Modelling paratransit in low data environments in Africa

Part II

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VREF
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Project partners:

Preface

This report is the final result of a cooperation between researchers from Rwanda, Malawi, South-Africa and Israel, funded by the Volvo Research and Educational Foundations' Mobility and Access in African Cities (MAC) Program, under project number EP-2022-MAC-07, Theme 6: Analytical Tools. Following up from an earlier VREF sponsored research project EP-2020-MAC-04, the research presented here developed an open-source toolbox (in *R*) that allows modelling and mapping transport justice indicators using an appropriate representation of paratransit operations in terms of frequencies, stop locations and route deviations. The toolbox is case tested using empirical data from Kigali, Rwanda and Blantyre, Malawi, which is representative for other cities in Sub-Sahara Africa.

Summary

MAC EXPLORATORY PROJECTS 2022- FINAL REPORT

FOR PROJECTS SUPPORTED BY THE VOLVO RESEARCH AND EDUCATIONAL FOUNDATIONS

PROJECT NUMBER (*given by the VREF*)	EP-2022-MAC-07
PROJECT TITLE	**MODELLING PARATRANSIT IN LOW DATA ENVIRONMENTS IN AFRICA**
NAME OF THE HOST INSTITUTION	**UNIVERSITY OF CAPE TOWN**
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START OF PROJECT: *(YYYY-MM-DD)*	*2023-01-01*
END OF PROJECT: *(YYYY-MM-DD)*	*2024-08-30*
TOTAL PROJECT TIME:	*20 months*
TOTAL GRANT AWARDED IN SEK	*SEK500,000*

SIGNATURE, PROJECT LEADER

RONDEBOSCH, 29/11/2024	*PROF MHP ZUIDGEEST*

PART A:

OVERVIEW OF PROJECT IMPLEMENTATION AND KEY FINDINGS (max 2 pages)

Introduction

Paratransit is a dominant mode of transport in Sub-Saharan Africa. The majority of commuters depend on paratransit services due to their convenience in comparison to walking or cycling and their affordability compared to private vehicles or (motorbike) taxis. Without an accurate description of paratransit in the analytical tools available to researchers in Sub-Saharan Africa (SSA), the urban poor's misrepresentation and exclusion in transport forecasting and analysis will only worsen.

In this work, we present a systematized inclusion and representation of the paratransit mode in the transport justice analysis and facilitate their incorporation in other planning contexts. As such this report presents an alternative, low-cost method for modelling paratransit systems and their associated data collection methods. The method is added and implemented in the toolkit for transport planning based on principles of justice, as developed in the previous VREF project (EP-2020-MAC-04) by the same core team members.

The specific objective of this project was to develop a transit feed specification for paratransit operations, thereby facilitating the representation of informal public transport modes in systematic planning methods. The second objective was to update existing transport justice models for Blantyre, Malawi and Kigali, Rwanda by including paratransit data introducing and case-testing what we will call a Paratransit Transit Service Feed (PTFS). The case studies highlight the application of PTFS in transport modelling in the context of informality and demonstrate how they can be used for transport justice analysis.

Summary of work

A three-step methodology was adopted in the work:

Develop the PTFS

A static General Transit Feed Specification (GTFS) feed is first created and subsequently converted to the GTFS-Flex, which mimics the operation of minibus taxi operations through the addition of continuous stopping capabilities that allow operators to stop not only at designated stops (if available) but also allows flexibility of stopping at other points along the corridor, which is a major characteristic of paratransit operations. This implies that a pickup or drop-off of passengers at any point on the corridor is possible, including between designated stops. The PTFS feed requires agency details, stops, routes, calendars, and trips, which are used to create the static feed. Once created, the continuous stopping capabilities are introduced to extend the static feed, allowing for a representation of paratransit-like services.

Update the r5r model

An initial transport justice model was developed for Kigali and Blantyre using a combination of the Geographic Information System (GIS) and the r5r. The methods used were heuristic, not fully automated and limited by the unavailability of public transport service data in Blantyre and relatively limited operational data for Kigali. This project updates these methods as richer PTFS data have been developed for both cities, and new functionality was added; hence, applying r5r to both cities becomes feasible.

Project activities

- Literature review – a review of relevant peer-reviewed and more tool-oriented literature was performed
- Data collection – data was collected in two African cities

- Transport justice modelling – the previously developed model (EP-2020-MAC-04) has been extended with the new data
- Reporting – a main report was written and drafting of a peer reviewed publication started

Project work experiences

- A key experience of the project activity was the realization that the informal nature of public transport in Kigali is significantly different (and less informal) than in Blantyre, which reconfirmed our interest in the need to better understand the stochastic nature of paratransit systems across Africa and particularly their differences.

Key research findings

- **Results – Kigali**

The average potential accessibility by car across the 35 Traffic Analysis Zones is about 110,000 jobs, representing about 50% of the total jobs (estimated as 212,000) in the study area. Compared to NMT, the average number of jobs 'potentially' reachable by walking is only about 8,400, while for cycling, it is about 41,600. From a transport justice perspective, this implies that households with access to a car are almost thirteen times better off than households with no car regarding potential opportunities within reach.

- **Results – Blantyre**

The average number of jobs 'potentially' reachable by car from all the zones is just over 117,000 jobs. This represents about 70% of the total jobs (280,000) in the study area. Compared to NMT, the average number of jobs 'potentially' reachable by walking is only about 21,000 jobs, while for cycling, it is about 113,000. This implies that households with access to a car are almost ten times better off than households with no car regarding potential opportunities within reach.

Deliverables from the project

1. Nnene, O., Zuidgeest, M. Mughogho, B., Nkurunziza, A., Imuentinyan, A., Martens, K., Behrens, R. (2025). Modelling Transport Justice in Africa. In: Badami, M., Mahendra, M., Venter, C. (2025). Advances in methods and metrics for transport equity analysis, Routledge [*under review*]
2. We are planning to publish a journal article on follow-up work we are now doing actually measuring the stochastic behaviour of paratransit operations in Blantyre, Kigali and Johannesburg, and will also include the findings of the project on which this is built.

Identified research gaps, suggestions for further work

The main gaps identified and addressed in this project are:

- The exclusion of public transport as a mode in the prior transport justice analysis developed in EP-2020-MAC-04
- The other gap was the lack of a formal representation of paratransit in transport justice analysis.

Two research projects are particularly envisaged for future work. The first one proposes to look into the actual stochastic nature of paratransit operations, work all partners have agreed to contribute on. The second research project looks further into the modelling of transport justice indicators in r5r and seeks to find a better representation of the potential mobility indicator, which in our current modelling is mode-specific, whereas we would like it to be area (TAZ)-specific.

PART B:

REFLECTIONS ON PROJECT WORK (max 2 pages)

In what areas was the project able to achieve its goals, and in what areas were there revisions or deviations in relation to the original project plan for the work?

The KPIs set in the project proposals were met as follows:

- Completing a literature review
- Developing a data collection for PTFS
- Developing PTFS, enabling the systematic inclusion of public transit modes in transport justice modelling
- Updating the existing transport justice model
- Exploring future work focused on improving the PTFS through the stochastic analysis of operational data from paratransit services, work the partners have started now.

What were the difficulties or challenges in carrying out the project (if any), and how were these dealt with? What are the lessons learned in relation to carrying out comparative work in SSA?

The major challenges encountered in this work revolve around the limited nature of public transport and other import data required for the study in both case study cities and the cost of acquiring the data at scale. These are similar to the challenges faced in the transport environment of many sub-Saharan African cities. These issues, however, limit the level of analysis and outcome of the transport justice transport planning approach in both cities.

- Public transport operations in Kigali and Blantyre are largely informal, with little or no available data about their schedules and operations. The inability to represent informal public transport, which accounts for the larger share of the public transport sector within the transport justice analysis framework, is considered a key limitation of the work.
- Furthermore, there is a lack of detailed socioeconomic data in both cities, which limits the level of analysis that can be done.
- Lastly, the aggregated opportunities data used in the analysis limits the assessment of transport justice to a zonal level.
- Operationally, there were also delays in collecting the data, particularly in Kigali. This, unfortunately, led to some delays in the project timelines.

These challenges were addressed by carrying out a limited data collection exercise to collect the minimum required data required to develop the PTFS on a limited number of routes. A more extensive data collection would enable the development of a more detailed PTFS covering the entire network in Kigali and Blantyre. The outcome will hopefully be more detailed and representative results.

What are some of the "success factors" of the project, i.e., factors that were key to being able to carry out the project?

- A great team. All partners have worked together before, and brought different expertise to the project.
- The main success factor of the project is successfully developing an approach for transport planning based on the principles of transport justice.
- The method incorporates the key modes of travel (motorized and non-motorized) that are used in sub-Saharan African cities and towns.
- Potentially, the approach can be replicated in more African cities with similar characteristics to those of the case study cities, including
- High dependency on paratransit and other forms of informal transit

• Data scarcity, especially in terms of the operational data for paratransit
In what ways has the project contributed to ongoing knowledge in the field and/or to the testing of new research approaches? • Establishing and testing transport justice theory in Africa • Providing an evidence-base of transport justice in Africa • Developing appropriate tools for transport justice in Africa
What are possible contributions of the project to education or supervisory work, and to the development of new research networks? • The project partners have established partnerships that will last beyond the project. Technion and the University of Rwanda have established other collaborations similar to Technion and the University of Cape Town. The Malawian partner is also a PhD student at the University of Cape Town.
What activities have you carried out by way of communicating the project findings with representatives of policy and practice, and how do you envisage they will be able to make use of the findings? • Not yet, work in progress.

PART C:

FINANCIAL REPORT (max 1 page)					
Total Project Cost	SEK500,000				
Distribution of project costs	**University of Cape Town**	**University of Rwanda**	**University of the Witwatersrand**	**MUBAS**	**Technion Israel**
Distribution of total project costs between the project partners	53%	10%	8%	10%	12%
Staff costs	SEK229,310	SEK51,975	SEK42,275	SEK51,975	SEK57,650
Other project costs					
University overheads	SEK33,407				

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1. Introduction

Two significant challenges stand out when planning transport systems with methods such as the conventional four-step model. First, the modelling tools developed are skewed towards automobiles and other motorised forms of transport; as such, road congestion is judged as the main transport problem to address. Consequently, investments to ease congestion often dominate the policy discourse and other implemented interventions. This approach fosters high levels of transport-related social exclusion, especially in Africa, where most of the population live in environments with very poor mobility and accessibility, thereby depending on active modes of transport like walking, cycling and informal public transportation to access their socioeconomic activities (Behrens et al. 2016). The informal public transportation modes typically come in the form of small busses operated by informal businesses, colloquially known as paratransit.

Second, most African cities exhibit data scarcity, high variability in commuter travel needs and behaviour, and the nature of transport services is primarily unscheduled and unreliable. This informality makes it challenging to plan these services methodically with the many proprietary transport planning models that are deterministic by nature. Instead, the described context lends itself to solutions that are more adaptable to uncertainty and data scarcity. Some transport planners and authorities respond to this problem by using costly GPS surveys to capture a representative sample of travel behaviour that is then hardcoded into the models, basically losing the variability observed earlier.

Paratransit is a dominant mode of transport in Sub-Saharan Africa. The majority of commuters depend on paratransit services due to their convenience in comparison to walking or cycling and their affordability compared to private vehicles or (motorbike) taxis. Without an accurate description of paratransit in the analytical tools available to researchers in Sub-Saharan Africa (SSA), the urban poor's misrepresentation and exclusion in transport forecasting and analysis will only worsen. To counter this, researchers have attempted to represent informal public transport modes in various ways, including by measuring actual movements of paratransit vehicles through GPS surveys (see the seminal work of Williams et al. 2015) in various African cities and the analysis thereof, for example for Cape Town's minibus taxis in Du Preez et al. (2019) or Kenya's Digital matatus project discussed in Klopp and Cavoli (2019). Other attempts at modelling paratransit services can be found in Nnene et al. (2023) and Ukam et al. (2024).

In this work, we present a systematized inclusion and representation of the paratransit mode in the transport justice analysis and facilitate their incorporation in other planning contexts. As such this report presents an alternative, low-cost method for modelling paratransit systems and their associated data collection methods. The method is added and implemented in the toolkit for transport planning based on principles of justice, as developed in the previous VREF project (EP-2020-MAC-04) by the same core team members. By doing this, a major gap that was identified in the previous project, i.e. the exclusion of public transport as a mode in that piece of analysis due to the inability to adequately represent paratransit in the *r5r* tool is now corrected. The improved and expanded analytical tool presented here can assist in planning for mobility and accessibility that reduce transport-related social exclusion by enhancing accessibility for low-income groups, which is of the utmost importance in countries with high spatial and social inequality levels. As such it will allow for a more effective way of planning for mobility and accessibility in African cities.

The specific objective of this project was to develop a transit feed specification for paratransit operations, thereby facilitating the representation of informal public transport modes in systematic planning methods. The second objective was to update existing transport justice models for Blantyre, Malawi and Kigali, Rwanda by including paratransit data introducing and case-testing what we will call a Paratransit Transit Service Feed (PTFS). The case studies highlight the application of PTFS in transport modelling in the context of informality and demonstrate how they can be used for transport justice analysis.

[WORK PACKAGE 1] – LITERATURE REVIEW

2. Social justice, transport and exclusion

Many works in the literature discuss what is considered a fair allocation of transportation goods and services. While fairness is sometimes seen as a personal, i.e. as a subjective matter, quite some progress has been made in systematically exploring what is and what is not just, mostly outside the domain of transport, but over the last two decades also increasingly within the domain of transport. The contemplation of social issues and their linkage to transport began in the 1950s. However, only by the mid-1990s did the evidence of the relationship between social justice and transport become apparent, leading to an increased interest in the discipline (Beyazit 2011). Issues such as disability, poor accessibility, and other socioeconomic issues drew the attention of various researchers such as Banister et al. (1994); Church et al. (2000); Bullard and Johnson (2000); Sánchez et al. (2003). Also, indicators like income got included by Cervero and Landis (1997); Leck et al. (2008); and Beyazit (2011), whilst Putnam (2000) looked at social involvement in transport. In addition, Lucas et al. (2001); and Lucas et al. (2016) discuss social justice and transport in the context of travel poverty. Other researchers also draw cross-cutting themes of transport infrastructure provision, social equality, and civil rights, including Bullard and Johnson (1997), who highlight that transport decision-making on investments and financial resources related to transport often advantages some communities whilst disadvantaging others.

A lack of participation in society is commonly highlighted in most definitions of social exclusion in the literature. 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). This thought can be extended to a transportation context, with the design and implementation of transportation infrastructure and the organisation of transport services hugely impacting social exclusion in communities. Transport policies also influence the societal and spatial structure of cities; if used effectively, they can guide transport intervention planning and investments positively and equitably. According to Litman (2014), policies are deemed fair when they benefit disadvantaged individuals regarding mobility, social inclusion, and the economy. Miller (2001) also argues that policies and investments are unjust if they do not include marginalised communities. Consequently, they carry more burdens and are less advantaged than other groups.

To conclude, land use planning also contributes to accessibility and social exclusion. In this context, the lack of access to opportunities is caused by spatial separation, which creates social exclusion (Preston & Rajé, 2007). For multiple reasons cities tend to develop outwards towards the periphery of city boundaries, leading to a pattern of urban sprawl. People living in these areas often have poor access to opportunities either due to the lack of cars, the lack of public transit services, or high transit fares, in combination with the long distances to activity locations which makes non-motorized transport not a viable option (Vasconcellos 2001). Therefore, social exclusion is perpetuated by a lack of transportation and the interaction of various factors. At the same time, transportation alone can't unravel exclusion issues; however, adequate transportation is an essential prerequisite to enable 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). In this regard, this work advocates a move away from traditional transport planning and modelling to incorporate accessibility sufficiency and other factors. As a key part of this shift, it proposes a better representation of actual mobility through the PTFS, which improves the robustness and inclusiveness of the transport planning process, thereby increasing the societal impacts of planned interventions.

2.1 Transport justice

Transport justice promotes a departure from transport planning focused on mobility, understood as the ease of movement, to a focus on accessibility, understood as the ease with which people can reach a broad range of activities dispersed over space. While the call to move from mobility to accessibility is at least three decades old, this shift is particularly essential from the perspective of transport justice.[1] In the context of justice, accessibility does not merely represent the essential "service" people receive from the transport system, as argued by many proponents of accessibility.[2] Instead, it captures the even more fundamental notions of choice and freedom. Accessibility, considered as the range of activities and destinations people can reach within a reasonable budget of time, costs and efforts, represents the choices available to persons. The higher people's accessibility level, the more destinations are available, the larger their freedom to choose from multiple options, and hence, the broader the possibilities to execute their agency and give direction to their lives. Accessibility can thus be seen rather as a technical measure of freedom, with freedom having a positive rather than a negative connotation, i.e. defined as "freedom to" rather than "freedom from".[3]

2.2 The transport justice quadrant

A vital feature of the proposed justice approach to the transport, presented in Martens (2017), is a quadrant system summarizing population groups' current, modelled levels of so-called potential mobility and accessibility juxtaposed on a set of axes (see Figure 1). Both axes represent a low to high-level continuum and create a coordinate system where population groups can be positioned. The axes intersect in the middle, at the points of mean potential mobility and mean accessibility. This simple

[1] See, for instance, Cervero, R. (1997) Paradigm shift: from automobility to accessibility planning. *Urban Futures*, 22, p. 9-20.

[2] See, for instance, Levine, J., J. Grengs, and L.A. Merlin (2019) *From mobility to accessibility: transforming urban and transportation planning*. Cornell University Press, Ithaca and London.

[3] Berlin, I. (1969, original 1958) Two Concepts of Liberty. In: I. Berlin (1968) *Four Essays on Liberty*, pages 118-172.

coordinate system enables the placement of population groups (depicted as dots in the diagram) on both axes based on measuring a group's potential mobility and accessibility. It also enables the introduction of a sufficiency threshold of accessibility (the dashed lines), which is positioned below the origin of the coordinate system. When a population's potential mobility and accessibility levels fall in the coordinate system's quadrant one (bottom-left) below the sufficiency threshold, the group experiences insufficient accessibility caused in large part by a low level of potential mobility. These groups are thus entitled to accessibility improvements first, because an insufficient supply of transportation services and infrastructure causes its accessibility shortfalls. Groups that fall in the second quadrant experience a low level of potential mobility but still enjoy a sufficient level of accessibility. The groups in the third quadrant experience a high level of potential mobility as well as sufficient accessibility, while those that fall in the fourth quadrant experience insufficient accessibility in spite of enjoying a high level of potential mobility. The accessibility of these latter groups can only be improved through the addition of destinations within reasonable travel time, cost and effort.

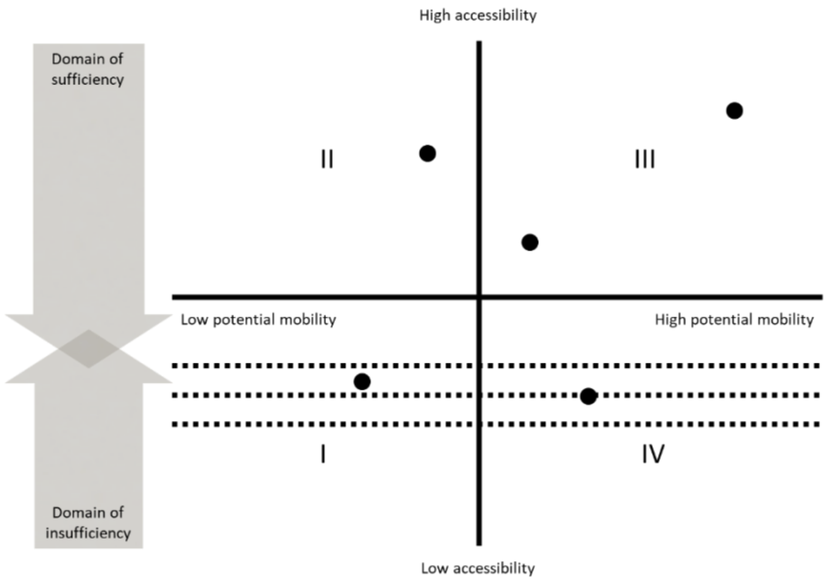


Figure 1: The transport justice quadrant (Martens, 2017)

Potential mobility is depicted on the horizontal axis (and could be normalised) and captures the extent to which the transport system enables people to move around. The vertical axis depicts the accessibility, using an indicator that measures the opportunities a population group can reach within a reasonable time and budget, considering the city's spatial structure, its transport network, the location of each population group and the mobility options at their disposal. Lastly, the accessibility-sufficiency threshold is a minimum level of accessibility required, as represented for three levels 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 the 'domain of insufficiency', interventions are required that aim to uplift these population groups to above the sufficiency threshold. Such measures include higher fare subsidies, new public transport routes, bicycle lanes and land use developments.

2.3 General transit feed specification – GTFS

The General Transit Feed Specification (GTFS) is a standard data format that reports transit service information globally. It comprises a series of text files (in *.txt* format) that model the given transit information. The feed can be in either static or real-time form. The static version only comprises pre-inserted transit data. The real-time GTFS feed allows operators to provide real-time updates regarding their operations, such as delays, route changes, cancellations, live congestion levels, etc. Six mandatory text files are required to successfully generate a valid GTFS feed: 1) agency, 2) stop times, 3) routes, 4) calendar dates, 5) trips and 6) stop locations (Williams et al., 2015).

The first static GTFS feed was developed in 2005 by the IT Manager at TriMet (a public agency that operates mass transit in Portland, USA) to make it easier for commuters to plan their public transport trips as it was to get driving directions (which required the use of a private car) (TransLoc, 2021). This became a collaboration between TriMet and Google Inc. and was initially named the Google Transit Feed Specification. Since its inception, over 400 GTFS feeds have been published worldwide (Koetsier et al., 2017).

GTFS feeds can be used for trip planning, ridesharing, timetable creation, and other crucial analyses. They can be easily deployed into transportation applications built to offer these services (Klopp et al., 2015; Koetsier et al., 2017). Therefore, the availability of GTFS often facilitates improving public transport services planning and commuter mobility by allowing users to compare the available services effectively. However, a significant shortcoming of existing GTFS feeds is that they are mainly applicable to formal public transport services such as scheduled bus and train services; this is seen in the frequent availability of the timetables, route maps and fares for these modes as displayed on the transport provider's websites or applications developed for the commuters (Zhang et al., 2015). The unavailability of GTFS for paratransit services, which as indicated before, dominate public transport services in Sub-Saharan Africa (SSA), hence undercuts the ability to organize and plan the services better. Recent attempts have been made to extend the capability of standard GTFS feed to incorporate demand responsiveness, also known as continuous stopping. This feature opens the door to representing paratransit systems in GTFS and lessens the difficulty of navigating through paratransit services by improving the transparency of their data to the community. These extensions incorporate parameters like continuous stops and route deviation. The extended GTFS feed is known as the GTFS-flex feed. An outline of the data components for a typical GTFS feed can be seen in Figure 2. The GTFS-Flex adds additional text files to the original GTFS feed to allow a more flexible transport system, such as paratransit, to reap the benefits a GTFS feed gives a transport system (Craig & Shippy, 2020).

Continuous stopping

Developers at Google introduced the continuous stop extension to account for transit systems that allow users to begin their trips at any point between the typical stop locations (Williams et al., 2015). This extension was added to the stop times and routes (or *trip_id*) tables to specify whether a given route will allow passengers to board and alight at any point on the route (Eros et al., 2014). This is done by assigning non-negative integer values in the final column of the feed. The values in question are a '0 or blank', representing a route that does not allow for pick-ups along the route, or a '1', representing a route that allows continuous stopping behaviour (Williams et al., 2015).

GTFS-Flex

GTFS-Flex is an extension to the current GTFS model that allows for demand-responsive transportation and incorporates route deviation in addition to continuous stops (Craig and Shippy, 2020). Like the extension of the continuous stop, GTFS-Flex is expressed as additional text files and columns within some of the original text files, such as stop times and routes, to account for flexible service in the system. An essential addition to GTFS-Flex incorporates the possibility of route deviation, which was previously unaccounted for even with the continuous stop's extension. This is expressed as a 'buffer zone' around the typical route that accounts for drivers temporarily deviating from their route to pick up or drop off passengers before returning to their original route (Craig and Shippy, 2020). To enable route deviations, users will input their pick-up and drop-off locations, and the respective route planner will assign the user a route that closely matches their pickup and drop-off locations. GTFS-Flex forms the basis for the PTFS that is implemented in the *r5r* code (discussed later).

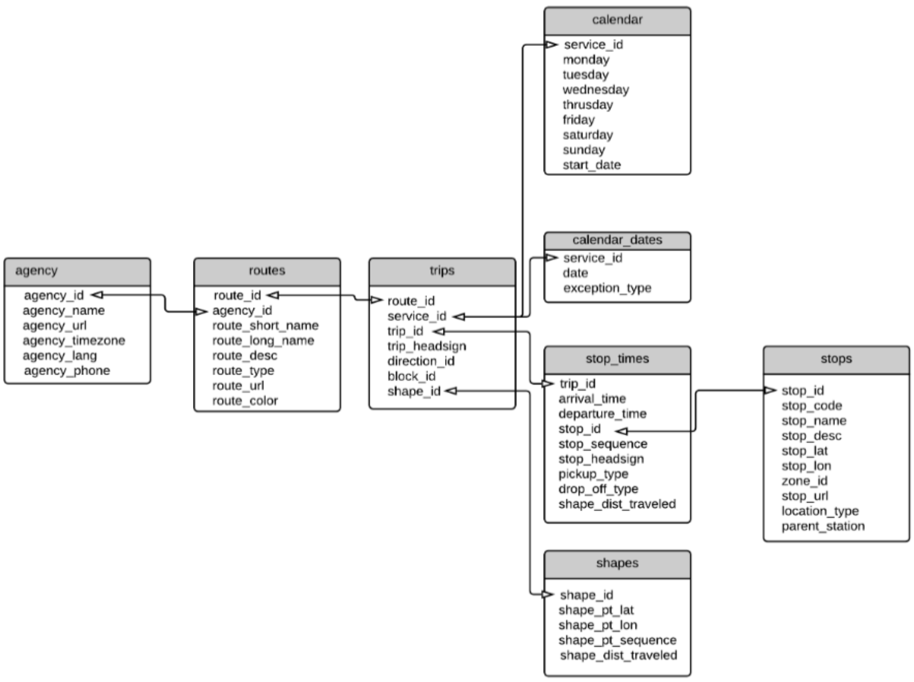


Figure 2: Components of a GTFS feed (Pereira et al., 2023)

[WORK PACKAGE 2] – DATA PROTOCOL

3. Data protocol for the PTFS data collection in Kigali and Blantyre

This section outlines the procedure for collecting, managing, and analyzing data needed to develop a PTFS feed, as case-tested in Kigali and Blantyre. Figure 3 shows the workflow for the data collection process. It starts with identifying the objectives of the data collection exercise and the data requirements to achieve those objectives. The primary data collection objective is to obtain the data required to enable the project team to develop a minimal working version of the network and operational schedules for paratransit services in the case study cities. This will facilitate the development of the PTFS for paratransit services in the stated cities. The required data includes network information like routes, stops, and service operations such as frequencies and headways. After defining the objective, the next step in the data collection process is to recruit and train a team of field data collectors. Next, primary and secondary data are collected from institutional stakeholders and service operators. Subsequently, the collected data is checked for errors and inconsistencies and validated to ensure it is error-free. Once the data checks are completed, the validated but raw data is processed and stored for use in the model development phase.

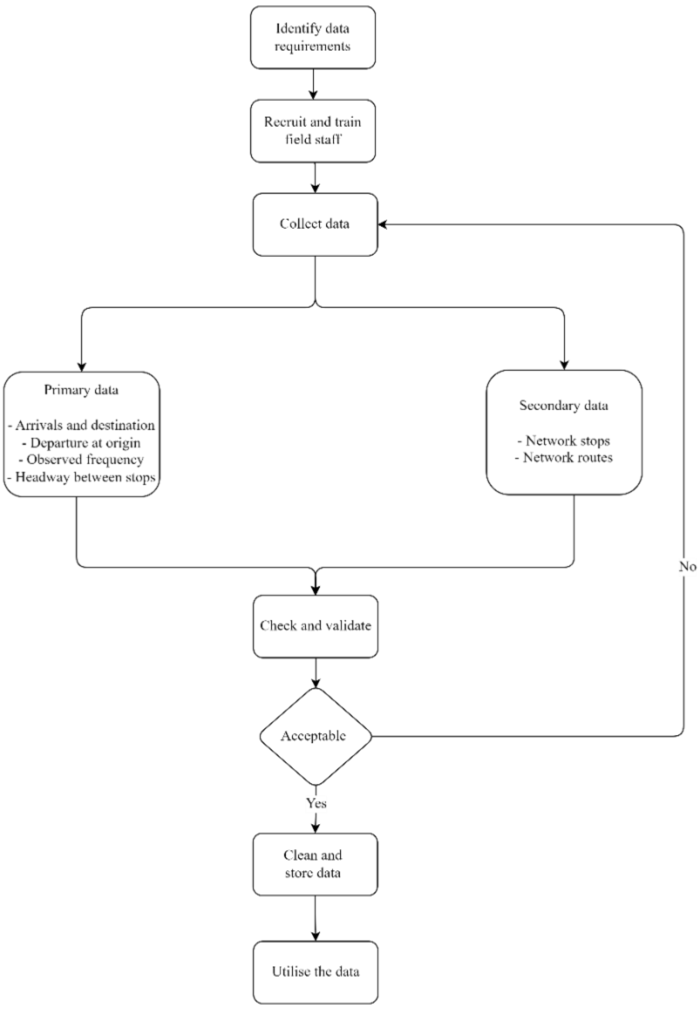


Figure 3: Workflow for the data collection process

3.1 Kigali, Rwanda

In the City of Kigali, data on routes, stops, schedules, service frequency, and geographic coordinates was collected in order to create the PTFS feed. The data collection team comprised 15 student field agents recruited for the ad-hoc data collection exercise. Training for the team was facilitated on the day preceding data collection by the project team member at the University of Rwanda. This session equipped the field agents to understand the study's objectives and the specific protocols for data collection for bus operations. Data collection also involved on-board surveys to determine the bus route travel time during peak and off-peak hours. The student data collectors also observed the buses along the route to get data on their headway. The data collected in Kigali include *a*) departure times from origin stops and terminals, *b*) arrival time at destination stops and terminals, *c*) observed frequency at a given checkpoint on the routes, *d*) stop sequence between origin and destination stops on each route, and *e*) GPS coordinates of the stops along each route.

Network data collection

In total 13 key routes with corresponding bus stops were selected for the data collection exercise. The routes and stops were extracted from the larger City of Kigali network. The extraction was done by the technical team at the City of Kigali's transport department and the University of Rwanda team members**.** It was then adjudged that the chosen routes were representative of travel demand and paratransit service operations in the city as they covered the main corridors and were very accessible. Once the routes were selected, the field agents travelled on the identified routes to validate the routes' stop locations and observe occurrences like deviations from the selected route. This was done by collecting GTFS traces at the stops along each route and comparing them with the existing route information. A key advantage of this process is that it allows the update of route information along the selected corridors, such as deleting redundant stops and updating the data in places where changes have occurred. The final clean and updated data for the 13 bus routes is then converted to a GIS-based network and stored for the Kigali PTFS development process.

Operational data collection

The data for paratransit service operations, such as bus departures at origin and arrivals at destination, as well as on frequencies and headways, was collected on the earlier identified bus routes. Data was collected over two weekdays (29 and 30 April 2024) and one Saturday (11 May 2024). The departures and arrivals were divided into peak and off-peak periods. Each field survey agent was assigned to ride on one bus route. The data collection started at 7:30 am and ended at 9:30 am. At the original terminal, primarily located in the city's peripheral areas, the surveyor records the boarding and departure times and the arrival time of the bus at its destination terminal. This enables the record of the travel time on each route to be kept. The same approach records data for the off-peak, evening peak, and on-the-weekend periods. The evening peak was mainly a return leg of the morning peak hour trips as the origin stops and terminals are the major terminals within the city centre area. At the same time, the destination points were the terminals in the residential areas around the city's periphery. Lastly, 2 field surveyors were assigned to collect data for bus frequency and headway at a checkpoint on each of the 13 designated routes. One surveyor collected data from 6 routes and recorded the number of buses passing the checkpoint over one hour, while the other surveyor collected similar data on each of the remaining routes. The data was collected using hardcopy instruments explicitly created for the data collection exercise. Details of the routes and checkpoints are available in Appendix 1. At the end of the data collection period, all information recorded on site was checked for inconsistencies and errors. They were then carefully entered into a *Microsoft Excel* spreadsheet for subsequent cleaning and analysis before creating the actual PTFS.

3.2 Blantyre, Malawi

In the City of Blantyre, a team of six people collected data, comprising one project team member from the Malawi University of Business and Applied Sciences (MUBAS), who was acting as supervisor, four recruited field agents, and a data expert. Data on arrivals of paratransit minibuses at destinations, departures at origins, and frequency were observed at a given checkpoint along each route. The supervisors trained and familiarized the team with the project's objectives and requirements. A data collection form was designed to facilitate data collection. Data collection commenced on 25 September 2023 with a pilot of the data collection form. The five data collectors proceeded to collect data thereafter. The implementation partner in Blantyre and a GPS and mapping expert from the collected GPS coordinates of the stops along the selected routes between origin and destination. The exercise lasted two days, but additional data was collected when the road network coverage was extended.

Network data collection

GPS coordinates of the stops between origin and destination along six routes were collected. The routes were chosen based on high traffic flows, major residential area dissection, business district connections, and their linkage to peripheral areas of the city. The routes included Blantyre CBD to Limbe CBD, Chilobwe township to Limbe CBD, Chilobwe to Ndirande township, Chilobwe to Blantyre CBD, Blantyre CBD to Ndirande and Kameza to Limbe CBD. The GPS coordinates for stops were collected similarly. Appendix 2 shows instruments used to collect data. After validating the stops and route, the information was cleaned and converted to GIS files for later use and for entering into the PTFS.

Operational data collection

Also, arrivals, departures, and frequency of paratransit services on selected routes was collected. The data collection sheet included the name of the Transport Analysis Zone (TAZ), the origin and destination of the vehicles being recorded, an indication of whether the bus stop was an intermediate stage, the time of recording and the data collection date. Names of the bus stops were also recorded on the data collection sheet. An extract of the data collection sheet can be seen in Appendix 2. Data collected enabled the estimation of frequencies of paratransit services for a given bus stop.

[WORK PACKAGE 3] – DEVELOPMENT OF THE PTFS FEED

4. The PTFS feed

The section describes the development of the PTFS itself as well as the *r5r* tool used to update the earlier-mentioned transport justice toolkit contexts of Kigali and Blantyre. In the first sub-section, a static GTFS feed is created and subsequently converted to the GTFS-Flex, which mimics the operation of minibus taxi operations through the addition of continuous stopping capabilities that allow operators to stop not only at designated stops (if available) but also allows flexibility of stopping at other points along the corridor, which is a major characteristic of paratransit operations. This implies that a pickup or drop-off of passengers at any point on the corridor is possible, including between designated stops. This is one of the primary observed operating attributes of paratransit services in sub-Saharan Africa.

4.1 The PTFS feed development

The schematic diagram in Figure 4 shows mandatory and optional components of the GTFS feed and how they interact. In this work, the mandatory files are created with a tool known as the *Static GTFS Manager*, developed by the World Resources Institute (WRI) for creating GTFS. It is a web-based interface program linked to a database, which facilitates the creation and storage of GTFS with relative ease. The tool was initially developed as a collaboration between the WRI and the Kochi Metro Rail Limited (KMRL) in India. Over time, the source code has been open-sourced, leading to its further development with community inputs and extending its capability to create GTFS feeds for other transit agencies. Developing the PTFS feed starts with defining the general information needed to create a conventional or static GTFS feed. Information such as agency details stops, routes, calendars, trips, and stops are used to create the static feed. Once created, the continuous stopping capabilities are introduced to extend the static feed allowing for a representation of paratransit-like services.

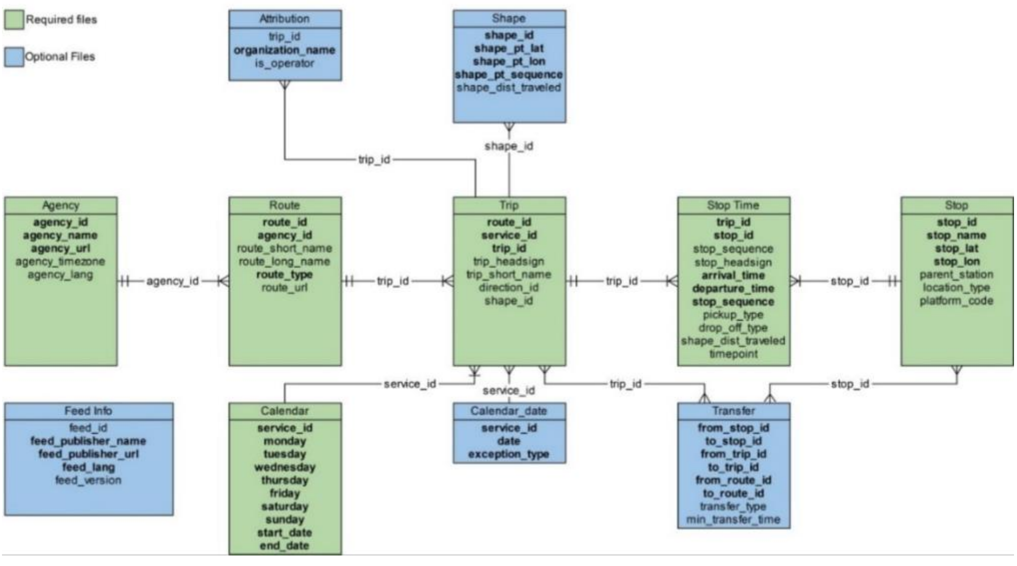


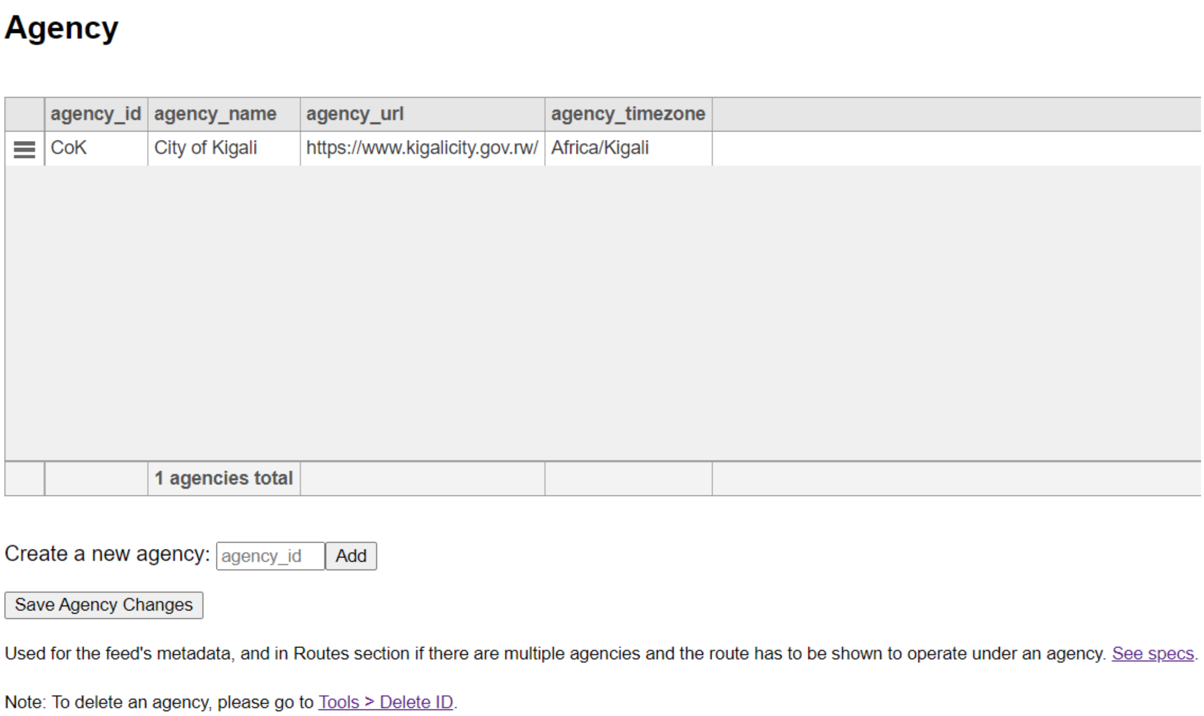
Figure 4: Static GTFS feed showing required and option files[4]

[4] https://www.trafiklab.se/docs/using-trafiklab-data/using-gtfs-files/static-gtfs-files/

Agency

The first data input for the PTFS is the name of the Agency or authority whose operational data are represented in the GTFS feed. For Kigali, the City of Kigali (CoK) is the authority for bus services, while the Minibus Owners' Association of Malawi was defined for Blantyre. The general information for the feed is also provided with the *Feed_info* interface. This has compulsory fields like *feed_publisher_name*, *feed_url*, and *feed_lang* that are also case-sensitive, while other fields like the *field_start_date* and *field_end_date* are not required but equally crucial. The *Agency* name and *Feed_info* interface are shown below in Figures 5 and 6, while the interface comprises the following fields:

- *Agency_id*: this is a conditionally required field. It identifies the transit brand, like the name of the area whose transit data will be represented. This is required when an agency or area has multiple transit services, i.e., formal and informal transit data.
- *Agency_name*: this is a required field where the name of the area of focus is stated.
- *Agency_url*: this is a required field where a URL is stated for the agency, i.e., a URL that directs the platform to a page showing information about the area of focus. Therefore, any URL of choice showing information about the agency is acceptable.
- *Agency_timezone*: this field is required. It states the continent and country, separated by a forward slash.



Agency

	agency_id	agency_name	agency_url	agency_timezone
	CoK	City of Kigali	https://www.kigalicity.gov.rw/	Africa/Kigali
		1 agencies total		

Create a new agency: agency_id Add

Save Agency Changes

Used for the feed's metadata, and in Routes section if there are multiple agencies and the route has to be shown to operate under an agency. See specs.

Note: To delete an agency, please go to Tools > Delete ID.

Figure 5: Agency feed interface for the PTFS (showing Kigali data)

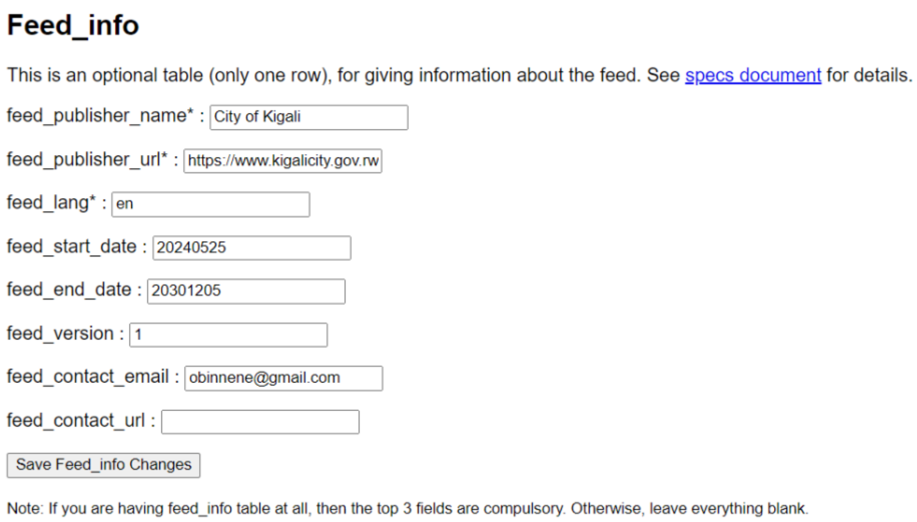


Figure 6: Feed_info interface for the PTFS (showing Kigali data)

Stops

The interface for the stop data allows the geographical mapping of service stop locations. The interface enables the addition, editing and viewing of stops by clicking on the area on the map. The stop data may be entered by clicking individual stop locations on the map and providing stop information as shown on the left of the interface presented in Figure 7. A second alternative enables the upload of stop information from comma-separated values (CSV) files that contain stop attributes like unique identifiers, stop names and geographical information – *stop_id, stop_name, stop_lon, stop_lat*. Subsequently, other information about the stops is updated. This approach was used in this project, as it is more efficient when dealing with many stops and multiple service routes. Map engines for *OpenStreetMaps*, *Google Maps* and others are built into the tool, offering users a suitable choice of maps. We chose to use *OpenStreetMap* in this work. The following fields are required for creating stops:

- *Stop_id*: This is a required field with a unique naming system for the stops, typically supplied by the transport authority.
- *Stop_name*: This is a conditionally required field where the stop's name is stated. The transport authority also supplies this information according to its naming convention.
- *Wheelchair boarding*: This optional field indicates whether the stop or station is accessible to wheelchair users.
- *Location*: This is a required field that indicates the latitude and longitude coordinates of the stop. It is automatically filled in once a stop is clicked on the map; however, it can be edited.
- *Zone_id*: This field is automatically filled after the *stop_id* field. However, it is a conditionally required field only when information about fares is added. Thus, it is used

for the fare rules section. This information is omitted in this work due to the unavailability of fare information.

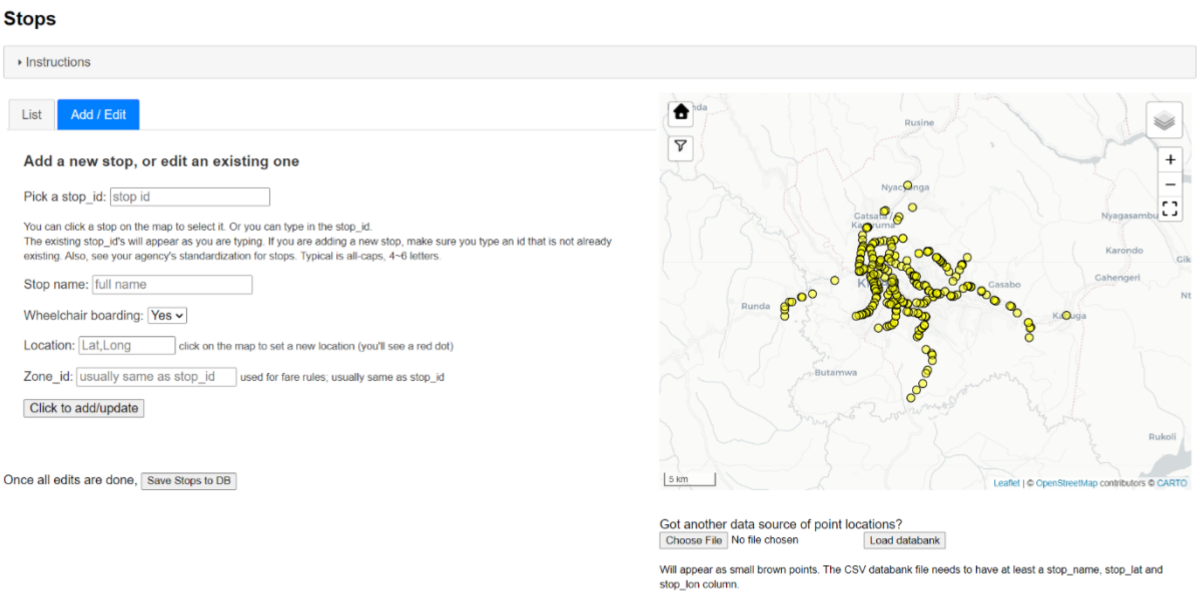


Figure 7: The stop creation interface for the PTFS (showing Kigali data)

Routes

This function enables the addition of route information to the GTFS feed. The attributes of the routes of service are first defined using variables like the *route_short_name, route_type, route_id* and *agency_id*, which respectively define a shortened name for the route, the route type in terms of the mode transport, a unique identifier for the route and the unique identifier for the agency. Once the routes have been completed, the next step is to provide the sequence of stops on the routes. This is defined using the 'default route sequence' tab, which allows users to add, rename and edit information relating to the routes for the given service regarding both the forward and backward journeys. The route creation interface is depicted in Figure 8.

Listing all the routes. You can click on any of the cells for editing.

	N...	route_id	route_short_name	route_long_name	route_type	route_color	route_text_color	agency_id
		filter by id	filter by name	filter by name				
	1	CoK013	Nyanza - Gahanga	Nyanza - Gahanga	3-Bus			CoK
	2	CoK012	Nyamirambo - Ryanyuma	Nyamirambo - Ryanyuma	3-Bus			CoK
	3	CoK011	Nyabugogo - Kagugu	Nyabugogo - ULK - Kagugu	3-Bus			CoK
	4	CoK010	Nyabugogo - Bishenyi	Nyabugogo - Ruyenzi - Bishenyi	3-Bus			CoK
	5	CoK009	Nyabugogo - Kimironko	Nyabugogo - Kibagabaga - Kimironko	3-Bus			CoK
	6	CoK008	Nyabugogo - Gasanze	Nyabugogo - Kagugu - Gasanze	3-Bus			CoK
	7	CoK007	Kabuga - Nyabugogo	Kabuga - Rwandex - Nyabugogo	3-Bus			CoK
	8	CoK006	Kimironko - Masiza	RFTC_Kimironko - Masiza	3-Bus			CoK
	9	CoK005	CBD - Nyacyonga	CBD - Nyabugogo - Nyacyonga	3-Bus			CoK
	10	CoK004	CBD - Bwerankori	CBD - Gikondo - Kigarama - Bwerankori	3-Bus			CoK
	11	CoK003	CBD - Nyanza	CBD - Gatenga - Kcenter - Nyanza	3-Bus			CoK
	12	CoK002	Remera - Masaka	Remera - Masaka	3-Bus			CoK
	13	CoK001	Remera - Nyabugogo	Remera - Kacyiru - Nyabugogo	3-Bus			CoK
				13 routes total				

Add a new route: CoK: City of Kigali Add

The system will auto-generate a new route_id.

Save Routes to DB

Be sure to save changes before proceeding to next tabs.

Figure 8: The route creation interface for the PTFS (showing Kigali data)

Calendars

The operational dates and duration for the paratransit feed are defined with the *Calendar* interface. Identifiers for the services are also set under a *service_id* field, where the service type in terms of days (weekday and weekend) of operation is defined. The operations are coded as 0 or 1, where 0 indicates that the service will not operate while 1 indicates that the service is operational. The duration of the validity of the feed is also defined using the *start_date* and *end_date* fields, respectively. An optional *Calendar_dates* field is defined to allow users to enter and alter specific dates and service exemptions like public holidays. The *Calendar* and *Calendar_dates* fields are shown in Figure 9 and Figure 10. This information is used to identify operational and nonoperational trips on different days in the 'trips, *stops_time*' tab, which is discussed next.

Calendar

Instructions

The service_id is referred to when defining trips. Typically there are different schedules followed on working days and holidays.

The service_id's get used in TRIPS table to define which days of the week a trip operates on. This allows for different timings on weekends.

Use the Tools > Delete ID section to delete a calendar service. Note that because the service_id field is required in trips table, deleting a calendar service will need cascading deleting of all trips and timings data associated with it. It would be a better option to change the service_id instead.

If you have made any additions or changes that you wish to revert and you haven't pressed the big "Save" button below, you may simply reload this page, and all changes will be dropped. Conversely, make sure to Save to preserve any changes you make.

	service_id	monday	tuesday	wednesday	thursday	friday	saturday	sunday	start_date	end_date
	filter by id								yyyymmdd	yyyymmdd
	weekend	0	0	0	0	0	1	1	20230710	20260710
	weekday	1	1	1	1	1	1	1	20230710	20260710
	2 services total									

Figure 9: The route creation interface for the PTFS

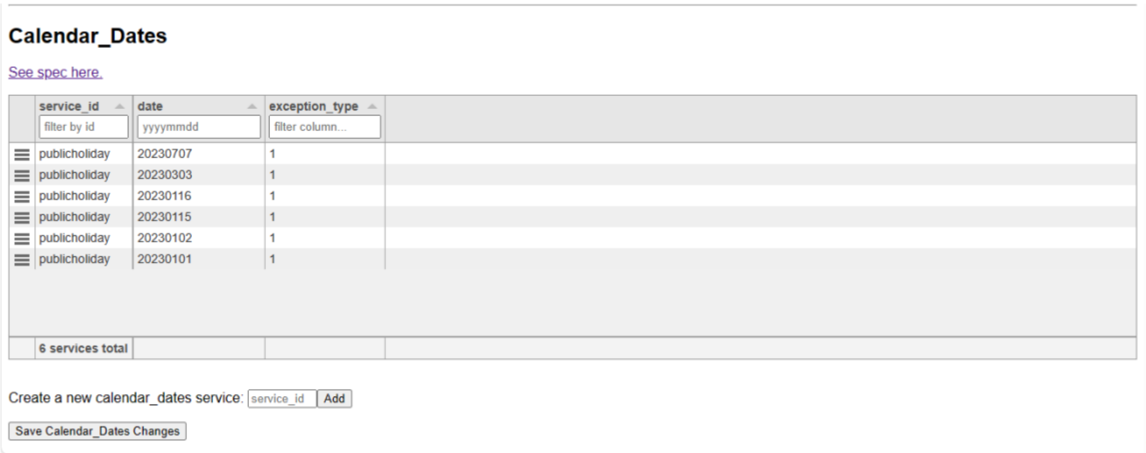


Figure 10: The route creation interface for the PTFS

Trips and timings

This function has two tabs: one named *trips*, which allows the user to enter trip details, and the other named *stop_times*, which enables the user to enter time-related information for each trip. The *trip and trip timings* interface is shown in Figure 11, while that for *stop_times* can be seen in Figure 12. The tab also provides flexibility by requiring only the departure and arrival times for the first and last stops in cases where detailed between-stop departures and arrival information is unavailable. This approach is used in this work due to the unavailability of data for the time between stops. The fields for the *trips* tab are as follows:

- *trip_id, stop_sequence* and *stop_id*: These are auto-generated fields taken from previous fields as discussed above.
- *shape_dist_traveled*: This field indicates the trip's distance from one stop to the next. In this case, it is not a required section because no shape file was inserted in the ‘default routes sequence’ tab. However, this is an optional field when generating a GTFS feed.
- *Timepoint*: This field indicates whether the arrival and departure times are strictly adhered to or approximated. A 0-value means approximated, and 1 means strictly adhered to. This is also an optional field.

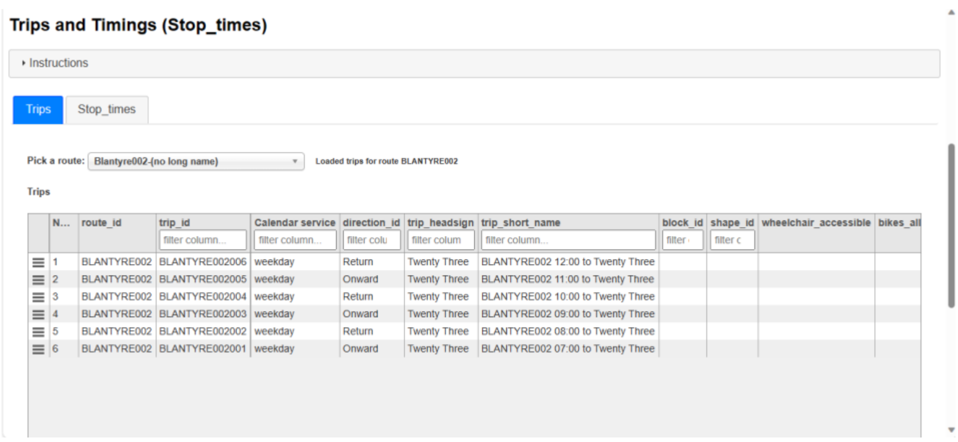


Figure 11: The Trip and Timings interface for the PTFS (showing Blantyre data)

The fields for the trip *stops_times* tab is listed below:

- *Route_id*: This field remains constant as named in the '*routes'* tab.
- *Trip_id*: This is an auto-generated field by the browser once the trip is created.
- *Calendar service*: This field can be edited and only has options in the '*calendar'* tab. In this case, it is either the weekend or weekday option. This is a required field to complete the '*trips'* section successfully.
- *Direction_id*: This is a required field indicating whether the trip is onward or a return trip, as explained in the '*routes'* section above.
- *Trip_headsign*: This field is auto-generated depending on the stops allocated for the route. The *trip_headsign* for every trip is stated as the journey's first stop. However, this is an optional field.
- *Trip_short_name*: This is also an auto-generated field indicating the *agency_id* and time of departure from the first stop. The public can use this to identify the trip. However, it is not a required field; it is optional.

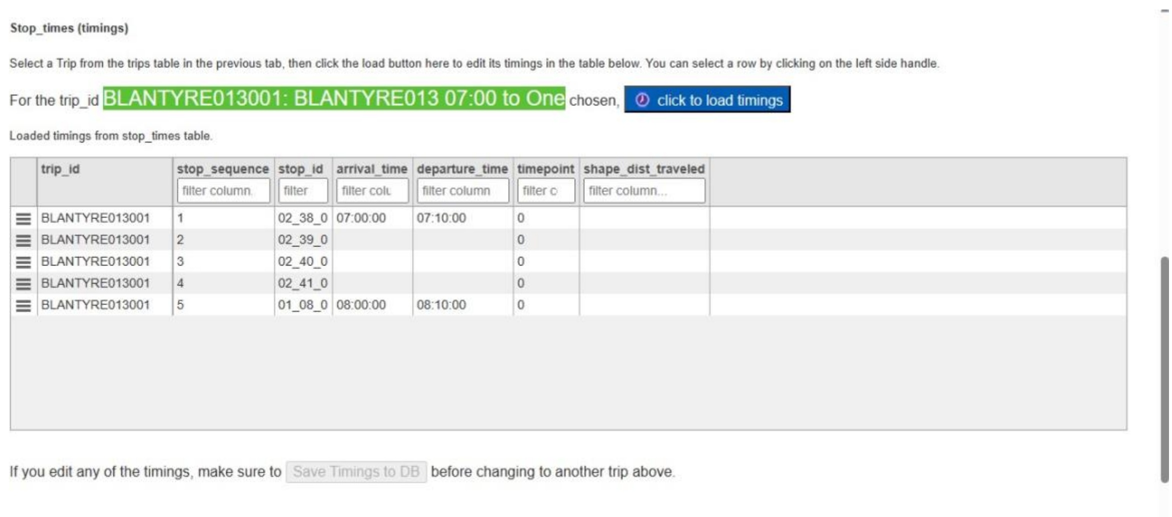


Figure 12: The stop_times interface for the PTFS (showing Blantyre data)

Feed validation

After creating the PTFS, it is validated to ensure it is error-free. A cross-platform, web-based GTFS schedule validator was used for the validation. The paratransit feed is loaded as a zip file compared to the standard GTFS feed format. After the integrity check, errors and warning messages are returned if they exist. The messages helped correct issues associated with the data types and information used to develop the GTFS feed, which are common, so also in our study. Typical examples of errors and warnings we encountered are shown in Figure 13, while Figure 14 shows the validation report after all errors and warnings had been corrected.

GTFS Schedule Validation Report

102 notices reported (1 errors, 101 warnings, 0 infos)

This validation report was generated using the Canonical GTFS Schedule validator.

Use this report alongside the rules page to get more details about the validation issues.

Notice Code	Severity	Total
+ mixed_case_recommended_field	WARNING	85
+ unexpected_enum_value	WARNING	16
+ invalid_color	ERROR	1

Figure 13: The validation report before with the error and warning messages

GTFS Schedule Validation Report

0 notices reported (0 errors, 0 warnings, 0 infos)

This validation report was generated using the Canonical GTFS Schedule validator.

Use this report alongside the rules page to get more details about the validation issues.

Notice Code	Severity	Total

Settings and version

Validator version: 4.1.0

Validation date and time: 2023-10-28 at 17:35:48 SAST

Parameters used (more about the available parameters in USAGE.md):

Figure 14: The validation report after the errors are resolved

Continuous stopping

After successfully creating the static GTFS feed for Blantyre and Kigali, the feed is edited to incorporate the continuous stops feature, which accounts for the observed behaviour of paratransit, and turns the GTFS into a PTFS. This feature accommodates the on-route demand-responsive trend observed in paratransit operations, where they pick up and drop off passengers at locations between stops. The continuous stopping feature is achieved by adding the *continuous_drop_off* and *continuous_pickup* columns to the *stops_times* information file. The columns are assigned values of ‘0,0’, which indicate that the trip allows continuous drop-off and pick-up between each allocated stop. Subsequently, the edited GTFS feed is validated again to ensure no errors and warnings are detected. Thus, the paratransit feed is successfully created.

4.2 Rapid realistic routing – *r5r*

The tool used for doing the transport justice assessment for Kigali and Blantyrew is known as *r5r*.[5] This is a package in the freeware R-statistical programming environment developed for routing on multimodal transport networks that include modes like walking, biking, public transport, and private cars. The package allows for the generation of a routable network of a city and a detailed routing analysis or calculation of travel time matrices using seamless parallel computing techniques. *r5r* first

[5] Pereira, R. H. M., Saraiva, M., Herszenhut, D., Braga, C. K. V., & Conway, M. W. (2021). *r5r*: Rapid Realistic Routing on Multimodal Transport Networks with R5 in *R. Findings*, 21262. https://doi.org/10.32866/001c.21262

builds the multimodal transport network used for routing. Travel times are computed between O-D pairs on the network based on available *GTFS* data. Other input variables in the *r5r* tool are the *maximum walking distance* in meters and the *maximum allowed trip duration* for each trip in minutes. The result is that distance and mode-wise travel time matrices are then generated. In the second step of the model, custom scripts are written in *R* to compute different potential mobility and potential accessibility indices for the transport justice analysis. The workflow for *r5r* is shown in Figure 15.

The *r5r* package has three main functions, which are described as follows:

1. setup_r5(): This is used to initialise an instance of *r5r*. It also builds a routable transport network using the OpenStreetMap street network and public transport feeds in *GTFS* format as input.
2. travel_time_matrix(): This function is used to quickly compute travel time estimates between O-D pairs on a network. It receives the integrated road network generated by the setup_r5() function and the zonal centroids data as input.
3. detailed_itineraries(): This function is used to obtain detailed information on one or multiple alternative routes O-D pairs on a network.

The *r5r* package essentially requires only the following input datasets:

1. An Open Street Map network of the study area in .pbf format (mandatory), prepared for Kigali and Blantyre.
2. A paratransit *GTFS* (PTFS) feed in *.zip* format for Kigali and Blantyre.
3. A points of interest file, in *.csv* format, containing the names and spatial coordinates of traffic analysis zones in Kigali and Blantyre.

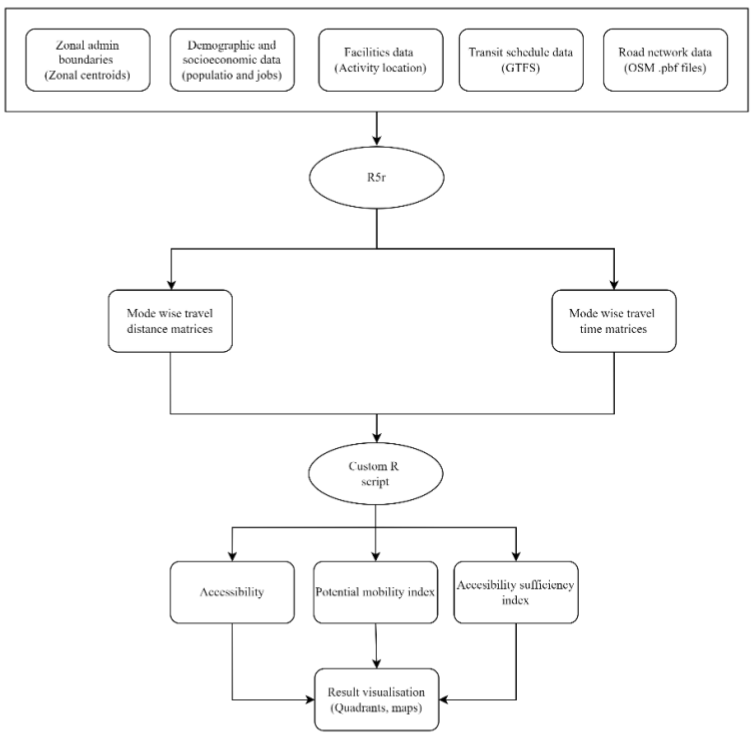


Figure 15: *r5r* workflow

[WORK PACKAGE 4] –TOOLKIT UPDATE

5. Transport justice toolkit update

An initial transport justice model was developed for Kigali and Blantyre using a combination of the Geographic Information System (GIS) and the *r5r*. The methods used were heuristic, not fully automated and limited by the unavailability of public transport service data in Blantyre and relatively limited operational data for Kigali. These methods are updated in this section as richer PTFS data have been developed for both cities and new functionality was added; hence, applying *r5r* to both cities becomes feasible. The two main benefits of the methods discussed in this section are that they can be extended to any location without formally planned transport services, making them relevant in almost all countries in sub-Saharan Africa where paratransit services account for a significant share of the market. Ultimately, the methods discussed here make implementation straightforward for applying justice principles to transport planning and are reproducible.

5.1 Analytical components of transport justice

First, accessibility relates to the potential of opportunities for interaction. This is a function of the spatial distribution of activities *X* across locations j in a region *r*, the generalised costs of travelling by m on the transport system between locations i and j, and the person's ability to overcome the spatial separation between i and j. We assume that the locations i, even though spatial, represent locations where population groups live. As in demand modelling, we are assuming homogeneity at the level of the locations *i*. These locations are typically, but not necessarily, traffic analysis zones (TAZ).

Several types of accessibility indicators have been described in the literature. Three of them were selected for this tool as:

a) they account for the effect of both the transportation network and spatial distribution of opportunities.
b) they do not require the derivation of additional theoretical constructs like a utility function and therefore the operationalization tasks of the study are simplified.
c) they do not merely focus on accessibility to specific facilities such as hospitals or fire stations but are generally applicable.

All three measures have the following general shape:

$$A_{i,m,p,r,s} = \sum_{j \in r}^{J} X_{j,p,s} \times f(t_{ij,m}) \qquad \forall i \in r, m, p, s \tag{1}$$

where:

- i is the origin location (out of *I* possible origin locations in region *r*).
- m is the mode of transport (walking, cycling, car, bus etc.).
- p is the activity type (working, school, leisure etc.).
- s is the socio-economic status of persons in *i*.
- j is the destination location (out of *J* possible destination locations in region *r*).
- $A_{i,m,p,r,s}$ is the zone i accessibility level for people of socio-economic status *s*, travelling by mode m for activities of type p [-].

- $t_{ij,m}$ is the generalized cost of travel (travel time, travel cost etc.) in minutes between zone *i* and *j* on mode *m* [h].
- $X_{j,p,s}$ is the number of opportunities of type *p* in zone *j* for socio-economic status *s*.

The first variant is the inverse power gravity function:

$$A^1_{i,m,p,r,s} = \sum_{j \in r}^{J} X_{j,p,s} \times t_{ij,m}^{-\alpha_{m,p}} \quad \forall i \in r, m, p, s \tag{2}$$

where:

- $\alpha_{m,p}$ is the travel impedance parameter, which is calibrated, and could be a function of mode *m* and activity type *p*

This means that if $\alpha=1$ the size of a possible interaction between locations i and j is inversely proportional to the travel time between them on mode m. I.e., if it takes longer to travel between *i* and *j* the potential for attending $X_{j,p}$ activities reduces.

The second variant to equation 1) is the exponential gravity accessibility measure:

$$A^2_{i,m,p,r,s} = \sum_{j \in r}^{J} X_{j,p,s} \times \exp(-\beta_{m,p} \times t_{ij,m}) \quad \forall i \in r, m, p, s \tag{3}$$

where:

- $\beta_{m,p}$ is the travel impedance parameter, which is calibrated, and could be a function of mode *m* and activity type *p.*

This measure thus discounts travel impedance exponentially and is thus more sensitive to the level of $t_{ij,m}$ than in the inverse model.

Finally, a third variant is the cumulative accessibility measure, also known as the isochrone measure:

$$A^3_{i,m,p,r,s} = \sum_{j \in (r \cap t_{ij,m} \leq \gamma_p)}^{J} X_{j,p,s} \quad \forall i \in r, m, p, s \tag{4}$$

where:

- γ_p is the generalized cost (travel time) threshold for activity type *p* in minutes.

Here, all activities of type *p* reachable under γ_p minutes will be counted (in full). Equation 4) can also be combined with one of the discount measures of equations 2) or 3).

The parameter estimates for $\alpha_{m,p}$, $\beta_{m,p}$ and γ_p can be calibrated as discussed in the next section.

5.2 Impedance Function and Parameter Calibration

A key component of gravity-type accessibility measure is the impedance function that describes the effect of spatial separation between origin and destination based on a defined travel cost attribute (distance, time or generalised cost). The impedance function weights the opportunities at destinations relative to the travel origin based on the travel cost. It must be emphasised that perception and valuation of travel cost, whether in terms of distance, time, or generalised cost, is very subjective and can vary from location to location across activity types and person groups. The impedance function is traditionally referred to as the distance-decay function based on the early models, which considered spatial separation only in terms of distance. Recent studies have also defined spatial separation in terms of travel time and generalised cost of travel.[6] Commonly utilised decay functions are the Exponential, Power, Tanner and Box-Cox functions, with parameters requiring calibration. The calibration is usually based on empirical data, such as trip length distributions for various travel modes and activity types in the location of interest. However, due to the rigours and challenges associated with detailed data collection and function calibration, it is common practice to assume a particular type of function and parameters from existing studies, ideally from locations or regions with similar characteristics to the location of interest.

The impedance function applied for the two case studies is the exponential function as described in the accessibility formulation (Equation 3), with travel cost defined in terms of travel time. The parameter values for travel by car was based on judgement from similar investigation for Cape Town, South Africa. The value defined for car was further adjusted for NMT, to reflect a difference in travel time sensitivity for travel by car and NMT. The exponential-decay curves for the modes are presented below.

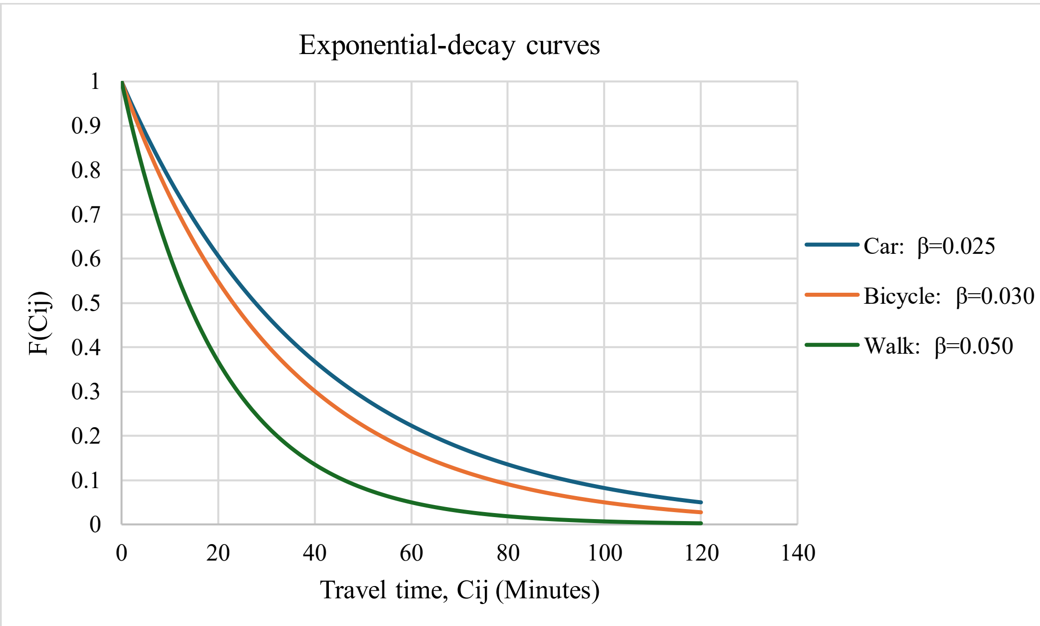


Figure 16: Exponential decay curves for accessibility computation

Next to the series of accessibility measures a potential mobility indicator ($M_{i,m,r,s}$) is used to quantify the contribution of the transport system to the potential mobility of a population group. This is a function of the both the speed of moving in mode *m* as well as the network structure for mode *m*. The potential mobility is defined in Martens (2017) as the quotient of the Euclidean distance and the travel time on the transport network between the origin and destination pair *ij*. The potential mobility indicator can be calculated for each origin *i* (and sub-group *s* and/or mode *m*) by taking the average of the $M_{i,m,r,s}$ values

[6] Typical example is the work of Martinez and Viegas (2013), a new approach to modelling distance-decay functions for accessibility assessment in transport studies.

for all relevant destinations *j* on a network:

$$M_{i,m,r,s} = \frac{1}{J}\sum_{j\in r}^{J}\frac{d_{ij}}{t_{ij,m}} \quad \forall i \in r, m, s \tag{5}$$

where:

- $M_{i,m,r,s}$ is the average aerial speed [km/h] for people of socio-economic status *s* and mode *m* for zone *i* in region *r*.
- d_{ij} is aerial distance [km] between zone *i* and zone *j*.
- $t_{ij,m}$ is travel time [h] on the transport network between zone *i* and zone *j* by mode *m*.
- *J* is the number of zones in region *r*.

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

Finally, sufficient accessibility is defined as the level below which a person belonging to a population group cannot sufficiently engage in out-of-home activities (of type *p* in region *r*). Defining this level is an exercise itself. In Martens (2017), this level is defined as a function of the average car-based accessibility (in region *r*), or:

$$T^{M}_{\sigma,p,r,s} = \sigma \times \frac{1}{J}\sum_{j\in r}^{J} A_{j,M,p,r,s} \quad \forall p, \sigma, r, s \tag{6}$$

where:

- $T^{M}_{\sigma,p,r,s}$ is the accessibility sufficiency threshold at level σ [%] for people of socioeconomic status *s*, activity type *p* in region *r* relative to reference mode *M* (typically the car).

The domain of insufficiency can now be identified as made up by those location, mode, and activity type combinations *i,m,p,s* in region *r* for whom:

$$A^{\text{insufficient}}_{i*,m*,p*,r,s} \leq T^{M}_{\sigma,p,r,s} \quad \forall i, m, p, r, s \tag{7}$$

where:

- $A^{\text{insufficient}}_{i*,m*,p*,r}$ are the locations for which the modal accessibility is below $T^{M}_{\sigma,p,r,s}$ in region *r*.

The domain of sufficiency is then obviously the reverse of this.

5.3 Analytical results

This section presents the updated transport justice analysis for Kigali and Blantyre. We are presenting the results with cut–off values of respectively 15, 30, 45 and 60 minutes of travel time.

Transport justice quadrants for Kigali

First, we present the results for Kigali with Figure 17, where each scatter point represents the potential mobility and cumulative accessibility index of a zone for the four modes considered separately.

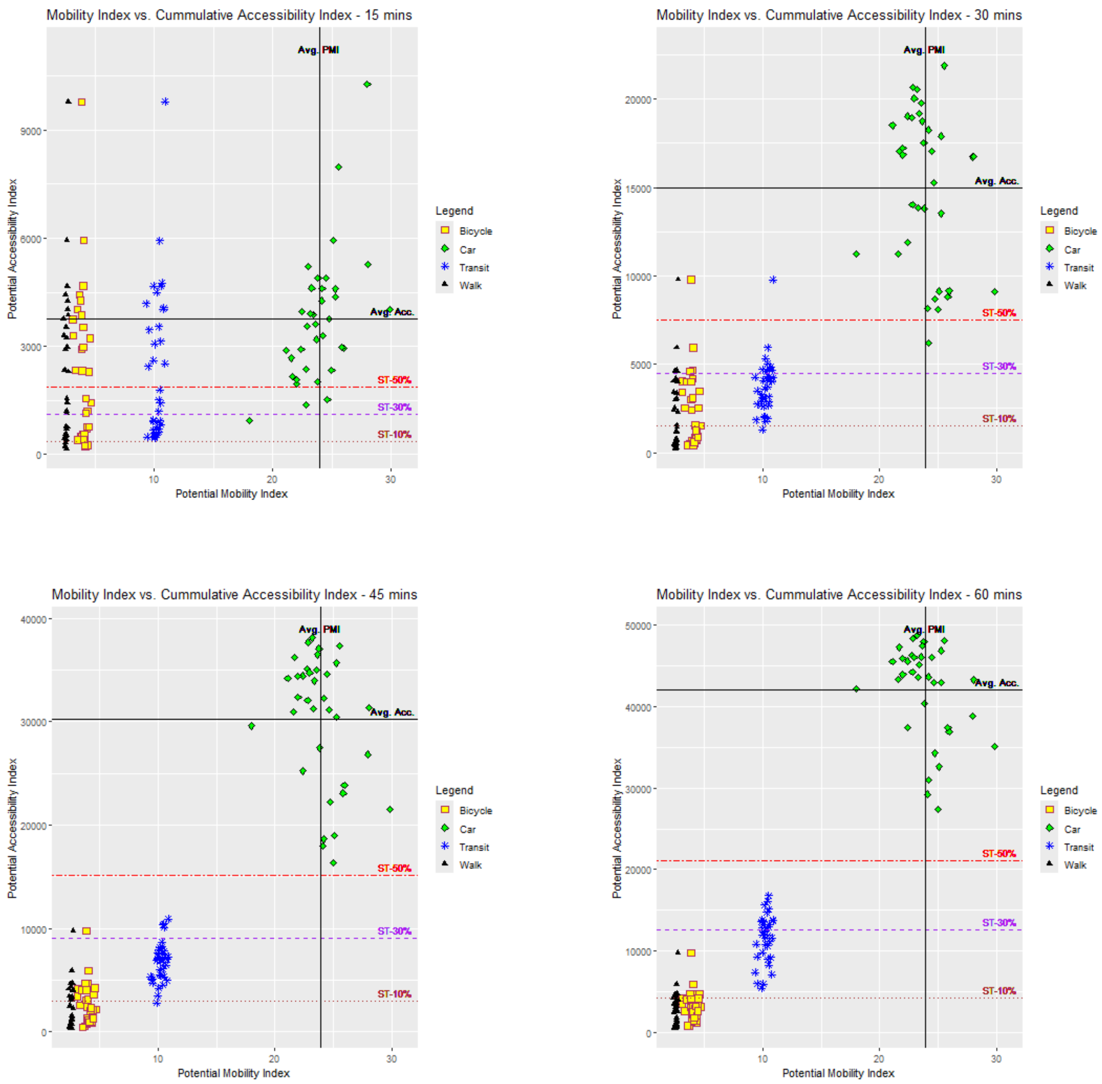


Figure 17: Accessibility and corresponding potential mobility for travel by car, paratransit, walking and cycling for different travel time thresholds in Kigali

The figure further reveals the disparity that exists between the opportunities ‘potentially’ accessible by car and those accessible by paratransit or NMT. The average potential accessibility by car across the 35 Traffic Analysis Zones is about 110,000 jobs, representing about 50% of the total jobs (estimated as 212,000) in the study area. In comparison to NMT, the average number of jobs ‘potentially’ reachable by walking is only about 8,400 jobs, while for cycling, it is about 41,600 jobs. From a transport justice perspective, this implies that households with access to car are almost thirteen times better off than households with no car, in terms of potential opportunities within reach.

The sufficiency thresholds further reveal the level of disparity in accessibility level. Sufficiency thresholds are measured as a percentage of the average potential accessibility by car. In other words, the threshold of accessibility by car is used to benchmark NMT accessibility. The two thresholds implemented in the analysis are σ =50%, σ=30% and σ=10% sufficiency thresholds. It can be seen from the plot that accessibility by walking and cycling shows similar trends, decreasing as the travel time increases; hence, between 45 minutes and 60 minutes, accessibility by walking and bicycles decreases below the 50% and 30% sufficiency thresholds, respectively. For cycling, all zones are also below the 50% sufficiency threshold, while some zones are above the 30% threshold. Furthermore, relating the measured accessibility by NMT to the population in each zone, the proportion of the total population that have accessibility 'above' and 'below' the sufficiency thresholds can be established. This is achieved by identifying the respective zones that are below or above the thresholds and taking the total population of individuals in those zones into account, while adjusting for estimated levels of car ownership. The Accessibility Sufficiency Index (ASI), which is a measure of the overall fairness of the transport system, is also computed. The ASI is mode specific and also dependent on the set sufficiency threshold. Table 1 gives a summary of the percentage of the population and their accessibility relative to the defined sufficiency level σ. Also presented is the ASI for walking and cycling for the respective sufficiency levels.

Table 1: Percentage of the population and their accessibility relative to sufficiency level, $T_{\sigma,p,\mathrm{r}}^{M}{}^{*}$ for Kigali

	Total Population (Persons) = 0.8 Million	ASI Mode M			
	σ	Car (%)	Walk (%)	Bicycle (%)	Transit (%)
15 mins	% of Total Population with above 50%	100	45	45	10
	% of Total Population with below 50%	0	55	55	90
	% of Total Population with above 30%	100	57	57	57
	% of Total Population with below 30%	0	43	43	43
	% of Total Population with above 10%	100	88	92	100
	% of Total Population with below 10%	0	12	8	0
30 mins	% of Total Population with above 50%	100	3	3	3
	% of Total Population with below 50%	0	97	97	97
	% of Total Population with above 30%	100	15	15	25
	% of Total Population with below 30%	0	85	85	75
	% of Total Population with above 10%	100	48	52	97
	% of Total Population with below 10%	0	52	48	3
45 mins	% of Total Population with above 50%	100	0	0	0
	% of Total Population with below 50%	0	100	100	100
	% of Total Population with above 30%	100	3	3	11
	% of Total Population with below 30%	0	97	97	89
	% of Total Population with above 10%	100	37	40	97
	% of Total Population with below 10%	0	63	60	3
	% of Total Population with above50%	100	0	0	60
60 mins	% of Total Population with below 50%	0	100	100	40
	% of Total Population with above 30%	100	0	0	43
	% of Total Population with below 30%	0	100	100	57
	% of Total Population with above 10%	100	18	20	100
	% of Total Population with below 10%	0	82	80	0

Accessibility Index Maps for Kigali

The maps of cumulative accessibility for the city of Kigali are presented for car, walk, bicycle and transit as shown below in Figures 4a to 4c.

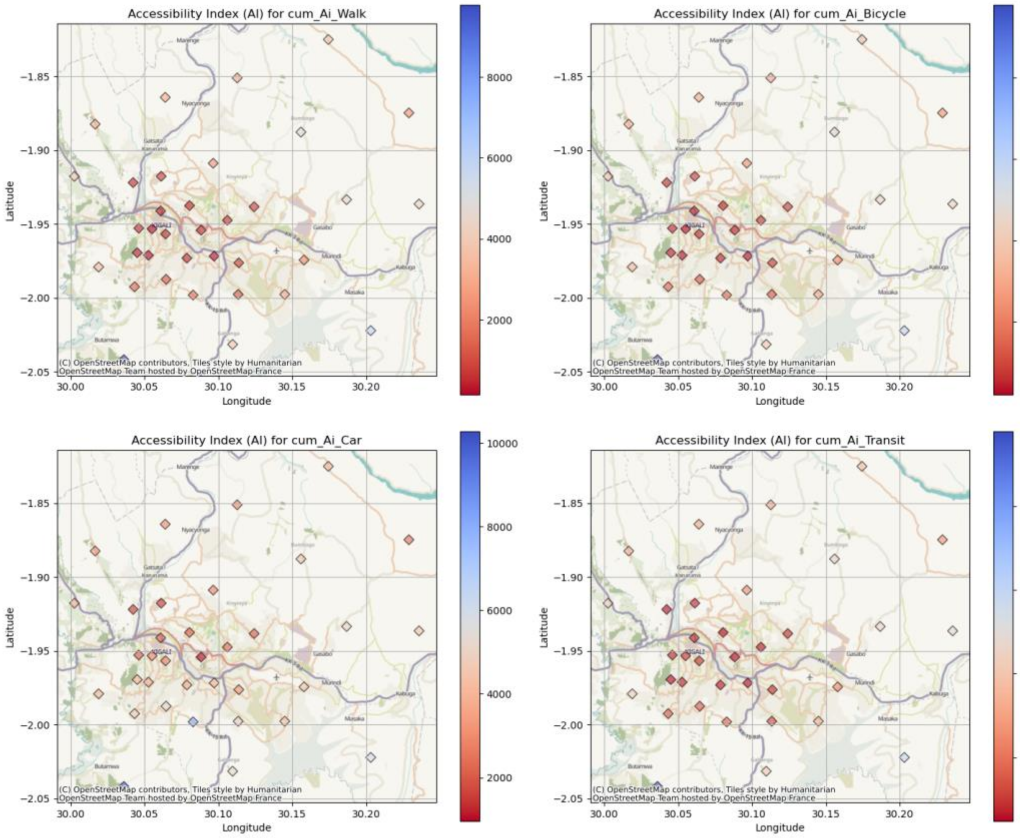


Figure 18: Potential accessibility by individual zones in the study area – 15 mins

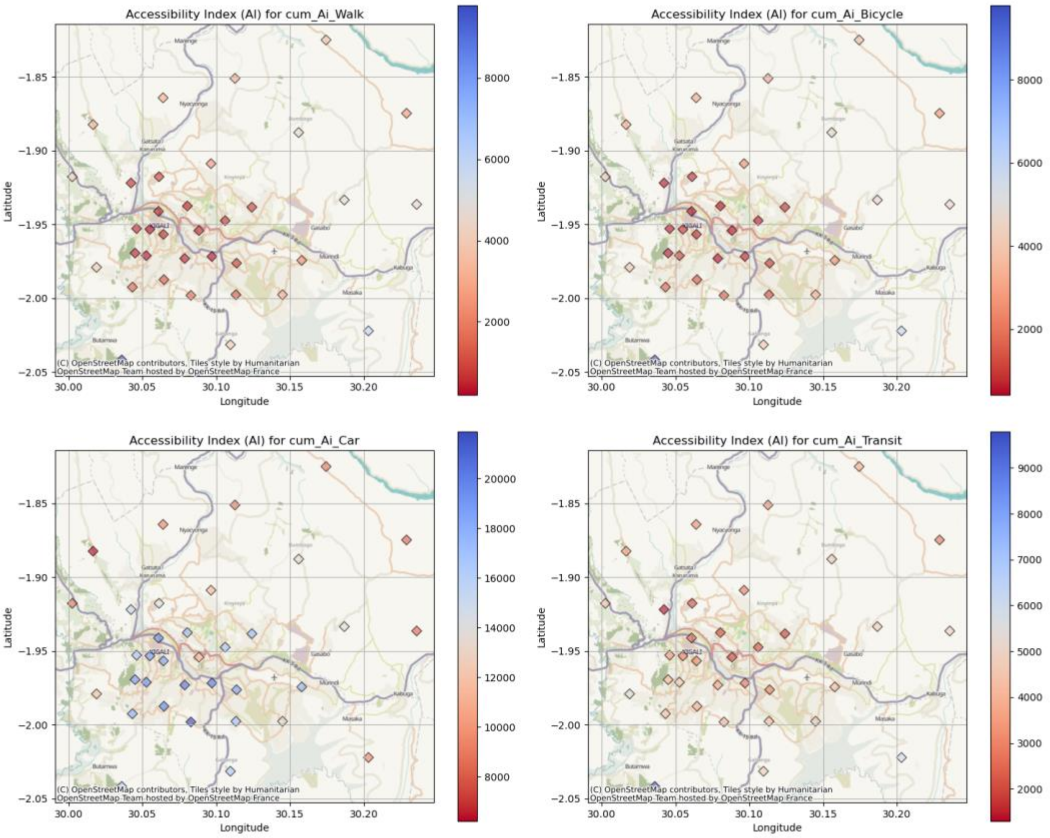


Figure 19: Potential accessibility by individual zones in the study area – 30 mins

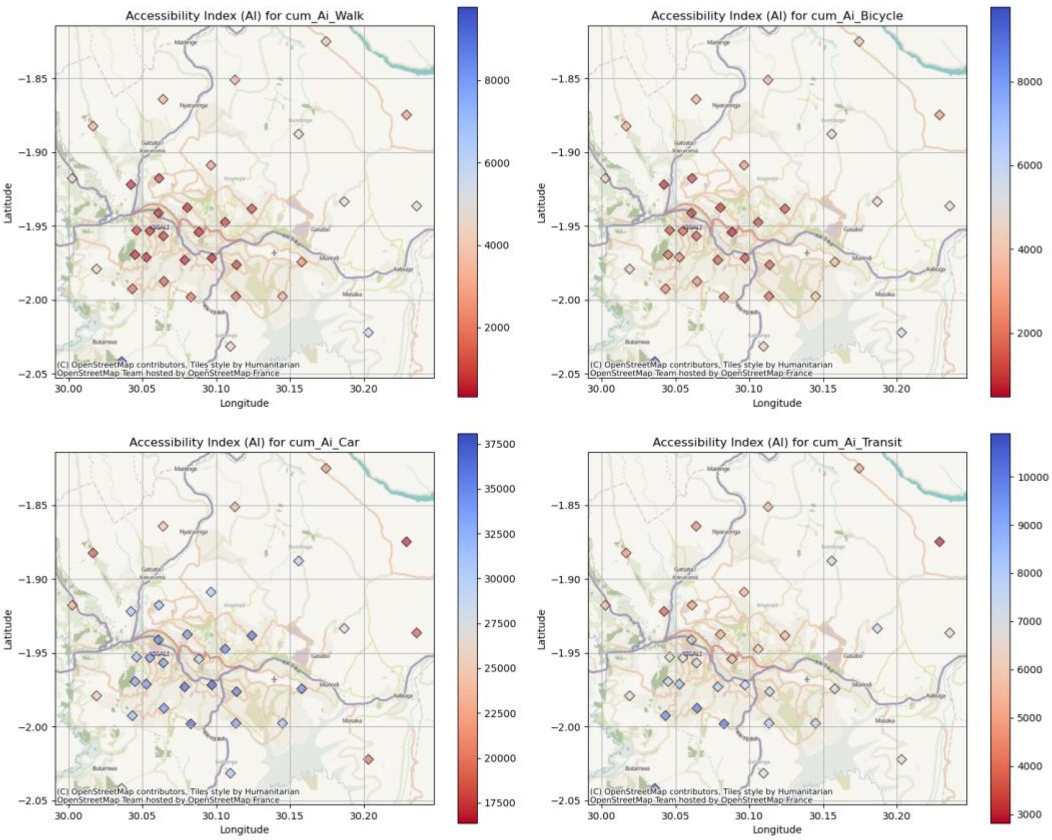


Figure 20: Potential accessibility by individual zones in the study area – 45 mins

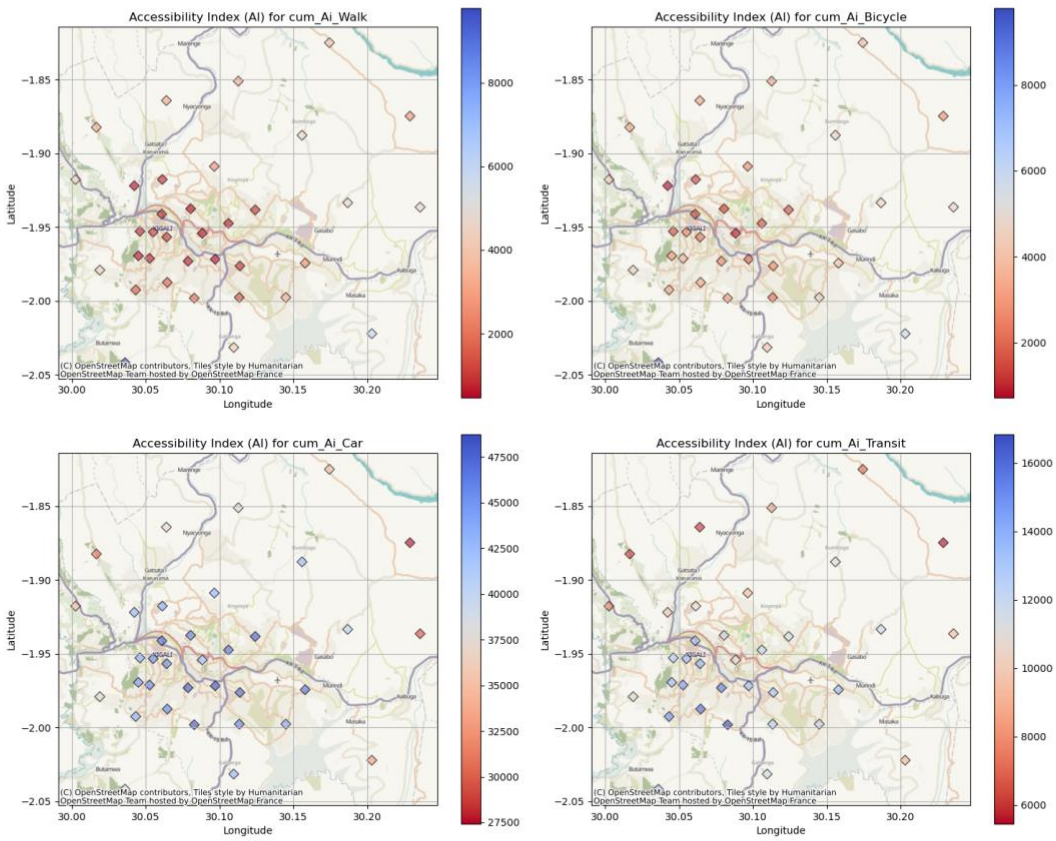


Figure 21: Potential accessibility by individual zones in the study area – 60 mins

Transport justice quadrants for Blantyre

Next we present the results for Blantyre from Figure 22, where again each scatter point represents the potential mobility and cumulative accessibility index of a zone for the four modes considered separately.

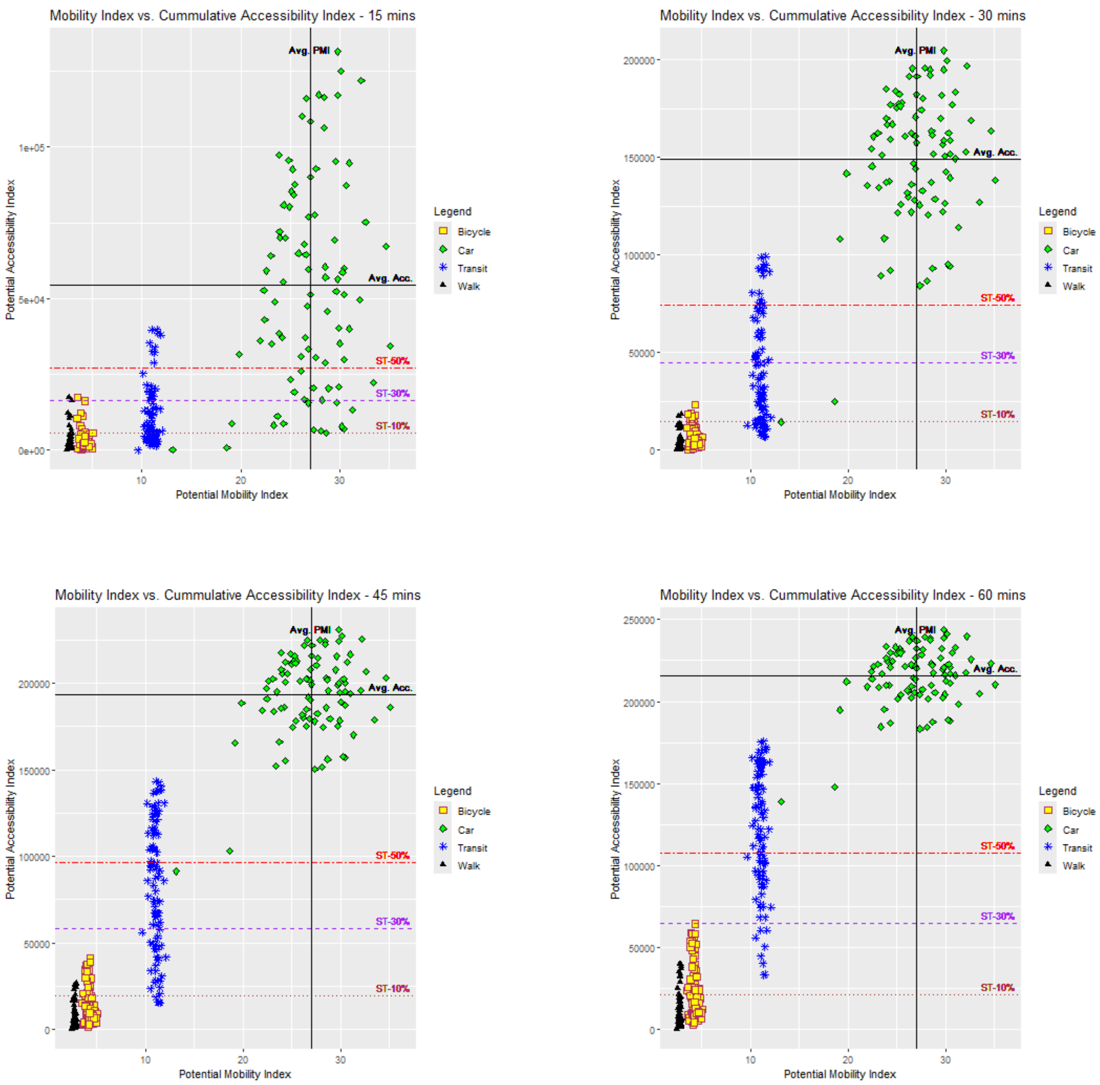


Figure 22: Accessibility and corresponding potential mobility for travel by car, paratransit, walking and cycling for different travel time thresholds in Blantyre

From the figure, the average number of jobs 'potentially' reachable by car from all the zones is just over 117,000 jobs. This represents about 70% of the total jobs (280,000) in the study area. In comparison to NMT, the average number of jobs 'potentially' reachable by walking is only about 21,000 jobs, while for transit, it is about 113,000 jobs. This implies that households with access to car and other motorised modes are almost ten times better off than households with no access to cars or paratransit services in terms of potential opportunities within reach.

In terms of sufficiency, accessibility by walking for all zones is below the 50% and 30% sufficiency thresholds. The proportion of the total population experiencing accessibility levels below or above the sufficiency thresholds is also established in Table 2, as in the case of Kigali.

Table 2: Percentage of the population and their accessibility relative to sufficiency level, $T^{M}_{\sigma,p,r}$* Blantyre

	Total Population (Persons) = 0.8 Million	ASI Mode M			
	σ	Car (%)	Walk (%)	Bicycle (%)	Transit (%)
15 mins	% of Total Population with above 50%	100	0	0	10
	% of Total Population with below 50%	0	100	100	90
	% of Total Population with above 30%	100	1	1	25
	% of Total Population with below 30%	0	99	99	75
	% of Total Population with above 10%	100	10	14	57
	% of Total Population with below 10%	0	90	86	43
30 mins	% of Total Population with above 50%	100	0	0	15
	% of Total Population with below 50%	0	100	100	85
	% of Total Population with above 30%	100	0	0	42
	% of Total Population with below 30%	0	100	100	58
	% of Total Population with above 10%	100	2	8	82
	% of Total Population with below 10%	0	98	92	18
45 mins	% of Total Population with above 50%	100	0	0	37
	% of Total Population with below 50%	0	100	100	62
	% of Total Population with above 30%	100	0	0	67
	% of Total Population with below 30%	0	100	100	32
	% of Total Population with above 10%	100	7	23	95
	% of Total Population with below 10%	0	93	77	4
60 mins	% of Total Population with above50%	100	0	0	60
	% of Total Population with below 50%	0	100	100	40
	% of Total Population with above 30%	100	0	0	90
	% of Total Population with below 30%	0	100	100	10
	% of Total Population with above 10%	100	11	43	100
	% of Total Population with below 10%	0	89	57	0

The justice assessment presented for this study is performed at the spatial aggregation level of zones. With more disaggregated data capturing more details about the population within each zone, say by household income level and car ownership, a more refined assessment of transport justice can be achieved at the household level. While the measure of opportunities considered in this case is jobs, other measures of opportunities such as education or health facilities distribution can equally be considered, given data availability. The type of opportunity considered would depend on and reflect the planning objective. and reflective of the planning objective and the population group of concern (e.g., youth, working-age adults, or elderly).

Accessibility Maps for Blantyre

The accessibility maps for Blantyre are presented for cars, walks, and bicycles, as shown below in Figures 23a to 23d.

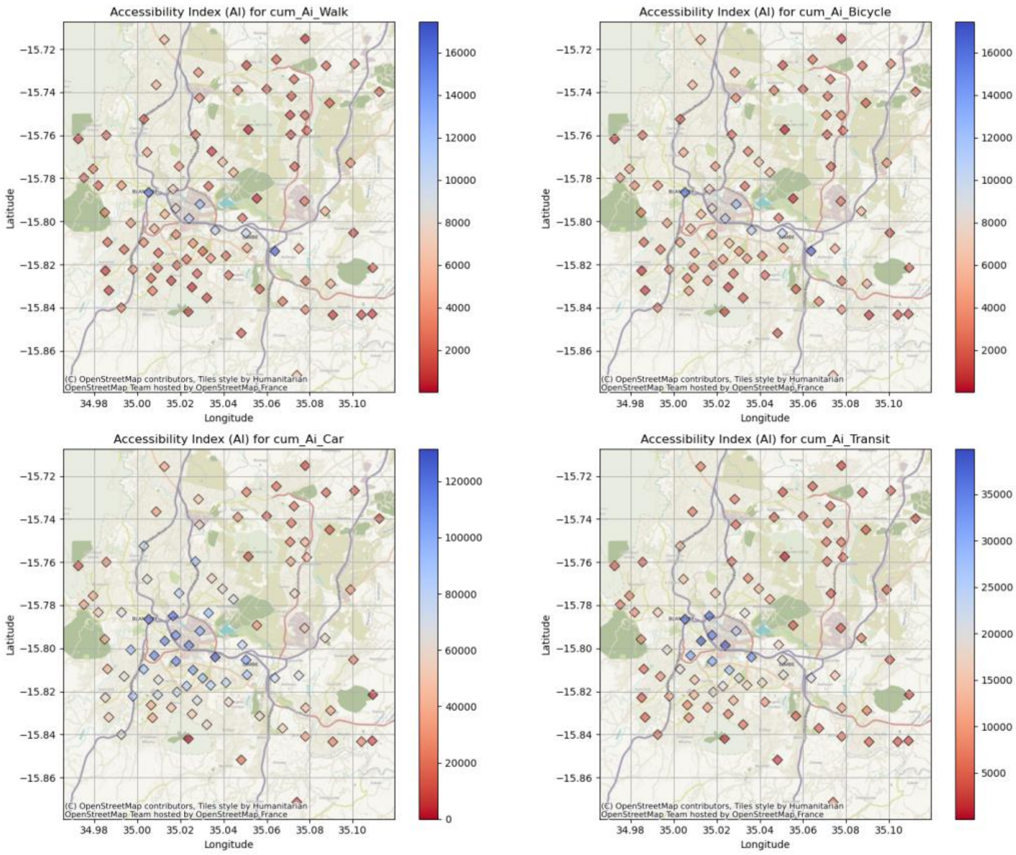


Figure 23: Potential accessibility by individual zones in the study area – 15 mins

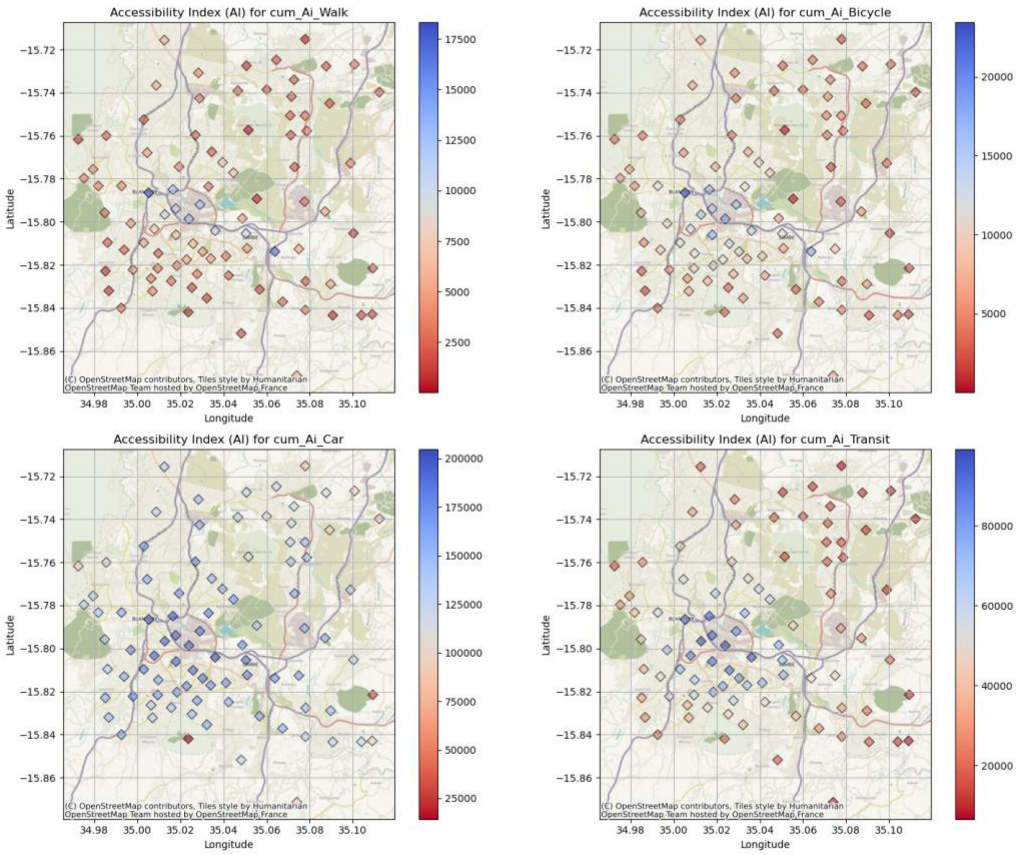


Figure 24: Potential accessibility by individual zones in the study area – 30 mins

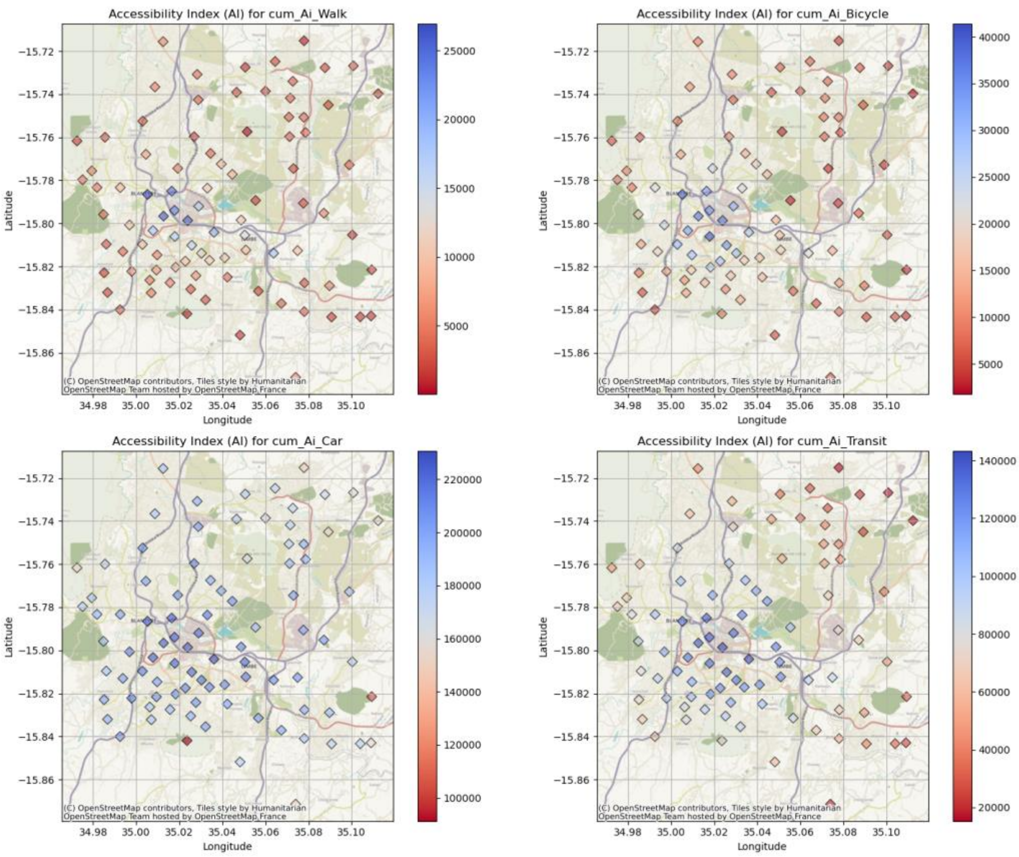


Figure 25: Potential accessibility by individual zones in the study area – 45 mins

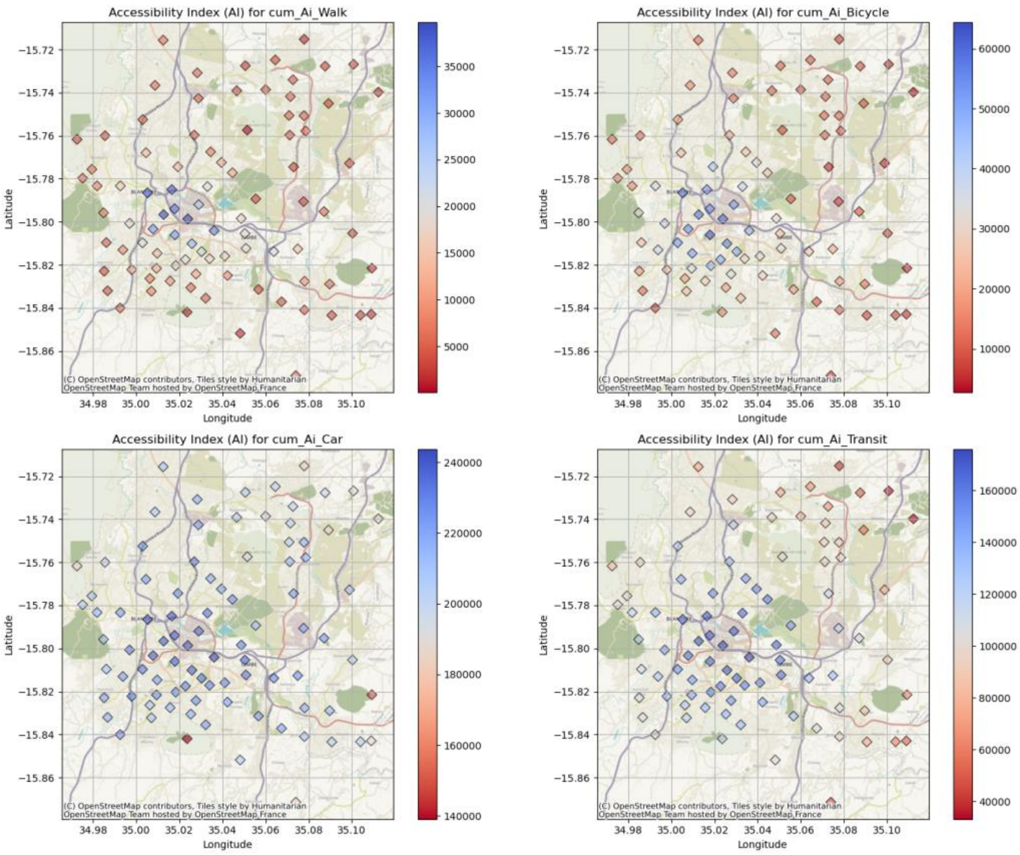


Figure 26: Potential accessibility by individual zones in the study area – 60 mins

5.4 Reflection

Detailed data on a transport system and its operational schedule are required for transport planning based on the principles of transport justice. The key data challenges addressed in this report revolve around the limited nature of public transport data and the lack of detailed socioeconomic and demographic data in both case studies cities. This confines the work to an aggregated analysis at the zonal level rather than a disaggregated household-level analysis. Public transport operations in Kigali and Blantyre are largely informal, with little or no available data about their schedules and operations. As such, the inability to fully represent informal public transport, which accounts for the larger share of the public transport sector within the transport justice analysis framework, is considered a key limitation of the work, and the results of the work should be interpreted within the context of limitations of the work. Furthermore, there is a lack of detailed socioeconomic data in both cities, which limits the level of analysis that can be done. Lastly, the aggregated opportunities data used in the analysis limits the assessment of transport justice at a zonal level. These issues affect the outcome of the transport justice transport planning approach in both cities. They are similar to the challenges faced in the transport environment of many sub-Saharan African cities.

6. Further research

This project set out to develop an improved representation for paratransit in commonly used transport model, implement it in the extended *r5r* tool for transport justice analysis, and case-test this approach in Kigali and Blantyre using empirical data. The toolbox that has been developed no allows to systematically derive quantitative indicators for transport justice. Particularly our toolbox allows the inclusion of paratransit in this analysis. This is an important step forward towards developing a set of transport modelling tools that are representative of the realities seen in urban transport contexts across the Global South.

Typically, transport planners and modelers, and even more so in the Global South, use existing, proprietary, tools, for their modelling and operations design. These models have (for lots of good reasons) been developed and calibrated over decades, and in a much different context. For example, public transport is typically represented as a formal, scheduled, service with fixed routes and stops, using GTFS feeds to represent them across models and platforms. Paratransit, even though mostly confined to fixed routes or corridors, don't have a scheduled service with fixed stops and often deviate from their assigned (licensed) routes. As such, their behaviour is more continuous (along a route) and stochastic (in space and time). Our work aims to develop a better, more realistic, appropriate, representation in existing proprietary but also newly built tools (which increasingly are open source, and thus allow for the specific kinds of development we are after).

In this project we were able to use an improved version of the open-source GTFS code, GTFS Flex, which was developed to represent on-demand, shared transport modes, to represent paratransit, now called PTFS. The PTFS allows us, amongst others, to make a better and more representative modelling of potential mobility and potential accessibility in *r5r*. The *r5r* model was further extended with the improved and appropriate networks for the paratransit modes and case-tested with empirical data from Kigali and Blantyre.

The successful implementation and testing of the PTFS in *r5r* for the two cities still allows scope for further development, which we hope to do in follow-up research projects involving all partners. Two research projects are particularly envisaged coming out of this work. The first one proposes to look into the actual stochastic nature of paratransit operations building a Monte-Carlo simulation (MCS) extension to the PTFS and *r5r*, based on an existing tool in R called MCS. We envisage the following steps:

1. Collect multiple strings of GPS data for the same paratransit routes over an extended period,

logging paths, stops and times (for headways and frequencies).

2. As this is a random process of route deviations, actual stop locations and headways/frequencies
    a. For each route derive:
        - A route adherence statistic
    b. For each route derive:
        - A statistical headway distribution
    c. For each notional 'stop' derive:
        - A spatial statistical distribution of stop locations
3. Simulate the paratransit behaviour based on the three random components in the MCS code
4. Summarize the simulation results
5. Convert and implement the stochastic PTFS
6. Run the *r5r* transport justice analysis, or other transport models

The second research project looks further into the modelling of transport justice indicators in *r5r*, and seeks to find a better representation of the potential mobility indicator, which in our current modelling is mode-specific whereas we would like it to be area (TAZ)-specific. To do that we need to collect data that allows for an area-wide potential mobility estimate using an area-wide potential modal split figure.

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Appendix 1 – Kigali Data collection

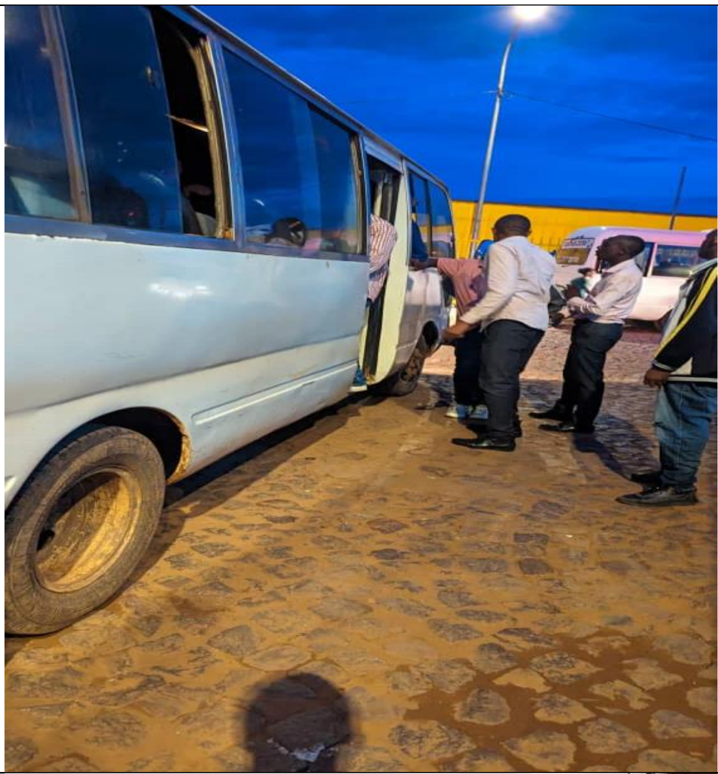
The data was collected on the identified 13 bus routes, namely:

S/N	Route ID	Route Name
1	203	Gatenga-Kicukiro Center-Nyanza
2	102	Kabuga-Rwandex-Nyabugogo
3	311	Nyabugogo-ULK-Kagugu
4	107	Remera-Masaka
5	404	Nyabugogo-Ruyenzi-Bishenyi
6	403	CBD-Nyabugogo-Nyacyonga
7	208	Royal-Centre-Gahanga
8	205	CBD-Gikondo-Kigarama-Bwerankori
9	306	Kimironko-Masiza
10	314	Nyabugogo-Kibagabaga-Kimironko
11	105	Remera-Kacyiru-Nyabugogo
12	321	Nyabugogo-Kagugu-Gasanze
13	401	CBD-Nyamirambo-Ryanyuma

Route name (ID)	Check points
CBD Gatenga-Kcenter-Nyanza (203)	Mount Kenya University
Kabuga-Rwandex-Nyabugogo (102)	Sonatube
Nyabugogo-ULK-Kagugu (311)	Kinamba
Remera-Masaka (107)	19 bus stop
Nyabugogo-Ruyenzi-Bishenyi (404)	Kamuhanda
CBD-Nyabugogo-Nyacyonga (403)	Akagera
Royal-Centre-Gahanga (208)	Merez
CBD-Gikondo-Kigarama-Bwerankori (205)	Merez fuel station 2
Kimironko-Masiza (306)	Zindiro
Nyabugogo-Kibagabaga-Kimironko (314)	Kacyiru
Remera-Kacyiru-Nyabugogo (105)	Chez Lando
Nyabugogo-Kagugu-Gasanze (321)	Beretoir
CBD-Nyamirambo-Ryanyuma (401)	40 bus stop

Bus Line Route and Name	Picture
Nyabugogo-Ulk-Kagugu (311)	
Nyabugogo-Kagugu-Gasanze (321)	

Nyabugogo-Kacyiru-Remera (105)	
Nyabugogo-Rwandex-Kabuga (102)	

Kimironko-Masizi (306)	
Remera-Masaka (107)	 Buses parked at Masaka terminal during off-peak hour

Appendix 2 – Blantyre data collection instrument

Blantyre City Paratransit GTFS Modelling

Name of TAZ: ____________________________ **Type: Origin** ◯ **Destination** ◯ **Intermediate** ◯

Date: ________________________________

No.	Route	Time	No.	Route	Time

Figure A2.1: An extract of the data collection sheet