How can an open-source analytical tool be identified and used to test the key aspects of transport justice planning in Southern Africa?
2. Can the tool rely on using basic and limited data?
3. Can a coding script be developed within the tool's environment to determine and compute the various transport justice indicators for the case study cities?
4. Are the outputs from the tool suitable to demonstrate how to evaluate the transport justice indicators for the case study cities?

The intention is that this work can be replicated in other similar African countries. Kigali and Nairobi are rapidly developing southern African countries and it would be suitable to demonstrate the tool on data from these cities to hopefully be useful in guiding future transport planning efforts in these cities.

1.6 CASE STUDY AREAS

Growing and sprawling African cities, increasing incomes and changing behavioural patterns, make conventional public transport less and less able to meet the mobility and accessibility needs of the majority of urban residents. Key government officials from various Southern African countries have started to acknowledge these challenges and pledged to work towards more nuanced and context-sensitive approaches and mitigation measures to improve mobility and accessibility in these cities. In the African context, if left unchecked, this ultimately results in a mostly unregulated growth of the "informal" transport sector, consisting of shared-ride taxis, minivans and buses, 3-wheeler, and motorcycle taxis. This study will focus on the southern African cities of Kigali (Rwanda) and Nairobi (Kenya).

1.6.1 KIGALI, RWANDA

Kigali is the economic, political and administrative hub of Rwanda. Kigali is estimated to have a population of 1,63 million people, a little over 14% of the national population of 12,6 million (Rwanda, 2022). Rwanda's urban population increased from 5,4% in 1990 to 29,8% in 2016 and is projected to reach 53% by 2050. (SSTAP, 2018a). In 2017, the nation's annual growth rate was 6,14%; by 2020, it was anticipated to reach 7,45% (World Bank, 2017).

Kigali is the primary point of entry for migrants from rural areas and beyond, due to its central location in the country. City of Kigali's Transport Master Plan (2013) reports that the city is approximately 730 km^2 in area, which translates into 0,03% of the total country's territory. As a result, Kigali is one of the most densely populated cities in Africa with approximately 1,060 people per km^2.

The national government is creating six regional cities (Rubavu, Musanze, Huye, Rusizi, Nyagatare, and Muhanga) with 100,000 residents each to reduce urbanization pressures and stimulate migration outside of Kigali City. This is supported through fundamental principles outlined in the Economic development and Poverty reduction Strategy 2 of 2013-2018

(EDPRS 2) and is guided by the revised targets of the Vision 2020 adopted in May 2012 (which outlined the objectives to be achieved as a pre-requisite for rapid growth, local upskilling and poverty reduction in Rwanda) (MINECOFIN, 2013). In order to foster local development that is evenly spread around the nation, one important overarching strategy was for the government to prioritize, promote, and support private investment. However, despite this planned decentralisation approach, Kigali continues to see tremendous growth, at a pace of roughly 4% annually. **Figure 2** shows the geographical positioning of the six regional cities in relation to the city of Kigali.

(Source: UrbanShift website: www.shiftcities.org/projects/rwanda)

Figure 2: Six regional cities across Kigali

Climate change effects has put further strain on already-strapped infrastructure, which leads to a range of interrelated problems such a lack of safe, affordable housing, a lack of open space, and deteriorating natural drainage systems. Currently, 63% of Kigali's residential settlements are informal or unplanned, frequently located in risky areas along steep hillside slopes. Despite the fact that a large portion of the urban population of Kigali has experienced significant improvements in living conditions, the majority of housing patterns in the city are still informal due to continued population influx into the city of Kigali with people seeking better opportunities. According to the 2015 Draft National Informal Settlement Upgrading Strategy published by the Ministry of Infrastructure (MININFRA), a staggering 79% of people in Kigali live in informal settlements. Interestingly this figure for Kigali has improved since 2007, when it stood at 90%; so there does appear to be positive change in this respect (MININFRA, 2015).

In terms of modal split in the city of Kigali non-motorised trips (NMT) are the highest at 52%, and in some instances even higher in the other regional cities. Nearly all Rwandan cities have a sizable number of "Abanyonzi," or bicycle taxi drivers. Although there are many cyclists, unfortunately most cities lack sufficient cycling facilities to encourage and promote this mode of transportation. Public transport trips (mostly conventional buses and shared minivans called "Matatus") contribute the next biggest share at 17%, followed closely by the very popular moto taxis (motorbike taxis) at 16%. The mode with the least share is private car at 15% as Kigali has low to moderate levels of private car ownership which is estimated at approximately 15 cars / 1,000 people (according to the City of Kigali's Transport Master Plan (2013)), however in recent years there has been a considerable spike in these statistics linked to the increase income, population and improvements in infrastructure (SSATP, 2018a).

Figure 3 highlights the modal split in Kigali as discussed above.

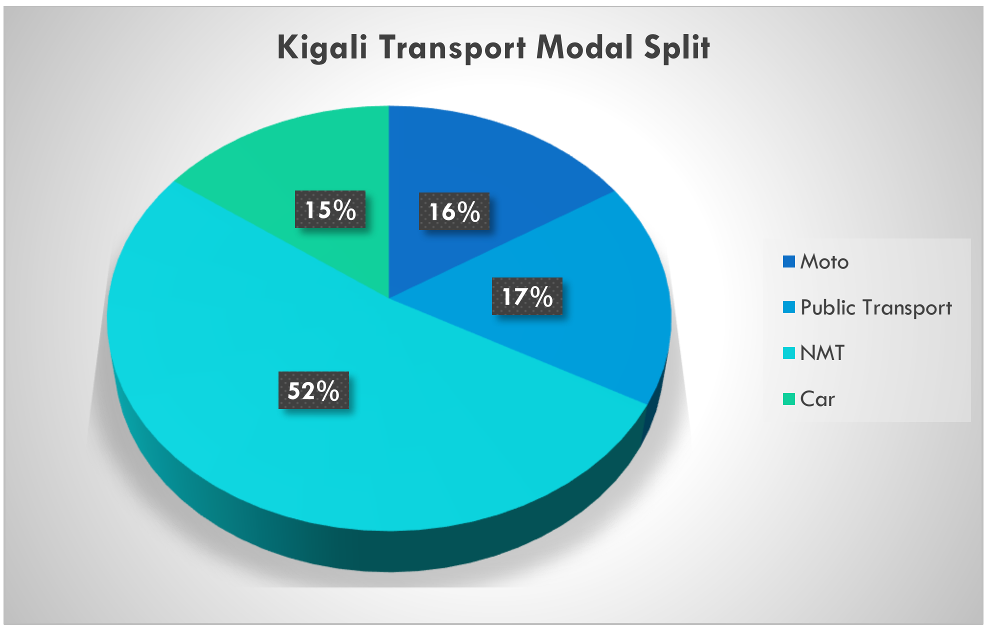


Figure 3: Kigali Modal Split (City of Kigali, 2018)

The City of Kigali Transportation Master Plan of 2013 is the most current document that leads planning and development across all modes of transport in the city (at the time of this study, this plan was being updated). However, in reality, traffic management enhancements at significant intersections within the road network in the city of Kigali are either poor or non-existent. During peak hours, traffic police are responsible for managing intersection control for vehicular traffic, as opposed to suitably conceived planning and infrastructure. At these intersections, the lack of regulated and managed pedestrian crossings exacerbates the negative impact on NMT users. A positive, however, is that major public transport interchanges are well located and connected and well utilised by public transport users (SSATP, 2018).

Despite the reliance on and rapid growth of moto taxis as a form of urban transportation, the management of these vehicles is not being improved or regulated at the same rate. They typically negatively impact NMT users (specifically during the peak periods at intersections) and also vehicular traffic flow. NMT can clearly have a position in a multimodal system as a last-mile-home service provider in the city, but it is evident that this mode needs greater attention (particularly in the planning space) (SSATP, 2018).

In Kigali paratransit operations have been formally converted into contracted bus operations from 2006 to 2013 between the national regulator Rwanda Utilities Regulatory Authority (RURA) and bus operators. However, outside Kigali most local public transport services are largely unscheduled. Furthermore, an agreement between RURA and the intercity bus operator, Rwanda Inter-Link Transport Company (RITCO Ltd), formalizes and regulates city-to-city public transport travel (SSATP, 2018a).

With government support, secondary cities have invested in road infrastructure and regulated bicycle and motorcycle taxi activities. The gradual improvement of public transportation interchange facilities shows how multimodal planning is used to put international, national, and local bus and minibus services and moto taxi ranking facilities in the same place. However, district staff, resources and road maintenance budgets need to be strengthened (SSATP, 2018).

Rwanda has a fair suite of legal frameworks for the governance of national transport and urban mobility, together with a number of important policy and strategy documents. The most important national legislation managing transportation is Rwanda's Law No. 55/2011 Governing Roads. The first public transportation policy and strategy plan for Rwanda was developed by the Ministry of Infrastructure (MININFRA) in 2011. The policy was created by a committee made up of technical personnel from the MININFRA, the City of Kigali, and the Rwanda Utilities Regulatory Authority (RURA). It was approved by the cabinet in October 2012 and served as the blueprint for the formalization of public transportation in Kigali. Rwanda is generally a progressive nation and its focus on growing the country and its people is prevalent in their Vision statements. Transport (specifically mobility and accessibility) is a key component and enabler of Rwanda's Vision.

A high-level overview of the key stakeholders in urban mobility in Rwanda are listed in **Annexure A1**.

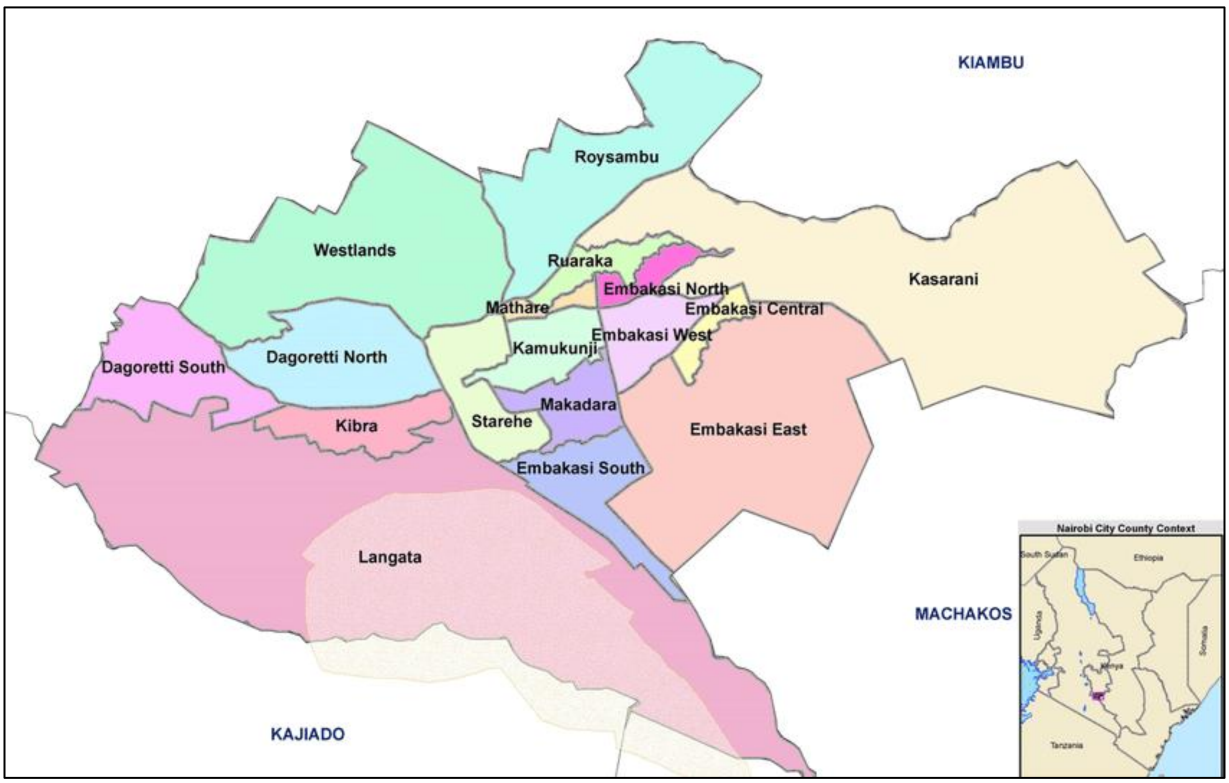
1.6.2 NAIROBI, KENYA

According to the 2019 Kenya Population and Housing Census conducted by the Kenya national Bureau of Statistics (KNBS) Kenya's total population is 47,6 million people with approximately 31,2% (14,8 million) people that live in urban areas. The urbanisation rate is projected to reach 46% by 2030. The projected population of Kenya by 2030 is expected to be 57,8 million.

Unlike its neighbouring countries, Kenya is not very urbanized. Kenyan cities are growing on average at 4,3% annually. Growth at the periphery leads to large cities, low population densities, informal settlements, and poor access to jobs and services. Residents have longer commute times, which leads to more motorized trips, thus causing undue congestion, increase in traffic crashes, pollution, greenhouse gas emissions, and more.

Nairobi city leads the urban hierarchy with a population of 4,4 million people, representing 29,6% of the total urban population in Kenya (the most populous city in Kenya) covers approximately 32,000 km^2. Nairobi is centrally located within the country and is also the administrative, political and cultural centre of Kenya. **Figure 4** shows the city of Nairobi County map and its constituency boundaries. Nairobi's local authority areas – City Council of Nairobi (684 km^2); County Councils of Kiambu, Olkejuado, Masaku and Thika; Municipal Councils of Ruiru, Thika, Kiambu, Limuru, Mavoko, and Machakos; and Town Councils of Karuri, Kikuyu, Kajiado, and Kangundo (Ministry of Nairobi Metropolitan Development, 2009).

Nairobi is the country's economic engine, accounting for half of formal employment and GDP. Nairobi has many transport projects underway e.g., BRT corridors, rail and light rail, road infrastructure, etc. Most often these projects are with international development. Nairobi Metropolitan Area Transport Authority (NaMATA) was established to organize urban mobility at the metropolitan scale, focusing on BRT implementation.



Source: Kiplagat et al (2020)

Figure 4: Nairobi City County map and constituency boundaries

Nairobi, like other sub-Saharan African countries, is growing economically and demographically, with 5,3 million residents predicted by 2030. It is currently one of Africa's most crowded cities, with long intersection waiting times and slow-moving traffic. Only 11% to 20% of public transportation users reside within a one-hour commute of their place of employment in Nairobi; making this city have one of the world's longest average commute times (aside from its traffic congestion issues) leading to an adverse effect on quality of life for its inhabitants (World Bank, 2016).

Nairobi's heavy air pollution harms pedestrians (Kinney et al, 2011; Maina et al, 2018), and high vehicle crash rates, which are linked to and exacerbated by poor infrastructure also adds to pedestrian burden (ODI, 2018).

According to Omwenga (2011) some of the major transport problems and challenges faced by the city of Nairobi include:

- "Inadequate integration of city development planning
- poor integration of the transportation network system
- inadequate public transport system to meet the rising travel demand
- long commuter distance and travel time
- high cost of transport compared to low level of income
- inadequate development of non-motorised infrastructure network
- poor safety and high incidence of motor traffic accidents, - increased pollution and deterioration of the urban environment."

Despite critical insufficiencies in NMT infrastructure, most Kenyan cities have a strong transport modal split towards walking (for example, 40% of trips in Nairobi are on foot). The matatu (mini- to medium-size buses) is the second most prevalent mode of public transportation mostly for longer trips at around 29% transport modal split. Private car modal split is approximately 12% with bus modal split around 10%. Finally, smaller vehicles that can readily navigate congested city streets are becoming increasingly vital (boda boda viz. moto-taxis and three-wheelers) and makes up 5%. Kenyan metropolitan centres are increasingly motorized and congested, however mass rapid transport systems may partially mitigate this trend. **Figure 5** shows the transport modal share split of Nairobi.

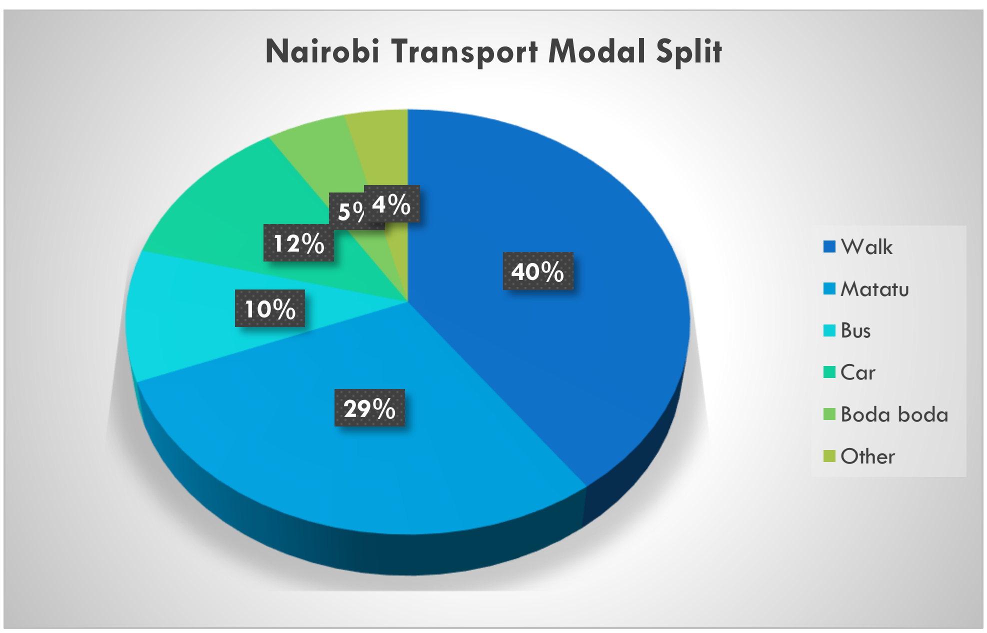


Figure 5: Transport modal split in Nairobi (World Bank, 2014)

Due to a sharp rise in the number of cars on the road, ineffective public transportation, and a lack of secure NMT facilities, traffic congestion has gotten worse in many cities in Kenya over the past decade. Future street designs must therefore provide vulnerable road users' needs first priority (SSATP, 2018b).

A high-level overview of the key stakeholders in urban mobility in Kenya are listed in **Annexure A2**.

1.7 SCOPE AND LIMITATIONS

For this study accessibility levels measured will be limited to the analysis of accessibility to employment only. Assessment of accessibility patterns vary and change in time and space. To capture the changes in accessibility levels using simple accessibility measures that differentiate between multiple accessibility measures the differences between persons and identification of population groups that are entitled to accessibility improvements are most representative. The cumulative-opportunity, inverse and exponential power gravity accessibility measures were calculated, however only the cumulative-opportunity accessibility measure will be compared and discussed.

The study focused only on the morning peak hour (between 7:30 and 8:30 am).

Two travel time thresholds (30 min and 15 min) will be considered only. The average travel time assumed during the peak hour based on all modes is 25 min (10 min for cars, 45 min for buses and 15 min for taxis) and that informed the use of the travel time thresholds.

A range of sufficiency thresholds of 10%, 30%, and 50% of the average car-based accessibility was chosen for this study to demonstrate a wide range of possibilities and variations. However only the 30% threshold will be discussed in the results.

Depending of the focus of one’s analysis many of the parameters above can be changed or selected to suit the situation or context of analysis in different cities. However, to demonstrate the objectives of this study these parameters were deemed suitable to identify and test and open-source tool.

Figure 6 details the steps undertaken in developing the transport justice analysis tool that this project is looking to unpack utilising the selected open-source tool / software package.

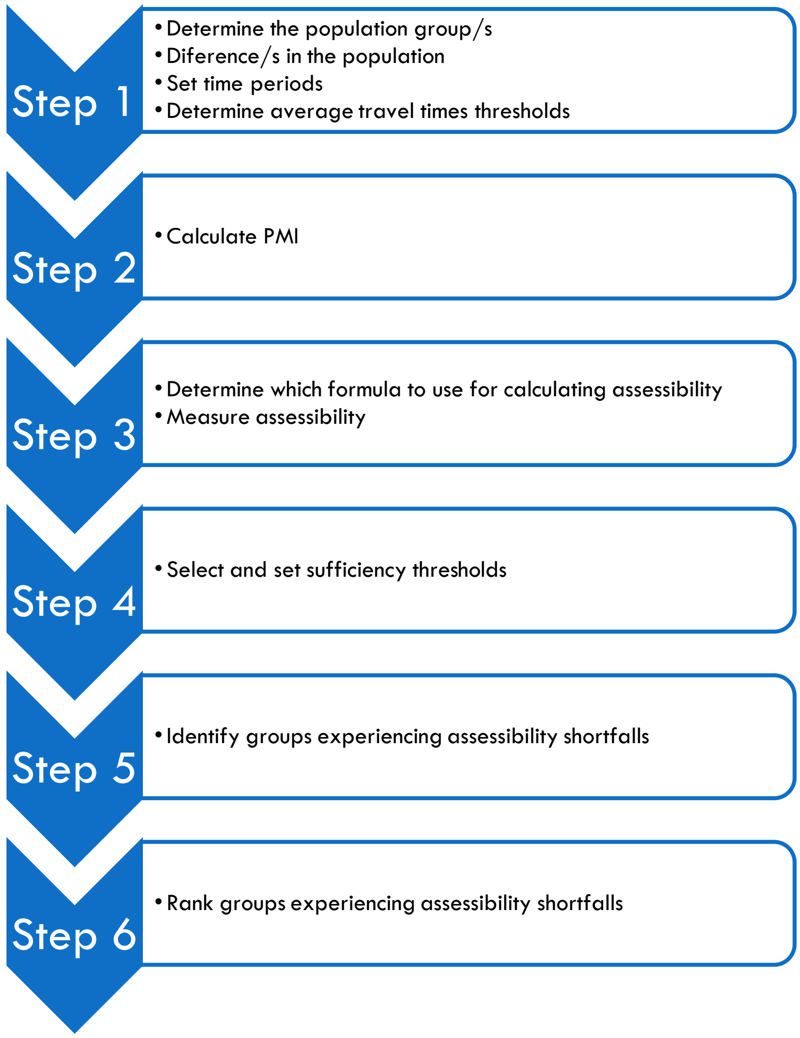


Figure 6: Steps of transportation planning for justice principles

The data requirements of this analysis tool, based on principles of justice, are relatively modest in scope. The minimum required data sets for this research project (needed in Step 1 above) included data on:

- transport analysis zones (TAZ)
- population size
- population income classes
- travel mode choice breakdown for the population
- travel times to all surrounding zones
- aerial distances between all zones
- number of jobs (employment opportunities) accessible by car or public transport modes within travel time threshold (15 and 30 minutes) per TAZ
- modal travel times to employment opportunities
- data per TAZ, such as income, main travel modes, etc.
- a road network / transport system including class of road, paved/unpaved, speed attributes, etc.

The data above is not an exhaustive list and should be expanded to ensure that the deliverables outlined in **Chapter 5** are met as required. The research project focussed on accessibility to employment opportunities; but the analysis criteria can change depending on the specific focus areas of concern.

This project will test the selected open-source tool's capabilities to generate detailed routing analysis and/or calculate travel time matrices to determine the potential mobility, potential accessibility (per measure) and accessibility fairness index within the software. This will be then used for basic evaluation of the TAZs in the case study cities.

1.8 STRUCTURE OF THE REPORT

Chapter 1: Introduces the concepts of accessibility, mobility expanding to how the transport justice approach can complement existing transportation planning. The chapter further presents the motivation, aim, objectives and limitations of the study.

Chapter 2: Gives a theoretical background based on the literature review on social exclusion, mobility, accessibility, transport justice, and transportation planning within the context of Africa.

Chapter 3: This chapter explores the chosen open-source analysis transport analysis tool and how it computes the various transport justice indicators viz. potential mobility, potential accessibility and potential accessibility fairness indices.

Chapter 4: Presents the steps of transportation planning with principles of justice and explains how these steps were followed in terms of data collection to develop the open-source analysis tool.

Chapter 5: This chapter presents the tool and its generated results and the interpretation of those results for Kigali and Nairobi as they relate to mobility and accessibility and gives possible and recommended solutions to tackle accessibility shortfalls in Kigali and Nairobi. This chapter also highlights the limitations of the study.

Chapter 6: Concludes the study, notes the advantages and disadvantages and gives recommendations for further research.

2 LITERATURE REVIEW

The focus of this chapter is to give an overview of literature related to transport planning approaches, as well as concepts that describe ‘fairness’ and ‘transport justice’ in the context of transport provision and land use planning. Furthermore, issues including social exclusion, transportation poverty, affordability, and their relationships to mobility and accessibility are examined. Given the scope of these concepts, this chapter just seeks to provide an overview of them and to highlight how they relate to some of the transport issues. In addition, the transport accessibility and mobility features of cities in some developing African countries, as well as their public transport concerns, were briefly examined. The final section explains approaches of transport justice as it relates to Rwanda and Kenya and reviews studies relating to transport justice principles as a planning tool focussed on sustainable transportation planning.

2.1 TRADITIONAL TRANSPORT PLANNING APPROACHES

South Africa (and arguably most African cities) has largely been stuck in time with regards to methods of transport modelling and fundamental principles. The aggregated four-stage computerized transport model described below is the most common model used as it is the most understood and forms the underlying basis of most models, (despite tweaks or complexity and sophistication of models and packages). This model focuses on anticipated transportation demand due to growing mobility and infrastructure needs.

The four stages of the model typically include:

1. Determining the amount of many trips that will be made (trip generation)
2. Estimating where those trips will go (trip distribution)
3. Determining the various modes that could be used to perform the trip (modal split)
4. Estimating what routes the modes will take to perform the trips (trip assignment)

Some of the intrinsic underpinnings (and critiques) of the aggregated four-stage models are:

- It would be possible to forecast future land use patterns without regard for changes in the transportation networks/ system.
- Household data averaged over transport analysis zones, would be sufficient to predict and extrapolate travel behaviour
- The relationship between household data and travel behaviour would be strong and consistent over a long period of time.
- A households travel decisions were largely hinged on minimization of cost and travel time
- Peak hour, average weekday and inter zonal vehicles trips would provide enough insight to inform decisions on transportation system improvements

Figure 7 summarises the evolution of Transport Planning Models and their specific focusses from the 1950's to present day (Behrens (2002a).

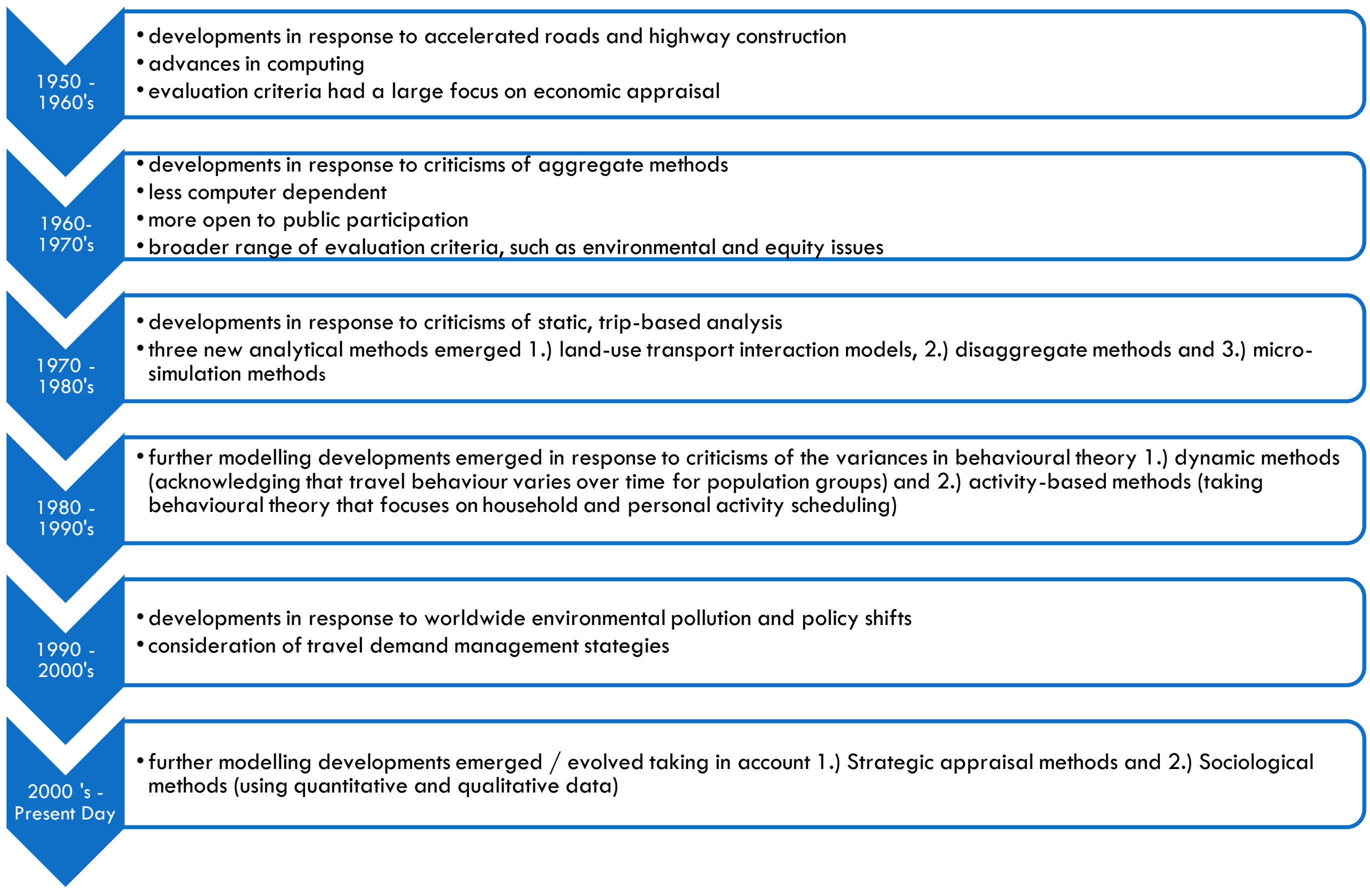


Figure 7: Evolution of Transport Planning Models

2.2 LIMITATIONS OF TRADITIONAL TRANSPORT PLANNING APPROACHES WITH RESPECT TO EQUITY

Lee (1973) from the USA and Atkins (1977) from the UK both slated large-scale urban models for being overly complex, expensive and based on unsubstantiated and biased techniques.

Further to this Kane (2001) and Behrens (2002a) presented papers which threw the spotlight on conventional transport policies and planning models (focusing on South Africa), claiming that they don't pay adequate attention to issues of transport equity (both vertically and horizontally[1]) as well as non-motorised transportation (NMT) users. Kane and Behrens (2002) summarised the historical development of transport planning (focusing on the development of transport planning models) highlighted some key milestones to get to us to where we are today.

[1] Horizontal equity assumes that people with similar needs and abilities should be treated equally; vertical equity assumes that disadvantaged groups should receive a greater share of resources (Litman, 2007).

Kane and Behrens (2002) further highlight that *"In a self-fulfilling prophesy, the four stage models built to consider road infrastructure improvements will implicitly tend to promote roads, since alternatives are not easily part of the four-stage modelling process"*

Typically, the literature largely suggests that transport planning models habitually overlook the needs of the poor or marginalized population groups and their preferred or captive travel modes. For transport planning to be holistic and fair in its considerations, demands of practitioners to do a thorough re-evaluation of the techniques that they are currently deploying in transport planning models. Planners need to not only reassess "what" they value but what they "value enough" to measure.

Vasconcellos (2001) argues that developing world countries would be better suited to 'sociological approaches' to transport planning. This would allow practitioners to focus on *"individuals instead of vehicles; lives instead of trips; within a framework of equitable provision"*.

Behrens (2004) argues that inherited inequities in transport systems can't be successfully remedied without a greater understanding of travel behaviour of the poor or marginalized population groups. Data collection methods which inform transport planning models currently lead to 'equity gaps' since they typically excluded data relating to NMT trips, non-work purposes trips and during off-peak periods trips. This in turn leads to great difficulty in ascertaining which population groups and in what way these groups may be disadvantaged in terms of transport and access to it.

Despite the reservations and critiques of the conventional four-stage aggregate transport planning model by academics and practitioners for decades it will likely continue to be utilised by planners and practitioners. The model still has value in that it is useful for providing data required for cost-benefit evaluations and assessments of operational efficiency in transport projects.

Furthermore, conventional four-stage aggregate transport planning models are not data intensive in their requirements unlike newer, more inclusive methods such as activity-based models, land-use models, dynamic network models and tour-based models. In most African country's this is convenient since data - and particularly reliable, rich data – is hard to secure or source. Acquiring such data is also expensive and quite labour intensive both from a governmental management point of view and on-the-ground collection (e.g., household surveys, travel surveys, national censuses, etc.).

Due to past criticisms of the model, model predictions, and parameter restrictions, it is likely that the forecasts will not precisely depict or predict the theoretically anticipated transport scenarios or reality Ortúzar & Willumsen (2011).

New Realist transport planning and the requirements of contemporary policy do not gel well with the inherent assumptions behind the conventional four-stage aggregate transport planning model; unfortunately, it appears that no amount of refinement, tweaks, complexity or sophistication within these models will enable them to fully meet the requirements of modern-day evaluation criterion in order to be progressive in planning and modelling.

2.3 ALTERNATIVE TRANSPORT PLANNING APPROACHES

Kane and Del Mistro (2003) present the idea of Soft Systems Methodology (SSM) and suggest that this method could have an important role to play in alternative transport planning methods.

SSM was developed in Lancaster University in an aim to apply Systems Engineering approaches to solve "management/business problems". By applying the Hard Systems approach to fix business problems, what they discovered was that "problem definition" at the onset was a challenge since different stakeholders would have different views on what constitutes the system, the purpose of the system and therefore the problem.

SSM realised that the real world is complex and messy and that different groups of people had different perceptions of the same situation based on their context or values. SSM then sought to take the messy arguments of the real world and create defendable and rational models. These are then used as a comparison to the real world, which in turns assists in judgments or recommendations as to the response to the issue or problem in the real world.

Jennings et al (2018) puts forward that the SSM method may be beneficial as an alternative transport planning approach as it focuses on the human and socio-political context of transportation and allows planners to explore and thus interpret these criterions properly.

In order for transport to focus on previously marginalized issues such as equity, accessibility, environmental impact, etc. there needs to be a shift in focus from infrastructure provision, cost efficiency, etc.

In a study by Walters (2008) that examines the overview of public transport policy developments in South Africa, she argues that the initial goal of correcting historical disparities has been overshadowed by the focus on transport system efficiency, budgetary restraints, and local labour issues (largely rooted in Apartheid spatial planning).

Kane (2006) before also agreed with these misalignments and criticized the post-Apartheid South African government for losing focus on one of its key values *("addressing poverty and redressing inequities")* but rather blindly following values fundamental in standard cost-benefit approaches, which largely (and unfortunately) misses the needs of marginalized population groups such as the poor, female, young and old.

Kane (2010) proposed the development of a *South Africa-specific Sustainable Transport Assessment Tool (STASSA)*. The indicator set included accessibility and social exclusion measures with the aim of addressing transport inequity, poverty alleviation and transport sustainability utilising the five historic types of capital: financial, natural, produced, human, and social. Kane further strengthens this framework by proposing the addition of a sixth form of capital – that of time: 'it is the ability of transport interventions to deliver time savings to the poor that distinguishes transport from other infrastructural improvements,' she suggests.

The tool would have been able to assess the way in which changes or new designs to public transport could amplify a time-constrained, marginalized individual's boundaries or perhaps increase their freedom of movement. Ultimately, facilitating a greater understanding of the newly 'acquired time' that these populations could now enjoy. For example, a parent's time is affected because they need to accompany children to school to ensure their safety; however, should improvements to road safety and security be realised and accomplished, this allows children independence thus affording parents more 'acquired time'.

Cost-Benefit Analysis (CBA) models typically with a broad stroke approach express time saving with a monetary value and prioritises efficiency over equity. The amount of time saved depends on the number of journeys made and the distances between them (savings), however this indicator has a bias towards population groups or communities that have greater car ownership and would thus benefit from projects been given the green light based on this indicator.

Focusing on travel behaviour parameters only (within a CBA model) may miss the hidden needs or desires of travel for the "travel poor" or marginalized population groups (for example predicting and accounting for trips not made due to financial constraints is challenging, or fear due to safety and security reasons, etc.) For this reason, the CBA method has a distribution "bug" which in turn inevitable leads to "inequitable decisions" as argued by Martens (2017). Furthermore, Beukers et al (2012) argued that the timesaving parameter is evaluated too late in the process and suggests that prioritisation of projects should occur earlier to avoid transport planning predispositions which may lead to inequitable decisions and proposals.

Farrington & Farrington (2005) suggests that accessibility (and its analysis) should be investigated in an integrated manner with policy development and interrogation; where it can feature centrally in the transport justice agendas. Accessibility based planning tools have the opportunity to highlight and circumvent social justice issues if used adequately and appropriately. Thus, an opportunity exists for transformation of typical utilitarian evaluations (such as the CBA method) to evaluation methods that focus on and address accessibility.

This section reviewed 3 alternative transport planning methods, namely the SSM method, the STASSA tool and the CBA model. Societal justice and its relevance in the transport context will be discussed in the next section

2.4 KEY THEORISTS FOR SOCIETAL JUSTICE

The key underpinning of social justice is the fair allocation of advantages and disadvantages through the three guiding principles of equality, need and desert that foster social inclusion (Miller, 2001). Farrington and Farrington (2005) define social inclusion as considering the distribution of advantages and disadvantages in that society and how simple (or complicated) is it for people to engage in the reasonable activities of its society.

John Bordley Rawls was an American moral and political philosopher in the liberal tradition. His "*theory of Justice*" (circa 1971) sort to provide a moral theory alternative to utilitarianism[2] which would address the problem of distributive justice (the socially just distribution of goods in a society). Further, his theory of "*justice as fairness* advocates for equal fundamental freedoms, equal opportunity, and ensuring that the most marginalized people of society receive the maximum benefit available in any scenario where disparity may be present. (Wenar, 2021)

Michael Laban Walzer is an American political theorist and public intellectual usually identified as one of the leading proponents of the communitarian[3] position in political theory. Walzer argues for his idea of "*complex equality*" (outlined in his 1983 work Spheres of Justice) as opposed to John Rawls' position that goods with varied meanings and substance may be put together into a broader category of basic goods. According to Walzer's "*distributive theory of justice*", distribution of goods may not be based on a single criterion because the society bases the value of the goods differently. It is for this reason that he developed distributive spheres for goods with distinct social meaning which can't be distributed through the criterion of free exchange such as education and health.

Various academics used the theories of Walzer and Rawls in a transport justice context which will be expanded upon in later chapters within this literature review.

2.5 SOCIETAL JUSTICE DEVELOPING INTO JUSTICE IN TRANSPORT THEORIES

The 1950s was the pivotal era where academics started contemplating social issues and how they could also relate to transport; however, it was only by the mid-1990s that saw a growing interest and evidence in the relationship between social justice and transport (Beyazit 2011).

Desert is one of the cores premises of justice; but social desert specifically, is one of the core premises of distributive justice. The idea of social desert is one that looks at how basic social resources (such as transport, safety, etc.) are distributed and allocated with an eye toward

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[2] Utilitarianism is a family of normative ethical theories that prescribe actions that maximize happiness and well-being for all affected individuals. (Duignan, 2000).

[3] Communitarianism is a philosophy that emphasises the connection between the individual and the community and is based upon the belief that a person's social identity and personality are largely moulded by community relationships.

social justice. A fair distribution of public transportation is a crucial element of a just society. Transit deserts are places where populations that rely on public transportation and are underserved by it. Measures such as the comprehensive public transit accessibility (CPTA) score were developed to evaluate accessibility to transit and to provide a holistic view of transit supply to give transit stakeholders, city officials, and organizations a uniform framework that may be widely used. (Jomehpour Chahar Aman & Smith-Colin, 2020)

Challenges such as disability, inaccessibility, race, age, gender, culture, income and class drew the attention of various academia (Banister 1994; Church et al. 2000; Bullard et al. 2000; Sánchez et al. 2003; Rajé et al. 2004; Beyazit 2011), together with indicators such as income (Cervero, Landis 1997; Leck et al. 2008; Beyazit 2011), social involvement (Putnam 2000; Banister 2005) and travel poverty (Lucas et al. 2001; Lucas et al. 2016). Supplementary to these various academics also began drawing cross cutting aspects within transport infrastructure provision and social equality and civil rights. Bullard, Johnson (1997) highlighted that transport decision making on investments and financial resources related to transport often advantage some communities and disadvantage others.

Brazilian transport planner and sociologist Eduardo A. Vasconcellos argued that traditional transport planning has not only created biased distribution of accessibility but has catalysed environmental and safety issues within urban landscapes. He highlights in his book, Urban Transport, Environment and Equity (2001), how transport policy should have a 'sociological' approach and to rather focus on the importance of social and political aspects and how a concerted effort should be made in coordinating urban, transport and traffic planning to focus on individuals instead of vehicles, and lives instead of trips, within a framework of equitable provision; also commenting on changing the view of how roads are built and used (Vasconcellos 2001).

Turkish academic, Eda Beyazit, defines social justice in transport as the fairness in the physical distribution of goods, accessibility, distribution and affordability of all modes of transport (Beyazit 2011); going further to state that transport systems have been developed on the basis of specific (industry) interests.

Swedish academic Stefan Gössling sought to identify ‘transport injustices’ in three categories exposure to traffic risks and environmental pollutants, distribution of space, and the lastly a person’s valuation of time. As such, he argues that public and political recognition of urban transport injustices provides a significant argument for changes in urban planning, transport infrastructure development and traffic management (Gössling, 2016).

As mentioned in Section 1, Dutch/Israeli academic, Karel Martens brings a new paradigm for transport planning based on principles of justice. He starts from the observation that the performance of the transport system (and the ways to improve it) have largely been the focus of transport planning and policy for the last five decades; and hardly any attention being paid to the people actually using, or failing to use, that system (Martens 2017). He asserts that the focus should radically shift towards being citizens/user centric and placing more focus on the contribution of the transport system to a person's ability to participate in activities offered by the city, thus being just (Martens 2017).

Adli and Chowdhury (2021) in their paper "A critical review of social justice theories in public transit planning" presents a critical analysis of transportation policies in regard to social justice. They argue that the theories don't specifically address social justice in the context of public transportation; rather, they concentrate on transportation as a whole. Furthermore, they argue that it is challenging to gauge the social justice results of transit planning techniques and policies and that specific social justice frameworks need to be developed and tested.

There is no one agreed-upon definition of transport justice, but there are currently a number of significant contributions to the discussion over what constitutes a fair allocation of transportation goods and services. This presents the challenge of subjectivity and what one person holds valuable in terms of transport fairness may be vastly different from the next person (and equally difficult to measure).

Pereira (2018) argues that Martens (2017) "selectively" draws on certain elements of Rawls, Dworkin and Walzer's theories on distributive justice frameworks and therefore this leads to an inconsistent framework (in the context transport). Furthermore, he argues that Martens' transportation equity framework (based on an absolute minimum level of accessibility) boils down to a sufficientarian problem. Lucas et al. (2015) and Tyler (2006) argue that increased accessibility across the board, ignoring relative distribution of accessibility, is morally questionable as it favours well-off groups (after the minimum standard has been applied for all groups). Martens' silence on issues of opportunity inequality is brought up again by Pereira. This issue is critical to many theories of justice, including the ones developed by Walzer, Rawls, and Dworkin and on which Martens' framework is based. Pereira goes on to further raise that Marten's narrow sufficientarian lens also presents critical questions of environmental justice issues e.g., excessive (auto)mobility makes alternative forms of transportation, such as public transportation, walking, and cycling less accessible by causing negative externalities like traffic accidents, air pollution, and road congestion that impair people's health. Put differently, when transport justice is reduced to a narrow lens of sufficientarianism, second and higher order consequences become invisible.

Further critiques of transport justice parameters and indices (generally) highlight that they have to be weighed alongside other concerns such as costs, economic effectiveness, budgetary restraint and environmental impacts when prioritising transport justice parameters in the overall transportation planning realm. Ultimately, the goal is to create a domain-specific standard for measuring the social justice of the transportation system, which can then be systematically used to examine the current situation and suggested policies (i.e., infrastructure improvements, tax and subsidy policies, demand responsive public transportation provision or on-demand transportation services)

2.6 THE ROLE OF TRANSPORT IN THE CONTEXT OF SOCIAL EXCLUSION

Although there is no universally agreed definition or benchmark for social exclusion, lack of participation in society is common in almost all definitions put forth by academics, government bodies, non-governmental organizations, etc. The United Nations (UN) surmises that "*social exclusion describes a state in which individuals are unable to participate fully in economic, social, political and cultural life, as well as the process leading to and sustaining such a state*." (UN, 2016). It is quite clear that the design of transportation infrastructure and organisation of transport services can hugely impact social exclusion in communities; linked to mobility disadvantages.

Transport policies also play a pivotal role in influencing the societal and spatial structure of cities; if used effectively they can guide investments and planning within the transportation sector in a positive and importantly, equitable manner. According to Litman (2014), policies are deemed fair when they benefit disadvantaged individuals in terms of mobility, inclusion in society, and the economy. Miller (2001) argues that policies and investments are unjust if they do not include those that are marginalised at the time; consequentially those that were marginalised have been dealt an inequitable hand and end up carrying more burden and being less advantaged than other groups.

The South African National Department of Transport (NDoT) together with UK academic Karen Lucas was possibly the first to look at the link between transportation and social exclusion in a developing nation focusing on social inclusion. It was the first research of its kind in South Africa to actively involve various demographic groups in discussions about their issues with regard to accessibility and transportation as well as how transport poverty impacts their day-to-day lives; and is one of the few qualitative studies in the field which involved focus group discussions the urban and peri-urban poor in Tshwane, Gauteng Province.

Lucas was particularly interested in assessing whether the concept of social exclusion was a valid one, especially since the majority of the population within the focus group area experienced transport and income poverty (Lucas, 2011). The outcome of the study identified and concluded that in addition to the pressures of basic daily survival (central to most low-income South African's everyday lives) transport poverty was also an important issue for them. Most participants felt that properly coordinated, available and cost effective local public transport services could help them gain considerable economic and social benefits (Lucas, 2011).

Looking critically at South Africa from a social inclusion stand point its Bill of Rights is arguably the part of the Constitution that has had the greatest impact on life. It enshrines the rights of all people in the country and affirms the democratic values of human dignity, equality and freedom. The Bill implicitly entrenches mobility and the right to mobility within the context of human dignity and rights. Without sufficient access to mobility a person's rights to access jobs, education, food, health care and clean water are impinged. Further, national transport policy in SA recognizes public transport as a 'basic need', placing public transport on an equal footing with other government priorities such as adequate housing, and water and sanitation (NDoT, 2007; Jennings, 2018). Based on the above, this could be why a transport-justice / right based framework has had more momentum in South Africa when compared to other developing countries and countries in Africa.

However, Pirie (2009) argues that despite SA's progressive Constitution, transport disadvantage beyond wellbeing still remains a direct challenge. He offers controversial proposals such as disadvantaged people being compensation for 'immobility'. He further probes on whether a rights-based mobility frameworks (open to judicial scrutiny) should be developed and aimed at countries founded on geographic immobility. He also asks which mobility provisions and practices might be made constitutionally 'just' and which 'unjust' and the consequences thereof. '*More pertinently, how can shocking public transport infrastructure and service in many parts of Africa be turned from a bland matter of budgetary allocation, and then managerial failure, into a question of human rights infringement? Can the persistent cumulative advantages given to car owners and users be addressed in law as an issue of social and environmental inequity*?' (Pirie, 2009).

A relatively new term in the transport planning realm is that of hypermobility and one that also impacts on social exclusion. Most modern modes of transport are designed to operate at higher speeds (mobility) and increased accessibility. However, the unintended consequence of this (together with a rapid expansion of the transport system focused largely on cars as a mode) leads to a condition of imbalanced mobility more commonly known as "hypermobility". This in turn leads to businesses being less productive, using more fuel, causing more pollution, and wasting countless hours of the society's time (Khisty & Zeitler 2001).

Land use also plays a role in contributing to inaccessibility and social exclusion. The lack of access to opportunities caused by spatial separation brings about social exclusion (Preston & Rajé, 2007). Urban sprawl causes cities to develop outwards and to the peripherals of the city boundaries due to a rapid increase in urban population. People living at these peripherals are often subjected to poor municipal services such as public transit services. It is thus often difficult to access services and opportunities due to lack of cars, high transit fare due to the distance the populations are placed at and inability to effectively use non-motorised transport due to the distance to the city centre (Vasconcellos 2001). Therefore, social exclusion is not only perpetuated by lack of transportation but interaction of a range of factors. Similarly, transportation alone can't unravel exclusion issues, however, it is essential for enabling social inclusion. Similarly social exclusion is an interaction of a range of factors hence addressing social exclusion should be a robust approach across different government agencies (Lucas et al. 2016).

2.7 GLOBAL POLICY AROUND SUSTAINABLE CITIES AND COMMUNITIES

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations (UN) in 2015 as a universal call to action to address the global challenges we face, including poverty, inequality, climate change, environmental degradation, peace and justice by 2030 for all people to enjoy; setting out a supremely ambitious and transformational vision. This is captured in the 17 SDGs that are aimed at freeing all nations and all segments of society from the challenges. Enshrined in the 2030 Agenda for Sustainable Development is the principle that every person should reap the benefits of prosperity and enjoy minimum standards of well-being.

The UN estimates that by 2050, two-thirds of the world population at that time (some 6.5 billion people) will live in urban spaces. Sustainable development can't be achieved without significantly transforming the way we build and manage our urban spaces. Transforming and maintaining sustainable cities means creating career and business opportunities, safe and affordable housing, and building resilient societies and economies. It involves investment in public transport, creating green public spaces, and improving urban planning and management in participatory and inclusive ways.

SDG 11 (Sustainable Cities and Communities) and particularly SDG 11.2 reads "*by 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons*". (UN, 2022). This links to the principles and focus of transport justice.

One of the current proposed indicators to measure progress along SDG 11.2 is the percentage of people within 500m of public transport services at a frequency of at least every 20 minutes. However, Quiros, Kerhners, & Avner (2019) argue that focusing on accessibility to jobs would be a more meaningful indicator, rather than proximity to transport services. Ultimately, the goal of transit systems is to link people to various opportunities i.e., economic, education, health care, etc.

2.8 REVIEW OF TRANSPORT JUSTICE PRINCIPLES AS A PLANNING TOOL IN AFRICA

According to the World Bank (2018), approximately 60% of the African population reside in rural areas which ultimately leads to limited access to education and health care; exacerbated by limited, affordable transportation options and infrastructure.

The WHO reports that Africa has the least number of car ownership (2%) however, a disproportionately high number of motor vehicle deaths; 16% road deaths, of which 38% accounts for pedestrians (WHO, 2013). Transport justice principles, specifically in Africa, if adopted could completely disrupt and revolutionise the way in which public transport interventions are planned, prioritised and evaluated.

There is a rapidly growing body of international literature on transport justice or equity together with a number of studies have been done in Africa founded on the principles of transport justice (investigating accessibility and mobility) often with the lens of "social exclusion as the core of most studies. Additionally, there is a growing interest in transport justice in South Africa (largely as policies or interventions that reduce the consequences of transport disadvantage), which is primarily catalysed by the implementation of BRT and the expectations they have sparked for better and more equal mobility. There are not that many quantitative studies though that actually measure transport justice, let alone studies that use open-source software packages making this form of transport planning and evaluation accessible to all key stakeholder and transport policymakers

Bryceson et al. (2010) in their study ‘Livelihoods, daily mobility, and poverty in Sub-Saharan Africa’, found that low-income earners make more shopping trips since they buy small amount frequently as opposed to high-income earners who may make less trips as they stock pile more. In the urban context, this exposes them to the harsh public transportation system more than necessary and increases their transportation expenditure.

A report conducted by the International Network for Transport and Accessibility in Low income Communities (INTALInC, 2019) titled Transport and social exclusion in five African cities gives a high level overview of the transport conditions and experiences of communities living in five selected case study cities viz. Cape Coast in Ghana, Cape Town in South Africa, Kampala in Uganda, Lagos in Nigeria and Nairobi in Kenya. By using desktop research and an anecdotal approach it looked at each city and how transport affects citizen’s everyday activities and livelihoods. Five key issues were identified across the five national studies:

1. Spatial exclusion and enforced mobility
2. Walking and the travel burdens of the urban poor
3. Exclusion from public and informal transport
4. Social exclusion as an outcome of transport exclusion
5. Transport inclusion as essential to realisation of the SDGs of African Cities

The report further stresses the need for suitable data (both quantitative and qualitative) as being critical for the development of evidence-informed policies in the African cities. This is turn can be used to enable policymakers to draw better conclusions about the mobility and accessibility challenges faced by poor urban communities.

Padaychee (2019) looked at the connection between transportation and social exclusion in Johannesburg, South Africa's Alexandra Township. The study outlined the intricate connection between transportation and social exclusion and reiterated the need for South African urban planners to take this relationship into account. In this township, women in particular continue to experience social exclusion. However, an intriguing finding was that people in this township do not remain passive in the face of transportation disadvantage; rather, they react in ways that help them manage and survive. The study concluded that because the connection between transportation and social exclusion has not been made in South African policy and implementation circles, it is unreasonable to think that a change toward a gender-based approach to transportation planning in South Africa is foreseeable.

In the Mistra Urban Futures Annual Report of 2018, author Sean Cooke’s article (Transport Justice for Poverty Reduction) notes that accessibility should be the primary focus for transport planning and infrastructure investment within the lens of the ‘transport justice’ approach. It is evident that many public and NMT users that fall within the categories of lower-income, older or female have levels of accessibility far below the minimum. Cooke (2019) writes "*A central tenet of this perspective is that there is a minimum level of accessibility that a transport system should provide every user, irrespective of their income, gender, age, spatial location or any other characteristic.*" The author further proposed that these vulnerable users should be given special consideration and assistance in order to enhance their accessibility to the bare minimum. Cooke further surmises that Transit-Oriented Development (TOD) is an important planning method that should be explored more as it shares some of the philosophies of transport justice where it aims to integrate public transportation and urban development; thereby catalysing economic and societal goals. One of the most important societal goals is the improvement of accessibility through spatial restructuring, which will help to restore some of the damage caused by Apartheid-era spatial design. TOD planning and measures in Cape Town should not be conceived as forcing people out of their automobiles, but rather being encouraged to invest in accessibility improvements for individuals who have long been unable to obtain even the most basic of services largely due to spatial segregation.

Critics in the academic world been argued that South Africa over-emphasises major transport infrastructure projects such as bus rapid transit (BRT) or the Gautrain (premium, higher-speed express commuter rail system in Gauteng). These system designs may not necessarily be appropriate or effective in low-income populations that are mostly captive public transport users. Gautrain specifically has been slated for being a 'political symbol' deepening mobility-related exclusion of low-income communities in Gauteng; and it's argued that it diverted public funding from other public transportation projects that could have provided a more integrated public transport system benefiting more users resulting in different, less expensive, more context-specific and gender-sensitive solutions. Mahapa and Mishiri (2001), who considered the transport needs of low-income populations in rural areas in South Africa, criticised transport policymakers with being too focused on higher technology fixes and efficiency savings rather than the travel needs of local 'beneficiary' communities. Similarly, Venter and Vaz (2012), in a quantitative critical review (small-sample household survey conducted in Soweto) of the poverty impacts of the Rea Vaya BRT system in Johannesburg found that the direct benefits of Rea Vaya are skewed in favour of middle rather than lower income residents. They proposed that the BRT system design focussed on enhancement of access to a variety of activities, rather than its direct expansion of accessibility to work opportunities (which would have benefited low-income communities more). Chakwisiza et al. (2011) further highlight South Africa's BRT failings in its network design space and note that most BRT spatial configurations and route alignments generally mimic prevailing operational and economic alignments and trunk services. This ultimately leads to reinforcing the hereditary geographical and spatial accessibility and mobility challenges in urban areas of South Africa (to the most disbenefits to low-income communities). Del Mistro and Maunganidze (2012) investigated the MyCiTi BRT service in Cape Town and reviewed the predicted BRT-based service levels against the actual service levels at the time. The study concluded that the services were not clearly beneficial to low-income communities in terms of service level improvements. 'While the poor commuters may benefit from more accessible, frequent and faster services as well as reduced travel times, ironically, these will be more expensive and, in some cases, unaffordable to them and therefore of no benefit to them.'

BRT systems, in their entirety, are by no means a total failing; Jennings (2015) notes that systems in Bogota (Colombia), Mexico City (Mexico), Jakarta (Indonesia) and Lagos (Nigeria) have been successful in delivering lower-cost, higher-quality mobility options to outlying areas, producing travel-time savings, cost savings and reducing waiting times. For example, some of the critical success factors of the Lagos BRT-Lite System (Africa's first BRT system) was the effort to define a form of BRT that meets local user needs, is appropriate to the context in which it is placed, and is affordable and deliverable in the broadest sense.

Venter et al (2019) presented a quantitative analysis of two typical "Global South" cities; Johannesburg, South Africa, and Mexico City, Mexico aimed at being illustrative case studies of the transportation problems facing the under-served urban residents. The term refers to the regions of Latin America, Asia, Africa, and Oceania that are largely (although not solely) low to middle income and often have similar socio-economic and political characteristics. The study calculated accessibility (to jobs specifically) using the cumulative opportunity measure method as well as Conveyal's Analysis package, a GIS based tool, to calculate the travel times of actual transit routes and transfers provided by operators (both formal and informal). The mobility metric was calculated taking the highest reported trip type / reason then normalizing the travel time and travel cost for this trip type (and taking the highest values from each City), relative to the overall average travel time and cost in Johannesburg and Mexico City. The results were then translated into a four-quadrant analysis that examined accessibility levels together with time and money spent on transportation. The accessibility-mobility framework summarised four groups of urban residents; either under-served by transportation (the stranded under-served and the mobile under-served) or well located in terms of access to opportunities (well-located commuters and well-located urbanites). The accessibility analysis revealed that there was an unequal distribution of accessibility to jobs in each city. Johannesburg showed an average access to jobs of 49%, however 42% of residents had below average access to jobs. Mexico City showed worse results with the average access to jobs of 37%, however 56% of residents had below average access to jobs. The mobility analysis component of the study categorised residents of each city according to their level of access and their mobility expenditures and is summarised in **Table 1.**

Table 1: Summary of Mobility Analysis for Johannesburg and Mexico City

Levels of Access	Johannesburg (% residents)	Mexico City (% residents)
Mobile under-served	25%	25%
Stranded under-served	17%	31%
Well-located commuters	49%	37%
Well-located urbanites	9%	7%

The study concluded that considering the results of the accessibility and mobility of each city two broad shifts are needed to improve travel conditions for the transport under-served urban residents:

1. Provide better access to opportunities and better mobility options for the stranded under-served.
2. Reduce mobility costs for the mobile under-served.

The qualitative research study of Lerango (2011) titled *"Sustainable Transport System: Mobility and Accessibility in Addis Ababa"* evaluated the sustainability of the transport system in Addis Ababa, Ethiopia which included performance indicators and sustainability goals (economic, social and environmental in its evaluation. With a focus on transportation sustainability, the study primarily provided insights into the problems that affect mobility and accessibility and reported that Addis Ababa has *"disorganized and unsustainable public transport service, inadequate road transport infrastructures, and lack of effective traffic management, very limited transport mode choice and prevalence of environmentally unfriendly transport practice which all together complicates the city's mobility characteristics especially for marginalized groups (e.g. urban poor)."* Lerango (2011). The study concludes that transport planning in Addis Ababa should be centred on accessibility, encouraging environmentally friendly transport modes, promoting public private partnership and developing alternative mass transit options.

The quantitative study of Maliwa (2019) titled *"Transit Accessibility and Equity Evaluation of Bus Rapid Transit System: The case of Dar es Salaam, Tanzania"* sought to evaluate the equity based on accessibility to formal job locations across socio-economic groups who were within 20 minutes walking distance to the proposed Dar es Salaam Bus Rapid Transit (DART) system. Additionally, it looked into probable residential areas close to the DART system to propose adding extensions to the system in order to improve equity in the city. The study adopted spatial and statistical methods (using GIS-based network analysis) to estimate the physical accessibility together with Lorenz and Gini-indices (using Excel and SPSS software) to measure inequity levels across the socio-economic groups. Predictably, the study concluded that although the DART connected Dar es Salaam's population to dispersed formal jobs opportunities, this was only applicable to the least and fairly deprived population groups (those located nearby the job concentration areas and with good DART coverage) compared to the most and highly deprived population groups (those at the outskirts of the city with limited DART coverage). Additionally, the equity evaluation showed that the most deprived population have a relative high degree of inequity to job locations than other deprived groups at all travel times. According to this trend, any expansions to the BRT system in Dar es Salaam could favour socio-economically affluent neighbourhoods more than less affluent areas, especially those on the outskirts of the city, if there is no intervention.

The City of Cape Town local municipality in terms of their transport planning has already begun considering equity, transport disadvantage and sustainable communities. The 2013 ITP Review was the first published public document which included a chapter titled *'Social Sustainability Framework for Transport in Cape Town'*, which states that:

"Focus is seldom placed on social dimensions of transport when it comes to transport related research, policy, planning and practice. Environmental, energy and economic factors tend to feature to a much higher degree. …The social impacts of transport decision-making are fundamentally undermining quality of life and the social wellbeing of citizens in towns, cities and rural settlements. Conversely, full and transparent consideration of these outcomes can significantly increase the quality, effectiveness and efficiency of both the transport system and a number of other important areas of economic and social policy delivery, including employment, health, education and economic development."

The document outlines three social sustainability principles:

- quality of life
- equity, and
- social cohesion

These recommendations emphasize the significance of access, including access for those with specific mobility needs, access to education, employment, community resources, and access to basic needs. However, it is unclear how to measure these in practice or how to incorporate them into the decision-making process (Jennings, 2015).

2.9 REVIEW OF TRANSPORT JUSTICE PRINCIPLES AS A PLANNING TOOL IN RWANDA AND KENYA

SSATP, the Africa Transport Policy Programme, established in 1987, is an international partnership of 42 African countries, eight regional economic communities (RECs), 2 continental institutions (African Union Commission and United Nations Economic Commission for Africa), public and private sector organisations, and international development agencies and organisations. The programme supports African countries to strengthen their policies and strategies to promote sustainable transport for economic growth and poverty reduction. Within the framework of its urban transport and mobility pillar, the SSATP launched an activity to support eight pilot countries (Ivory Coast, Ethiopia, Guinea, Ghana, Kenya, Nigeria, Rwanda, and Senegal) in the development of policies to improve accessibility and mobility in urban areas of Africa. The outcome was a conceptual framework for action paper addressed to policy and decision-makers in these City's titled "*Policies for Sustainable Accessibility and Mobility in Urban Areas of Africa*" (SSTAP, 2015). In Rwanda, this work was led in close partnership with the National Ministry of Infrastructure (MININFRA) and within this Ministry, the Minister of State for Transport in developing the country specific paper titled "*Policies for Sustainable Accessibility and Mobility in Cities of Rwanda*" (SSTAP 2018a). As similar document was developed for Kenya titled "*Policies for Sustainable Accessibility and Mobility in Cities of Kenya*" (SSTAP 2018b). This work was led in close partnership with the Ministry of Transport, Infrastructure, Housing and Urban Development in Kenya.

The works focused primarily on the main issues of mobility and accessibility by determining and focusing priority areas in the cities of the case study areas:

1. Strengthening the institutional framework for urban transport management
2. The creation of funding sources dedicated to the management of urban transport
3. Promoting the effective participation of civil society in urban transport management
4. Improvement of multi-modal planning and operation of city centres
5. Improving the performance of public transport (in particular the reform of small-scale transport)
6. Organization and implementation of national government assistance for the management of urban transport in secondary cities

This study intends to transform how key stakeholders and decision-makers view accessibility and mobility and to inform them on the benefits of adopting sound national and local policies, strategies, and operational practices that include these parameters that can significantly improve urban transportation and mobility in African cities.

The SSTAP report for Rwanda (SSTAP 2018a) began with a diagnosis of urban mobility trends in Rwanda; established through the experience of the mobilized experts, field visits to the cities of Kigali and Musanze, interviews with national and local political and technical leaders, as well as an in-depth analysis of relevant documents and data. The established Rwandan Urban Mobility Forum, utilising the EASI concept the analysis led to the proposal of a pragmatic list of top priority recommendations as well as the drafting of an action plan to transform the mobility conditions for the population living in urban areas in Rwanda.

The top four noteworthy priorities for Rwanda that emanated from the EASI concept are listed below:

1. "Improve urban road infrastructure in Kigali with the view to create dedicated high occupancy vehicle lanes and facilitate the development of Mass Rapid Transit in order to enhance modal shift from private to public transport vehicles.
2. Prioritize Public Transport interchange and bus termini improvement in Kigali in order to improve vehicular flow and passenger safety as well as attractiveness and functionality of these interchanges
3. Build the requisite spatial planning and urban mobility capacity at City and District level, both at a human resource and partnership level
4. Develop a customized NMT infrastructure network in Kigali and "secondary" cities in order to facilitate access to public transport from informal settlements and better connect the various parts of the cities." (SSTAP 2018a)

Similarly, the SSTAP report for Kenya (2018b) assessed urban mobility trends in Kenya by field visits to the cities of Nairobi and Mombasa, undertaking interviews with national and local political and technical leaders, as well as an in-depth analysis of relevant documents and data.

The top four noteworthy priorities for Kenya that emanated from the EASI concept are listed below:

1. "Develop a clear finance and fiscal framework, increasing the legibility and predictability of public contributions to the public transport sector.
2. Better integrate land use and transport planning in urban areas, through the preparation of integrated multimodal urban development plans.
3. Avoid mistakes made by others in implementing Mass Rapid Transit systems, in particular with regard to excessive focus on infrastructure investment, and insufficient foresight of operations.
4. Improve the Nairobi traffic signalling system, starting with the definition of a traffic management strategy" (SSTAP 2018b)

The analysis aspires to become a powerful policy tool to improve accessibility and mobility in urban areas of Rwanda and Nairobi (SSTAP, 2018a & SSTAP, 2018b).

Further investigation into similar research in Kigali specifically found the quantitative study from Bajpai et al. (2016) where the primary objective of this study was to introduce accessibility principles for improved planning and monitoring of interventions in Kigali. The study aimed to provide awareness to Kigali Transport planners and decision makers on the power of accessibility as a criterion for planning, decision-making, and monitoring and evaluating of the city's overall performance. The study used a simple open-source mapping tool which could measure the impacts of planned investments or policies on accessibility to job opportunities and Conveyal's accessibility analysis package called Transport Analyst (also open-source, web-based package powered by OpenTripPlanner (OTP)) to calculate travel times. It was founded on the isochronic measure of accessibility which counted the number of opportunities that could be reached from a location by public bus, within 60 minutes during the morning peak hours or distance or cost. Conveyal's Transport Analyst uses bus and road network data, bus service attributes, and locations of opportunities and population data to calculate the accessibility of each location in the city (100 square metre cells). The study tested 7 scenarios to examine the accessibility level fluctuations if certain changes were affected to the public transport network (e.g., changes in journey speeds, introduction of BRT corridors, etc.) A high-level summary of the base case results showed that given the concentration of businesses and people along major highways and bus routes in the central city of Kigali, a significant majority of the population (almost 64%) has easy access to employment; with the average percentage of jobs accessible by bus in 60 minutes being 58% and the average percentage of people living below the accessibility mean landing at 36%. However, similarly to the study of Maliwa (2019) in Dar es Salaam, as one moves away from major thoroughfares and the city centre, overall accessibility tends to dwindle (which was shown visually using the GIS mapping tool).

2.10 DEFINING THE PRINCIPLES OF TRANSPORT JUSTICE

As previously outlined, the focus of transport planning methods should radically shift towards being citizen/user centric. Understanding the contribution of the transport system to a person's ability to participate in activities within their communities arguable holds more weight than the previously biased focus to improved car mobility that this space has enjoyed for far too long.

The following section will expand upon and further define the fundamental principles of transport justice and highlight how it can be used as an additional tool within the transport modelling space and how the traditional transport modelling space can be steered towards being more citizen/user centric.

2.10.1 ACCESSIBILITY

Martens (2012) proposes that inequality in accessibility is inevitable and unavoidable due to the creation of centres and thus peripherals in space. In most developing African countries (as in the case of Kigali, Rwanda and Nairobi, Kenya), this is a stark reality and one that should be considered in forward thinking transport planning principles.

Rural populations are often the most negatively impacted by lack of accessibility since they can't always rely on NMT due to distances. Although there may be similarities in the accessibility constraints between rural and urban areas, there are differences in the levels of mobility for each. Thus, it stands to reason that if transport planners observe the growth pattern, service provision, and equality of a city by using accessibility as a lens it could unlock how cities connect individuals with opportunities effectively.

Farrington & Farrington (2005) in their paper defining a conceptual framework placing accessibility centrally in the social justice and social inclusion agenda notes that UK policies aimed at social inclusion have largely overlooked poverty of access; but rather focussed on issues of poverty, income, age, and gender. And while these issues can result in access poverty, considering access poverty as a factor in its own right inserts spatial consideration in policies designed to address social justice.

Both Martens (2012) and Pereira, Schwanen, & Banister (2016) advocate that the distinct social meaning of transportation lies in *accessibility*. Martens & Golub (2011) uniquely combined the theories of Walzer and Rawls in a transport justice context and focused on *access* as the major benefit of transport. They argue that transportation improvements are only fairly distributed if the gap between the lowest and highest accessibility (by mode or in space) is as small as possible or limited, while average access is maximised. They further expand by stating that the examination of access levels should be the emphasis of transportation planning authorities: "*this would be a most just approach, considering the importance of access in determining life chances.*"

Both Martens (2017) and Litman (2011) define accessibility as the potential of opportunities for interaction coupled with the ease of accessing these opportunities with a transport system It is challenging to quantify accessibility since it is a multi-dimensional concept.

Kwan (1998) argues that conventional integral measures of accessibility have several limitations, especially when evaluating individual accessibility. She suggests that the measure to be used depends on the purpose and situation. Wee et al (2013) propose measuring accessibility taking four different components of accessibility into account:

1. Transportation (centring on the transportation system)
2. Temporal component (taking into account the time of day and the amount of time individuals have to engage in activities)
3. People component (examines how a person's level of accessibility is influenced by their wealth, physical capabilities, needs, hobbies, and education)
4. Land-use component (pertains to the geographic distribution of opportunities and measures the availability and demand for opportunities)

Wee et al., 2013 further propose using two or more accessibility components which they placed in four categories of accessibility measures:

1. Infrastructure based (used in transportation planning and solely focuses on supply and demand of infrastructures)
2. Utility-based (focus on persons' benefits from the spatial distribution of activities. It is based on the utility theory; people choose the option that maximizes their utility (Makri & Carolin, 1969))
3. Location-based (these are typically macro-level measures that investigate access to an opportunity such as employment between origins within a specified travel time interval such as cumulative and gravity-based accessibility measures (Kwan, 1998; Makri & Carolin, 1969))
4. Person-based (focused on how easily a person can access activity locations (Kwan, 1998))

Morris et al (1978) finally propose the following guidelines that one should consider when choosing an accessibility measure:

1. The indicator should include a spatial separation component that adapts to changes in the transport system's performance.
2. The measure should be based on solid behavioural principles.
3. The indicator should be easy operationally and technically viable
4. The measure should be easy to understand and clear to the layman.

Several authors (Krizek et al., 2009; Golub & Martens, 2014; Guzman et al., 2017) have studied accessibility provided by transportation, using a range of measures and indicators, but mostly to income and employment opportunities. This goes to show how influential income and employment opportunities are believed to affect access to opportunities.

Peralta-Quiros et al. (2019) developed a novel methodology in assessing transit accessibility in 11 African countries, (including Rwanda and Nairobi). They used the concepts of the Lorenz curve[4] and Gini coefficient[5] to represent accessibility distribution in the cities whilst attempting to overcome two significant data challenges that are very often encountered in African countries and other developing countries viz.

1. the scarcity of information on employment distribution (spatially), and
2. the lack of adequate GTFS data (detailing transit routes and journey times for modes)

Despite the lack of data in some cities the analysis looked at estimating the distribution of employment opportunities and overlayed that with comprehensive mapping of informal transit networks and how this performed in connecting people to employment opportunities. Further to this the study highlighted that this method could be used for assessment of future transport investments and/or land use changes whilst overcoming data scarce environments.

The data used for Kigali was sourced from the International Growth Centre (IGC) for another study on accessibility performed in 2016 (viz. GTFS data, population, etc.), whilst the employment data came from the establishment census, finalised in 2017, which gave information on the number of employees for each city sector.

While the study revealed some trends and patterns in urban spatial development of cities, in general, three distribution typologies in terms of equity were found:

1. Equitable Cities
2. In-equitable Cities
3. In-between Cities

Although Kigali placed well in the "Equitable Cities" typology by displaying low levels of spatial inequality in accessibility (Gini coefficients of 0.26) it differed drastically with regards to the average share of accessible jobs that people could connect to within 60 mins; with the third worst percentage in this regard with 15.2% average accessibility.

Nairobi had slightly better levels of spatial inequality in accessibility (Gini coefficients of 0.36) and had marginally better average share of accessible jobs that people could connect to within 60mins; with the fifth worst percentage in this regard with 28.5%. Both Nairobi and Kigali placed in the second half of results in terms of average accessibility.

The methodology is also scalable and can be further built on to understand the dynamics and challenges of urban agglomeration in Africa. Peralta-Quiros et al. (2019) further proposed that *"It can potentially serve as a component for transport planning, transit-oriented development, land use planning, and investments in increasing labour markets and employment opportunities in African cities."*

[4] Lorenz Curve is a graphical representation of income inequality.
[5] Gini coefficient measures the deviation of the income distribution from a totally equal distribution.

Potential Accessibility

The level of accessibility experienced by a person is determined by the *spatial distribution of activities*, *by the available transportation systems, and by a person's ability to overcome spatial separation*. That ability is, in turn, shaped by the resources available to a person, in terms of time, money, vehicle ownership, knowledge of the transportation systems, knowledge of the spatial pattern of activities, physical and cognitive capabilities, ability to handle discomfort, concerns about personal safety, and so on. Accessibility has multiple dimensions and is likely to show substantial variation over time.

First, it may be clear from the description above that there is not one single and best way to measure accessibility. Since accessibility varies by purpose and changes over time and in accordance with circumstances, it would be a mistake to search for a measure that 'most accurately' captures accessibility as experienced by persons. The measurement of accessibility is thus a measurement of the risk of participation poverty, i.e., of the chance that a person will experience a lack of activity participation due to problems in accessibility.

To gain a substantial understanding of accessibility levels experienced, it is ideal for measuring access to different activities, to encompass people's interest in a range of opportunities and to identify people that could be entitled to increased accessibility. Martens (2017) recommended using various spatial scales and at different times of the day to capture the changes in accessibility levels e.g., access to the health care may be better during off-peak hours due to less congestion on the roads.

Two types of integral accessibility indices, namely, two gravity-types and one cumulative-opportunity measure, are specified for this comparative analysis.

These types of accessibility indices are selected based on three criteria:

a) They take into account the effect of both the transportation network and spatial distribution of opportunities
b) They do not require the derivation of additional theoretical constructs like the utility function and therefore the operationalization tasks of the study are simplified
c) They do not merely focus on accessibility to infrastructural facilities such as hospitals or fire stations, but generally applicable to the problem of access to various urban opportunities

Equation 1: Inverse power gravity accessibility measure

$$\boldsymbol{A(i,m) = \sum W_j.(t_{ij,m})^{-\alpha}\ \forall i,m \qquad [\alpha\ =\ 0,8]}$$

Equation 2: Exponential gravity accessibility measure

$$\boldsymbol{A(i,m) = \sum W_j\,.\,e^{-\beta(t_{ij,m})}\ \forall i,m \qquad [\beta\ =\ 0,22]}$$

Equation 3: Cumulative accessibility measure

$$A(i,m) = \sum W_j \cdot \left(1 - \frac{t_{ij,m}}{T_{ij,m}}\right) \ \forall i,m \qquad T_{(ij,m)} \leq \ 30\ (min)$$

where:

- A(i,m) = zone accessibility level for mode m
- α = Travel impedance parameter
- $t_{ij,m}$ = travel time in minutes between zone i and j for mode m
- β = region's travel impedance
- W_j = Number of opportunities in destination zone j
- $T_{ij,m}$ = Travel time threshold in minutes

In terms of the two gravity-type accessibility measures the parameter estimates for this study were selected as α = 0,8 for the inverse power function and β = 0,22 of the exponential function as proposed by Kwan (1998). In Kwan's study she outlined estimates that can be used in the absence of calibrated parameters.

It is envisaged that this study will calculate the three options of accessibility measures, however only the cumulative accessibility measure will be discussed in its determination of potential accessibility for the case study cities.

2.10.2 MOBILITY

Litman (2003) proposed that mobility be measured by considering person-km, travel speed, level of service and traffic count data. Mobility measurements, on the other hand, only take into account the means of travel, not the aim itself; therefore, using mobility to measure the level of service provides limited insights and solutions to improving access and tends to be biased towards suggesting an increase in infrastructure capacity and speed. The consequence of this is that private car users are favoured, ultimately leading to exclusion of NMT and transit users.

Sager, (2005) defined potential mobility as a person's ability and freedom to overcome distance in space. Martens (2007; 2017) developed the Potential Mobility Index (PMI) which focussed on the contribution of transport networks to accessibility by taking the quotient of the aerial distance and travel time between O-Ds whilst capturing the geometric design and speed of the network for different modes. This assessment is far superior to level of service consideration only as it links travel time to the lowest possible distance between two points in space. Furthermore, this indicator is useful in comparing accessibility to areas and travel by communities; notwithstanding their location in the study area and generated travel by these communities (Martens, 2007).

In a working paper by Bajpai (2014) for the IGC titled The Role of the Government in Sustaining Mobility and Accessibility in Rwanda the author reviews the EDPRS 2 policies for the road sector (the strategic plan to advance the goals of Vision 2020) and based on the lessons learned from global best practices, makes suggestions for how to make planned investments and policies in the road sector more responsive to the EDPRS 2 objectives.

The EDPRS 2's urbanization section underlines the significance of a healthy and functional Kigali for Rwanda's anticipated economic progress and transformation.
The following five points are a condensed version of the author's forecast of the primary factors that will largely determine the future condition of mobility in Kigali:

1. *Traffic engineering and management* - enhancements in the road network's operational efficiency with a greater focus on the provision of NMT facilities
2. *Regular and affordable public transport services* – whilst balancing demand across modes of transport
3. *Effective national government and city level institutions* - primary responsibility, skills and knowledge for urban transport planning and policy making
4. *Advocacy for transit-oriented development (TOD)*
5. *Effective regulatory regime* - advocating greater participation of the private sector in transport service provision (e.g., bus, para-transit, freight, road construction and maintenance)

An interesting qualitative study on "the daily experience" of the South African commuter was undertaken by Fester (2018) titled Dreams derailed: An investigation into the experiences of travel cost burdens for female commuters who are low-income earners. It looked at the commute experiences of seven Cape Town women and was framed around the 1996 White Paper on National Transport Policy (South Africa) where public transport services should aim to be user-focused, affordable and time-efficient. Unfortunately, generally all respondents reported a negative and frustrating commute experience (majority rail users) differing significantly from what the policy had promised to deliver.

The study proposes that a renewed emphasis should be placed on integrated land-use and transportation planning that shortens travel distances and speaks to increase mobility. Other recommendations include giving priority to investments in public transportation infrastructure, fare and ticketing integration, reorganizing public transportation subsidy frameworks, and placing a greater emphasis on safety on public transport services.

Potential Mobility

Potential mobility relates to the transport system's contribution to the potential people have to move around. Its indicator represents both the speed as well as the structure of the mobility options available (and affordable) to the population group in an area.

The Potential Mobility Index (PMI) is defined as for one origin–destination pair, the PMI is the quotient of the aerial or Euclidean distance ('as the crow flies') and the travel time on the transport network between that origin and that destination. A PMI score can be calculated for each origin *i* by taking the average of the PMI values for all relevant destinations for that origin.

Equation 4: Potential Mobility

$$PMI(i,m) = \frac{1}{n}.\sum_{i=1}^{n} \frac{d(i\,j)}{t(i\,j,m)} \quad \forall i,m$$

where:

- $PMI_{(i)}$ = average aerial speed for mode m in zone i
- $d_{(i\,j)}$ = aerial distance between zone i and zone j
- $t_{(i\,j)}$ = travel time on the transport network between zone i and zone j by mode m
- m = mode of transport
- n = number of zones considered

The main advantage of the PMI measure is that it captures the impact of both the structure of the transport network and the speed on the links of the network. Network inefficiencies are thus revealed by the PMI measure. This makes the measure particularly suited to determining the contribution of the transportation system to accessibility.

It is envisaged that this study will present a suitable open-source transport analysis tool that will be able to rapidly and accurately compute the travel time estimates between origin/destination pairs in Kigali to adequately model Potential Mobility. Testing of this tool should also include if the measure can be applied to zones of any spatial scale, ranging from neighbourhoods to transport activity zones and from census tracts to individual buildings if the required data is available.

Accessibility Fairness Index

It is not always possible to address accessibility shortfalls for all the population groups because of budget limitations. Hence it is necessary to identify which population groups experiencing shortfalls to prioritize. To establish fairness, the AFI was used to determine the prevalence and intensity of accessibility shortfalls amongst population groups. The index was adopted from a poverty measure index developed by Foster, Greer, and Thorbecke (1984; as cited in Martens 2017, p 160).

The aim of this step was thus to calculate the Accessibility Fairness Index that represents the fairness of the city's transportation system using Equation 5. This step also allows planners to identify population groups that contribute the most to this index and consequently may be more deserving of improvements for accessibility in the city. The index takes into account the size of the population groups, the exact accessibility level experienced by the groups, and the share of groups experiencing accessibility shortfalls.

Sufficiency thresholds are defined as a percentage of the average accessibility level of the cities. A range of sufficiency thresholds of 10%, 30%, and 50% of the average car-based accessibility was chosen/assumed for this study. This is because car-based accessibility is generally higher than any of the other mobility options. Furthermore, testing varied sufficiency thresholds avoid having one random result and to rigorously capture the difference in experienced accessibility levels in cities being tested.

Equation 5: Accessibility Fairness Index

$$AFI_r = \frac{1}{N}\sum_{i=1}^{q} n_i \cdot \left(\frac{z - y_i}{z}\right)^2$$

where:

- *N* represents the total population in region *r*;
- *q* the number of groups in region *r* experiencing accessibility levels below the sufficiency threshold *z*;
- n_i the size of the *i*-th group in number of persons;
- y_i the accessibility level experienced by the *i*-th group below the sufficiency threshold z.

The score on the AFI_r denotes the *severity of the accessibility deficiency* in a region. The score of a region on the AFI_r measure is dependent on three components:

1. the position of the accessibility sufficiency threshold;
2. the share of the population that falls below the sufficiency threshold; and
3. the exact level of accessibility experienced by persons below the threshold.

The lower a group is below the accessibility threshold; the more accessibility shortfalls are experienced and the larger the weight it contributes to the overall measurement of accessibility. Although accessibility is multi-faceted, it does not mean that AFI should not strongly aid decision-makers in the process of making a project priority list (Martens, 2017).

3 METHOD OF INVESTIGATION

The following chapter looks to identify and test the capabilities of an open-source analytical tool; using a simple, user-friendly and rapid open-source routing engine to test the key aspects of transport justice viz. potential mobility, potential accessibility and accessibility fairness index.

The tool for this study started will require the collection of data for the modelling exercise. These data sets include administrative unit level traffic analysis zones, demographic data (population), socio-economic data (employment), transit data in GTFS format and road network data. Details and sources of these data sets will be discussed in the next section.

3.1 INVESTIGATING THE R5R PACKAGE

The r5r was the open-source tool selected for this study. r5r is an R package using R^5, developed by a team at the Institute for Applied Economic Research (Ipea), Brazil (Pereira et al., 2021), for rapid realistic routing on multimodal transport networks (walk, bike, public transport and car). It provides a simple and friendly interface to R^5, a really fast and open-source routing engine based in Java developed by Conveyal. R^5 stands for Rapid Realistic Routing on Real-world and Reimagined networks. The package allows users to generate detailed routing analysis or calculate travel time matrices using seamless parallel computing on top of the R^5 Java machine.

The r5r package was found to have 3 fundamental functions as it relates to the development of the open-source transport justice analysis tool:

1. setup_r5() to initialize an instance of r5r, that also builds a routable transport network given an Open Street Map Street network and public transport feeds in GTFS format;
2. travel_time_matrix() to calculate travel times between origin/destination pairs;
3. detailed_itineraries() to get detailed information on one or multiple alternative routes between origin/destination pairs.

To use r5r, the following in terms of data sets is required:

- Road network data set from OpenStreetMap in .pbf format (mandatory)
- GTFS feed file in .zip format (optional)
- Raster file of Digital Elevation Model data in .tif format (optional)
- Zonal centroid file in .csv format contained the zone date, population, employment, etc.

The r5r package is regularly maintained and upgraded and is housed on GITHUB[6] (online software development hub; for storing, tracking, and partnering on software projects) with all its installation and setup instructions. User support is readily available from the developers (a group of academics) as well as documented on change log records[7] making the tool user friendly to

[6] https://github.com/ipeaGIT/r5r
[7] https://ipeagit.github.io/r5r/news/index.html

even the most junior coders. Most importantly, and critical to this study, the r5r tool is currently free to download and use, with no usage restrictions, other than acknowledging and crediting the developers in studies and future work.

The datasets were then collected and used in the r5r model setup to compute the most primary inputs for the transport justice analysis which includes distances and mode-wise travel times between each origin to each destination. These distance and travel time matrices were then used in the computation of transport justice indicators as potential mobility, potential accessibility and potential accessibility fairness indices per mode. **Figure 8** details the process flow for the development of the transport justice indicators.

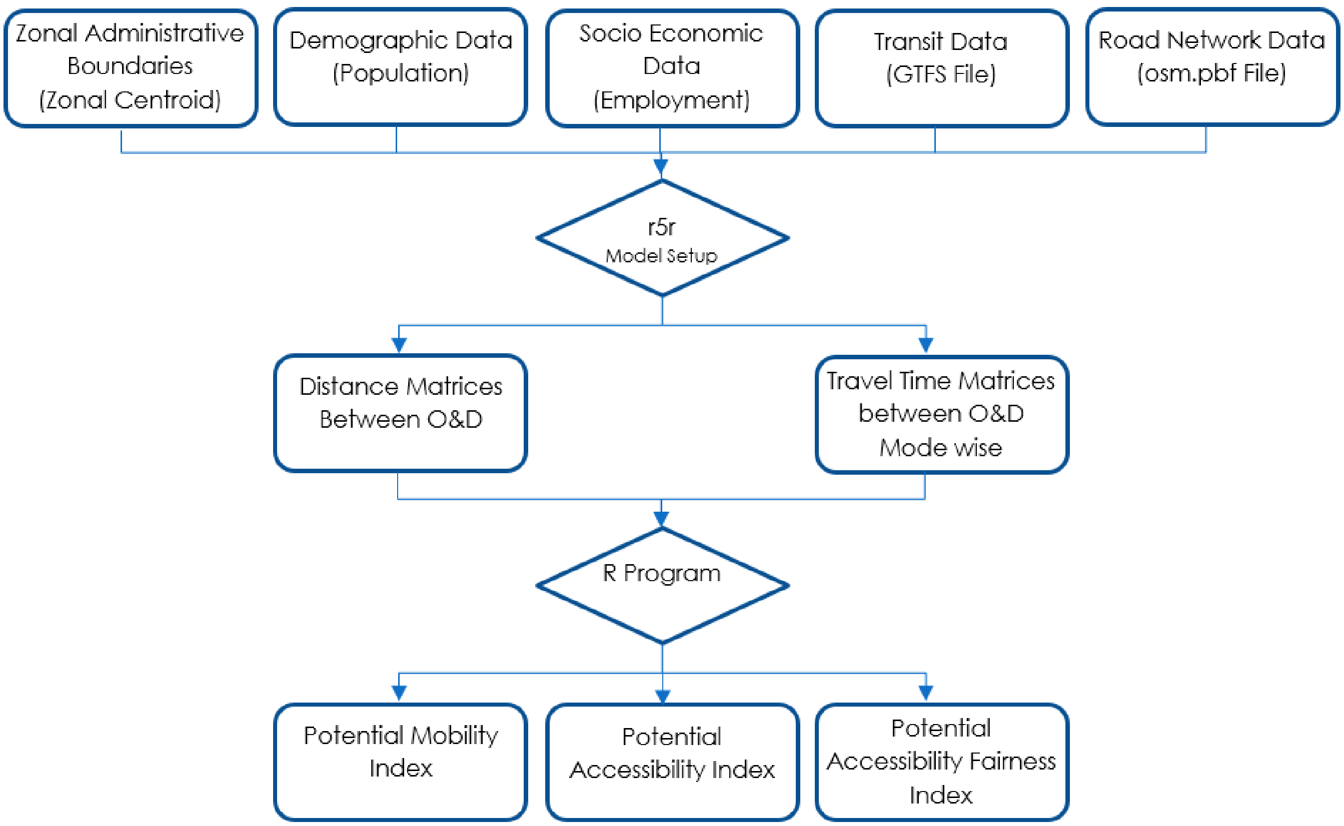

Figure 8: Process flow for the development of the transport justice indicators

3.2 R5R MODEL DEVELOPMENT

The next section will give a high-level overview of the model development in the r5r package including the input parameters, their associated assumptions and the outputs.

The first step was to build the multimodal transport network used for routing in R5. This is done with the setup_r5 function. This function does two things: (1) downloads/updates a compiled JAR file of R5 and stores it locally in the r5r package directory for future use; and (2) combines the osm.pbf and gtfs.zip data sets to build a routable network object.

The second step was to determine the travel_time_matrix function which is a really simple and fast function to compute travel time estimates between one or multiple origin/destination pairs. The origin/destination input can be either a spatial sf POINT object, or a data.frame containing the columns id, longitude and latitude. The function also receives as inputs the max walking distance, in metres, and the max trip duration, in minutes. The resulting travel times are also output in minutes. The resultant distance and mode-wise travel time matrices, as generated as an output of r5r model, are then used in the computing in later steps.

The r5r software was then able to output the following four main components of transport justice:

- Potential mobility indicator (PMI):
- Potential accessibility indicator (A)
- Accessibility Fairness Index (AFI)
- a graphical representation of the potential accessibility and mobility indicators in a quadrant system with a sufficiency threshold line/s.

Annexure B1 and B2 contains the code and relevant syntax line descriptions to understand the workings of the code and the steps that are being written and performed using r5r in the R environment. The code has been written in a very user-friendly manner and is easily exchangeable with new data sets that require testing and analysis.

Transport justice indicator computation requires a selection of input parameters that govern limits, impedances and comparison thresholds to indicate the transport justice phenomena. Input parameters can vary and be selected as per the comparison that one wishes to test and study.

In terms of the two gravity-type accessibility measures, the parameter estimates were selected as $\alpha = 0.8$ for the inverse power function and $\beta = 0.22$ of the exponential function. It is envisaged that this study will calculate the three options of accessibility measures, however only the cumulative accessibility measure will be discussed in its determination of potential accessibility for the case study cities.

Travel Time thresholds of 30 min and 15 min were chosen and is the limit used in comparison to actual travel time by mode; which means if actual travel time is greater than the travel time threshold, then that particular zone shows no accessibility for that respective travel mode.

A range of sufficiency thresholds of 10%, 30%, and 50% of the average car-based accessibility were chosen/assumed for this study. Furthermore, the three sufficiency thresholds were chosen to potentially avoid having one random result and is envisaged to rigorously capture and test the difference in experienced accessibility levels in chosen cities.

Table 4 provides values and definitions of the input parameters selected and used in this study together with notes and assumptions pertaining to the inputs.

Table 2: Summary of key calculations and inputs required

<table>
<tr><th>INDICATOR</th><th>CALCULATION INPUTS</th><th>NOTES / ASSUMPTIONS</th></tr>
<tr><td>Potential Mobility (PMI)</td><td>• $PMI_{(i)}$ = average aerial speed for mode m in zone i
• d_{ij} = aerial distance between zone i and zone j
• $T_{ij,m}$ = travel time on the transport network between zone i and zone j for mode m</td><td rowspan="4">Theoretical / logical data was assumed when no data was available (in order to adequately test the model).

Data was assumed at zonal level; level of income, residential location, level of car ownership per household, and the zonal modal split.

Analysis period: Morning peak hour (between 7:30 and 8:30 am)

Open Street Map network was used within r5r together with QGIS (freeware)

The average travel time assumed during peak hour based on all modes is 23 min (9 min for cars, 48 min for buses and 13 min for taxis)

Two travel time thresholds for cumulative accessibility measures (30 min and 15 min) were chosen.

Sufficiency thresholds of 10%, 30%, and 50% of the average car-based accessibility was chosen

The parameter estimates selected as α = 0.8 for the inverse power function and β = 0.22 of the exponential function</td></tr>
<tr><td>Potential Accessibility (A)</td><td>• A(i,m) = zone accessibility level for mode m
• α = Travel impedance parameter (calibration factor indicating resistance of commuters to travel within the study area; assumed at 0,8, as detailed in Section 2.8)
• $t_{ij,m}$ = travel time in minutes between zone i and j for mode m
• β = region's travel impedance (calibration factor indicating resistance of commuters to travel to certain regions in the study area; assumed at 0,22, as detailed in Section 2.8)
• W_j = Number of opportunities in destination zone j
• $T_{ij,m}$ = Travel time threshold in minutes</td></tr>
<tr><td>Accessibility Fairness Index for region r (AFI)</td><td>• r is the region / area
• N represents the total population in region r;
• q the number of groups in region r experiencing accessibility levels below the sufficiency threshold z;
• n_i the size of the i-th group in number of persons;
• y_i the accessibility level experienced by the i-th group below the sufficiency threshold z.</td></tr>
<tr><td>Sufficiency thresholds</td><td>• 10%, 30%, and 50% of the average car-based accessibility</td></tr>
</table>

As mentioned previously the r5r model provided the information of distance and travel times by modes between origins and destinations, which are the most critical inputs for the computation of the transport justice indicators. However, r5r does not have any functionality to compute the mobility, accessibility or fairness index equations directly in the package. Therefore, a separate coding had to be written within the R programming environment, and integrated within the r5r model to make it work for computation of the transport justice indicators (creating the analysis tool, in a “one-stop shop” environment). Details of the method and steps to run the r5r script is detailed within the syntax as contained in **Annexure B**.

4 DATA COLLECTION

Traditional transport modelling inputs essentially requires demographic and socio-economic data sets segregated in certain administrative level zones overlayed with its relevant road network information. Provided the data is available in the first place, this in turn provides indicators for the transport demand requirements of the transport system in each zone and also provides a basis for comparisons of this demand with respect to transport supply by comparing the road network and transit facilities available or being tested. Framing a transport modelling exercise using the theories of transport justice requires almost all the traditional transport modelling with a few additional and relatively easily computed / derived inputs.

The following chapter will detail the data that was gathered for the r5r model setup to compute the most primary inputs for the transport justice analysis which includes distances and mode-wise travel times between each origin to each destination; thereafter used in the computation of transport justice indicators. Furthermore, it will highlight the data limitations and shortcomings.

4.1 TRAFFIC ANALYSIS ZONAL (TAZ) LEVEL DATA

Transport modelling requires spatial data aggregation in Traffic Analysis Zones (TAZs). A TAZ boundary is a geographically bounded region which can generate or attract traffic. The bounded area of a TAZ varies in size based on population size and socio-economic characteristics. The spatial extent of zones typically varies in models, ranging from very large areas in the exurb to as small as city blocks or buildings in central business districts. There are no technical reasons zones can't be as small as single buildings, however additional zones add to the computational burden required in analyses.

TAZs are constructed typically by census block information. Characteristically, these blocks are used in transportation models by providing socio-economic data. Zonal boundaries are typically governed through statistics such as the population, number of vehicles per household, household income and employment within these zones. Zone boundaries are carved out with due consideration of geographical barriers such as rivers, canals, sea, railway lines, etc. These geographical features typically prevent trip crossing into these zones except where man-made facilities exist; for example, a river can't be crossed except over bridges. This information helps to further the understanding of trips that are produced and attracted within the zone. TAZ boundaries are flexible and these zones can change or be altered as mentioned in the first paragraph, depending on the analysis focus and also to optimise areas to limit the computational burden required in analysis.

Design and construction of TAZ boundaries depends on many factors which are sometimes contradictory to each other; for example, key stakeholder/decision makers' preferences may insist that cognisance of physical separators are not strictly enforced. Therefore, it requires careful design and trade-off to meet certain constraints so as to properly define the TAZs. The following list describes a few constraints as it relates to construction and design of TAZ boundaries:

- Contiguity and convexity of zones (compactness of TAZ shapes)
- Exclusiveness of zones (no doughnuts or islands)
- Equity in terms of trip generation (small standard deviation across zones)
- Adjustment of TAZ boundaries to political, administrative, or statistical boundaries
- Cognisance of physical separators (geographical barriers such as rivers, canals, sea, railway lines, etc.)
- Key stakeholder/decision makers' preferences (considered in determining the number of TAZs)
- Avoiding main roads as TAZ boundaries (provides better connectivity to TAZs)
- Optimised zone size selection and geographical precision (reduces the aggregation error caused by the assumption that all activities are concentrated at the centroids of TAZs).

It is difficult to equally consider and implement all of the above criteria in the process of TAZ design and construction. Rigid administration-based TAZ designs do not take into account the ongoing changes of land use (spatially and temporarily), which can deeply affect TAZs homogeneity and compactness, producing significant misestimates of trip generation and O-D matrices. Therefore, this study avoids using the administrative boundaries / districts of Kigali city as zones, instead, the districts were divided into smaller zones (which considered the zone design constraints above). This finer level of aggregation can then easily be aggregated to higher levels to re-form district boundaries for the purposes of geographical statistical summaries.

The City of Kigali comprises of three districts namely Gasabo, Kicukiro and Nyarugenge. Gasabo is the largest district by geographical area at 429,3 km^2, followed by Kicukiro at 166,7 km^2 and lastly Nyarugenge at 134 km^2. The districts are also cumulatively divided into 35 administrative sectors within Gasabo, Kicukiro and Nyarugenge; segregated into 15, 10 and 10 administrative units respectively. These 35 administrative units have been selected as the TAZs for this study, as they are the least number of bounded units that fulfil the requirements for a suitable TAZ as well as utilising the available data as received from the City of Kigali. **Figure 9** shows geographically, the administrative boundaries of the 35 administrative sectors selected within Gasabo, Kicukiro and Nyarugenge.

Nairobi County officially has seventeen (17) constituencies however the data obtained split Nairobi County into eleven (11) zones therefore the analysis focussed on these as TAZs. The zones are Dagoretti, Embakasi, Kamukunji, Kasarani, Kibra, Lang'ata, Makadara, Mathare, Njiru, Starehe and Westlands. **Figure 10** shows the 11 administrative sectors / zones selected within Nairobi.

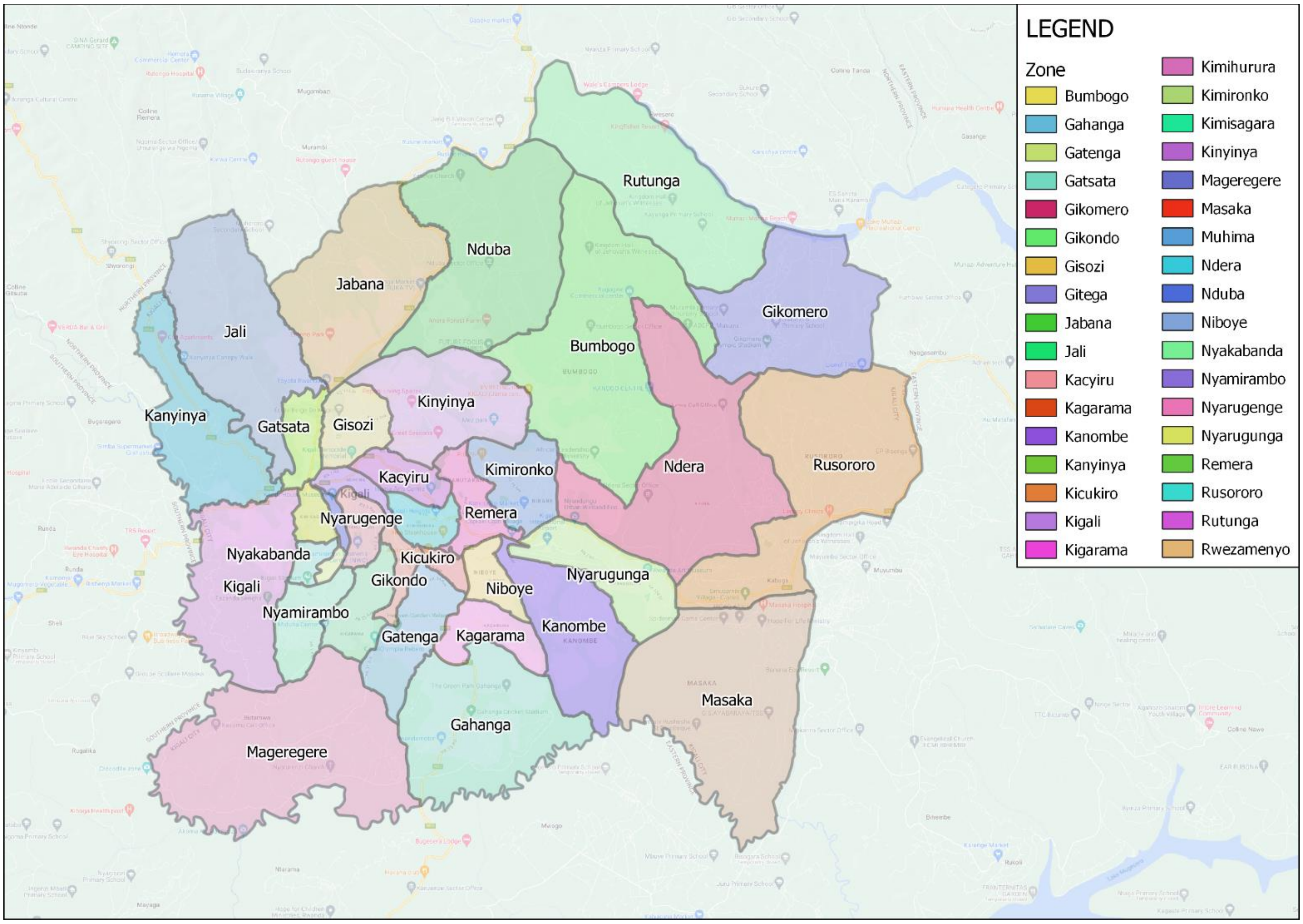

Figure 9: 35 administrative sectors (zones) selected within Gasabo, Kicukiro and Nyarugenge districts

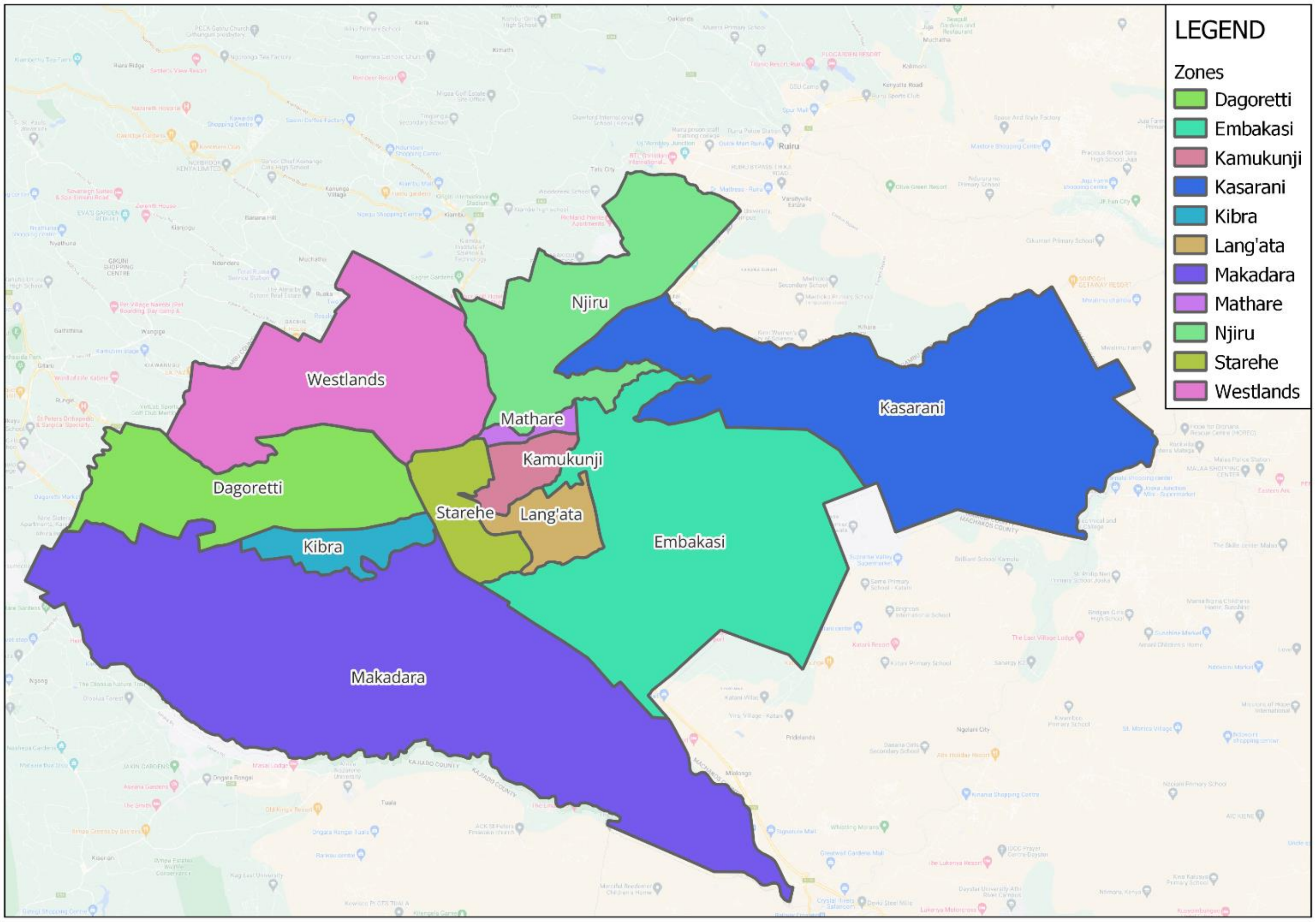

Figure 10: 11 administrative sectors (zones) selected within Nairobi

The population data for the 35 administrative regions was extracted from City of Kigali's official website[8] based on the official national census data from 2012. At the time of this study's conclusion the 2022 census had been undertaken but the results were yet to be published. Population and employment data was available, however, only at a districts level i.e., Gasabo, Kicukiro and Nyarugenge. Population counts were 529,559, 301,002 and 284,560 respectively for each district making the total population estimate to be around 1,115,121 people. These district level population data sets were then projected and distributed among the 35 administrative regions based on the weighted proportion method using the area of each TAZ as a proxy for distribution. Similarly, the available employment data for the 3 districts was distributed across the 35 administrative regions.

According to Kenya's 2019 Population and Housing Census, the population of Nairobi was 4,397,073. The census data also gave the populations for the constituencies of Nairobi and the weighted proportion method using the area of each of the 11 TAZs as a proxy for distribution was used. Employment data obtained at a county level was also distributed across the 11 TAZs.

[8] https://www.kigalicity.gov.rw/about/districts

Figures 11 and 12 show the population of the cities, while **Figures 13 and 14** shows employment data distribution geographically of the cities. **Annexure C** (Tables 19 and 20) summarizes the TAZ IDs, region names, zonal centroid latitudes and longitudes that generate the population and employment distribution statistics (according to area) of the administrative regions of the cities.

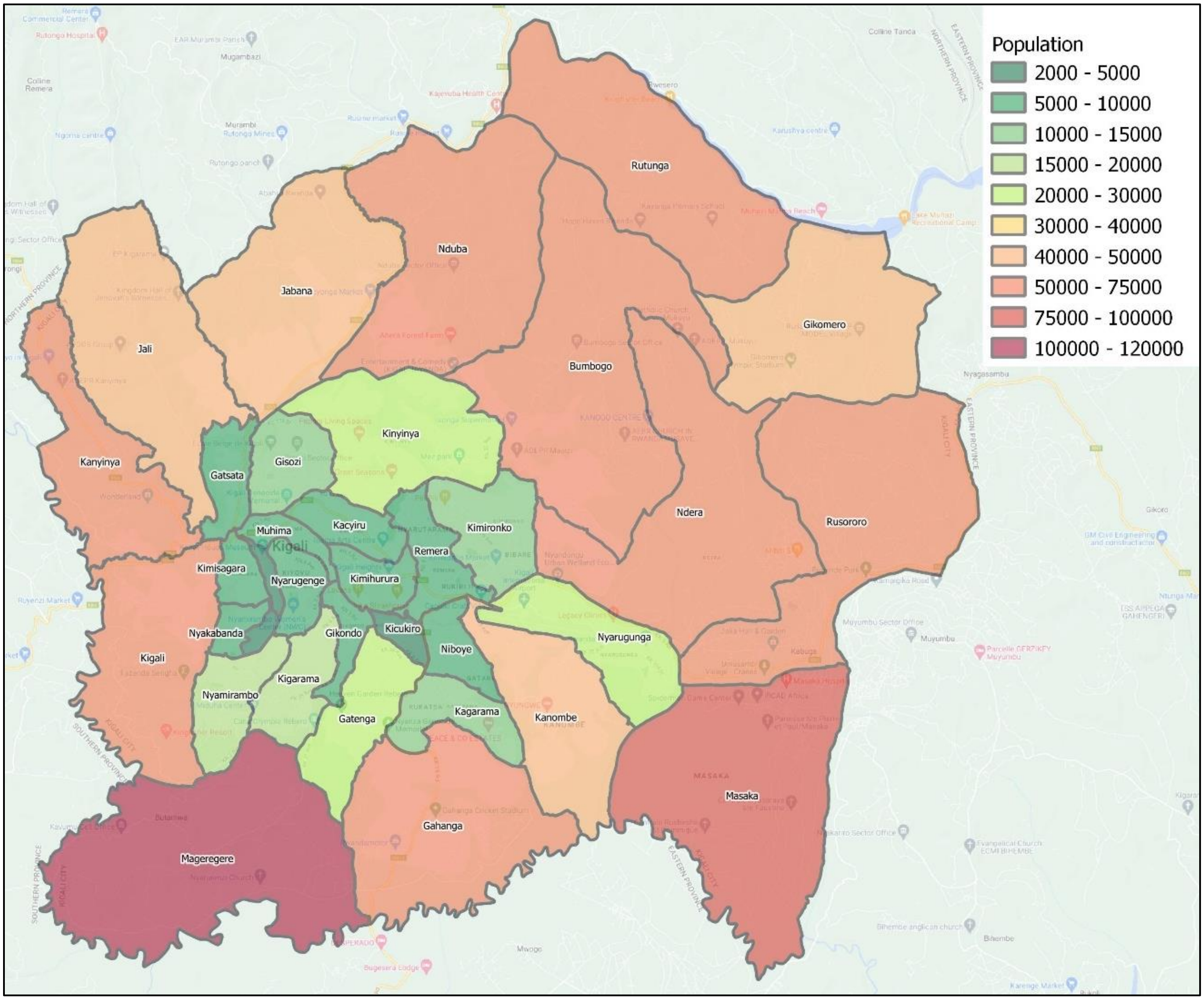

Figure 11: Population distribution across the 35 zones of Kigali

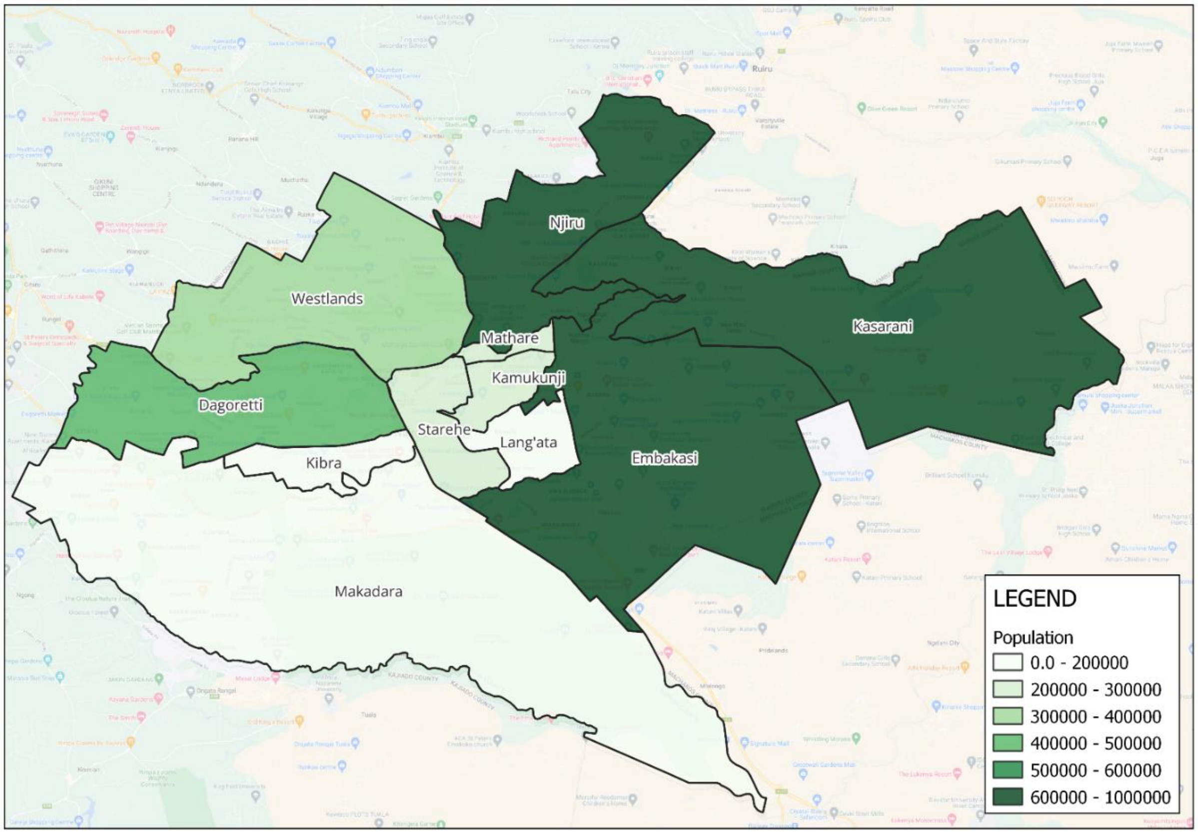

Figure 12: Population distribution across the 11 zones of Nairobi

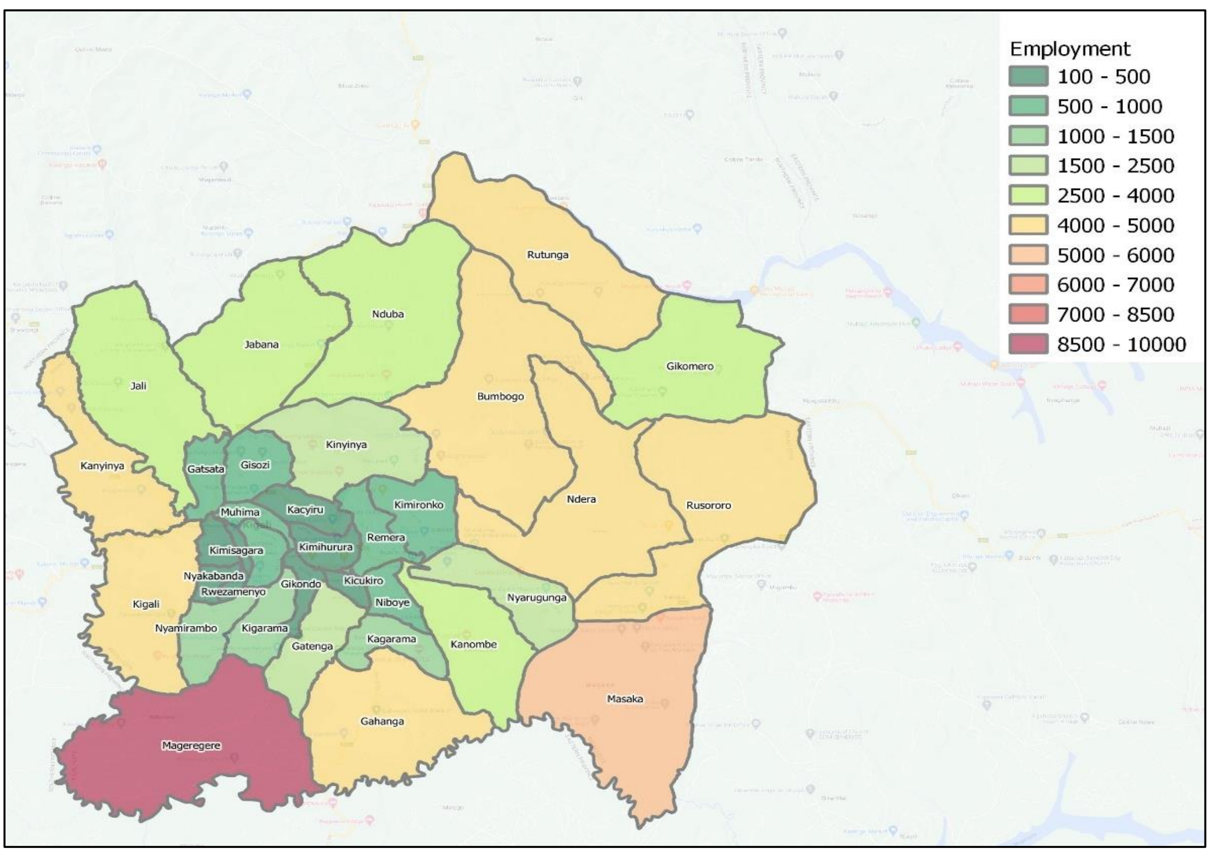

Figure 13: Employment data distribution across the 35 zones of Kigali

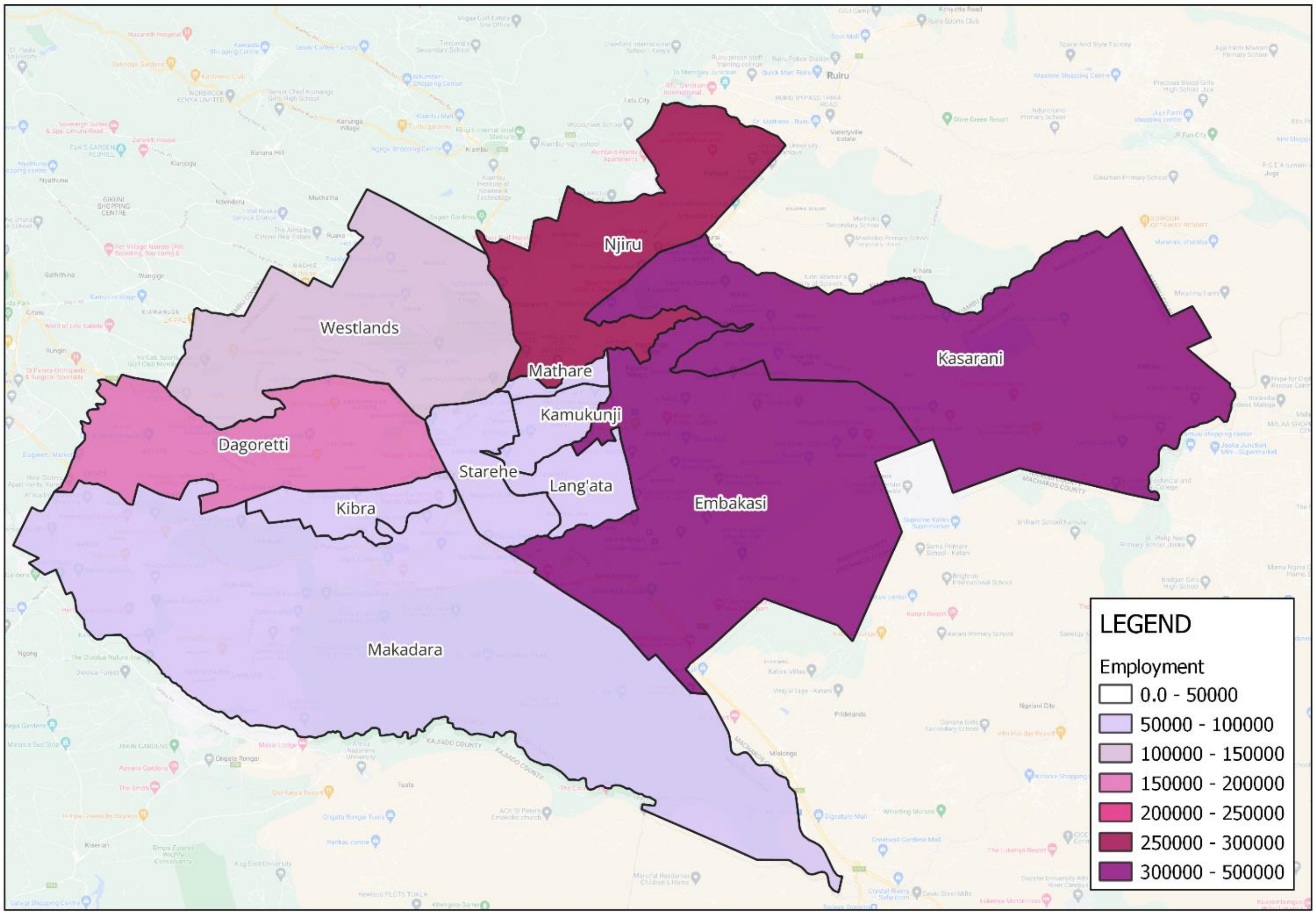

Figure 14: Employment data distribution across the 11 zones of Nairobi

4.2 ROAD NETWORK DATA

Road network information are the most important indicators to provide insights on the supply side of a transport system in contrast to potential travel demand. A road network model is a virtual representation that allows the description of relevant features of a road network and related infrastructure. Using such a model, a schematic of the road network infrastructure can be designed. These schemas can in turn be populated by data, producing the replication of real-life phenomena representing aspects of a specific road network.

Different aspects of a road-network infrastructure can be of interest, depending on the purpose of study. A road network data model consists of several interrelated sub-models, each of which targets different, specific aspects of a road network.

A road network model typically consists of poly lines of road segments representing the actual geometry of the road including its horizontal alignment. These poly lines are provided with specific characteristics of road segments such as road width, number of lanes, free flow speed (FFS), road capacity (or traffic capacity), actual travel speed, travel direction regime (one way or two way), turning provisions at intersections and U-turns, actual traffic data (wherever traffic survey data is available) and a host of other relevant and useful information.

Road network details for the cities of Kigali and Nairobi were retrieved from the OSM platform and has been selected for getting preliminary existing road alignment in vector and digitised format. The OSM platform is an open-source data platform that is built by a community of mappers that contribute and maintain data about roads, trails, cafés, railway stations, and much more, all over the world. The advantage of using OSM is that it is managed and updated frequently by a vast community of mappers making it a high-resolution source of information. Furthermore, and most importantly, as it is an open-source platform, it is free to use (without limits), which makes it a more suitable data source to be used for the development of a transport justice analysis tool for developing countries in Africa (or the world) where access to data sources may be limited. **Figure 15** shows the road network overlayed over the city of Kigali, while **Figure 16** shows the road network overlayed over the city of Nairobi.

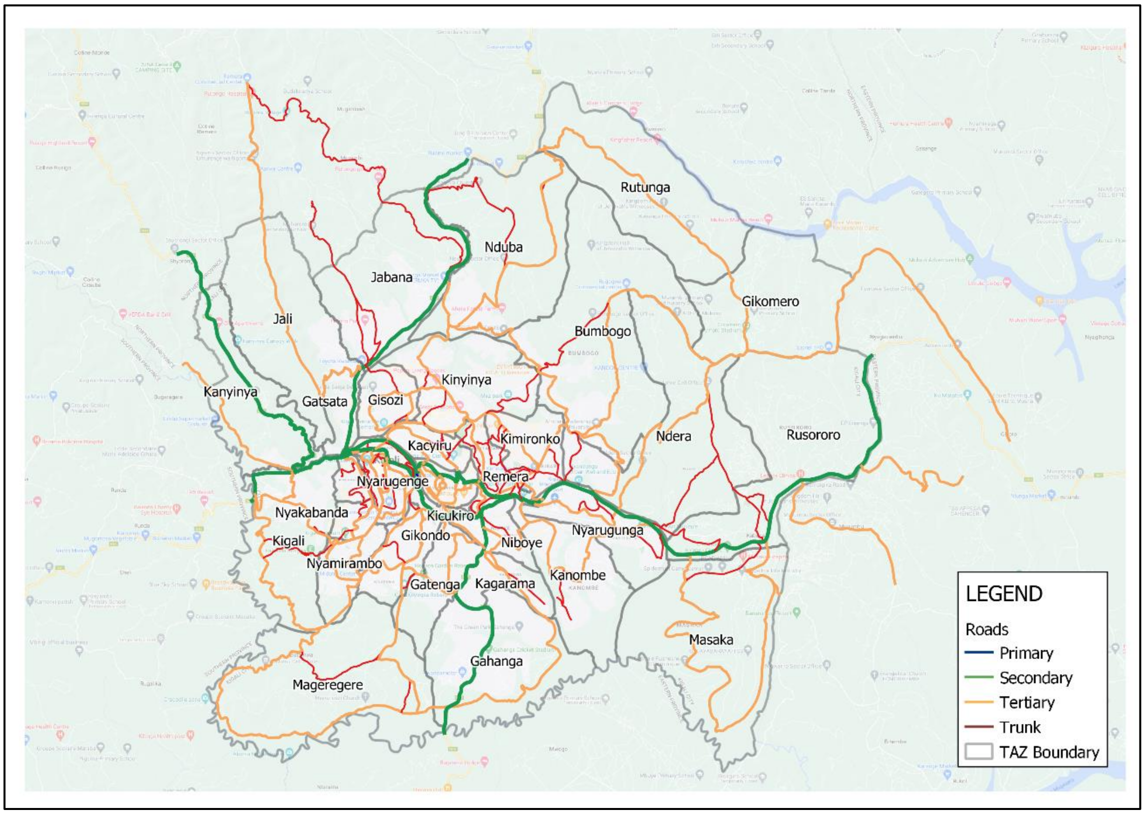

Figure 15: Road network overlayed over the city of Kigali

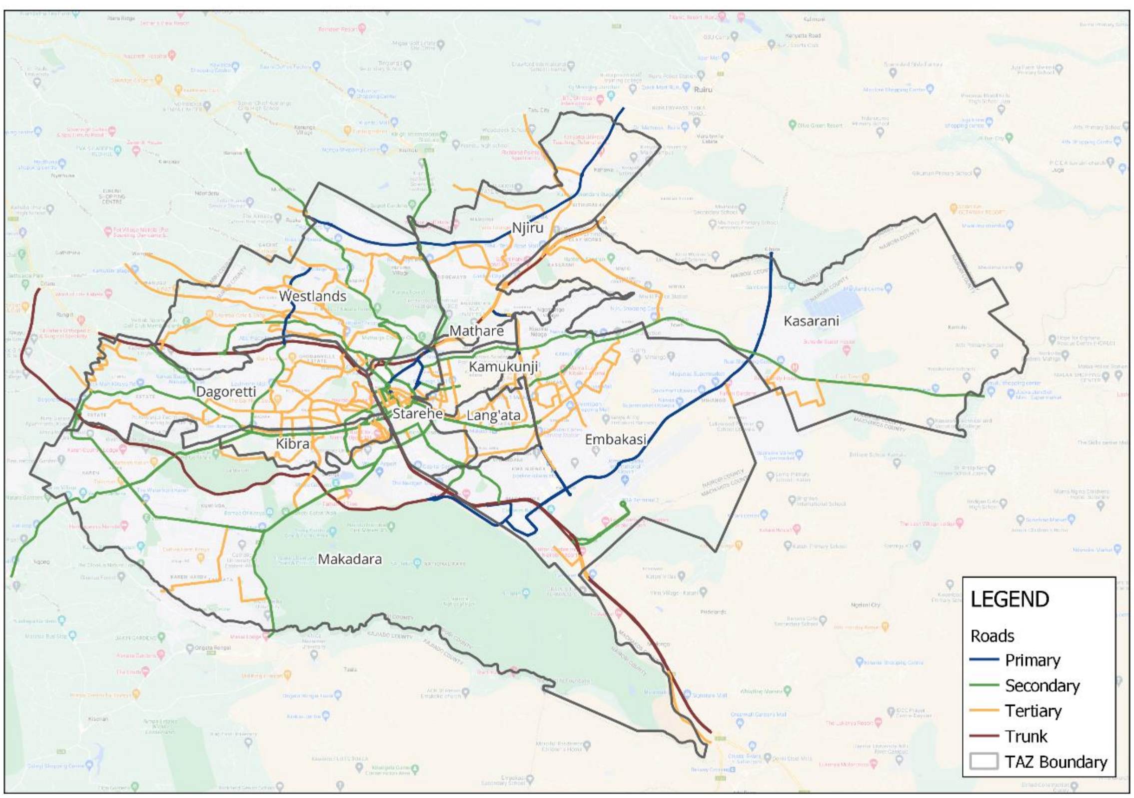

Figure 16: Road network overlayed over the city of Nairobi

4.3 TRANSIT DATA

Transit data is very essential in the development of a transport justice analysis tool as public transit modes usually serve the higher proportion of day-to-day mobility users in an urban region. Buses routes, frequency, timetables and schedules are important parameters in the estimation of the accessibility index (as defined by the principles of transport justice) of an urban region.

Transit data is the most readily available in GTFS format. According to the GTFS.org website "*GTFS is a data specification that allows public transit agencies to publish their transit data in a format that can be consumed by a wide variety of software applications*". The GTFS data format is used by thousands of public transport providers. GTFS is split into a schedule component that contains schedule, fare, and geographic transit information and a real-time component that contains arrival predictions, vehicle positions and service advisories.

GTFS data for Kigali was provided by government agencies, however this only contained information about one operational bus service listed as *KBS - Zone I* (Kigali Bus Service), despite there being 3 bus operators in Kigali (KBS, Royal Express and RFTC). The GTFS data showed that KBS-I operates on 16 different routes with 209 bus stops with headways of between 15 to 30 minutes and services running from 6:00am till 8:00pm. **Figure 17** displays the 16 operational routes of KBS in Kigali while **Figure 19** shows the respective stopping points along these routes.

GTFS data for Nairobi was sourced from the University of Nairobi (2019). The GTFS data showed that 136 different routes with 4285 transit stops with headways of between 15 to 20 minutes and services running from 5:00am till 7:30pm. **Figure 18** displays the operational transit routes while **Figure 20** shows the respective stopping points along these routes.

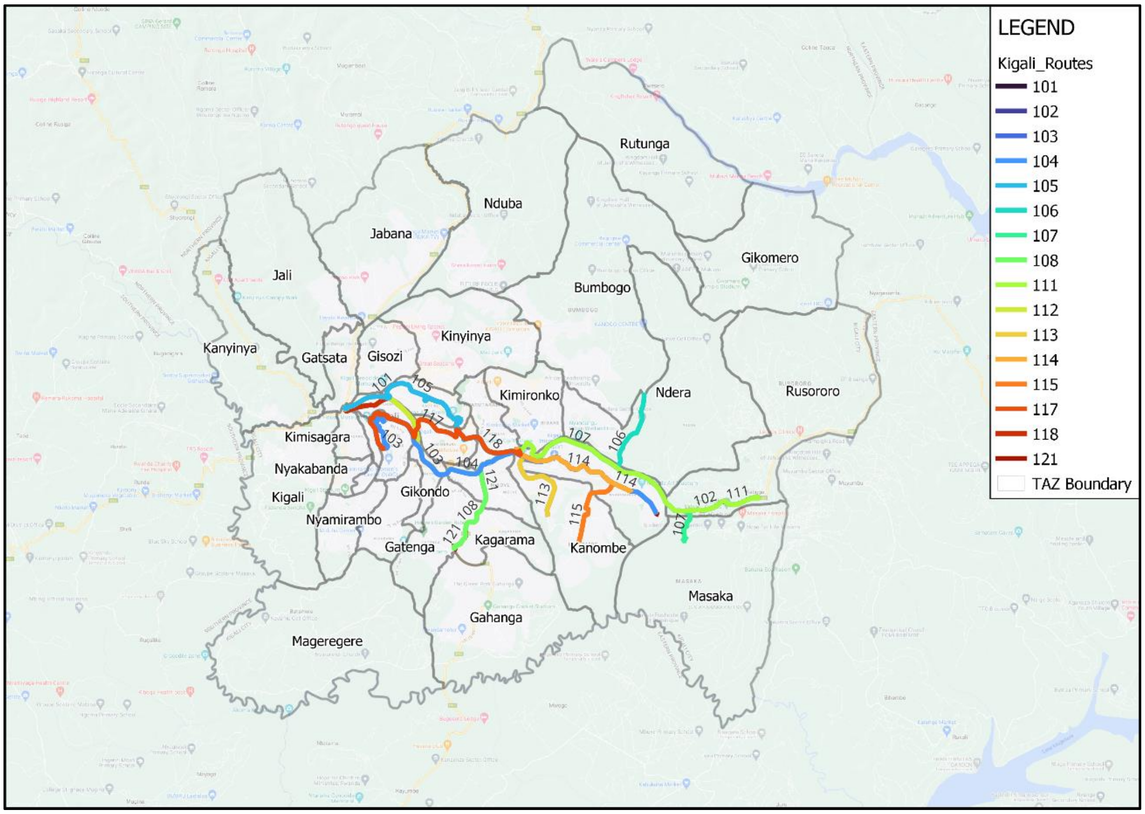

Figure 17: GTFS data showing the 16 operational routes of KBS in Kigali

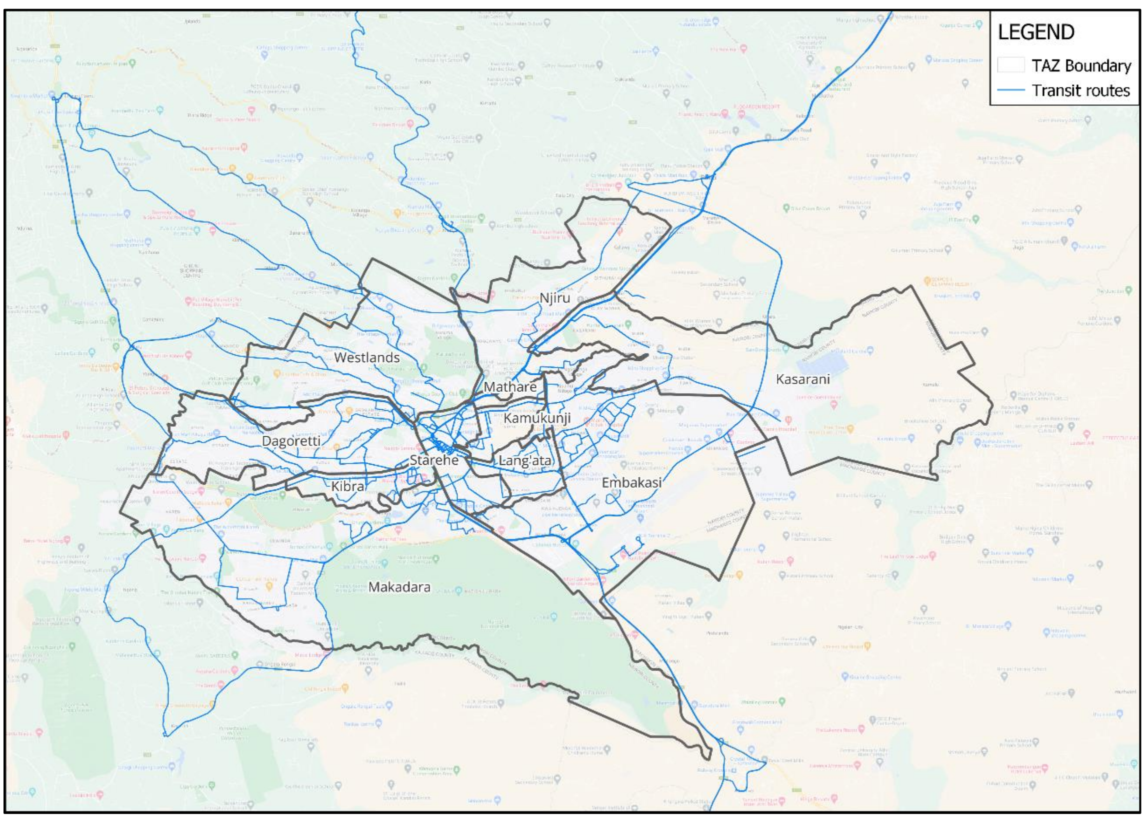

Figure 18: GTFS data showing the available transit routes in Nairobi

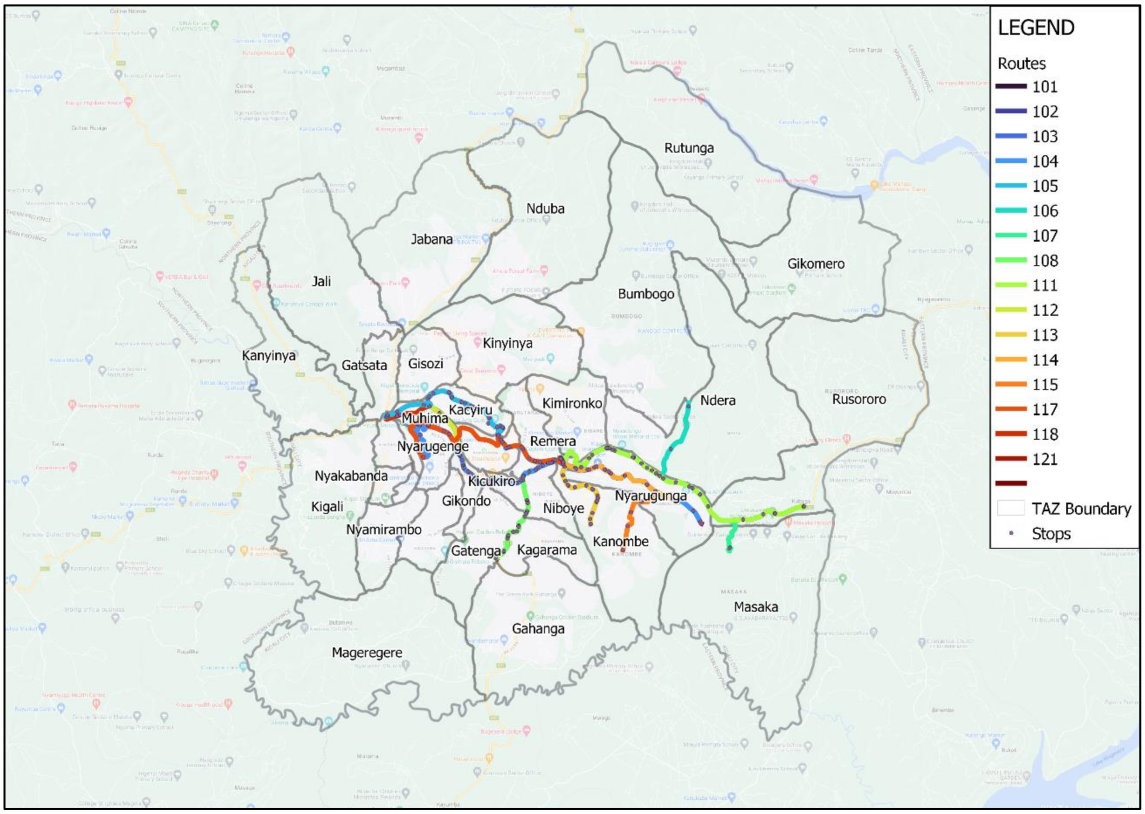

Figure 19: Stopping points along the 16 operational routes in Kigali

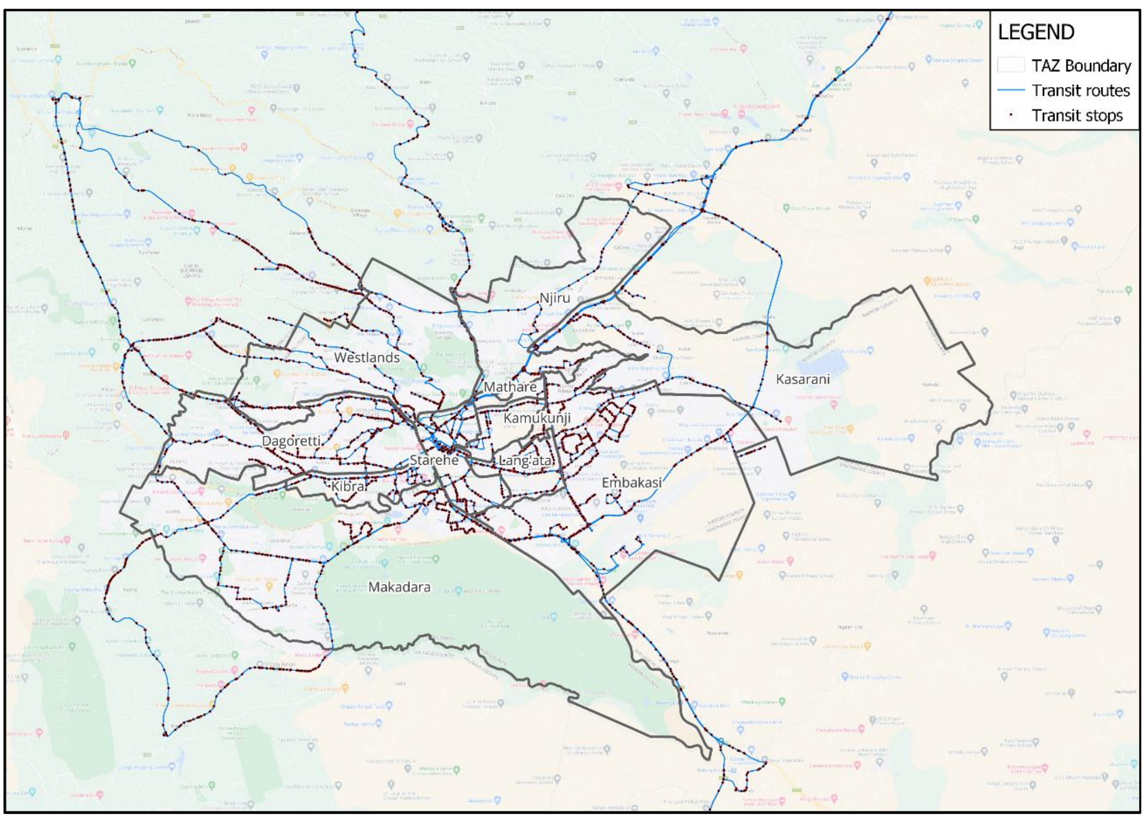

Figure 20: Stopping points along the transit routes in Nairobi

At its most basic level the data described in the previous sections is what is absolutely needed as a minimum to build a suitable open-source transport justice analysis tool that could denote detailed information on one or multiple alternative routes between origin/destination pairs focussing on the theories of transport justice for this study.

4.4 DATA LIMITATIONS

As mentioned, transport justice analyses require minimal and basic data sets of population, socio economic, administrative level zonal centroids and road network data. These data sets are usually easily available from national census data sets for most countries. However, for developing countries like Rwanda and Kenya, the availability and digitisation of these basic data sets is still limited. The following points briefly highlight the issues and considerations to bear in mind in how this study proceeded based on the available data.

1. Population data set

   Population data utilised was very outdated. Furthermore, this data was only available at a district level for Rwanda (3 districts: Gasabo, Kicukiro and Nyarugenge). Therefore, this had to be projected proportionally for each of the 35 regions based on their respective area proportion. Updated data at a regional level will greatly improve and increase the reliability in the results, however, for this study it is limited to projected statistics to demonstrate the design and replicability of the open-source transport justice analysis tool being developed in this study.

2. Socio-economic data set

   Similarly, the employment data was also only available at a district (Kigali) and county (Nairobi) level and had to be projected proportionally for each of the zones based on their respective area proportion. Data at a finer level will greatly increase the tool's outputs.

3. Road network data

   The OpenStreetMap platform was utilised, however, despite this open-source map platform being free of charge it is important to note that it is created from contributions from volunteers and may have some discrepancies/errors. It would be more appropriate to calibrate and validate the road network data set from more reliable data sets or results should they be available. The .osm format is also non-editable so network parameters can't be changed or manipulated as required.

4. GTFS transit data set

   The GTFS data sets only had data for limited transit services, furthermore, the data set for Kigali showed formatting / compatibility issues. This issue may have arisen due to weak formatting of the GTFS data or due to coding compatibility issues. Efforts have been made to validate the formatting of the GTFS data using a GTFS validator website[9], but with no success. Nevertheless, the GTFS data for Nairobi was also used to demonstrate r5r's robustness, versatility, scalability and replicability with similar African cities and their available data sets.

[9] http://gtfsvalidator.omnimodal.io/upload

5 RESULTS AND ANALYSIS

The following chapter will discuss the desk study findings and outline the interpretation and analysis of the results for Kigali and Nairobi at a high level as they relate to mobility and accessibility. The section will also touch on and give possible and recommended solutions to tackle accessibility or mobility shortfalls in the cities.

5.1 KIGALI: DISCUSSION OF RESULTS

The Kigali road network is designed in a conventional way where road densities are more concentrated towards the city centre and outlying areas typically have low accessibility to the road network and public transit options. The results of the transport justice analysis show a very similar pattern as described in the following section.

5.1.1 POTENTIAL MOBILITY INDEX

The computed potential mobility indices per zone, per mode are shown in **Table 5** (and ranked by car PMI, as it had the best PMI results in Kigali). In most instances, the car mode has the best PMI results showcasing the impact of both the structure of the transport network and the superior travel speed on the links and the network biased towards cars. However, in environments with grade separated public transport systems, this might be different. Network inefficiencies for other modes are thus revealed by the PMI measure (average aerial speed). This makes the measure particularly suited to determining the contribution of the transportation system's modes to accessibility and where to focus prioritisation and investments in upgrades to certain modes.

By way of example, the PMI results per mode in **Table 5** highlighted that the Rutunga, Gahanga and Mageregere zones respectively provided the top 3 best PMI scores for the car mode, while the Kinyinya, Nyarugenge and Kimihurura zones showed the 3 worst PMI scores; indicating that if investment needed to be prioritised the zones with the worst PMI scores would likely be considered for improvement in road network and transport infrastructure in order to improve the average level of mobility available between certain zones for the car mode. Similarly, the Gikomero, Jali and Kanyinya zones had the 3 worst PMI scores for the bicycle mode; indicating that if investment needed to be prioritised these zones would likely be considered for improvement for NMT/cycling facilities first.

Table 3: Potential mobility indices per zone, per mode (ranked by car PMI) for the 30min travel time thresholds (Kigali)

Ranked by Car PMI	Zone	Zone Name	PMI (Walk) km/hr	PMI (Bicycle) km/hr	PMI (Car) km/hr	PMI (Transit) km/hr
1	25	Rutunga	2.7	3.5	29.9	2.7
2	26	Gahanga	2.7	3.9	28.1	2.7
3	5	Mageregere	2.7	3.9	28	2.7
4	15	Jabana	2.5	3.8	26	2.5
5	22	Nduba	2.6	4	25.9	2.6
6	27	Gatenga	2.6	4.2	25.6	2.7
7	11	Bumbogo	2.6	4	25.3	2.6

Ranked by Car PMI	Zone	Zone Name	PMI (Walk) km/hr	PMI (Bicycle) km/hr	PMI (Car) km/hr	PMI (Transit) km/hr
8	35	Nyarugunga	2.7	4.5	25.3	3
9	33	Masaka	2.6	4	25.1	2.6
10	13	Gikomero	2.5	3.3	25	2.5
11	2	Kanyinya	2.3	3.1	24.7	2.3
12	12	Gatsata	2.5	3.7	24.6	2.7
13	29	Kagarama	2.6	4.4	24.5	2.8
14	8	Nyamirambo	2.6	4.7	24.2	2.7
15	16	Jali	2.4	3.1	24.2	2.4
16	24	Rusororo	2.7	3.8	24.1	2.7
17	19	Kimironko	2.5	4.3	23.8	2.9
18	21	Ndera	2.5	3.7	23.8	2.5
19	34	Niboye	2.6	4.5	23.7	3
20	10	Rwezamenyo	2.6	4.4	23.6	2.8
21	7	Nyakabanda	2.5	4.1	23.4	2.7
22	30	Kanombe	2.6	4.6	23.3	2.9
23	31	Kicukiro	2.5	4.1	23.2	2.8
24	32	Kigarama	2.6	4.2	23	2.7
25	28	Gikondo	2.6	4	22.9	2.7
26	6	Muhima	2.6	4.1	22.8	3.1
27	14	Gisozi	2.6	4.3	22.8	2.8
28	1	Gitega	2.5	4.2	22.4	2.9
29	3	Kigali	2.6	4	22.4	2.7
30	4	Kimisagara	2.5	4	22	2.7
31	17	Kacyiru	2.5	3.9	22	2.7
32	23	Remera	2.5	4.1	21.7	2.8
33	20	Kinyinya	2.4	3.9	21.6	2.4
34	9	Nyarugenge	2.5	3.9	21.2	2.7
35	18	Kimihurura	2.4	3.5	18.9	2.5

5.1.2 POTENTIAL ACCESSIBILITY INDEX

In this study, three different methods were followed to compute the potential accessibility index of each zone i.e., Inverse function, exponential function and the cumulative function. Travel times between zones, as computed from the r5r model, is then programmed in the R environment with mathematical models for computation of potential accessibility and mobility levels per method, per mode, for each travel time threshold, as shown in **Tables 6**.

The discussion of results focussed on the cumulative accessibility measure result as this considered the sum of all possible accessibility options in space and time. Differences between persons and identify population groups that are entitled to accessibility improvements are more represented in this option of the accessibility measure. Ranking the cumulative accessibility function by car, the results of the potential accessibility for the 30 min travel time threshold of Kigali city shows that all the zones had better accessibility when compared to other modes. Although, with slightly lower trends in accessibility to remote zones like Jali. However, the mobility index (i.e., average travel speed in kilometres per hour (km/hr)) of different zones of Kigali are varied between 18 km/hr to 30 km/hr. The results thus indicate that while there may be ample supply of road network available for travel by car, the travel speed in the zones are variable;

possibly linked to the condition of road pavement or congestion being variable in different zones). **Table 6** details the focus zones with PMI values highlighted in red that indicate requiring improvement in pavement / congestion conditions. These zones include Kimihurura, Nyarugenge etc. which are showing average travel speeds of around 18km/hr to 21 km/hr.

Table 4: Potential mobility and potential accessibility indices per zone, per mode for the 30min travel time threshold (Kigali)

Zone No.	Zone Name	Walk				Bicycle				Car				Transit			
		PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai
27	Gatenga	2.6	1152	1558	1558	4.2	1612	1559	1558	25.5	7441	4286	21883	2.7	1180	1558	1558
28	Gikondo	2.5	1202	424	424	4	1724	426	424	22.9	7129	2201	20682	2.7	1256	424	424
31	Kicukiro	2.5	1186	205	205	4.1	1782	240	608	23.2	7289	2237	20532	2.8	1266	205	205
32	Kigarama	2.6	1175	1152	1152	4.2	1673	1157	1263	23	7005	3248	20040	2.7	1196	1152	1152
10	Rwezamenyo	2.6	1227	156	251	4.4	1815	213	945	23.6	7020	2023	19779	2.7	1259	156	251
7	Nyakabanda	2.5	1160	328	372	4.1	1661	347	516	23.4	6876	2117	19167	2.7	1189	328	372
1	Gitega	2.5	1173	211	210	4.2	1726	240	839	22.4	6878	1900	19029	2.9	1240	211	210
6	Muhima	2.6	1150	528	527	4	2123	425	558	22.8	7243	1773	18932	3	1217	528	527
34	Niboye	2.6	1160	755	755	4.5	1749	766	864	23.7	6861	2308	18742	2.9	1218	755	755
9	Nyarugenge	2.5	1163	552	552	3.9	1650	560	707	21.1	6661	1952	18506	2.8	1221	553	552
8	Nyamirambo	2.6	1112	1436	1436	4.7	1616	1439	1528	24.2	6519	2996	18264	2.7	1127	1436	1436
35	Nyarugunga	2.7	1085	2296	2296	4.5	1577	2303	2526	25.3	6491	3646	17904	3	1157	2297	2296
19	Kimironko	2.5	1101	777	777	4.3	1631	778	777	23.8	6596	1794	17538	2.9	1161	777	777
17	Kacyiru	2.5	1132	496	496	3.9	1586	496	496	22	6517	1605	17229	2.7	1175	496	496
29	Kagarama	2.6	1116	1201	1201	4.4	1603	1202	1201	24.5	6711	2878	17071	2.8	1152	1201	1201
23	Remera	2.5	1142	561	561	4.1	1669	562	561	21.7	6566	1599	17044	2.8	1200	561	561
4	Kimisagara	2.5	1127	445	445	4	1582	452	543	22	6459	1673	16846	2.7	1167	445	445
26	Gahanga	2.7	5050	3326	4006	3.9	5309	3326	4006	28	9993	4365	16758	2.7	5057	3326	4006
5	Mageregere	2.7	702	9789	9789	3.9	920	9789	9789	28	4558	10219	16729	2.7	702	9789	9789
12	Gatsata	2.5	999	516	516	3.7	1350	516	516	24.6	6255	1545	15286	2.7	1026	516	516
14	Gisozi	2.6	1055	712	712	4.3	1540	712	712	22.8	6127	1454	14033	2.7	1078	712	712
30	Kanombe	2.6	4463	2774	3341	4.6	4931	2778	3494	23.3	9215	3624	13841	2.8	4475	2774	3341
21	Ndera	2.5	5634	3812	4592	3.7	5874	3812	4592	23.8	9977	4301	13816	2.5	5635	3812	4592
11	Bumbogo	2.6	888	4676	4676	4	1139	4676	4676	25.3	10022	4146	13530	2.6	889	4676	4676
3	Kigali	2.6	2452	2001	4182	4	2784	2001	4182	22.4	6573	2394	11894	2.7	2470	2001	4182
20	Kinyinya	2.4	3454	1998	2406	3.9	3882	1998	2406	21.6	8078	2414	11249	2.4	3463	1998	2406
18	Kimihurura	2.4	1110	435	435	3.5	1976	349	421	18	6305	953	11221	2.5	1150	435	435
15	Jabana	2.5	3908	2502	3014	3.8	4188	2502	3014	25.9	8052	2724	9145	2.5	3908	2502	3014
33	Masaka	2.6	711	5942	5942	4	956	5942	5942	25.1	4250	6056	9133	2.6	711	5942	5942
25	Rutunga	2.7	711	4027	4027	3.5	848	4027	4027	29.9	4681	4222	9102	2.7	711	4027	4027
22	Nduba	2.6	4023	2562	3086	4	4268	2562	3086	25.9	8138	2802	8794	2.6	4023	2562	3086
2	Kanyinya	2.3	3221	2789	4041	3.1	3418	2789	4041	24.7	7132	2993	8684	2.3	3221	2789	4041

Zone No.	Zone Name	Walk				Bicycle				Car				Transit			
		PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai
24	Rusororo	2.7	3593	3173	4598	3.8	3770	3173	4598	24.1	7046	3276	8147	2.7	3593	3173	4598
13	Gikomero	2.5	2254	1742	2525	3.3	2412	1742	2525	25	5990	1962	8082	2.5	2254	1742	2525
16	Jali	2.4	4253	2827	3406	3.1	4443	2827	3406	24.2	7925	2935	6202	2.4	4253	2827	3406

From a general mobility point of view, a fair number of transit mode options are available in zones close to the central business district, which increases their mobility attraction towards transit-based travel. Remote and outlying zones had little or no connectivity with transit modes and facilities therefore have more attraction towards car-based travel. NMT modes did not score highly in the analysis. No traffic analysis zone showed attraction towards walk based travel, however, certain zones such as Kigali, Kigarama and Nyakabanda did have fair infrastructure available to encourage bicycle-based travel, and therefore score higher than the walk mode and have bicycle as the preferred mode from a PMI perspective.

Similarly, when considering the results of the potential accessibility for the 15 min travel time threshold of Kigali city (focussing on and ranking the cumulative accessibility function by car) most of the zones decrease significantly by almost half as expected. If you halve the travel time threshold it would stand to reason that employment opportunities that can be reached in that time period is roughly half that of the 30min travel time threshold. Thus, the travel time threshold can be seen as a control variable which the city of Kigali can use to determine the amount of focus, resources, investments, etc. that could be dedicated to plan and provide better in Kigali. The table of results of the potential accessibility for the 15 min travel time threshold of Kigali city are contained in **Annexure D1**. To understand the trends of the preferred mode of transport in terms of accessibility indices the QGIS software package has been used to plot and visualise the indices for each traffic analysis zones with respect to the four modes of transport.

The results show that the Car is the preferred mode from an accessibility point of view, for all the regions. However, as indicated in the previous section, the results on the PMI suggest that it may require a significant overhaul to increase prioritisation of an inclusive, multi-modal, non-motorised transport focused infrastructure with increased accessibility for the other modes of transport.

Figure 21-23 shows the accessibility differentials for the car mode per zone (for the 30% sufficiency threshold and 30min travel time threshold) using the various accessibility formulae (Cumulative, Exponential gravity and Inverse power gravity) and highlights which zones enjoy the best (darker shades)) and worst (lighter shades) accessibility. It is interesting to note, that using the various accessibility formulae give different outcomes and wou˙ ˙ need to be considered when choosing which accessibility measure is most appropriate to use in studies going forward.

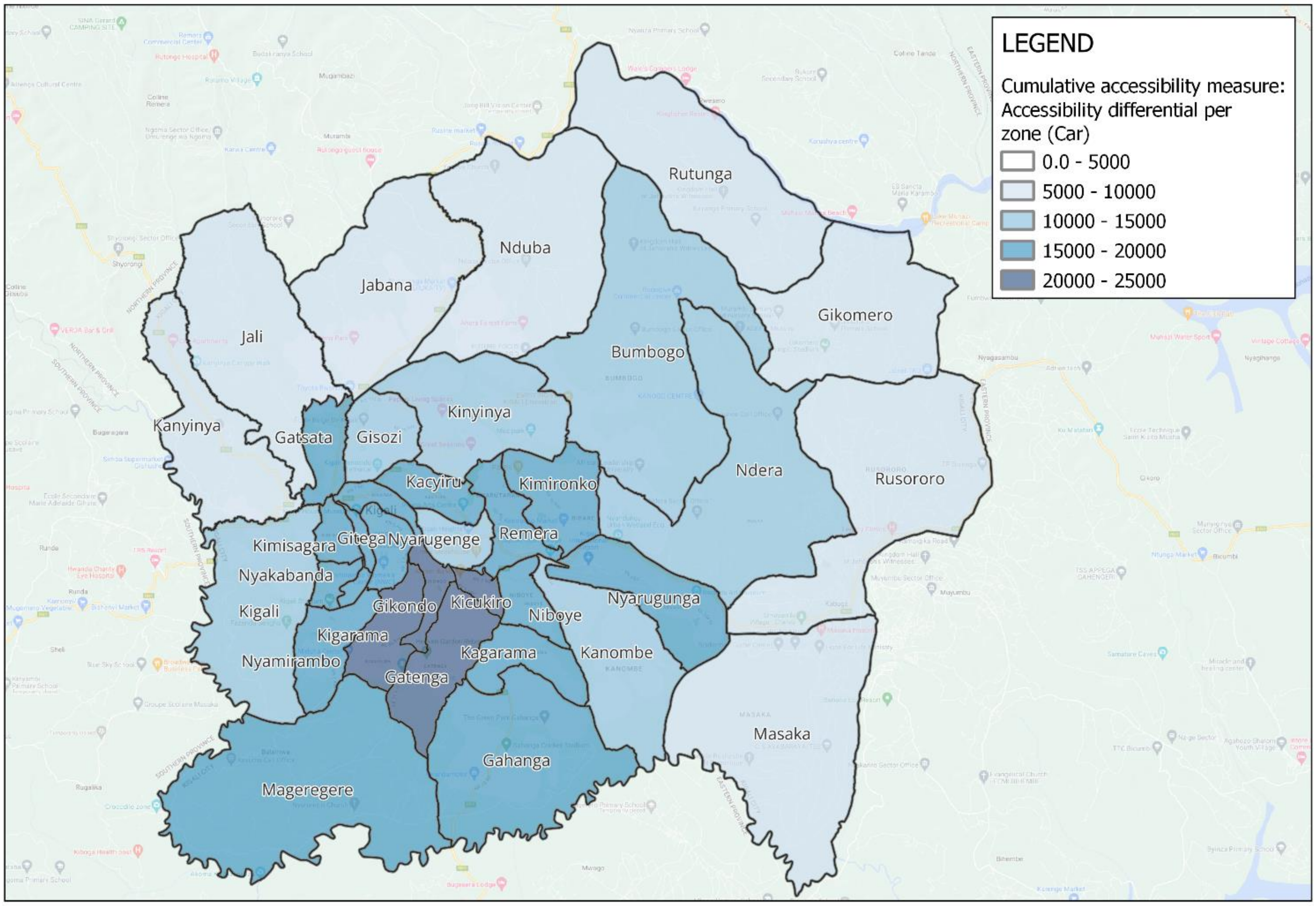

Figure 21: Cumulative accessibility measure: Accessibility differential per zone (Car) for Kigali (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Cumulative accessibility measure the Jali zone has the least accessibility while the Gatenga zone has the best accessibility.

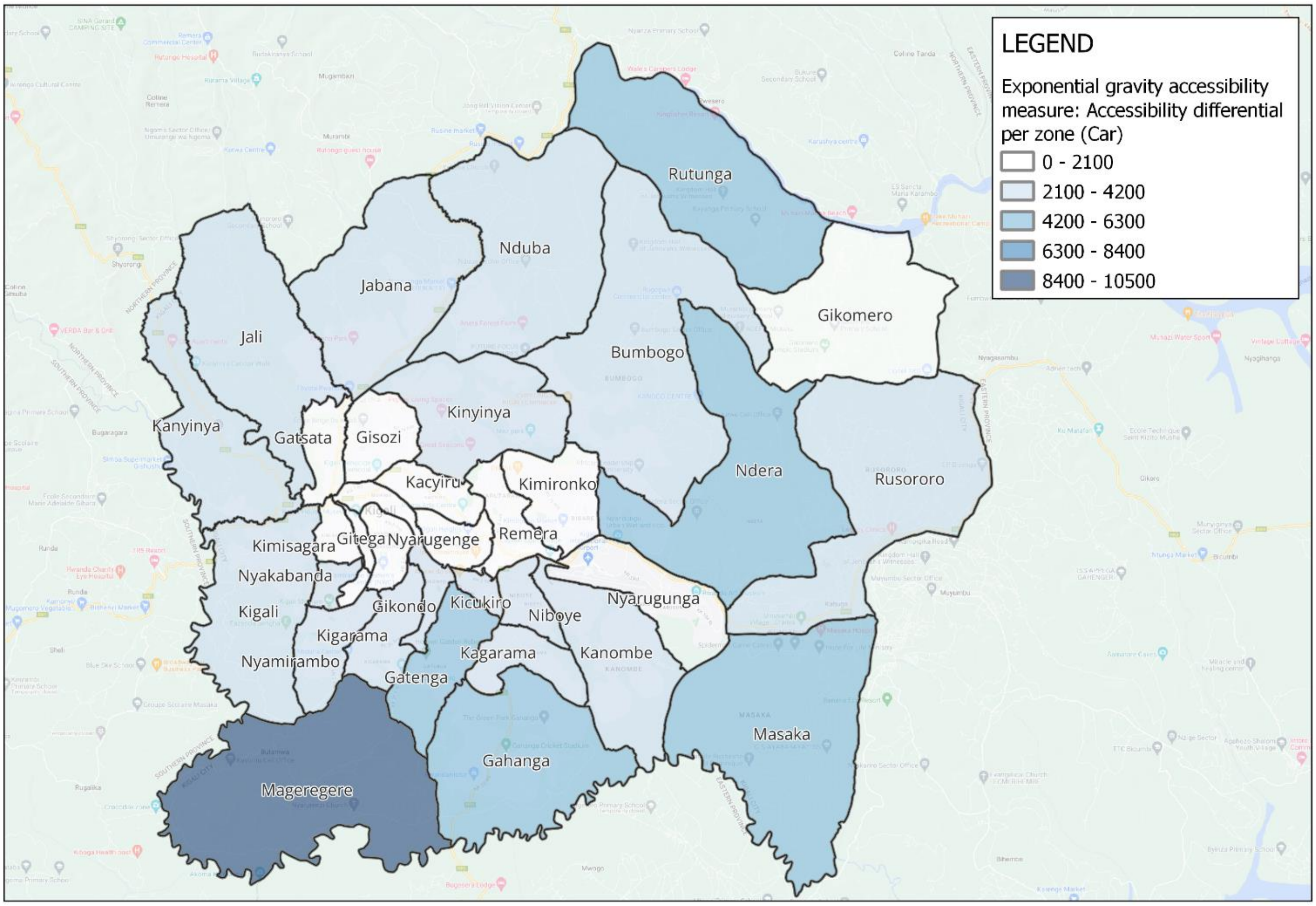

Figure 22: Exponential gravity accessibility measure: Accessibility differential per zone (Car) for Kigali (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Exponential gravity accessibility measure the Kimihurura zone has the least accessibility while the Mageregere zone has the best accessibility.

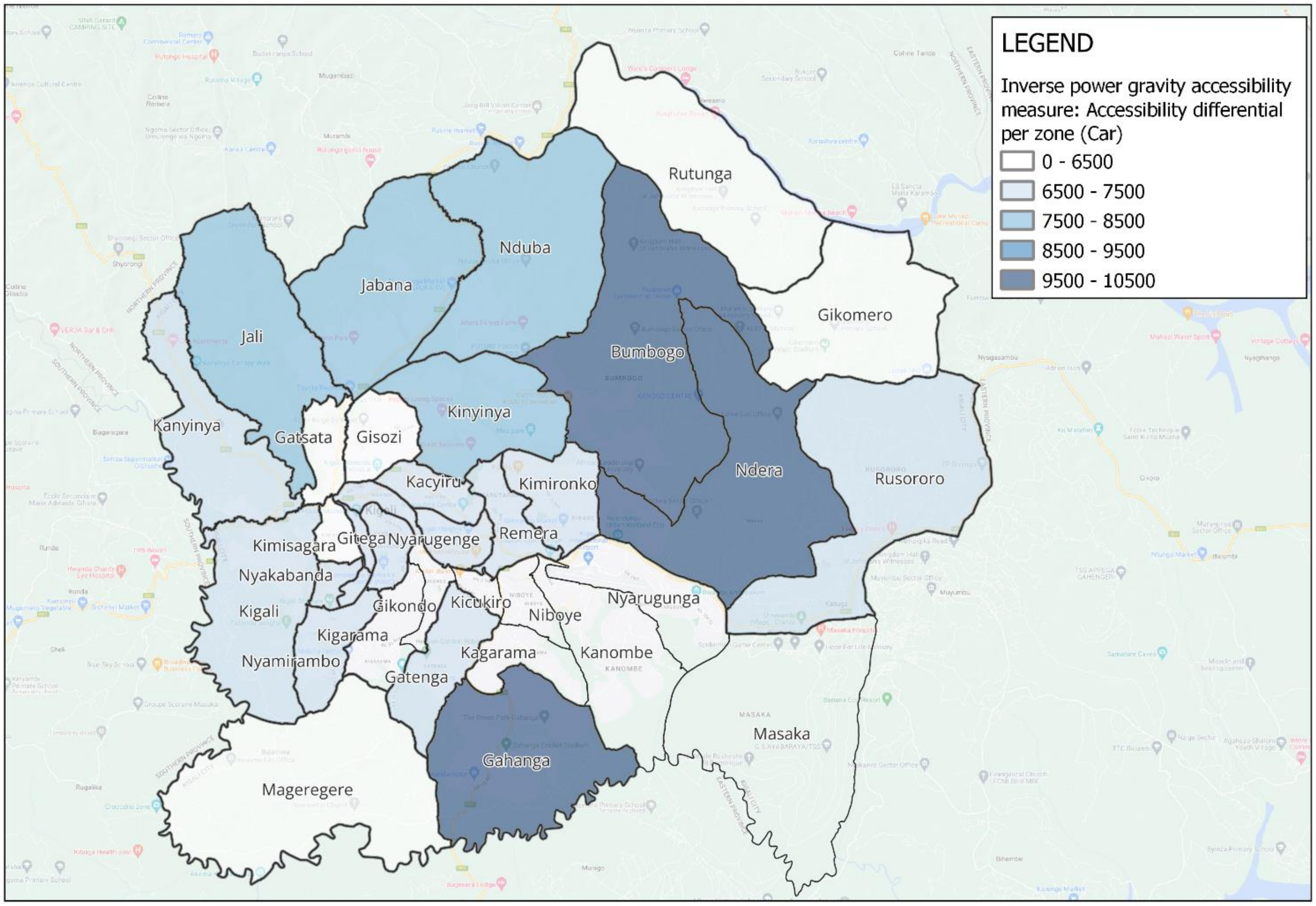

Figure 23: Inverse power gravity accessibility measure: Accessibility differential per zone (Car) for Kigali (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Inverse power gravity accessibility measure the Mageregere zone has the least accessibility while the Bumbogo zone has the best accessibility.

5.1.3 REPRESENTATION OF POTENTIAL MOBILITY AND ACCESSIBILITY

The analysis of the potential mobility vs. potential accessibility for all population groups for each travel time threshold are graphically shown in **Figures 24 and 25** for the peak hour in Kigali. The cumulative accessibility measure and 30% sufficiency threshold will be discussed only. Additionally, the average car-based accessibility and average car-based potential mobility axes (solid vertical and horizontal lines) demarcate the four quadrants while the dashed lines demarcate the accessibility sufficiency threshold lines for 50%, 30%, and 10% accessibility sufficiency thresholds.

It is important to note that since the average PMI and average accessibility level for car-based groups make up the axes of the quadrants therefore, some car-based population groups will fall below the average PMI and average accessibility levels. Furthermore, key stakeholders may differentiate acceptable levels of sufficient accessibility and potential mobility based on other criteria e.g., political will, mandates and other community commitments. Different sufficiency threshold levels could also be chosen which would broaden (or lessen) the investigation; consequently, requiring more resources to carry out transportation planning analysis with principles of justice (Martens, 2017).

Broadly the analysis of the cumulative accessibility vs. mobility index in **Figure 24** revealed that most of the modes per zone in Kigali lacked in achieving sufficient accessibility levels as they mostly fell in Quadrant I and IV (low accessibility values) below the average car mode accessibility level. It can be observed that accessibility indices for the car mode mostly lies above the sufficiency threshold of 30% indicating fair accessibility levels among zones with the car mode as the major mode of transport. However, it can be also noted that accessibility indices for transit overlaps mostly with the NMT modes of transport. This is due to the GTFS file of Kigali having minimal transit data information. Therefore, the model "defaults" by assuming that no transit modes are available for travel, thereby assigning them to NMT modes (as it is deemed faster to walk or cycle the distance than wait for the next transit option). This subsequently makes the outcomes of the transit and NMT modes accessibility very similar to each other. Zones performed fairly in terms of mobility indices for the car mode showing that approximately half the zones lie in Quadrant III and IV (high mobility values). PMIs for the NMT modes ranged mostly below the average PMI between 21-24km/hr.

Overall, the results suggest that the Kigali region needs improvements to increase potential accessibility indices for NMT modes, whilst the low mobility indices for the car mode suggest road network or congestion challenges that would require focus.

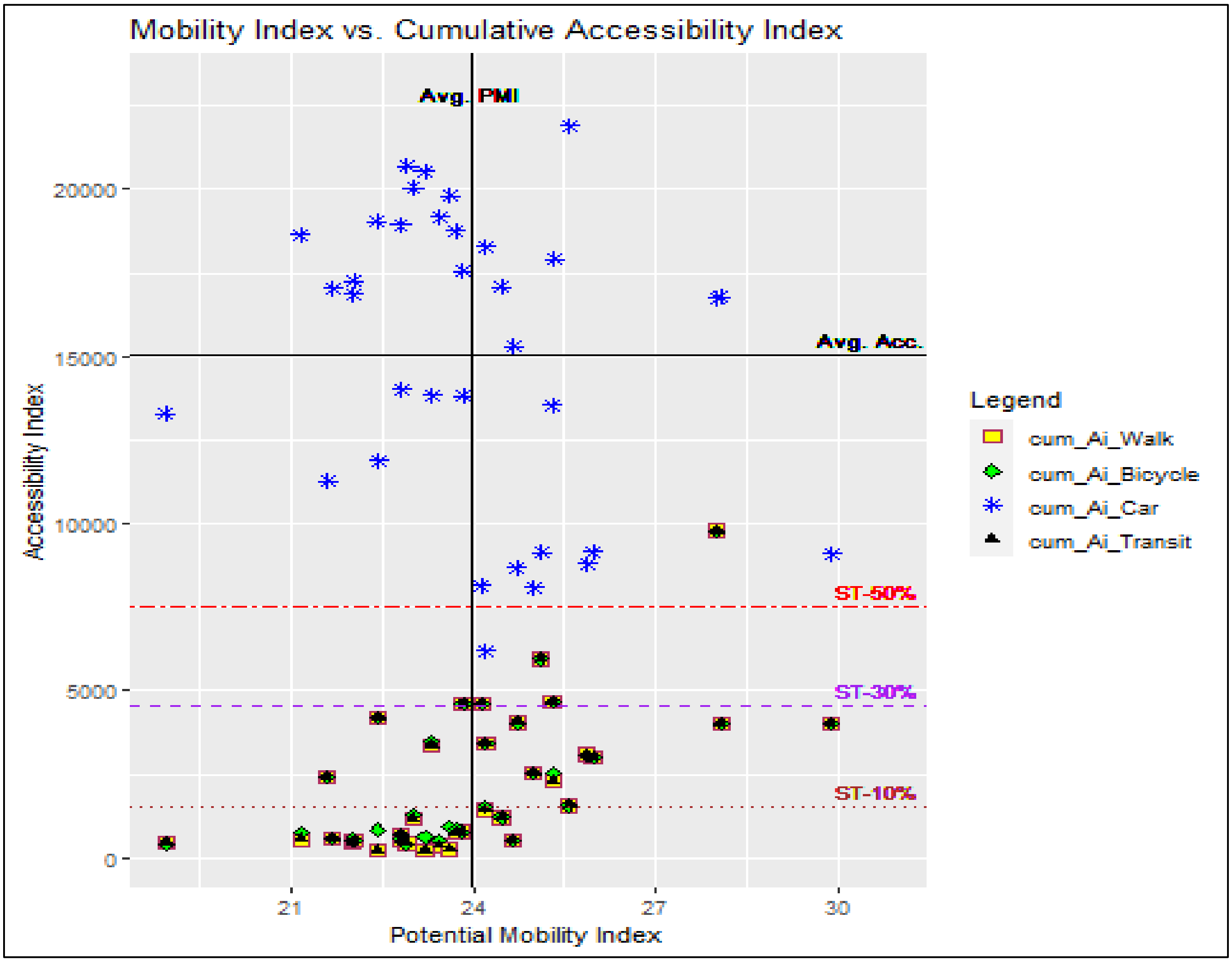

Figure 24: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) – cumulative accessibility

If one were to decrease (or increase) the threshold travel time, accessibility levels would fluctuate accordingly; this showcases how travel time changes may affect two similar modes, purely because of the way they are operated. **Figure 25** also shows the cumulative accessibility measure and 30% sufficiency threshold but at the 15 min travel time threshold. Broadly the analysis showed a similar trend to the 30min analysis although the car mode accessibility indices were significantly lower, as can be expected. Less options are available in a shorter travel time threshold. Overall, the results suggest that key stakeholders may differentiate acceptable levels of sufficient accessibility and potential mobility based on other criteria or mandates at the time and the travel time threshold could be used as a that differentiation factor.

Annexure D2 contains the Inverse power gravity and exponential gravity accessibility measure analysis of the potential mobility vs. potential accessibility for the 15 and 30min time thresholds for comparison.

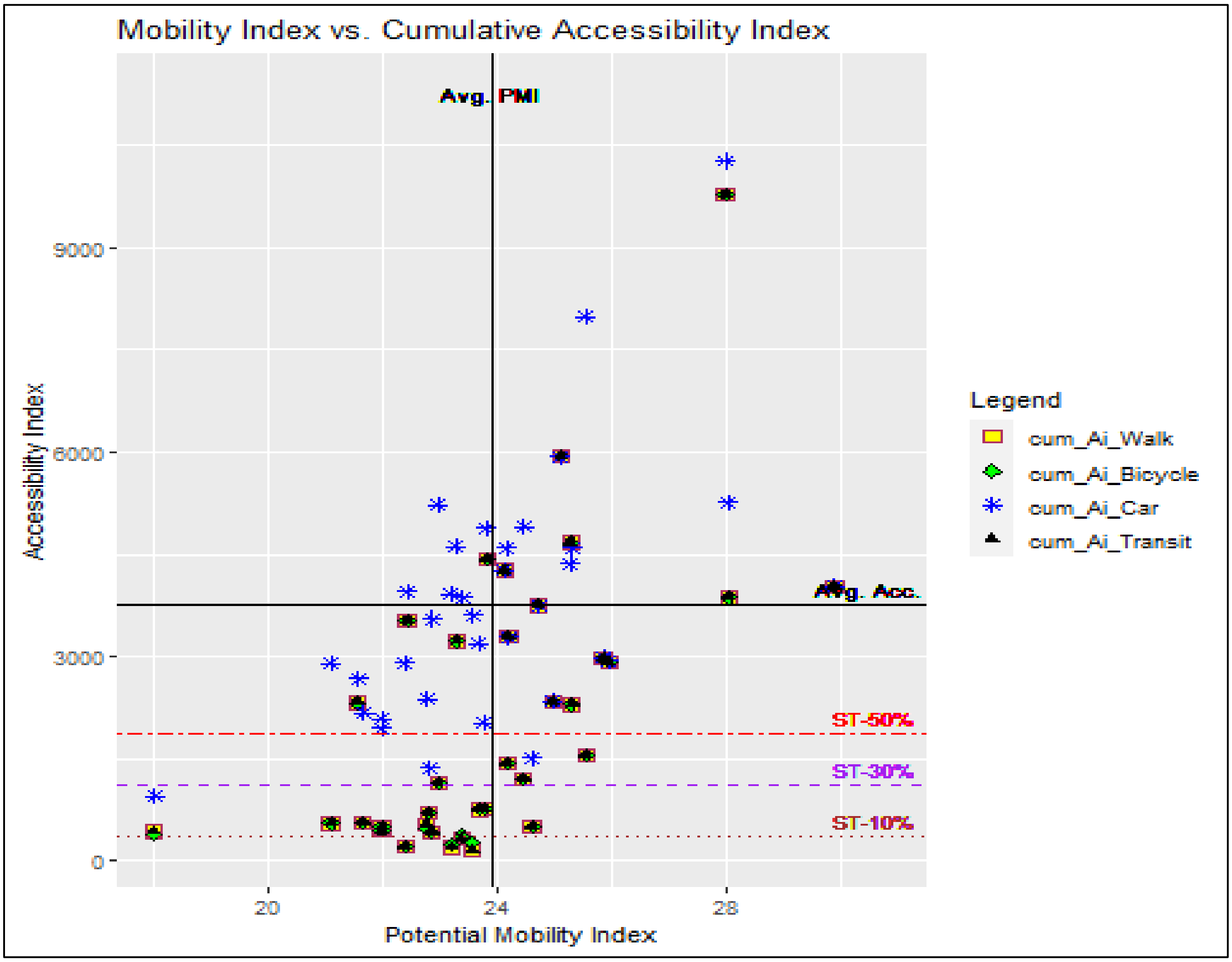

Figure 25: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) – cumulative accessibility

5.1.4 POTENTIAL ACCESSIBILITY FAIRNESS INDEX

The AFIs are used to rate the shortfall of accessibility among TAZs. These are essential indicators to focus efforts to prioritise zones with less-than-optimal accessibility levels. For computation of AFI, the accessibility sufficiency thresholds are set to classify zones with ample accessibility levels. The index takes into account the size of the population groups, the exact accessibility level experienced by the groups, and the share of groups experiencing accessibility shortfalls.

Table 7 shows the AFI for all zones, per method, per mode, for the 30% sufficiency threshold at 30 min travel time threshold (based of the car mode) as computed following the mathematical equations in the R environment.

Table 5: Comparison of AFI for all zones, per method, per mode, for the 30% sufficiency threshold at 30 min travel time threshold (based of the car mode) for Kigali

Zone No.	Zone Name	Inverse Function (1000s)				Exponential Function (1000s)				Cumulative Function (1000s)			
		Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit
1	Gitega	0.50	0.08	-	0.43	1.46	1.33	-	1.46	2.29	1.67	-	2.29
2	Kanyinya	-	-	-	-	-	-	-	-	0.54	0.54	-	0.54
3	Kigali	-	-	-	-	-	-	-	-	0.31	0.31	-	0.31
4	Kimisagara	1.55	0.45	-	1.43	1.74	1.68	-	1.74	5.78	5.50	-	5.78
5	Mageregere	52.38	37.41	-	52.38	-	-	-	-	-	-	-	-
6	Muhima	1.31	-	-	1.14	1.01	1.69	-	1.01	4.93	4.85	-	4.93
7	Nyakabanda	1.06	0.24	-	1.00	2.05	1.91	-	2.05	4.38	4.08	-	4.38
8	Nyamirambo	4.22	1.04	-	4.10	-	-	-	-	8.71	8.19	-	8.71
9	Nyarugenge	2.01	0.48	-	1.77	1.37	1.32	-	1.37	7.65	7.06	-	7.65
10	Rwezameny o	0.39	0.04	-	0.36	1.49	1.27	-	1.49	1.97	1.38	-	1.97
11	Bumbogo	25.14	15.89	-	25.08	-	-	-	-	-	-	-	-
12	Gatsata	2.07	0.97	-	1.97	1.27	1.27	-	1.27	5.82	5.82	-	5.82
13	Gikomero	-	-	-	-	-	-	-	-	8.33	8.33	-	8.33
14	Gisozi	2.57	0.75	-	2.46	0.37	0.37	-	0.37	7.26	7.26	-	7.26
15	Jabana	-	-	-	-	-	-	-	-	4.89	4.89	-	4.89
16	Jali	-	-	-	-	-	-	-	-	2.72	2.72	-	2.72
17	Kacyiru	1.54	0.45	-	1.41	1.36	1.35	-	1.36	5.65	5.65	-	5.65
18	Kimihurura	1.41	0.03	-	1.30	1.60	2.27	-	1.60	5.10	5.14	-	5.10
19	Kimironko	3.21	0.73	-	2.84	0.19	0.19	-	0.19	9.57	9.57	-	9.57
20	Kinyinya	-	-	-	-	-	-	-	-	6.46	6.46	-	6.46
21	Ndera	-	-	-	-	-	-	-	-	-	-	-	-
22	Nduba	-	-	-	-	-	-	-	-	5.66	5.66	-	5.66
23	Remera	1.90	0.40	-	1.68	1.18	1.17	-	1.18	6.87	6.87	-	6.87
24	Rusororo	-	-	-	-	-	-	-	-	-	-	-	-
25	Rutunga	23.21	18.89	-	23.21	-	-	-	-	0.58	0.58	-	0.58
26	Gahanga	-	-	-	-	-	-	-	-	0.79	0.79	-	0.79
27	Gatenga	4.64	1.26	-	4.38	-	-	-	-	9.58	9.58	-	9.58
28	Gikondo	1.14	0.21	-	1.01	1.64	1.62	-	1.64	5.01	5.01	-	5.01
29	Kagarama	3.21	0.84	-	2.98	-	-	-	-	7.74	7.74	-	7.74
30	Kanombe	-	-	-	-	-	-	-	-	2.75	2.07	-	2.75
31	Kicukiro	0.71	0.09	-	0.59	2.17	1.95	-	2.17	3.36	2.76	-	3.36
32	Kigarama	2.97	0.66	-	2.84	-	-	-	-	8.34	7.80	-	8.34
33	Masaka	41.83	28.52	-	41.83	-	-	-	-	-	-	-	-
34	Niboye	1.84	0.27	-	1.63	0.18	0.15	-	0.18	6.27	5.91	-	6.27
35	Nyarugunga	6.52	1.77	-	5.64	-	-	-	-	6.60	5.29	-	6.60

The data above can be represented spatially in GIS packages to highlight the accessibility deficiencies among the modes and their dependent population groups in the regions. This can be tested against various sufficiency thresholds for accessibility to employment (or any other attractor), the various travel time threshold and the various accessibility measures for the selected analysis period (e.g., peak hours, etc.).

5.1.5 RANKED CONTRIBUTION TO OVERALL ACCESSIBILITY FAIRNESS

The essence of any transport justice analysis is to identify zones which lack in transport infrastructure and requires focus or improvement in terms of mobility and accessibility provision. It also prioritises zones with severe accessibility shortage by ranking them compared to other zones. An accessibility fairness (deficiency) analysis using the AFI indices was carried out for the same, to identify the overall shortage of accessibility in the region of Kigali and is then ranked and prioritised into zones with severe shortages/deficiencies.

The AFI considers accessibility levels and the number of people with accessibility levels below the sufficiency thresholds selected (in this case of 30%) to show the intensity of the accessibility shortfalls. The following section presents the share of population groups' contribution to overall accessibility deficiency based on the 30% sufficiency threshold during peak hour per accessibility measure (Inverse, Exponential and Cumulative functions). **Table 8** highlights the summary of the overall accessibility deficiency of the Kigali region with sufficiency threshold of 30% comparing three different methods of accessibility computation. The lower a group is below the accessibility threshold; the more accessibility shortfalls are experienced and the larger the weight it contributes to the overall measurement of accessibility. The index ranges between 0-1, the closer to one (1) it is the more severe the population group is experiencing accessibility shortfalls.

The cumulative measure analysis indicates that 30 zones out of 35 zones shows lower accessibility level compared to the 30% threshold limit. These groups have an overall population of around 701,000 people which equates to approximately 63% of the overall Kigali population. From these results it can be surmised that the Kigali region severely lacks in accessibility provision and would need a major overhaul in transport infrastructure and road networks to improve travel attraction by walk, bicycle and transit modes.

Table 6: Overall accessibility deficiency of Kigali region with Sufficiency Threshold of 30% with comparison of three different methods of accessibility measurement

Indicator	Inverse Function				Exponential Function				Cumulative Function			
	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit
Accessibility Fairness Index (AFI)	0.17	0.10	-	0.16	0.02	0.02	-	0.02	0.14	0.13	-	0.14
Number of Groups below Sufficiency Threshold (30%)	24	23	-	24	15	15	-	15	30	30	-	30
Percentage of Groups below Sufficiency Threshold (30%) %	69	66	-	69	43	43	-	43	86	86	-	86
Number of People below Sufficiency Threshold (30%) (in 1000s of persons)	544	537	-	544	106	106	-	106	701	701	-	701
Percentage of People below Sufficiency Threshold (30%) %	49	48	-	49	10	10	-	10	63	63	-	63

The analysis further pointed out individual zones with accessibility challenges. There are 35 zones with 4 different choices of mode of transport making it overall 140 different levels of improvements (i.e., 35 zones x 4 modes of transport). **Annexure D3** shows the complete list of ranked zones which needs improvement in term of the mentioned mode of transport that lacked severely in terms of the accessibility fairness index (cumulative accessibility measure at 30% sufficiency threshold and 30min travel time threshold).

Figures 26 to 29 show the AFI contribution per zone per mode while **Tables 9 to 12** show the Top 10 zones with the highest AFI contribution (i.e., zones that most severely lacked in terms of accessibility using that mode).

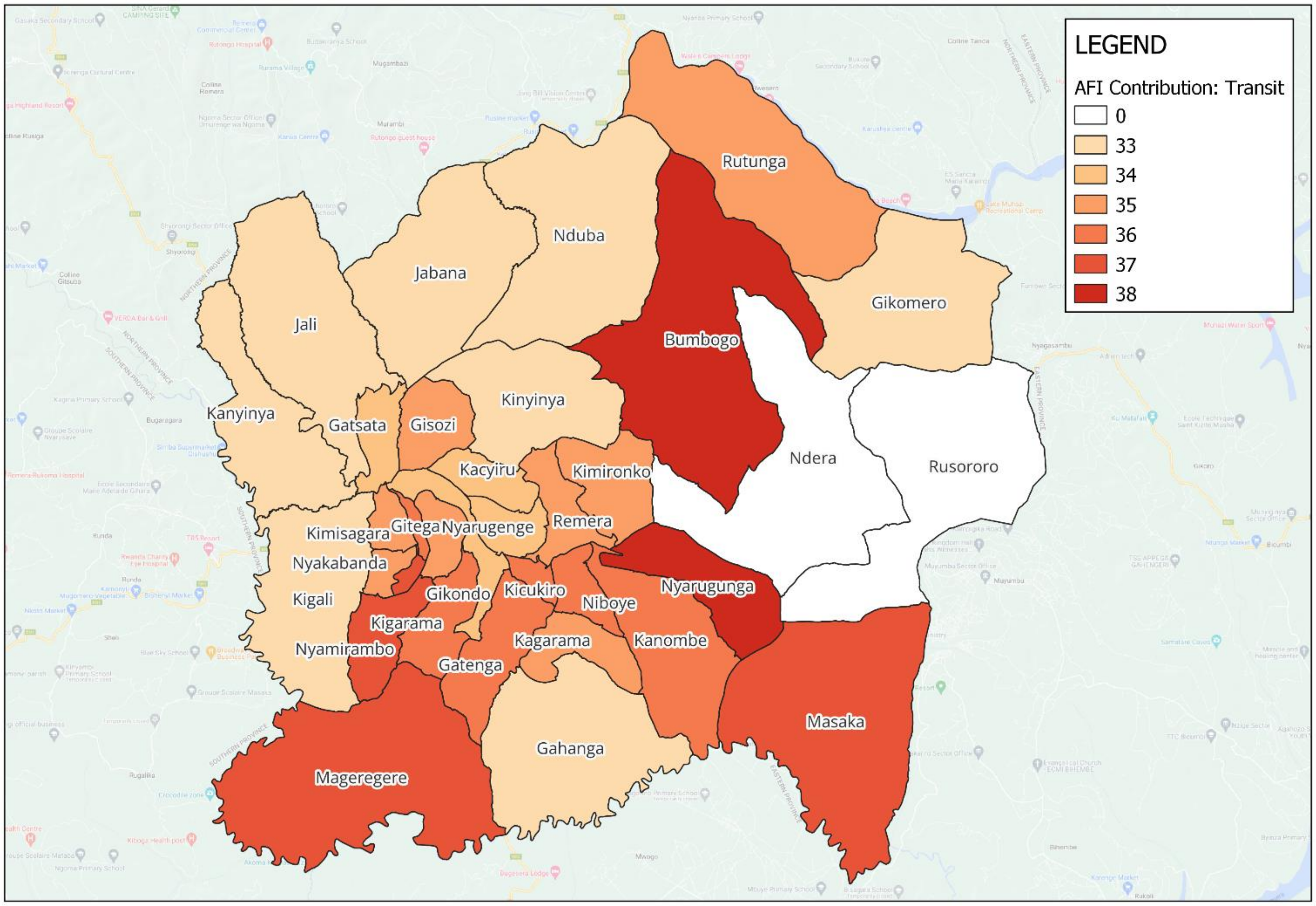

Figure 26: AFI Contribution per zone for Transit mode in Kigali

Table 7: Top 10 Zones for AFI Contribution for Transit mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Bumbogo	11	38
2	Nyarugunga	35	38
3	Mageregere	5	37
4	Nyamirambo	8	37
5	Rwezamenyo	10	37
6	Masaka	33	37
7	Gitega	1	36
8	Gatenga	27	36
9	Kanombe	30	36
10	Kicukiro	31	36

In terms of the transit mode, zone 11 (Bumbogo) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the transit mode.

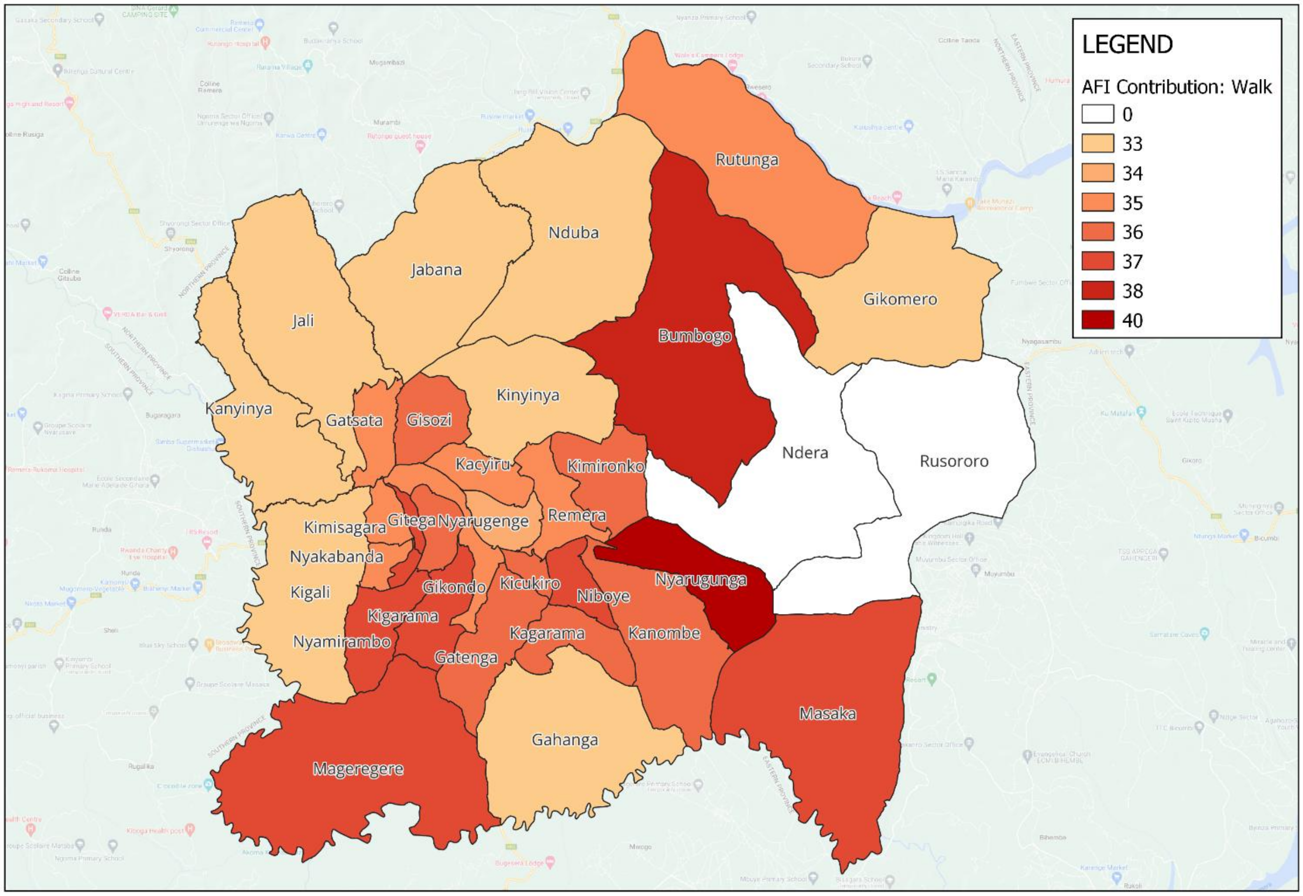

Figure 27: AFI Contribution per zone for Walk mode in Kigali

Table 8: Top 10 Zones for AFI Contribution for Walk mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Nyarugunga	35	40
2	Bumbogo	11	38
3	Gitega	1	37
4	Mageregere	5	37
5	Nyamirambo	8	37
6	Rwezamenyo	10	37
7	Kigarama	32	37
8	Masaka	33	37
9	Niboye	34	37
10	Nyarugenge	9	36

In terms of the walk mode, zone 35 (Nyarugunga) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the walk mode.

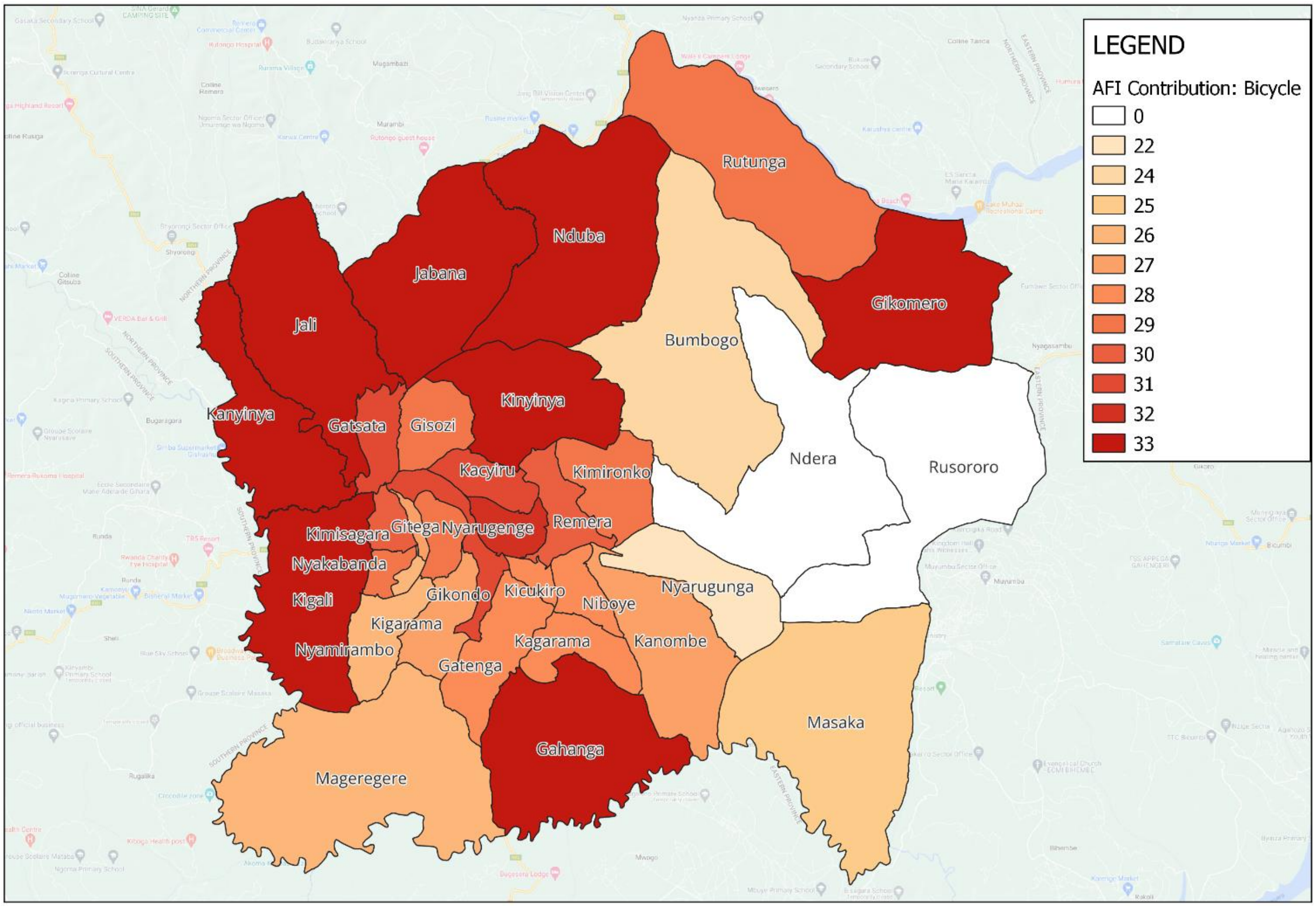

Figure 28: AFI Contribution per zone for Bicycle mode in Kigali

Table 9: Top 10 Zones for AFI Contribution for Bicycle mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Kanyinya	2	33
2	Kigali	3	33
3	Gikomero	13	33
4	Jabana	15	33
5	Jali	16	33
6	Kinyinya	20	33
7	Nduba	22	33
8	Gahanga	26	33
9	Kimihurura	18	32
10	Muhima	6	31

In terms of the walk mode, zone 2 (Kanyinya) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the bicycle mode.

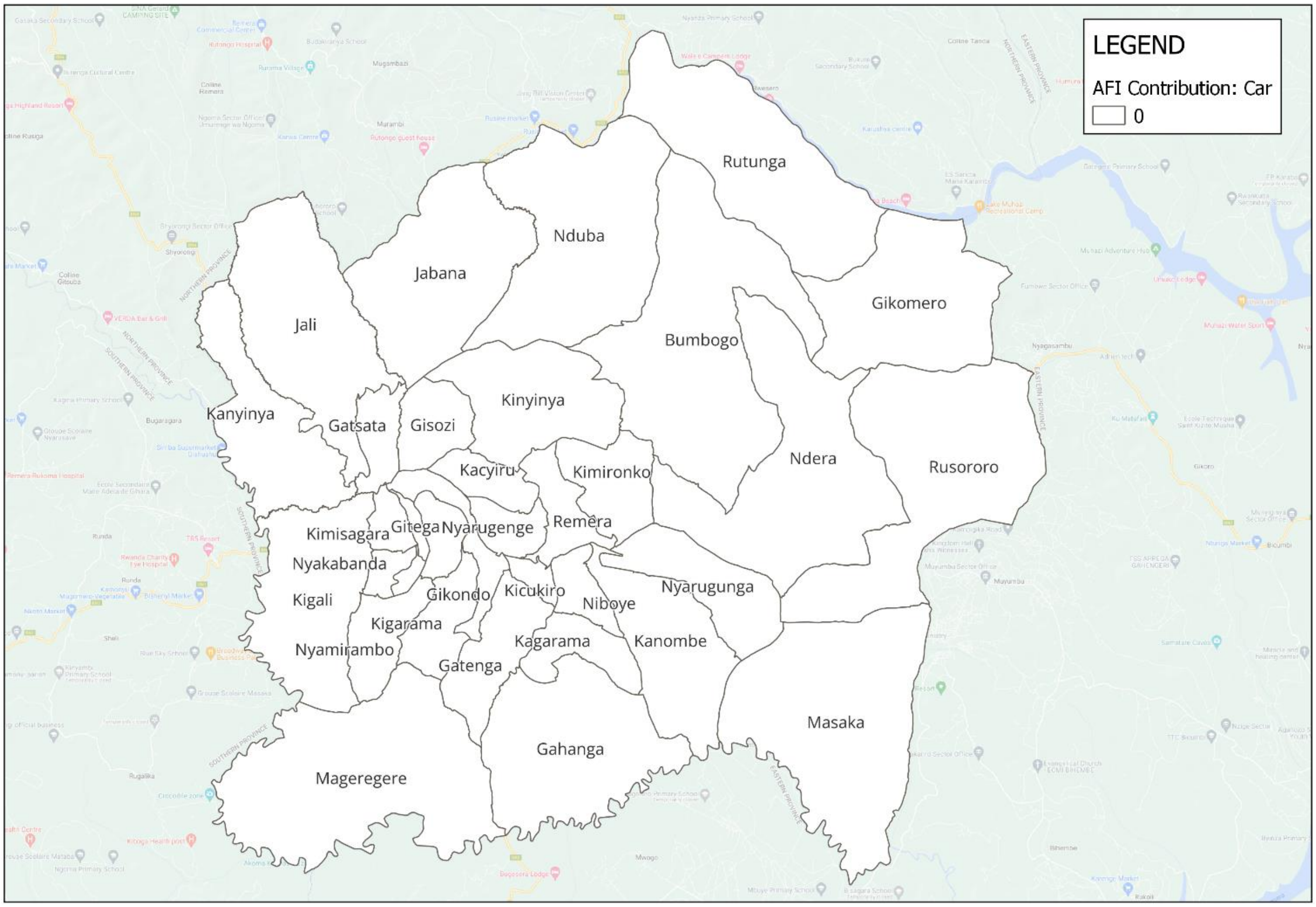

Figure 29: AFI Contribution per zone for Car mode in Kigali

Table 10: Top 10 Zones for AFI Contribution for Car mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Gitega	1	0
2	Kanyinya	2	0
3	Kigali	3	0
4	Kimisagara	4	0
5	Mageregere	5	0
6	Muhima	6	0
7	Nyakabanda	7	0
8	Nyamirambo	8	0
9	Nyarugenge	9	0
10	Rwezamenyo	10	0

In terms of the car mode, all zones displayed an AFI contribution of 0% thus implying that all zones did not have an challenges in terms of accessibility.

5.2 NAIROBI: DISCUSSION OF RESULTS

The results for the transport justice analysis tool for Nairobi have been summarized in the following section with the same descriptions and definitions as defined in **Section 5.1** for Kigali.

Similarly, the Nairobi road network is designed in a conventional way where road densities are more concentrated towards the city centre and outlying areas typically have low accessibility to the road network and public transit options. The results of the transport justice analysis show a very similar pattern as described in the following section.

5.2.1 POTENTIAL MOBILITY INDEX

The computed potential mobility indices per zone, per mode for Nairobi are shown in **Table 13** (and ranked by car PMI, as it had the best PMI results in Nairobi). Again (as in Kigali), car mode has the best PMI results. It highlighted that the Dagoretti, Embakasi and Kamukunji zones respectively provided the top 3 best PMI scores for the car mode, while the Njiru, Starehe and Westlands zones showed the 3 worst PMI scores; indicating that if investment needed to be prioritised the zones with the worst PMI scores would likely be considered for improvement in road network and transport infrastructure in order to improve the average level of mobility available between certain zones for the car mode. Similarly, the Embakasi, Kasarani and Makadara zones had the 3 worst PMI scores for the bicycle mode; indicating that if investment needed to be prioritised these zones would likely be considered for improvement for NMT/cycling facilities first.

Table 11: Potential mobility indices per zone, per mode (ranked by car PMI) for the 30min travel time thresholds (Nairobi)

Ranked by Car PMI	Zone No.	Zone Name	PMI (Walk) km/hr	PMI (Bicycle) km/hr	PMI (Car) km/hr	PMI (Transit) km/hr
1	1	Dagoretti	2.8	2.8	29.9	5.2
2	2	Embakasi	2.5	2.5	31.8	4.9
3	3	Kamukunji	2.7	2.7	22.8	6.7
4	4	Kasarani	2.5	2.5	33.4	5.4
5	5	Kibra	2.7	2.7	26.3	5
6	6	Lang'ata	2.7	2.7	27.3	5.2
7	7	Makadara	2.6	2.6	24.4	5.2
8	8	Mathare	2.6	2.6	25.1	4.7
9	9	Njiru	2.7	2.7	27.4	5.6
10	10	Starehe	2.7	2.7	22.5	6.8
11	11	Westlands	2.8	2.8	28.3	5.2

5.2.2 POTENTIAL ACCESSIBILITY INDEX

Table 14 details the potential mobility indices and potential cumulative accessibility levels for each mode for each of the 11 TAZs in Nairobi. Ranking the cumulative accessibility function by car, the results of the potential accessibility for the 30% sufficiency threshold and 30 min travel time threshold indicates that the car mode has the most zones of highest, and thus good accessibility levels; the zones of Embakasi and Westlands have the highest accessibility levels of 990,000 and 954,000 respectively. The lowest accessibility levels for the car mode belong to the zones of Lang'ata and Dagoretti and have the lowest accessibility levels of 237,000 and 402,000 respectively.

PMI values or mobility indices (i.e., average travel speed in kilometre per hour (km/hr)) of different zones of Nairobi for the car mode are varied between 23 km/hr to 34.7 km/hr. This would indicate that there is ample supply of road network available for travel by car, but factors such as the condition of road pavement/s or localised congestion may be variable in different zones. Zones with low PMI values, particular within the transit mode, such as Mathare (4.9 km/hr) or Embakasi (5 km/hr) with the lowest average travel speeds highlights zones that would need prioritisation in terms of interventions to increase their PMI values or mobility indices. Kibra is the zone that performed the worst for all potential mobility indices and cumulative accessibility levels across each mode; suggesting poor road network coverage in this zone together with congestion that could be leading to the low average travel speeds.

Table 12: Potential mobility and potential accessibility indices per zone, per mode for the 30min travel time threshold (Nairobi)

Zone No.	Zone Name	Walk				Bicycle				Car				Transit			
		PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)
2	Embakasi	2.5	18	412	412	4.1	440	331	398	34.7	560	372	990	5	28	412	412
11	Westlands	2.8	29	138	138	4	39	138	138	29	203	230	954	5.6	52	138	146
4	Kasarani	2.5	20	328	328	3.9	32	328	328	33.7	154	373	906	5.6	32	328	328
7	Makadara	2.6	31	83	83	3.8	44	83	83	24.3	206	178	870	5.7	53	83	83
3	Kamukunji	2.7	35	97	107	3.9	47	97	123	23.1	193	168	860	7.3	73	98	125
8	Mathare	2.6	31	85	85	4	44	85	85	25.3	194	159	845	4.9	51	85	85
10	Starehe	2.7	37	79	91	3.8	125	64	105	23.1	275	143	817	7.4	75	80	136
9	Njiru	2.7	23	256	256	4.8	39	256	256	27.9	142	283	742	5.9	35	256	256
5	Kibra	2.7	26	69	69	4	36	69	69	23	146	87	495	5.3	43	69	69
1	Dagoretti	2.8	17	183	183	4.9	27	183	183	29.6	120	191	402	5.4	28	183	183
6	Lang'ata	2.7	17	83	83	3.9	24	83	83	27.7	117	88	237	5.4	27	83	83

From a general mobility point of view, transit mode options performed poorly with remote and outlying zones even worse with very little connectivity; therefore, zones had more attraction towards car-based travel. NMT modes did not score highly in the analysis and were similar to transit options, due to the GTFS data (as was the case with Kigali) having limited transit data to assign trips.

Similarly, when considering the results of the potential accessibility for the 15 min travel time threshold of Nairobi city (focussing on and ranking the cumulative accessibility function by car) most of the zones decrease significantly by almost half as expected. The table of results of the potential accessibility for the 15 min travel time threshold of Nairobi city are contained in **Annexure E1.**

Again, the results show that the Car is the preferred mode from an accessibility point of view, for all the regions. However, as indicated in the previous section, the results on the PMI suggest that it may require a significant overhaul to increase prioritisation of an inclusive, multi-modal, non-motorised transport focused infrastructure with increased accessibility for the other modes of transport.

Figure 30 - 32 shows the accessibility differentials for the car mode per zone using the various accessibility formulae (Cumulative, Exponential gravity and Inverse power gravity accessibility measures) and highlights which zones enjoy the best (darker shades)) and worst (lighter shades) accessibility.

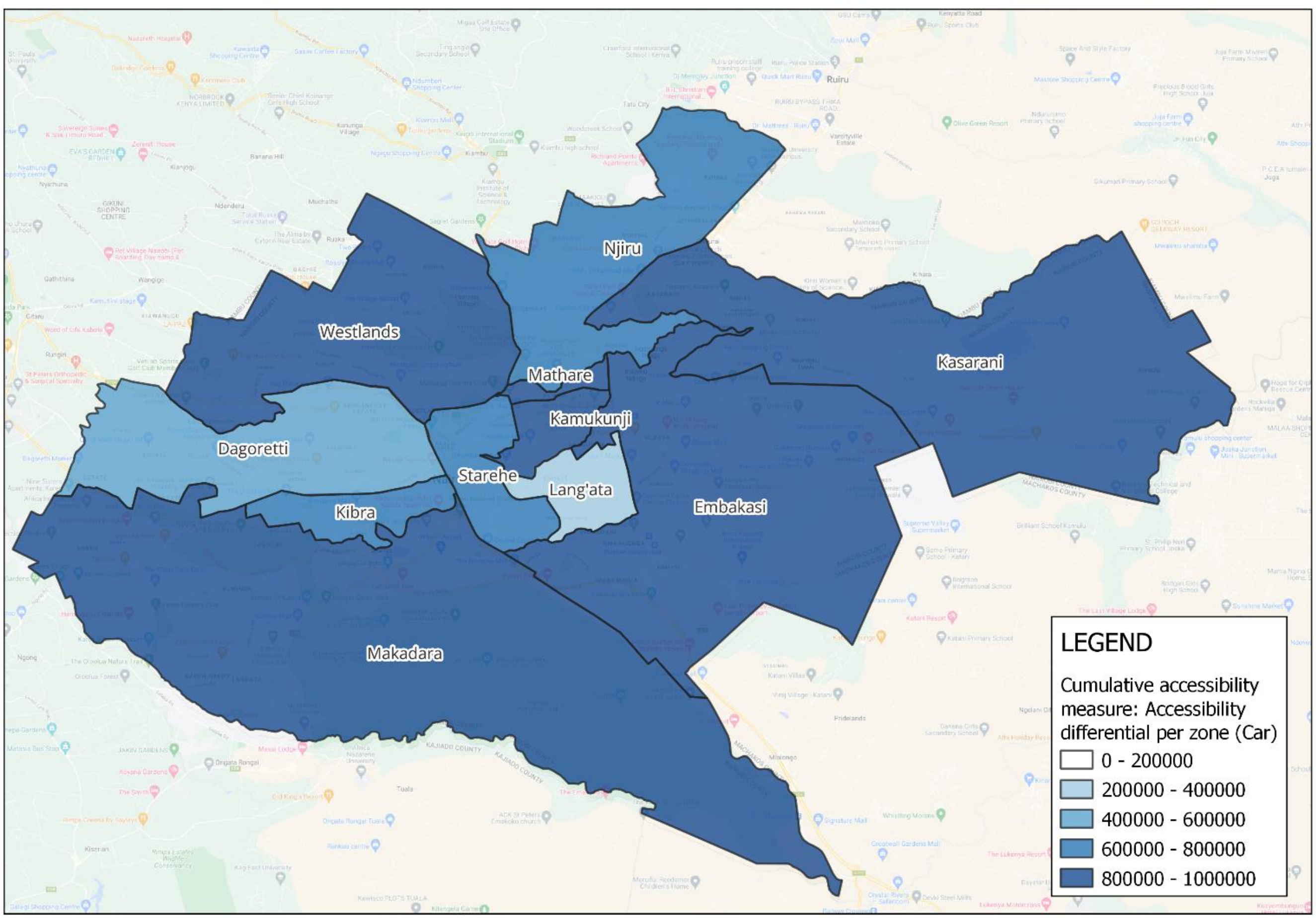

Figure 30: Cumulative accessibility measure: Accessibility differential per zone (Car) for Nairobi (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Cumulative accessibility measure the Lang'ata zone has the least accessibility while the Embakasi has the best accessibility.

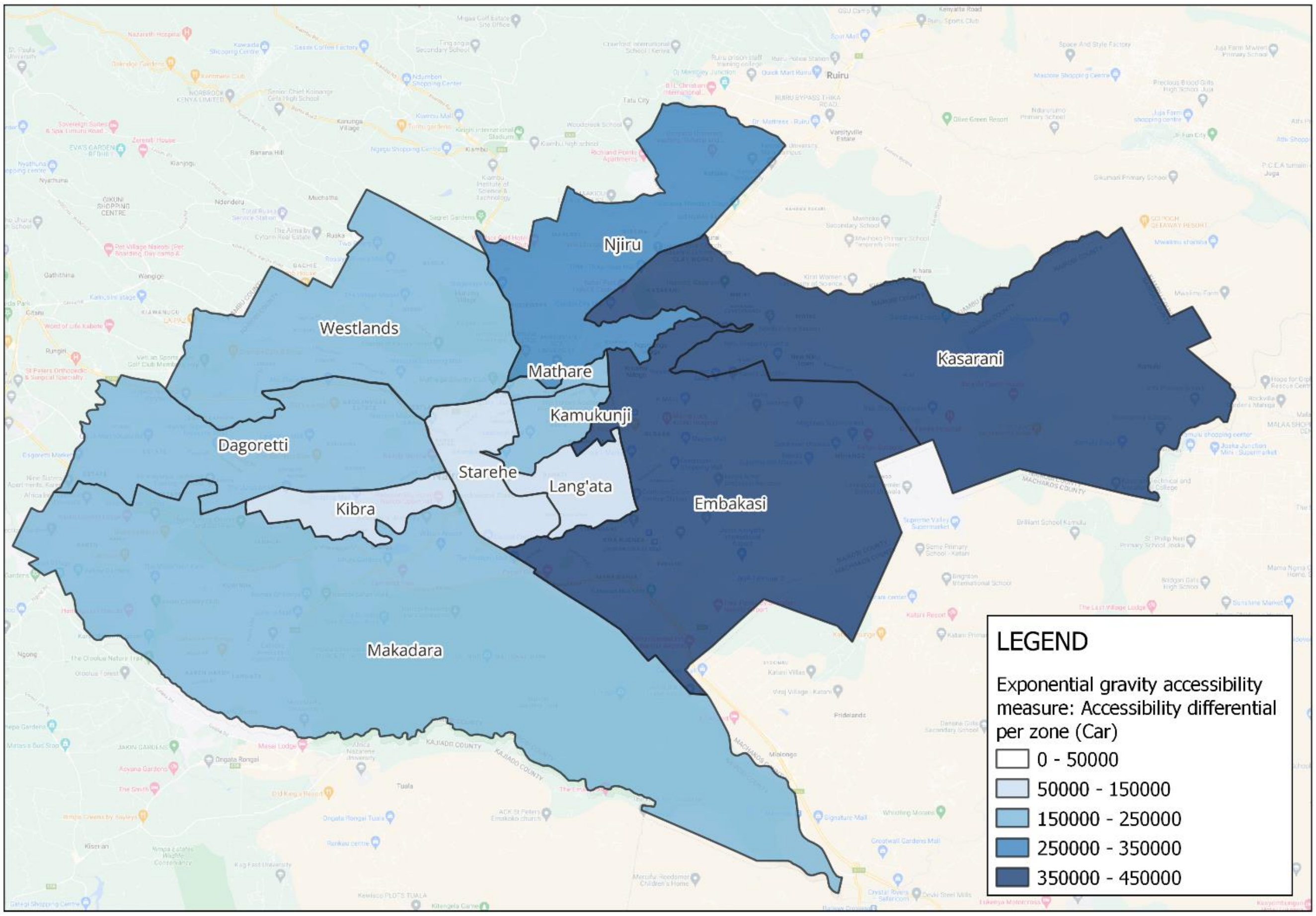

Figure 31: Exponential gravity accessibility measure: Accessibility differential per zone (Car) for Nairobi (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Exponential gravity accessibility measure the Kibra zone has the least accessibility while the Kasarani zone has the best accessibility.

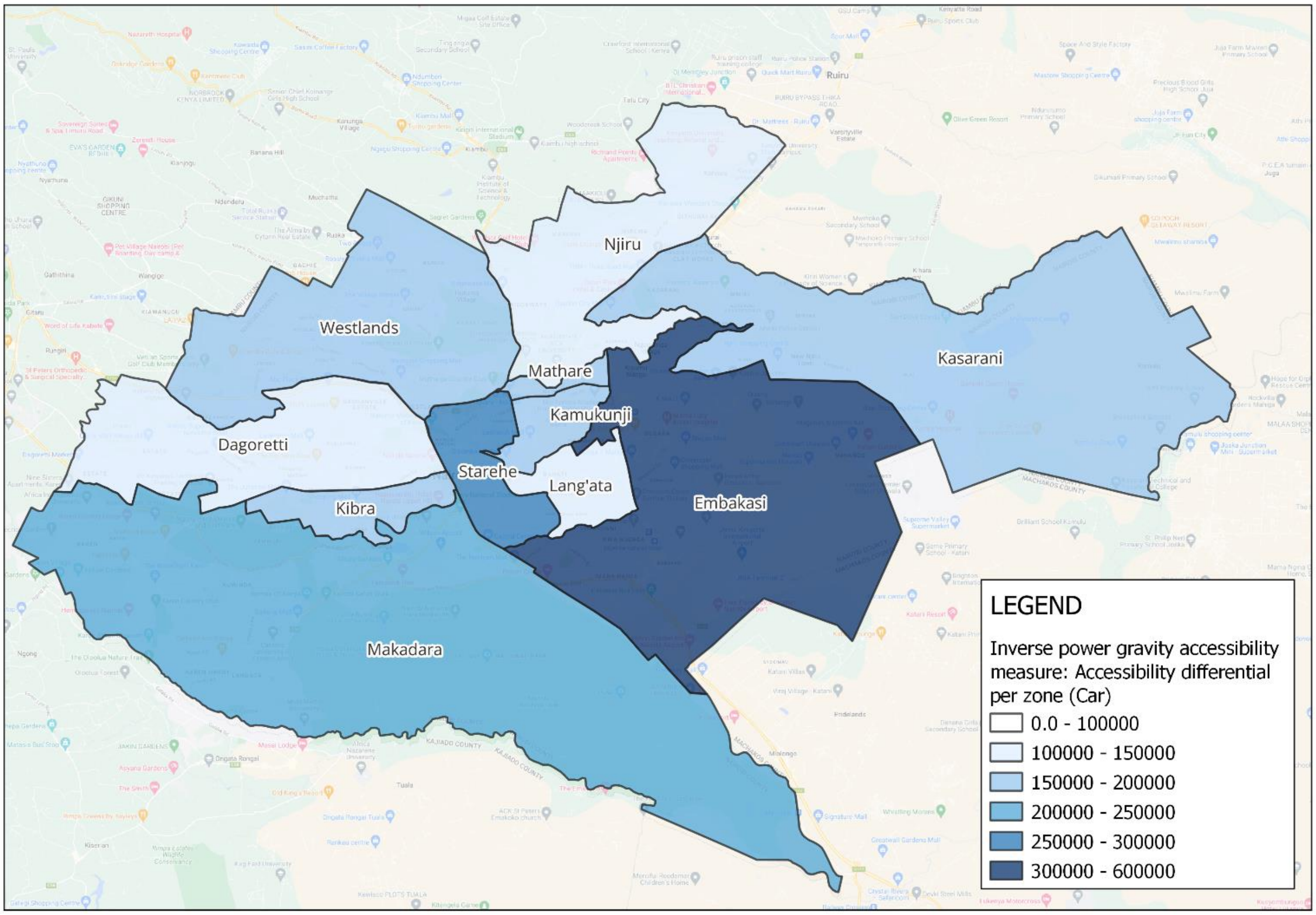

Figure 32: Inverse power gravity accessibility measure: Accessibility differential per zone (Car) for Nairobi (30% sufficiency threshold and 30min travel time)

Comparing the accessibility using the Inverse power gravity accessibility measure the Lang'ata zone has the least accessibility while the Embakasi has the best accessibility.

5.2.3 REPRESENTATION OF POTENTIAL MOBILITY AND ACCESSIBILITY

The analysis of the potential mobility vs. potential accessibility for all population groups for each travel time threshold are graphically shown in **Figures 33 and 34** for the peak hour in Nairobi. The cumulative accessibility measure and 30% sufficiency threshold will be discussed only.

Broadly the analysis of the cumulative accessibility vs. mobility index in **Figure 33** revealed that most of the modes per zone in Nairobi lacked in achieving sufficient accessibility levels as they mostly fell in Quadrant I and IV (low accessibility values) below the average car mode accessibility level. It can be observed that accessibility indices for the car mode mostly lies above the sufficiency threshold of 30% indicating fair accessibility levels among zones with the car mode as the major mode of transport. However, it can be noted that accessibility indices for transit overlaps mostly with the NMT modes of transport. This is due to the GTFS file of Kigali having minimal transit data information. The model therefore “defaults” by assuming that no transit modes are available for travel, thereby assigning them to NMT modes (as it is deemed faster to walk or cycle the distance than wait for the next transit option); making the transit and

NMT mode accessibility very similar to each other. Zones performed fairly in terms of mobility indices for the car mode showing that approximately half the zones lie in Quadrant III and IV (high mobility values). PMIs for the NMT modes ranged mostly below the average PMI between 21-24km/hr.

Overall, the results suggest that the Nairobi region needs improvements to increase potential accessibility indices for NMT modes, whilst the low mobility indices for the car mode suggest road network or congestion challenges that would require focus.

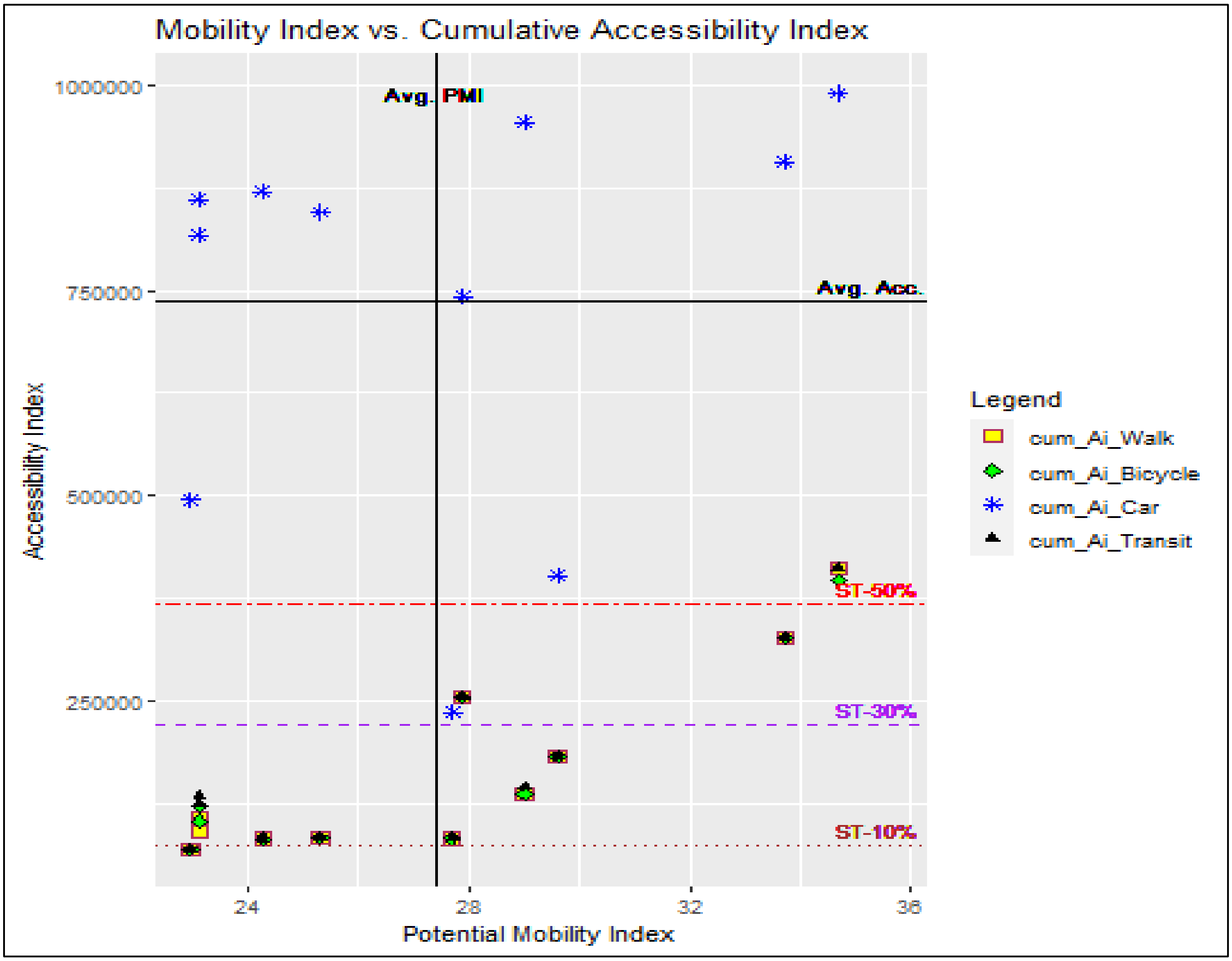

Figure 33: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) – cumulative accessibility

If one were to decrease (or increase) the threshold travel time, accessibility levels would fluctuate accordingly; this showcases how travel time changes may affect two similar modes purely because of the way they are operated. **Figure 34** also shows the cumulative accessibility measure and 30% sufficiency threshold but at the 15 min travel time threshold. Broadly the analysis showed a similar trend to the 30min analysis although the car mode accessibility indices were significantly lower, as can be expected. Less options are available in a shorter travel time threshold. Overall, the results suggest that key stakeholders may differentiate acceptable levels of sufficient accessibility and potential mobility based on other criteria or mandates at the time and the travel time threshold could be used as a that differentiation factor.

Annexure E2 contains the Inverse power gravity and exponential gravity accessibility measure analysis of the potential mobility vs. potential accessibility for the 15- and 30-min time thresholds for comparison.

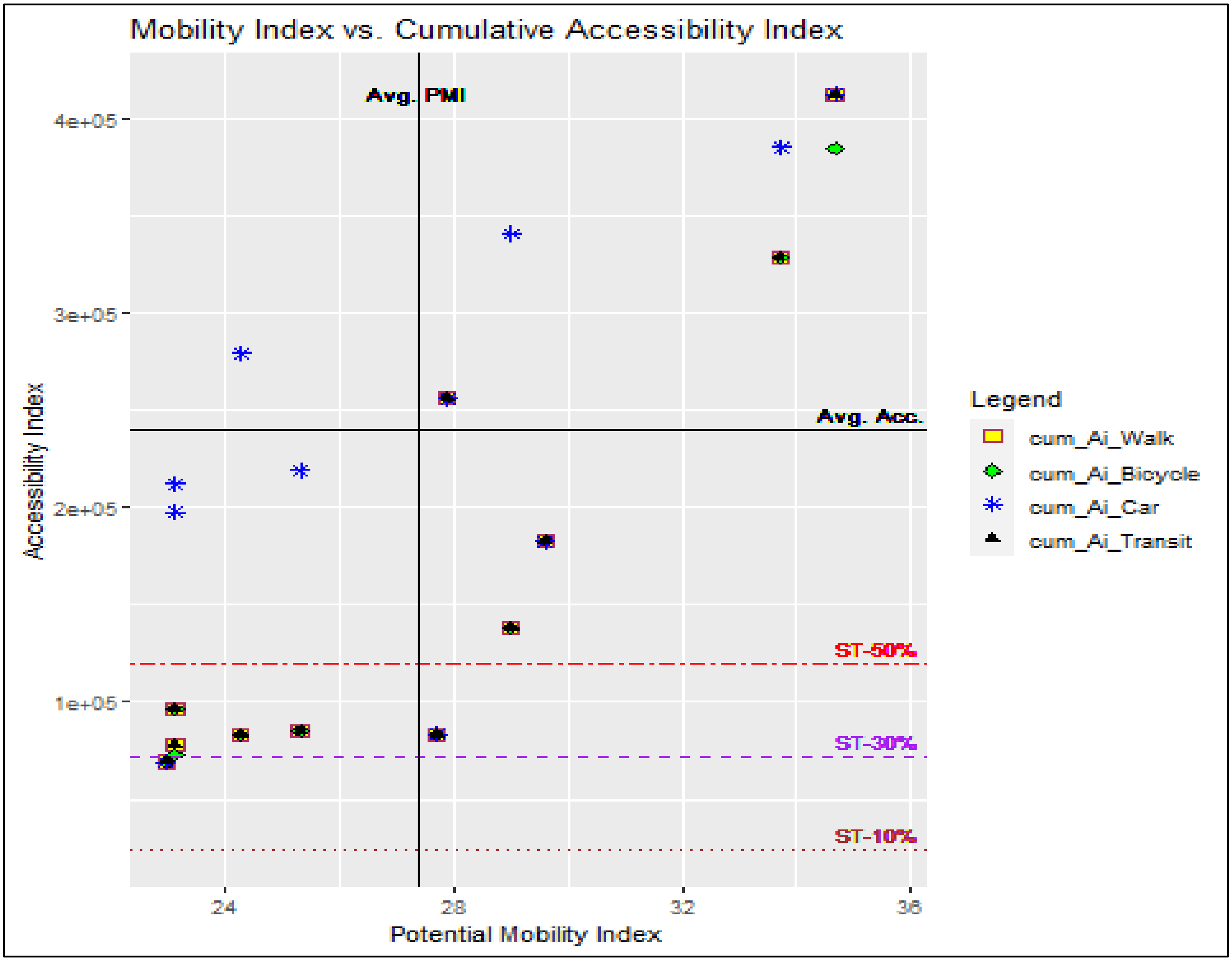

Figure 34: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) – cumulative accessibility

5.2.4 POTENTIAL ACCESSIBILITY FAIRNESS INDEX

Table 15 shows the AFI for all zones in Nairobi, per method, per mode, as computed following the mathematical equations in the R environment.

Table 13: Comparison of AFI for all zones, per method, per mode, for the 30% sufficiency threshold at 30 min travel time threshold (based of the car mode) for Nairobi

Zone No.	Zone Name	Inverse				Exponential				Cumulative			
		Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit
1	Dagoretti	230	143	0	135	0	0	0	0	13	13	0	13
2	Embakasi	498	0	0	307	0	0	0	0	0	0	0	0
3	Kamukunji	52	17	0	0	0	0	0	0	72	53	0	51
4	Kasarani	359	194	0	190	0	0	0	0	0	0	0	0
5	Kibra	66	35	0	18	0	0	0	0	88	88	0	88
6	Lang'ata	104	77	0	66	0	0	0	0	77	77	0	77
7	Makadara	49	17	0	5	0	0	0	0	74	74	0	74
8	Mathare	52	18	0	8	0	0	0	0	79	79	0	79
9	Njiru	253	90	0	120	0	0	0	0	0	0	0	0
10	Starehe	36	0	0	0	0	0	0	0	73	59	0	31
11	Westlands	88	45	0	9	0	0	0	0	44	44	0	36

The data above can be represented spatially in GIS packages to highlight the accessibility deficiencies among the modes and their dependent population groups in the regions. This can be tested against various sufficiency thresholds for accessibility to employment (or any other attractor), the various travel time threshold and the various accessibility measures for the selected analysis period (e.g., peak hours, etc.).

5.2.5 RANKED CONTRIBUTION TO OVERALL ACCESSIBILITY FAIRNESS

Table 16 highlights the summary of the overall accessibility deficiency of the city of Nairobi with sufficiency threshold of 30% comparing three different methods of accessibility computation.

Similar to Kigali the cumulative accessibility deficiency analysis results showed that Nairobi also severely lacked in terms of potential mobility and accessibility performance levels, as around eight (8) of the eleven (11) zones lay below the sufficiency threshold of 30%, which translated into impacting approximately 46% of the population (approximately 2,001,000 people) of Nairobi. **Table 16** details the results discussed.

From these results it can be surmised that most zones in Nairobi severely lacks in accessibility provision and would need a major overhaul in transport infrastructure and road networks to improve travel attraction by walk, bicycle and transit modes.

Table 14: Overall accessibility deficiency of Nairobi region with Sufficiency Threshold of 30% with comparison of three different methods of accessibility measurement

Indicator	Inverse Function				Exponential Function				Cumulative Function			
	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit	Walk	Bicycle	Car	Transit
Accessibility Fairness Index (AFI)	0.41	0.14	-	0.20	-	-	-	-	0.12	0.11	-	0.10
Number of Group below Sufficiency Threshold (30%)	11	9	-	9	-	-	-	-	8	8	-	8
Percentage of Groups below Sufficiency Threshold (30%) %	100	82	-	82	-	-	-	-	73	73	-	73
Number of People below Sufficiency Threshold (30%) (in 1000s of persons)	4 397	3 198	-	3 918	-	-	-	-	2 001	2 001	-	2 001
Percentage of People below Sufficiency Threshold (30%) %	100	73	-	89	-	-	-	-	46	46	-	46

Further, the accessibility deficiency analysis carried out highlighted and ranked zones in Nairobi in terms of the zone's AFI contribution (by mode) which points to improvements in terms of the mentioned mode of transport. There are 11 zones with 4 different choices of mode of transport making it overall 44 different levels of improvements (i.e., 11 zones x 4 modes of transport). **Annexure E3** shows the complete list of ranked zones which needs improvement in term of the mentioned mode of transport that lacked severely in terms of the accessibility fairness index (cumulative accessibility measure at 30% sufficiency threshold and 30min travel time threshold).

Figures 35 to 38 show the AFI contribution per zone per mode while **Tables 17 to 20** show the ranked zones with the highest AFI contribution (i.e., zones that most severely lacked in terms of accessibility using that mode).

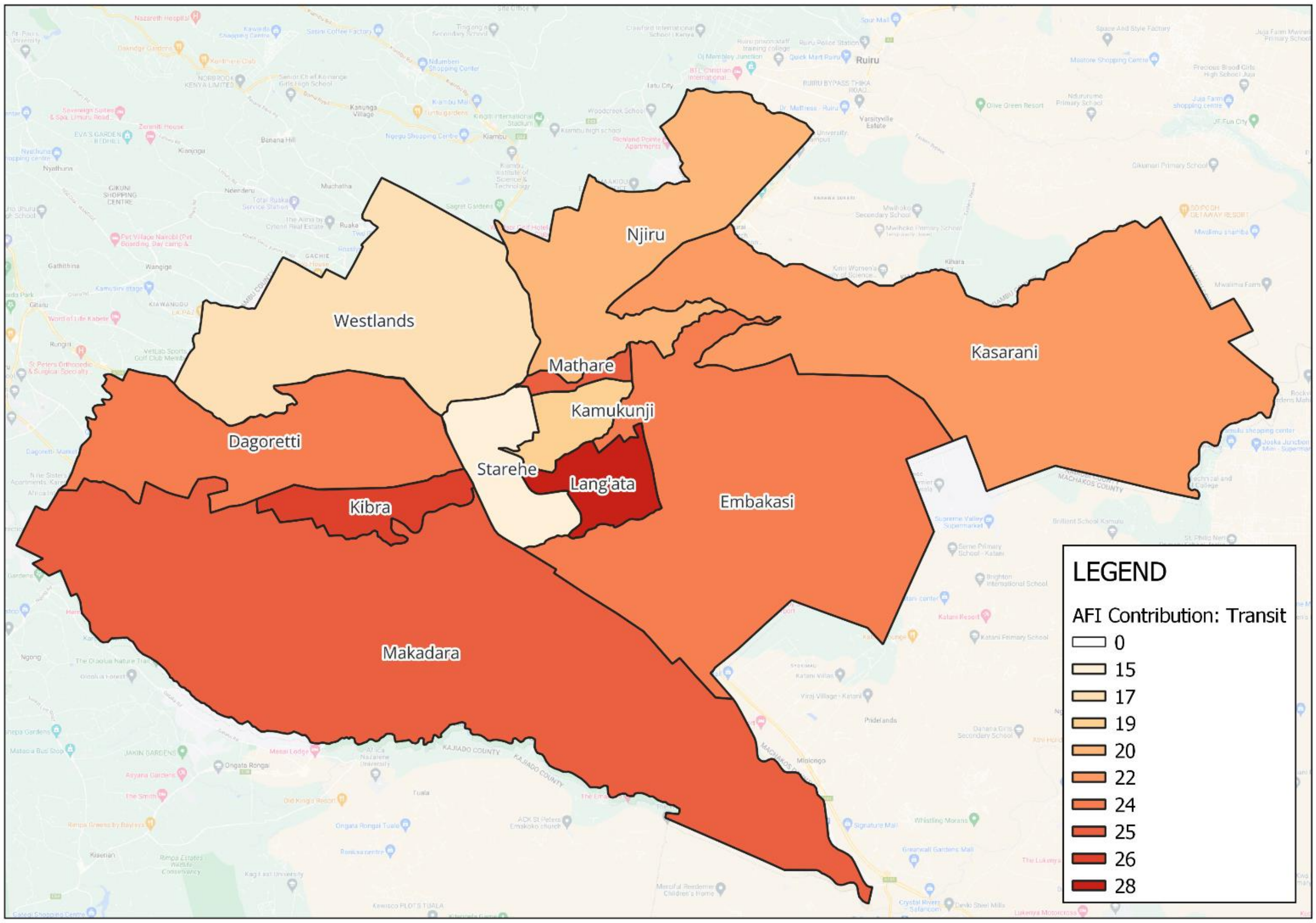

Figure 35: AFI Contribution per zone for Transit mode in Nairobi

Table 15: Ranked Zones for AFI Contribution for Transit mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Lang'ata	6	28
2	Kibra	5	26
3	Makadara	7	25
4	Mathare	8	25
5	Dagoretti	1	24
6	Embakasi	2	24
7	Kasarani	4	22
8	Njiru	9	20
9	Starehe	10	0
10	Kamukunji	3	0
11	Westlands	11	0

In terms of the transit mode, zone 6 (Lang'ata) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the transit mode.

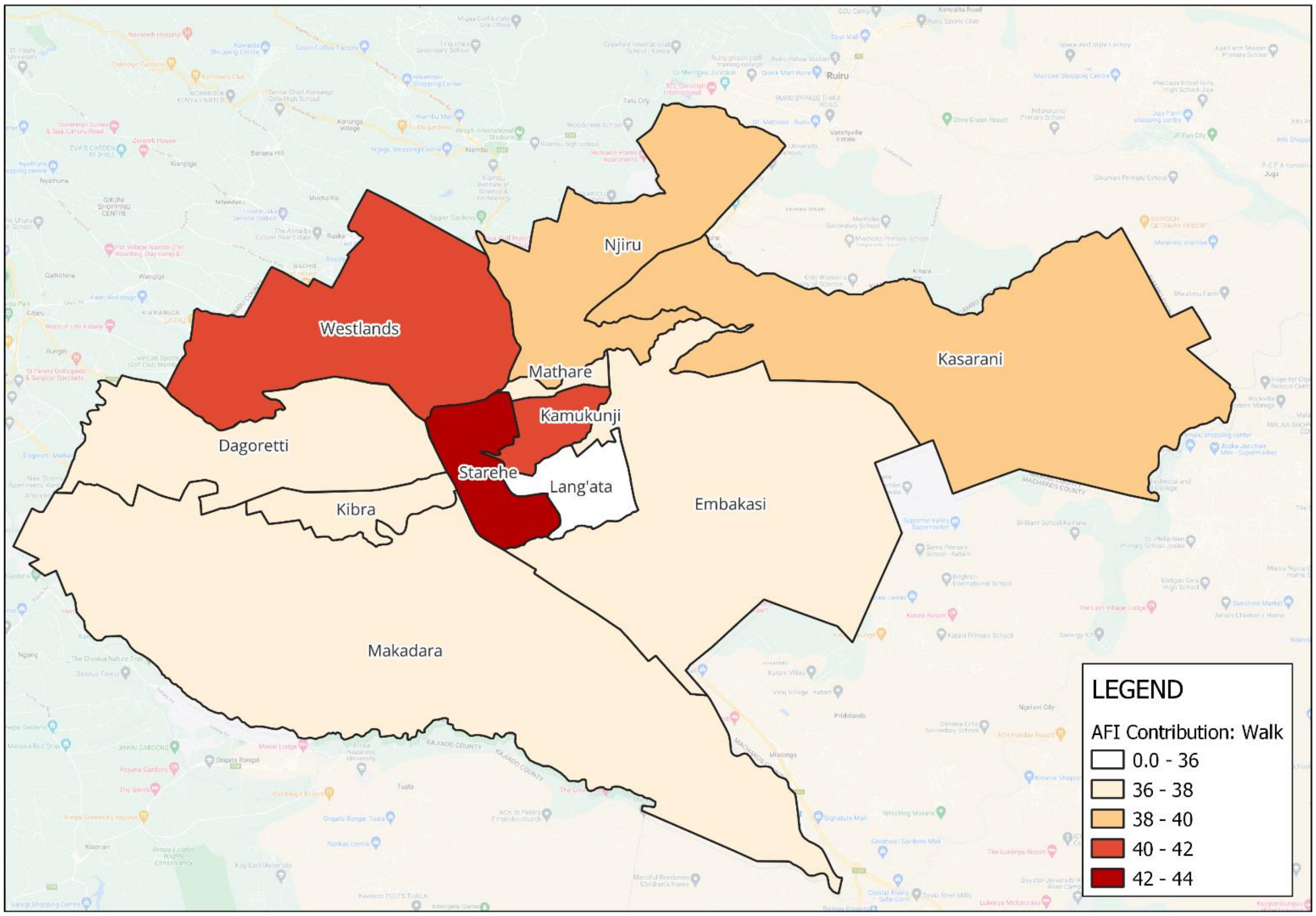

Figure 36: AFI Contribution per zone for Walk mode in Nairobi

Table 16: Ranked Zones for AFI Contribution for Walk mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Starehe	10	43
2	Kamukunji	3	41
3	Westlands	11	41
4	Njiru	9	40
5	Kasarani	4	39
6	Dagoretti	1	38
7	Embakasi	2	38
8	Kibra	5	37
9	Makadara	7	37
10	Mathare	8	37
11	Lang'ata	6	36

In terms of the walk mode, zone 10 (Starehe) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the walk mode.

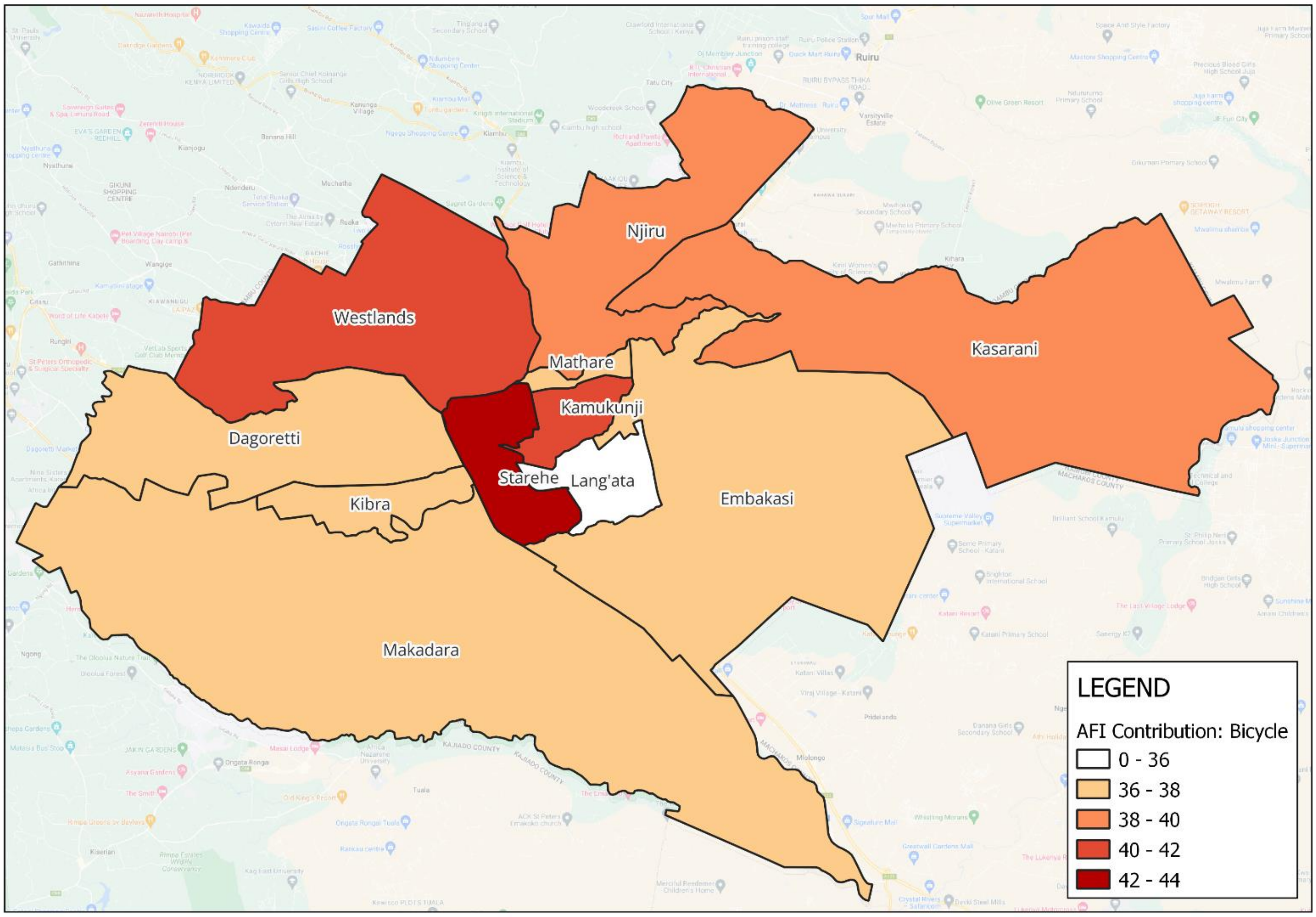

Figure 37: AFI Contribution per zone for Bicycle mode in Nairobi

Table 17: Ranked Zones for AFI Contribution for Bicycle mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Starehe	10	43
2	Kamukunji	3	41
3	Westlands	11	41
4	Njiru	9	40
5	Kasarani	4	39
6	Dagoretti	1	38
7	Embakasi	2	38
8	Kibra	5	37
9	Makadara	7	37
10	Mathare	8	37
11	Lang'ata	6	36

In terms of the bicycle mode, zone 10 (Starehe) had the highest AFI contribution and was the most severely lacked zone in terms of accessibility to the bicycle mode.

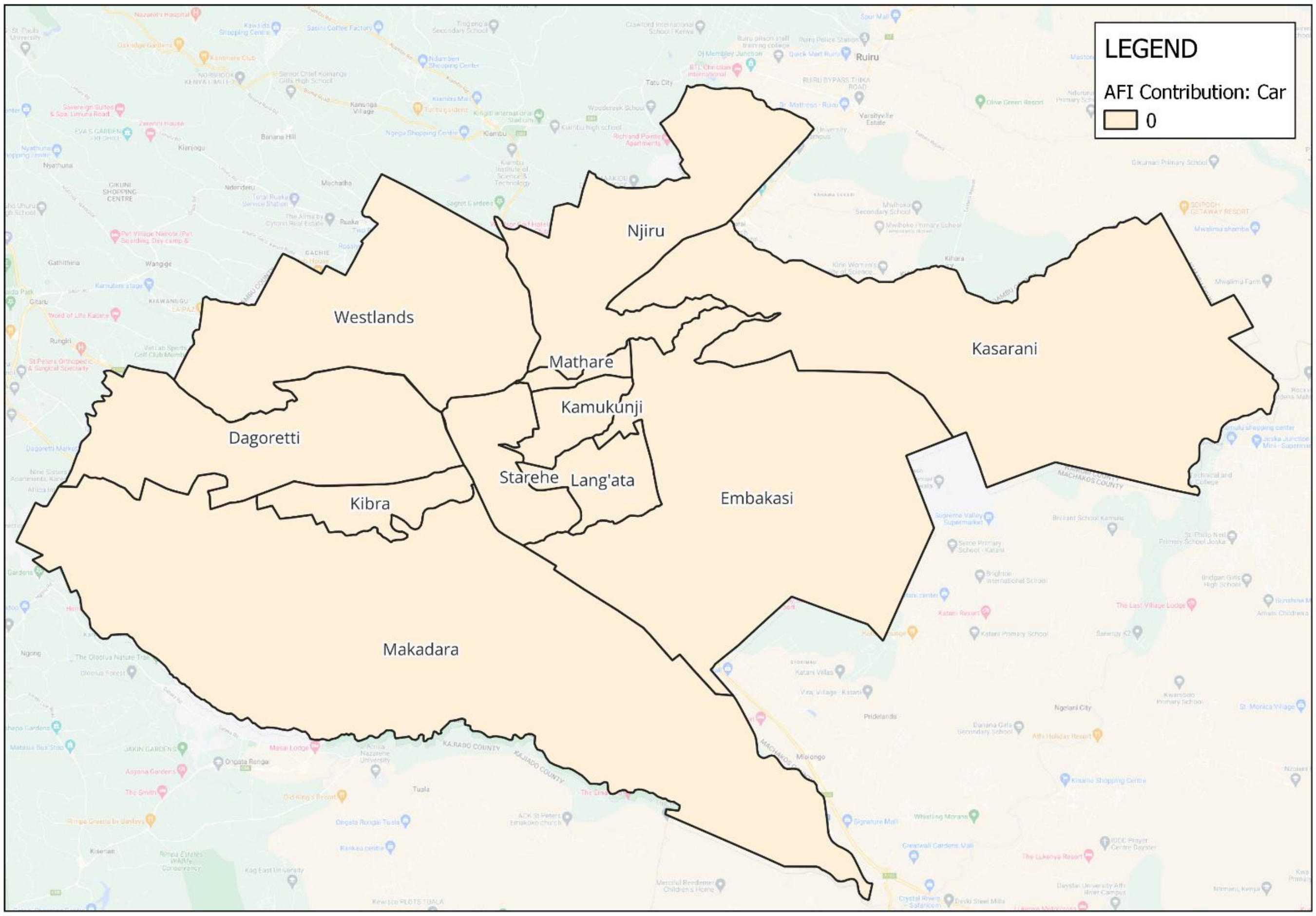

Figure 38: AFI Contribution per zone for Car mode in Nairobi

Table 18: Ranked Zones for AFI Contribution for Car mode

Rank	Zone Name	Zone No.	AFI Contribution (%)
1	Lang'ata	6	0
2	Kibra	5	0
3	Makadara	7	0
4	Mathare	8	0
5	Dagoretti	1	0
6	Embakasi	2	0
7	Kasarani	4	0
8	Njiru	9	0
9	Starehe	10	0
10	Kamukunji	3	0
11	Westlands	11	0

In terms of the car mode, all zones displayed an AFI contribution of 0% thus implying that all zones did not have an challenges in terms of accessibility.

The analysis of the AFI contributions revealed the zones that require improvements per mode. Starehe zone had the highest AFI contribution for the walking and bicycle mode; indicating that improvements to expand NMT as a mode in this zone should be prioritised in Nairobi city planning. Similarly, the Lang'ata zone showed the highest contribution of AFI for improvements could be attributed and prioritised for transit facilities in this zone.

6 CONCLUSION AND RECOMMENDATIONS

The principles of transport justice focus on marginalised and poorer communities or groups of people. Transportation planning based on these principles can assist in refocusing and directing transportation infrastructure investment away from political objectives and toward the improvement of the transport poor, especially in the context of Africa. The objective of this research project was to determine to what extent and how the approach and underlying analytical methods could be applied by testing an open-source analytical tool for transport planning based on principles of transport justice. Using open-source software allows universal, free use thereby circumventing the typical cost barriers associated with licensed transport modelling software and the skills required to operate these software tools (which are sometimes quite complex). The tool used basic and limited data and proved to be easily replicable to other data scarce African cities.

6.1 STUDY LIMITATIONS

The potential accessibility and mobility indicators for the transport justice analysis tool being developed in this study (for the Kigali region) proved to have limitations in terms of availability, accuracy and integrity regarding the demographic data, socio economic data and transit data (GTFS data), which questions the tool's capability and reliability. To further show the applicability, integrity and true potential of the r5r based transport justice tool that was developed in this study it was applied to data sets from Sao Paulo (Brazil), Nairobi (Kenya), Algiers (Algeria) and Tunis (Tunisia) where the tool performed much better, with relatively no issues on varied data sets.

The case study for Nairobi, Kenya, whose data was available and supported the format by r5r, was selected to showcase the transport justice analysis tool and a high-level discussion of the analysis was discussed in **Chapter 5**.

As with Kigali, only one bus service's data was available for Nairobi; however, the GTFS integrity issues regarding the format did not seem to exist in the Nairobi data set. Furthermore, most of the analysis zones too did not have any connectivity with transit modes, therefore, transit and walk times were mostly equivalent for them. Basic data sets of population, socio economic, administrative level zonal centroids and road network data were also assumed for Nairobi, as detailed in **Chapter 4** for Kigali. Most notable though, the r5r code worked well on this data set and showed no error issues; suggesting that the transport justice analysis tool is robust and scalable.

However, it can be noted that accessibility indices for transit overlaps mostly with the NMT modes of transport. The model "defaults" by assuming that no transit modes are available for travel, thereby assigning them to NMT modes; making the transit and NMT mode accessibility very similar to each other.

6.2 CONCLUSION

The main objectives of this study were to identify a suitable open-source analytical tool to test the key aspects of transport justice. Firstly, the tool needed to make use of basic and/or limited and importantly needed to be replicable relatively easily to other data scarce African cities. Secondly, a code was then developed using the tool, and its associated environment software, to determine and compute the various transport justice indicators. These were then used to calculate the transport justice indicators for the case study cities. Lastly, the outputs were then interrogated at a high level to demonstrate how to evaluate the transport justice indicators for the case study cities.

The R program, integrated with the r5r package, was the open-source tool of choice that was selected for this study. The r5r package showed true potential to compute all the relevant and potential statistics and parameters as required to evaluate the transport justice indicators of any region. But as with any program r5r has certain limitations, advantages and disadvantages in comparison to other software packages and suites available that could perform a similar task. The following are some of the key advantages and disadvantages of the r5r package as it relates to its capability of being an adequate and effective open-source transport justice planning tool for Southern Africa.

<u>Advantages</u>

- r5r shows incredibly fast processing speeds as compared to licensed competitor software such as PTV Visum, TransCAD, Cude, QGIS AequilibraE, ArcGIS Network Analyst tool pack
- It requires very minimal and typically readily available input data sets viz. OSM network data set, GTFS file for transit data and zonal centroid coordinates in .csv format to compute the most critical parameters of mode-wise travel times between ODs in each TAZ
- Travel times, as calculated from r5r, can be inputted into any external modelling environment (which was the R programme in the case of this study) for the calculation of the transport justice indicators
- The r5r script was tested and proved to work with multiple data sets from across the world (Sao Paulo, Nairobi, Algiers and Tunis).
- Two case study areas were tested to confirm the robustness and scalability of the code underlying the r5r model; all providing satisfactory and reasonable results (based on the key assumptions and inputs in data) for the transport justice analysis.
- The r5r code that has been written for this study can be easily manipulated (with basic coding knowledge) to be updated for any other area/data sets.

<u>Disadvantages</u>

- r5r does not have any functionality to directly compute mobility, accessibility or fairness indices. It only provides the information of travel times by modes between ODs, which is critical inputs for the computation of the transport justice indicators. The remainder of the calculation needs to be performed within any external modelling environment

- r5r has compatibility and flexibility limitations to support different data formats. r5r only takes network data in the OpenStreetMap (osm.pbf) format, which is a non-editable file in the conventional way. This means that network parameters, such as speed, one-way directions, allowed traffic mode/s on links, bus stop locations etc. can't be changed or manipulated from what is available in OpenStreetMap.
- r5r has a limit with the number of kilometres that can be assessed with a transport network, which may suggest that analyses of bigger cities would need to be performed in parts (which could be problematic)
- r5r lacks a user-friendly interface when compared to licensed competitor software such as Visum, TransCAD, Aimsun, EMME, ArcGIS Network Analyst and QGIS (AquelibraE). It is strictly a programming environment which requires hands on coding knowledge and it can be difficult to be used by non-programmers.

The tool was able to utilise basic and limited data. It successfully generated detailed routing analyses and calculated travel time matrices. Richer data (especially transit data) would have been more advantageous to show the true potential of the tool, although it sufficiently demonstrated its robustness and scalability.

A coding script was successfully developed within the R environment for both cities. The coding language is simplistic and can be easily modified and applied to other case cities. The code uses the detailed routing analyses and calculated travel time matrices within the r5r environment to determine and output the potential mobility, potential accessibility (per measure) and accessibility fairness indices. This was then used successfully for basic evaluation of the TAZs in the case study cities. The outputs from the tool was found to be suitable to demonstrate how to evaluate the transport justice indicators for the case story cities (as well as other cities).

Overall, the study was successful in identifying a suitable open-source analytical tool to test the key aspects of transport justice and the tool was able to demonstrate its replicability easily. The code / script was developed in a way that could be easy to edit and analyse other data scarce African cities, or any city for that matter.

6.3 RECOMMENDATIONS

The GTFS data set for Nairobi, albeit small, yielded much better results in the r5r programme. The allocation to mode and travel times were much more realistic (based on the information within the GTFS data set) than the Kigali set. It adequately demonstrated the reliability of the r5r coding and r5r programme capabilities as it relates to computing the most primary inputs for the transport justice analysis, which includes distances and mode-wise travel times between each origin to each destination. Also noting that different GTFS data sets, from various sources will yield different results; It is however recommended that further African cities be tested using credible and richer GTFS data as inputs into the tool which in turn may output better results.

This study projected proportionally the population and socio-economic data sets for each of the City's regions based on their respective area proportion. Furthermore, the road network data used .osm format data (which is not verified). The .osm format is also non-editable so network parameters can’t be changed or manipulated as required. It is recommended that updated data at a regional level as well as calibrated and validated road network data sets be used to test the results that this study showed to further demonstrate the design and replicability of the open-source transport justice analysis tool being developed in this study.

The parameter estimates for two gravity-type accessibility measures for this study were selected as α = 0,8 for the inverse power function and β = 0,22 of the exponential function as proposed by Kwan (1998). It is recommended that further studies be pursued that seek to calibrate these parameters with an African context.

It is widely accepted that travel behaviour fluctuates throughout the day, especially with varied activities that population groups partake in. It is recommended that further studies be pursued that investigate different times within the day for varied activities. This can then highlight how access and mobility may change within a wider analysis period for other African cities.

Most accessibility studies focus on determining access to employment. While employment access is arguably the highest ranked priority in terms of access, other activities such as access to education or health care are also high on the priority list in ensuring social inclusion and aiming to alleviate transport poverty. Transportation's influence in people's exclusion or inclusion should be the subject of additional research that includes a greater number of activities.

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8 ANNEXURES

ANNEXURE A1: High-level overview of the key stakeholders in urban mobility in Rwanda

Ministries

- Ministry of Infrastructure (MININFRA)Ministry of Lands, Housing and Urban Development
- Ministry of Finance and Economic Planning (MINECOFIN)
- Ministry of Local Government (MINALOC)
- Ministry of Environment (MINIRENA)

National Authorities

- Rwanda Transport Development Authority (RTDA)
- Rwanda Housing Authority (RHA)
- Rwanda Utilities Regulatory Authority (RURA)
- Rwanda National Police (RNP)
- Rwanda Environment Management Authority (REMA)
- Rwanda's Fund for the Environment and Climate Change (FONERWA)
- National Institute of Statistics (NISR)

Local Authorities

- Rwanda Association of Local Government Authorities (RALGA)

Funding and development institutions in urban mobility

- African Development Bank (AfDB)
- Belgium Development Agency
- Japan International Cooperation Agency (JICA)
- United Nations Development Program (UNDP)
- United Nations Human Settlement Program (UN-HABITAT)
- United States Agency for International Development (USAID
- World Bank International Development Association

Academia

- University of Rwanda

Public transport service providers

- Kigali Bus Service (KBS)
- Royal Express
- Rwanda Federation of Transport Cooperatives (RFTC)

The following lists the main policies, strategies, and plans that regulate Rwanda's roads and public transportation as well as the legal and regulatory framework that is currently in place driven by the various main stakeholders listed above (SSATP, 2018).

Law No. 55/2011 of 14/12/2011 Governing Roads in Rwanda

- This law establishes the maintenance and classification of roads as well as determines the management, financing and the responsibilities for the roads.

Passenger Roads Transport Regulations No. 007/TRANS/RT/RURA/2015

- In order to accomplish an effective and sustainable development and operation of public transportation services, this is a regulatory framework for the performance of passenger road transport activities.

National Feeder Road Policy and Strategy

- This policy seeks to promote and enable rural socioeconomic development by creating a legal framework for the operation of feeder roads and ensuring the effective use of available funds and resources.

Fleet Policy of Government of Rwanda

- This policy aims to lower the cost of construction, upkeep, and operation, as well as cutting back on waste and improper use of public resources.

Public Transport Policy and Strategy for Rwanda

- This policy aims to evaluate the current public transportation issues and proposing viable short-, medium-, and long-term policy solutions.

National Transport Policy (under the Vision 2020)

- This policy aims at enhancing the institutional and legal framework to aid in the formation of a climate favourable environment for development of the transportation sector.

National Decentralization Policy

- Goal is to enhance citizen engagement, strengthen the local government system, and maintain functional and accountable links between Central and Local Government organizations to deepen and preserve democratic governance and promote equitable local development.

Kigali Transport Master Plan

- This document provides a framework for the smart and sustainable development and expansion of Kigali's transportation systems by providing long-term plans and suggestions at the policy and network enhancement levels for the design horizon of 2040.

Kigali Conceptual Master Plan

- This plan aims to create a conceptual master plan for the city's transportation system, infrastructure, land use, and environmental management program (more specific planning at the District, CBD and Sub Area level).

Rwanda Green Growth and Climate Resilience Strategy

- Promotes energy security, low-carbon energy, urban development, social protection, health, and climate change resilience.

The National Investment Strategy

Focuses on the support of the private sector for infrastructure development.

ANNEXURE A2: High-level overview of the key stakeholders in urban mobility in Kenya

Ministry of Transport, Infrastructure, Housing and Urban Development

- State Department for Transport
- State Department for Infrastructure
- National Transport and Safety Authority (NTSA)

National Authorities

- Kenya National Highways Authority (KeNHA)
- Kenya Urban Road Authority (KURA)
- Kenya Roads Board (KRB)
- Transport Licensing Appeals Board (TLAB)
- National Environment Management Authority (NEMA)

Local Authorities

- Nairobi City County Government (NCC)
- Nairobi Metropolitan Area Transport Authority (NaMATA)
- Mombasa County Government (MCG)
- Savings and Credit Cooperative Organizations (SACCOS)
- The Kenyan Alliance of Resident Associations (KARA)

Funding and development institutions in urban mobility

- The Chinese Development Bank
- Asian Infrastructure Investment Bank (AIIB)
- Official Development Finance (ODF)
- African Development Bank (AfDB)
- Belgium Development Agency
- Japan International Cooperation Agency (JICA)
- United Kingdom
- Germany
- France
- United Nations Development Program (UNDP)
- World Bank International Development Association
- United Nations Environment Program (UNEP)
- United Nations Human Settlements Program (UN Habitat)
- The Institute for Transportation and Development Policy (ITDP)
- Flone Initiative

Academia

- University of Nairobi
- African Centre of Excellence for Studies in Public and Non-Motorized Transport (ACET)
- Centre for Urban Sustainable Development (CSUD)

Public transport service providers

- The Matatu Welfare Association
- Matatu Owners Association (MOA)

- Kenya Bus Service Management Ltd (KBS)

The following lists the main legislature, policies, strategies, and plans that regulate and shape the environment for urban mobility in Kenya; driven by the various main actors listed above (SSATP, 2018b).

The Constitution of Kenya (2010)

- Primary objective (devolution) to devolve power, resources and representation to county and gives local governments the bulk of the responsibility of urban management.

County Government Act of 2012

- Chapter 11 (devolution) provides for county governments' powers, functions and responsibilities (power to control development and investment guided by County Integrated Plans and land use plans).

Urban Areas and Cities Act No. 33 of 2011

- Act provides for a three-tier administrative structure (city, municipal board and town committee) of governance and management of urban areas and cities and encourages participation and consultation by residents.

Kenya Roads Act No. 2 of 2007

- Act provides for management and provision of road infrastructure (including NMT) for all road classes In Kenya throughout the various authorities (KeNHA, KURA and Kenya Rural Roads Authority).

The Traffic Act Cap. 403 (2012)

- Laws governing road traffic (including NMT) including the framework for enforcement.

National Urban Development Policy (NUDP 2015)

- Provides frameworks for sustainable urban development in the country focussing on areas such as, urban economy, urban governance and management, urban planning (national and county level) and urban safety; thereby improving urban mobility and accessibility in the country.

Integrated National Transport Policy (INTP 2009)

- Focuses on improving public transport and NMT for the country and seeks to translate this mandate into technical, legal and institutional mandates of transport agencies; thereby improving urban mobility and accessibility in the country.

Non-Motorized Transport Policy (June 2017)

- Policy to promote the NMT in Nairobi County and have it be the mode of choice for short and medium trips within Nairobi. It aims to increase mobility, accessibility and transport safety and ensure that the relevant funding is earmarked for NMT infrastructure and development.

Kenya Vision 2030

Contains several nationwide objectives for urban planning and development of its transport network and relevant institutional frameworks to increase connectivity and reduce transport and infrastructure costs.

ANNEXURE B: Steps to setup and run the xxx.R file for the Transport Justice tool

This section shows the steps to setup and run the R program for Transport Justice Analysis integrated with r5r model developed for this study based on the code script that was developed. This could be seen as a "recipe" in which to follow should any input parameters wished to be changed or testing other accessibility parameters (other than employment)

R Setup and Installation

- Download and Install R from webpage https://cran.r-project.org/bin/windows/base/
- Download and Install RStudio from webpage https://www.rstudio.com/products/rstudio/download/
- Download and Install Java SE Development Kit 11 from webpage https://www.oracle.com/java/technologies/javase-jdk11-downloads.html

Data sets required

Three types of data required to run r5r travel time script, namely, osm.pf, gtfs.zip, zonal centroid.csv.

1. ".pbf" file is non-editable network file. It can be downloaded for any location using the following webpage, http://download.geofabrik.de/
2. GTFS file is transit schedule which is needed in ".zip" format. One reference source for downloading GTFS data is https://transitfeeds.com/
3. Zonal Centroid.csv is required as positional coordinates (i.e., Latitude and Longitude) of each study zone along with their unique IDs in a set format viz.:
    - Col A - id
    - Col B - Code
    - Col C - Name
    - Col D - lat
    - Col E - lon
    - Col F - Population
    - Col G - Employment

Change the name of data set as osm.pbf, GTFS.zip and Zonal_Centroid.csv to avoid errors for each city run

Steps in RStudio

- Open RStudio and type following command in console
    - install.packages('r5r')
    - install.packages('ggplot2')
    - install.packages('data.table')
    - install.packages('svDialogs')
    - install.packages('dplyr')
    - install.packages('reshape2')
    - library('Rcpp')

- Open the input data folder in: "C:\Users**local directory**\AppData\Local\R\win-library\4.2\r5r\extdata**Data**"
  Make the folder name "**Data**". Copy and paste into this folder: GTFS.zip, osm.pbf and Zonal_Centroid.csv files in "…*extdata***Data**" folder.

- Open the "**xxx**.*R*" file from Tab "File-Open File" and browse the location of updated script.

- Make changes in the "**xxx**.*R" as follows:*
  - Input values required in Accessibility calculation in lines 45 – 48

  - Change the address of the Data set folder and "Zonal Centroid.csv" in line 62 as highlighted in line below,
    data_path <- system.file("**extdata/Data**", package = "r5r")

  - Change the date and time in the command on line 77, as highlighted in red colour below:

    departure_datetime <- as.POSIXct("**05-08-2021 07:30:00**", format = "%d-%m-%Y %H:%M:%S" tz = "Africa/**City**")

    GTFS files for dates and times > check 'calendar.txt' (for dates) & 'stop_times.txt' (for departure times) for the City's GTFS feed file

  - Update line 518 to 521 as this writes an output .csv file showing the variable data used for each run/analysis

  - The output folder will be the same folder where the "**xxx**.*R*" script is stored

- Run the script "xxx.*R*". Results will be stored in output folder.

Once the results are outputted these tables and graphs can then be used to analyse the relevant transport justice indicators and support transport planning approaches as required.

ANNEXURE B1:

R code: Kigali, Rwanda

**Always check for package updates to ensure you have the latest versions. Pay attention to the warning messages of 'package was built in R version…' and check that you are running the right version. [Go to Tools, select Global options, look at the General version on your left].

1. CALLING LIBRARIES NEEDED FOR R5R MODELLING

- Below is code increasing the java memory (line12)
- Code for the libraries required
- setting your working directory. Please remember that this directory is where all your output shall be stored and hence no need to instruct `r5r` to set an output directory as before.

```
#IMPORTANT: Where the input files must sit: 'C:\Users\prava\AppData\Local\R\win-lib
rary\4.2\r5r\extdata\Kigali'

#IMPORTANT:Where you place and run the R script file from is where the OUTPUTS will
 be stored automatically

options(java.parameters = "-Xmx2G")
#-------------------------------------------------------------
library('r5r')
library('ggplot2')#graphs
library('data.table')
library('dplyr')#data manipulation
library('reshape2')#transform data shapes
library('Rcpp')
#---------------------------------------
```

2. INPUT DATA FOR EACH ACCESSIBILITY CALCULATION

```
alpha = 0.8
beta = 0.22
Tijm = 30
access_suff_thres = 30

#--------------------------------------------
#Need to run the code each time for each Tijm (15 /30mins). To do: Change above and
 LINE 520 for input parameter.csv file report
#Need to run the code each time for each Sufficiency Threshold (10%, 30% & 50%) sep
```

```
arately. To do: Change above and LINE 521 for input parameter.csv file report
#-------------------------------------------
```

3. DEFINE DATAPATH

- Data paths

```
data_path <- system.file("extdata/Kigali", package = "r5r")
list.files(data_path)

[1] "GTFS.zip"                "network.dat"             "network_settings.json"
[4] "osm.pbf"                 "osm.pbf.mapdb"           "osm.pbf.mapdb.p"
[7] "Zonal_Centroid.csv"

#update GTFS data file location above (Line 62)
#keep file format the same at all times: headers and case of text and in terms of t
he order of the columns
points <- fread(file.path(data_path, "Zonal_Centroid.csv"))
head(points)

   id   Code       Name       lat      lon Population Employment
1:  1 RW1101     Gitega -1.953415 30.05507       2521        210
2:  2 RW1102   Kanyinya -1.917824 30.00253      51930       4330
3:  3 RW1103     Kigali -1.979172 30.01896      63121       4825
4:  4 RW1104 Kimisagara -1.952944 30.04611       7117        445
5:  5 RW1105 Mageregere -2.041920 30.03604     117405       9789
6:  6 RW1106     Muhima -1.941219 30.06093       6324        527

# Indicate the path where OSM and GTFS data are stored-----------------------------
--------
r5r_core <- setup_r5(data_path = data_path, verbose = FALSE)

#----------------------------------------------------------------------------------
------------------
# set inputs "23-11-2020 07:30:00"  "Africa/Kigali" OR  "01-01-2014 07:30:00" "Afri
ca/Nairobi"
# GTFS files for dates and times > check 'calendar.txt' (for dates) & 'stop_times.t
xt' (for departure times) > chose the first trip start time e.g. 07:30 (study is an
alysing peak hour from 07:30 to 08:30) and the analysis runs from that time till th
e time each trip leaving at 07:30 reaches its destination.

departure_datetime <- as.POSIXct("23-11-2020 07:30:00",
                                 format = "%d-%m-%Y %H:%M:%S",tz="Africa/Kigali")
```

4. TRAVEL TIME MATRICES FOR THE DIFFERENT MODES

```
# Specification of these values is down to personal preference and what their goal
is.
# The function has defined defaults for some of the arguments. For further help che
ck `?travel_time_matrix()`
```

```
#--------------------------------------------------------------------------------
----------------
md <- 100000 #[max walk time]- max walk dist and max bike distance not used in the
argument, deprecated in newer version of r5r
mtd <- 60000 #[max trip duration]
#-----------------------------------------

# calculate a travel time matrix for WALK
ttmw <- travel_time_matrix(r5r_core = r5r_core,
                          origins = points,
                          destinations = points,
                          mode = "WALK",
                          departure_datetime = departure_datetime,
                          max_walk_time = md,
                          max_trip_duration = mtd,
                          verbose = FALSE)## error one is in the arguments specifie
d, this function has no provision for `max_walk_dist`

head(ttmw)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             174
3:       1     3             118
4:       1     4              30
5:       1     5             205
6:       1     6              36

# calculate a travel time matrix for TRANSIT
ttmt <- travel_time_matrix(r5r_core = r5r_core,
                          origins = points,
                          destinations = points,
                          mode = "TRANSIT",
                          departure_datetime = departure_datetime,
                          max_trip_duration = mtd,
                          verbose = FALSE)

head(ttmt)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             174
3:       1     3             118
4:       1     4              30
5:       1     5             205
6:       1     6              36

# calculate a travel time matrix for BICYCLE
ttmb <- travel_time_matrix(r5r_core = r5r_core,
                           origins = points,
                           destinations = points,
                           mode = "BICYCLE",
                           departure_datetime = departure_datetime,
```

```
                              max_bike_time = md,
                              max_trip_duration = mtd,
                              verbose = FALSE)

head(ttmb)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             146
3:       1     3              70
4:       1     4              16
5:       1     5             145
6:       1     6              23

# calculate a travel time matrix CAR
ttmc <- travel_time_matrix(r5r_core = r5r_core,
                              origins = points,
                              destinations = points,
                              mode = "CAR",
                              departure_datetime = departure_datetime,
                              max_car_time = md,
                              max_trip_duration = mtd,
                              verbose = TRUE)

head(ttmc)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2              16
3:       1     3              14
4:       1     4               5
5:       1     5              22
6:       1     6               6

#combines all Travel Time files by mode and writes the updated data_zone variable f
ile (all info sits here)
data_time = data.frame(ttmw[,1:2],Walk = ttmw[,3],Bicyle = ttmb[,3],Car = ttmc[,3],
Transit = ttmt[,3])
colnames(data_time) = c("To_ID","From_ID","Walk","Bicycle","Car","Transit")

#saving a Zonal Centroid file called "data_zone" - this is the variables file (all
call up info sits here)
data_zone <- data.frame(points)
```

#PMI Calculation Start (per mode)

```
#calculating euclidean distance between zones (calling up the lat/long details from
 the data_zone file Col 4 & 5) and multiplying it by a factor of 111.11 to convert
decimal degrees to kilometres

d = as.matrix(dist(data_zone[,4:5], method = "euclidean"))*111.11

#calculates the Origin to Destination distance value (for each zone pair) in km's--
```

```
------------------

dist_km = data.frame(origin=colnames(d)[as.vector(col(d))],destination=rownames(d)[
as.vector(row(d))],
                     dist_km=as.vector(d))

#calculation of Origin to Destination speed (for each zone pair) and conversation t
o km/hr---------

speed_kph = data.frame(origin=colnames(d)[as.vector(col(d))]
                       ,destination=rownames(d)[as.vector(row(d))]
                       ,as.matrix(dist_km[,3]/data_time[,3:6]*60))

#correction for same zone calcs - replaces with zero instead of infinity-----------
------------------

speed_kph[is.na(speed_kph)] <- 0

pmi_walk = aggregate(x = speed_kph$Walk, by = list(speed_kph$origin), FUN = mean)
pmi_bicycle = aggregate(x = speed_kph$Bicycle, by = list(speed_kph$origin), FUN = m
ean)
pmi_car = aggregate(x = speed_kph$Car, by = list(speed_kph$origin), FUN = mean)
pmi_transit = aggregate(x = speed_kph$Transit, by = list(speed_kph$origin), FUN = m
ean)

#generates output file for PMI calculation and sorts zones by descending order-----
--------

PMI = (data.frame(Zone = as.numeric(pmi_walk[,1]),PMI_Walk = pmi_walk[,2]
                  ,PMI_Bicycle = pmi_bicycle[,2],PMI_Car = pmi_car[,2]
                  ,PMI_Transit = pmi_transit[,2]))

PMI <-PMI[with(PMI, order(Zone)),]

#PMI Calculation End------------------------------
```

#Start of Accessibility Index calculations - the three equations: inverse, exponential and cumulative equations

```
#Getting relevant data from data_zone file and associated columns

#wj refers to employment data

wj=data.frame(employee= rep(as.array(data_zone[,7]),times=length(data_zone[,7])))

#writes the inverse_power_Ai.csv file

inverse_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
                              ,destination=rownames(d)[as.vector(row(d))]
                              ,Inverse_power_Ai_Walk = wj*(data_time[,3])**(-alpha)
                              ,Inverse_power_Ai_Bicycle = wj*(data_time[,4])**(-alp
ha)
```

```
                              ,Inverse_power_Ai_Car = wj*(data_time[,5])**(-alpha)
                              , Inverse_power_Ai_Transit = wj*(data_time[,6])**(-al
pha))

colnames(inverse_power_Ai) <- c("Origin", "Destination","INV_Ai_Walk","INV_Ai_Bicyc
le","INV_Ai_Car","INV_Ai_Transit")
inverse_power_Ai[inverse_power_Ai == Inf] <- 0


#writes the exp_power_Ai.csv file

exp_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
                          ,destination=rownames(d)[as.vector(row(d))]
                          ,exp_power_Ai_Walk = wj*exp(data_time[,3]*(-beta))
                          ,exp_power_Ai_Bicycle = wj*exp(data_time[,4]*(-beta))
                          ,exp_power_Ai_Car = wj*exp(data_time[,5]*(-beta))
                          , exp_power_Ai_Transit = wj*exp(data_time[,6]*(-beta)))

colnames(exp_power_Ai) <- c("Origin", "Destination","EXP_Ai_Walk","EXP_Ai_Bicycle",
"EXP_Ai_Car","EXP_Ai_Transit")
exp_power_Ai[exp_power_Ai == Inf] <- 0


#writes the cum_power_Ai.csv file

cum_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
                          ,destination=rownames(d)[as.vector(row(d))]
                          ,cum_power_Ai_Walk = wj*(1-(data_time[,3]/Tijm))
                          ,cum_power_Ai_Bicycle = wj*(1-(data_time[,4]/Tijm))
                          ,cum_power_Ai_Car = wj*(1-(data_time[,5]/Tijm))
                          , cum_power_Ai_Transit = wj*(1-(data_time[,6]/Tijm)))

colnames(cum_power_Ai) <- c("Origin", "Destination","cum_Ai_Walk","cum_Ai_Bicycle",
"cum_Ai_Car","cum_Ai_Transit")
cum_power_Ai[cum_power_Ai == Inf] <- 0
cum_power_Ai[cum_power_Ai < 0] <- 0


#writes a combined csv file for all Accessibility calc equations for each OD pair

Ai= data.frame(inverse_power_Ai,exp_power_Ai[,3:6],cum_power_Ai[,3:6])

#Start of the Accessibility Index calcs for each zone

Accessibility_Index = aggregate(x = Ai[,3:14], by = list(Ai$Origin), FUN = sum)
colnames(Accessibility_Index)[1]<- "Zone"

#Sorting line to rank the data in descending zone order

Accessibility_Index[,1] = as.numeric(Accessibility_Index[,1])
Accessibility_Index <-Accessibility_Index[with(Accessibility_Index, order(Zone)),]
```

```
#Start of the Accessibility Deficiency Index calcs (as part of the Accessibility Fa
irness Index)

ZINV = (mean(Accessibility_Index[,4]) * (access_suff_thres/100))
ZEXP = (mean(Accessibility_Index[,8]) * (access_suff_thres/100))
ZCUM = (mean(Accessibility_Index[,12]) * (access_suff_thres/100))

#Controlling variables for INV, EXP and CUM - stipulates that if the Accessibility
indexes are below the stipulated levels then consider/collect (constructs a binary
matrix to sort/collect)

chk_INV = Accessibility_Index[,2:5]
chk_INV[chk_INV < ZINV] <- 1
chk_INV[chk_INV >= ZINV] <- 0

chk_EXP = Accessibility_Index[,6:9]
chk_EXP[chk_EXP < ZEXP] <- 1
chk_EXP[chk_EXP >= ZEXP] <- 0

chk_CUM = Accessibility_Index[,10:13]
chk_CUM[chk_CUM < ZCUM] <- 1
chk_CUM[chk_CUM >= ZCUM] <- 0


#Start of the Accessibility Fairness Index calculation per zone (using the controll
ing variables in lines above)
AFI = data.frame(Zone= Accessibility_Index[,1]
                 ,AFI_INV_Walk = chk_INV[,1]*(data_zone[,6]* ( (ZINV - Accessibilit
y_Index[,2] ) / ZINV )**2)
                 ,AFI_INV_Bicycle =chk_INV[,2]*(data_zone[,6] * ( (ZINV - Accessibi
lity_Index[,3] ) / ZINV )**2)
                 ,AFI_INV_Car = chk_INV[,3]*(data_zone[,6]*( (ZINV - Accessibility_
Index[,4] ) / ZINV )**2)
                 ,AFI_INV_Transit = chk_INV[,4]*(data_zone[,6]*( (ZINV - Accessibil
ity_Index[,5] ) / ZINV )**2 )

                 ,AFI_EXP_Walk = chk_EXP[,1]*(data_zone[,6]* ( (ZEXP - Accessibilit
y_Index[,6] ) / ZEXP )**2)
                 ,AFI_EXP_Bicycle = chk_EXP[,2]*(data_zone[,6] * ( (ZEXP - Accessib
ility_Index[,7] ) / ZEXP )**2)
                 ,AFI_EXP_Car = chk_EXP[,3]*(data_zone[,6]*( (ZEXP - Accessibility_
Index[,8] ) / ZEXP )**2)
                 ,AFI_EXP_Transit = chk_EXP[,4]*( data_zone[,6]*( (ZEXP - Accessibi
lity_Index[,9] ) / ZEXP )**2 )

                 ,AFI_CUM_Walk = chk_CUM[,1]*(data_zone[,6]* ( (ZCUM - Accessibilit
y_Index[,10] ) / ZCUM )**2)
                 ,AFI_CUM_Bicycle = chk_CUM[,2]*( data_zone[,6] * ( (ZCUM - Accessi
bility_Index[,11] ) / ZCUM )**2)
                 ,AFI_CUM_Car = chk_CUM[,3]*( data_zone[,6]*( (ZCUM - Accessibility
_Index[,12] ) / ZCUM )**2)
                 ,AFI_CUM_Transit = chk_CUM[,4]*( data_zone[,6]*( (ZCUM - Accessibi
```

```
lity_Index[,13] ) / ZCUM )**2 )

)


AFI[AFI < 0] <- 0
```

Start of the Accessibility_Deficiency_Index calculation (severity of accessibility deficiency in a region/zone

#TABLE OF RANKED CONTRIBUTION TO OVERALL ACCESSIBILITY DEFICIENCY

```
Accessibility_Deficiency_Index = data.frame(Accessibility_Deficiency_Index_INV_Walk
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,2]) )
                                            ,Accessibility_Deficiency_Index_INV_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,3]))
                                            ,Accessibility_Deficiency_Index_INV_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,4]))
                                            ,Accessibility_Deficiency_Index_INV_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,5]))

                                            ,Accessibility_Deficiency_Index_EXP_Wal
k = (1/(sum(data_zone[,6]))) * (sum(AFI[,6]) )
                                            ,Accessibility_Deficiency_Index_EXP_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,7]))
                                            ,Accessibility_Deficiency_Index_EXP_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,8]))
                                            ,Accessibility_Deficiency_Index_EXP_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,9]))

                                            ,Accessibility_Deficiency_Index_CUM_Wal
k = (1/(sum(data_zone[,6]))) * (sum(AFI[,10]) )
                                            ,Accessibility_Deficiency_Index_CUM_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,11]))
                                            ,Accessibility_Deficiency_Index_CUM_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,12]))
                                            ,Accessibility_Deficiency_Index_CUM_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,13])  )


)
```

#Start of the OUTPUT files

```
#control variable - calcs how many zones are in the data_zone set (robust feature)
to confirm how many zones the data set has and will be commuting with

nz = as.numeric(nrow(data_zone))

#table 5 sorting and generating summary
t5 = t(data.frame(
  t(Accessibility_Deficiency_Index[,1:12]),
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM))),
```

```
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)))/nz*100,
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)*data_zone[,6])),
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)*data_zone[,6])/(sum(data_zone[,6]))*
100)
))

#Formatting and rounding off values

colnames(t5) = c("INV_Walk","INV_Bicycle","INV_Car","INV_Transit","EXP_Walk","EXP_B
icycle","EXP_Car","EXP_Transit","CUM_Walk","CUM_Bicycle","CUM_Car","CUM_Transit")
rownames(t5) = c("Accessibility Fairness Index (AFI)","Number of Group below Suffic
iency Threshold","Percentage of Group below Sufficiency Threshold","Number of Peopl
e below Sufficiency Threshold","Percentage of People below Sufficiency Threshold")
t5 = round(t5, digits = 2)

#Table 4 ->Mobility Index And Accessibility Index

t4 = round(data.frame(PMI[,1:2],Accessibility_Index[2],Accessibility_Index[6],Acces
sibility_Index[10],
                      PMI_Bicycle = PMI[,3],Accessibility_Index[3],Accessibility_In
dex[7],Accessibility_Index[11],
                      PMI_Car = PMI[,4],Accessibility_Index[4],Accessibility_Index[
8],Accessibility_Index[12],
                      PMI_Transit = PMI[,5],Accessibility_Index[5],Accessibility_In
dex[9],Accessibility_Index[13]
),digits = 1)
gv = round(data.frame(PMI, Accessibility_Index[,2:13]),digits = 2)

#Table 6 -> Ranked Contribution to Overall Accessibility Deficiency

#working variable t6w to make a "working file"to generate the mean of the AFI value
 for each mode being calc'd by each method (inv, power, cum)

t6w = data.frame(Walk = rowMeans(data.frame(AFI[2],AFI[6],AFI[10])),
                 Bicycle = rowMeans(data.frame(AFI[3],AFI[7],AFI[11])),
                 Car = rowMeans(data.frame(AFI[4],AFI[8],AFI[12])),
                 Transit = rowMeans(data.frame(AFI[5],AFI[9],AFI[13]))
)

#calling from the above variable (mean of all modes and to generate a mode % )
AFI_Contribution = round(data.frame(Walk = t6w[,1]/(rowSums(t6w))*100,
                                    Bicycle = t6w[,2]/(rowSums(t6w))*100,
                                    Car = t6w[,3]/(rowSums(t6w))*100,
                                    Transit = t6w[,4]/(rowSums(t6w))*100
),digits = 0)

#Fix line for any errors from above AFI_contribution to deal with rowSums in t6w wh
ich have total populations of ZERO (if any)

AFI_Contribution[is.na(AFI_Contribution)] <- 0
tm = c("Walk","Bicycle","Car","transit")
```

```
library("dplyr")

#generates final Table 6 file
t6 = data.frame(zone= rep(as.array(data_zone[,1]),times=ncol(AFI_Contribution)),
                Mode = rep(as.array(tm),times=as.numeric(length(AFI_Contribution[,1
]))),
                AFI_CONTRIBUTION = vctrs::vec_c(AFI_Contribution[,1],AFI_Contributi
on[,2]
                                                  ,AFI_Contribution[,3],AFI_Cont
ribution[,4]))

t6[1:nz,2] = "Walk"
t6[(nz+1):(2*nz),2] = "Bicycle"
t6[(2*nz+1):(3*nz),2] = "Car"
t6[(3*nz+1):(4*nz),2] = "Transit"

#sorting to give highest Contribution rank value first

t6 <-t6[with(t6, order(AFI_CONTRIBUTION,decreasing = TRUE)),]
```

5. START OF THE PLOTTING THE QUADRANT GRAPHS

```
#file name of the .png exports

png('Mobility Index vs Inverse Power Accessibility Index.png')

# Graph for Inverse Power Ai - numbers below correspond to symbols and colours; als
o sets the PMI value as CAR mean and the Sufficiency thresholds as selected 10,30 a
nd 50%

gv.long <- melt(gv, id = "PMI_Car", measure = c("INV_Ai_Walk","INV_Ai_Bicycle","INV
_Ai_Car","INV_Ai_Transit"))
g1= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Inverse Power Accessibility Index",x = "Potentia
l Mobility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g1 = g1+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4]), label = "Avg. Acc.",
 vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.50) ,linetype="twodash",
 color = "red")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.50, label = "ST-50%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.30) ,linetype="dashed",
color = "purple")+
```

```
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.30, label = "ST-30%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.10) ,linetype="dotted",
color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.10, label = "ST-10%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,4])+1000, label = "Avg. PMI"
),size = 3)
print(g1)
dev.off()#returns the number and name of the new active device (after the specified
 device has been shut down)

png
  2
```

6. GRAPH FOR EXPONENTIAL POWER AI

```
png('Mobility Index vs Exponential Power Accessibility Index.png')

gv.long <- melt(gv, id = "PMI_Car", measure = c("EXP_Ai_Walk","EXP_Ai_Bicycle","EXP
_Ai_Car","EXP_Ai_Transit"))
g2= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Exponential Power Accessibility Index",x = "Pote
ntial Mobility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g2 = g2+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8]), label = "Avg. Acc.",
 vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.50) ,linetype="twodash",
 color = "red")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.50, label = "ST-50%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.30) ,linetype="dashed",
color = "purple")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.30, label = "ST-30%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.10) ,linetype="dotted",
color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.10, label = "ST-10%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,8])+1000, label = "Avg. PMI"
),size = 3)
```

```
print(g2)
dev.off()

png
  2
```

7. GRAPH FOR CUMULATIVE POWER AI

```
png('Mobility Index vs Cumulative Accessibility Index.png')

gv.long <- melt(gv, id = "PMI_Car", measure = c("cum_Ai_Walk","cum_Ai_Bicycle","cum
_Ai_Car","cum_Ai_Transit"))
g3= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Cumulative Accessibility Index",x = "Potential M
obility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g3 = g3+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12]), label = "Avg. Acc."
, vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.50) ,linetype="twodash"
, color = "red")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.50, label = "ST-50%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.30) ,linetype="dashed",
 color = "purple")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.30, label = "ST-30%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.10) ,linetype="dotted",
 color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.10, label = "ST-10%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,12])+1000, label = "Avg. PMI
"),size = 3)
print(g3)
dev.off()

png
  2

#Preferred Mode based on Potential Mobility Index Computation

avg_PMI = data.frame(Walk = colMeans(data.frame(PMI[2])),
                     Bicycle = colMeans(data.frame(PMI[3])),
                     Car = colMeans(data.frame(PMI[4])),
                     Transit = colMeans(data.frame(PMI[5])))
```

```
pref_PMI = PMI[,2:5]

pref_PMI[,1] = as.logical(avg_PMI[1,1]<PMI[,2])
pref_PMI[,2] = as.logical(avg_PMI[1,2]<PMI[,3])
pref_PMI[,3] = as.logical(avg_PMI[1,3]<PMI[,4])
pref_PMI[,4] = as.logical(avg_PMI[1,4]<PMI[,5])

pref_PMI[,5]  = ifelse (pref_PMI[,3]==TRUE, "Car",
                        ifelse (pref_PMI[,4]==TRUE, "Transit",
                                ifelse (pref_PMI[,2]==TRUE, "Bicycle",
                                        ifelse (pref_PMI[,1]==TRUE, "Walk","Car"
                                        ))))
colnames(pref_PMI)[5]<- "PMI_Prefer_Mode"


#Preferred Mode based on Potential Accessibility Index Computation
pref_acc = t6w
pref_acc = data.frame(Walk = rowMeans(data.frame(Accessibility_Index[2],Accessibili
ty_Index[6],Accessibility_Index[10])),
                      Bicycle = rowMeans(data.frame(Accessibility_Index[3],Accessib
ility_Index[7],Accessibility_Index[11])),
                      Car = rowMeans(data.frame(Accessibility_Index[4],Accessibilit
y_Index[8],Accessibility_Index[12])),
                      Transit = rowMeans(data.frame(Accessibility_Index[5],Accessib
ility_Index[9],Accessibility_Index[13]))
)

pref_acc[,5] = apply(pref_acc, 1, max, na.rm = TRUE)
pref_acc[,6]  = ifelse (pref_acc[,3]==pref_acc[,5], "Car",
                        ifelse (pref_acc[,4]==pref_acc[,5], "Transit",
                                ifelse (pref_acc[,2]==pref_acc[,5], "Bicycle",
                                        ifelse (pref_acc[,1]==pref_acc[,5], "Walk",
"Car"
                                        ))))
colnames(pref_acc)[5:6]<- c("Max_AI","Acc_Prefer_Mode")


data_zone [,8] = pref_PMI[,5]
data_zone [,9] = pref_acc[,6]
colnames(data_zone)[8:9]<- c("PMI_Prefer_Mode", "Acc_Prefer_Mode")

#writes an output .csv file showing the variable data used for each run/analysis
input_data = data.frame(
  alpha = 0.8,
  beta = 0.22,
  Tijm = 15,
  access_suff_thres = 10
)

# writing all the files require and housed in the OUTPUT folder as set in line 27
write.csv(data_zone,'Zone Data.csv', row.names=FALSE)
write.csv(data_time,'Travel Times in minutes.csv', row.names=FALSE)
```

```
write.csv(PMI,'Potential Mobility Index.csv', row.names=FALSE)
write.csv(Accessibility_Index,'Potential Accessibility Index.csv', row.names=FALSE)
write.csv(AFI,'Accessibility Fairness Index.csv', row.names=FALSE)
write.csv(t4,'Table 4 Mobility Index and Accesibility Index.csv', row.names=FALSE)
write.csv(t5,'Table 5 Group Entitled to Improvements.csv')
write.csv(t6,'Table 6 Ranked Contribution to Overall Accessibility Deficiency.csv',
 row.names=FALSE)
write.csv(input_data,'Input Parameters.csv', row.names=FALSE)
```

8. STOPPING R5R AND RESTORING THE JAVA MEMORY

```
stop_r5(r5r_core)
rJava::.jgc(R.gc = TRUE)
```

ANNEXURE B2

R code: Nairobi, Kenya

**Always check for package updates to ensure you have the latest versions. Pay attention o the warning messages of 'package was built in R version…' and check that you are running the right version. [Go to Tools, select Global options, look at the General version on your left].

NB: The osm file for Nairobi was replaced with a download from bbbike.org ***https://download.bbbike.org/osm/extract/planet_36.695,-1.388_36.958,-1.216.osm.pbf***
This was due to the original OSM file have a very large street area that exceeded the limits taken by the r5r set up.

1. CALLING LIBRARIES NEEDED FOR *R5R* MODELLING

- Below is code increasing the java memory (line12)
- Code for the libraries required
- setting your working directory. Please remember that this directory is where all your output shall be stored and hence no need to instruct *r5r* to set an output directory as before.

```
#IMPORTANT: Where the input files must sit: 'C:\Users\prava\AppData\Local\R\win-library\4.2\r5r\extdata\Nairobi'

#IMPORTANT:Where you place and run the R script file from is where the OUTPUTS will be stored automatically

options(java.parameters = "-Xmx2G")
#-----------------------------------------------------------
library('r5r')
library('ggplot2')#graphs
library('data.table')
library('dplyr')#data manipulation
library('reshape2')#transform data shapes
library('Rcpp')
#---------------------------------------
```

2. INPUT DATA FOR EACH ACCESSIBILITY CALCULATION

```
alpha = 0.8
beta = 0.22
Tijm = 30
access_suff_thres = 10

#-------------------------------------------
```

```
#Need to run the code each time for each Tijm (15 /30mins). To do: Change above and
 LINE 520 for input parameter.csv file report
#Need to run the code each time for each Sufficiency Threshold (10%, 30% & 50%) sep
arately. To do: Change above and LINE 521 for input parameter.csv file report
#--------------------------------------------
```

3. DEFINE DATAPATH

- Data paths

```
data_path <- system.file("extdata/Nairobi", package = "r5r")
list.files(data_path)

[1] "GTFS.zip"              "network.dat"           "network_settings.json"
[4] "osm.pbf"               "osm.pbf.mapdb"         "osm.pbf.mapdb.p"
[7] "Zonal_Centroid.csv"

#update GTFS data file location above (Line 62)
#keep file format the same at all times: headers and case of text and in terms of t
he order of the columns
points <- fread(file.path(data_path, "Zonal_Centroid.csv"))
head(points)

   id Code      Name       lat      lon Population Employment
1:  1   N1 Dagoretti -1.288983 36.72807     434208     182767
2:  2   N2  Embakasi -1.323786 36.89996     988808     411983
3:  3   N3 Kamukunji -1.284780 36.83377     268276      96482
4:  4   N4  Kasarani -1.225399 36.89764     780656     328353
5:  5   N5     Kibra -1.311484 36.78795     185777      69420
6:  6   N6  Lang'ata -1.364094 36.74763     197489      83422

# Indicate the path where OSM and GTFS data are stored----------------------------
--------
r5r_core <- setup_r5(data_path = data_path, verbose = FALSE)

#---------------------------------------------------------------------------------
------------------
# set inputs "23-11-2020 07:30:00"  "Africa/Kigali" OR  "01-01-2014 07:30:00" "Afri
ca/Nairobi"
# GTFS files for dates and times > check 'calendar.txt' (for dates) & 'stop_times.t
xt' (for departure times) > chose the first trip start time e.g. 07:30 (study is an
alysing peak hour from 07:30 to 08:30) and the analysis runs from that time till th
e time each trip leaving at 07:30 reaches its destination.

departure_datetime <- as.POSIXct("01-01-2014 07:30:00",
                                 format = "%d-%m-%Y %H:%M:%S",tz="Africa/Nairobi")
```

4. TRAVEL TIME MATRICES FOR THE DIFFERENT MODES

```
# Specification of these values is down to personal preference and what their goal
is.
# The function has defined defaults for some of the arguments. For further help che
ck `?travel_time_matrix()`
#-----------------------------------------------------------------------------------
----------------
md <- 100000 #[max walk time]- max walk dist and max bike distance not used in the
argument, deprecated in newer version of r5r
mtd <- 60000 #[max trip duration]
#-----------------------------------------

# calculate a travel time matrix for WALK
ttmw <- travel_time_matrix(r5r_core = r5r_core,
                           origins = points,
                           destinations = points,
                           mode = "WALK",
                           departure_datetime = departure_datetime,
                           max_walk_time = md,
                           max_trip_duration = mtd,
                           verbose = FALSE)## error one is in the arguments specifie
d, this function has no provision for `max_walk_dist`

head(ttmw)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             373
3:       1     3             219
4:       1     4             394
5:       1     5             141
6:       1     6             222

# calculate a travel time matrix for TRANSIT
ttmt <- travel_time_matrix(r5r_core = r5r_core,
                           origins = points,
                           destinations = points,
                           mode = "TRANSIT",
                           departure_datetime = departure_datetime,
                           max_trip_duration = mtd,
                           verbose = FALSE)

head(ttmt)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             272
3:       1     3              93
4:       1     4             253
5:       1     5              88
6:       1     6             169

# calculate a travel time matrix for BICYCLE
ttmb <- travel_time_matrix(r5r_core = r5r_core,
```

```
                             origins = points,
                             destinations = points,
                             mode = "BICYCLE",
                             departure_datetime = departure_datetime,
                             max_bike_time = md,
                             max_trip_duration = mtd,
                             verbose = FALSE)

head(ttmb)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2             214
3:       1     3             125
4:       1     4             239
5:       1     5              76
6:       1     6             118

# calculate a travel time matrix CAR
ttmc <- travel_time_matrix(r5r_core = r5r_core,
                             origins = points,
                             destinations = points,
                             mode = "CAR",
                             departure_datetime = departure_datetime,
                             max_car_time = md,
                             max_trip_duration = mtd,
                             verbose = TRUE)

head(ttmc)

   from_id to_id travel_time_p50
1:       1     1               0
2:       1     2              25
3:       1     3              25
4:       1     4              30
5:       1     5              17
6:       1     6              22

#combines all Travel Time files by mode and writes the updated data_zone variable f
ile (all info sits here)
data_time = data.frame(ttmw[,1:2],Walk = ttmw[,3],Bicyle = ttmb[,3],Car = ttmc[,3],
Transit = ttmt[,3])
colnames(data_time) = c("To_ID","From_ID","Walk","Bicycle","Car","Transit")

#saving a Zonal Centroid file called "data_zone" - this is the variables file (all
call up info sits here)
data_zone <- data.frame(points)
```

5. #PMI Calculation Start (per mode)

```
#calculating euclidean distance between zones (calling up the lat/long details from
 the data_zone file Col 4 & 5) and multiplying it by a factor of 111.11 to convert
decimal degrees to kilometres
```

```
d = as.matrix(dist(data_zone[,4:5], method = "euclidean"))*111.11

#calculates the Origin to Destination distance value (for each zone pair) in km's--
------------------

dist_km = data.frame(origin=colnames(d)[as.vector(col(d))],destination=rownames(d)[
as.vector(row(d))],
                     dist_km=as.vector(d))

#calculation of Origin to Destination speed (for each zone pair) and conversation t
o km/hr---------

speed_kph = data.frame(origin=colnames(d)[as.vector(col(d))]
                       ,destination=rownames(d)[as.vector(row(d))]
                       ,as.matrix(dist_km[,3]/data_time[,3:6]*60))

#correction for same zone calcs - replaces with zero instead of infinity----------
------------------

speed_kph[is.na(speed_kph)] <- 0

pmi_walk = aggregate(x = speed_kph$Walk, by = list(speed_kph$origin), FUN = mean)
pmi_bicycle = aggregate(x = speed_kph$Bicycle, by = list(speed_kph$origin), FUN = m
ean)
pmi_car = aggregate(x = speed_kph$Car, by = list(speed_kph$origin), FUN = mean)
pmi_transit = aggregate(x = speed_kph$Transit, by = list(speed_kph$origin), FUN = m
ean)

#generates output file for PMI calculation and sorts zones by descending order-----
--------

PMI = (data.frame(Zone = as.numeric(pmi_walk[,1]),PMI_Walk = pmi_walk[,2]
                  ,PMI_Bicycle = pmi_bicycle[,2],PMI_Car = pmi_car[,2]
                  ,PMI_Transit = pmi_transit[,2]))

PMI <-PMI[with(PMI, order(Zone)),]

#PMI Calculation End------------------------------
```

6. #Start of Accessibility Index calculations - the three equations: inverse, exponential and cumulative equations

```
#Getting relevant data from data_zone file and associated columns

#wj refers to employment data

wj=data.frame(employee= rep(as.array(data_zone[,7]),times=length(data_zone[,7])))

#writes the inverse_power_Ai.csv file

inverse_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
```

```
                              ,destination=rownames(d)[as.vector(row(d))]
                              ,Inverse_power_Ai_Walk = wj*(data_time[,3])**(-alpha)
                              ,Inverse_power_Ai_Bicycle = wj*(data_time[,4])**(-alp
ha)
                              ,Inverse_power_Ai_Car = wj*(data_time[,5])**(-alpha)
                              , Inverse_power_Ai_Transit = wj*(data_time[,6])**(-al
pha))

colnames(inverse_power_Ai) <- c("Origin", "Destination","INV_Ai_Walk","INV_Ai_Bicyc
le","INV_Ai_Car","INV_Ai_Transit")
inverse_power_Ai[inverse_power_Ai == Inf] <- 0


#writes the exp_power_Ai.csv file

exp_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
                          ,destination=rownames(d)[as.vector(row(d))]
                          ,exp_power_Ai_Walk = wj*exp(data_time[,3]*(-beta))
                          ,exp_power_Ai_Bicycle = wj*exp(data_time[,4]*(-beta))
                          ,exp_power_Ai_Car = wj*exp(data_time[,5]*(-beta))
                          , exp_power_Ai_Transit = wj*exp(data_time[,6]*(-beta)))

colnames(exp_power_Ai) <- c("Origin", "Destination","EXP_Ai_Walk","EXP_Ai_Bicycle",
"EXP_Ai_Car","EXP_Ai_Transit")
exp_power_Ai[exp_power_Ai == Inf] <- 0


#writes the cum_power_Ai.csv file

cum_power_Ai = data.frame(origin=colnames(d)[as.vector(col(d))]
                          ,destination=rownames(d)[as.vector(row(d))]
                          ,cum_power_Ai_Walk = wj*(1-(data_time[,3]/Tijm))
                          ,cum_power_Ai_Bicycle = wj*(1-(data_time[,4]/Tijm))
                          ,cum_power_Ai_Car = wj*(1-(data_time[,5]/Tijm))
                          , cum_power_Ai_Transit = wj*(1-(data_time[,6]/Tijm)))

colnames(cum_power_Ai) <- c("Origin", "Destination","cum_Ai_Walk","cum_Ai_Bicycle",
"cum_Ai_Car","cum_Ai_Transit")
cum_power_Ai[cum_power_Ai == Inf] <- 0
cum_power_Ai[cum_power_Ai < 0] <- 0


#writes a combined csv file for all Accessibility calc equations for each OD pair

Ai= data.frame(inverse_power_Ai,exp_power_Ai[,3:6],cum_power_Ai[,3:6])

#Start of the Accessibility Index calcs for each zone

Accessibility_Index = aggregate(x = Ai[,3:14], by = list(Ai$Origin), FUN = sum)
colnames(Accessibility_Index)[1]<- "Zone"

#Sorting line to rank the data in descending zone order
```

```
Accessibility_Index[,1] = as.numeric(Accessibility_Index[,1])
Accessibility_Index <-Accessibility_Index[with(Accessibility_Index, order(Zone)),]

#Start of the Accessibility Deficiency Index calcs (as part of the Accessibility Fa
irness Index)

ZINV = (mean(Accessibility_Index[,4]) * (access_suff_thres/100))
ZEXP = (mean(Accessibility_Index[,8]) * (access_suff_thres/100))
ZCUM = (mean(Accessibility_Index[,12]) * (access_suff_thres/100))

#Controlling variables for INV, EXP and CUM - stipulates that if the Accessibility
indexes are below the stipulated levels then consider/collect (constructs a binary
matrix to sort/collect)

chk_INV = Accessibility_Index[,2:5]
chk_INV[chk_INV < ZINV] <- 1
chk_INV[chk_INV >= ZINV] <- 0

chk_EXP = Accessibility_Index[,6:9]
chk_EXP[chk_EXP < ZEXP] <- 1
chk_EXP[chk_EXP >= ZEXP] <- 0

chk_CUM = Accessibility_Index[,10:13]
chk_CUM[chk_CUM < ZCUM] <- 1
chk_CUM[chk_CUM >= ZCUM] <- 0


#Start of the Accessibility Fairness Index calculation per zone (using the controll
ing variables in lines above)
AFI = data.frame(Zone= Accessibility_Index[,1]
                 ,AFI_INV_Walk = chk_INV[,1]*(data_zone[,6]* ( (ZINV - Accessibilit
y_Index[,2] ) / ZINV )**2)
                 ,AFI_INV_Bicycle =chk_INV[,2]*(data_zone[,6] * ( (ZINV - Accessibi
lity_Index[,3] ) / ZINV )**2)
                 ,AFI_INV_Car = chk_INV[,3]*(data_zone[,6]*( (ZINV - Accessibility_
Index[,4] ) / ZINV )**2)
                 ,AFI_INV_Transit = chk_INV[,4]*(data_zone[,6]*( (ZINV - Accessibil
ity_Index[,5] ) / ZINV )**2 )

                 ,AFI_EXP_Walk = chk_EXP[,1]*(data_zone[,6]* ( (ZEXP - Accessibilit
y_Index[,6] ) / ZEXP )**2)
                 ,AFI_EXP_Bicycle = chk_EXP[,2]*(data_zone[,6] * ( (ZEXP - Accessib
ility_Index[,7] ) / ZEXP )**2)
                 ,AFI_EXP_Car = chk_EXP[,3]*(data_zone[,6]*( (ZEXP - Accessibility_
Index[,8] ) / ZEXP )**2)
                 ,AFI_EXP_Transit = chk_EXP[,4]*( data_zone[,6]*( (ZEXP - Accessibi
lity_Index[,9] ) / ZEXP )**2 )

                 ,AFI_CUM_Walk = chk_CUM[,1]*(data_zone[,6]* ( (ZCUM - Accessibilit
y_Index[,10] ) / ZCUM )**2)
                 ,AFI_CUM_Bicycle = chk_CUM[,2]*( data_zone[,6] * ( (ZCUM - Accessi
```

```
bility_Index[,11] ) / ZCUM )**2)
                 ,AFI_CUM_Car = chk_CUM[,3]*( data_zone[,6]*( (ZCUM - Accessibility
_Index[,12] ) / ZCUM )**2)
                 ,AFI_CUM_Transit = chk_CUM[,4]*( data_zone[,6]*( (ZCUM - Accessibi
lity_Index[,13] ) / ZCUM )**2 )

)


AFI[AFI < 0] <- 0
```

7. Start of the Accessibility_Deficiency_Index calculation (severity of accessibility deficiency in a region/zone

#TABLE OF RANKED CONTRIBUTION TO OVERALL ACCESSIBILITY DEFICIENCY

```
Accessibility_Deficiency_Index = data.frame(Accessibility_Deficiency_Index_INV_Walk
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,2]) )
                                             ,Accessibility_Deficiency_Index_INV_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,3]))
                                             ,Accessibility_Deficiency_Index_INV_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,4]))
                                             ,Accessibility_Deficiency_Index_INV_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,5]))

                                             ,Accessibility_Deficiency_Index_EXP_Wal
k = (1/(sum(data_zone[,6]))) * (sum(AFI[,6]) )
                                             ,Accessibility_Deficiency_Index_EXP_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,7]))
                                             ,Accessibility_Deficiency_Index_EXP_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,8]))
                                             ,Accessibility_Deficiency_Index_EXP_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,9]))

                                             ,Accessibility_Deficiency_Index_CUM_Wal
k = (1/(sum(data_zone[,6]))) * (sum(AFI[,10]) )
                                             ,Accessibility_Deficiency_Index_CUM_Bic
ycle = (1/(sum(data_zone[,6]))) * (sum(AFI[,11]))
                                             ,Accessibility_Deficiency_Index_CUM_Car
 = (1/(sum(data_zone[,6]))) * (sum(AFI[,12]))
                                             ,Accessibility_Deficiency_Index_CUM_Tra
nsit = (1/(sum(data_zone[,6]))) * (sum(AFI[,13])  )


)
```

8. #Start of the OUTPUT files

```
#control variable - calcs how many zones are in the data_zone set (robust feature)
to confirm how many zones the data set has and will be commuting with

nz = as.numeric(nrow(data_zone))
```

```
#table 5 sorting and generating summary
t5 = t(data.frame(
  t(Accessibility_Deficiency_Index[,1:12]),
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM))),
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)))/nz*100,
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)*data_zone[,6])),
  (colSums(data.frame(chk_INV,chk_EXP,chk_CUM)*data_zone[,6])/(sum(data_zone[,6]))*
100)
))

#Formatting and rounding off values

colnames(t5) = c("INV_Walk","INV_Bicycle","INV_Car","INV_Transit","EXP_Walk","EXP_B
icycle","EXP_Car","EXP_Transit","CUM_Walk","CUM_Bicycle","CUM_Car","CUM_Transit")
rownames(t5) = c("Accessibility Fairness Index (AFI)","Number of Group below Suffic
iency Threshold","Percentage of Group below Sufficiency Threshold","Number of Peopl
e below Sufficiency Threshold","Percentage of People below Sufficiency Threshold")
t5 = round(t5, digits = 2)

#Table 4 ->Mobility Index And Accessibility Index

t4 = round(data.frame(PMI[,1:2],Accessibility_Index[2],Accessibility_Index[6],Acces
sibility_Index[10],
                      PMI_Bicycle = PMI[,3],Accessibility_Index[3],Accessibility_In
dex[7],Accessibility_Index[11],
                      PMI_Car = PMI[,4],Accessibility_Index[4],Accessibility_Index[
8],Accessibility_Index[12],
                      PMI_Transit = PMI[,5],Accessibility_Index[5],Accessibility_In
dex[9],Accessibility_Index[13]
),digits = 1)
gv = round(data.frame(PMI, Accessibility_Index[,2:13]),digits = 2)

#Table 6 -> Ranked Contribution to Overall Accessibility Deficiency

#working variable t6w to make a "working file"to generate the mean of the AFI value
 for each mode being calc'd by each method (inv, power, cum)

t6w = data.frame(Walk = rowMeans(data.frame(AFI[2],AFI[6],AFI[10])),
                 Bicycle = rowMeans(data.frame(AFI[3],AFI[7],AFI[11])),
                 Car = rowMeans(data.frame(AFI[4],AFI[8],AFI[12])),
                 Transit = rowMeans(data.frame(AFI[5],AFI[9],AFI[13]))
)

#calling from the above variable (mean of all modes and to generate a mode % )
AFI_Contribution = round(data.frame(Walk = t6w[,1]/(rowSums(t6w))*100,
                                    Bicycle = t6w[,2]/(rowSums(t6w))*100,
                                    Car = t6w[,3]/(rowSums(t6w))*100,
                                    Transit = t6w[,4]/(rowSums(t6w))*100
),digits = 0)

#Fix line for any errors from above AFI_contribution to deal with rowSums in t6w wh
ich have total populations of ZERO (if any)
```

```
AFI_Contribution[is.na(AFI_Contribution)] <- 0
tm = c("Walk","Bicycle","Car","transit")

library("dplyr")

#generates final Table 6 file
t6 = data.frame(zone= rep(as.array(data_zone[,1]),times=ncol(AFI_Contribution)),
               Mode = rep(as.array(tm),times=as.numeric(length(AFI_Contribution[,1
]))),
               AFI_CONTRIBUTION = vctrs::vec_c(AFI_Contribution[,1],AFI_Contributi
on[,2]
                                                         ,AFI_Contribution[,3],AFI_Cont
ribution[,4]))

t6[1:nz,2] = "Walk"
t6[(nz+1):(2*nz),2] = "Bicycle"
t6[(2*nz+1):(3*nz),2] = "Car"
t6[(3*nz+1):(4*nz),2] = "Transit"

#sorting to give highest Contribution rank value first

t6 <-t6[with(t6, order(AFI_CONTRIBUTION,decreasing = TRUE)),]
```

5. START OF THE PLOTTING THE QUADRANT GRAPHS

```
#file name of the .png exports

png('Mobility Index vs Inverse Power Accessibility Index.png')

# Graph for Inverse Power Ai - numbers below correspond to symbols and colours; als
o sets the PMI value as CAR mean and the Sufficiency thresholds as selected 10,30 a
nd 50%

gv.long <- melt(gv, id = "PMI_Car", measure = c("INV_Ai_Walk","INV_Ai_Bicycle","INV
_Ai_Car","INV_Ai_Transit"))
g1= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Inverse Power Accessibility Index",x = "Potentia
l Mobility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g1 = g1+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4]), label = "Avg. Acc.",
 vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.50) ,linetype="twodash",
 color = "red")+
```

```
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.50, label = "ST-50%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.30) ,linetype="dashed",
color = "purple")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.30, label = "ST-30%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,4])*.10) ,linetype="dotted",
color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,4])*.10, label = "ST-10%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,4])+1000, label = "Avg. PMI"
),size = 3)
print(g1)
dev.off()#returns the number and name of the new active device (after the specified
 device has been shut down)

png
  2
```

6. GRAPH FOR EXPONENTIAL POWER AI

```
png('Mobility Index vs Exponential Power Accessibility Index.png')

gv.long <- melt(gv, id = "PMI_Car", measure = c("EXP_Ai_Walk","EXP_Ai_Bicycle","EXP
_Ai_Car","EXP_Ai_Transit"))
g2= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Exponential Power Accessibility Index",x = "Pote
ntial Mobility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g2 = g2+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8]), label = "Avg. Acc.",
 vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.50) ,linetype="twodash",
 color = "red")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.50, label = "ST-50%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.30) ,linetype="dashed",
color = "purple")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.30, label = "ST-30%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,8])*.10) ,linetype="dotted",
color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,8])*.10, label = "ST-10%"
, vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
```

```
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,8])+1000, label = "Avg. PMI"
),size = 3)
print(g2)
dev.off()

png
  2
```

7. GRAPH FOR CUMULATIVE POWER AI

```
png('Mobility Index vs Cumulative Accessibility Index.png')

gv.long <- melt(gv, id = "PMI_Car", measure = c("cum_Ai_Walk","cum_Ai_Bicycle","cum
_Ai_Car","cum_Ai_Transit"))
g3= ggplot(gv.long, aes(PMI_Car, value, group = variable)) + geom_point(aes(shape=v
ariable, color=variable, fill = variable, size = variable))+
  labs(title = "Mobility Index vs. Cumulative Accessibility Index",x = "Potential M
obility Index", y = "Accessibility Index")+
  scale_shape_manual(name = "Legend",values=c(22, 23, 8, 17))+
  scale_color_manual(name = "Legend",values = c("maroon","black","blue","black"))+
  scale_fill_manual(name = "Legend",values = c ("yellow","green","blue","black"))+
  scale_size_manual(name = "Legend",values = c(3,2,2,2))
g3 = g3+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])))+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12]), label = "Avg. Acc."
, vjust = - 0.5, hjust = 0.7),size = 3)+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.50) ,linetype="twodash"
, color = "red")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.50, label = "ST-50%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "red")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.30) ,linetype="dashed",
 color = "purple")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.30, label = "ST-30%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "purple")+
  geom_hline(aes(yintercept=mean(Accessibility_Index[,12])*.10) ,linetype="dotted",
 color = "brown")+
  geom_text(aes(max(PMI[,4])+1, mean(Accessibility_Index[,12])*.10, label = "ST-10%
", vjust = - 0.5, hjust = 0.7),size = 3, color = "brown")+
  geom_vline(aes(xintercept=mean(PMI[,4])))+
  geom_text(aes(mean(PMI[,4]),max(Accessibility_Index[,12])+1000, label = "Avg. PMI
"),size = 3)
print(g3)
dev.off()

png
  2

#Preferred Mode based on Potential Mobility Index Computation

avg_PMI = data.frame(Walk = colMeans(data.frame(PMI[2])),
```

```
                     Bicycle = colMeans(data.frame(PMI[3])),
                     Car = colMeans(data.frame(PMI[4])),
                     Transit = colMeans(data.frame(PMI[5])))
pref_PMI = PMI[,2:5]

pref_PMI[,1] = as.logical(avg_PMI[1,1]<PMI[,2])
pref_PMI[,2] = as.logical(avg_PMI[1,2]<PMI[,3])
pref_PMI[,3] = as.logical(avg_PMI[1,3]<PMI[,4])
pref_PMI[,4] = as.logical(avg_PMI[1,4]<PMI[,5])

pref_PMI[,5]  = ifelse (pref_PMI[,3]==TRUE, "Car",
                        ifelse (pref_PMI[,4]==TRUE, "Transit",
                                ifelse (pref_PMI[,2]==TRUE, "Bicycle",
                                        ifelse (pref_PMI[,1]==TRUE, "Walk","Car"
                                        ))))
colnames(pref_PMI)[5]<- "PMI_Prefer_Mode"


#Preferred Mode based on Potential Accessibility Index Computation
pref_acc = t6w
pref_acc = data.frame(Walk = rowMeans(data.frame(Accessibility_Index[2],Accessibili
ty_Index[6],Accessibility_Index[10])),
                      Bicycle = rowMeans(data.frame(Accessibility_Index[3],Accessib
ility_Index[7],Accessibility_Index[11])),
                      Car = rowMeans(data.frame(Accessibility_Index[4],Accessibilit
y_Index[8],Accessibility_Index[12])),
                      Transit = rowMeans(data.frame(Accessibility_Index[5],Accessib
ility_Index[9],Accessibility_Index[13]))
)

pref_acc[,5] = apply(pref_acc, 1, max, na.rm = TRUE)
pref_acc[,6]  = ifelse (pref_acc[,3]==pref_acc[,5], "Car",
                        ifelse (pref_acc[,4]==pref_acc[,5], "Transit",
                                ifelse (pref_acc[,2]==pref_acc[,5], "Bicycle",
                                        ifelse (pref_acc[,1]==pref_acc[,5], "Walk",
"Car"
                                        ))))
colnames(pref_acc)[5:6]<- c("Max_AI","Acc_Prefer_Mode")


data_zone [,8] = pref_PMI[,5]
data_zone [,9] = pref_acc[,6]
colnames(data_zone)[8:9]<- c("PMI_Prefer_Mode", "Acc_Prefer_Mode")

#writes an output .csv file showing the variable data used for each run/analysis
input_data = data.frame(
  alpha = 0.8,
  beta = 0.22,
  Tijm = 30,
  access_suff_thres = 10
)
```

```
# writing all the files require and housed in the OUTPUT folder as set in line 27
write.csv(data_zone,'Zone Data.csv', row.names=FALSE)
write.csv(data_time,'Travel Times in minutes.csv', row.names=FALSE)
write.csv(PMI,'Potential Mobility Index.csv', row.names=FALSE)
write.csv(Accessibility_Index,'Potential Accessibility Index.csv', row.names=FALSE)
write.csv(AFI,'Accessibility Fairness Index.csv', row.names=FALSE)
write.csv(t4,'Table 4 Mobility Index and Accesibility Index.csv', row.names=FALSE)
write.csv(t5,'Table 5 Group Entitled to Improvements.csv')
write.csv(t6,'Table 6 Ranked Contribution to Overall Accessibility Deficiency.csv',
 row.names=FALSE)
write.csv(input_data,'Input Parameters.csv', row.names=FALSE)
```

8. STOPPING R5R AND RESTORING THE JAVA MEMORY

```
stop_r5(r5r_core)
rJava::.jgc(R.gc = TRUE)
```

ANNEXURE C

Table 19: Population and employment distribution statistics (according to area) of the 35 zones of Kigali

No.	TAZ ID	District	Zone Name	Lat	Long	Area (km²)	% Area Proportion of Zone	Population	Employment
1	RW1 101	**Nyarugenge** Population 284,560 (25.5% of Kigali) Employment 22,593	Gitega	-1.95342	30.05507	1.176	0.9%	2,521	210
2	RW1 102		Kanyinya	-1.91782	30.00253	24.222	18.2%	51,930	4,330
3	RW1 103		Kigali	-1.97917	30.01896	29.442	22.2%	63,121	4,825
4	RW1 104		Kimisagara	-1.95294	30.04611	3.32	2.5%	7,117	445
5	RW1 105		Mageregere	-2.04192	30.03604	54.762	41.3%	117,405	9,789
6	RW1 106		Muhima	-1.94122	30.06093	2.95	2.2%	6,324	527
7	RW1 107		Nyakabanda	-1.96952	30.04505	2.429	1.8%	5,208	326
8	RW1 108		Nyamirambo	-1.99259	30.04327	8.764	6.6%	18,789	1,436
9	RW1 109		Nyarugenge	-1.95682	30.06428	4.636	3.5%	9,939	552
10	RW1 110		Rwezamenyo	-1.97125	30.05265	1.029	0.8%	2,206	153
11	RW1 201	**Gasabo** Population 529,559 (47.5% of Kigali) Employment 36,903	Bumbogo	-1.88784	30.15591	60.74	14.1%	74,765	4,676
12	RW1 202		Gatsata	-1.92204	30.04228	6.035	1.4%	7,428	516
13	RW1 203		Gikomero	-1.87485	30.22898	35.145	8.2%	43,261	2,705
14	RW1 204		Gisozi	-1.91778	30.06129	8.322	1.9%	10,243	712
15	RW1 205		Jabana	-1.86433	30.06403	36.459	8.5%	44,878	3,118
16	RW1 206		Jali	-1.88247	30.01659	37.449	8.7%	46,096	3,523
17	RW1 207		Kacyiru	-1.93761	30.08047	5.797	1.3%	7,135	496
18	RW1 208		Kimihurura	-1.95429	30.08831	5.082	1.2%	6,256	435
19	RW1 209		Kimironko	-1.93836	30.12423	11.358	2.6%	13,981	777
20	RW1 210		Kinyinya	-1.90894	30.09651	24.247	5.6%	29,846	2,489
21	RW1 211		Ndera	-1.93358	30.18683	50.493	11.7%	62,152	4,750
22	RW1 212		Nduba	-1.85118	30.11273	46.644	10.8%	57,415	3,192
23	RW1 213		Remera	-1.94756	30.10608	7.283	1.7%	8,964	561
24	RW1 214		Rusororo	-1.93654	30.23586	52.357	12.2%	64,447	4,926
25	RW1 215		Rutunga	-1.82513	30.17445	42.807	10.0%	52,692	4,027
26	RW1 301	**Kicukiro** Populatio n 301,002 (27% of	Gahanga	-2.03161	30.10965	36.848	22.0%	66,259	4,144
27	RW1 302		Gatenga	-1.99817	30.08289	12.467	7.4%	22,418	1,558

28	RW1 303		Gikondo	-1.97319	30.07869	3.393	2.0%	6,101	424
29	RW1 304		Kagarama	-1.99774	30.1134	8.011	4.8%	14,406	1,201
30	RW1 305		Kanombe	-1.99772	30.14496	23.051	13.8%	41,449	3,456
31	RW1 306		Kicukiro	-1.97182	30.09716	2.053	1.2%	3,691	205
32	RW1 307		Kigarama	-1.98752	30.06459	8.38	5.0%	15,069	1,152
33	RW1 308		Masaka	-2.02226	30.20316	52.838	31.6%	95,012	5,942
34	RW1 309		Niboye	-1.97635	30.11382	5.038	3.0%	9,060	755
35	RW1 310		Nyarugunga	-1.97447	30.15799	15.314	9.1%	27,537	2,296

Table 20: Population and employment distribution statistics (according to area) of the 11 zones of Nairobi

No.	TAZ ID	Zone Name	Latitude	Longitude	Area (km²)	% Area Proportion of Zone	Population	Employment
1	N1	Dagoretti	-1.2889834	36.7280692	53.705154	7.6%	434208	182767
2	N2	Embakasi	-1.3237858	36.8999616	126.76575	17.9%	988808	411983
3	N3	Kamukunji	-1.2847801	36.8337743	8.837455	1.2%	268276	96482
4	N4	Kasarani	-1.2253995	36.8976372	136.2742108	19.3%	780656	328353
5	N5	Kibra	-1.3114845	36.7879475	12.330317	1.7%	185777	69420
6	N6	Lang'ata	-1.3640944	36.7476257	11.997234	1.7%	197489	83422
7	N7	Makadara	-1.2952979	36.8721139	209.8090967	29.7%	189536	82935
8	N8	Mathare	-1.261914	36.8584703	2.902835	0.4%	206564	84898
9	N9	Njiru	-1.2504554	36.9270856	55.284031	7.8%	626482	255777
10	N10	Starehe	-1.2854576	36.8223358	16.83635277	2.4%	210423	78295
11	N11	Westlands	-1.2675001	36.812022	72.704258	10.3%	308854	137979

ANNEXURE D – Kigali Results

ANNEXURE D1

Table 21: Potential mobility and potential accessibility indices per zone, per mode for the 15min travel time threshold (Kigali)

Zone No.	Zone Name	Walk				Bicycle				Car				Transit			
		PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai	PMI (km/hr)	Inverse Ai	Exponential Ai	Cumulative Ai
5	Mageregere	2.7	702	9789	9789	3.9	920	9789	9789	28	4558	10219	10273	2.7	702	9789	9789
27	Gatenga	2.6	1152	1558	1558	4.2	1612	1559	1558	25.5	7441	4286	7985	2.7	1175	1558	1558
33	Masaka	2.6	711	5942	5942	4	956	5942	5942	25.1	4250	6056	5942	2.6	711	5942	5942
26	Gahanga	2.7	5050	3326	3868	3.9	5309	3326	3868	28	9993	4365	5264	2.7	5058	3326	3868
32	Kigarama	2.6	1175	1152	1152	4.2	1673	1157	1152	23	7005	3248	5222	2.7	1200	1152	1152
29	Kagarama	2.6	1116	1201	1201	4.4	1603	1202	1201	24.5	6711	2878	4901	2.8	1152	1201	1201
21	Ndera	2.5	5634	3812	4433	3.7	5874	3812	4433	23.8	9977	4301	4893	2.5	5634	3812	4433
30	Kanombe	2.6	4463	2774	3226	4.6	4931	2778	3226	23.3	9215	3624	4617	2.8	4476	2774	3226
8	Nyamirambo	2.6	1112	1436	1436	4.7	1616	1439	1436	24.2	6519	2996	4603	2.7	1128	1436	1436
35	Nyarugunga	2.7	1085	2296	2296	4.5	1577	2303	2296	25.3	6491	3646	4594	3	1102	2296	2296
11	Bumbogo	2.6	888	4676	4676	4	1139	4676	4676	25.3	10022	4146	4364	2.6	890	4676	4676
24	Rusororo	2.7	3593	3173	4269	3.8	3770	3173	4269	24.1	7046	3276	4269	2.7	3593	3173	4269
25	Rutunga	2.7	711	4027	4027	3.5	848	4027	4027	29.9	4681	4222	4027	2.7	711	4027	4027
3	Kigali	2.6	2452	2001	3538	4	2784	2001	3538	22.4	6573	2394	3958	2.7	2471	2001	3538
31	Kicukiro	2.5	1186	205	205	4.1	1782	240	255	23.2	7289	2237	3917	2.9	1262	205	205
7	Nyakabanda	2.5	1160	328	326	4.1	1661	347	377	23.4	6876	2117	3873	2.6	1186	328	326
2	Kanyinya	2.3	3221	2789	3753	3.1	3418	2789	3753	24.7	7132	2993	3753	2.3	3221	2789	3753
10	Rwezamenyo	2.6	1227	156	153	4.4	1815	213	262	23.6	7020	2023	3616	2.8	1262	156	153
28	Gikondo	2.5	1202	424	424	4	1724	426	424	22.9	7129	2201	3559	2.7	1254	424	424
16	Jali	2.4	4253	2827	3288	3.1	4443	2827	3288	24.2	7925	2935	3288	2.4	4253	2827	3288
34	Niboye	2.6	1160	755	755	4.5	1749	766	769	23.7	6861	2308	3194	2.9	1214	755	755
22	Nduba	2.6	4023	2562	2979	4	4268	2562	2979	25.9	8138	2802	2979	2.6	4023	2562	2979
15	Jabana	2.5	3908	2502	2910	3.8	4188	2502	2910	25.9	8052	2724	2945	2.5	3908	2502	2910
1	Gitega	2.5	1173	211	210	4.2	1726	240	210	22.4	6878	1900	2911	2.8	1234	211	210
9	Nyarugenge	2.5	1163	552	552	3.9	1650	560	552	21.1	6661	1952	2902	2.7	1211	552	552
20	Kinyinya	2.4	3454	1998	2323	3.9	3882	1998	2323	21.6	8078	2414	2676	2.4	3465	1998	2323
6	Muhima	2.6	1150	528	527	4	2123	425	492	22.8	7243	1773	2371	3	1222	528	527
13	Gikomero	2.5	2254	1742	2344	3.3	2412	1742	2344	25	5990	1962	2344	2.5	2254	1742	2344
23	Remera	2.5	1142	561	561	4.1	1669	562	561	21.7	6566	1599	2174	2.8	1203	561	561
17	Kacyiru	2.5	1132	496	496	3.9	1586	496	496	22	6517	1605	2080	2.7	1171	496	496
19	Kimironko	2.5	1101	777	777	4.3	1631	778	777	23.8	6596	1794	2022	2.9	1160	777	777
4	Kimisagara	2.5	1127	445	445	4	1582	452	445	22	6459	1673	1953	2.7	1170	445	445
12	Gatsata	2.5	999	516	516	3.7	1350	516	516	24.6	6255	1545	1519	2.7	1031	516	516
14	Gisozi	2.6	1055	712	712	4.3	1540	712	712	22.8	6127	1454	1378	2.8	1082	712	712
18	Kimihurura	2.4	1110	435	435	3.5	1976	349	406	18	6305	953	954	2.4	1139	435	435

ANNEXURE D2

Kigali Results: Potential mobility and potential accessibility quadrant analysis for the 30 & 15min travel time threshold using the inverse and exponential power accessibility measure to assess employment during peak hour in Kigali

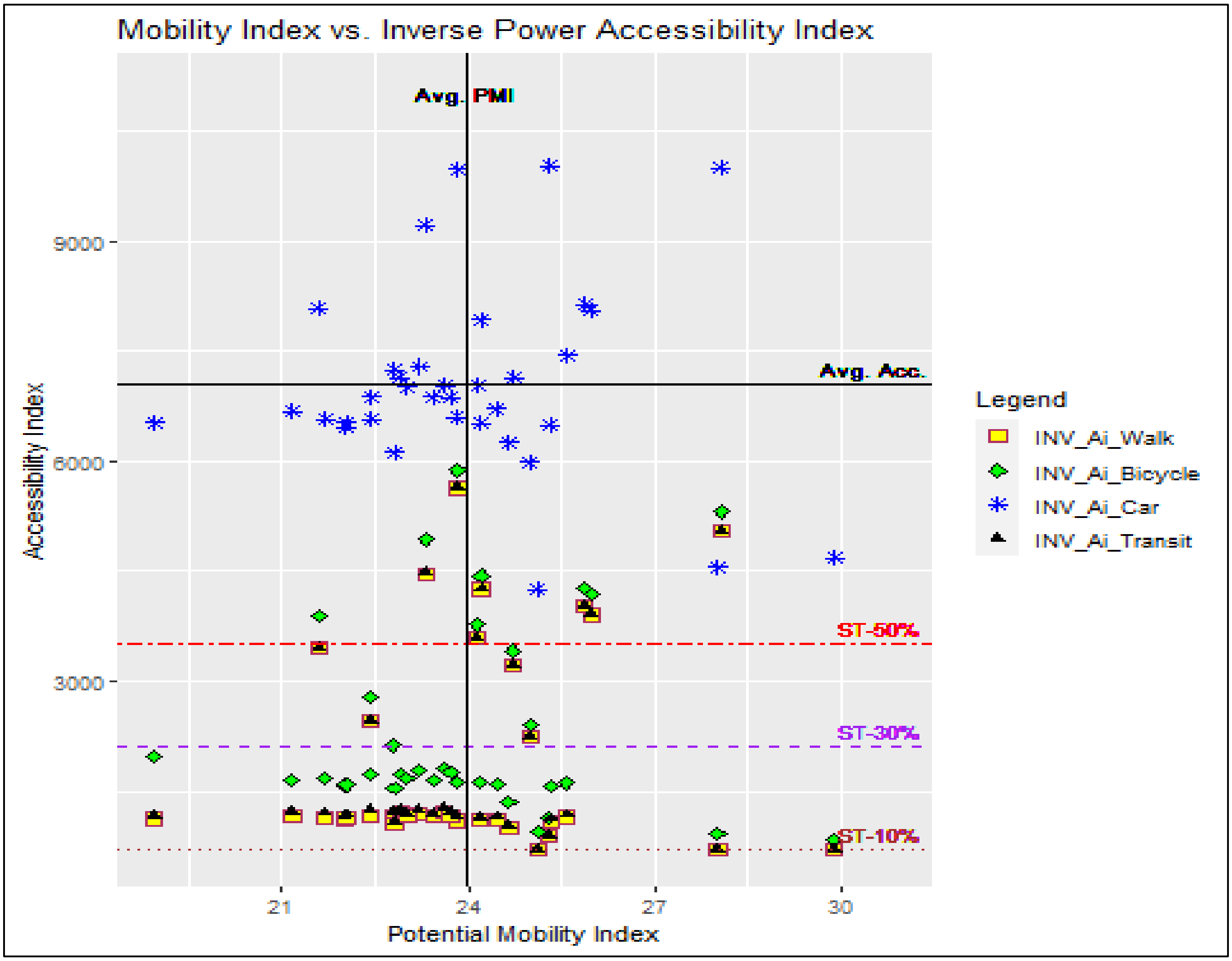

Figure 39: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) - Inverse power accessibility

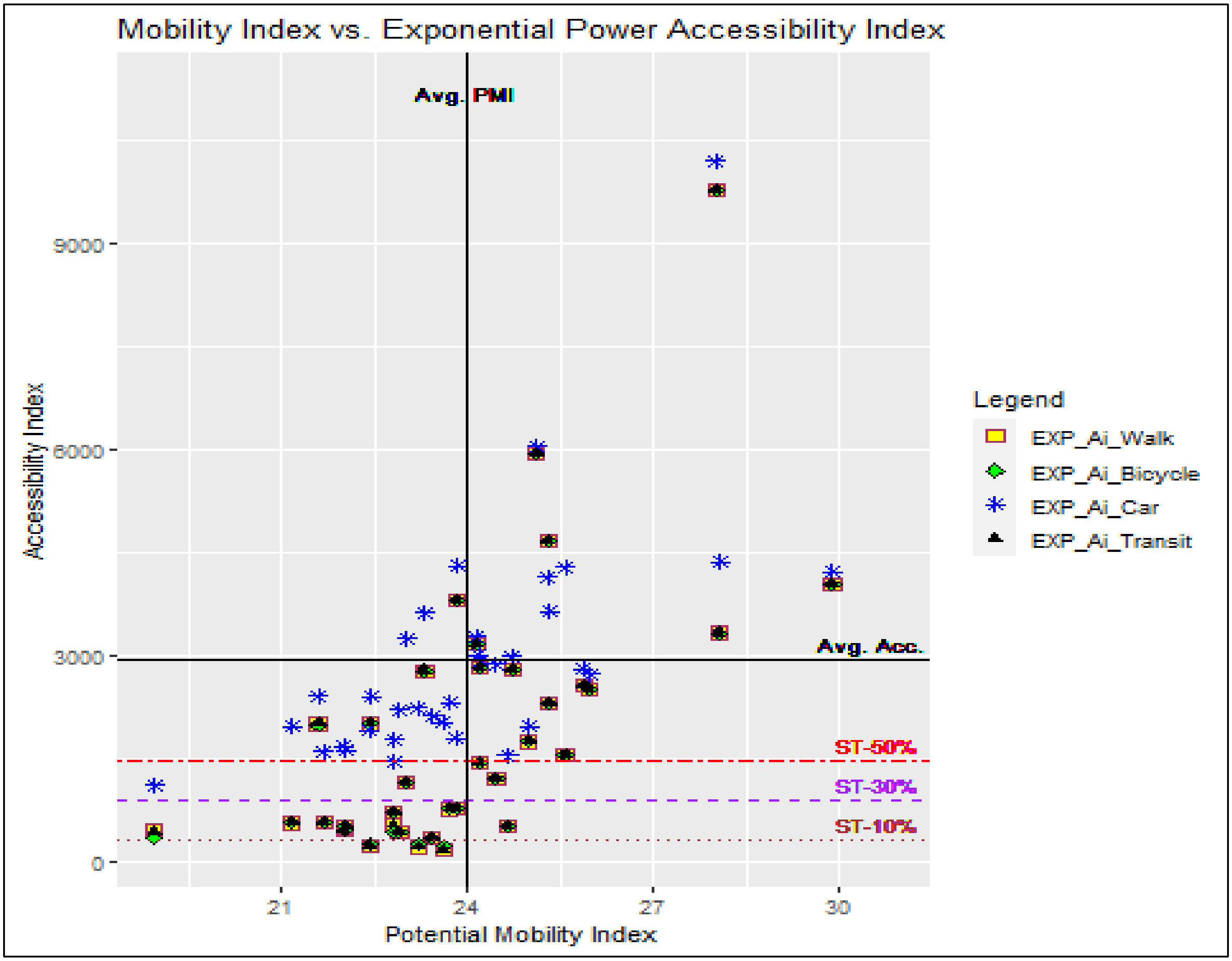

Figure 40: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) – exponential power accessibility

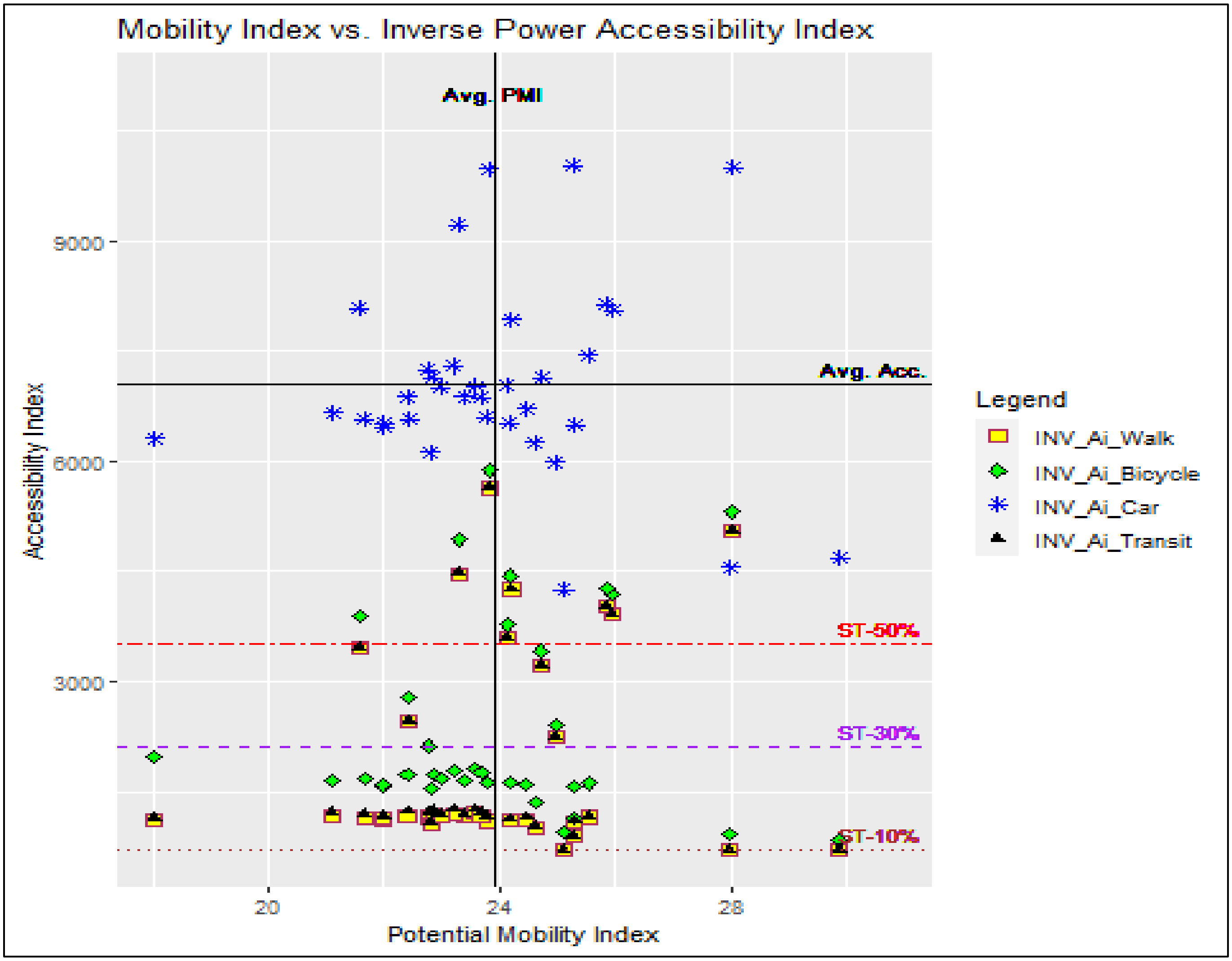

Figure 41: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) - Inverse power accessibility

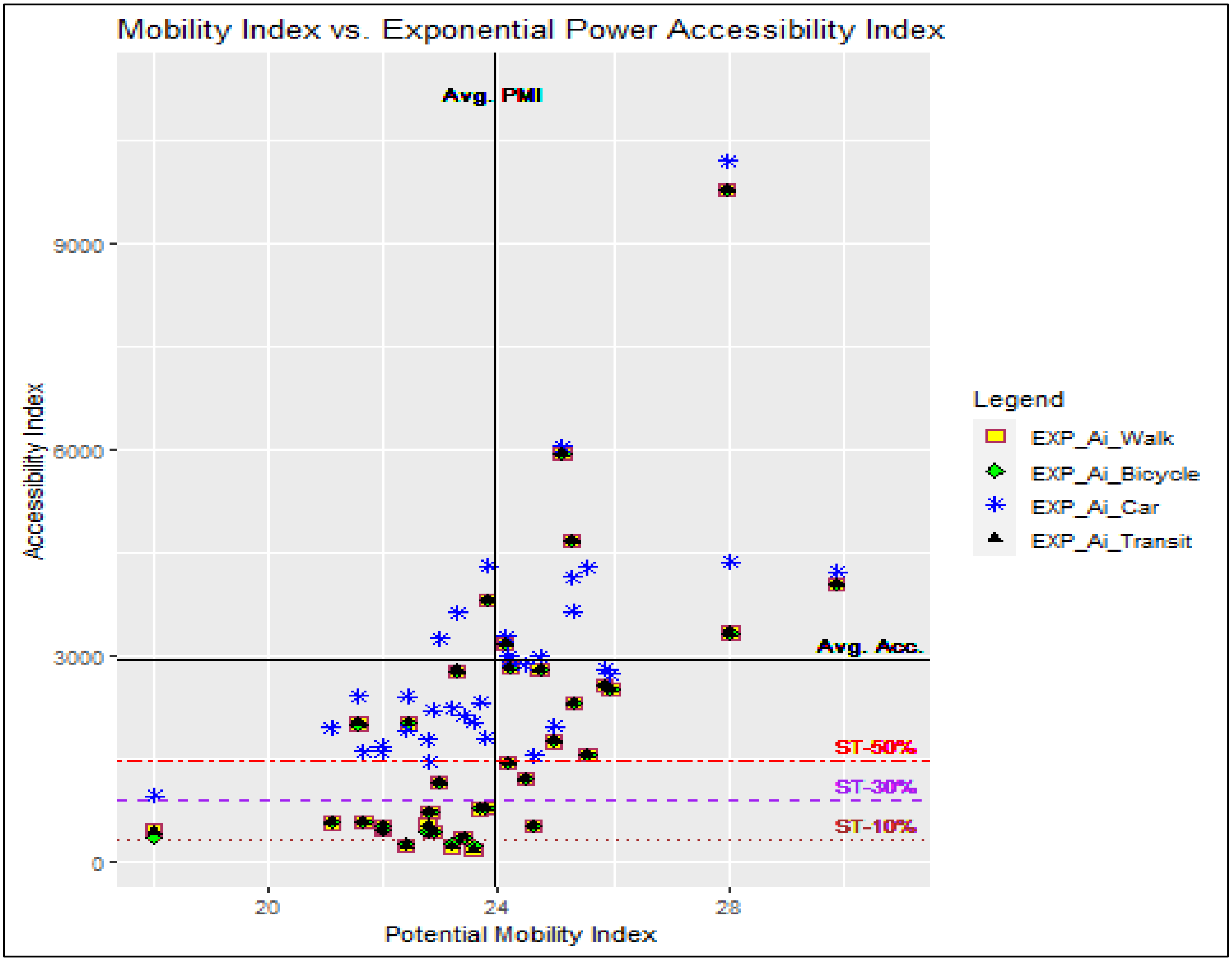

Figure 42: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) – exponential power accessibility

ANNEXURE D3

Table 22: AFI Analysis - Top ranked zones per mode needing improvement (Kigali)

Ranked	Zone	Mode	AFI Contribution (%)
1	35	Walk	40
2	11	Walk	38
3	11	Transit	38
4	35	Transit	38
5	1	Walk	37
6	5	Walk	37
7	8	Walk	37
8	10	Walk	37
9	32	Walk	37
10	33	Walk	37
11	34	Walk	37
12	5	Transit	37
13	8	Transit	37
14	10	Transit	37
15	33	Transit	37
16	9	Walk	36
17	14	Walk	36
18	19	Walk	36
19	27	Walk	36
20	29	Walk	36
21	30	Walk	36
22	31	Walk	36
23	1	Transit	36
24	27	Transit	36
25	30	Transit	36
26	31	Transit	36
27	32	Transit	36
28	34	Transit	36
29	4	Walk	35
30	6	Walk	35
31	7	Walk	35
32	12	Walk	35
33	17	Walk	35
34	23	Walk	35
35	25	Walk	35
36	28	Walk	35
37	4	Transit	35
38	7	Transit	35
51	2	Walk	33
52	3	Walk	33
53	13	Walk	33
54	15	Walk	33
55	16	Walk	33
56	20	Walk	33
57	22	Walk	33
58	26	Walk	33
59	2	Bicycle	33
60	3	Bicycle	33
61	13	Bicycle	33
62	15	Bicycle	33
63	16	Bicycle	33
64	20	Bicycle	33
65	22	Bicycle	33
66	26	Bicycle	33
67	2	Transit	33
68	3	Transit	33
69	13	Transit	33
70	15	Transit	33
71	16	Transit	33
72	20	Transit	33
73	22	Transit	33
74	26	Transit	33
75	18	Bicycle	32
76	6	Bicycle	31
77	12	Bicycle	31
78	17	Bicycle	31
79	28	Bicycle	31
80	4	Bicycle	30
81	23	Bicycle	30
82	7	Bicycle	29
83	9	Bicycle	29
84	14	Bicycle	29
85	19	Bicycle	29
86	25	Bicycle	29
87	27	Bicycle	28
88	29	Bicycle	28
101	24	Walk	0
102	21	Bicycle	0
103	24	Bicycle	0
104	1	Car	0
105	2	Car	0
106	3	Car	0
107	4	Car	0
108	5	Car	0
109	6	Car	0
110	7	Car	0
111	8	Car	0
112	9	Car	0
113	10	Car	0
114	11	Car	0
115	12	Car	0
116	13	Car	0
117	14	Car	0
118	15	Car	0
119	16	Car	0
120	17	Car	0
121	18	Car	0
122	19	Car	0
123	20	Car	0
124	21	Car	0
125	22	Car	0
126	23	Car	0
127	24	Car	0
128	25	Car	0
129	26	Car	0
130	27	Car	0
131	28	Car	0
132	29	Car	0
133	30	Car	0
134	31	Car	0
135	32	Car	0
136	33	Car	0
137	34	Car	0
138	35	Car	0

Ranked	Zone	Mode	AFI Contribution (%)
39	9	Transit	35
40	14	Transit	35
41	19	Transit	35
42	23	Transit	35
43	25	Transit	35
44	29	Transit	35
45	18	Walk	34
46	6	Transit	34
47	12	Transit	34
48	17	Transit	34
49	18	Transit	34
50	28	Transit	34

Ranked	Zone	Mode	AFI Contribution (%)
89	31	Bicycle	28
90	34	Bicycle	28
91	1	Bicycle	27
92	30	Bicycle	27
93	32	Bicycle	27
94	5	Bicycle	26
95	8	Bicycle	26
96	10	Bicycle	26
97	33	Bicycle	25
98	11	Bicycle	24
99	35	Bicycle	22
100	21	Walk	0

Ranked	Zone	Mode	AFI Contribution (%)
139	21	Transit	0
140	24	Transit	0

ANNEXURE E – Nairobi Results

ANNEXURE E1

Table 23: Potential mobility and potential accessibility indices per zone, per mode for the 15min travel time threshold (Nairobi)

Zone No.	Zone Name	Walk				Bicycle				Car				Transit			
		PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)	PMI (km/hr)	Inverse Ai (1000s)	Exponential Ai (1000s)	Cumulative Ai (1000s)
2	Embakasi	2.5	18	412	412	4.1	440	331	385	34.7	560	372	412	5.1	28	412	412
4	Kasarani	2.5	20	328	328	3.9	32	328	328	33.7	154	373	385	5.6	32	328	328
11	Westlands	2.8	29	138	138	4.0	39	138	138	29.0	203	230	341	5.7	53	139	138
7	Makadara	2.6	31	83	83	3.8	44	83	83	24.3	206	178	279	5.7	53	83	83
9	Njiru	2.7	23	256	256	4.8	39	256	256	27.9	142	283	256	6.0	36	256	256
8	Mathare	2.6	31	85	85	4.0	44	85	85	25.3	194	159	219	4.9	50	85	85
3	Kamukunji	2.7	35	97	96	3.9	47	97	96	23.1	193	168	212	7.3	73	98	96
10	Starehe	2.7	37	79	78	3.8	125	64	73	23.1	275	143	197	7.4	76	81	78
1	Dagoretti	2.8	17	183	183	4.9	27	183	183	29.6	120	191	183	5.4	28	183	183
6	Lang'ata	2.7	17	83	83	3.9	24	83	83	27.7	117	88	83	5.4	27	83	83
5	Kibra	2.7	26	69	69	4.0	36	69	69	23.0	146	87	69	5.4	43	69	69

ANNEXURE E2

Nairobi Results: Potential mobility and potential accessibility quadrant analysis for the 30 & 15min travel time threshold using the inverse and exponential power accessibility measure to assess employment during peak hour in Nairobi.

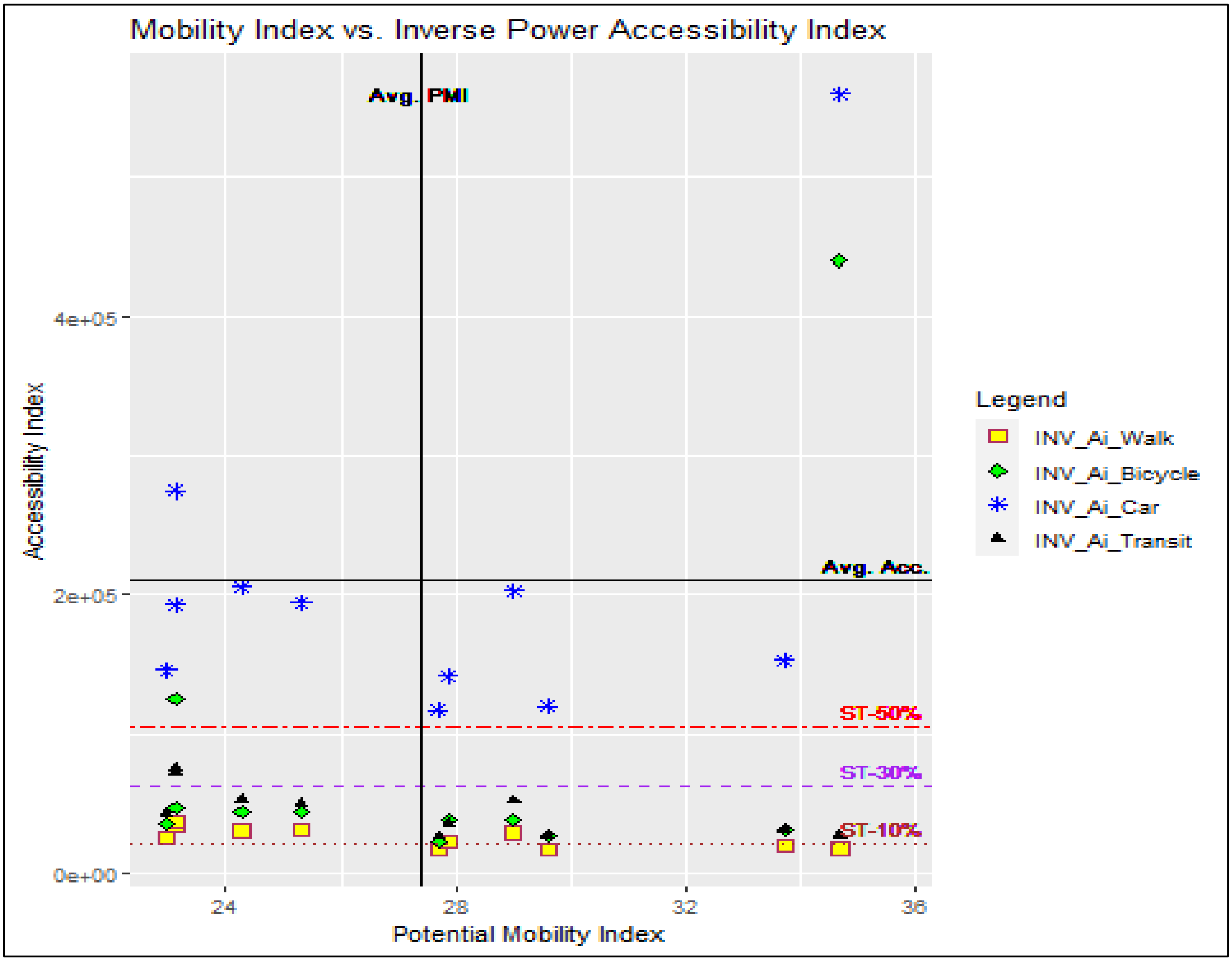

Figure 43: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) - Inverse power accessibility

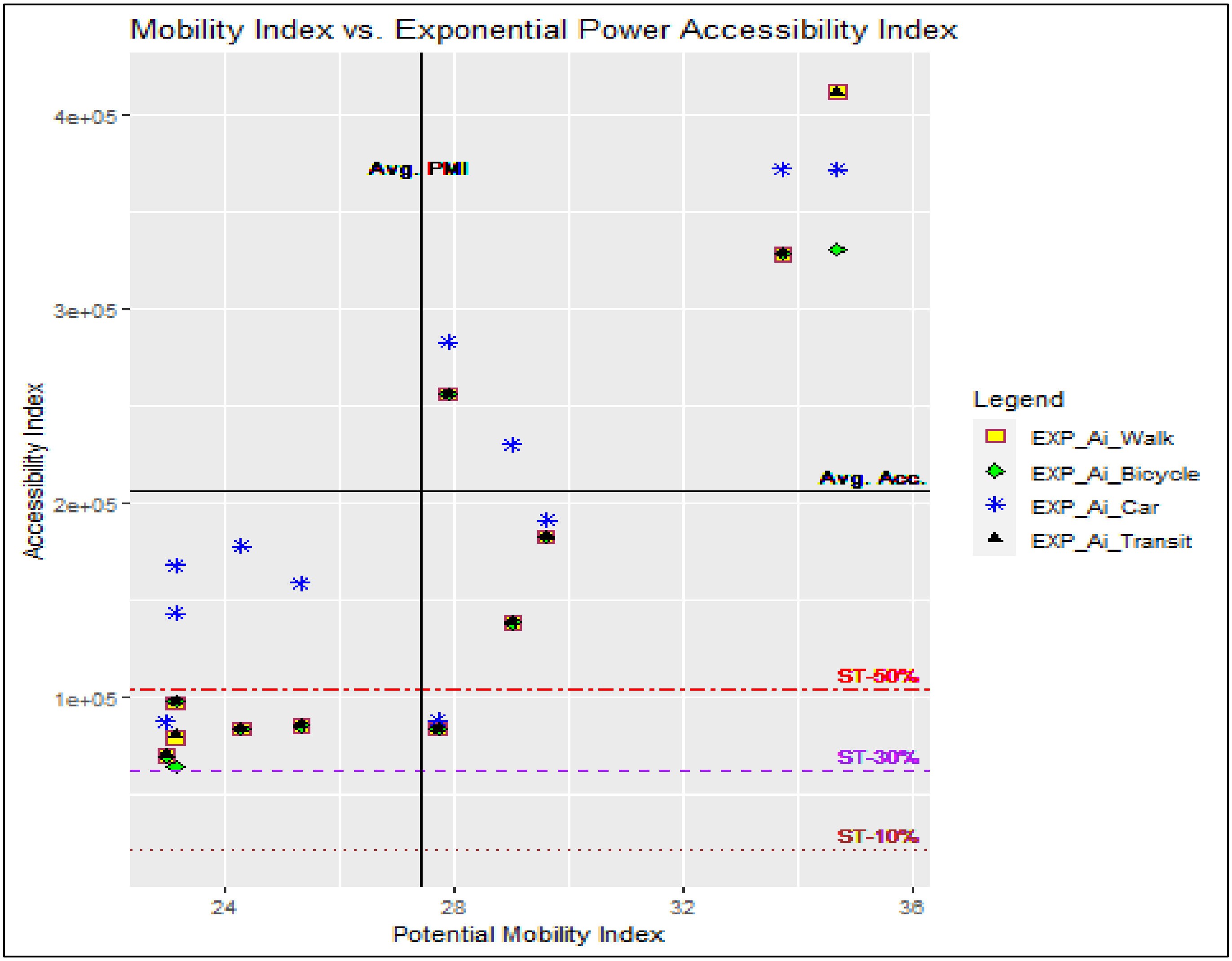

Figure 44: Representation of PMI vs. A (for 30 min & 30% sufficiency thresholds) – exponential power accessibility

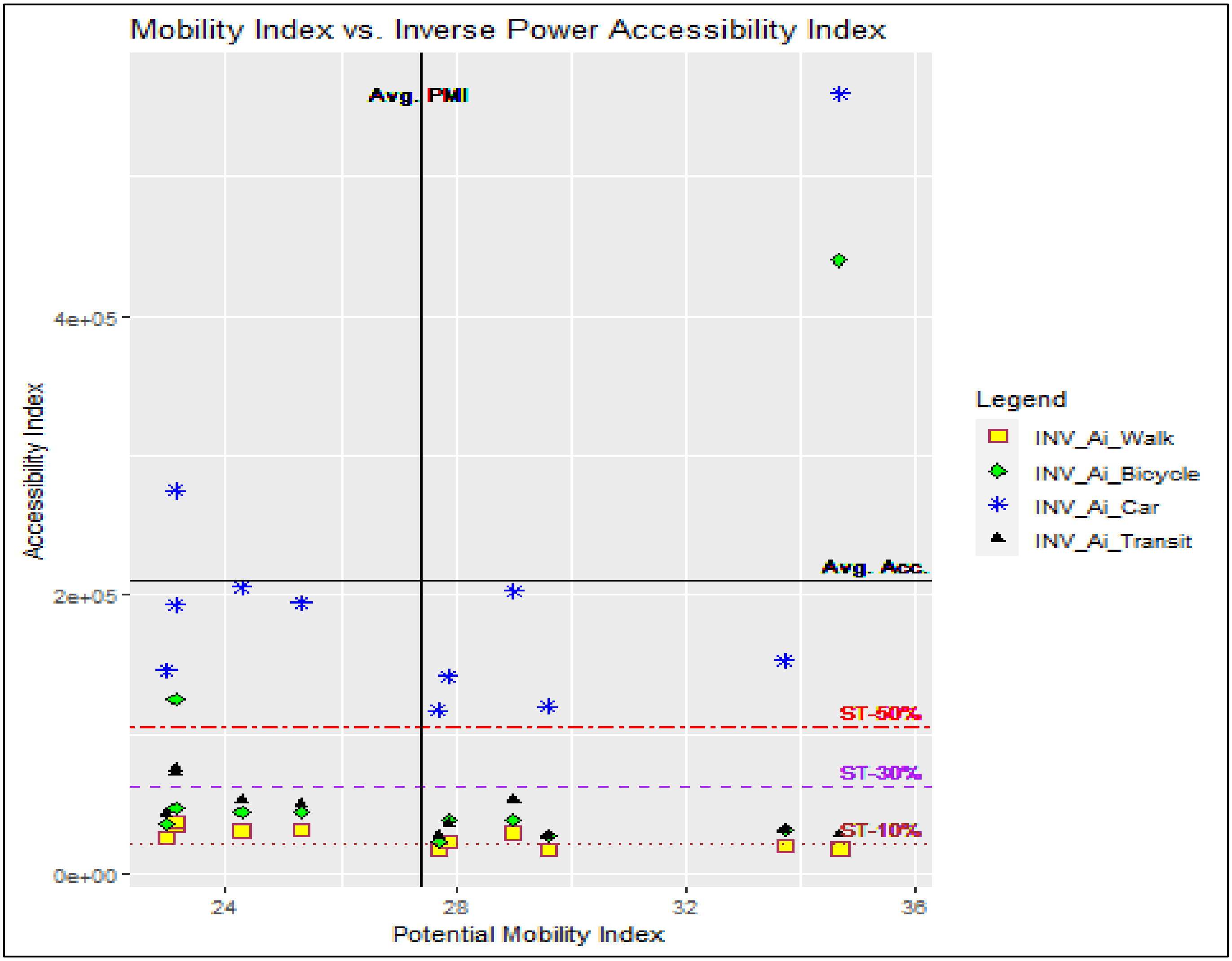

Figure 45: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) - Inverse power accessibility

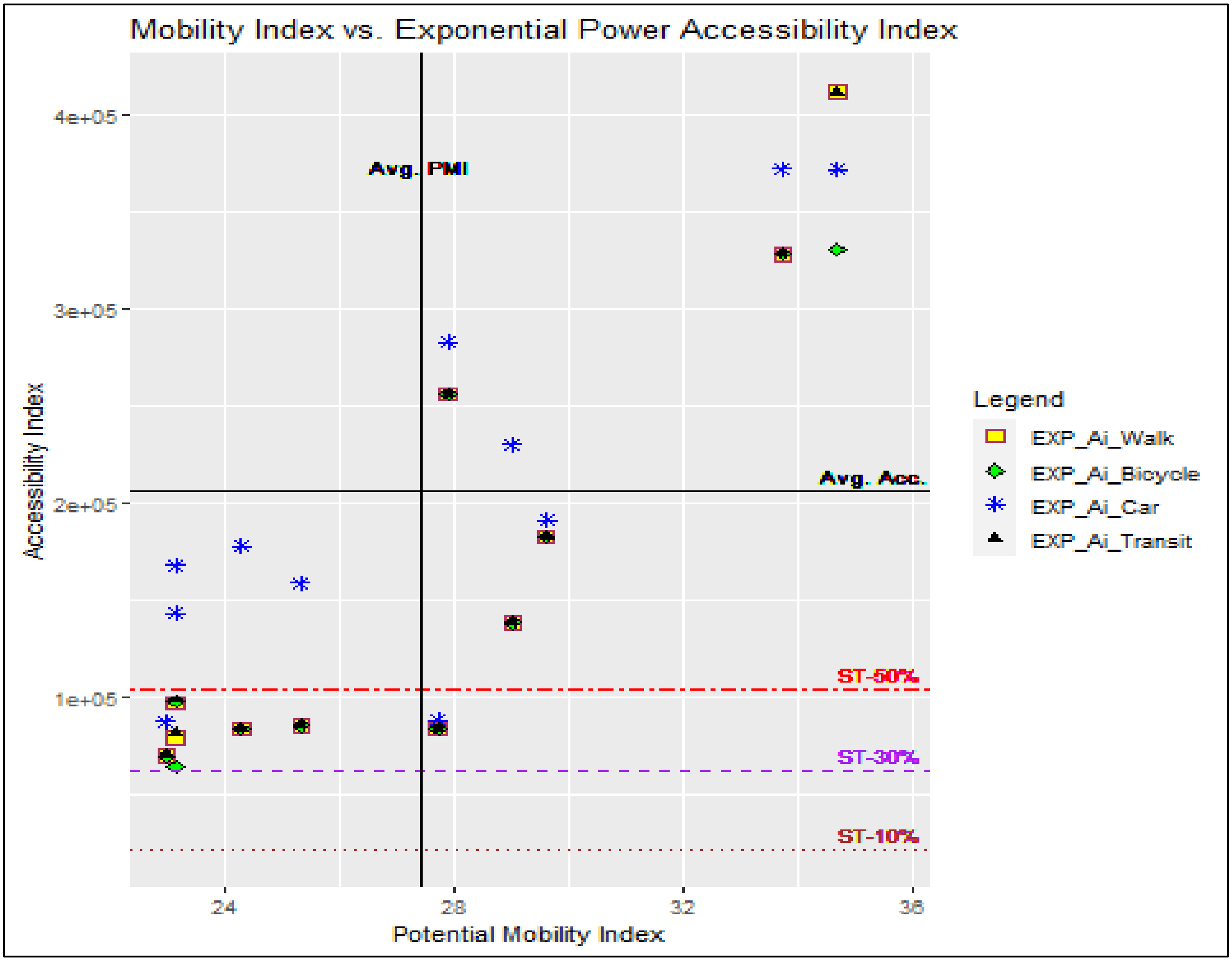

Figure 46: Representation of PMI vs. A (for 15 min & 30% sufficiency thresholds) – exponential power accessibility

ANNEXURE E3

Table 24: AFI Analysis - Top ranked zones per mode needing improvement (Nairobi)

Ranked	Zone	Mode	AFI Contribution (%)	Ranked	Zone	Mode	AFI Contribution (%)	Ranked	Zone	Mode	AFI Contribution (%)
1	Embakasi	Walk	62	16	Makadara	Bicycle	31	31	Westlands	Transit	17
2	Njiru	Walk	55	17	Mathare	Bicycle	31	32	Starehe	Transit	16
3	Starehe	Walk	55	18	Lang'ata	Transit	30	33	Dagoretti	Car	0
4	Kamukunji	Walk	50	19	Kamukunji	Bicycle	29	34	Embakasi	Car	0
5	Westlands	Walk	50	20	Starehe	Bicycle	29	35	Kamukunji	Car	0
6	Kasarani	Walk	48	21	Dagoretti	Bicycle	28	36	Kasarani	Car	0
7	Dagoretti	Walk	44	22	Kibra	Transit	28	37	Kibra	Car	0
8	Makadara	Walk	42	23	Mathare	Transit	28	38	Lang'ata	Car	0
9	Mathare	Walk	42	24	Dagoretti	Transit	27	39	Makadara	Car	0
10	Kibra	Walk	40	25	Makadara	Transit	27	40	Mathare	Car	0
11	Embakasi	Transit	38	26	Kasarani	Bicycle	26	41	Njiru	Car	0
12	Lang'ata	Walk	38	27	Kasarani	Transit	26	42	Starehe	Car	0
13	Westlands	Bicycle	33	28	Njiru	Transit	26	43	Westlands	Car	0
14	Kibra	Bicycle	32	29	Kamukunji	Transit	21	44	Embakasi	Bicycle	0
15	Lang'ata	Bicycle	32	30	Njiru	Bicycle	20				