UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Job accessibility in Gauteng: measuring and visualizing location-based travel time.

by

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Plagiarism Declaration Statement

I hereby declare that this research report is my own work and is submitted in fulfilment of the requirement for the degree of Master of Science in GIS and Remote Sensing at University of the Witwatersrand, Johannesburg. This work has not been submitted to any institution before for any degree or examination.

(Candidate Signature)

Signed on the 04th day of November, year 2022, at the University of the Witwatersrand, Johannesburg

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Abstract

Accessibility is an important indicator to measure spatial interaction and equity involving urban land-use activities and transportation systems. Transport plays a fundamental role in accessibility by influencing spatial choices and enabling communities to participate in social and economic activities with ease. Therefore, inadequate accessibility could potentially contribute to social and economic exclusion, longer commuting time, as well as spatial mismatch problems. The transport sector in South Africa suffers from the legacy of apartheid spatial planning and as a result, most of the residential and major urban areas are disconnected in terms of accessibility. Measuring job accessibility, in particular, can assist to measure spatial inequality between locations where jobs are and where people reside. The aim of this study was to model travel-time accessibility for Gauteng inhabitants from places of residence to places of work. The computation of the job accessibility measure was implemented in GIS.

GIS applications offer a variety of tools to measure and assess spatial accessibility. The analysis used the gravity measure approach to calculate accessibility and the implementation of the methodology was GIS-based. This study used Origin-Destination (OD) Cost Matrix analysis in *Network Analyst* tools, Proximity Analysis, and interpolation methods to achieve the study aim. The research study made use of the residential location data, population data, transportation routes data, and economic activity (as a proxy for job opportunities) data, and referred to previous accessibility studies for common accessibility standards as input data to analyse travel-time accessibility within Gauteng. The study made use of geospatial visualization techniques such as hexagon tessellations, and dasymetric maps to visually present the accessibility findings.

The major findings of the research revealed that travel-time accessibility within the study area differs based on the type of transportation mode, the availability of transport infrastructure, and places of work. The results based on travel-time to places of work using two modes of transportation modes (public and private), revealed that car users had adequate access to road network transport infrastructure and as a result had better advantage compared to those that rely on rail transportation in terms of the travel-time radius. Accessibility using the road network (private) gives a far wider access to places of work in the City of Johannesburg, City of Ekurhuleni, Emfuleni, Lesedi and Merafong City as compared to accessibility using rail network (public). The results from the location-based measure (gravity-based equation) revealed that areas with high job accessibility scores using a car are mostly located in the inner parts of the study area with a few located on the outskirts. Furthermore, the main municipalities with a higher percentage of places of work that can accessed within 30 minutes using a car are City of Johannesburg (100%), City of Ekurhuleni (100%), Emfuleni (100%), Lesedi (100%), Merafong City (100%), and Rand

West City (100%), followed and the City of Tshwane (99%), Midvaal (99%), and Mogale City (99%). Moreover, accessibility to places of work using rail revealed that the City of Johannesburg (100%), City of Ekurhuleni (100%), and the Rand West City (100%) had a higher percentage of places of work located within 45 minutes.

In conclusion, the study found that more residential areas could access places of work within 30 minutes using a car with a few residential areas outside the 30 minutes catchment areas. Whereas the results from using a rail revealed a relatively high number of residential areas considered inaccessible (areas located beyond the 45 minutes threshold). Furthermore, the results revealed that there were limited places of work and accessible transport infrastructure in some municipalities such as the Emfuleni local municipality which resulted in poor job accessibility. The study recommends expanding the scope of the study area beyond a local municipality, metro and district level, to consider accessibility to places of work located outside the provincial borders of Gauteng when measuring travel-time to obtain an accurate picture of accessibility to places of work at a higher level as commuters and job seekers are not restricted to provincial boundaries. It also recommends considering data related to the influence in travel behaviour such as socioeconomic and demographic characteristics. Lastly, it encourages exploring other data that could provide a holistic overview of accessibility to places of work in Gauteng including multiple public transportation modes (i.e., buses, minibus taxis), and accessibility to a various job classes not considered in this study.

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List of Abbreviations:

BRT	Bus Rapid Transit
CBD	Central Business District
CSIR	Council for Scientific and Industrial Research
DEFF	Department of Environment, Forestry and Fisheries
EAs	Enumeration Areas
ESRI	Environmental Systems Research Institute
GCR	Gauteng City-Region
GCRO	Gauteng City-Region Observatory
GFIP	Gauteng Freeway Improvement Project
GIPT	Gauteng Infrastructure Planning Tool
GIS	Geographic Information Systems
Ha	Hectares
Km^2	Square Kilometre
NATMAP	National Transport Master Plan
NDP	National Development Plan
OD	Origin-Destination
OECD	Organisation for Economic Co-operation and Development
PRASA	Passenger Rail Agency of South Africa
QoL	Quality of Life
RDP	Reconstruction and Development Programme
PRMSE	Percent Root Mean Square Error
SARS	South African Revenue Service

SA	South Africa
SMH	Spatial Mismatch Hypothesis
SPLUMA	Spatial Planning and Land Use Management Act 16 of 2013
StatsSA	Statistics South Africa

CHAPTER ONE: INTRODUCTION

1.1 Background and Significance of the Study

Spatial accessibility studies indicate that accessibility is important in assessing spatial equity and transport planning strategies for a sustainable urban area (Gulhan *et al*., 2014; Ford *et al*., 2015). The concept of accessibility to locations has been widely studied since the late 1950s (Lionjanga and Venter, 2017). Zhou *et al*. (2016) and Lionjanga and Venter (2017) explain accessibility as the use of any transport system to easily reach any land-use activity or service from a particular location. According to Charman *et al*. (2017) and Luke and Pisa (2018), inaccessibility to a Central Business District (CBD) prevents people from taking part in social and economic activities. Poorly located residential areas, unemployment, low incomes, and skills shortages are associated with inadequate access to the CBDs (Culwick and Patel, 2020; The World Bank, 2018). Proper planning for public transport services can enable people from less privileged communities to participate in social and economic activities that are important for improving the quality of life (Fransen *et al*., 2015). In developed countries such as the United Kingdom, accessibility has been utilised in urban planning (Curl *et al*., 2011) including assessing sustainability of transport in the city of London (Ford *et al*., 2015) and measuring location advantage to improve employment accessibility in Glasgow (Dixon *et al*., 2019). The concept of accessibility has also been explored in many developing African countries to alleviate spatial challenges related to job accessibility, for example in Kenya, Nakamura and Avner (2021) investigated how the spatial distribution of employment locations and residential areas impacts poverty within the capital of Nairobi. Meanwhile in South Africa, accessibility has also been explored to understand the impact of public transport post-apartheid (Jennings, 2015), to measure patterns related to mobility in Gauteng (Culwick *et al.*, 2015), and time-series analysis of transport affordability in the City of Johannesburg (Lionjanga and Venter, 2017). According to Curtis (2008), sustainable planning for accessibility requires sophisticated tools such as Geographic Information Systems (GIS)[1], which has become necessary in supporting spatial planning as cities all over the world strive for more sustainable mobility[2] (Curl *et al.*, 2015). Furthermore, it offers tools that evaluate accessibility and functionalities that disaggregate representations to provide a detailed geographical representation of urban form (Weber, 2003; Curl *et al*., 2015; Silalahi *et al*., 2020). In light

[1] GIS represents information through layers and enables us to analyse, model, and visualize various data to study and understand geographic phenomena (Church, 2002; Chen *et al*., 2011).

[2] *Mobility* is defined as the ease of an individual to travel or move about (Giannopoulos and Boulougaris, 1989; Mokonyama and Mubiwa, 2014; Venter and Cross, 2014).

of the above, the significance of this study is to contribute towards accessibility studies in South Africa through the use of GIS tools and the gravity-based measure to model job accessibility for Gauteng inhabitants from their residential areas based on travel-time. The study will also seek to demonstrate how job accessibility studies can be used to inform transport planning and spatial transportation policies.

1.2 Problem Statement and Motivation

South Africa's history of racial inequality has played a crucial role in shaping the patterns of residential areas and black people's flow of movement into urban areas (Ruhiiga, 2014). Cities and towns were developed in an unbalanced and fragmented manner (Department of Environmental Affairs and Tourism, 2005; Thompson, 2001). For example, the "Native Urban Areas Act (No. 21 of 1923)" during the colonialism era contributed to the development of "locations" in the country (Harrison and Todes, 2015a). Residential areas inhabited by black people were poorly serviced and placed on the margins of the towns, far from urban facilities and employment (Department of Environmental Affairs and Tourism, 2005). On the other hand, areas inhabited by white people were well-serviced and suitably located in close proximity to city centres (Department of Environmental Affairs and Tourism, 2005; Katumba and Everatt, 2021). Post-apartheid, South Africa's landscape still primarily reflects the spatial legacy effects of colonialism (van Wyk, 2015). As a result, most of the residential locations are disconnected from the main urban areas in terms of transport networks (City of Johannesburg, 2016) and spatially distant from employment[3] opportunities (van Wyk, 2015; Wray and Cheruiyot, 2015; Everatt, 2017; van der Merwe *et al*., 2020). The disconnection between residential areas and areas of employment prevents people from employment prospects and exacerbates poverty (Chakwizira *et al*., 2014); however, improving access to people creates economic opportunities and reduces poverty (Linard *et al*., 2012). For example, if residential and job locations are balanced, commuters can avoid long travel distances and costs (Geyer and Molayi 2018).

The disconnection can be understood through the concept known as the "Spatial-Mismatch Hypothesis" (SMH)[4] introduced by Kain (1968) post-World War II spatial transformation in the United States of

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[3] The Statistics South Africa Census 2004/5 report defines employment as an activity that an individual performs for pay, profit or family gain (Statistics South Africa, 2004).

[4] Spatial Mismatch Hypothesis theory emerged in America in 1968 and was backed up by evidence suggesting that geographical limitations on black residential choice, affected the aggregate level of demand for black workers (Kain, 1968; Kain, 1992). The report will use SMH to refer to Spatial Mismatch Hypothesis.

America (USA). The idea of spatial mismatch[5] theory suggested a mismatch between African Americans and employment prospects due to a lack of transportation (Kain, 1968; Gobillon *et al*., 2007), and years later, the idea of spatial mismatch expanded to other countries (Liu and Kwan, 2020). Budlender and Royston (2016) applied the theory of spatial mismatch in South Africa and the findings revealed evidence suggesting a spatial mismatch between residential areas and job locations across South Africa's main urban centres. Urban sprawl in Gauteng has been linked to the inadequate use of urban land, which often results in challenges such as traffic congestion, vehicle dependence, high public transport fares, and limited access to transport (Yusuf and Allopi, 2004). Gauteng is the smallest province in South Africa, with the agglomeration of cities, towns, and urban nodes that form the economic hub of the country and a trading centre for southern countries (Rogerson, 1996; Wray and Cheruiyot, 2015). Additionally, Bobbins (2013) notes that the remnants of the mining legacy in Gauteng have created further physical barriers to the movement of people and presented challenges for spatial redevelopment programmes and the development of transport infrastructure. Consequently, this has led to fragmentation and marginalisation of settlements, with limited access to the road networks across the areas to the close the mines (Bobbins, 2013).

At the same time, Gauteng province is experiencing a rapid population increase due to natural urban growth (Parnell and Walawege, 2011) as well as the rural-urban migration (Rogerson, 1996), of those seeking economic and social opportunities (Chakwizira *et al*., 2018). The population increase has led to a demand for housing, which has exacerbated the issue of urbanization (Culwick and Patel, 2020) noticed through a high prevalence of informal structures such as backyard dwellings and shacks (Katumba *et al*., 2019) as well as increasing demand for other natural resources and basic service delivery. The spatial trends in Gauteng are compounding the effects of apartheid; thus, there is a need to understand whether the province's spatial form, fabric and function are resilient to deal with change (GCRO, 2015). Furthermore, Mokonyama and Mubiwa (2014) add that population expansion increases mobility in cities; however, this has not translated into ease of accessibility. GCRO (2015) states that transport accessibility and affordability are critical development concerns where spatial dislocation exists. Thus, the post-apartheid Government has put in substantial efforts through developing explicit policies to restructure cities and towns away from the fragmentation and sprawl associated with the legacy of apartheid (Harrison and Todes, 2015b). Legislation and policies such as the Spatial Planning and Land Use

[5] *Spatial mismatch* is defined by Liu and Kwan (2020) as a geographic separation between residences and places of work that inhibits equal access to opportunities.

Management Act 16 of 2013 (SPLUMA), the National Development Plan (NDP) 2030[6] and Programmes seek to address the spatial injustice and social exclusion associated with apartheid (van Wyk, 2015; Pieterse and Owens, 2018). The spatial injustice components addressed by the NDP relate to the transformation of informal settlements and improving land-use accessibility through integrating transportation networks with them by 2030 (National Planning Commission, 2011). While SPLUMA also seeks to address the issues of spatial justice, sustainability, and administration through spatial planning. The government has also invested in public transport (e.g. Bus Rapid Transit (BRT), Gautrain Rapid Rail Link, Gauteng Freeway Improvement Project (GFIP)) as well as residential areas through various programmes, such as the Reconstruction and Development Programme (RDP) and high-density mixed-use developments to connect people that were previously disadvantaged to the city centres (City of Johannesburg, 2016; Scorcia and Munoz-Raskin, 2019; Pieterse and Owens, 2018). However, these interventions. An essential provision of accessible transport (Aropet, 2017). The RDP's mandate neglected to develop fundamental amenities that complement housing with places of work[7] and recreational activities (Lukhele, 2014). Van Wyk (2015) has also criticized the implementation of the RDP which was intended to eradicate spatial inequality. The author argues that the housing programmes have instead increased urban sprawl in the last decade by keeping low-income groups on the outskirts of cities away from opportunities (van Wyk, 2015). Dugard *et al.* (2016) also highlighted that a holistic approach to the supply of government subsidised houses such as RDP houses had not met the demand for needed accommodation in suitable locations close to places of work. Instead, the emphasis on the supply of RDP houses was mainly on the number of housing units provided (Landman, 2010).

Employment accessibility has also become a valuable indicator for assessing inequality in socio-economic interactions and developing urban policies that include transportation and land use (Pan *et al*., 2020). The Quarterly Labour Force Survey in the fourth quarter of 2019[8] in South Africa indicated that 59.8% lower employment levels are due to employment areas far from reach. According to Venables (2016), investments in transport infrastructure intensify economic interactions that increase productivity and remove barriers to efficient land use. It also impacts the labour market, potentially enabling more workers to access jobs through unlocking residential development and redevelopment of urban and other areas (Venables, 2016). Additionally, some scholars (Kwan, 1999; Liu and Kwan, 2020; Subal *et al*., 2021), argue that transport accessibility and mobility play a fundamental role in promoting quality of life

[6] National Planning Commission *National Development Plan: Vision for 2030* (2013)

[7] Places of work in this context refer to geographical locations of employment. Places of work and job opportunities are used interchangeably throughout the paper.

[8] The Quarterly Labour Force Survey (Statistics South Africa, 2019).

and addressing social exclusion in communities (Venter and Cross, 2014). By contrast, Terwin (2019)'s view is that job profiles are changing and becoming less dependent on spatially bound locations due to opportunities provided by telecommunications. As such, there has been increasing purposeful planning observed in government departments.

In line with these global studies, the Gauteng Provincial Treasury commissioned the development of the Gauteng Infrastructure Planning Tool (GIPT) in 2012 (Wray and Cheruiyot, 2015). The tool utilises a GIS-based model with three functions: a weighted overlay model, a location-allocation analysis, and a capacity balance model to determine suitable locations for public facilities. However, despite the variety of urban modelling initiatives or tools currently utilised, a long-term strategic plan or model is required on how to model Gauteng due to its dynamic relationship with external neighbouring provinces (Wray and Cheruiyot, 2015; City of Johannesburg, 2016; Pieterse and Owens, 2018). The City of Johannesburg as a case in point with its approved Nodal Review policy 2019/20 states that cities should be predominantly established on the foundation of connectivity and access; allowing transformation to a compact-polycentric, mixed-use and a walkable city which will be more efficient and sustainable (City of Johannesburg, 2020). Moselakgomo *et al*. (2017) also suggest that assessing the nature of travelling time and commuting distances can assist in evaluating the impact of urban form policy reforms and their effectiveness on spatial transformation. In light of the above, this research seeks to examine spatial accessibility to places of work from all residential areas within the Gauteng Province.

1.3 Aim of the Study

The primary aim of the study was to model travel-time accessibility for Gauteng inhabitants from residential areas to places of work.

1.4 Specific Objectives

The specific objectives to achieve the aim were:

1. To map the distribution of places of work in relation to residential areas in Gauteng.
2. To model travel-time accessibility to places of work based on the mode of transport and types of jobs available in Gauteng.

1.5 Research Question

To what extent does the spatial distribution of places of work and mode of transport affect travel-time accessibility of the inhabitants in Gauteng?

1.6 Structure of the Report

This research report consists of six (6) chapters; Chapter One introduces the background and significance of the study, the problem statement and motivation for the research, and concludes with the aim, specific objectives, as well as the research question. In Chapter Two, the study reviews and discusses the literature relevant to the scope of the study, the conceptual framework of accessibility measure and provides a summary table of the empirical literature on local and international accessibility studies. Chapter Three starts by introducing the study area and provides a flow diagram of the process followed to achieve the final results. The chapter also discusses details of various data obtained for the analysis, the methodology to meet the objectives, and techniques for validating spatial accessibility results. Chapter Four presents the findings of the analysis, while Chapter Five gives a detailed discussion of the results obtained. Chapter Six briefly highlights the concluding remarks, limitations identified during the study, and recommendations for future studies. Lastly, the report provides a list of the bibliography consulted in the study and appendices.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter covers the background and discussion of relevant literature consulted for the study. The first section of the chapter provides a historical background of the study area, followed by a section which defines the concept of accessibility and the role of geography in conceptualizing accessibility. The third section explains the importance of measuring accessibility and highlights the existing accessibility measures. The chapter also focuses on both international and local literature reviewed under the subject of accessibility. The fourth section reviews the role of the GIS application in modelling spatial accessibility, while the fifth section dissects literature on job accessibility and the concept of spatial mismatch. The conclusion of the literature review chapter gives the literature synthesis which discusses the reviewed literature and highlights the common trends in the studies and lastly a summary of the intention of this research.

2.2 Defining the Concept of Accessibility

The concept of accessibility is defined as the ease or difficulty of reaching an opportunity or a service at a particular location (Hansen, 1959; Levinson, 1998; Weber, 2003; Ford *et al*., 2015; Lionjanga and Venter, 2017). Accessibility is also described as the degree to which land-use activities can be accessed from any location by individuals using a particular transport (Dalvi and Martin, 1976; Geurs and van Wee, 2004). Transport represents distance friction between the places of origin and the desired destinations, which is often measured in terms the cost and the duration of the trip (van der Merwe *et al*., 2020). Accessibility is considered as an essential instrument in spatial planning and geography for decades. According to Brain and Prieto (2021), the role of geography in spatial and accessibility analysis addresses the fact that opportunities are located spatially and not always in a balanced way. Accessibility is used widely in scientific fields such as transport planning, urban planning, and geography (Geurs and van Wee, 2004). Spatial accessibility, in particular, has been identified as one of the essential principles of transport geography, where spatial separation of origins and destinations occurs (Weber, 2006; Burdziej, 2018). The ease with which a specific location can be reached is typically measured against accessibility measures or indicators (Ford *et al*., 2015). Accessibility measures are designed as an objective representation of reality to provide a reference for planning decisions and tracking change over time (Curl *et al*., 2015). However, Curl *et al.* (2015) indicated that the duration of the journey is usually the preferred basis of measurement and is calculated as travel-time through a transport network, often using GIS as a tool.

2.2.1 Role of Geography in Conceptualizing Accessibility

Accessibility measures have been used in spatial planning and social and urban geography studies since the late 1940s (Stewart, 1947; Hansen, 1959; Geurs and van Wee, 2004; Wang and Chen, 2015). The early version of the gravitational approach includes work by Reilly (1929), Stewart (1947), and later Hansen (1959). Newton's Law of Gravity uses the conceptual principles of physical science to explain a social interaction phenomenon in space[9] (Huff, 1963; Rosenfeld, 1965; Tóth and Kincses, 2015). Reilly (1929) introduced the Law of Retail Gravitation, an approach to measuring the interaction between two retail stores using the distance between them and determining the attraction of the stores. Stewart (1947) used Newton's concept of masses[10] and applied the component of the population to derive demographic gravitation for retail planning. According to Munson (1965), Stewart made a considerable contribution to the development of the gravity formula by introducing the human influence measure in the equation to predict the potential retail customers between two competing areas. However, the early version of the gravitational approach was later used by Hansen (1959), to explore a different destination opportunity which was accessibility to employment opportunities. The study applied the concept of gravity to assess spatial interaction between the number of job opportunities and the residential zones to estimate the potential employment in Washington D.C (Hansen,1959). The work has since contributed to the vast evolution of gravity-based measures in accessibility to locations of employment (Shen, 1998; Geurs and van Wee, 2004; Cheng and Bertolini, 2013; Hu and Downs, 2019).

In the early 1960s, geographers used Isaac Newton's concept of space for quantitative and statistical approaches in geography, while in the 1970s, various approaches of a scholarship referred to as 'critical geography' emerged using Leibnizian understanding of space and time (Koops and Galič, 2017). According to de Jong and van Eck (1996), accessibility measures are used in differently; however, the time-space measures are more efficient. Tobler's first law of geography was introduced in the 1970s, stating that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Since then, the concept of accessibility has become prevalent in addressing spatial issues, as Webb (1986) highlighted that between the period of the 1960s and 1970s, spatial science became an essential term in geography. Koops and Galič (2017) also add that these approaches gave rise to behavioural geography, which stems from human geography and studies on how people interact with the environment. Therefore conceptual frameworks for understanding the concepts of accessibility

[9] Principles of physical science in the Newton's Law of Gravity include the force (attraction) between two respective masses (opportunities), and the separation by distance (Huff, 1963).

[10] The law of Gravity (Stewart, 1947; Munson, 1965)

were developed in different accessibility studies (Geurs and van Wee, 2004; Cheng and Bertolini, 2013; Mokgalaka *et al.*, 2013; Xiao *et al.*, 2021; Arranz-López *et al.*, 2021). The components can be characterized by four questions of 'who,' 'where,' 'how,' and 'what,' which are vital in geography (Amer, 2007; Mokgalaka *et al.*, 2013). Three common interrelated components are identified from the conceptualization of accessibility include land-use (i.e., locations of the demand and supply for opportunities), transportation (i.e., infrastructure, mode, costs, time, distance), and individual characteristics (i.e., skills, income, age). Furthermore, studies by Shen, (1998), Amer (2007), Cheng and Bertolini (2013) add those non-spatial aspects such as human behaviour, politics, and planning policies influence the locations of places offering services (i.e., jobs, hospitals, retail, etc.) and residential areas. Therefore, this study refers to the accessibility concepts (such as land-use and transportation individual), which are essential to understanding and computing location-based accessibility (Geurs and van Wee, 2004). A conceptual framework similar to the one proposed by Cheng and Bertolini (2013) was adopted in the context of this study to assess the accessibility between residential areas (origin) and work (destination) using transport. Figure 1 provides a conceptual framework that illustrates the interaction of spatial and non-spatial key components in accessibility.

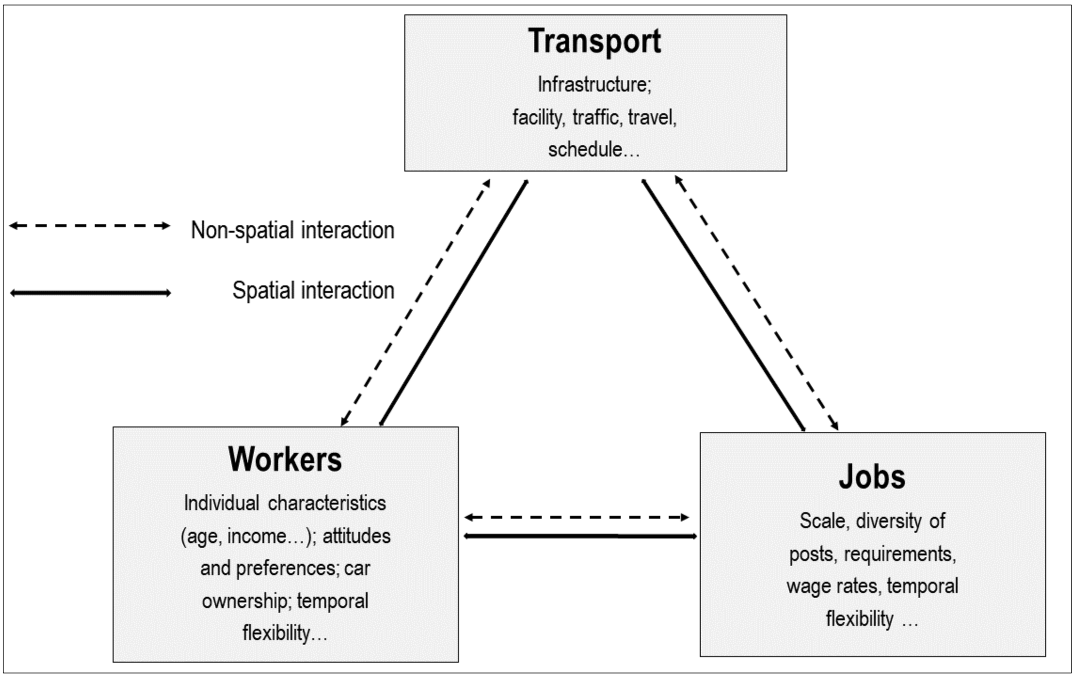

Figure 1: A conceptual framework of accessibility to jobs, source: (Cheng and Bertolini, 2013).

2.3 The Importance of Measuring Accessibility

According to Tenkanen *et al.* (2016) the key to understanding the functionality of urban regions is to study the spatial patterns of accessibility. Researchers with a spatial perspective are interested in explaining accessibility by studying the variation of daily human mobility behaviour by land-use patterns within urban areas (Hu and Wang, 2016). A wide range of approaches for measuring accessibility has been developed and modified since the work introduced by Hansen (1959), with efforts focused on improving or proposing new accessibility measures (Yin *et al.*, 2015). According to Porter (2002), the lack of transport infrastructure, transportation services, and the overall amount of time spent travelling away from home reduce the potential of participating in economic activities that promote sustainable livelihoods. It is argued that the evaluation of the distribution of existing and planned facilities (e.g., employment, education, health) concerning the distribution of the population determines how efficiently the existing system serves the residents of an area (Ahmed *et al*., 2006; Ford *et al*., 2015; Gulhan *et al*., 2014; Burdziej, 2019). These accessibility measures are classified into four groups: opportunity-based, gravity-based, utility-based, and space-time-based (Geurs and van Wee, 2004; Ahmed *et al*., 2006; Guan *et al*., 2020). The significance of proximity in accessibility measures can be justified by the reliance on urban models that revolve around employment centres, as access from such models is a function of distance from a particular location to the centre (Weber, 2003). Furthermore, measuring accessibility serves as an indicator of performance for urban transportation systems in catering to the needs of residents (Levinson, 1998; Zhao *et al*., 2009; Rau and Vega, 2012; Yin *et al*., 2015; Curl *et al*., 2015).

2.3.1 Job Accessibility Measures

According to Yin *et al*. (2015), various accessibility measures have been developed for evaluation and analytical purposes. In referring to the four accessibility measures introduced in section *(2.3 The Importance of Measuring Accessibility)*, opportunity-based measures are identified as measures that deal with the accessibility of opportunities within a certain distance or travel-time (Yin *et al*., 2015). The Gravity-based measure[11] is based on the principle that the opportunity between two places is positively related to the weight of their attractiveness and negatively related to the travel impedance[12] variables between them (Hansen, 1959; Yin *et al.*, 2015). Utility-based measures are concerned with individual traveller preference, while space-time introduces the aspect of temporal accessibility (Liu and Zhu, 2004; El-Geneidy *et al.*, 2006). Both utility-based and space-time measures are complex and require large amounts of spatial data such as transportation networks, land-use, and economic information for computation (Liu and Zhu, 2004).

[11] Gravity-based measure it is simply known as “people-based” and it is often based on perception (Miller, 2007).

[12] Travel impedance in accessibility studies refers to the variables used to measure travel time or cost (Liu and Kwan, 2020).

The measures listed in Table 1 allow us not only to assess spatial accessibility but to also translate it into maps that provide a platform for visually identifying spatial planning issues (Cheng and Bertolini, 2013). Another advantage of these accessibility measures is that they are easy to use and interpret (Makrí and Folkesson, 1999). The most commonly used measure in accessibility literature, as indicated in Table 1, is the gravity-based measure; however, the application contexts of the measure are very diverse. To elaborate further on the diversity of the application, a few areas where the measure has been used include jobs and services (Shen, 1998; Levinson, 1998; Cheng and Bertolini, 2013; Venter and Mohammed, 2013; Bao *et al*., 2014), as well as restaurants, and urban development zones (Geertman and Ritsema Van Eck, 1995; Kelobonye *et al*., 2020). Hansen's gravity-based measure is more appreciated for its ability to tackle the spatial analysis of various scenarios such as "what is and what if" (Geertman and Ritsema Van Eck, 1995). Regardless of Hansen's gravity-based measure having its advantages (Hu and Wang, 2016) and being widely used to model transportation planning, some studies have criticized the measure for its limitations (Shen, 1998; Levinson, 1998; Guagliardo, 2004; Sanchez *et a*l., 2004; Cheng and Bertolini, 2013; Bao *et al.*, 2014; Hu *et al*., 2017). Hu and Downs (2019) highlighted three cons of Hansen's gravity-based measure, i) sensitivity to the geographical scale, and units of analysis; ii) assuming that the temporal dynamics of job opportunities and workers remain constant over time, and iii) the lack of dynamic geovisualization methods for mapping place-based job accessibility of multiple periods. Huff (1963) also adds that the measure does not assume an individual's behavioural or individual characteristics, which may affect the conclusions on accessibility (Geurs and van Wee 2004). Despite these cons, the gravity-based measure is still generally preferred by researchers; the pros of the method include that it can be modified to introduce different components to suit various study areas (Shen, 2001; Cheng and Bertolini, 2013; Hu and Wang, 2016). Kelobonye *et al.* (2019) further add that gravity-type measures are also preferred for their more realistic treatment of distance and travel-time impediments. Another commonality noticed in the studies in Table 1 is the approach applied in diverse contexts and using GIS to address accessibility issues. Table 1 summarises a non-exhaustive list of common accessibility measures featured in most accessibility studies.

Table 1: Overview and characteristics of important literature on job accessibility analysis.

Author & Year[13]	Approach[14]	Measure[15]	Spatial Disaggregation[16]	Socio-economic[17] Disaggregation	Friction Movement[18]	Focus[19]	Country[20]	GIS[21]	Service[22]
Reilly (1929)	'What is'	Proposed "The Law of Retail Gravitation"	__	Population, size	Euclidean	Urban	United States	No	Retail
Stewart (1947)	'What is'	Proposed replacing Newton's concept of masses with	__	Population, size	Euclidean	Urban and rural	United States	No	Potential opportunity

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[13] Author refers to the name(s) of the person(s) that contributed to a publication/written work and the year is the date when the work was published.

[14] Approach is the type of scenario outlook established to tackle the accessibility challenges in research.

[15] Measure is the type of accessibility measure used to achieve the set research objectives.

[16] Spatial Disaggregation refers to the spatial unit of analysis selected to represent and improves accuracy of data.

[17] Socio-economic Disaggregation is a variable(s) identified for analysis in a study.

[18] Friction movement differs according to various studies, it can be the threshold of time or a value of resistance in movement.

[19] Focus is to indicate the location set up of the study area, which is mainly between rural and urban or both.

[20] Country is the study area where the case studies took place.

[21] GIS is to indicate whether the methodology made use of GIS techniques for the analysis or not.

[22] Service is the type of supply /demand that is under investigation.

Author & Year[13]	Approach[14]	Measure[15]	Spatial Disaggregation[16]	Socio-economic[17] Disaggregation	Friction Movement[18]	Focus[19]	Country[20]	GIS[21]	Service[22]
		population to derive laws of demographic gravitation.							
Hansen (1959)	'What is'	Gravity-based	Administration zone	Population, number of jobs, annual retail sales	Travel-time	Urban	United States	No	Employment, social opportunity, shopping and residential growth
Geertman and Ritsema Van Eck (1995)	'What is'	Cumulative accessibility	Administration zone	Population, employment	Network	Urban	Netherlands	Yes	Jobs, services
Levinson (1998)	'What is'	Gravity-based	__	Household travel survey	Euclidian and travel-time	Urban	United States	No	Work
Shen (1998)	'What is'	Gravity-based	Census block groups	Population, low-wage workers	Travel-time	Urban	United States	Yes	Employment

Author & Year[13]	Approach[14]	Measure[15]	Spatial Disaggregation[16]	Socio-economic[17] Disaggregation	Friction Movement[18]	Focus[19]	Country[20]	GIS[21]	Service[22]
Zhao *et al*. (2009)	'What is'	Multiple regression analysis	—	Worker's gender, annual household income, household composition and the worker's occupation	Travel-time	Urban	China	No	Jobs
Cheng and Bertolini (2013)	'What is'	Gravity-based	Postcode level	Population, employment data	Distance decay and network	Urban	Netherlands	Yes	Jobs
Venter and Mohammed, (2013)	'What is'	Gravity-based and threshold model	Residential zone	Household travel survey, addition survey on taxi routes and fares	Distance, travel-time and travel costs	Urban	South Africa	Yes	Jobs
Bao *et al*. (2014)	'What is'	Multiple regression analysis	Traffic zone	Population and employment in each traffic zone, the	Travel-time	Urban	China	Yes	Jobs

Author & Year[13]	Approach[14]	Measure[15]	Spatial Disaggregation[16]	Socio-economic[17] Disaggregation	Friction Movement[18]	Focus[19]	Country[20]	GIS[21]	Service[22]
				gender, age, job, income and personal basic attributes as well as travel conditions					
Liu and Zhu (2004)	‘What is’	Integrating accessibility measures such as (cumulative-opportunity measures, gravity-type measures, and utility-based measures)	Sub-zones	Population census (working population), housing	Travel-time	Urban	Singapore, Asia	Yes	New economic development zones
Maritz and Moagi (2015)	‘What is’	Catchment analysis and proximity counts	1km x 1km hexagon sizes	Population count (2011 census), dwelling frame, transport network, court distribution	Travel distance, proximity to population	Rural and urban	North West and Gauteng, South Africa	Yes	Justice (courts) facilities

Author & Year[13]	Approach[14]	Measure[15]	Spatial Disaggregation[16]	Socio-economic[17] Disaggregation	Friction Movement[18]	Focus[19]	Country[20]	GIS[21]	Service[22]
Wang *et al*. (2018)	'What is''	Gravity-based	Grid (300m x 300m cells)	Taxi-tracking and facility information dataset	Travel-time	Urban	China	Yes	Restaurants
Kelobonye *et al.* (2020)	'What is'	Cumulative accessibility and modified gravity-based	Zones	Population, housing, employment, census data, travel survey data and employment survey	Travel-time, distance delay	Urban	Australia	Yes	Activity centres ("jobs and other key services")
Silalahi *et al*., (2020)	'What is'	Gravity-based	Grid (100 × 100 m^2) cells	Population density, administrative boundaries, hospital and settlement layers	Travel-time, service area	Urban	Jakarta, Indonesia	Yes	Health care facilities

Author & Year[13]	**Approach**[14]	**Measure**[15]	**Spatial Disaggregation**[16]	**Socio-economic**[17] **Disaggregation**	**Friction Movement**[18]	**Focus**[19]	**Country**[20]	**GIS**[21]	**Service**[22]
Wanghe *et al.*, (2020)	'What is'	Gravity-based and network analysis tool	Centroids[23] of nodes	Public green spaces	Distance weighted by impedance/resistance, network	Urban	Beijing, China	Yes	Building and prioritizing the green corridors in urban areas

[23] Are the generated geometric centres (usually in points) of a shape (polygon) representing the origins or destinations (Liu and Zhu, 2004).

2.3.2 Travel-Time and Distance-Based Measures in Accessibility

Accessibility measure studies use Euclidean distance or network-based path as a measurement method; however, travel-time for any trip relies on both the mode of travel and time of the day when the trip is made (Miller, 2018). Time and distance are some of the primary elements used in accessibility models to measure inequality between the location of jobs and residential areas (Levinson, 1998). However, several scholars also identified several limitations in accessibility measures. For example, Liu and Zhu (2004) highlight that most accessibility measures built into applications are only proximity-based and disregard personal preferences as a critical factor in the space-time variable in travel behaviour. In addition, the travel-time approach has been criticized for being static and not considering how human behaviour, activity patterns, and population composition varies by the time of day (Kim and Kwan, 2003; Liu and Zhu, 2004; Weber, 2006). They ignore the participation of time possible at a particular location and the fact that many opportunities will not be accessible during the evening (Kim and Kwan, 2003). Also, Venter and Cross (2014); Dahlgren (2008) highlighted that the challenge with spatial measures is that they do not consider the speed and frequencies at which you can travel along the road network. Miller (2018) adds that the dynamics in measuring accessibility is that travel-time is a sensitive variable, changing in response to changes in both the demand and supply of the system. While on the contrary, distance-based measures only change based on the attraction variable levels in the measure; this means that factors such as the size of the location in a measure might influence the attractiveness of a particular location (Miller, 2018). Nevertheless, studies (Hu and Downs, 2019; Liu and Kwan, 2020) show that although travel-time is a complex variable, it is generally a preferred impedance option over distance in accessibility studies. Researchers have developed various operational GIS methods that incorporate the spatial distribution of opportunities (Geertman and Ritsema Van Eck, 1995; Cheng and Bertolini, 2013), varying travel speeds, the physical properties of the transportation system, and network distances in the model to counteract these limitations (Kim and Kwan, 2003; Miller, 2018; Hu and Downs, 2019).

2.3.3 Applications of Job Accessibility Measures and Spatial Diversity

Transport studies worldwide, particularly in the USA, have used and modified the gravity-based measure adapted from Hansen (1959) to assess spatial accessibility to various economic opportunities (Levinson, 1998; Cheng and Bertolini, 2013; Hu *et al.*, 2017). Accessibility as a spatial phenomenon integrates the concept of mobility with an understanding that journeys are driven by the desire to reach a destination (Owen and Levinson, 2015). The relevant and valuable methods to measure accessibility should be considered based on the objective of the study, and the understanding and interpretation of the model (Bertolini *et al*., 2005; Kelobonye *et al.*, 2020). Many accessibility measures have limited their scope to one type of urban service, such as job accessibility, to reveal comprehensive and critical information about the urban spatial structure (Cheng and Bertolini, 2013; Fransen *et al*., 2015; Owen and Levinson, 2015; Kelobonye *et al*., 2020).

Levinson (1998) analysed the accessibility and journey to work in the Washington DC area using the gravity measure and found that accessibility to jobs had a significant impact on the commute duration. The results showed that accessibility to jobs declined as the distance from the city centre increased (Levinson,1998). Similarly, although through an alternative lens, Burdziej (2019) also noted that, longer commutes not only affected the quality of life of citizens but they had a negative impact on the urban environment and road conditions of Turon in Poland. Another study by Fransen *et al*. (2015) used the time-dependent accessibility measure to identify public transport gaps by looking at the public transit needs and public transit provision in Belgium. Their study revealed that mainly suburban areas were characterized by high public transport gaps (Fransen *et al*., 2015).

Contrary to the above studies on commuting duration, Liu and Kwan (2020) explained that the presence of transport alone does not guarantee access to places of work as the existence of other challenges may prohibit full utilization of such facilities, especially amongst socially vulnerable groups. Challenges such as job diversity, transportation costs, gender roles, housing affordability, household structure, individual needs, and other aspects may also affect traditional measures of accessibility to jobs. Furthermore, several studies (Shen, 1998; Geurs and van Wee, 2004; Cheng and Bertolini, 2013) have shown that both dimensions of spatial match and non-spatial match (i.e. social, political, economic, and cultural) have effects that impact an individual's employability[24]. They argued that a residential area might be located close to many economic opportunities, but residents may not have the skills to qualify for those opportunities (Shen, 1998; Geurs and van Wee, 2004; Cheng and Bertolini, 2013). Additionally, a study by Kwan (1999), demonstrated that using the length of commute trip alone as a relative measure may misrepresent the accessibility experience for women with children since their access to jobs may be constrained by the location of essential facilities such as child care facilities rather than the opposite.

Some studies however have made efforts to incorporate other aspects that were not initially addressed by the gravity-based model. Hu *et al.* (2017) used the gravity model to explore how changes in the socio-economic and spatial landscape between 2000 and 2010 affected job accessibility of low and high education groups in Beijing. The results revealed that changes in the city's economy minimized job opportunities for the population with high-education levels while opportunities for proportions of the population with low-education levels remained stable. Furthermore, results for spatial structure revealed

[24] The potential ability of an individual to obtain employment.

slight spatial segregation between the two education groups with a great percentage of the high-education group in the outer parts of the city and the low-education group in the inner ring of the city. Another job accessibility study conducted in the Chicago metropolitan[25] area (post-industrial city) particularly considered accessibility by race and household income using a modified gravity model and regression analysis. The findings suggested that African Americans from low-income households had high accessibility to job opportunities however this did not have a significance on the household income due to the lack of entry-level jobs for job seekers (Jin and Paulsen, 2018). This implies that job accessibility should incorporate the element of job diversity to account for the skills and occupational match of respective job seekers (Geurs and van Wee, 2004; Reggiani *et al*., 2011; Cheng and Bertolini, 2013).

2.4 Modelling of Spatial Accessibility in the GIS Application

Spatial modelling combines project information and data from other sources into an organized framework to simulate a full spatial model and the impact of a project (Venables, 2016). Studies in Table 1, show that accessibility analysis and modelling incorporate the use of GIS tools to draw out techniques that evaluate land use, transportation, as well as issues relating to social and economic impacts (Geurs and van Wee, 2004; Roth *et al*., 2016; van der Merwe and Krygsman, 2020; Verma and Dash, 2020). Various studies by Cheng and Bertolini (2013); Fransen *et al*. (2015); Kelobonye *et al*. (2020); and Wanghe *et al*. (2020) adopted the modified gravity-based measure and based on their desired objectives incorporated the use of GIS tool to simulate and visualize their results. Other studies by Zhao *et al*. (2009), Bao *et al*. (2014) and Verma and Dash (2020) made use of both statistical analysis and spatial analyst tools in GIS to model the geographical accessibility of public health care and jobs. Studies reflected in Table 1 also show the impact and contribution of GIS in computing accessibility analysis under various fields of application (for example Liu and Zhu (2004), Silalahi *et al*. (2020) and Wanghe *et al*. (2020)). The application of integrated tools in GIS such as Network Analyst and Spatial Analyst were leveraged to evaluate the efficiency of transportation networks and produce a surface model of job accessibility levels in Singapore (Liu and Zhu, 2004). Silalahi *et al*. (2020) also used the GIS network analysis and modelling

[25] The word “metro” will be adopted throughout this research report instead of metropolitan.

through the application of Origin-Destination (OD) Cost Matrix[26] and Service Area[27] analysis to estimate the travel-time and distance to healthcare services in Jakarta, Indonesia. Furthermore, Miller (2004) also adds that in recent years researchers have been encouraged by the developments in GIS which have expanded the scope of theories and techniques for analyzing space-time behaviour.

2.5 Job Accessibility and Spatial Mismatch Studies

2.5.1 Concept of Spatial Mismatch in International Studies

Zhou *et al*. (2016) explored the concept of spatial mismatch and the efficiency of the transport system through job accessibility analysis using the actual commuting distance and accessibility indicators from a cumulative opportunity model and proved the existence of a hypothetical job-housing imbalance in Shanghai, China. On the other hand, Bao *et al.* (2014) studied the impact spatial mismatch has on the commute time of residents in China and noted that a method that assumes that the opportunity demand is equally distributed or there is no restriction on the number of employment opportunities could lead to inaccurate results when applied in the context of China. Empirical studies based only on commuting indicators such as time, distance, etc. did not fully prove the existence of spatial-mismatch and therefore they followed a method proposed by Shen (1998) which adopted job accessibility as a measurement indicator for studying spatial mismatch (Bao *et al*., 2014). The improved method they came up with considers the weight coefficient (probability of job opportunities) that quantifies the degree of uneven distribution of employment opportunities (Bao *et al*., 2014). Spatial accessibility studies conducted on transport and public facilities accessed by residents within urban areas have yielded evidence which suggests the existence of spatial inequality in the USA, Europe, and Asia (Gobillon *et al.*, 2007; Zhou *et al.*, 2016; Burdziej, 2018; Liu and Kwan, 2020). Moreover, in one of the largest African cities Nairobi (Kenya), Nakamura and Avner (2021) highlighted that the level of job accessibility depends on the locations of jobs and residential areas as well as the transport network. Nakamura and Avner's, findings further suggest that residents located in informal settlements of Nairobi, particularly the poor, are far from job opportunities compared to those living in what they term “high-value locations”.

[26] The Origin-Destination Cost Matrix is a network analyst tool in GIS used to calculate accessibility from multiple origins to multiple destinations and makes use of properties such as impendence (minutes) and cut-off value (time) (Silalahi *et al.*, 2020). OD will be used as an abbreviation for Origin-Destination Cost Matrix in this document.

[27] *Service area analysis* is a network analyst tool in GIS used to measure the distance in which a facility can supply its services (Fransen *et al.*, 2015).

2.5.2 Concept of Spatial Mismatch in Local Studies

Research on spatial mismatch has also been done in the South African context, mainly on the urban growth and mobility patterns within urban areas (Culwick *et al*., 2015). Budlender and Royston (2016), followed the concept of spatial mismatch in the case of South African metro municipalities to examine the relative significance of employment distance on the unemployment rate. Budlender and Royston's results from the regression analysis revealed evidence of a spatial mismatch between residential areas and job locations within the City of Tshwane, the City of Johannesburg, City of Ekurhuleni, eThekwini, Mangaung, Buffalo City, Nelson Mandela Bay and the City of Cape Town. Furthermore, van der Merwe *et al*. (2020) use employment duration and spatial location data (of where employees live and places of employment) from South African Revenue Service (SARS)'s IRP5 administration datasets which show all income earners in South Africa to assess individuals' employment duration and the travel distances from residential areas to work. The results confirmed the existence of a spatial mismatch in South African metro areas and constrained job search areas for lower-income workers compared with higher-income workers, further aggravating inequality (van der Merwe *et al*., 2020).

A study by Rospabe and Selod (2006) investigated a mismatch between jobs and residential areas within the City of Cape Town by using employment location data from Cape Town's Regional Service Council Levy Business Database and the 1998 Migration and Settlement in the Cape Metropolitan Area survey dataset compiled by the Cape Metropolitan Council. The results from a logistic regression model revealed that an increase in commuting distance will increase one's likelihood of being employed (Rospabe and Selod, 2006). Regardless of this evidence, Mubiwa and Annegarn (2013) state that the post-apartheid government continued to establish houses even further from urban centres and transport corridors. Sinclair-Smith and Turok (2012), had also discovered that the spatial economy of South African cities is undergoing a process of selective outward spread of economic activity (i.e. businesses) due to more affordable land outside the city, deteriorating environmental conditions, security and congestion in the older economic centres. A spatial mismatch was found between areas where the poor reside and economic opportunities in many Sub-Saharan African cities, particularly in Gauteng (Chakwizira *et al*., 2014). Geyer and Molayi (2018) used a statistical method called Analysis of Variance (also known as ANOVA) in Gauteng to examine the relationship between the job-employed ratio (i.e., the percentage of residents that work in the same location in which they live) and the average travel-time. The results showed that workers who were employed within the exact areas where they reside had a lower average travel-time than those who reside in areas outside their work (Geyer and Molayi, 2018).

On mobility patterns in Gauteng, evidence from a study conducted by Culwick *et al.* (2015) using private and public transport revealed that the mean Euclidean distance travelled to work by both African and White population groups was the same. However, on average, the White respondents travel 42 minutes to work compared with 56 minutes for African respondents who travel from areas in the fringe of the province such as Soshanguve, Orange Farm, and Daveyton. According to Culwick *et al.* (2015), the difference may be explained by the majority proportion of affluent white residents that have access to private vehicles as well as gated residential developments on the urban fringe that enables them to travel long distances to work. Culwick *et al*. (2015) also examined spatial accessibility in the region and found that traffic flow was an important concern as congestion affects business efficiency, regional competitiveness and the quality of life of the residents. Similarly, Lionjanga and Venter (2017) used the Access Envelope methodology to assess the accessibility to jobs locations and the cost of using public transport (minibus taxi and BRT) biennially from 2009 to 2013 in the City of Johannesburg, focusing on a select group of townships namely, Alexandra, Soweto, and Orange Farm. The study revealed that Alexandra has high levels of accessibility due to its proximity to crucial economic nodes compared to Soweto and Orange Farm. The results also indicated that the absence of low-fare high-speed trails limited commuters to minibus taxis, resulting in high fares and restricted accessibility (Lionjanga and Venter, 2017). Moreover, a study by Mubiwa and Annegarn (2013) mentioned Diepsloot (also a township in Gauteng) as one of the examples of settlements developed on the outskirts of the city centre with no formal public transport infrastructure.

The Spatial Development Framework 2040 by the City of Johannesburg (2016) points out that the car-oriented developments (e.g., malls, gated communities) by the private sector have increased spatial segregation (City of Johannesburg, 2016). However, the NDP document, which contains the 2030 national vision, highlights that the South African government plans to develop strategies for densifying inner cities to promote suitable settlement locations and bring people closer to economies. Also, the approved Nodal Review Policy 2019/20 document notes that since the early 2000s, the city's approach to urban growth management has been that of a compact development which, in principle, allows people to live closer to work and schools (City of Johannesburg, 2020).

Lastly, Venter and Cross (2014) used case studies of Mamelodi and Soshanguve in the City of Tshwane metro municipality to compare the impact of employment accessibility on earning potential for poor households and looked at the influence of transport plans and spatial planning. The results showed that Soshanguve accessed job opportunities within key clusters of employment in Tshwane and took home at least R100 daily; simultaneously, Mamelodi revealed a more significant advantage than Soshanguve. The findings were attributed to the passenger rail service connecting Soshanguve to the city, and similarly to the old central part of Mamelodi, which is located close to rail, bus, and taxi facilities that offer relatively low travel-time to the city (Venter and Cross, 2014).

2.6 Literature Synthesis

The reviewed literature indicates that the concept of accessibility has been widely studied to understand the human interaction with space and its socio-economic impacts. Accessibility measures and modelling travel-time can be used to identify areas for improving public transport to reduce spatial inequalities in accessibility (Büttner *et al*., 2018). Studies indicate that the traditional gravity-based model is widely used (Hansen, 1959; Levinson, 1998; Shen, 1998) and has been improved over the years to overcome the spatial barriers from residential areas to areas of economic opportunities (Cheng and Bertolini, 2013). Some studies have gone as far as including non-spatial factors such as income, cost of transportation, and race to assess the dynamics of spatial accessibility to economic opportunities. Despite its popularity, which justifies its reliability and accuracy, the measure is relatively more complex and computation intensive (Kelobonye *et al*., 2021). Literature conducted in South Africa suggests that the current urban form and transport system exacerbates urban segregation despite efforts to rectify this (van der Merwe and Krygsman, 2020). Kgwedi and Krygsman (2019) used the 2013 National Travel Time Survey to measure the level of public transport for commuters focusing on South Africa's metro areas; the results revealed that an average of 55 minutes was spent by commuters using public transportation modes. In Gauteng, a study by Lionjanga and Venter (2017) indicated that the absence of affordable high-speed trails limited commuters to minibus taxis resulting in the payment of high fares and, consequently, broad areas of poor spatial accessibility in some parts of the province. According to Cheng and Bertolini (2013), only a few studies focus on the impact of diversity on available opportunities in studies related to job accessibility. In South African literature (Venter and Cross, 2014; Culwick *et al*., 2015; Van Dijk *et al*., 2015; Budlender and Royston, 2016; Geyer and Molayi, 2018; van der Merwe and Krygsman, 2020) reveals that only a few studies on spatial accessibility to places of work mainly at a regional scale using GIS are in existence. Therefore, this study seeks to contribute to spatial accessibility studies by incorporating the diversity in places of work at a regional scale in Gauteng.

The study's methodology incorporates a useful spatial analysis tool (GIS) that can add value in modelling and visualizing travel-time to places of work. Accessibility to places of work as a valuable indicator to assess inequality in socio-economic interactions (Pan *et al*., 2020) can also be used to assess the progress made in Gauteng towards achieving spatial transformation through inclusive service delivery of services pertaining to human settlements and transportation infrastructure. The use of GIS as a planning tool in analyzing accessibility to basic facilities (Mokgalaka *et al*., 2013; Maritz and Moagi, 2015; Baloyi *et al*., 2017) has yielded results that have shown that its application in planning could help improve spatial accessibility in the marginalized communities. The application of the tool also applies to identifying areas with poor spatial accessibility to economic opportunities and removing spatial barriers that restrict residents from participating in economic activities (Lionjanga and Venter, 2017; Venter and Cross, 2014). The study applied the modified gravity-based model within the context of Gauteng using GIS. The target population was broadened by considering all the residential areas to include all types of residential areas to cater to all potential job seekers and explore the probability of labour market participation within the study area.

2.7 Ethical Consideration

The data in this study was acquired for the sole purpose of this research and will not be redistributed to any third parties, especially without permission from the data custodians. The data used in the analysis does not include any personal information of individuals.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter provides the background of the study area and a diagram illustrating the processes followed to achieve the research objectives. The chapter also contains the description of the required data, a brief data accuracy assessment to evaluate the suitability and usability of the acquired data, and the process followed in the data manipulation and analysis. The last part of the chapter focuses on displaying maps of the processed data and the accessibility measure parameters used for the analysis.

3.2 Study Area

The spatial footprint of Gauteng covers five municipalities, three metro and two district municipalities (Greenberg, 2010; Mubiwa and Annegarn, 2013). The three metro municipalities are Johannesburg, Tshwane, and Ekurhuleni, and the districts include Sedibeng and the West Rand (Wray, 2010; Mubiwa and Annegarn, 2013; Luke and Pisa, 2018; Terwin, 2019). Gauteng has a total land surface area estimated to be 18 176 km^2 (Bobbins, 2013). The province has a diverse socio-economic landscape and represents one-quarter of the country's population (Luke and Pisa, 2018). The discovery of gold in 1886 in the Witwatersrand and later the short-lived coal near Boksburg in 1887 Gauteng (Fair and Mallows, 1959; Mabin, 2013), transformed the share of economic activity and population in South Africa (Gotz *et al.*, 2014). The mining industry led to the establishment of a mining camp in 1886 which grew into a village before becoming a mining town (Mubiwa and Annegarn, 2013). In the years following, a series of independent mining camps surfaced along the gold reef, they and later grew into small towns from Krugersdorp to Benoni, with Nigel isolated to the south-east (Fair and Mallows, 1959). According to Gotz *et al*. (2014), the gold discovery attracted huge international investments and institutional development, such as Rand Water. The gold discovery also played a critical supportive role in the development of South Africa's (previously known as the Transvaal) economy, infrastructural development, and the governmental centre in Pretoria (Fair and Mallows, 1959). The mining town also had a railway line that served as the leading transport support service prior to the origin of Johannesburg's CBD *(*Chakwizira *et al.*, 2018). Over the years, the town grew due to the perception of employment and economic opportunities that attracted opportunity seekers within and outside the borders of South Africa (Coggin and Pieterse, 2015). According to Fair and Mallows (1959), the extension of deep-level mining in 1916 led to the establishment of an industrial development area in the East Rand, which contributed to the growth of towns such as Benoni, Boksburg, Brakpan, Springs, and Nigel. The map in Figure 2 shows the study area and the municipal boundaries that make up the province of Gauteng.

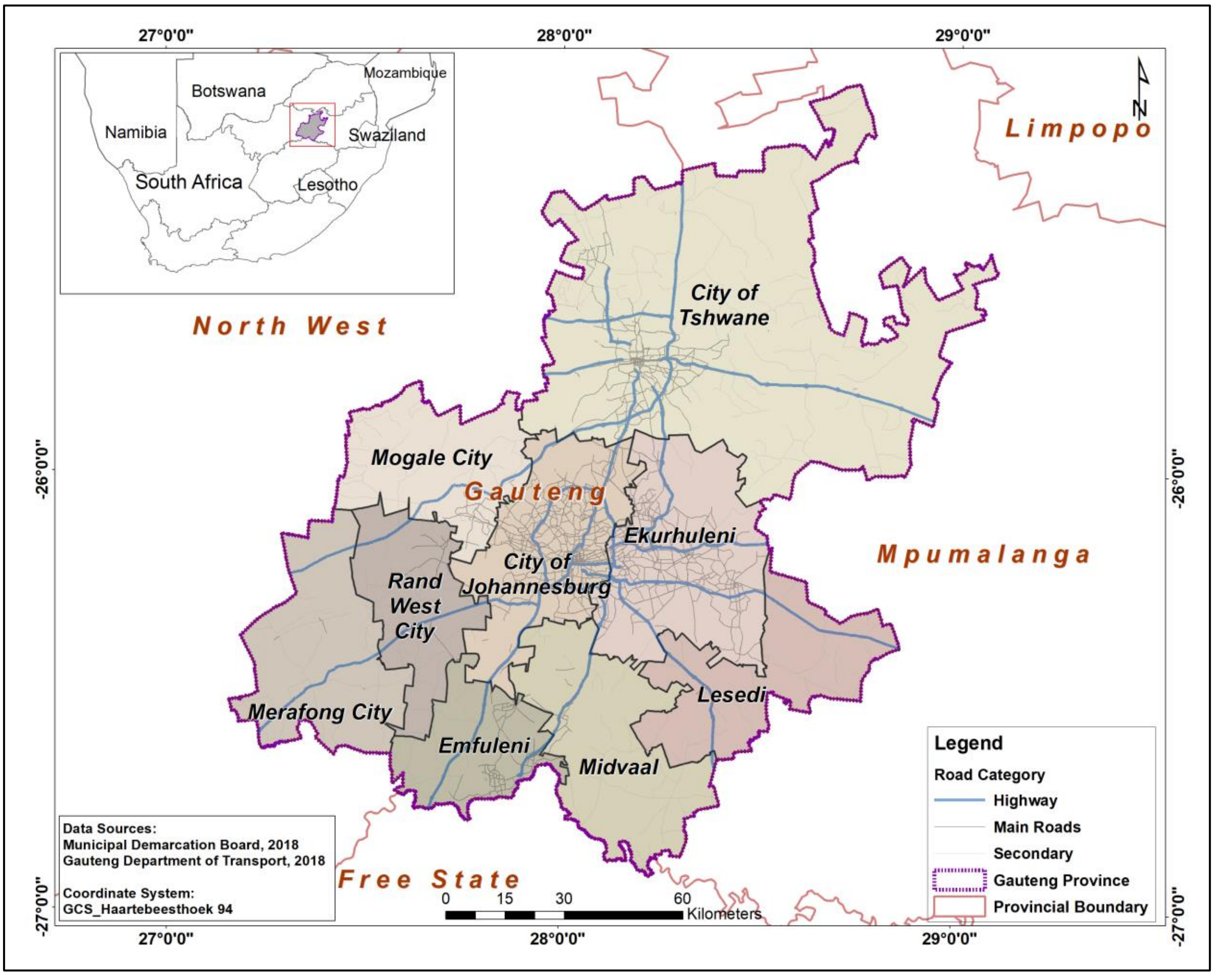

Figure 2: Map showing the location of the study area, Gauteng.

The province of Gauteng alone generates about 40% of the country's gross domestic product; however, it only accounts for 1.5% of the total land mass of South Africa (Everatt, 2014; de Kadt *et al*., 2019). Nonetheless, Gauteng experiences the highest levels of migration compared to other provinces in South Africa (Chakwizira *et al.,* 2018). The StatsSA General Household Survey (2016) indicated a growth rate of 39% for Gauteng province between 2002 and 2013, while the Western Cape only recorded a rate of 12.3%. Also, the StatsSA Census 2011 report released in 2012 revealed that the province of Gauteng had roughly 12.3 million people in 2011 (Statistics South Africa, 2012). The population figure is predicted to be almost double the 2011 size by 2055 (Mubiwa and Annegarn, 2013). Gauteng attracts migrants seeking opportunities in the province from various provinces of South Africa and cross-border migrants from other countries within and outside the continent of Africa (Peberdy, 2013; Coggin and Pieterse, 2015). The province is largely urban (Mushongera *et al*., 2015) and dominated by formal dwellings, yet a large percentage of the population resides in informal settlements (Dlamini *et al.*, 2020). According to Coggin and Pieterse (2015), black and poor migrants tend to settle in informal settlements that are mostly found in the urban periphery of the province.

The existing spatial structure has implications for traffic congestion, long commuting times, and distances between areas of residence and areas of socio-economic opportunities (Chakwizira *et al*., 2018). Gauteng's history of car-centric transport planning and related infrastructure investment has also strengthened and exacerbated spatial inequality (Coggin and Pieterse, 2015). According to a report on Trends in Passenger Transport in South Africa (2007), in 2003, Gauteng had the highest mean travel time to work at 50.6 minutes, while the Western Cape only had 40.3 minutes (Lombard *et al*., 2007). The National Household Travel Survey of 2013 showed that private vehicles and minibus taxis in South Africa are commonly used in the metro areas compared to bus and rail transport (Statistics South Africa, 2013). The 2013 Quality of Life (QoL) survey data[28] recorded that more than 56% of Gauteng residents rely on public modes of transport, and 29.7% use private vehicles, while 10.2% are pedestrians (Venter and Badenhorst, 2011). According to the National Transport Master Plan (NATMAP) 2050, the lack of appropriate land-use and transport integration impact negatively on the implementation of mass public transportation (Department of Transport, 2010) as well as the attempts to address transport disadvantages and improve accessibility (Jennings, 2015). A study by Chakwizira *et al*. (2011) investigated the impact of significant transport interventions such as the Gautrain rapid rail link and BRT towards reversing the challenges faced by the urban public transportation systems in the Gauteng Region. Their findings revealed that public transport interventions such extending the existing rapid rail link to areas where growth is taking place to reduce transport challenges in the region (Chakwizira *et al*., 2011). Risimati and Gumbo (2018), also observed that the implementation of the Gautrain rapid rail link and BRT transportation services serves only a low percentage of the commuting public and this is due to the lack of integration in the public transport networks which results in a lack of collaboration between facilities of traditional transportation modes. As such, the Gautrain is limited to strategic areas between Pretoria, Sandton, Johannesburg, and the Kempton Park area, it only carries 1% of commuters in the province while the BRT only carries 2% (Terwin, 2019). On the other hand, conventional buses carry 8% and Metrorail 21% (Venter *et al*., 2018).

The spatial configuration of Gauteng demonstrates a polycentric province due to the flow of economic activities between its nodes (Todes, 2012; Brand *et al*., 2017; Geyer and Molayi, 2018). The province is at the centre of a web of nationwide infrastructure networks such as national roads, gas, and oil pipelines passenger and freight rail, road freight routes, electricity transmission lines, water transfer schemes, and

[28] The Quality of Life (QoL) survey is conducted every two years in Gauteng Province and it measures the quality of life based on characteristics such as socio-economic circumstances, attitudes to service delivery, psycho-social attitudes, value-base, and other characteristics (Hamann and de Kadt, 2021)

national and international air corridors that converge on and radiate from its towns as well as cities (Gotz *et al*., 2014). The economy of Gauteng is also anchored to the north of the province by Rosslyn, found within the City of Tshwane, and linked to the City of Ekurhuleni which lies in the east of the province (Cheruiyot, 2020). The economy which was previously centred in central Johannesburg started declining in the 1980s (Bremner, 2000), and in 1994 after the fall of the apartheid government, most of the top commercial businesses that were located in the CBD relocated to decentralized areas while a few remained behind (Bremner, 2000; Mubiwa and Annegarn, 2013). According to Bremner's study, the Johannesburg City Council developed strategies to revive the image of the inner city in response to the challenges and one of the strategies included a light rail link project to integrate Soweto with the city. The move from the Johannesburg CBD gravitated towards the northern suburbs with the development of economic hubs such as Sandton, Randburg, and Rosebank (Mubiwa and Annegarn, 2013). The City of Ekurhuleni metro is characterized by industrial areas and logistic areas such as Jet Park, Boksburg, and Germiston (Cheruiyot, 2020). The development of transport, and mobility infrastructure in Gauteng has also led to the construction of rapid development of industrial and office parks in Midrand, along the N1 highway which connects Johannesburg and Pretoria (Mokonyama, 2009).

In summary, the interaction between transport and land-use systems affects the urban form *(*Venables, 2016*;* Zhou *et al*., 2016). Consequently, the public transport challenges in South Africa prompted the provincial government of Gauteng to implement critical transport initiatives such as the BRT system and Gautrain rapid rail link (Mokonyama and Mubiwa, 2014; City of Johannesburg, 2016; Geyer and Molayi, 2018). The BRT system was implemented in Ekurhuleni (Harambee), Johannesburg (Rea Vaya), and Tshwane (A Re Yeng) to connect the previously disadvantaged residents in the townships to the economic centres within Gauteng (Gotz and Wray, 2014). Despite the province being an economic muscle of the country it still faces challenges of post-apartheid policies, inefficient transport systems, the spatial fragmentation of labour markets, rapid urbanization[29], and high densities in the low-income settlements located on the urban edges (Chakwizira *et al*., 2018; Culwick and Patel, 2020). According to the authors, these challenges increase issues of inequality and deepens urban poverty (Chakwizira *et al*., 2018; Culwick and Patel, 2020). Moreover, urbanization in developing countries comes with challenges, such as pressures on resources, lack of adequate services, development of slums, poor planning, and degradation of land (UN-HABITAT, 2009). A common goal outlined in planning and policy documents such as NDP, NSDP, and SPLUMA is to bring previously disadvantaged communities closer

[29] Urbanization refers to movement of people for the countryside to town (Parnell and Walawege, 2011).

to economic opportunities and enable them to participate in the job markets (National Planning Commission, 2011; NSDF, 2018).

3.2.1 Overview of the Research Process

Figure 3 shows the process that was followed in conducting this research to achieve the final results. The general flow involved identifying important data for the analysis, the process was then followed by assessing the accuracy of the data prior to manipulating the data. The spatial analysis was carried out on the data to produces the desired end product. Refer to the diagram in Figure 3 for detailed information.

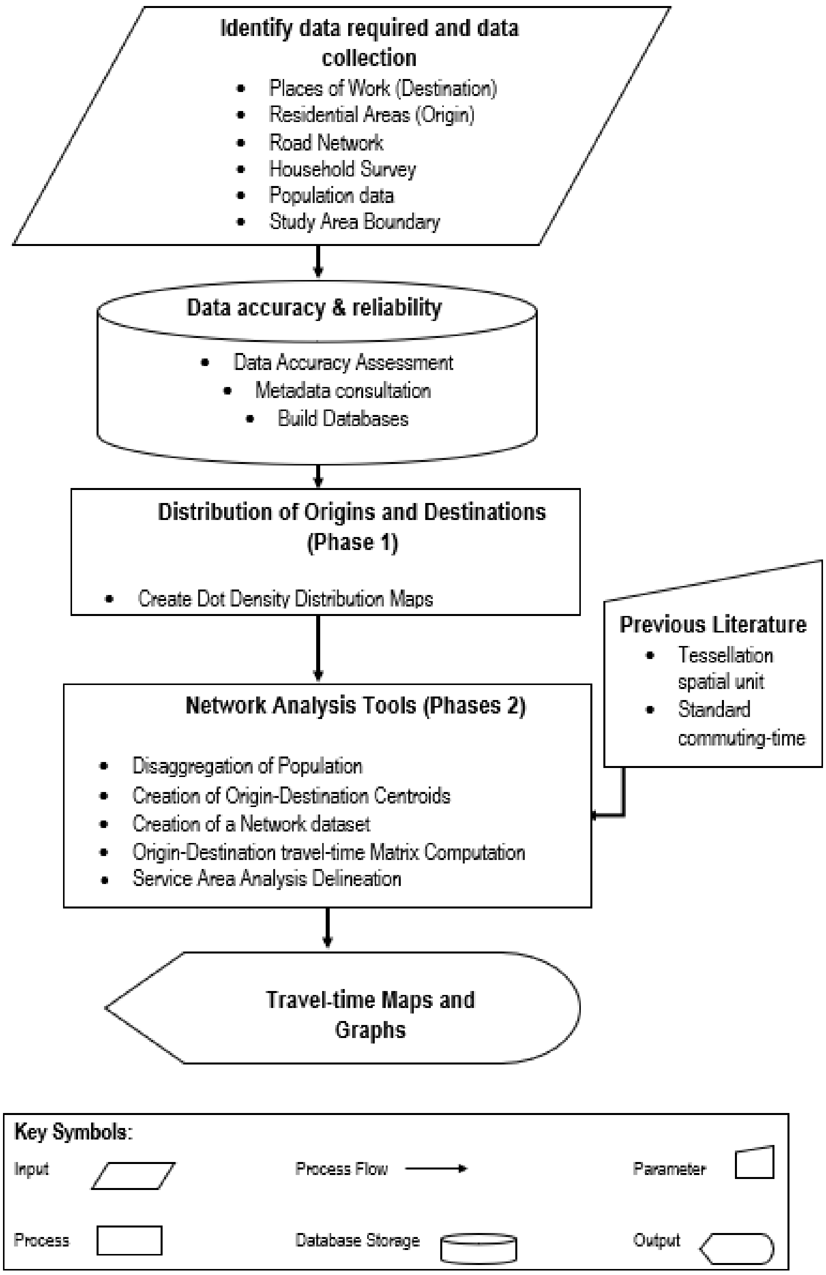

Figure 3: A flowchart illustrating the research process.

3.3 Data Collection

The study acquired secondary data in the form of GIS shapefiles and excel spreadsheets. Accessibility parameters such as standard commuter time were sourced through a literature review of previous accessibility studies and surveys. The data was collated from both private and public sources. A literature review was used to obtain the acceptable accessibility standard to places of work internationally and in the South African context. Two datasets were obtained online, while the rest of the data[30] was acquired through formal request letters following standard data request procedures outlined by the data custodians. The letters submitted with the data request applications described the aim of the study and how the sourced datasets will be utilized and published. The titles of all data collected and their descriptions were listed in Table 2. The temporal scale of the data used in the study varies (between 2016 and 2018) due to the availability of current data and various sources consulted.

According to Manjia *et al*. (2018), measuring geographical accessibility requires information about the place of origin and destination as well as the road network that connects them. As such, a transport network dataset and Passenger Rail Agency of South Africa (PRASA) railway stations for the study area were obtained from the Gauteng Department of Transport on a regional scale. The attribute fields of the transport network data included the name of the road, direction, road category, and average car speed permitted on each road. The administrative boundary (i.e., municipalities) shapefile was downloaded online from the Municipal Demarcation Board (MDB) GIS portal[31]. For population data, the SA CSIR Mesozones[32] dataset containing the 2016 population estimates at a mesozone[33] level was obtained online from StepSA[34] on a national scale, and metadata accompanied data. The mesozones are demarcations created to represent the population at a lower detailed level (Maritz and Moagi, 2015; Le Roux *et al*., 2019). A summary of details on the description of the SA CSIR Mesozones dataset is included

[30] The transport network data was obtained from the Gauteng Transport Department, QoL survey data from GCRO, the Gauteng dwelling points and commercial buildings from GeoTerra Image.

[31] https://dataportal-mdb-sa.opendata.arcgis.com/

[32] *SA CSIR MesoZone 2018 v2* dataset population estimate for 2016 was obtained using principles of dasymetric mapping using the 1996 EAs, 2001, 2011, and 2016 SPs demarcations as well as the Spot Building Count (SBC) as a secondary data to estimate the underlying statistical surface (Maritz and Moagi, 2015).

[33] A *mesozone level* is described as irregular boundary shape that fit within the administrative demarcations of South Africa and are divided into almost the same size of approximately 50 km^2 zones (CSIR, 2018).

[34] http://stepsa.org/socio_econ.html#Indicator

in *Appendix A.* The Gauteng municipalities were selected from the attribute table to demarcate the study area. The attribute fields included the estimated population figures from 1996, 2001, 2011, and 2016 at a meso-level. The 2017/18 QoL survey data was obtained from the GCRO in an excel database and focused on various demographic, economic and psychosocial questions. However, for the scope of this study the 'transport indicators' were selected for the analysis. Three indicators were selected for the research analysis: frequent trips[35], mode of transport[36], and destination time[37]. The indicators from the QoL survey data were summarized in Tables (3 to 7) in *Appendix B*.

The study also identified residential areas and places of work as another set of data required for answering the research objectives (Table 2). The Building Based Land-Use (BBLU) and dwelling frame data sets were obtained from GeoTerra Image (GTI) in point format. The BBLU data comprised of 3,783,180 records, while the dwelling frame had a total of 3,394,110 records of all residential buildings in the province. The attribute fields of the datasets contained the main land-use class and sub-class codes, region name and enumeration area[38] (EAs) codes. The GTI data sets were also accompanied by metadata documents. Cheng and Bertolini (2013), highlighted the importance of considering the diversity of jobs when measuring job accessibility to also account for a skills match. Therefore, the commercial land-use class was selected from the BBLU data to represent places of work. This particular land-use class was considered to broaden the scope of the targeted population within the study area by including both skilled and non-skilled labour markets. Table 2 presents the datasets acquired for the study and the sources from which they were obtained.

[35] To determine whether the respondents make trips to work

[36] To determine the predominant mode of transport within the study area

[37] To estimate travel time impedance

[38] The smallest geographical unit (a piece of land) into which the country is divided for enumeration purposes, which typically contains between 100 to 250 households.

Table 2: Names of datasets used for the analysis, description and their relevant sources.

Data Set	Description	Year	Data Type	Source(s)
Gauteng (Municipalities and Wards)	Administrative Boundaries	2018	Vector (polygon)	Municipal Demarcation Board (MDB)
Transport Network	Street centrelines, highways and routes	2018	Vector (line)	Gauteng Department of Transport
SA CSIR MesoZone	2016 Population estimates (Mesozone boundary base)	2018	Vector (polygon)	Council for Scientific and Industrial Research (CSIR)
Household surveys	Quality of Life survey	2017/18	Excel spreadsheet database	GCRO
Building Based Land-Use (BBLU)	Residential areas (dwelling frame) and places of wok within Gauteng	2016	Vector (point)	GeoTerra Image

The Environmental Systems Research Institute (ESRI) ArcGIS (version 10.6), Microsoft Excel, and Quantum GIS (QGIS) 3.12 software packages were used for pre-processing the datasets, analyzing the data, and visualizing the output results in the form of maps, graphs, and tables. The Spatial Analysis and Network Analysis tools in ArcMap 10.6 were applied to compute accessibility analysis to places of employment.

3.4 Data Accuracy and Reliability

The study relied on secondary data and the datasets were collected from both the public and private sectors. The process of quality assessment for the data was carried out to ensure accuracy, checking especially the attribute table, geometry, position, scale, and validity of the data. The attribute information of the PRASA railway stations (i.e. names, locations) was verified against the information provided on the PRASA website and the BBLU points from GTI. The datasets were accompanied by metadata documents except for the provincial administrative boundary, road network, and the survey data from GCRO. The metadata for the QoL (2017/2018) survey data was downloaded from the GCRO website, and the information about the Gauteng administration boundaries was also listed on the website. The metadata of the various datasets was evaluated to assess the quality of the data (i.e. GCRO and GTI datasets), and the details were summarized in *Appendix A*.

The metadata documents of the four datasets assisted in ascertaining the quality and reliability of the datasets. The metadata documents also provided descriptions of the corresponding codes captured in the attribute tables (i.e. QoL survey data, building-based land-use points, dwelling points). The coordinate system used on the various datasets was assessed and changed before merging geometry and attributes for analysis purposes (Devillers *et al.*, 2005). The data was re-projected into a standard coordinate system to ensure one common projection. The spatial reference frame that was selected to represent the various datasets within the study areas was the WGS 84/UTM Zone 35 S.

3.5 Limitations

The first limitation of this study was the lack of more recent data, the creation dates of the obtained data varied between 2016 and 2018. This was mainly due to the availability of usable data from various consulted sources. As a result, the study used the SA CSIR MesoZone 2018 dataset instead of the 2011 Census Population (SALs) data. The dates affected the compatibility of the data; for instance, the 2011 SALs could not be joined with the most recent data (i.e. 2016, 2018) due to changes in the municipal demarcations within the study area. Typically, population censuses are only collected every 5, 10, or even 20 years due to the cost implications involved and data collection complexities (Pajares *et al.*, 2021b) however, in South Africa the interval is every 5 to 10 years (Ngidi *et al.*, 2017). Based on empirical studies, accurate computation in accessibility requires spatially disaggregated data (Pajares *et a*l., 2021b). Therefore, spatial disaggregation methods are recommended to estimate the population when data is limited at lower levels because of their ability to (Goodchild and Lam, 1980; Rayer, 2015). To mitigate the challenge of temporal and spatial scale, an alternative was sought to avoid misrepresentation of the population of the ground. Another limitation was the lack of packaged metadata information on the acquired data, the quality of data that did not come with this information could potentially affect the research findings. An example in this instance was the road network data which did not have accompanying metadata.

Furthermore, the COVID-19 pandemic has also had an impact on the acquisition of sufficient data from various sources, this includes the data on the transportation modes used to access employment opportunities within the study area. An alternative from the existing data was established to represent the mode of transport data in the analysis. However, using alternative data could also add to a possible misrepresentation of the current conditions on the ground. Finally, three assumptions were applied in estimating travel-time to places of work from the residential areas in Gauteng. Firstly, it was assumed that the trips were only restricted to the origins (residential areas) and destinations (places of work) within the boundary of Gauteng. Secondly, the origin-destination (OD) matrix is under the assumption of a one-way traffic flow. The third one was that there was a supply and demand of jobs and workers in Gauteng to go ahead with the analysis. The analysis of the study did not consider these listed factors due to the scope of the study. However, despite the limitations outlined, the analysis of this study made use of the most recent, and available datasets and as such the results from this study are still valid.

3.6 Data Manipulation and Analysis

All input datasets that were obtained were clipped using the Gauteng boundary as a mask in ArcMap. The clipping through the application of the *Clip* tool under *Geoprocessing tools* to display features that are only contained within the boundary of the study area. The places of work (commercial buildings) and residential areas (dwelling frame) layers were derived by running a query to filter out classes and sub-classes from the BBLU data set that were out of the scope of the analysis[39]. After omitting the redundant facilities, the analysis layer only consisted of the relevant residential classes i.e. formal, informal, cluster/complexes, estates, security villages, smallholdings/agriculture, and rural workers' housing. The identified commercial building points were further divided into relevant sub-classes[40] for the study. The description of the codes corresponding to the selected land-use classes for residential areas and places of work was identified in the accompanying metadata document. Subsequently, an additional field called "Type" was added to each attribute table of both layers (residential areas and places of work), and the

[39] For example, facilities such as student residences, retirement villages, and correctional services were omitted from the newly derived residential areas layer.

[40] Commercial (office parks, shopping mall, shopping centres, retail, petrol station, financial institutions, restaurants, services, post offices conference centre and informal trading.)

description of the classes for the corresponding codes was manually captured in the attribute table as detailed in the accompanying metadata. To compute accessibility analysis, previous studies were consulted to refer to recommended parameter values to consider. The accessibility parameters and the sources they were adapted from are listed in Table 3.

Table 3: The accessibility measure parameters considered for the analysis.

Parameter	**Value**	**Source**
Spatial unit and type of shape to tessellate	Smallest unit (previous studies) Shape type: Hexagon grid	(Liu and Zhu, 2004) (Cheng and Bertolini, 2013) (Maritz and Moagi, 2015) (Baloyi *et al*., 2017) (Burdziej, 2019)
Type of job	Places of work – Commercial (office parks, shopping mall, shopping centres, retail, petrol station, financial institutions, restaurants, services, post offices conference centre and informal trading.)	Cheng and Bertolini, (2013)
Modes of transport	Private (car) versus public transport (rail)	Road network and rail
Origins and destinations	From residential areas (origins) to identified places of work across the province (destinations)	Cheng and Bertolini, (2013)
Friction Coefficient	Friction Coefficient (previous studies)	Cheng and Bertolini, (2013), (Kerr, 2015)

Travel impedance	Travel time (previous studies and survey): ***International standard**: T*= 30 Minutes by private transport and *T*=45 minutes by public transport Average of 55 minutes for all transportation modes in metros ***Local survey***: Travel time between 16 to 30 minutes was the highest recorded from the QoL respondents. See *Table B_2: Time Destination* in Appendix B	Cheng and Bertolini, (2013) and Cheng *et al*. (2013) Marchetti, (1994) (Kgwedi and Krygsman, 2019) 2017/18 QoL Survey data

The methodology followed the research process illustrated in Figure 3 under Chapter 3. The analysis comprises two parts; the first phase of the analysis process is to identify and show the locational spread of places of work and residential locations for Gauteng in a map. In the second phase, travel-time accessibility is computed from residential areas to diverse places of work based on the mode of transport in Gauteng.

3.6.1 Phase One: Distribution of Residential Areas and Places of Work

a) Processing the Residential Areas and Places of Work

Cheng and Bertolini (2013), highlighted the importance of mapping the residential and work locations as a pre-requisite for many decisions related to job accessibility. The type field (with work categories) was then used to extrapolate only the point locations of potential work opportunities and residential areas within the study area, resulting in 63 981 and 1 729 078 points, respectively. The data were joined using the *Spatial Join* tool in ArcMap, to separately join the residential areas and job opportunities layer with the municipal wards layer. The data was mapped using the dot density symbology to show the spatial distribution of both residential areas and places of work for the study area. Dot density maps a symbol of points to represent the spatial distribution of phenomena over a geographic location (Walker, 2018), and the spatial location of each dot relates to the value at that location (Gomes, 2017). This type of visualization technique was chosen to represent the geographic distribution of the residential areas and places of work data because of their ability to convey patterns of clustering and dispersion (Walker, 2018), and categorical data (Allen, 2021). For example, studies have used dot density maps to visualize spatial distributions of categorical data such as employment and housing (Manduca, 2021). In this study, the dot density thematic maps were produced to show the densities of residential areas and places of work per municipality.

3.6.2 Phase Two: Computing Travel Time to Different Types of Work Using Different Transport Modes

The following accessibility equation adopted from Cheng and Bertolini (2013), and Hu and Downs (2019) was used to measure the overall job opportunities accessible to residential locations. The equation stems from the gravity-based measure by Hansen (1959) which has been modified over the years to suit various accessibility scenarios and achieve different objectives (Shen, 1998; Cheng and Bertolini, 2013; Hu and Downs, 2019). The gravity-based measure has been widely used (Pan *et al*., 2020) and is believed to be reliable and more advanced compared to the cumulative-based method (Kelobonye *et al*., 2021). The reason for adopting this specific gravity-based equation besides its popularity in measuring accessibility to employment locations was that the gravity-based measures are not sensitive to accessibility in space and time (Reggiani *et al*., 2011; Hu and Downs, 2019). The equation considers the demand and supply of jobs (Kanuganti *et al*., 2016). They can be easily modified to include the distance decay function that considers the attractiveness of a centre to be indirectly proportional to distance/travel time, and the measure can be implemented in GIS (Reggiani *et al*., 2011; Kelobonye *et al*., 2021). Lastly, Ziemke *et al*. (2018) highlighted that the approach could to the South African context due to dwelling patterns and diversity in society. The modified gravity-based measure is expressed in the following equation:

$$A_i = \sum_{j=1}^{n} S_j f(d_{ij}) \qquad (1)$$[41]

Job accessibility to residence at location i *is* aggregated as A_i, S_j *is* total number of work opportunity available at *j (n* represent the number of employment zones*)*, d_{ij} represent travel impedance *(time) for* a trip between location i and *j,* and $f(d_{ij})$ is a distance decay function. Travel time t_{tj} is based on

41 Hansen’s Gravity-based model equation.

equations (4), which consider the distance decay function[42] (Geurs and van Wee, 2004). Equation number two is a modified version by Shen (1998) of Hansen's measure to consider the demand potential. The equation is defined as follows, assume that there are n number of employers with a potential of employing workers who reside at a zone/location i:

$$A_i = \sum_{j=1}^{n} S_j f(d_{ij})/D_j \qquad (2)[43]$$

$$D_j = \sum_{k=1}^{m} P_k f(d_{kj}) \qquad (3)$$

$$f(d_{ij}) = e^{-B(k) \times t_{ij}} \qquad (4)[44]$$

In equation 4, $f(d_{ij})$ is the distance decay function denoted by a negative exponential function of the trip duration (travel-time). The distance-decay function concept is used in spatial interaction modelling for measuring time-travel through a network or the willingness to make trips in order to access opportunities (Chen, 2015; Ahmed *et al.*, 2006). The function simply depicts a decline in the interaction as the distance between two places (origin and destination) increases (Ahmed *et al.*, 2006). The researchers of this method suggest using the mean trip length (MTL) of each traveller in order to obtain the distance decay parameter which can be obtained from previous travel-time studies to define the friction coefficient in the analysis. Therefore, a mean travel time of 0.81 which looked at commuting costs in South Africa was adapted from a study by Kerr (2015) and used as a $f(d_{ij})$. Estimations made at large scales are prone to errors and the equation should therefore be calculated using centroids of zones which assumes that the jobs and residential areas are located at the centres between zones (Wang *et al.*, 2018; Hu and Downs, 2019).

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42 Distance decay explained as a function a negative exponential function. The elements that makes a potential destination less desirable in accessibility studies for example, distance, costs and time (Chen, 2015).

43 D_j is the demand in a zone job located at j. It is captured by p_k the number of workers located at k m represents the residential zones/ locations. d_{kj}, is the travel impedance between zone k and zone j, while m represents the residential zones/ locations. d_{kj}, is the travel impedance between zone k and zone j. All other symbols are the same as equation 1.

44 t_{lj} is a measures spatial barrier between residential location l and job location j. Finally, $B(k)$ is the travel friction coefficient corresponding to worker-type k (e.g. higher income rate or lower income rate) which was beyond the scope of this study.

3.6.3 Implementation in a GIS Application

This study applied a GIS-based approach to determine the jobs that residents can be accessed within the study area while considering the commuting time standard from previous literature and survey data. The methodology was implemented in GIS software to obtain the OD travel-time matrix values for the gravity-based measure equation. According to Wang *et al.*, (2005), Salonen and Toivonen (2013), Burdziej (2019), and Silalahi *et al*. (2020), GIS software offers a simple technique to compute travel-time and locations which can be reached within a certain time threshold using Network Analyst tool based on a transport network which can be built in ArcCatalog (Silalahi *et al*., 2020). Network datasets are useful to model transportation networks and are used to represent the typology, connectivity rules, and the restrictions for the mode of transport using the transportation network layer (Silalahi *et al*., 2020). The Network Analyst tool is often used to model network problems such as finding an optimal location to allocate services (Baloyi *et al*., 2017), proximity to basic facilities (Ragoasha *et al*., 2018) as well as locating the fastest routes and distance costs (Wang *et al*., 2005; Flisek and Lewandowicz, 2019). The techniques use a built network dataset variable such as road length, directions, time, and speed limit, to determine an optimal route to reach the closest facility and service area (Wang *et al.*, 2005; Tao *et al*., 2020). It uses an algorithm to return the shortest path or time between the origin and destination location (Wang *et al*., 2005; Silalahi *et al*., 2020). Therefore, to account for the travel-time dynamic to places of work, the *Network Analyst* tool under the *Geoprocessing toolbox* in ArcGIS 10.6 is used to perform accessibility calculations to various locations of the identified work opportunities using a standard time threshold and transport network dataset within the study area. The OD matrix tool calculates the closest demand point (residential areas) to each facility along the road network (Wang *et al*., 2005; Silalahi *et al.*, 2020; Tao *et al.,* 2020). The output of the *OD cost matrix* analysis solver is cartographically represented as straight lines on a map however the values generated in the attribute table the traversed network distance (Silalahi *et al.*, 2020).

On the other hand, the *Service area* analysis, also known as 'Catchment Area', estimates how far a facility can effectively provide its services (Fransen *et al.*, 2015). The technique develops a polygon(s) of the service catchment area based on a specified time-threshold using a network distance (Flisek and Lewandowicz, 2019). The authors further explain that the resultant polygon shape from running the service area is not influenced by barriers only dependents on the network model (Flisek and Lewandowicz, 2019). As a result, the returned shape is built according to the network dataset. The *Service area* analysis was selected because the use of buffer zones in GIS applications is criticized because they do not consider the transport network, and for assigning the same weight to all the points that fall within the same buffer even though one might be located at a maximum distance of a buffer than the other (de Jong and van Eck, 1996). For example, job locations situated at a minimum distance of a buffer threshold are considered the same as those situated at a maximum distance of a buffer threshold (de Jong and van Eck, 1996). Therefore, to find places of work accessible within the acceptable time using public transport, the *Service area analysis* was used to develop a time-based service area from places of work using a rail network. The OD matrix and service analysis techniques are based on the concept of the Gravity-based measure which considers the distance (or time) between two points of origin and destination (Wang *et al.*, 2005). The preparation processes and the analysis implementation using the *Network Analyst* tools are detailed in this section. Relevant statistics relating to travel-time results by specified mode of transportation were extracted and summarized to show accessibility per municipality. To visualize the data dasymetric maps of hexagon grids were used over choropleth maps since they have a limited utility for displaying detailed analysis of population data (Lwin and Murayama, 2009).

a) *Tessellating the Study Area and Disaggregating Population*

Spatial accessibility studies recommend the use of a finer small unit to measure accessibility (Liu and Zhu, 2004; Baloyi *et al.*, 2017; Burdziej, 2019), especially in urban environments, where the total spatial unit would be too large to produce accurate results for accessibility calculations (Cheng and Bertolini, 2013). Data disaggregation plays an important role in geospatial modelling and analysis (Le Roux et al., 2019). This is because using a smaller comparable spatial unit can help to mitigate significant aggregation errors when working with accessibility measurement (Cheng and Bertolini, 2013; Hu and Wang, 2016; Hu and Downs, 2019). The study used the SA CSIR MesoZone; the reason was that a fine granular census population was not available. The data collected by the local census bureau, StatsSA are obtained at various administrative units (i.e. provincial, municipal, ward, SAL, EA level) to show the distribution of the population in South Africa. For instance, the wards are geopolitical subdivisions of municipalities delimited for electoral purposes in South Africa (Orkin, 2020). A challenge with the administrative units is that the spatial grain of features such as population distribution and land-use patterns may not be accurately presented due to generalization in the area (Maritz *et al.*, 2017). Thus, a detailed regular tessellation[45] of the study area was employed to account for the distribution of data in the study area at a lower spatial unit level. A regular tessellation projects a uniform shape and size, it is also useful for visualizing data in an orderly manner (Birch *et al.*, 2007). The type of tessellation used was a hexagon grid layer (Figure 4) because the distance from its centre to the edges is more equal than other types of tessellation shapes such as the triangle and squares (Burdziej, 2019). The hexagon grids

[45] Tessellation method used for disaggregating population into cell (triangle, hexagon or square) grids (Gold, 2016).

are preferred in most accessibility studies because they show better distribution and give an accurate estimation of distance (Liu and Zhu, 2004; Mokgalaka *et al*., 2013; Burdziej, 2019). Figure 4 gives an illustration of a regular tessellation hexagon grid.

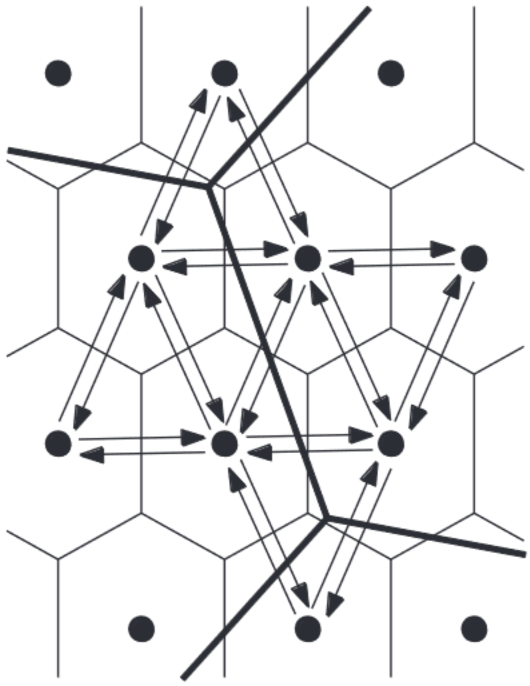

Figure 4: Regular tessellation in a hexagon shape, source: (Gold, 2016).

Different hexagon sizes from previous literature were tested, the sizes were in hectares (ha) and converted into km^2 for the purpose of this study. It was noted that most of these hexagon sizes were applied at a city, metro, and local municipality except for the 1 km^2 size which was applied in studies focusing at the metro, regional and provincial levels. The tested hexagon sizes included 0.026 km^2 (Burdziej, 2019), 0.2 km^2 (Mokgalaka *et al*., 2013), 0.25 km^2 (Cheng and Bertolini, 2013), 0.3 km^2 (Baloyi *et al*., 2017 and Ragoasha *et al*., 2018) and 1 km^2 (Maritz and Moagi, 2015; Naidoo *et al*., 2016; Maritz *et al*., 2017 and Joubert, 2022). Finally, after several trial and error attempts a spatial unit of 1 km^2 was selected to create a tessellated layer for the study area and disaggregate population in Gauteng. This particular spatial unit was the most suitable to use for the study area boundary because it provides a fine analysis surface compared to using wards (Mans, 2012) or sub-places (Mokgalaka *et al*., 2013). A layer of equally sized hexagons overlapping the study area was developed using the *Create grid layer* tool under the *MMQGIS Plugin* in QGIS. The hexagon grid layer has been used in many accessibility studies before (Mokgalaka *et al*., 2013; Green *et al*., 2014; Maritz and Moagi, 2015; Baloyi *et al*., 2017; Burdziej, 2019 and Arranz-López *et a*l., 2021) to estimate accurate distance, to disaggregate and aggregate population data at a detailed level. For example, Maritz and Moagi (2015) used the 1 km^2 hexagon size in their study which focused on improving access to justice in South Africa by measuring proximity to the courts using North West and Gauteng as case studies.

To account for the population at smaller spatial units, Mans (2012) and Ngidi *et al*. (2017) proposed the principles of dasymetric mapping as a solution in situations where population data is unavailable at a suitable finer resolution for analysis. Dasymetric mapping is defined as the process of using an ancillary dataset of existing aggregate data that is different but related to the underlying statistical surface of unknown data to assign values to it (Mans, 2012; Green *et al.*, 2014; Maritz *et al*., 2017; Ngidi *et al*., 2017). The principles of dasymetric mapping has been adopted by many international and local accessibility studies; the process involves disaggregating the population from a census spatial unit into a grid level (Holt *et al.*, 2004; Maantay *et al*., 2007; Linard *et al.*, 2012; Mans, 2012; Cheng and Bertolini, 2013; Mokgalaka *et al*., 2013; Baloyi *et al*., 2017; Ngidi *et al.*, 2017; Apparicio *et al*., 2017 and Ragoasha *et al.*, 2018). One credit owed to its popularity is that the mapping method yields accurate estimate values that represent a graphic distribution of population at a lower level compared to the choropleth mapping technique (Holt *et al.*, 2004; Maantay *et al*., 2007). On the other hand, Raadsen *et al*. (2020) add that disaggregation methods may achieve their objectives and yet suffer information loss. Contrary to this, Maritz *et al*. (2017) and Hu and Downs (2019) state that the accuracy of the method relies on the quality of the ancillary data used.

The ancillary datasets used for this method were the CSIR 2016 population data estimates at the mesozone level and the dwelling frame data to account for population density at a 1 km^2 spatial unit. According to the metadata document accompanying the dwelling frame dataset, 1) each point on the dataset is allocated on top of each household structure, which means that the data exclude points that are not residential or commercial, and 2) it allows for value-addition modelling applications to be completed. The data dwelling frame assisted in eliminating uninhabitable areas, this way population data will not be allocated in any other land-use classes except for residential areas. Population distribution was then assigned to the hexagon tessellation layer of the study area. The disaggregation of population data into the 1 km^2 (analysis units) tessellated layer of Gauteng with habitable locations yielded 15 239 cells. This figure excludes hexagon grid cells containing a value of zero (areas with no household structures) which were removed from the derived layer population within residential areas. To know the population density within the residential hexagons, the CSIR mesozone 2016 population estimates were intersected with the residential hexagon tessellation layer of the study area. The process included using of *Spatial Join* under *Analysis* tools to select the disaggregated population within residential areas that intersect with the tessellated layer of the study area. This process was done to assign the attributes of population estimates data to the residential hexagon tessellation layer of the study area (Mans, 2012). Figure 5 illustrates of the steps followed to tessellate the study area and disaggregate the population data. After intersecting the 2016 population estimates with the tessellated grid layer of residential areas, the population density within the 1km^2 hexagons was estimated.

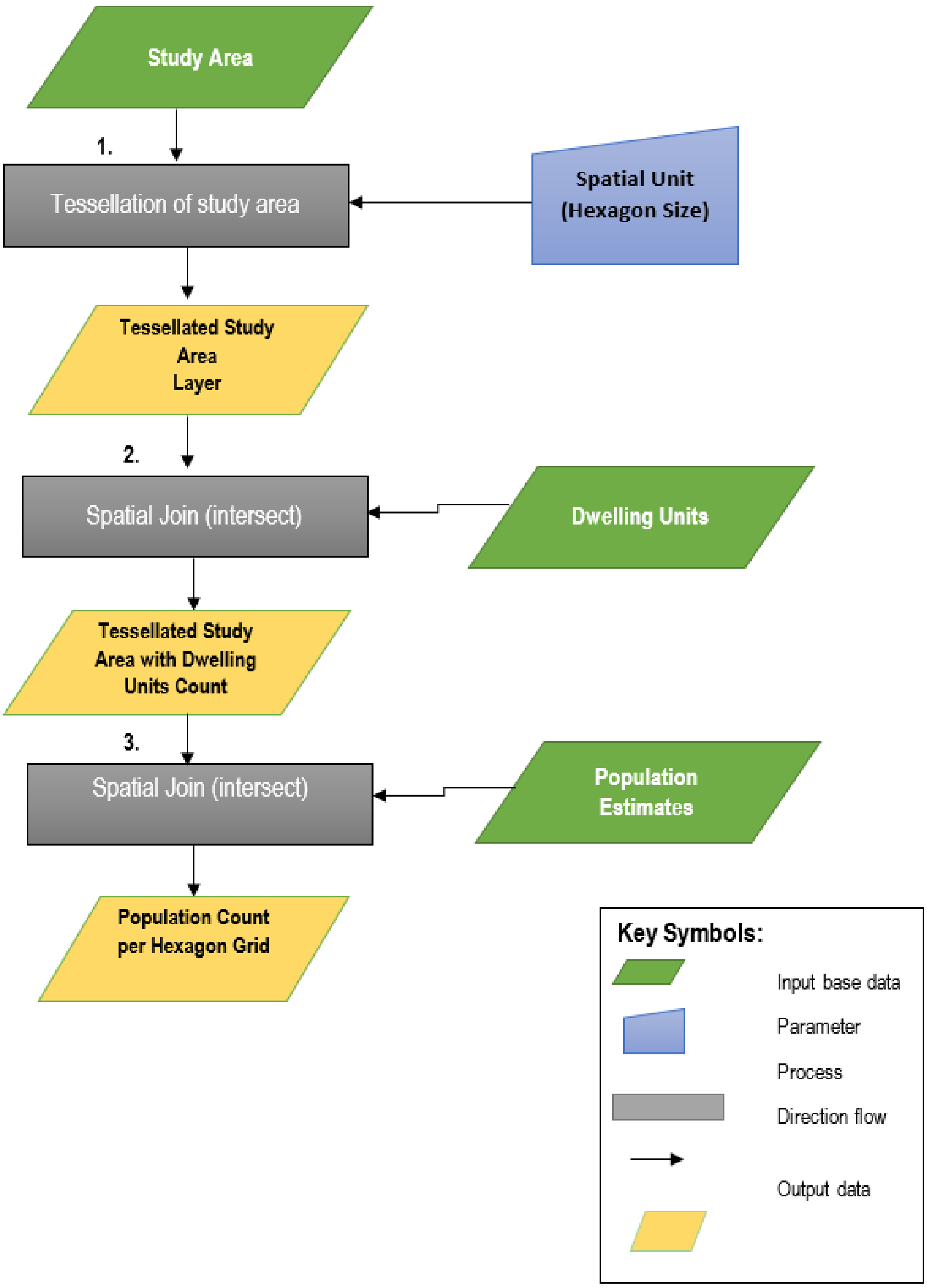

Figure 5:Tessellation of the study area and disaggregate the population data.

The map in Figure 6 gives an illustration of disaggregated population and an inset map of a zoomed area in the City of Ekurhuleni. The residential buildings per 1 km^2 were geographically distributed within the tessellated hexagon grid layer of Gauteng and overlaid with the residential points. Finally, the places of work (commercial buildings) intersected with the hexagon grid to create a grid-based dataset.

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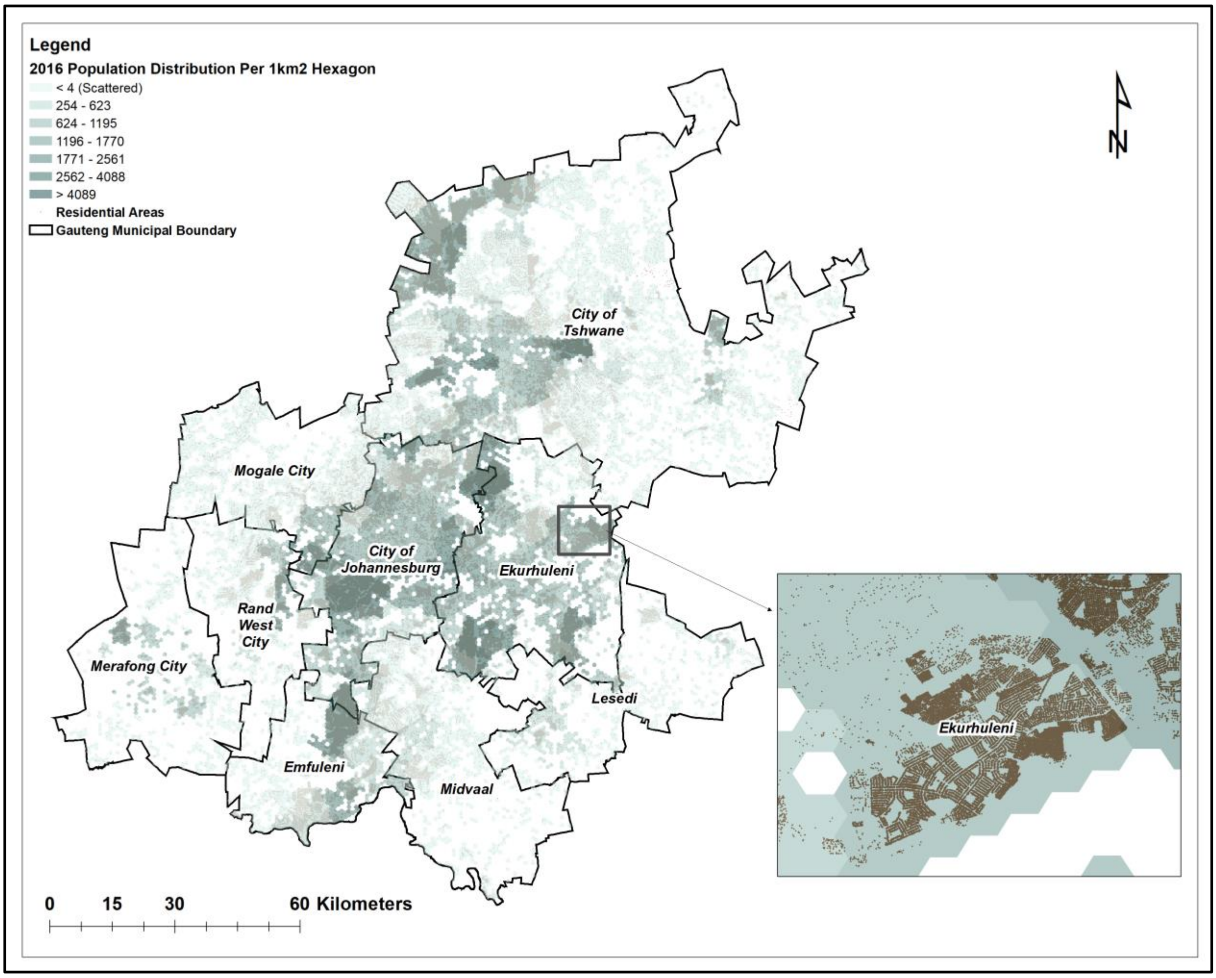


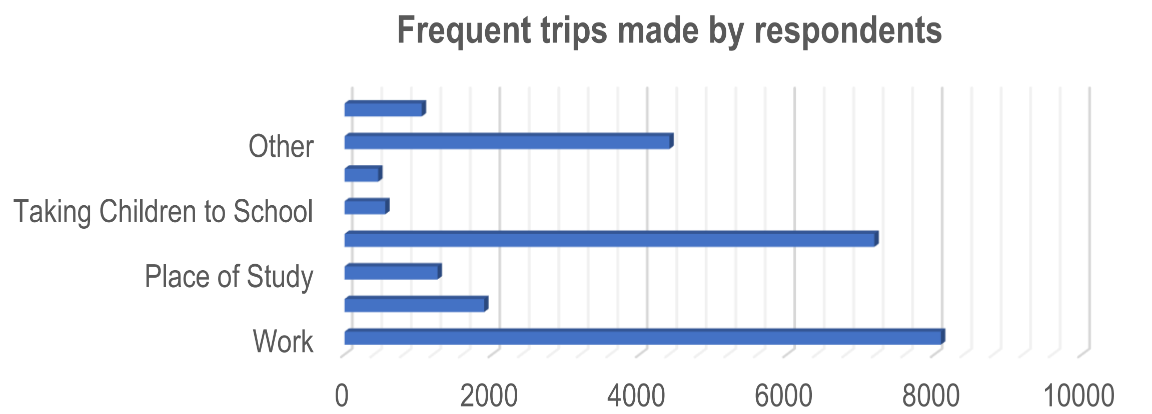
Figure 6: The maps show the tessellated layer of Gauteng into hexagon grid.

b) Accessibility Standard (Travel-Time threshold)

As indicated in Table 2 in *Section 3.6 (Data Manipulation and Analysis)*, this study made reference to both international and local literature on commuter guidelines as well as local surveys for acceptable commuting time thresholds for workers (Marchetti, 1994; Culwick *et al*., 2015; Hitge and Vanderschuren, 2015; Gauteng Department of Roads and Transport and CSIR, 2020). The threshold was based on the average travel-time observed since there were no clear local standards on the acceptable travel-time to places of work using public and private transportation. For example, a Household Travel Survey (2019/20) mentioned that 45 minutes was the average travel time for commuters in Gauteng; however the mode of transport was not stated (Gauteng Department of Roads and Transport and CSIR, 2020). On the other hand, a study conducted by the Organisation for Economic Co-operation and Development

[OECD] (2011), revealed that South Africa had the highest mean commuting time averaging to 56 minutes in 2011 compared to other international countries

The 2017/18 QoL Household survey data was obtained in an excel spreadsheet, and only the fields of interest as detailed in *Section 3.3 (Data Collection)* were used for the purpose of the analysis. The QoL survey excel spreadsheet had 24 889 records of respondents across Gauteng, and according to the metadata, the points were selected randomly at a ward level. As shown in Figure 6, the selected transport indicators from the 2017/18 QoL survey data indicated that most of the respondents in Gauteng travel for work purposes (32.5%) and to do shopping (28.9%). Also, the results indicated that most of the respondents spent up to 30 minutes trips frequently made to reach destinations within Gauteng (captured in *Table B_2: Time Destination* under *Appendix B*). A total of 34.87% of respondents travelled by a private vehicle (either as a driver, passenger, or in a lift club) while 7.90% travelled using public transport (rail). The GCRO QoL survey data was used because of the population sampling technique which ensures that a reasonable and accurate image of sub-place level characteristics can be produced (Mushongera *et al*., 2015). Moreover, the data also provides a representative picture of the population distribution in the three metros and the smallest municipalities of Gauteng. Therefore, the data served as a reference for modelling the travel-time threshold in the province. The graph in Figure 7 shows a summary of frequent trips made by the respondents in Gauteng.



	Work	Look for work	Place of Study	Shopping	Taking Children to School	Place of Leisure	Other	No trips
Total	8088	1893	1261	7186	552	456	4406	1047

Figure 7: Frequent trips made by respondents in Gauteng based on the 2017/18 QoL survey data.

In local studies, Culwick *et al*. (2015) studies the average commuting times based on mobility patterns in Gauteng found that black Africans spent an average of 56 minutes, while whites spent 42 minutes commuting. In the Cape Town metro, Hitge and Vanderschuren (2015) observed that commuting took 70 minutes by private transportation and 110 minutes by public transportation. Based on the reviewed literature and surveys, the study decided on 30 minutes by private transportation and 45 minutes by public transportation (Marchetti, 1994) as acceptable commuting-time thresholds to access places of work in Gauteng.

c) *Transportation Modes (Car and Rail)*

Based on the QoL survey dataset, most of the sampled population in Gauteng use private transportation for their trips within the province (see QoL summary tables included in Appendix B). Sufficient and reliable state transport infrastructure is vital to ensure access to basic services and opportunities (The World Bank, 2018). Public commuter rail often offers an alternative affordable mode of transportation (Wang and Chen, 2015) due to subsidies provided through the state (Kerr, 2015). An economic advantage of a railway transport system is that it transports large volumes of people over a long distance (Bouraima *et al*., 2020) compared to other means of transportation (African Development Bank, 2015). The commuter rail in South Africa is operated by Metrorail which is managed by PRASA (Kerr, 2015). According to the 2015 Green paper on National Rail Policy, PRASA aims to divert congestions on the roads to the rails by providing reliable service to commuters and reducing their travel-time journey to places of work (Department of Transport, 2015). White Paper on National Rail Policy states that the current rail infrastructure is underutilized and outdated, however, it intends to transform the infrastructure to be competitive and functions effectively (Department of Transport, 2022).

d) Creation of a Network dataset using the Road Network Data

The network data was used to represent a car as a mode of transportation. The obtained transportation network layer was a realistic representation of the roads within the study area. The network layer considered road connectivity, directions of the routes, and physical barriers such as buildings, terrain, and water bodies. The data consisted of six (6) road categories: highway, arterial, secondary, main roads, street, and others listed in the attribute table. A spatial query was used to select the suitable categories for analyzing accessibility using a private mode of transportation (car), and the road category listed as "other" was excluded from the analysis. The selected roads were highways, secondary, main roads, arterial, and streets as depicted in Figure 8. To enable the computation of travel-time between origins and destinations a network dataset was first built in ArcCatalog within ArcMap to set relevant network elements such as connectivity rules (turns), attributes for the network (e.g. travel-time units), directions, and mode of transport. To enable the computation of travel-time using between origins and destinations a network dataset was first built in ArcCatalog within ArcMap to set relevant network elements such as connectivity rules (turns), attributes for the network (e.g. travel time units), directions and mode of transport.

The travel-time by private transportation mode (car) was computed using the *OD cost matrix* which is found in the *Network Analyst Toolbar.* The appropriate parameters for analysis settings, accumulation, and network locations were set in the properties of the OD cost matrix analysis layer. The travel-time impendence (minutes), cut-off value, U-turns at junctions and output shape type were set under the analysis settings of the OD cost matrix layer properties. A diagram showing the set parameters T=30 as the cut-off value and the impendence in minutes was included in Appendix D. The map in Figure 8 shows coverage of the road network in Gauteng.

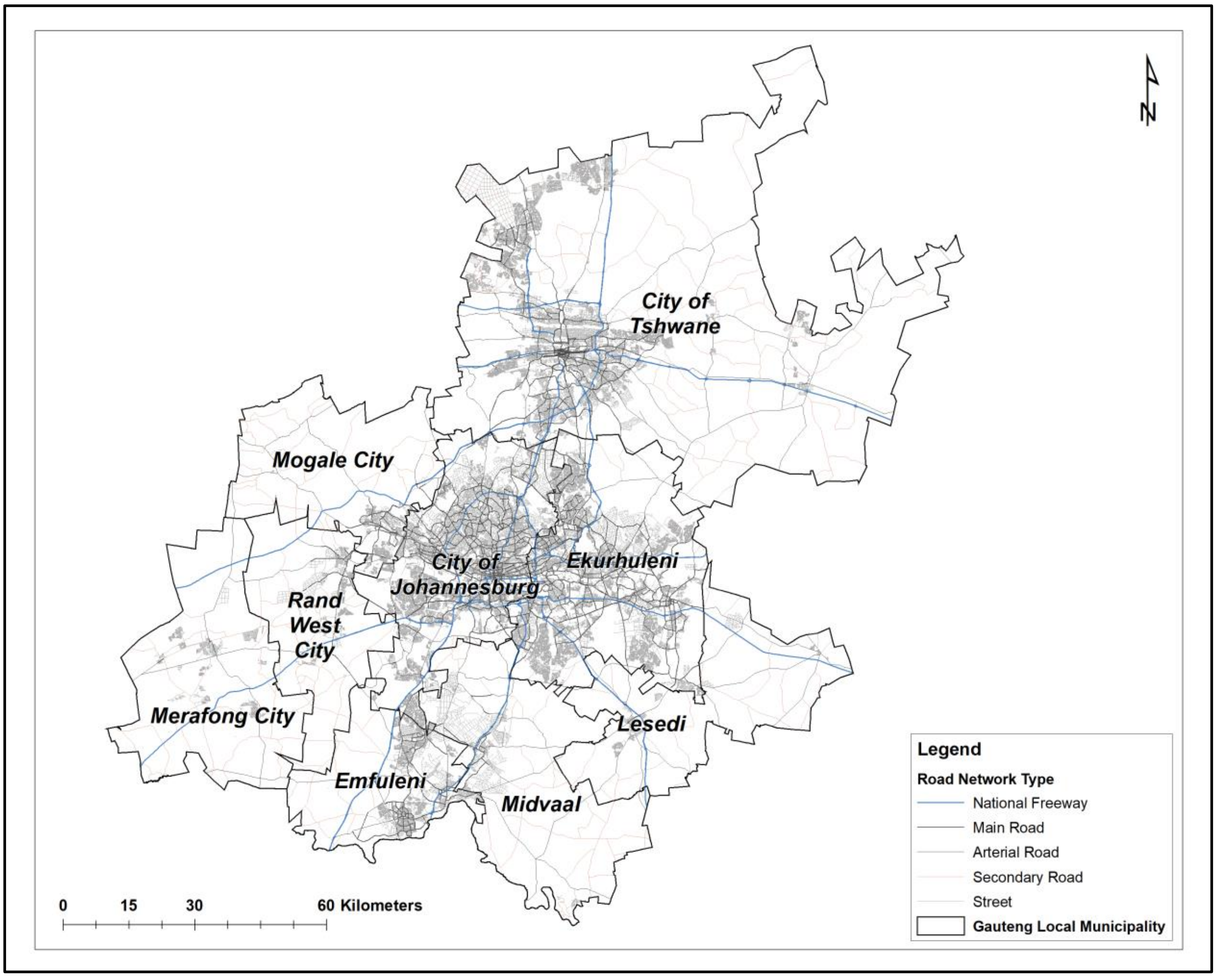


Figure 8: Distribution of the road network within Gauteng.

e) Creating Centroids for Residential Areas and Places of Work data

To compute travel-times between residential areas to places of work using the network travel-time, the hexagon grid layers obtained in section *a) Tessellating the Study Area and Disaggregating Population* under (*3.6.2 Phase Two: Computing Travel-Time to Different Types of Work Using Different Transport Modes)* had to be converted into centroids. A centroid is a point located at the centre of the bounds of a polygon (hexagon) with a single point of entry or exit *(*Raadsen *et al., 2020;* Silalahi *et al.*, 2020; Pajares *et al*., 2021a). The use of centroids instead of hexagons allows distances (in this case, travel-time) between the origins and destinations to be calculated (Liu and Zhu, 2004), as the *Network Analyst* tool in ArcMap software only reads the geometry of points as input data representing origins and destinations. The total number of centroids generated from the disaggregated population data was 15 238, while the commercial layer had 3 897 which resulted in a travel-time matrix[46] of 15 238 (origin grid cells) X 3 897 (destination grid cells). As a result, processing the data required a lot of processing time and computer storage capacity. Cheng and Bertolini (2013); Hu and Downs (2019) and Graser *et al*. (2019) and Kuehnel *et al*. (2020) also highlighted that smaller grid cells improve accuracy compared to larger grid cells and zones, however, smaller grid cells require more computation time to process and big storage capacity to store the results. Different solutions are suggested by accessibility studies to overcome this challenge. For example, some studies apply the clustering methods to reduce the size of the input data (e.g. population, residential areas, etc.) for the analysis and select only areas with a high level of clustering to speed up the computation time (Cheng and Bertolini, 2013; Luo *et al.*, 2017; Graser *et al*., 2019). Hu and Downs (2019), selected only ten census tracts with 156 residential cells to visualize OD matrix results to show hourly travel-time in Tampa, Florida. Centroids of disaggregated datasets are often used to measure accessibility at a fine level and can also save computational time of the analysis model (Raadsen *et al*., 2020). Therefore, the study used the CSIR Mesozones layer to compute travel-time analysis. As already indicated under *3.3 Data Collection,* the mesozones are approximately 50 km^2 in size, there for the population is still represented at a finer scale to conduct spatial accessibility analysis compared to a population distribution represented by administrative units such as wards, districts, etc. (Mans, 2012; Maritz and Moagi, 2015). To achieve this, the CSIR Mesozones layer was converted into centroids using Add Geometry Attributes *in Data Management* tools. Lastly, the Feature to Point tool in *Data Management was used to* depict the two centroid layers of hexagon grids for places of work and residential areas. The generated centroids layer for the CSIR Mesozones in Gauteng had a total of 373

[46] An OD table or matrix uses a two-dimensional array storage of cells (rows and columns) to represent the origin and destinations within a particular location (Graser *et al*., 2019).

centroids as displayed in Figure 9. The distribution of the generated centroids layer is displayed in Figure 9.

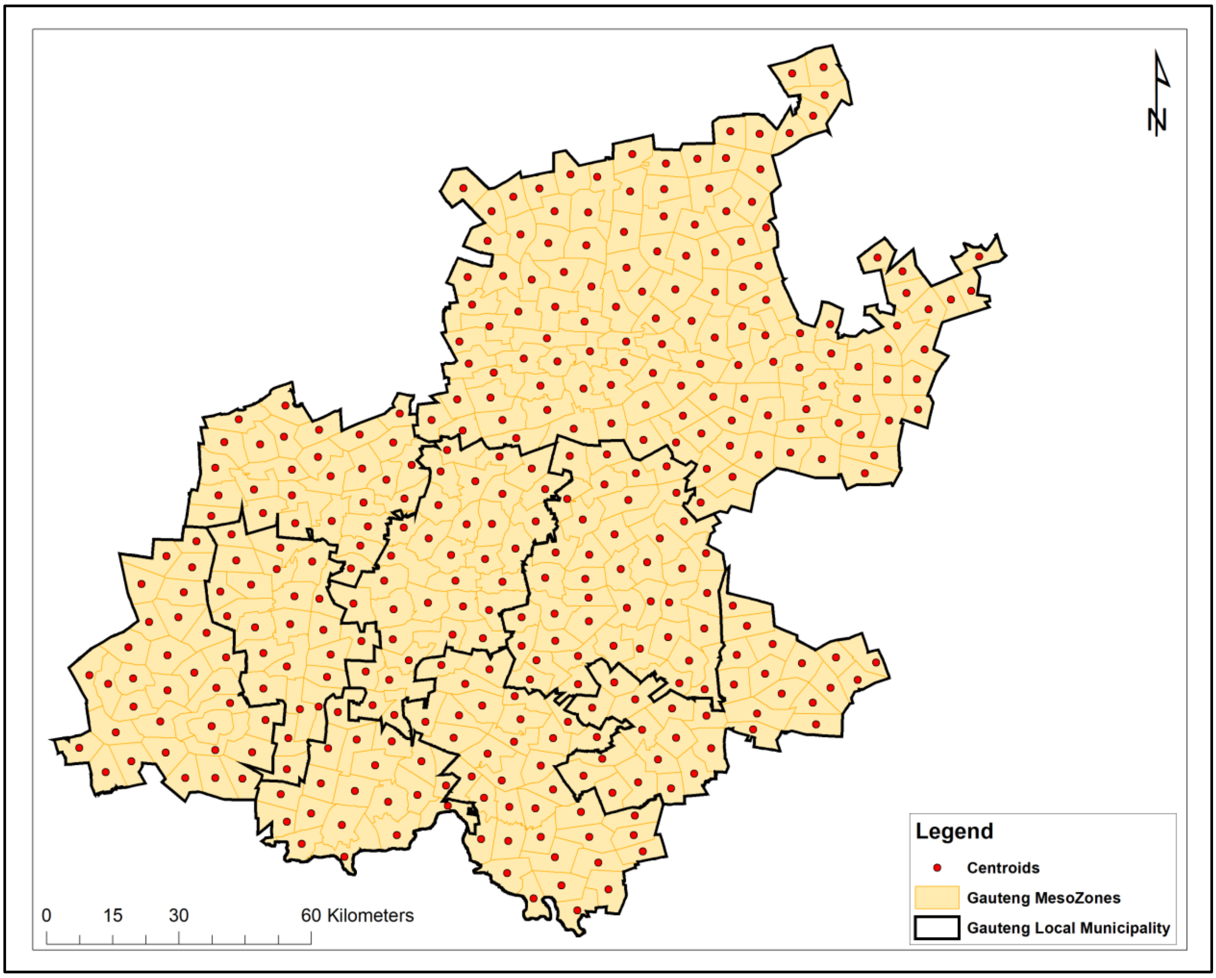


Figure 9: Distribution of the Mesozones centroids within Gauteng.

f) Computing Travel-time for Private Transportation (Car)

The *OD matrix* analysis tool was used to compute travel-time to places of work from the meso-zone centroids representing residential areas. After setting the appropriate fields under the properties of the network layer as discussed in *3.6.3 Implementation in a GIS Application* under sub-section d) *Creation of a Network dataset using the Road Network Data*, the centroids were loaded as origins and places of work as destinations into the OD matrix layer. The solve button was then used to solve for travel-time accessibility from residential areas to places of work using the road network dataset in minutes. This led to an OD cost (travel-time) matrix 373 mesozone centroids (origins) X 3 897 places of work (destinations) = 1 453 581 pairs solved. The results between any pair of origins and destinations were in a geometrical shape of lines, and the calculated travel-time values were stored in the attribute table in a specific field for storing travel-time. The attribute table was then used to compute job accessibility using the gravity-based equation described under *3.6.2 Phase Two: Computing Travel-Time to Different Types of Work*

Using Different Transport Modes. The friction coefficient of 0.81 obtained from the previous studies and the mean travel-time of 18.4 obtained from the descriptive statistics of the OD travel-time matrix results (Table 4_D1 in Appendix D) were used in the gravity-based equations discussed for determining job accessibility (*3.6.2 Phase Two: Computing Travel-Time to Different Types of Work Using Different Transport Modes*), and the calculations were executed in Microsoft Excel. The obtained results were then joined with the residential areas data in ArcGIS using the ID attribute field to map job accessibility at a finer spatial unit. The details of the outputs in this section are discussed in the following chapter (Chapter 4).

g) Computing Travel-time for Public Transport (Rail)

The *Service area* analysis in the *Network Analyst* tool was used to compute a time-based service area for job accessibility using the railway line that stretches across the study area boundary. A time threshold of 45 minutes was adapted from the previous literature (Marchetti, 1994; Cheng and Bertolini, 2013) as discussed in *3.6.3 Implementation in a GIS Application* under sub-section *b) Accessibility Standard (Travel-Time threshold*). The places of work were loaded as facilities into the *Service area* properties, and the appropriate parameters were set (i.e. selecting the time threshold, the direction, and not allowing U-turns at junctions). The *Service area* properties layer was used to process the residential areas that can be reached within the specified travel-time from places of work across all the municipalities. A diagram showing the set threshold as the cut-off value and the travel-time in minutes was included in Appendix D for reference. A *Service area* was run and an output of a 45 minutes polygon denoting the accessibility catchment area was returned. To find residential areas that can access places of work within the obtained catchment area of 45 minutes using public rail transport in Gauteng. After obtaining the results, two maps were developed to show residential areas within the acceptable time threshold and places of work accessible to the residential areas including the summary statistics per municipality. The railway lines and stations cut across all the municipalities with other municipalities having access to more railway stations than the others. The map in Figure 10 illustrates the railway network and the distribution of railway stations along the railway lines across the province of Gauteng.

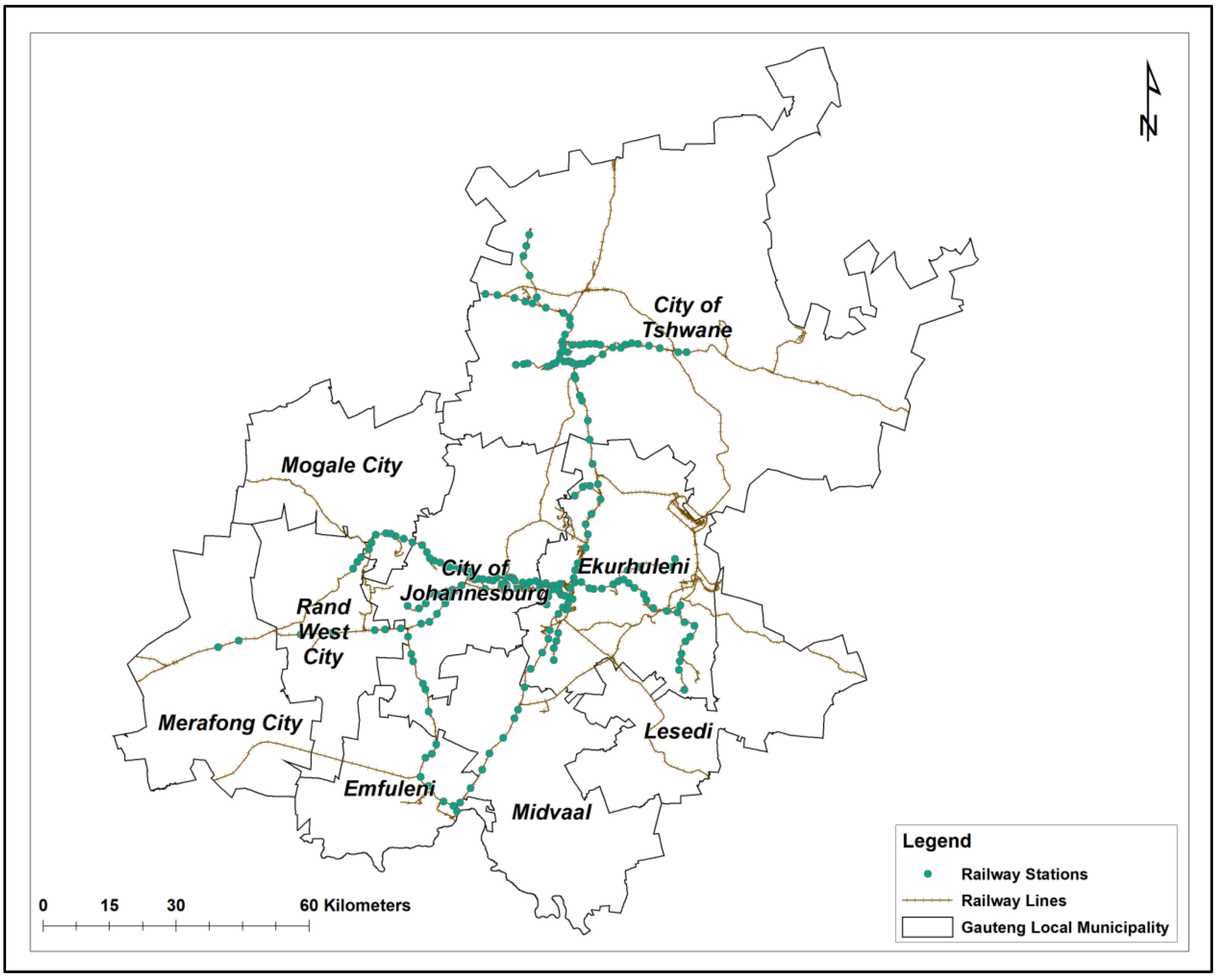


Figure 10: Distribution of railway network and stations in Gauteng.

All the findings of the analysis in this chapter were captured in a form of maps and tables. The summarized results in the Chapter 4 along with detailed interpretation of the results.

3.7 Methods of Validating Spatial Accessibility Results

Studies of accessibility have a lot of short-comings, and some of them include limited data due to challenges such as census collection periods (Ngidi *et a*l., 2017; Pajares *et al*., 2021b), privacy concerns (Lwin and Murayama, 2009), the geographical scale, and demarcation changes (Mans, 2012) which may lead to error in spatial analysis conducted at a micro-level. For example, according to Mans (2012) boundary divisions are normally used for administrative purposes as already highlighted in *section a) Tessellating the Study Area Disaggregation of Population* under *3.6.3 Implementation in a GIS Application*. As such, these boundaries have no association with the actual realities on the ground and may be subjected to constant change over time (Mans, 2012), hence the proposal of incorporating dasymetric mapping principles. Furthermore, administration boundaries spatial units tend to generalize the population distribution within an area (Maritz *et al*., 2017; Huand Downs, 2019). Khuluse-Makhanya *et al.* (2016), highlighted the spatial unit accuracy challenge which is associated with changes in municipal demarcations; for example, the 2016 local government elections affected the Gauteng demarcations, therefore using varied temporal scales of the data may result in the loss of some information. However, there are empirical analysis methods and conceptual frameworks to address the accuracy issue in accessibility studies (Naude *et al.*, 2008). Validation of results in accessibility studies has been achieved in various ways. Researchers such as Mokgalaka *et al*. (2013); Maritz and Moagi, (2015); Maritz *et al.* (2017); Baloyi *et al*. (2017); Le Roux *et al*. (2019), and Ragoasha *et al*. (2018) to name a few have used the tessellated spatial method to avoid issues of errors in modelling accessibility at a finer spatial unit. In addition, the use of residential buildings point data (i.e. SBC points) as a secondary input data adopted in their dasymetric mapping methods was noted as a common factor in some studies. Le Roux *et al*. (2019), applied the method suggested by Mans (2012) to validate the gridded cell population. Their study used data from 2001 to derive an estimated gridded layer of disaggregate population counts for the 2011 census using ESKOM's SPOT[47] building count data (Le Roux *et al.*, 2019). The ESKOM's SPOT building count data was also recommended to validate results when superimposed with other datasets on a map (Khuluse-Makhanya *et al*., 2016).

Other methods of validating results were discussed and applied in studies by (Lwin and Murayama, 2009; LaMondia *et al.*, 2010; Scholz *et al*., 2013; Mokgalaka *et al.*, 2014; Le Roux *et al*., 2019; van der Merwe *et al.*, 2020) where statistical methods such as the correlation coefficient, Percent Root Mean Square Error (PRMSE) and regression analysis were applied for comparison of results and to extend on the descriptive analysis of their studies. These statistical methods are often used to assess the effectiveness of results predicted in two accessibility measures (LaMondia *et al.*, 2010) and two datasets (Lwin and Murayama, 2009).

For example, Mokgalaka *et al.* (2014) investigated the distribution of three population demand scenarios relative to the supply of health care facilities within the City of Johannesburg and used the Pearson Correlation Coefficient to examine the correlation between the number of patients allocated in the catchment area analysis model at each health facility compared with the actual visits. The study's results revealed that there was no significant difference in the catchment area extent across the three scenarios however showed that there was an increase in numbers for all three scenarios (Mokgalaka *et al.,* 2014). LaMondia *et al.* (2010); Lwin and Murayama (2009) explained that Root Mean Squared Error (RMSE) assesses the bias and accuracy of the results, whereby the value 0% is associated with a low value of

[47] ESKOM's SPOT building count data also known as the dwelling layer and is a derived from a 2.5 metre resolution SPOT 5 imagery (Mudau, 2010; Ngidi *et al*., 2017).

variation, and 100% indicates a high level of variation in the measures. For example, Lwin and Murayama (2009) applied the RMSE to compare the variance between two accessibility measures (LaMondia *et al.*, 2010). Therefore, this research used the same method to validate the results, however, the datasets (actual and predicted) were the only information available to verify the input data used to model the travel-time in this study. The RMSE technique used by Lwin and Murayama (2009) to compared the variance between two accessibility measures. The calculation is obtained by the RMSE equation displayed in Figure 11. In this study, the RMSE was computed in Microsoft Excel using the travel-time and job accessibility values obtained from the gravity-based model. The RMSE equation is used to evaluate the correlation between the estimated and observed travel-time (Le Roux *et al.*, 2019). The potential job accessibility travel-time used was based on the friction coefficient from the previous studies (0.81) and the calculated mean (18.4) for the travel-time obtained from the OD matrix of the study. The two results of travel-time were used to evaluate the correlation between the estimated and observed travel-time.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{Actual} - \mathrm{Estimated})^2}{n}}$$

Figure 11: RMSE equation, source:(Lwin and Murayama, 2009).

CHAPTER FOUR: RESEARCH RESULTS

4.1 Introduction

This chapter displays the results of the analysis undertaken to meet the research objectives and interprets the findings from the analysis achieved in the previous chapter. The results present the findings related to job accessibility for inhabitants of Gauteng. The results are presented in spatial outputs of maps following the specific objectives detailed in Chapter One. The results under section *4.2 Distribution of Residential Areas and Places of Work* discusses the findings obtained from the dot-density maps where three maps were generated, two maps showing the spatial distribution of the residential areas and places of work within Gauteng. Lastly, objective two presents the results in two phases; it displays the spatial maps of the results and then focuses on the interpretation of travel-time results obtained from computing travel-time to places of work using two modes of transportation accompanied by summary statistics related to the findings.

4.2 Distribution of Residential Areas and Places of Work

The first objective of the research was to map the distribution of places of work in relation to residential areas in Gauteng. Firstly, the places of work (commercial buildings) are displayed separately to give a clear spatial spread using a dot distribution map. It is worth noting that for the sake of interpretation of the results, the distribution of places of work was associated with the representation of employment opportunities available within the study area. However, it is important for this not to be interpreted as the number of vacant opportunities available in Gauteng. Likewise, Khuluse-Makhanya *et al.* (2016), highlighted that there is a limitation in existing workplace data in South Africa. The authors made example of the scarcity in the number of workers employed by places of work at a lower geographical level. Figure 12 shows the distribution of the places of work in Gauteng municipalities. One dot symbol represented by the legend represents 100 places of work on the map, while in Figure 12 one dot represents 1000 residential areas (dwelling structures) on the ground. The dot values of the distributions in both maps were selected based on the number of points in each layer. The layer representing residential areas has more point data than places of work. In Figure 12, an uneven spread of job opportunities across the province can be noticed by the dispersed points in municipalities such as Lesedi, Midvaal, and Merafong City, Rand West City, and Emfuleni. The least number of places of work are found in Lesedi, Midvaal and Merafong City, Rand West City local municipalities. Places of work are more concentrated in the City of Johannesburg, the City of Tshwane as well as the City of Ekurhuleni. A common factor with the three municipalities where more concentration of places of work are found is that they are all metro municipalities indicating a high number of commercial activities compared to the rest of the municipalities in the province. The map in Figure 12 illustrates the spatial distribution of places of work across the province of Gauteng.

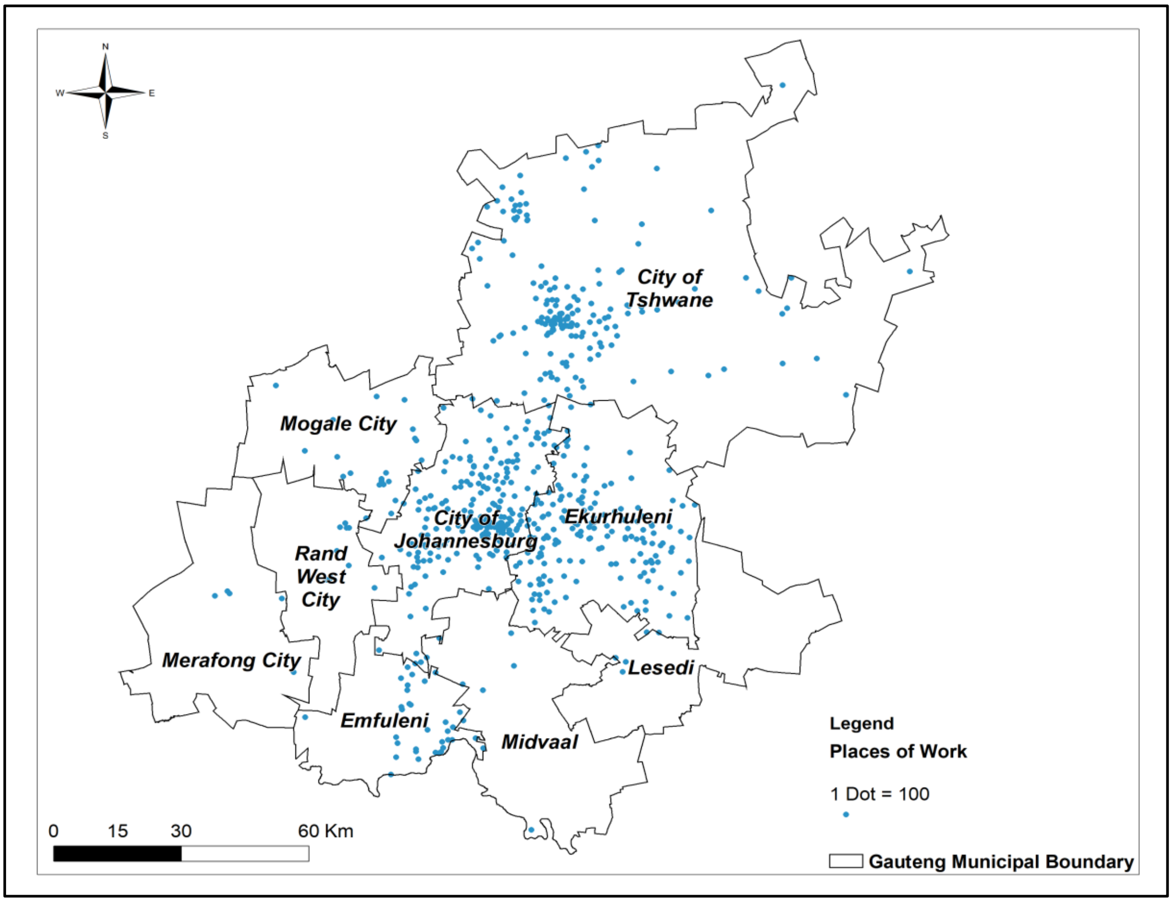


Figure 12: Distribution of job opportunities in Gauteng.

Figure 13 shows the spatial distribution of residential areas across the province of Gauteng; one dot represents 1000 residential areas on the ground. The map depicts the spread of both clustered and sparse dots of residential areas across the study area. For example, in the City of Tshwane, more dots are clustered in the centre and towards the northwest of the city boundary in the periphery. Whereas in the City of Johannesburg the dots are more clustered in the centre and the southeast of the boundary. In the City of Ekurhuleni, the dots representing residential areas are more clustered towards the north, east, south, and west peripheries of the metro boundary. Municipalities with sparse distribution of dots are Lesedi, Midvaal, Mogale City, Merafong City, and Rand West City.

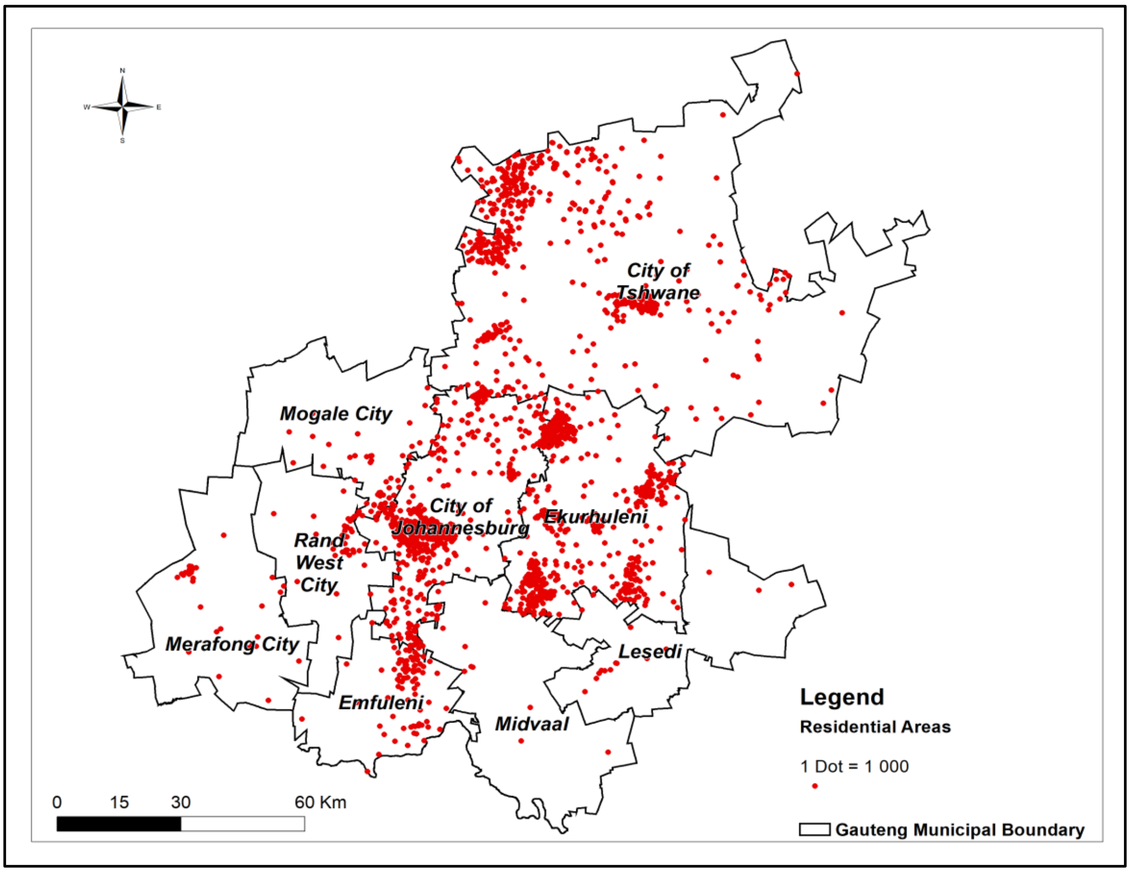


Figure 13: Distribution of residential areas in Gauteng.

In Figure 14, the job opportunities layer was superimposed with the residential areas layer within Gauteng and a transparency of 30% was applied to both layers to show the overlap between places of work and residential areas. The overlapping dots are shown by the purple colour in the map. The main purpose of the map in Figure 14 was to show the concentrations of both residential areas in relation to the job locations and make a comparison. The spread of the overlapping purple is mostly concentrated in the three metro municipalities with a few overflowing into the boundaries of neighbouring municipalities such as Emfuleni as well as Mogale City. Figure 14 shows the distribution of job opportunities in relation to residential areas in Gauteng.

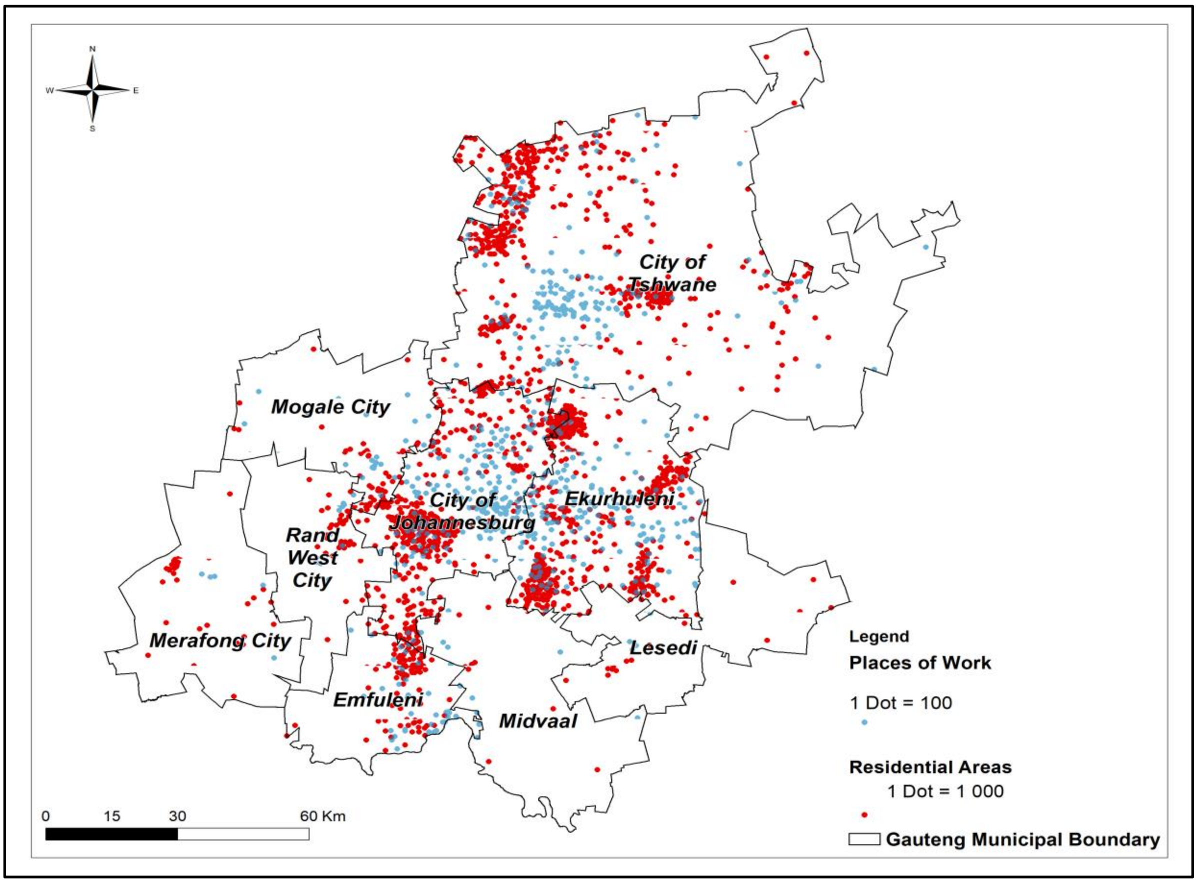


Figure 14: Distribution of job opportunities in relation to residential areas in Gauteng.

The following sections present results obtained from computing travel-time to places of work from residential areas.

4.3 Computing Travel-Time to Different Types of Work Using Different Transport Modes Measuring Travel-Time to Places of Work

In this phase, the first step was to model travel-time accessibility to places of work from all the residential areas in Gauteng based on two modes of transport. To account for the mode of transport, the research used the network dataset that was generated from the Gauteng road network layer as discussed in *Chapter Three* under *sub-section f) Computing Travel-time for Private Transportation (Car)* to model travel-time for residential areas of Gauteng using private and public transport to access places of work.

4.3.1 Accessibility of Places of Work using Private Transportation (Car)

The OD travel-time matrix analysis was used to determine residential locations that can access selected places of work around them within an acceptable travel-time threshold of 30 minutes (Appendix D: *Figure D_6: Residential Areas within a 30 Minutes catchment area of Places of Work*). The residential areas within 30 minutes' reach of places of work are indicated by orange colour, while the ones outside the catchment are indicated by grey colour. The catchment area is represented by a light purple and a transparency of 50% was applied to the data. A map also showing the results obtained from the OD matrix is included under Appendix D. The results obtained from the OD matrix were used to model travel-time job accessibility from residential areas using the gravitation method as discussed in *Chapter 3* under sub-section *f) Computing Travel-time for Private Transportation (Car)*. The high concentration of lines representing the OD travel-time matrix of 30 minutes threshold are represented by a grey colour (Appendix D: *Figure D_5: OD cost matrix travel-time for places of work accessible within 30 minutes*). The map in Figure 15 shows a service area of 30 minutes using a private car; as shown by the map, the shape of the catchment took the shape of the road network (light purple). This was to show the places of work that commuters can access using private transportation mode. Table 4 indicated that all the work opportunities (commercial) within the municipalities in Gauteng are accessible within a 30 minutes travel time as obtained from the service area results. Figure 15 illustrated places of work that can access job opportunities within a threshold time of 30 minutes together with a table showing the summary of the results (Table 4).

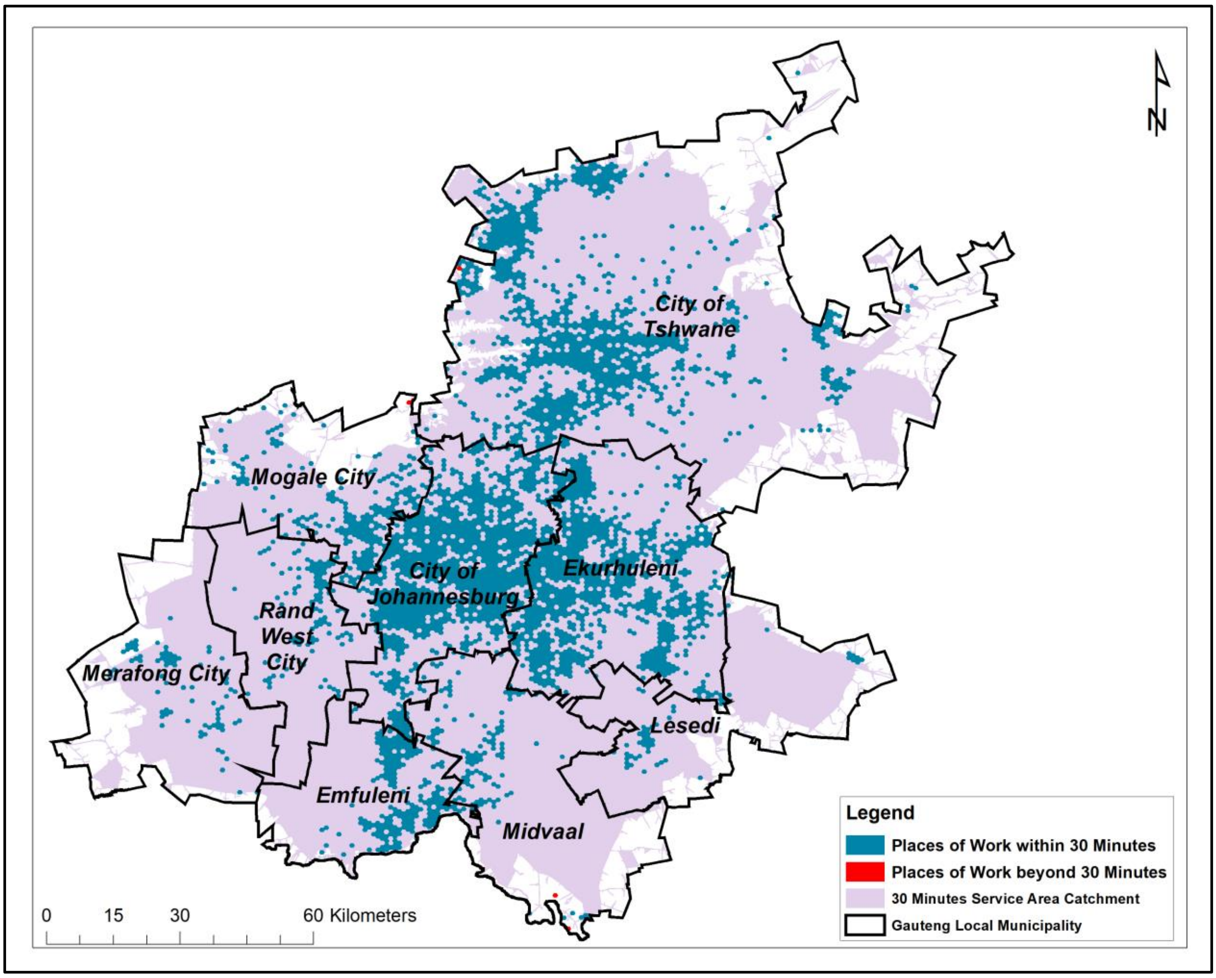


Figure 15: Service area catchment for places of work (car).

Table 4: Municipalities with places of work within 30 minutes (via car).

Municipality name	Total number of places of work within each municipality	Places of work area accessible within 30 minutes	Places of work area accessible within 30 minutes (percentage)	Places of work area accessible beyond 30 minutes	Places of work area accessible within 30 minutes (percentage)
City of Johannesburg	21 098	21 098	100%	0	0
City of Tshwane	17 054	17 053	99%	1	0
Ekurhuleni	16 297	16 297	100%	0	0
Emfuleni	3 295	3 295	100%	0	0
Lesedi	530	530	100%	0	0
Merafong City	710	710	100%	0	0
Midvaal	964	957	99%	7	0.73%
Mogale City	2 637	2 634	99%	3	0.11%
Rand West City	1 396	1 396	100%	0	0
Total	**63 981**	**63 970**		**11**	

To further understand the results displayed in Figure 15 and Table 4, a descriptive statistic obtained from the travel-time table was captured and included in Table D_1 *Descriptive statistics of Travel-Time OD Matrix from Residential Area to Places of Work via Car* in Appendix D as well as a screenshot of the travel-time attribute output. The results showed the mean travel-time which was later used in the gravity-based equation to denote *T.* Figure 16 illustrate residential areas that can access job opportunities within a threshold time of 30 minutes. The results indicated five different ranges of accessibility scores to places of work within Gauteng using a car. The model looked at the demand from the origin (residential units) and the supply from destinations (places of work). The model did not consider actual number of available employment opportunities from each commercial building and workers or job seekers from the residential areas. The 30 minutes travel threshold used in the equation was obtained from the average time spent on trips across the province as indicated by the 2017/18 QoL survey dataset. The results in Figure 16 revealed that spatial accessibility in Gauteng using a car had different score levels; however not all the score levels are represented in each municipality, which indicated that there was no balance in the accessibility of jobs across the municipalities. Figure 16 illustrates the potential job accessibility scores obtained from the gravity-based equation.

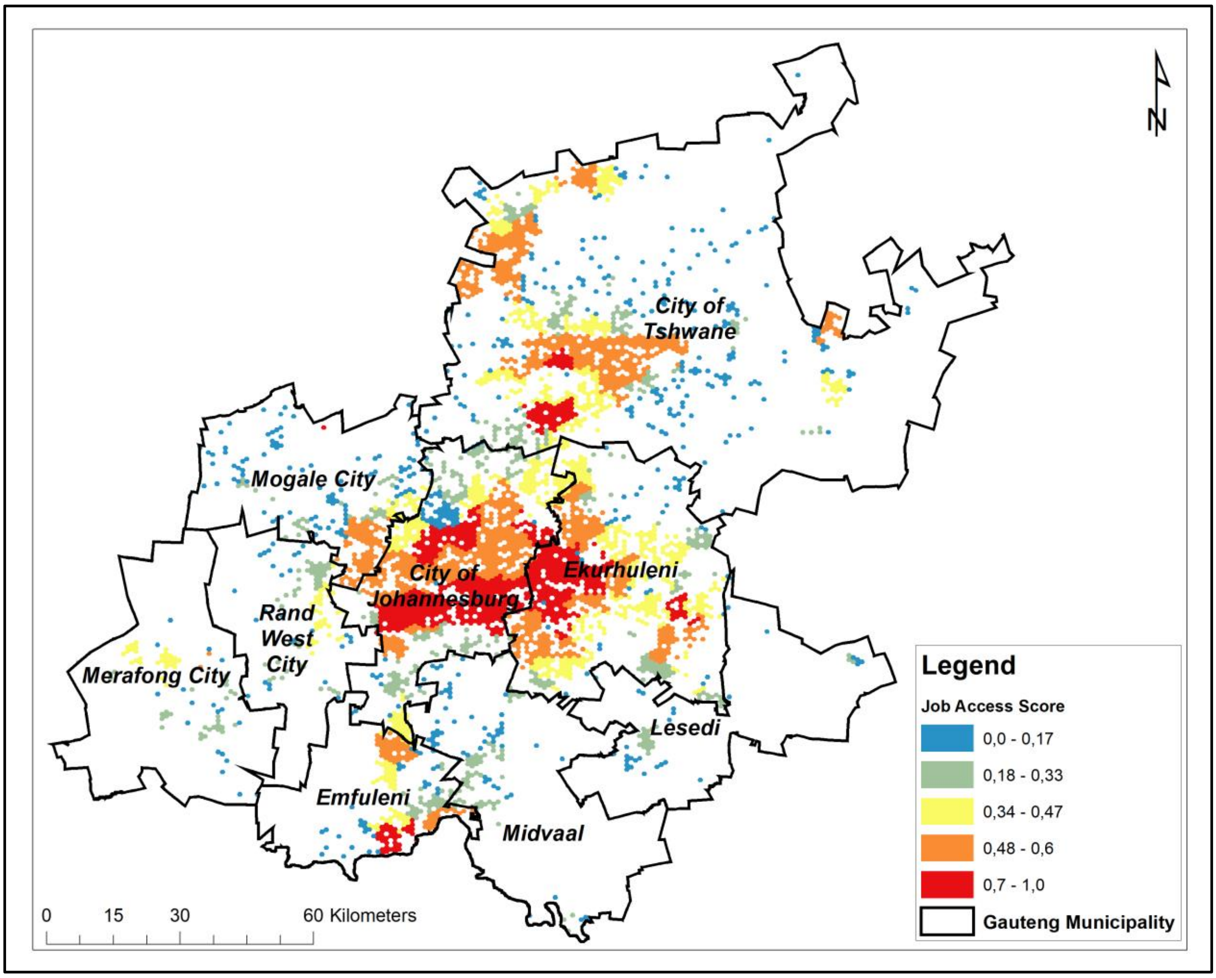


Figure 16: Potential job accessibility scores obtained from the gravity-based equation.

A frequency distribution plot was prepared using the job access scores displayed in Figure 16 and included in Appendix D (Figure D_8). Further discussions on findings in this section were included in Chapter Five.

4.3.2 Accessibility of Places of Work using Public Transportation (Rail)

To account for travel-time to places of work using public transportation (rail) in Gauteng, a *Service area* analysis was applied to determine the service area for places of work within 45 minutes using a rail. The results obtained gave an output of a polygon taking a shape of a railway line across Gauteng. The places of work and residential in hexagon grid layers were superimposed with the results from the *Service area* analysis (polygon of the catchment area) to show both residential areas (Figure 17) and places of work (Figure 17) that fall within 45 minutes reach from the railway line. The output in Figure 17 revealed that residential areas (orange) within 45 minutes from the railway lines are within the service area polygon and those beyond 45 minutes (light grey). The results in Figure 17 suggest that the residential areas that are located on the outskirts of the study area are not well serviced by the rail network within the desirable time as compared to places of work that are within the centre of the study area. This result could be attributed to the high presence of railway stations in the inner parts of the study area (covering entire municipality of the City of Johannesburg, Rand West City and the City of Ekurhuleni) indicating that the job opportunities in these metro municipalities benefit from access to this public transport. Figure 17 shows the time-based service area results for the residential areas in Gauteng using rail transportation.

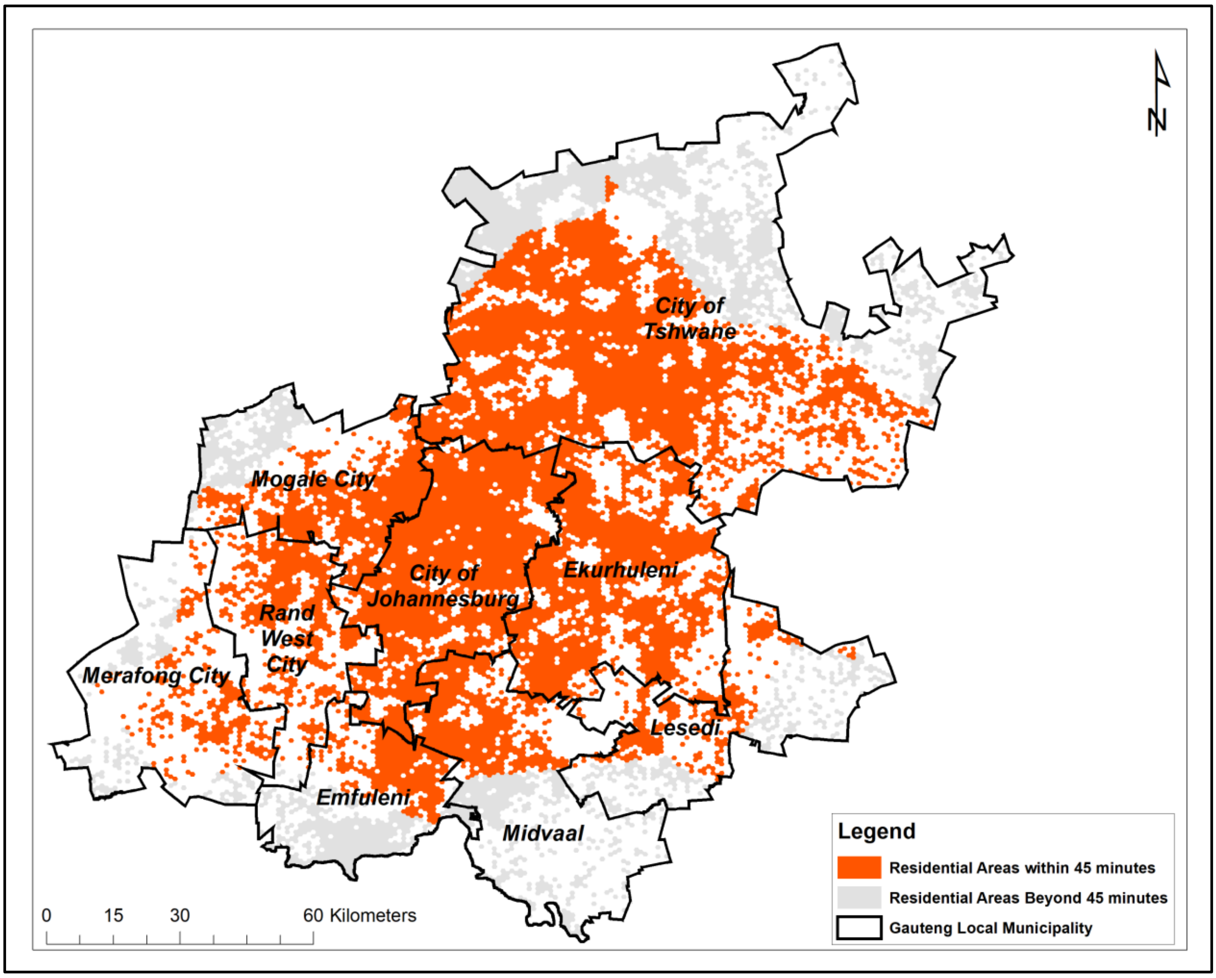


Figure 17: Service area analysis for residential areas within 45 minutes.

Table 5 displays a breakdown of the results obtained from the service area analysis. The table classifies the accessibility to places of work using rail according to the municipalities to compare those well served by the rail transportation within the specified threshold. The municipalities with a high population count within a specified threshold indicate a good service area coverage, meaning that the residential areas in these municipalities can access places of work using a rail public transport. Table 5, shows residential areas within the City of Johannesburg municipality which have full access to all the places work within its boundaries resulting in 100% service area, together with the City of Ekurhuleni, followed by the Rand West City at 99% coverage. Other municipalities with a good service area coverage are Mogale City (74%) and the City of Tshwane (70%). The rest of the municipalities have a moderate service area coverage. The municipality with commuters that spend more than 45 minutes to reach places of work for job opportunities and are less exposed to job opportunities is Emfuleni which only has 45% of its residential population within the acceptable travel-time threshold for rail transport. Table 5 shows a summary of statistics of accessibility levels for residential areas via rail and estimated population density per hexagon.

Table 5: Accessibility of residential areas via rail and estimated population density per hexagon.

Name of municipality	**No. Of 1km^2 hexagon grids covering land occupied residential buildings per municipality**	**Area accessible within 45 minutes by rail (in 1km^2 hexagons grids)**	**Estimated population accessible to job opportunities within 45 minutes**	**Estimated population count (%)**	**Area accessible beyond 45 minutes by rail (in 1km^2 hexagons grids)**	**Estimated population inaccessible to job opportunities within 45 minutes**	**Estimated population count (%)**
City of Johannesburg	2 195	2 195	2 289.71	100%	0	0	0
City of Tshwane	5 600	3 938	844.08	70%	1 662	2 000	30%
City of Ekurhuleni	2 039	2039	1758.75	100%	0	0	0%
Emfuleni	893	425	1 831.76	48%	468	1 663.46	52%
Lesedi	737	410	283.31	56%	327	355.22	44%
Merafong City	578	360	598.87	62%	218	988.96	38%
Midvaal	1 196	717	178.73	60%	479	267.55	40%
Mogale City	1 241	920	454.54	74%	321	1 302.74	26%
Rand West City	760	753	392.157	99%	7	42 184.90	1%
Total	**15 239**	**11 757**	**8 631.91**		**3 482**	**48 762.83**	

After obtaining residential areas that can access the places of work within 45 minutes using the rail transport within the study area it was also necessary to show places of work that are accessible using rail. The results obtained were by overlapping the service area analysis polygon (45 minutes threshold) with the places of work within the study area as indicated in the previous sub-section [*b) Accessibility of Places of Work using Public Transportation (Rail)]*. Figure 18 illustrates the places of work accessible within 45 minutes threshold and those outside the threshold.

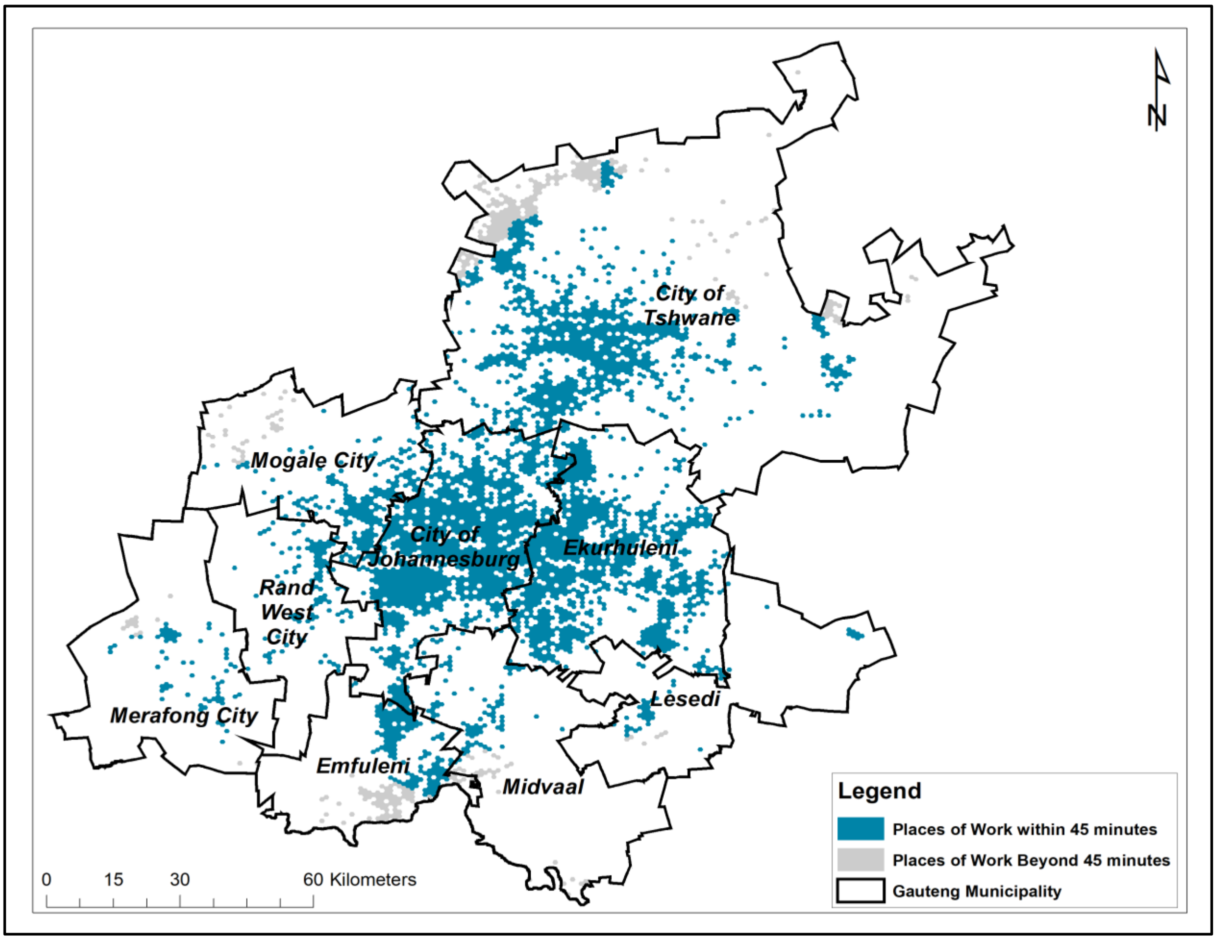


Figure 18: Service area analysis for places of work within 45 minutes.

Table 6 is a summary of results from Figure 18, it displays the total number of places of work per municipality accessible within 45 minutes threshold as well as those that are outside the 45 minutes threshold. The table shows that the City of Johannesburg has many places of work (commercial) with 21098 within locations close to the rail public transportation. The City of Johannesburg is followed by City of Ekurhuleni (16 297), the City of Tshwane (14 866), Emfuleni (3 295), Mogale City (2 637) as well as Rand West City (1 396). The remaining municipalities have relatively low numbers, and the lowest number of places of work is Lesedi local municipality with 530. The municipality with the high number of places of work located beyond the 45 minutes reach of rail transportation is the City of Tshwane. Table 6 displays accessibility of places of work via rail and travel time service area.

Table 6: Accessibility of places of work via rail and travel-time service area.

Municipality name	Total number of places of work within each municipality	Places of work area accessible within 45 minutes	Places of work area accessible within 45 minutes (percentag e)	Places of work area accessible beyond 45 minutes	Places of work area accessible beyond 45 minutes (percenta ge
City of Johannesburg	21 098	21 098	100%	0	0
City of Tshwane	17 054	14 866	87%	2 188	13%
Ekurhuleni	16 297	16 297	100%	0	0
Emfuleni	3 295	2 385	72%	910	28%
Lesedi	530	511	96%	19	4%
Merafong City	710	622	88%	88	12%
Midvaal	964	776	80%	188	20%
Mogale City	2 637	2 450	93%	187	7%
Rand West City	1 396	1 396	100%	0	0
Total	**63 981**	**60 401**		**3 580**	

The summary of the quantities displayed in Table 6 were displayed on a map in Figure 19. The figure shows the places of work that fall within 34 minutes including total number of places of work summed at each hexagon grid. The hexagon grid cells with dark brown colour represent the areas with the high number of places of work, while a yellow colour represent areas with the low number of places of work.

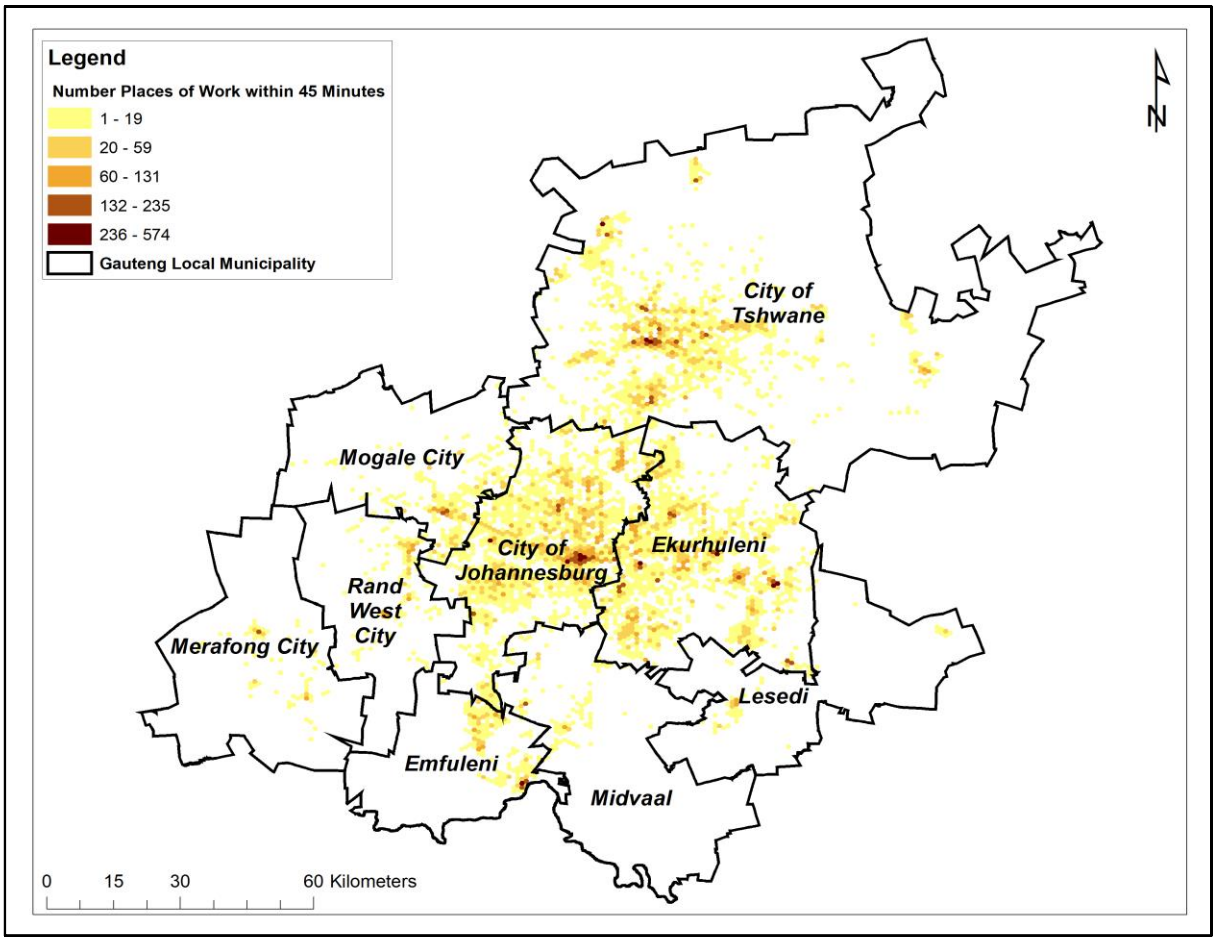


Figure 19: Number of places of work accessible within 45 minutes via rail.

4.4 Validation of the Spatial Accessibility Results

Firstly, the use of dasymetric mapping principles and tessellating of the study area recommended by researchers to help improve accuracy in accounting for the population at a lower level in spatial accessibility studies (discussed in *sub-section a) Tessellation of the Study Area and Disaggregation of Population under 3.6.3 Implementation in a GIS Application*), made it possible to overcome a challenge the population in residential areas (hexagon grids) that intersect the municipal boundary lines. The population estimates may not have been accurately classified within the respective demarcations as summarized in the statistics tables representing the level of accessibility per municipality (displayed in Tables 4,5 and 6) under Section *4.3 Computing Travel-Time to Different Types of Work Using Different Transport Modes*). Applying dasymetric mapping principles also assisted transferring the attribute information from an existing comprehensive dataset (2016 population estimates) to an unknown surface layer (tessellated hexagon layer for the study area). Based on previous data capturing exercises, capturing of information located on the boundary lines (e.g. fine hexagon grids) manually using the options of spatial selection methods in the *Select by Spatial location* tool available in GIS, either omitted the data from the selection (e.g. completely within the source layer feature) or inaccurately placed the data under a different boundary (e.g. intersect with the source layer feature). Using of techniques such as overlaying data with reliable secondary data such as a land-use classification (i.e. household units from the dwelling frame) are satisfactory for validating census data used in urban modelling applications (Khuluse-Makhanya *et al.*, 2016). Figure 20 shows results from a linear regression model using the obtained potential job accessibility scores and the travel-time results at each centroid. The sample size had a total of n=373 centroids using the CSIR Mesozones for Gauteng. The obtained results were used to calculate the residuals, the residuals were then squared and summed to find the RMSE. The results of the calculated RMSE was 0.273308387 which is associated with a low value of variation demonstrating the best fit (Lwin and Murayama, 2009). The index score in Figure 19 (R^2 =0.3792) indicated that there is a correlation between the estimated and observed travel-time.

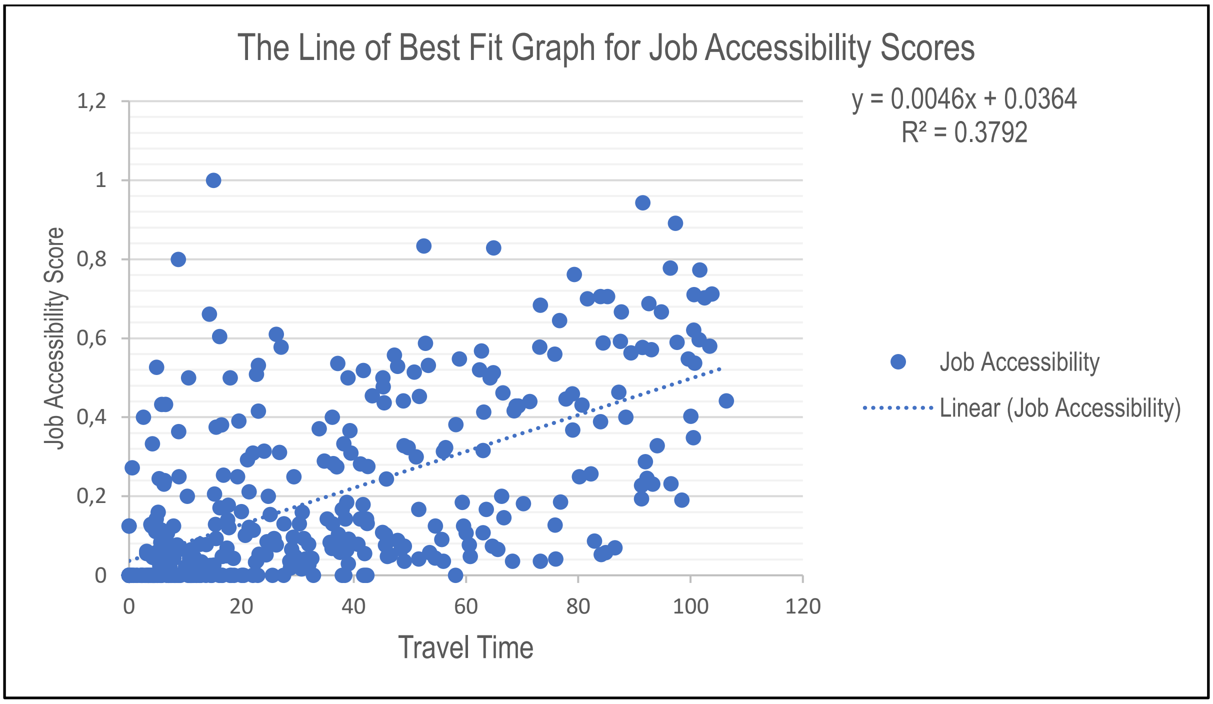


Figure 20: The line of the best fit graph.

CHAPTER FIVE: DISCUSSION OF RESULTS

5.1 Introduction

This chapter discusses the general findings of the maps and tables produced from the analysis. The results were based on the methodologies utilized to achieve the objectives detailed in chapter one. Discussion of the findings is also broken down into two parts to follow the sequence of the two-phase approaches in the objectives followed by validation of the results and a conclusion of the discussion.

5.2 Distribution Residential Areas and Places of Work

The spatial distribution map of residential areas revealed that more settlements are found in the three metros namely the City of Johannesburg, the City of Tshwane, and the City of Ekurhuleni. The high concentration of residential areas in the City of Johannesburg may be related to the high number of work opportunities, as previously shown in Figure 12 (*Chapter 4 Research Results*), which maps the distribution of job opportunities in relation to residential areas across the province. Places of work with available work opportunities are associated with high numbers of the population as they tend to populations seeking opportunities in those areas. This is also highlighted in previous studies (Mubiwa and Annegarn, 2013; Culwick *et al*., 2015; Budlender and Royston, 2016; Geyer and Molayi, 2018; Chakwizira *et al.*, 2018; Culwick and Patel, 2020), where a high concentration of residential areas is attributed to rapid urbanization resulting in urban sprawl, informal settlements due to backlog in the provision of government housing programmes as well as economic opportunities within the province. The results presented in Figure 14 focused on comparing the two dot density maps displaying the distribution of residential and places of work. The results indicate more concentration of residential areas than places of work across the municipalities in Gauteng. A general assumption based on these results is that there is a spatial-mismatch between the locations of residential areas and places of work. The overlapping dots with a purple colour suggest the available job opportunities close to residential areas in the municipalities depicted. Based on the results presented in the map, the residential area dots are many compared to the places of work across all the municipalities within the study area. As discussed in the reviewed literature this could be related to the concept of SMH explained by (Kain, 1992) in Chapter One and also revealed in local studies conducted by (Budlender and Royston, 2016; Geyer and Molayi, 2018). Geyer and Molayi (2018), conducted a study in 147 main places within Gauteng Region and the findings revealed that there was an imbalance between the distribution of jobs and residential areas within the province whereby high concentration of residential areas were located further away (outer periphery) from areas with a high concentration of jobs (inner outer periphery). Moreover, the results obtained in Figure 14 presented a similar trend also seen in a study by Budlender and Royston (2016), which applied regression analysis in the South African major urban areas; such as the City of Tshwane, the City of Johannesburg, City of Ekurhuleni, eThekwini, Mangaung, Buffalo City, Nelson Mandela Bay, and the City of Cape Town metro. The results presented evidence of a spatial mismatch between residential areas and job locations resulting in long commuting hours within the City of Tshwane, the City of Johannesburg, City of Ekurhuleni, and eThekwini metro municipalities (Budlender and Royston, 2016).

5.3 Computing Travel-Time to Different Types of Work Using Different Transport Modes

The findings of the analysis conducted to achieve objective two only used the centroids of residential areas and all the locations of places of work within the study. However, the results are important as they provide some insight into the reality that once existed[48] or may still persist because of other challenges that have not been considered for the purposes of this study. Furthermore, the results found in this section confirm the output displayed in the dot density maps produced in 4.2 *Distribution of Residential Areas and Places of Work*. However, some of the evidence on the casualties are slightly different in some municipalities (i.e., Merafong City and City of Tshwane) compared to the results in the dot density distribution maps under 4.2 *Distribution Residential Areas and Places of Work,* the details are discussed in this section. The spatial accessibility analysis was carried out at a finer scale and as such the results revealed more details than the results in 4.2 *Distribution of Residential Areas and Places of Work*.

5.3.1 Accessibility of Places of Work using Public Transportation (Car)

The OD cost matrix analysis also generated travel-time results from the origin (residential areas) to various destinations (places of work) in the form of straight lines for 225 370 locations within the study area that can access commercial work opportunities within 30 minutes. The results obtained from the OD matrix were used to model travel-time job accessibility from residential areas using the gravitation method as discussed in *Chapter 4 Research Results* under 4.3 *Computing Travel-Time to Different Types of Work Using Different Transport Modes*. The gravity-based measure equation gave an output of different job accessibility score levels ranging from 0.0 to 1.0 (Figure 16). According to Hu and Downs (2019), and Wanghe *et al*. (2020), the job accessibility level is denoted by A_i where higher values indicate better accessibility while the lower values indicate a low level of job accessibility. The job accessibility score level of 0.7 – 1.0 represented by a red colour is noticed only in four municipalities (the City of Johannesburg, City of Ekurhuleni, the City of Tshwane as well as Emfuleni), while the level 0.48 – 0.6 is observed again in the same municipalities except in this level is Mogale City included. The low-level score of 0.0 – 0.17 is noticed across all the municipalities, and the score seemed to be randomly distributed

[48] This is partly because of the use of outdated data and time before the covid-19 pandemic reality.

within every municipality. The gravity-based equation results indicated a high job accessibility score within the City of Johannesburg, the City of Ekurhuleni, the City of Tshwane, and Emfuleni by car. The frequency plot for job accessibility scores displayed in Figure D_8 under Appendix A also shows that the highest number of jobs are accessible between score levels of 0.4 and 0.5, however, the service area output table indicated that all the municipalities had good accessibility to all places of employment using a car.

5.3.2 Accessibility of Places of Work using Public Transportation (Rail)

The results in Figure 17 (*Service area analysis for residential areas within 45 minutes*) show the time-based service area analysis for the residential areas in Gauteng using rail transportation. The residential residents in the City of Johannesburg and the City of Ekurhuleni have good accessibility to public transport (rail), followed by the Rand West City to access work opportunities in Gauteng. Their commuting time and access to work opportunities are relatively good (100% coverage) compared to other municipalities with a minimum service area coverage. Other municipalities with good service area coverage and estimated population count within the hexagon units include Mogale City (74%) and the City of Tshwane (70%). An observation made on the distribution of the places of work and residential areas within 45 minutes (displayed in Figures 17 and 18) is that the follow the pattern of a railway network within each municipality (road network displayed in Figure 8). In some municipalities, such as the City of Johannesburg and the City of Ekurhuleni the rail passes through the centre of the municipalities while in Emfuleni and Lesedi it only cuts through a small portion of the municipalities. This could explain why many residential areas appeared outside of the rail threshold. Another possible explanation could be associated with the size of the area; for example, the City of Tshwane is larger than the city of Johannesburg and the city of Ekurhuleni hence the total coverage of the catchment area was able to reach only 70% of the estimated population count. The results of service area analysis for residential areas within 45 minutes previously displayed in Figure 17 revealed that the places of work located within 45 minutes are spread within the core of the municipalities while few are located on the edges of the municipalities. The results were backed up by the summary of statistics in Table 6 (*Accessibility of places of work via rail and travel-time service area*) which indicated that there were few places of work outside the threshold of 45 minutes except for the City of Tshwane which had a slightly high number of job opportunities (places of work) compared with the rest of other municipalities. This means public transport users (rail) on the outskirts of the province are at a disadvantage in terms of accessibility to work opportunities. The trend in results obtained in this section was similar to studies conducted by Kerr (2015), Kgwedi and Krygsman (2019) were noted. The studies revealed that areas located in the peripheries of the provinces generally have poor accessibility to places of work. Poor accessibility to public transport modes and long travel distances can impact job opportunities prospects (Kain, 1968). As already indicated the summary statistics results displayed in Table 5 (*Accessibility of residential areas via rail and estimated population density per hexagon*) and 6 (*Accessibility of places of work via rail and travel-time service area*) correlate with the output maps in Figure 17 (*Service area analysis for residential areas within 45 minutes*) and Figure 18 (*Service area analysis for places of work within 45 minutes*) and a detailed discussion is provided in the following section.

5.4 Comparison of the Results Based on the Selected Mode of Transportation

The graph displayed in Figure 21 was based on the service area analysis results from the two maps in Figure 17 (*Service area analysis for residential areas within 45 minutes*) and Figure 18 (*Service area analysis for places of work within 45 minutes*). The graph in Figure 20 was achieved by combining the estimated population count from Table 5 and Table 6. This was to allow a clear comparison to be made for accessibility via rail transportation in the municipalities. The service area analysis using rail (Figure 17) showed that the City of Johannesburg had the highest number of residential areas located within a reasonable access time threshold acceptable for rail transportation as indicated by the graph displayed in Figure 21. The results have also shown that the existing rail infrastructure is not accessible to some residential areas in previously disadvantaged communities located in the peripheries of both metro and non-metro municipalities such as the City of Tshwane, Midvaal, Emfuleni, Mogale City, Merafong City as well as Lesedi (Figure 17). For example, a similar trend is noted in a study by Culwick *et a*l. (2015), which looked at the overall mobility patterns in Gauteng and revealed that the travel time for residential areas (Soshanguve, Orange Farm, and Daveyton), particularly black Africans spent an average of 56 minutes. The results displayed in the graph indicated a need for a reliable and integrated multi-modal system to compete with private vehicles within Gauteng. The findings in Figure 15 obtained from the service area to places of work using a car and Figure D_7 under (Appendix D showing residential areas accessible within 30 minutes) revealed that the majority of places of work and residential areas could be accessed within 30 minutes except for those located in the edges of the municipal boundaries.

On the other hand, the results suggested that accessibility by public rail transport in the City of Johannesburg and City of Ekurhuleni is better compared to Midvaal, Emfuleni, Mogale City, Merafong City, and Lesedi due to the widespread availability of public rail transport network in those metros as depicted by the rail network in Figure 10. Based on the maps, interventions by the government to provide an integrated transport system as stated in the National Transport Master Plan (Department of Transport, 2010) are yet to be fully accomplished as results reveal that the current passenger rail system in Gauteng may not be fully attractive as a private vehicle in terms of accessibility time. The municipalities that require urgent intervention in terms of spatial accessibility to places of work are Midvaal and Lesedi. Even though the overall time-based service area results as previously seen in (Figure 17 and Table 6) indicated that places of work located in the three metro municipalities (the City of Johannesburg, City of Ekurhuleni, and Rand West City) are located within acceptable proximity to the public rail transportation, but this output does not imply that the residents within these municipalities have full access to the job opportunities in these places of work as there are other dynamics at play such as the inter-municipal movements by residents from other municipalities within the province as well as other provinces (Statistics South Africa, 2015). However, according to gravitational approaches to measuring accessibility, the proximity to a location indicated by travel-time makes the employment locations f attractive to potential job seekers (de Jong and van Eck, 1996; Hu and Downs, 2019). An observation made from the results displayed in Table 6 was that the City of Tshwane did not only have a high number of places of work situated within the accessible time threshold but also a significant number of jobs located further away from the rail transportation as indicated in Figure 17. The City of Tshwane had the highest number of places of work that were located in areas not accessible within the acceptable rail commuting time. The findings (in Table 6) suggested that the employees that work in these locations (i.e. City of Tshwane) spend more time travelling to reach places of work, as a result, those that seek employment may not find the locations attractive. The graph displayed in Figure 21 showed that Rand West City has good accessibility to residential areas within 45 minutes of rail, however, the municipality needs the intervention of work opportunities. The findings observed in Rand West City were also backed up by the findings displayed in the map illustrating job accessibility scores from using a car (previously displayed in Figure 16). The results in Figure 14 revealed that the Rand West City had a distribution of low accessibility scores ranging from 0.0 to 0.47. Figure 21 illustrates the population accessible by rail vs places of work.

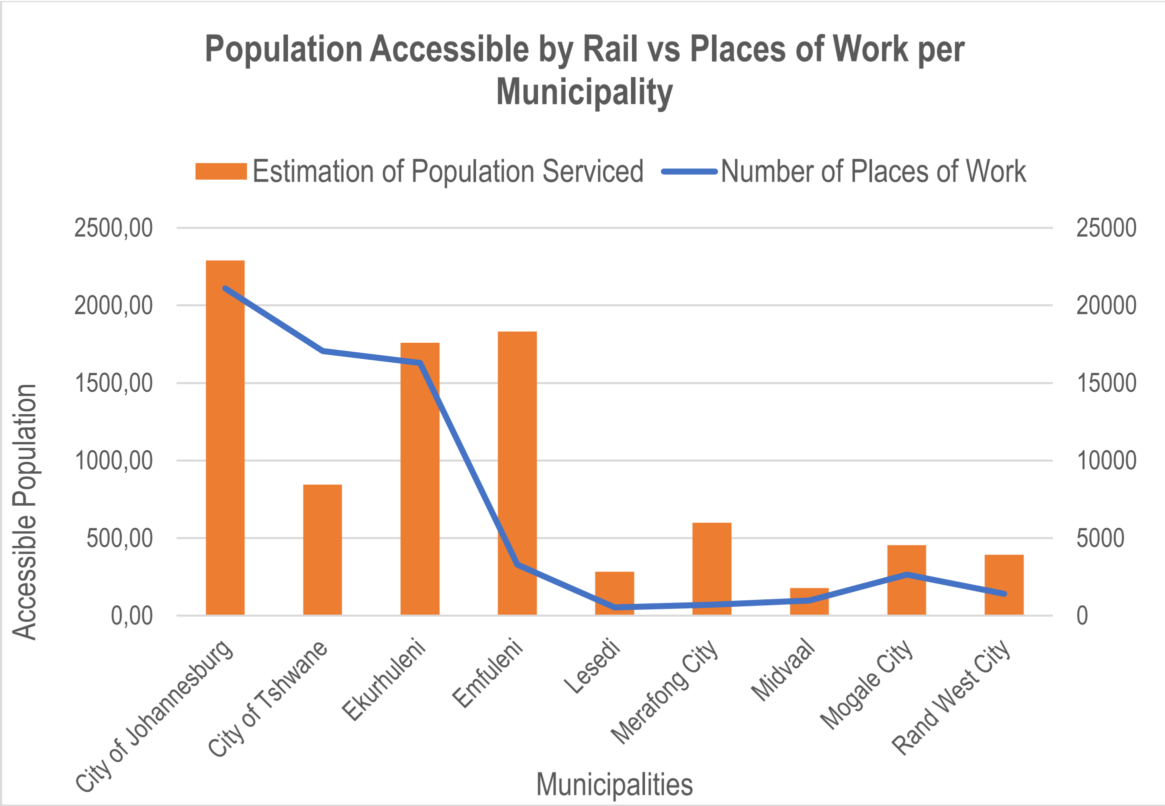


Figure 21: Population accessible by rail vs places of work per municipality.

CHAPTER SIX: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Spatial accessibility particularly in transport geography is one of the fundamental challenges that prevent the ability to access key activities (opportunities from certain locations (Burdziej, 2019). South Africa has been associated with a higher fraction of low-income earners (United Nations, 2015), unemployment, and spatial inequality challenges (National Planning Commission, 2011). As such, the decision to travel to seek work and relocate closer to one's place of employment tends to be influenced by affordability (United Nations, 2015). This results in high employment rates and longer commuting hours in the country (United Nations, 2015). Moreover, Culwick and Patel (2020) add that the legacy of apartheid has continued to influence spatial inequality across the country. In South Africa, spatial accessibility focus on various aspects, from general accessibility (Lionjanga and Venter, 2017), to service delivery issues such as accessibility to transportation infrastructure, and health care (Tsoka and le Sueur, 2004; Mokgalaka *et a*l., 2013; Baloyi *et al*., 2017; Ragoasha *et al.*, 2018), fire stations, justice (Maritz and Moagi, 2015), social welfare (Lionjanga and Venter, 2018), commuting affordability (Kerr, 2015), education facilities as well as the mode of transportation (Hitge and Vanderschuren, 2015) compared to job accessibility aspect (van der Merwe and Krygsman, 2020; Culwick *et al*., 2015).

This study was based on a location-based measure suitable for modelling and visualizing travel-time accessibility to job opportunities in the context of Gauteng. Literature was reviewed and location-based measures were selected due to their popularity in measuring job accessibility, the ability to use readily available data as well as the ease of results interpretation (Wang *et al*., 2005; Cheng and Bertolini, 2013; Chen, 2015; Tóth and Kincses, 2015; Wanghe *et al*., 2020). The analysis utilized a GIS-based approach to compute the OD travel-time matrix from residential areas to places of work centroids. The results were then employed in a gravity-based measure equation adopted from previous accessibility studies to calculate accessibility. The measure made use of secondary data to complete the analysis. The study's findings showed that spatial accessibility of places of work using private transportation (car) is much more advantageous than public transportation (rail) in terms of travel-time. More residential areas could access places of work within 30 minutes and a few residential areas outside the 30 minutes catchment while results from using a rail had more residential areas considered inaccessible (areas located beyond the 45 minutes threshold). The study also revealed that spatial growth of urban areas tends to lock some residential areas located in the urban edges out of the economy due to limited or lack of accessible infrastructure. Furthermore, the results revealed the need for integrated spatial planning for settlements, transportation and economic development in the province.

According to the guidelines for settlement planning by CSIR (2000), there is a need to develop balanced communities with employment activities within the residential communities in order to limit the need to travel far to seek employment opportunities. According to local literature reviewed in Chapter Two, the spatial form of Gauteng is a legacy of apartheid and has been perpetuated by spatial planning policies, however, the incorporation of the GIS tool could be used for spatial justice by informing policies and measuring the progress that has been made to address spatial transformation planning issues and ultimately assists in contributing towards reversing the spatial inequalities of the past to support the National Development Plan 2030 vision for an inclusive future (National Planning Commission, 2011). In conclusion, the availability of data, the use of suitable spatial analysis methods and mapping applications such as GIS, if incorporated into planning, could improve people's livelihoods by providing well-located accommodation to integrated public transportation infrastructure and economic opportunities such as job opportunities.

6.2 Limitations of the Study

The challenges encountered in this study were the availability of data on transportation modes such as buses and mini taxis to incorporate as part of public transportation modes hence the focus was only limited to rail transport. The study conducted in the City of Johannesburg by Lionjanga and Venter (2017) also highlighted the challenge of sufficient and accurate spatial data of operational public transport especially the routes and transfer points. The lack of data on transportation modes limited the study from going into detail in modelling spatial accessibility, particularly for residential areas that rely on public transport within the study area. Additionally, the 2019/20 Household Travel Survey by Gauteng Department of Roads and Transport and CSIR (2020) showed that rail users only accounts for a lower percentage of public transport users in Gauteng compared to other mode of public transport (i.e., buses, minibus taxis). Therefore, the results obtained in this study may be limited in their applicability and considering how the COVID-19 Pandemic may have affected working arrangements. It is also important to note that the study only limited the places of work class to commercial buildings; as such the results displayed in the maps did not address the overall job accessibility within Gauteng in detail. Another limitation is that the methodology used in this study did not consider the quality of the transportation infrastructure which in reality may influence the perception of individuals to travel and also affect travel-time to access places of work.

There were also technical limitations encountered in this study, firstly the extent of the study area, wherein the analysis was only limited to places of work within the study area and disregarded the places of work closer to the border of Gauteng in the neighbouring provinces such as Mpumalanga, North West, Free

State and Limpopo which could potentially be accessed through private transportation. Secondly, the maps visualizing the OD matrix output results (travel-time lines) were not included in the results, however, the results were interpreted through statistical graphs. Travel-time modelling through OD matrices is static, they have a good advantage when it comes to measuring connections between different spatial locations, however, can be difficult to visualize when using large datasets which tend to clutter the visualization of maps (Graser *et al.*, 2019). Large datasets affect the computation time to process the layers; and hence, studies such as Luo *et al.*, (2017) and Graser *et al.*, (2019) recommend the use of clustering methods in order to reduce computation time and clearly visualize the results.

6.3 Recommendations

Although the study provided valuable insights into the distribution of job opportunities as well as residential areas and the time required to access them, it also presented prospects for future studies to improve the work. The identified limitations by the study ranged from the process of data collection to the technical challenges in the analysis stage. Therefore, the limitations of the research will also serve as a reference point for future research studies on job accessibility by providing guidance for input data requirements, spatial units for creating a demand layer for services, reducing computation for travel-time analysis, and comparison between private and public mode of transportation within Gauteng.

Regarding the limitation of input data this study only focused on two modes of transportation (car and rail) and one land-use class (commercial) within Gauteng, therefore future research could expand on the scope of the research through exploring other data such as socioeconomic and demographic characteristics, transportation modes (i.e., buses, minibus taxis), and accessibility to a various land-use classes not considered in this study. The use of comprehensive public transport data to determine the extent at which such modes of transportation affect job accessibility could provide a holistic overview of accessibility to places of work in Gauteng. Secondly, the study used the gravity-based measure which relied on the use of a friction coefficient (mean travel-time) adopted from previous accessibility studies and travel-time surveys, however the challenge with this requirement is that such information may not be available for a particular location being studied and therefore international standards may have to be considered which consequently may lead to the results being unreliable. In addition to this, spatial accessibility of a location or service is perceived differently by people of different socioeconomic backgrounds and demographic characteristics as indicated in previous studies on accessibility (Wang *et al.*, 2005), therefore individual perceptions need to be accounted for by models.

Furthermore, the study used a combination of two *Network Analyst* tools (i.e., the *OD cost matrix* and *Service area*), and based on the analysis of the spatial unit recommended for accuracy purposes, it was discovered that the use of finer spatial units (such as 0.026 km^2, 0.2 km^2, 0.25 km^2, 0.3 km^2, and 1 km^2) to disaggregate population data and tessellate the study area based on previous accessibility studies (Mokgalaka *et al*., 2013; Baloyi *et al*., 2017; Ragoasha *et al*., 2018; Cheng and Bertolini, 2013; Burdziej, 2019) resulted in large databases due to the extent of the study area. Consequently, this affected the storage capacity and computation time. Even though this was a common experience in other spatial accessibility studies (e.g. Cheng *et al*., 2013; Cheng and Bertolini, 2013; Maritz and Moagi, 2015), the use of a tessellated spatial framework proved useful in the analysis. The tessellated spatial framework also assists in eliminating possible errors when accounting for population distribution at a finer spatial unit in accessibility studies *(*Khuluse-Makhanya *et al.,* 2016 and Burdziej, 2019) and hence the 1 km^2 was also preferred for visualizing the accessibility results for the study. While previous accessibility studies have focused on modelling accessibility at micro levels (i.e., local, metro, and district municipal level) with few at a provincial level due to issues of accuracy. This study however recommends for future studies to consider an effective methodology that could allow the expansion of study areas from micro levels to consider analysing accessibility at a higher level (i.e., regional level-areas outside the borders of Gauteng) to improve the reliability of the models to measure job accessibility.

REFERENCES

African Development Bank, 2015. *Rail Infrastructure in Africa*, African Development Bank Group, Côte d'Ivoire.

Ahmed, M., El-Geneidy and Levinson, D.M., 2006. *Access to destinations: Development of accessibility measures.* University of Minnesota, Minneapolis.

Allen, J., 2021. Temporal transitions of demographic dot maps. *International Journal of Cartography*, 8(2), pp.208–222.

Amer, S., 2007. *Towards spatial justice in urban health services planning: a spatial-analytic GIS-based approach using Dar es Salaam, Tanzania as a case study*, International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands.

Apparicio, P., Gelb, J., Dubé, A.-S., Kingham, S., Gauvin, L. and Robitaille, É., 2017. The approaches to measuring the potential spatial access to urban health services revisited: distance types and aggregation-error issues. *International Journal of Health Geographics*, 16(32), pp.1–24.

Aropet, R., 2017. Southern African Solutions to Public Transport Challenges. *36th Southern African Transport Conference (SATC 2017)*. Pretoria, South Africa, 10 - 13 July 2017, pp.805–810.

Arranz-López, A., Mejía-Macias, L.M. and Soria-Lara, J.A., 2021. Combining walking accessibility measures to map spatial inequalities. *Journal of Maps*, 17(1), pp.85–94.

Baloyi, E., Mokgalaka, H., Green, C. and Mans, G., 2017. Evaluating public ambulance service levels by applying a GIS based accessibility analysis approach. *South African Journal of Geomatics*, 6(2), pp.172–183.

Bao, D., Guo, T. and Xia, H., 2014. Impacts of spatial mismatch on commuting time of urban residents in China. *Promet - Traffic and Transportation*, 26(3), pp.227–233.

Bertolini, L., le Clercq, F. and Kapoen, L., 2005. Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy*, 12(3), pp.207–220.

Birch, C.P.D., Oom, S.P. and Beecham, J.A., 2007. Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. *Ecological Modelling*, 206(3–4), pp.347–359.

Bobbins, K.L., 2013. The legacy and prospects of the Gauteng City-Region's mining landscapes. *The Sustainable City VIII*, 179 (2), pp.1363–1374.

Bouraima, M.B., Qiu, Y., Yusupov, B. and Ndjegwes, C.M., 2020. A study on the development strategy of the railway transportation system in the West African Economic and Monetary Union (WAEMU) based on the SWOT/AHP technique. *Scientific African*, 8(2020), pp.1–11.

Brain, I. and Prieto, J., 2021. Understanding changes in the geography of opportunity over time: The case of Santiago, Chile. *Cities*, 114(2021), pp.1–22. Available at: https://doi.org/10.1016/j.cities.2021.103186 [Accessed November 30, 2021].

Brand, A., Geyer, H.S. and Geyer, H.S., 2017. Corridor development in Gauteng, South Africa. *GeoJournal*, 82(2), pp.311–327.

Bremner, L., 2000. Reinventing the Johannesburg inner city. *Cities*, 17(3), pp.185–193.

Budlender, J. and Royston, L., 2016. *Edged out: Spatial Mismatch and Spatial Justice in South Africa's Main Urban Areas*, Socio-Economic Rights Institute of South Africa (SERI), South Africa. Available at: http://www.seri-sa.org/images/images/SERI_Edged_out_report_Final_high_res.pdf [Accessed November 6, 2019].

Burdziej, J, 2019. Using hexagonal grids and network analysis for spatial accessibility assessment in urban environments – a case study of public amenities in Toruń. *Miscellanea Geographica – Regional Studies on Development*, 23(2), pp.99–110.

Büttner, B., Kinigadner, J., Ji, C., Wright, B. and Wulfhorst, G., 2018. The TUM accessibility atlas: visualizing spatial and socioeconomic disparities in accessibility to support regional land-use and transport planning. *Networks and Spatial Economics*, 18(2), pp.385–414.

Chakwizira, J., Bikam, P. and A. Adeboyejo, T., 2018. Restructuring Gauteng City Region in South Africa: Is a transportation solution the answer? In Bahri Ergen, Y., ed., *An Overview of Urban and Regional Planning*. London, UK: IntechOpen, pp.83–102. Available at: https://www.intechopen.com/books/an-overview-of-urban-and-regional-planning/restructuring-gauteng-city-region-in-south-africa-is-a-transportation-solution-the-answer [Accessed June 24, 2020].

Chakwizira, J., Bikam, P. and Adeboyejo, T.A., 2011. Functional and dysfunctional urban mass transportation systems in the greater Gauteng region of South Africa. In Brebbia, C.A., ed., *Sustainable Development and Planning VI*. WIT Transactions on Ecology and the Environment, New Forest, UK, pp.737–748. Available at: http://library.witpress.com/viewpaper.asp?pcode=SDP11-061-1 [Accessed May 18, 2022].

Chakwizira, J., Bikam, P. and Adeboyejo, T.A., 2014. The impact of rapid urbanisation on public transport systems in the Gauteng Region of South Africa. *International Scholarly and Scientific Research and Innovation*, 8(5), pp.564–575.

Charman, A., Tonkin, C., Denoon-Stevens, S. and Demeetére, R., 2017. *Post-apartheid spatial inequality: obstacles of land use management on township micro-enterprise formalisation.* A report by Sustainable Livelihoods Foundation. Cape Town, South Africa pp.1–66.

Chen, J., Shaw, S.-L., Yu, H., Lu, F., Chai, Y. and Jia, Q., 2011. Exploratory data analysis of activity diary data: a space–time GIS approach. *Journal of Transport Geography*, 19(3), pp.394–404.

Chen, Y., 2015. The distance-decay function of geographical gravity model: Power law or exponential law? *Chaos, Solitons and Fractals*, 77, pp.174–189. Available at: https://doi.org/10.1016/j.chaos.2015.05.022 [Accessed March 31, 2022].

Cheng, J. and Bertolini, L., 2013. Measuring urban job accessibility with distance decay, competition and diversity. *Journal of Transport Geography*, 30(2013), pp.100–109.

Cheng, J., Bertolini, L., Clercq, F. le and Kapoen, L., 2013. Understanding urban networks: Comparing a node-, a density- and an accessibility-based view. *Cities*, 31, pp.165–176.

Cheruiyot, K., 2020. Exploring evidence of spatial economic agglomeration in Ekurhuleni Metropolitan Municipality, Gauteng, South Africa. *Economic Research Southern Africa*, 808, pp.1–26.

Church, R.L., 2002. Geographical Information Systems and location science. *Computers and Operations Research*, 29(6), pp.541–562.

City of Johannesburg, 2020. Nodal Review POLICY 2019/20: City Transformation and Spatial Planning. Available at: http://www.parkview.org.za/sites/default/files/inline-files/Nodal%20Review%20Approved%20Feb%202020.pdf [Accessed August 01, 2021].

City of Johannesburg, 2016. Spatial Development Framework 2040. Available at: http://bit.ly/joburg-sdf-16 [Accessed April 5, 2019].

Coggin, T. and Pieterse, M., 2015. A right to transport? Moving towards a rights-based approach to mobility in the city. *South African Journal on Human Rights*, 31(2), pp.294–314.

Council for Scientific and Industrial Research (CSIR), 2000. *Guidelines for human settlement planning and design: The red book (Public Transport)*, CSIR Building and Construction Technology, Pretoria, South Africa. CSIR, 2018. Available at: http://stepsa.org/socio_econ.html. [Accessed June 29, 2022].

Council for Scientific and Industrial Research (CSIR) Mesozone 2018v2 Dataset. Available at: http://stepsa.org/socio_econ.html. [Accessed June 29, 2022].

Culwick, C., Gotz, G., Katumba, S., Trangoš, G. and Wray, C., 2015. Mobility patterns in the Gauteng City-Region, South Africa. *Regional Studies, Regional Science*, 2(1), pp.309–311.

Culwick, C. and Patel, Z., 2020. Building just and sustainable cities through government housing developments. *Environment and Urbanization*, 32(1), pp.133–154.

Curl, A., Nelson, J.D. and Anable, J., 2011. Does accessibility planning address what matters? A review of current practice and practitioner perspectives. *Research in Transportation Business and Management*, 2(2011), pp.3–11.

Curl, A., Nelson, J.D. and Anable, J., 2015. Same question, different answer: A comparison of GIS-based journey time accessibility with self-reported measures from the National Travel Survey in England. *Computers, Environment and Urban Systems*, 49(2015), pp.86–97. Available at: https://doi.org/10.1016/j.rtbm.2011.07.001 [Accessed July 14, 2020].

Curtis, C., 2008. Planning for sustainable accessibility: The implementation challenge. *Transport Policy*, 15(2), pp.104–112.

Dahlgren, A., 2008. *Geographic Accessibility Analysis- Methods and Applications.* Real Estate Science, Department of Technology and Society, Lund University, Lund, Sweden.

Dalvi, M.Q. and Martin, K.M., 1976. The measurement of accessibility: Some preliminary results. *Transportation*, 5(1), pp.17–42.

de Jong, T. and van Eck, J.R., 1996. Location profile-based measures as an improvement on accessibility modelling in GIS. *Computers, Environment and Urban Systems*, 20(3), pp.181–190.

de Kadt, A.J., Ballard, R., Cheruiyot, K., Culwick, C., Hamann, C., Khanyile, S., Maree, G., Matjomane, M., Moore, R., Naidoo, Y., Parker, A. and Sondzaba, S., 2019. *Insights from GCRO's Quality of Life V Survey (2017/18)*, GCRO, Gauteng.

Department of Environmental Affairs and Tourism, 2005. *Human Settlements*, Department of Environmental Affairs and Tourism.

Department of Rural Development and Land Reform, 2018. National Spatial Development Framework [NSDF] (Draft). Available at: https://www.dpme.gov.za/keyfocusareas/gwmeSite/The%20PME%20Forum%202018/The%20Draft%20National%20Spatial%20Development%20Framework%20(NSDF).pdf [Accessed July 14, 2020].

Department of Transport, 2015. *National Rail Policy Green Paper 2015*, Pretoria, South Africa.

Department of Transport, 2022. National Rail Policy: White Paper, Pretoria, South Africa. Available at: https://www.gov.za/sites/default/files/gcis_document/202205/46356gon2077.pdf [Accessed February 6, 2022].

Department of Transport, 2010. *National Transport Master Plan: NATMAP 2050*, Department of Transport. Available at: https://books.google.co.za/books?id=vN5vnQAACAAJ [Accessed May 18, 2022].

Devillers, R., Bédard, Y. and Jeansoulin, R., 2005. Multidimensional management of geospatial data quality information for its dynamic use within GIS. *Photogrammetric Engineering and Remote Sensing*, 71(2), pp.205–215.

Dixon, S., Johnson, D. and Batley, R., 2019. A job accessibility index to evaluate employment impacts in isolated regions now restored to the rail network. *Transportation Planning and Technology*, 42(5), pp.515–537.

Dlamini, S., Tesfamichael, S.G., Shiferaw, Y. and Mokhele, T., 2020. Determinants of environmental perceptions and attitudes in a socio-demographically diverse urban setup: The case of Gauteng Province, South Africa. *Sustainability*, 12(9), pp.1–15.

El-Geneidy, A.M., Levinson, D.M. and County, H., 2006. *Access to destinations: Development of accessibility measures*, University of Minnesota. Available at: https://conservancy.umn.edu/bitstream/handle/11299/638/200616.pdf.Gordon?sequence=1 [Accessed April 3, 2020].

Everatt, D., 2014. Poverty and inequality in the Gauteng City-Region. In Harrison, P., Gotz, G., Todes, A. and Wray, C., eds., *Changing Space, Changing City: Johannesburg after apartheid-Open Access selection*. Johannesburg, Wits University Press, pp.63–82.

Everatt, D., 2017. Quality of Life in the Gauteng City-Region, South Africa. *Social Indicators Research*, 130(1), pp.71–86.

Fair, T.J.D. and Mallows, E.W.N., 1959. The Southern Transvaal: An Emerging Metropolitan Complex in Africa. *The Town Planning Review*, 30(2), pp.125–138.

Flisek, P. and Lewandowicz, E., 2019. A methodology for generating service areas that accounts for linear barriers. *ISPRS International Journal of Geo-Information*, 8(9), pp.1–22.

Ford, A., Barr, S., Dawson, R. and James, P., 2015. Transport accessibility analysis using GIS: Assessing sustainable transport in London. *ISPRS International Journal of Geo-Information*, 4(1), pp.124–149.

Fransen, K., Neutens, T., Farber, S., De Maeyer, P., Deruyter, G. and Witlox, F., 2015. Identifying public transport gaps using time-dependent accessibility levels. *Journal of Transport Geography*, 48, pp.176–187.

Gauteng City-Region Observatory, 2015. *Gauteng City-Region Observatory Annual Report 2014/15*, Gauteng City-Region Observatory, Gauteng. Available at: www.gcro.ac.za. [Accessed December 4, 2020]

Gauteng Department of Roads and Transport and CSIR, 2020. Gauteng Province Household Travel Survey Report 2019/2020. Available at: https://www.csir.co.za/sites/default/files/Documents/GHTS%20201920%20FINAL_LOW%20RES%20%281%29.pdf [Accessed March 21, 2022].

Geertman, S.C.M. and Ritsema Van Eck, J.R., 1995. GIS and models of accessibility potential: an application in planning. *International Journal of Geographical Information Systems*, 9(1), pp.67–80.

Geurs, K.T. and van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2), pp.127–140.

Geyer, H.S. and Molayi, R.S.A., 2018. Job-employed resident imbalance and in Gauteng: exploring the determinants of longer travel time. *Urban Forum*, 29(1), pp.33–50.

Giannopoulos, G.A. and Boulougaris, G.A., 1989. Definition of accessibility for railway stations and its impact on railway passenger demand. *Transportation Planning and Technology*, 13(2), pp.111–120.

Gobillon, L., Selod, H. and Zenou, Y., 2007. The Mechanisms of Spatial Mismatch. *Urban Studies*, 44(12), pp.2401–2427.

Gold, C., 2016. Tessellations in GIS: Part I—putting it all together. *Geo-spatial Information Science*, 19(1), pp.9–2518.

Gomes, E., 2017. Creating a dot density map: Resident population in Mainland Portugal. *The Cartographic Journal*, 54(2), pp.157–162.

Goodchild, M. and Lam, N.S.N., 1980. Areal interpolation: A variant of the traditional spatial problem. *Geo-Process*, 1(3), pp.29–312.

Gotz, G. and Wray, C., 2014. Introduction: A New 'Golden Era' for Transport Planning. In Wray, C. and Gotz, G., eds. *Mobility in the Gauteng City-Region*. Johannesburg, Gauteng City-Region Observatory (GCRO). pp.1–15.

Gotz, G., Wray, C. and Mubiwa, B., 2014. The ‘thin oil of urbanisation’? Spatial change in Johannesburg and the Gauteng City-Region. In: Harrison, P., Gotz, G., Todes, A., Wray, C., eds. *Changing Space, Changing City: Johannesburg after apartheid - Open Access selection*. Wits University Press, pp.42–62.

Graser, A., Schmidt, J., Roth, F. and Brändle, N., 2019. Untangling origin-destination flows in Geographic Information Systems. *Information Visualization*, 18(1), pp.153–172.

Green, C., Mans, G., Schmitz, P. and McKelly, D., 2014. Planning for emergency services using GIS-based geographic accessibility analysis. *Town and Regional Planning*, 64, pp.53–64.

Greenberg, S., 2010. *The Political economy of the Gauteng City-Region*, GCRO Occasional Paper, Gauteng. Available at: https://cdn.gcro.ac.za/media/documents/gcro_occasional_paper_2_greenberg.pdf [Accessed March 2, 2020].

Guan, J., Zhang, K., Shen, Q. and He, Y., 2020. Dynamic modal accessibility gap: measurement and application using travel routes data. *Transportation Research Part D: Transport and Environment*, 81, pp.1–13. Available at: https://doi.org/10.1016/j.trd.2020.102272 [Accessed August 03, 2021].

Gulhan, G., Ceylan, Huseyin, Baskan, O. and Ceylan, Halim, 2014. Using potential accessibility measure for urban public transportation planning: A case study of Denizli, Turkey. *Promet-Traffic and Transportation*, 26(2), pp.129–137.

Hamann, C. and de Kadt, D.J., 2021. *GCRO Quality of Life Survey 6 (2020/21): Sample design*, Gauteng City-Region Observatory, Johannesburg. Available at: https://cdn.gcro.ac.za/media/documents/2021.11.17_QoL_6_Sample_design.pdf [Accessed December 24, 2021].

Hansen, W., 1959. How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2), pp.73–76

Harrison, P. and Todes, A., 2015a. Spatial considerations in the development of urban policy in South Africa: a research paper as input into the preparation of the Integrated Urban Development Framework (IUDF). In *IUDF Stakeholder Workshop,* Johannesburg, pp.1–59.

Harrison, P. and Todes, A., 2015b. Spatial transformations in a “loosening state”: South Africa in a comparative perspective. *Geoforum*, 61, pp.148–162.

Hitge, G. and Vanderschuren, M., 2015. Comparison of travel time between private car and public transport in Cape Town. *Journal of the South African Institution of Civil Engineering*, 57(3), pp.35–43.

Holt, J.B., Lo, C.P. and Hodler, T.W., 2004. Dasymetric estimation of population density and areal interpolation of census data. *Cartography and Geographic Information Science*, 31(2), pp.103–121.

Hu, L., Fan, Y. and Sun, T., 2017. Spatial or socioeconomic inequality? Job accessibility changes for low- and high-education population in Beijing, China. *Cities*, 66, pp.23–33.

Hu, Y. and Downs, J., 2019. Measuring and visualizing place-based space-time job accessibility. *Journal of Transport Geography*, 74, pp.278–288.

Hu, Y. and Wang, F., 2016. Temporal trends of intra-urban commuting in Baton Rouge, 1990–2010. *Annals of the American Association of Geographers*, 106(2), pp.470–479.

Huff, D.L., 1963. A probabilistic analysis of shopping center trade areas. *Land Economics*, 39(1), pp.81–90.

Jennings, G., 2015. Public Transport Interventions and Transport Justice in South Africa: A Literature and Policy Review. *34th Southern African Transport Conference Proceedings*. Pretoria, South Africa, 6-9 July, pp.764–775.

Jin, J. and Paulsen, K., 2018. Does accessibility matter? Understanding the effect of job accessibility on labour market outcomes. *Urban Studies*, 55(1), pp.91–115.

Joubert, J.W., 2022. Accounting for population density in econometric accessibility. *Procedia Computer Science*, 201, pp.594–600.

Kain, J. F, 1968. Housing segregation, negro employment, and metropolitan decentralization. *Quarterly Journal of Economics*, 82(2), pp.175–197.

Kain, J.F., 1992. The spatial mismatch hypothesis: three decades later. *Housing Policy Debate*, 3(2), pp.371–460.

Kanuganti, S., Sarkar, A.K. and Singh, A.P., 2016. Quantifying accessibility to health care using Two-step Floating Catchment Area Method (2SFCA): A Case Study in Rajasthan. *Transportation Research Procedia*, 17, pp.391–399.

Katumba, S., Cheruiyot, K. and Mushongera, D., 2019. Spatial change in the concentration of multidimensional poverty in Gauteng, South Africa: Evidence from Quality of Life Survey Data. *Social Indicators Research*, 145(1), pp.95–115.

Katumba, S. and Everatt, D., 2021. Urban Sprawl and Land Cover in Post-Apartheid Johannesburg and the Gauteng City-Region, 1990–2018. *Environment and Urbanization ASIA*, 12(1_suppl), pp. S147–S164.

Kelobonye, K., McCarney, G., Xia, J. C, Swapan, M.S.H., Mao, F. and Zhou, H., 2019. Relative accessibility analysis for key land uses: a spatial equity perspective. *Journal of Transport Geography*, 75, pp.82–93.

Kelobonye, K., Zhou, H., McCarney, G. and Xia, J. C, 2020. Measuring the accessibility and spatial equity of urban services under competition using the cumulative opportunities measure. *Journal of Transport Geography*, 85, pp.1–13.

Kelobonye, K., Zhou, H., Xia, J. C and McCarney, G., 2021. Assessing the potential of an effective density-based measure against accessibility models for evaluation and prioritisation of activity centres. *Applied Geography*, 128, pp.1–12.

Kerr, A., 2015. *Tax(i)ing the poor? Commuting costs in South Africa.* A Southern Africa Labour and Development Research Unit, Cape Town: SALDRU, University of Cape Town.

Kgwedi, R. and Krygsman, S., 2019. Accessibility of public transport - with focus on access, egress and the line haul travel time. *South African Annual Transport Conference (SATC 2019)*. Pretoria, Gauteng, 8-11 July, pp.1–12.

Khuluse-Makhanya, S., Dudeni-Tlhone, N., Holloway, J., Schmitz, P., Waldeck, L., Stein, A., Debba, P., Stylianides, T., Plessis, P. du, Cooper, A. and Baloyi, E., 2016. The applicability of the South African Census 2011 data for evidence-based urban planning. *Southern African Journal of Demography*, 17(1), pp.67–132.

Kim, H.-M. and Kwan, M.-P., 2003. Space-time accessibility measures: A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration. *Journal of Geographical Systems*, 5(1), pp.71–91.

Koops, B.-J. and Galič, M., 2017. Conceptualizing space and place: lessons from geography for the debate on privacy in public. In: Timan, T., Newell, B. C and Koops, B.-J., eds. *Privacy in Public Space: Conceptual and Regulatory Challenges,* pp.19–46.

Elgar Law, Technology and Society series. Edward Elgar Publishing, pp.19–46. Available at: https://www.elgaronline.com/view/9781786435392.00007.xml [Accessed January 14, 2022].

Kuehnel, N., Ziemke, D., Moeckel, R. and Nagel, K., 2020. The end of travel time matrices: individual travel times in integrated land use/transport models. *Journal of Transport Geography*, 88, pp.1–12.

Kwan, M.-P., 1999. Gender and individual access to urban opportunities: A study using space–time measures. *The Professional Geographer*, 51(2), pp.211–227.

LaMondia, J.J., Blackmar, C.E. and Bhat, C.R., 2010. Comparing transit accessibility measures: a case study of access to healthcare facilities. *89rd Annual Meeting of Transportation Research Board, Washington, DC, USA.* Texas Department of Transportation Project, 10-17 January, pp.1–22.

Landman, K., 2010. A home close to opportunities in South Africa: top down vision or bottom up demand? *Town and Regional Planning*, 56, pp.8–57.

Le Roux, A., Makhanya, S., Arnold, K., van Tonder, L., Wools, L. and Mans, G., 2019. *Green Book - Projecting the Future Growth of South African Settlements: Developing a Concept Model for Town Growth Forecasting in South Africa. Technical report*, CSIR, Pretoria. Available at: https://s3-eu-west-1. amazonaws. com/csir-greenbook/resources/WS3_SettlementGrowth_Report_2019 [Accessed July 11, 2022].

Levinson, D.M., 1998. Accessibility and the journey to work. *Journal of Transport Geography*, 6(1), pp.11–21.

Linard, C., Gilbert, M., Snow, R.W., Noor, A.M. and Tatem, A.J., 2012. Population distribution, settlement patterns and accessibility across Africa in 2010. *PLoS ONE*, 7(2), pp.1–8.

Lionjanga, N. and Venter, C., 2018. Does public transport accessibility enhance subjective well-being? a study of the City of Johannesburg. *Transportation Economics*, 69, pp.523–535.

Lionjanga, N. and Venter, C., 2017. Time-series analysis of accessibility in the City of Johannesburg. *36th Southern African Transport Conference (SATC 2017) Proceedings*. Pretoria, South Africa, 10-13 July, pp.416–429.

Liu, D. and Kwan, M.-P., 2020. Measuring spatial mismatch and job access inequity based on transit-based job accessibility for poor job seekers. *Travel Behaviour and Society*, 19, pp.184–193.

Liu, S. and Zhu, X., 2004. Accessibility Analyst: An integrated GIS tool for accessibility analysis in urban transportation planning. *Environment and Planning B: Planning and Design*, 31(1), pp.105–124.

Lombard, M., Cameron, B., Mokonyama, M. and Shaw, A., 2007. *Report on trends in passenger transport in South Africa*, Development Bank of Southern Africa, Midrand, Johannesburg.

Luke, R. and Pisa, N., 2018. The spatial trend association between socio-economic factors and households' travel pattern in Gauteng. *37th Annual Southern African Transport Conference (SATC2018) Proceedings*. Pretoria, South Africa, 9-12 July, pp.418–427.

Lukhele, T., 2014. Mixed-income housing, urban transformation and social cohesion in post-apartheid South Africa. *Mediterranean Journal of Social Sciences*, 5(25), pp.36–43.

Luo, D., Cats, O. and van Lint, H., 2017. Constructing transit origin–destination matrices with spatial clustering. *Transportation Research Record: Journal of the Transportation Research Board*, 2652(1), pp.39–49.

Lwin, K. and Murayama, Y., 2009. A GIS approach to estimation of building population for micro-spatial analysis. *Transactions in GIS*, 13(4), pp.401–414.

Maantay, J., Astrud, A., Maroko, R. and Herrmann, C., 2007. Mapping population distribution in the urban environment: The Cadastral-Based Expert Dasymetric System (CEDS). *Cartography and Geographic Information Science*, 2(34), pp.77–102.

Mabin, A., 2013. The map of Gauteng: Evolution of a city-region in concept and plan. *Johannesburg: GCRO*, GCRO Occasional Paper 5, pp.1–64.

Makrí, M.-C. and Folkesson, C., 1999. Accessibility measures for analyses of land use and travelling with Geographical Information Systems. In: Lahrmann, H., ed., *Proceedings from the Annual Transport Conference at Aalborg University*, Trafikdagepp, Denmark, pp.1–15.

Manduca, R., 2021. The spatial structure of US metropolitan employment: New insights from administrative data. *Environment and Planning B: Urban Analytics and City Science*, 48(5), pp.1357–1372.

Manjia, M.B., Kouamou, G.E. and Pettang, C., 2018. The geographical accessibility as a key access parameter to health care in Cameroon: modelling, measurement and evaluation. *Journal of Decision Systems*, 27(sup1), pp.155–163.

Mans, G., 2012. Developing a geo-data frame to facilitate data integration (Part 1). *Position IT*, pp.40–43.

Marchetti, C., 1994. Anthropological invariants in travel behavior. *Technological Forecasting and Social Change*, 47(1), pp.75–88.

Maritz, J., le Roux, A. and Mans, G., 2017. Developing Spatial Indicators Using a Uniform Tessellation to Measure Urban Transformation. In Gervasi, O., Murgante, B., Misra, S., Borruso, G., Torre, C. M., Rocha, A. M. A. C., Taniar, D., Apduhan, B. O., Stankova, E. and Cuzzocrea, A., eds., *Computational Science and Its Applications – ICCSA 2017*. Lecture Notes in Computer Science. Springer International Publishing, Cham, pp.408–421. Available at: http://link.springer.com/10.1007/978-3-319-62401-3_30 [Accessed July 6, 2022].

Maritz, J. and Moagi, M., 2015. Seeking to improve spatial justice - the case of rationalising the district court areas in South Africa - utilising several spatial analysis methods. In: Sluter, C. R., Cruz, Carla B. M., Camboim, S. P., Delazari, L. S., Fernandes, M. C., de Barros, R. S., Firkowski, H., and de Menezes P. M. L., eds., *Proceedings of the 27th International Cartographic Conference and 16th General Assembly*. International Cartographic Conference (ICC), Rio De Janeiro, Brazil, 23-28 August, pp.1–24.

Miller, E.J., 2018. Accessibility: measurement and application in transportation planning. *Transport Reviews*, 38(5), pp.551–555.

Miller, H., 2007. Place-based versus people-based Geographic Information Science. *Geography Compass*, 1(3), pp.503–535.

Miller, H.J., 2004. Tobler's first law and spatial analysis. *Annals of the Association of American Geographers*, 94(2), pp.284–289.

Mokgalaka, H., Mans, G., Smit, J. and McKelly, D., 2013. GIS-based accessibility analysis- a mixed method approach to determine public primary health care demand in South Africa. *Global Geospatial Conference Proceeding*. Addis Ababa, Ethiopia, 4-8 November, pp.1–23.

Mokgalaka, H., Mans, G., Smit, J. and McKelly, D., 2014. Validating the accuracy of GIS-based accessibility analysis in determining public primary health care demand in metropolitan areas. *Second AfricaGEO Conference Proceedings*. CONSAS Conference, Cape Town, South Africa, 1-3 July, pp.1–19.

Mokonyama, M., 2009. Forecasting household transport energy demand in South African cities. In *Forecasting in an Ever-changing Environment*. Eskom conference. Midrand, Johannesburg, pp.1–14.

Mokonyama, M. and Mubiwa, B., 2014. Transport in the shaping of space. In P. Harrison, G. Gotz, A. Todes, and C. Wray, eds., *Changing Space, Changing City*. Johannesburg after apartheid - Open Access selection. Wits University Press, pp.194–214. Available at: http://www.jstor.org/stable/10.18772/22014107656.14 [Accessed May 12, 2022].

Mudau, N., 2010. SPOT Building Count supports informed decisions. *Position IT*, pp.50–51.

Munson, M., 1965. Geographic Potential Surfaces. *Journal of the Minnesota Academy of Science*, 3(1), pp.33–39.

Mushongera, D., Zikhali, P. and Ngwenya, P., 2015. A multidimensional poverty index for Gauteng Province, South Africa: Evidence from Quality of Life Survey Data. *Social Indicators Research*, 130(1), pp.277–303.

Naidoo, M., Mokonyama, M. and Nkosi, M., 2016. Towards a detailed on-road vehicle emissions inventory: The use of a Travel Demand Model. *Annual Conference Proceedings of the National Association for Clean Air Conference 2016*. Emnotweni Arena, Nelspruit, South Africa, pp.1–6.

Nakamura, S. and Avner, P., 2021. Spatial distributions of job accessibility, housing rents, and poverty: The case of Nairobi. *Journal of Housing Economics*, 51, pp.1–15.

National Planning Commission, 2011. National Development Plan: Vision for 2030. Available at: https://nationalplanningcommission.wordpress.com/downloads/ [Accessed June 12, 2021].

Naude, A., van Huyssteen, E. and Goss, H., 2008. Geospatial analysis platform and tools: supporting planning and decision making across scales, borders, sectors and disciplines. *Planning Africa Conference*. Sandton Convention Centre, Johannesburg, South Africa, pp.329–348.

Ngidi, M., Mans, G., McKelly, D. and Sogoni, Z., 2017. Using a hybrid methodology of dasymetric mapping and data interpolation techniques to undertake population data (dis)aggregation in South Africa. *South African Journal of Geomatics*, 6(2), pp.232–244.

Organisation for Economic Co-operation and Development (OECD), 2011. *How's life?: Measuring well-being*. Paris, OECD. Available at: https://www.oecd-ilibrary.org/economics/how-s-life_9789264121164-en [Accessed January 19, 2022].

Orkin, M., 2020. *Technical Review of the GCRO QoL Surveys: Synthesis Report*, Gauteng City-Region Observatory, Gauteng.

Owen, A. and Levinson, D.M., 2015. Modeling the commute mode share of transit using continuous accessibility to jobs. *Transportation Research Part A: Policy and Practice*, 74, pp.110–122.

Pajares, E., Büttner, B., Jehle, U., Nichols, A. and Wulfhorst, G., 2021a. Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility. *Journal of Transport Geography*, 93, pp.1–16.

Pajares, E., Muñoz Nieto, R., Meng, L. and Wulfhorst, G., 2021b. Population disaggregation on the building level based on outdated Census Data. *ISPRS International Journal of Geo-Information*, 10(10), pp.1–21.

Pan, Q., Jin, Z. and Liu, X., 2020. Measuring the effects of job competition and matching on employment accessibility. *Transportation Research Part D: Transport and Environment*, 87, pp.1–16.

Parnell, S. and Walawege, R., 2011. Sub-Saharan African urbanisation and global environmental change. *Global Environmental Change*, 21, pp.S12–S20.

Peberdy, S., 2013. *Gauteng: a province of migrants*. GCRO Data Brief No.5, GCRO, Johannesburg, South Africa.

Pieterse, E. and Owens, K., 2018. Johannesburg: Confronting Spatial Inequality. World Resources Report Case Study. *Washington, DC: World Resources Institute*, Available at: www. citiesforall.org [Accessed February 19, 2021].

Porter, G., 2002. Living in a walking world: rural mobility and social equity issues in Sub-Saharan Africa. *World Development*, 30(2), pp.285–300.

Raadsen, M.P.H., Bliemer, M.C.J. and Bell, M.G.H., 2020. Aggregation, disaggregation and decomposition methods in traffic assignment: historical perspectives and new trends. *Transportation Research Part B: Methodological*, 139, pp.199–223.

Ragoasha, M.V., Maritz, J. and Cooper, A.K., 2018. Geospatial accessibility analysis of primary health care clinics in the Mbizana Local Municipality in the Eastern Cape. *Proceedings of the AfricaGEO 2018 Conference*. The AfricaGEO 2018 Conference. Emperors' Palace, Kempton Park, 17-19 September, pp.52–65.

Rau, H. and Vega, A., 2012. Spatial (im)mobility and accessibility in Ireland: implications for transport policy. *Growth and Change*, 43(4), pp.667–696.

Rayer, S., 2015. Demographic Techniques: Small-area Estimates and Projections. In Wright, J. D., ed., International Encyclopedia of the Social and Behavioral Sciences (Second Edition). Elsevier, Oxford. Available at: https://www.sciencedirect.com/science/article/pii/B9780080970868310157 [Accessed March 18, 2022].

Reggiani, A., Bucci, P., Russo, G., Haas, A. and Nijkamp, P., 2011. Regional labour markets and job accessibility in City Network systems in Germany. *Journal of Transport Geography*, 19(4), pp.528–536.

Reilly, W., 1929. *Methods for the Study of Retail Relationship*, University of Texas Bulletin, Texas, Austin, pp.1–56.

Risimati, B. and Gumbo, T., 2018. Exploring the applicability of location-based services to delineate the state public transport routes integratedness within the City of Johannesburg. *Infrastructures*, 3(3), pp.1–14.

Rogerson, C.M., 1996. Urban poverty and the informal economy in South Africa's economic heartland. *Environment and Urbanization*, 8(1), pp.1–13.

Rosenfeld, L., 1965. Newton and the Law of Gravitation. *Archive for History of Exact Sciences*, 2, pp.365–386.

Rospabe, S. and Selod, S., 2006. Does city structure cause unemployment? The case of Cape Town. In: Bhorat, H. and Kanbur, R. eds. *Poverty and Policy in Post-Apartheid South Africa*. HSRC Press, Cape Town, South Africa, pp.262–287.

Roth, S., Landry, M., Ebener, S., Marcelo, A., Kijsanayotin, B. and Parry, J., 2016. The Geography of Universal Health Coverage. *Asian Development Bank Briefs No. 55*, pp.1–11.

Ruhiiga, T.M., 2014. Urbanisation in South Africa: a critical review of policy, planning and practice. *African Population Studies*, 28, pp.610–622.

Salonen, M. and Toivonen, T., 2013. Modelling travel time in urban networks: comparable measures for private car and public transport. *Journal of Transport Geography*, 31, pp.143–153.

Scholz, J., Andorfer, M. and Mittlboeck, M., 2013. Spatial accuracy evaluation of population density grid disaggregations with Corine Landcover. In *Geographic Information Science at the Heart of Europe. 16th AGILE conference on Geographic Information Science*, City of Leuven, Belgium.

Scorcia, H. and Munoz-Raskin, R., 2019. Why South African cities are different? Comparing Johannesburg Rea Vaya Bus Rapid Transit System with its Latin American siblings. *Case Studies in Transport Policy Journal*, 7(2), pp.395–403.

Shen, Q., 2001. A spatial analysis of job openings and access in a U.S. Metropolitan Area. *Journal of the American Planning Association*, 67(1), pp.53–68.

Shen, Q., 1998. Location characteristics of inner-city neighborhoods and employment accessibility of low-wage workers. *Environment and Planning B: Planning and Design*, 25(3), pp.345–365.

Silalahi, F.E.S., Hidayat, F., Dewi, R.S., Purwono, N. and Oktaviani, N., 2020. GIS-based approaches on the accessibility of referral hospital using network analysis and the spatial distribution model of the spreading case of COVID-19 in Jakarta, Indonesia. *BMC Health Services Research*, 20(1), pp.1–20.

Sinclair-Smith, K. and Turok, I., 2012. The changing spatial economy of cities: An exploratory analysis of Cape Town. *Development Southern Africa*, 29(3), pp.391–417.

Statistics South Africa, 2004. *Census 2001: Concepts and definitions*, Pretoria, South Africa. Available at:

http://www.statssa.gov.za/census/census_2001/concepts_definitions/concepts_definitions.pdf [Accessed June 22, 2020].

Statistics South Africa, 2012. *Census 2011 Statistical release (Revised)*, Pretoria, South Africa. Available at: https://www.statssa.gov.za/publications/P03014/P030142011.pdf [Accessed June 22, 2020].

Statistics South Africa, 2015. *Census 2011: Migration dynamics in South Africa*, Pretoria, South Africa Available at: http://arks.princeton.edu/ark:/88435/dsp01ns064843z [Accessed July 21, 2022].

Statistics South Africa, 2013. *National Household Travel Survey 2013*, Pretoria, South Africa. Available at: https://www.statssa.gov.za/publications/P0320/P03202013.pdf [Accessed July 13, 2020].

Statistics South Africa, 2019. *Quarterly Labour Force Survey*, Pretoria, South Africa. Available at: https://www.statssa.gov.za/publications/P0211/P02112ndQuarter2019.pdf [Accessed December 8, 2021].

Stewart, J.Q., 1947. Empirical Mathematical Rules concerning the Distribution and Equilibrium of Population. *Geographical Review*, 37(3), pp.461–485.

Tao, Z., Zhou, J., Lin, X., Chao, H. and Li, G., 2020. Investigating the impacts of public transport on job accessibility in Shenzhen, China: a multi-modal approach. *Land Use Policy*, 99, pp.1–10.

Tenkanen, H., Heikinheimo, V., Järv, O., Salonen, M. and Toivonen, T., 2016. Open data for accessibility and travel time analyses: Helsinki Region Travel Time and CO2 Matrix. In: Sarjakoski, T., Santos, M. Y., and Sarjakoski, L. T., eds., *Proceedings of the Geospatial Data in a Changing World, 19th AGILE International Conference on Geographic Information Science*. Geospatial Research Institute, Helsinki, Finland.

Terwin, S., 2019. Restructuring the fragmented Gauteng City Region: Could smart shelters be the answer?. *38th International Southern African Transport Conference*. Southern African Transport Conference, CSIR International Convention Centre, Pretoria, South Africa, 8-11 July, pp.1–18.

The World Bank, 2018. *Overcoming Poverty and Inequality in South Africa: An Assessment of Drivers, Constraints and Opportunities*, Washington DC. Available at: https://www.statssa.gov.za/wp-content/themes/umkhanyakude/documents/South_Africa_Poverty_and_Inequality_Assessment_Report_2018.pdf [Accessed September 10, 2021].

Thompson, L., 2001. *A history of South Africa.* 3rd ed., Yale University Press, United States of America. Available at: https://www.sahistory.org.za/sites/default/files/archivefiles3/leonard_monteath_thompson_a_history_of_south_afrbook4me.org_.pdf [Accessed February 19, 2020].

Tobler, W.R., 1970. A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography*, 46, pp.234–240.

Todes, A., 2012. Urban growth and strategic spatial planning in Johannesburg, South Africa. *Cities*, 29(3), pp.158–165.

Tóth, G. and Kincses, Á., 2015. Accessibility Models Based on the Gravity Analogy: In Theory and Practice. *Regional Statistics*, 5(1), pp.137–158.

Tsoka, J.M. and le Sueur, D., 2004. Using GIS to measure geographical accessibility to primary health care in rural South Africa. *South African Journal of Science*, (100), pp.329–30.

UN-HABITAT, 2009. *Global report on human settlements 2011: Cities and Global Change*, Nairobi. pp.1–300.

United Nations, 2015. World Urbanization Prospects: The 2014 Revision. *United Nations Department of Economics and Social Affairs, Population Division: New York, NY, USA*, pp.1–517. Available at: https://population.un.org/wup/publications/files/wup2014-report.pdf [Accessed March 19, 2021]

van der Merwe, J., Krygsman, S., and UNU-WIDER, 2020. *The relationship between transport accessibility and employment duration.* 56th ed., UNU-WIDER. pp.1–30. Available at: https://www.wider.unu.edu/node/237151 [Accessed November 11, 2021].

Van Dijk, J.T., Krygsman, S. and De Jong, T., 2015. Toward spatial justice: The spatial equity effects of a toll road in Cape Town, South Africa. *Journal of Transport and Land Use*, 8(3), pp.95–114.

van Wyk, J., 2015. Can SPLUMA play a role in transforming spatial injustice to spatial justice in housing in South Africa? *Southern African Public Law*, 30(1), pp.26–41.

Venables, A.J., 2016. Incorporating Wider Economic Impacts within Cost–Benefit Appraisal. In *Quantifying the Socio-Economic Benefits of Transport*. International Transport Forum. Organisation for Economic Co-operation and Development, Paris, pp.1–30.

Venter, C. and Badenhorst, W., 2011. 2011 GCRO Quality of Life Survey: Analysis of transport data. In Wray, C. and Gotz, G., eds. *Mobility in the Gauteng City-Region*. Gauteng City-Region Observatory (GCRO), pp.15–56.

Venter, C. and Cross, C, 2014. Access envelopes: A new accessibility mapping technique for transport and settlements planning. *Town and Regional Planning,* (64), pp.43–52.

Venter, C., Jennings, G., Hidalgo, D. and Valderrama Pineda, A.F., 2018. The equity impacts of bus rapid transit: A review of the evidence and implications for sustainable transport. *International Journal of Sustainable Transportation*, 12(2), pp.140–152.

Venter, C.J. and Mohammed, S.O., 2013. Estimating car ownership and transport energy consumption: a disaggregate study in Nelson Mandela Bay. *Journal of the South African Institution of Civil Engineering*, 55(1), pp.1–10.

Verma, V.R. and Dash, U., 2020. Geographical accessibility and spatial coverage modelling of public health care network in rural and remote India. *PLoS ONE*, 15(10), pp.1–23.

Walker, K.E., 2018. Scaling the interactive dot map. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 53(3), pp.171–184.

Wang, C.-H. and Chen, N., 2015. A GIS-based spatial statistical approach to modeling job accessibility by transportation mode: case study of Columbus, Ohio. *Journal of Transport Geography*, 45, pp.1–11.

Wang, F., Jin, F. and Gu, C., 2005. GIS-based method for delineating urban hinterlands in northeast China. *Annals of GIS*, 11(2), pp.113–121.

Wang, Y., Chen, B.Y., Yuan, H., Wang, D., Lam, W.H.K. and Li, Q., 2018. Measuring temporal variation of location-based accessibility using space-time utility perspective. *Journal of Transport Geography*, 73, pp.13–24.

Wanghe, K., Guo, X., Wang, M., Zhuang, H., Ahmad, S., Ullah Khan, T., Xiao, Y., Luan, X. and Li, K., 2020. Gravity model toolbox: An automated and open-source ArcGIS tool to build and prioritize ecological corridors in urban landscapes. *Global Ecology and Conservation*, pp.1–14.

Webb, G., 1986. Spatial Ability and Achievement in Geography: The Case of Cambridge GCE A Level Examinations. *Area*, 18, pp.285–290.

Weber, J., 2003. Individual accessibility and distance from major employment centers: An examination using space-time measures. *Journal of Geographical Systems*, 5(1), pp.51–70.

Weber, J., 2006. Reflections on the future of accessibility. *Journal of Transport Geography*, 14(5), pp.399–400.

Wray, C., 2010. Working towards a successful Gauteng City-Region. *PositionIT*, Jan/Feb 2010, pp.38–42.

Wray, C. and Cheruiyot, K., 2015. Key Challenges and Potential Urban Modelling Opportunities in South Africa, with Specific Reference to the Gauteng City-Region. *South African Journal of Geomatics*, 4(1), pp.14–35.

Xiao, W., Wei, Y.D. and Wan, N., 2021. Modeling job accessibility using online map data: An extended two-step floating catchment area method with multiple travel modes. *Journal of Transport Geography*, 93, pp.1–11.

Yin, S., Li, M., Tilahun, N., Forbes, A. and Johnson, A., 2015. Understanding transportation accessibility of Metropolitan Chicago through interactive visualization. T*he 1st International ACM SIGSPATIAL Workshop on Smart Cities and Urban Analytics Proceedings - UrbanGIS'15*. Association for Computing Machinery Press, Bellevue, WA, USA, 3-6 November, pp.77–84. Available at: http://dl.acm.org/citation.cfm?doid=2835022.2835036 [Accessed March 5, 2020].

Yusuf, M.P. and Allopi, D., 2004. The impact of urban sprawl on the inhabitants of the eThekwini Municipality and the provision of infrastructure. *23rd Southern African Transport Conference (SATC 2004)*. Document Transformation Technologies cc, Pretoria, South Africa, 16 -19 August, pp.520–526.

Zhao, P., Roo, G. and Lu, B., 2009. Planning for low-carbon urban growth: the impact of urban form on transport and the environment on the urban fringe of Beijing. In: ISOCARP, ed., *Proceedings of the 45th ISOCARP Congress*. ISOCARP. Porto, Portugal, 18-22 October, pp.1–12.

Zhou, X., Chen, X. and Zhang, T., 2016. Impact of megacity jobs-housing spatial mismatch on commuting behaviors: A case study on central districts of Shanghai, China. *Sustainability*, 8(2), pp.1–22.

Ziemke, D., Joubert, J.W. and Nagel, K., 2018. Accessibility in a post-apartheid city: Comparison of two approaches for accessibility computations. *Networks and Spatial Economics*, 18(2), pp.241–271.

APPENDICES:

Appendix A: *Metadata Summary*

1. *Quality of Life (QoL) survey data from GCRO*

The Quality of Life survey data was captured between the period of 2017 and 2018.The method employed by the survey was a random selection process to select the required number of survey locations in each ward. The random points were drawn from the building-based land-use data which provided the coordinates and number of dwelling units for all residential buildings in Gauteng. The composition was 50 interview locations per ward in the province's local municipalities and 65 interview locations per ward in the metro municipalities. However, the sample was eventually reduced to a minimum sample size of 22 220 surveys due to slow data collection progress. The survey had a total of 16 section questionnaires including 248 closed ended questions. The final total number of respondents that participated in the survey was 24 889 across 529 wards (2016 demarcation) throughout the province of Gauteng. For the purpose of this research analysis we only zoomed into section 5 (Transport) and the variable names of interest were "frequent trip", "time destination" and "longest mode" which basically assess the purpose of the trips Lastly, the metadata highlighted the limitations of the dataset, the compatibility and the disclaimer on the dissemination of the dataset.

2. *Building Based Land-Use data and Dwelling Frame from GTI*

The data consists of points based on various land-use classification such as agriculture, mining, transport, forestry, conservation, utilities and infrastructure, residential, institutions, commercial, community services, health care, education, commercial, industrial, tourism and lastly recreational and leisure. The data is further main land-use classes are further broken down into sub-classes. Furthermore, a dwelling unit layer for the study area was also acquired in point format. The dwelling frame layer consisted of 3,394,110 records of various residential buildings. Each building or complex is represented as a point at the centroid of the building's areal coverage. The dataset compliments the National Census data and allows for value-addition modelling applications to be completed. The land-use classes that represent the identified job opportunities and residential areas were selected from the land-use points for the purpose of the analysis. The reference system used on the datasets was the WGS 84 projection. Lastly, the metadata highlighted the limitations of the dataset, the compatibility and the disclaimer on the dissemination of the dataset.

3. SA CSIR Mesozones *dataset*

The SA CSIR Mesozones 2018 (version 2) dataset is a boundary base of mesozones at a national level. The dataset was aligned with the latest district municipal and provincial data, it was designed to offer support to various planning activities and the issue of modifiable area unit problem (MAUP). The mesozones are not uniformly designed but the size of the shapes use almost equal scale of 50 km^2. The data uses the original data provided by StatsSA at subplace level to give population estimations for 2016. The grid has a total of 25 000 spatial units (or mesozones) and Gauteng province alone has a total of 373. The layer was obtained online (stepSA) together with a metadata document. The reference system used on the datasets was the WGS 84 projection.

Appendix B: Summary of the QoL 2017/18 QoL survey data responses based on the transport variable

Table B_1: Frequent trips made (Q5_01).

Code	Answers	Total
1	Work	8088
2	Look for work	1893
3	Place of Study	1261
4	Shopping	7186
5	Taking Children to School	552
6	Place of Leisure	456
7	Other	4406
8	No trips	1047
Total no. of Respondents		**24889**

Table B_2: Time destination (Q5_05).

Code	Answers	Total
1	15 minutes	5859
2	16 minutes to 30 minutes	8684
3	31 minutes to 45 minutes	5041
4	46 minutes to 60 minutes	2851
5	61 minutes to 90 minutes	1009
6	More	1445
Total no. of Respondents		**24889**

Table B_3: Car as driver (Q5_06_04).

Code	Answers	Total
0	No	18235
1	Yes	6654
Total no. of Respondents		**24889**

Table B_4: Car as passenger (Q5_06_05).

Code	Answers	Total
0	No	21122
1	Yes	3767
Total no. of Respondents		**24889**

Table B_5: Car as passenger through lift club (Q5_06_06).

Code	Answers	Total
0	No	23741
1	Yes	1148
Total no. of Respondents		**24889**

Table B_6: Rail (Q5_06_08).

Code	Answers	Total
0	No	22913
1	Yes	1976
Total no. of Respondents		**24889**

Appendix B: Summary of the Places of Work Classes from the BBLU data

Table B_7: Summary of Commercial sub-classes (places of work).

Main Land-Use Code	Sub-class code	Commercial	Sub-Class Code Description	Total
11	11.1	Shopping Mall	Major Regional Shopping Centre and all associated buildings	448
11	11.2	Shopping Centre	Smaller Shopping Centres and all associated buildings	1 546
11	11.3	Commerce	Offices, Shops, Retail, Services, Financial Institutions, Restaurants, Conference Centre, post offices, stand-alone post boxes, etc.	54 514
11	11.4	Petrol Station, Service Station	Petrol Station and Service Stations including all associated buildings. Excludes the associated shop	1 703
11	11.5	Office Parks	Office and Business Parks, point at main entrance	516
11.6		Informal Trading	Informal Trading Structures	5 249

Appendix C: Summary of the Gauteng Municipal demarcation Data and CSIR SA Mesozones

Table C_1*: Gauteng demarcations and mesozones breakdown.*

Municipality (2016)	Wards (2016)	Mesozones (2018)
City of Johannesburg	135	33
City of Tshwane	107	130
Ekurhuleni	112	41
Sedibeng District		
Emfuleni	45	19
Lesedi	13	31
Midvaal	15	36
West Rand District		
Mogale City	39	28
Rand West City	35	23
Merafong City	28	32

Appendix D: Travel-Time Settings and Analysis Results

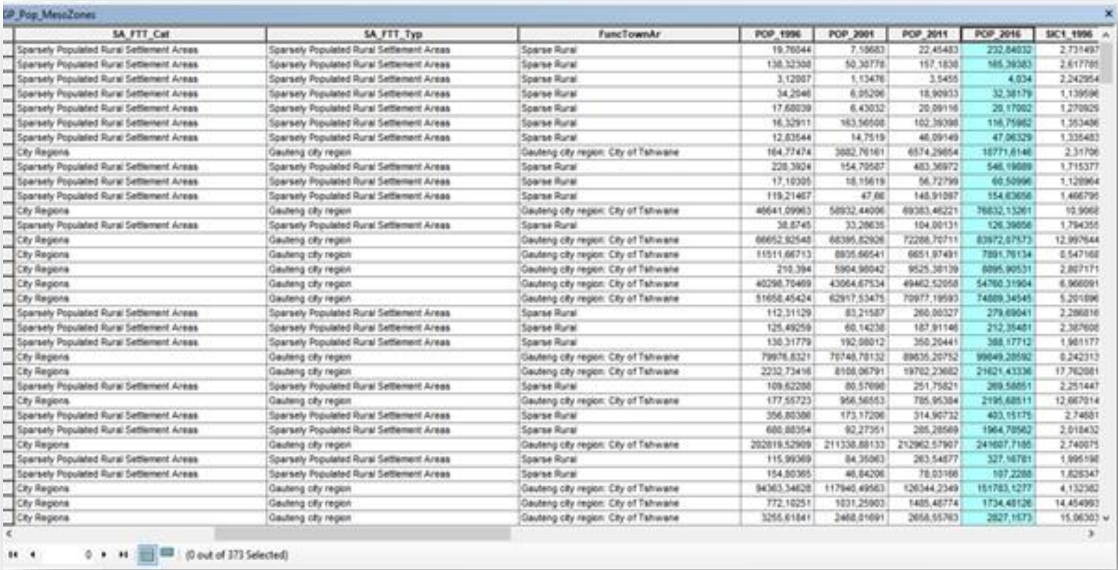


Figure D_1: Attribute table of the population mesozones layer.

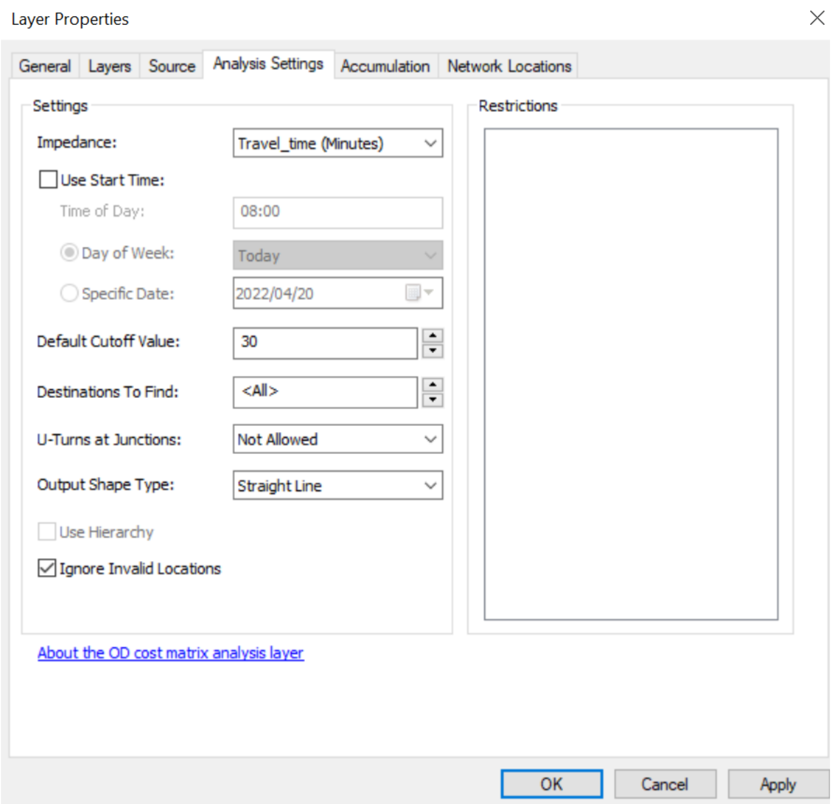


Figure D_2: Setting of properties for private transport (car) in the OD cost matrix layer.

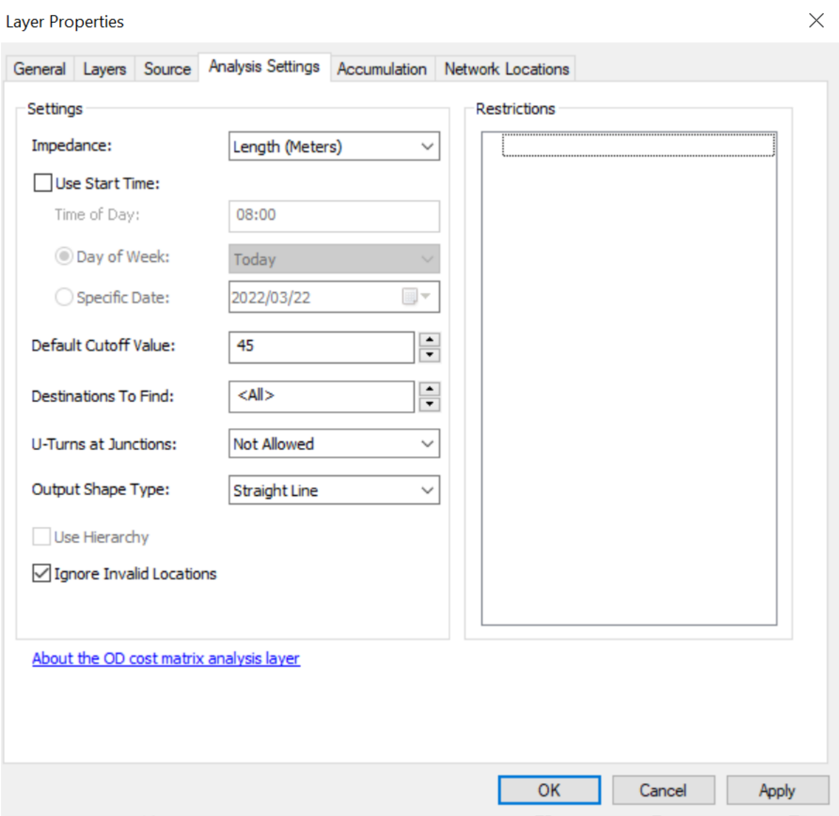
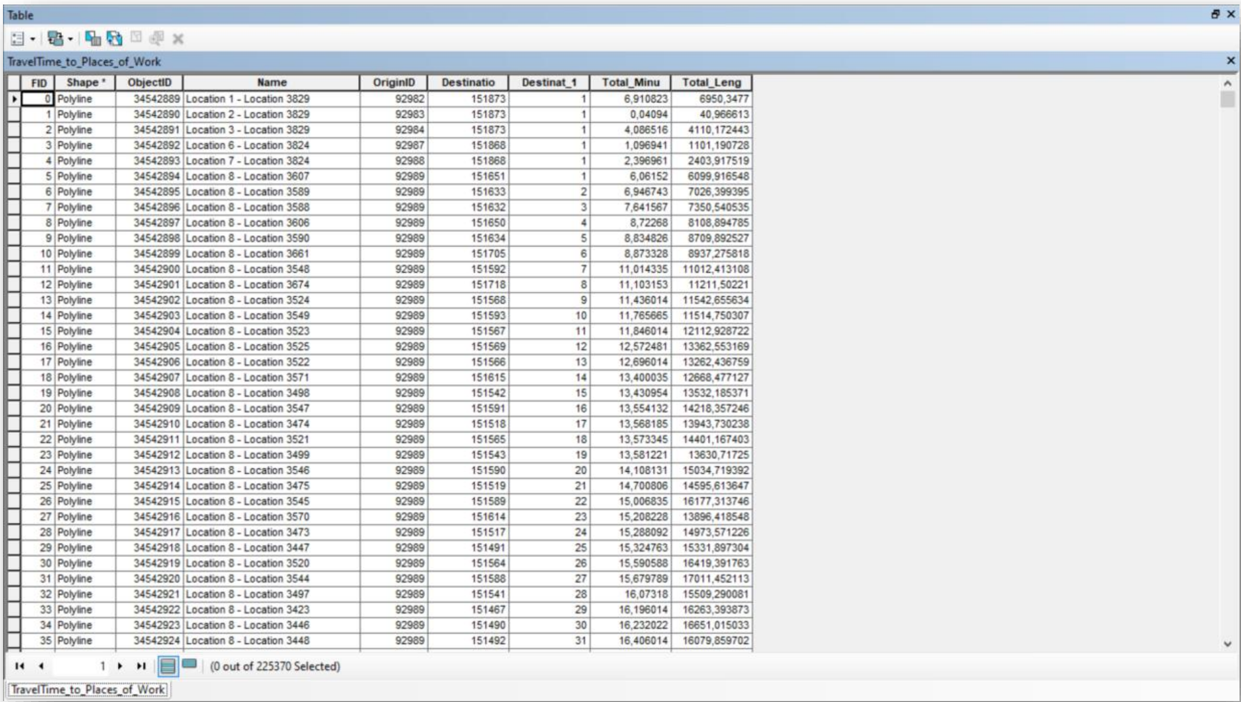


Figure D_3: Setting of properties for public transport (rail) in the service area layer.



Table

TravelTime_to_Places_of_Work

FID	Shape *	ObjectID	Name	OriginID	Destinatio	Destinat_1	Total_Minu	Total_Leng
0	Polyline	34542889	Location 1 - Location 3829	92982	151873	1	6,910823	6950,3477
1	Polyline	34542890	Location 2 - Location 3829	92983	151873	1	0,04094	40,966613
2	Polyline	34542891	Location 3 - Location 3829	92984	151873	1	4,086516	4110,172443
3	Polyline	34542892	Location 6 - Location 3824	92987	151868	1	1,096941	1101,190728
4	Polyline	34542893	Location 7 - Location 3824	92988	151868	1	2,396961	2403,917519
5	Polyline	34542894	Location 8 - Location 3607	92989	151651	1	6,06152	6099,916548
6	Polyline	34542895	Location 8 - Location 3589	92989	151633	2	6,946743	7026,399395
7	Polyline	34542896	Location 8 - Location 3588	92989	151632	3	7,641567	7350,540535
8	Polyline	34542897	Location 8 - Location 3606	92989	151650	4	8,72268	8108,894785
9	Polyline	34542898	Location 8 - Location 3590	92989	151634	5	8,834826	8709,892527
10	Polyline	34542899	Location 8 - Location 3661	92989	151705	6	8,873328	8937,275818
11	Polyline	34542900	Location 8 - Location 3548	92989	151592	7	11,014335	11012,413108
12	Polyline	34542901	Location 8 - Location 3674	92989	151718	8	11,103153	11211,50221
13	Polyline	34542902	Location 8 - Location 3524	92989	151568	9	11,436014	11542,655634
14	Polyline	34542903	Location 8 - Location 3549	92989	151593	10	11,765665	11514,750307
15	Polyline	34542904	Location 8 - Location 3523	92989	151567	11	11,846014	12112,928722
16	Polyline	34542905	Location 8 - Location 3525	92989	151569	12	12,572481	13362,553169
17	Polyline	34542906	Location 8 - Location 3522	92989	151566	13	12,696014	13262,436759
18	Polyline	34542907	Location 8 - Location 3571	92989	151615	14	13,400035	12668,477127
19	Polyline	34542908	Location 8 - Location 3498	92989	151542	15	13,430954	13532,185371
20	Polyline	34542909	Location 8 - Location 3547	92989	151591	16	13,554132	14218,357246
21	Polyline	34542910	Location 8 - Location 3474	92989	151518	17	13,568185	13943,730238
22	Polyline	34542911	Location 8 - Location 3521	92989	151565	18	13,573345	14401,167403
23	Polyline	34542912	Location 8 - Location 3499	92989	151543	19	13,581221	13630,71725
24	Polyline	34542913	Location 8 - Location 3546	92989	151590	20	14,108131	15034,719392
25	Polyline	34542914	Location 8 - Location 3475	92989	151519	21	14,700806	14595,613647
26	Polyline	34542915	Location 8 - Location 3545	92989	151589	22	15,006835	16177,313746
27	Polyline	34542916	Location 8 - Location 3570	92989	151614	23	15,208228	13896,418548
28	Polyline	34542917	Location 8 - Location 3473	92989	151517	24	15,288092	14973,571226
29	Polyline	34542918	Location 8 - Location 3447	92989	151491	25	15,324763	15331,897304
30	Polyline	34542919	Location 8 - Location 3520	92989	151564	26	15,590588	16419,391763
31	Polyline	34542920	Location 8 - Location 3544	92989	151588	27	15,679789	17011,452113
32	Polyline	34542921	Location 8 - Location 3497	92989	151541	28	16,07318	15509,290081
33	Polyline	34542922	Location 8 - Location 3423	92989	151467	29	16,196014	16263,393873
34	Polyline	34542923	Location 8 - Location 3446	92989	151490	30	16,232022	16651,015033
35	Polyline	34542924	Location 8 - Location 3448	92989	151492	31	16,406014	16079,859702

1 (0 out of 225370 Selected)

TravelTime_to_Places_of_Work

Figure D_4: OD cost matrix travel-time output for job opportunities accessible within 30 minutes.

Table 4: D_1 Descriptive statistics of travel-time od matrix from residential area to places of work via car.

	Minimum	**Maximum**	**Mean**	**Average**	**Standard deviation**
Travel-time (minutes)	6.91	29.88	18.40	18.40	16.24
Distance (meters)	6 950.35	37 645.65	22 298.00	22 298.00	21 704.86
Distance (kilometres)	6.95	37.6457	22.298	22.298	21.70485

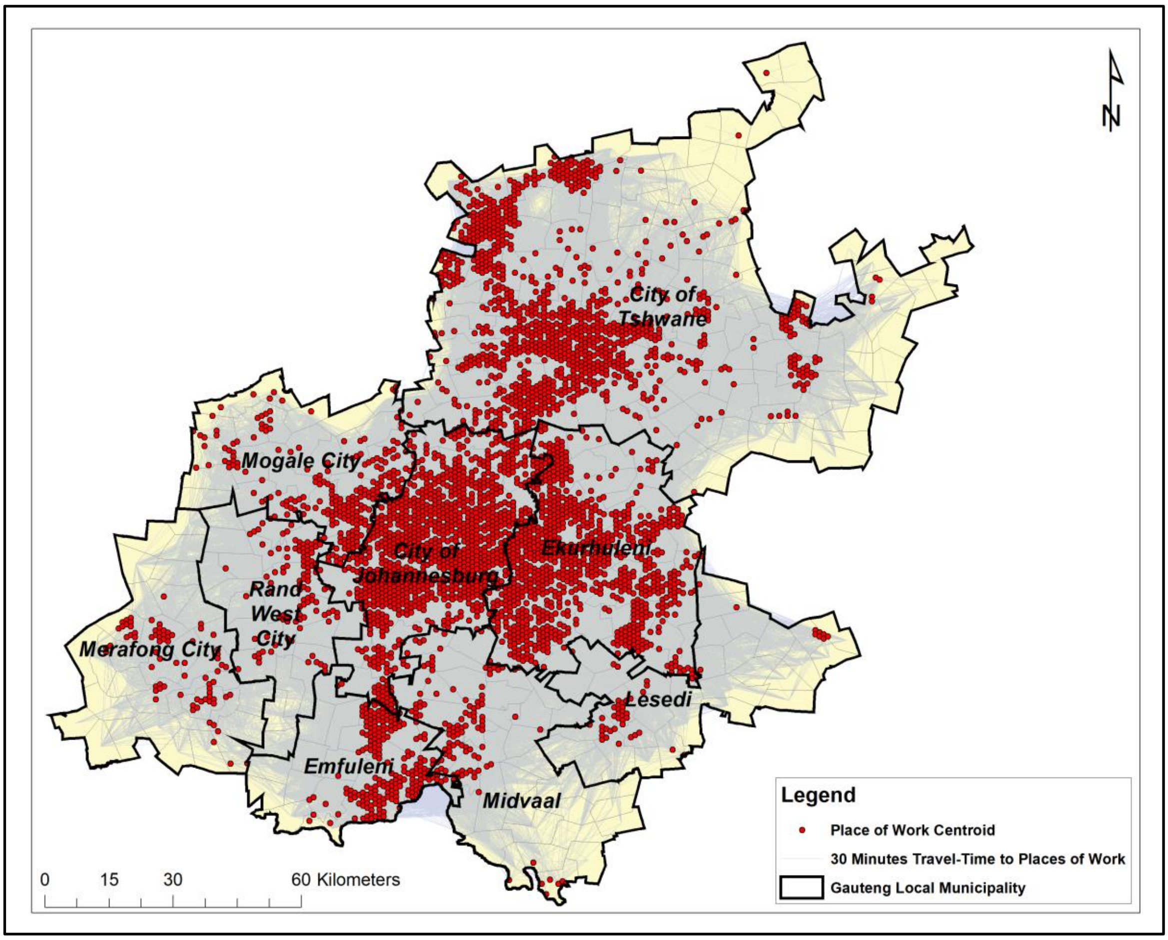


Figure D_5: OD cost matrix travel-time for places of work accessible within 30 minutes.

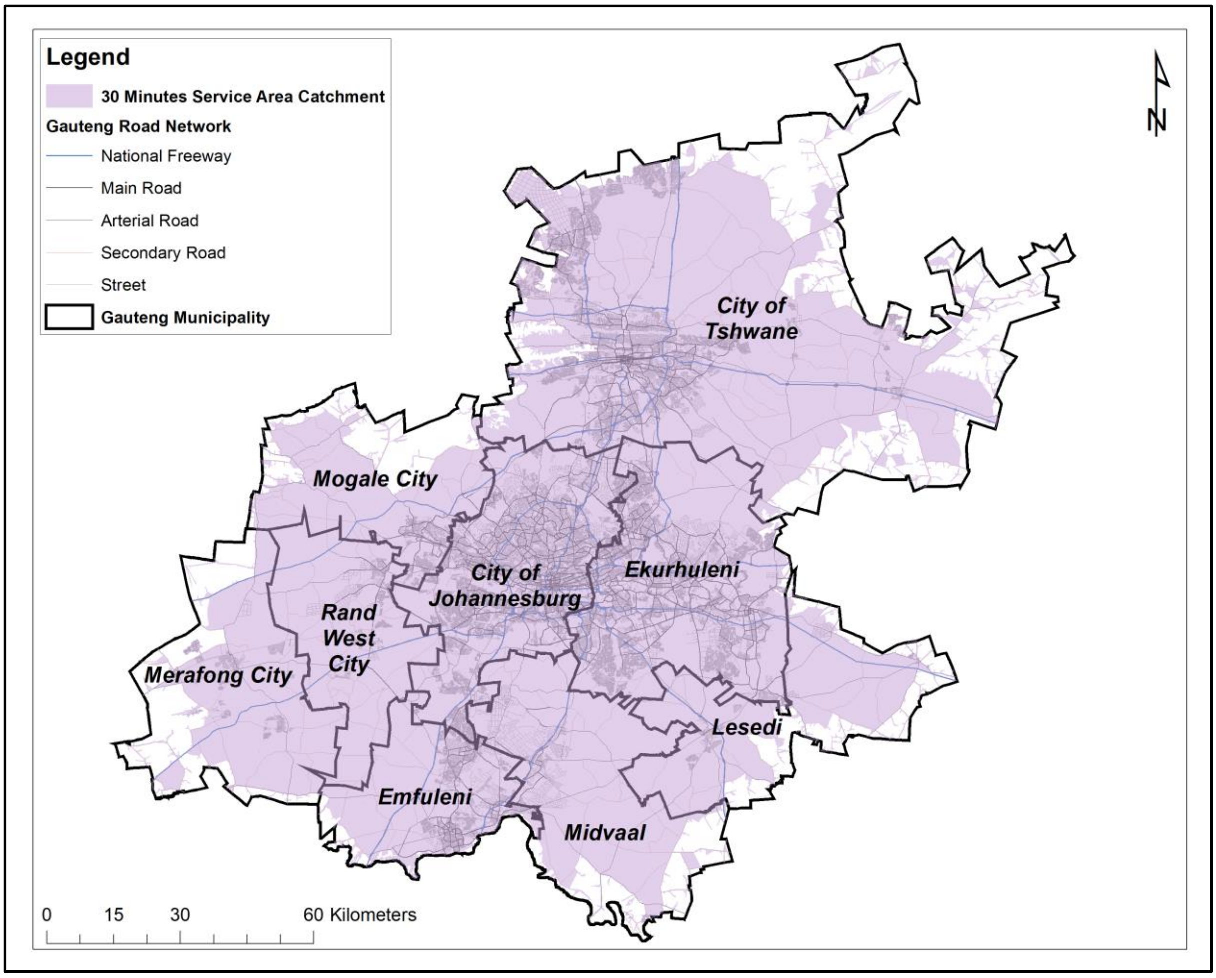


Figure D_6: Service area around places of work (30 minutes).

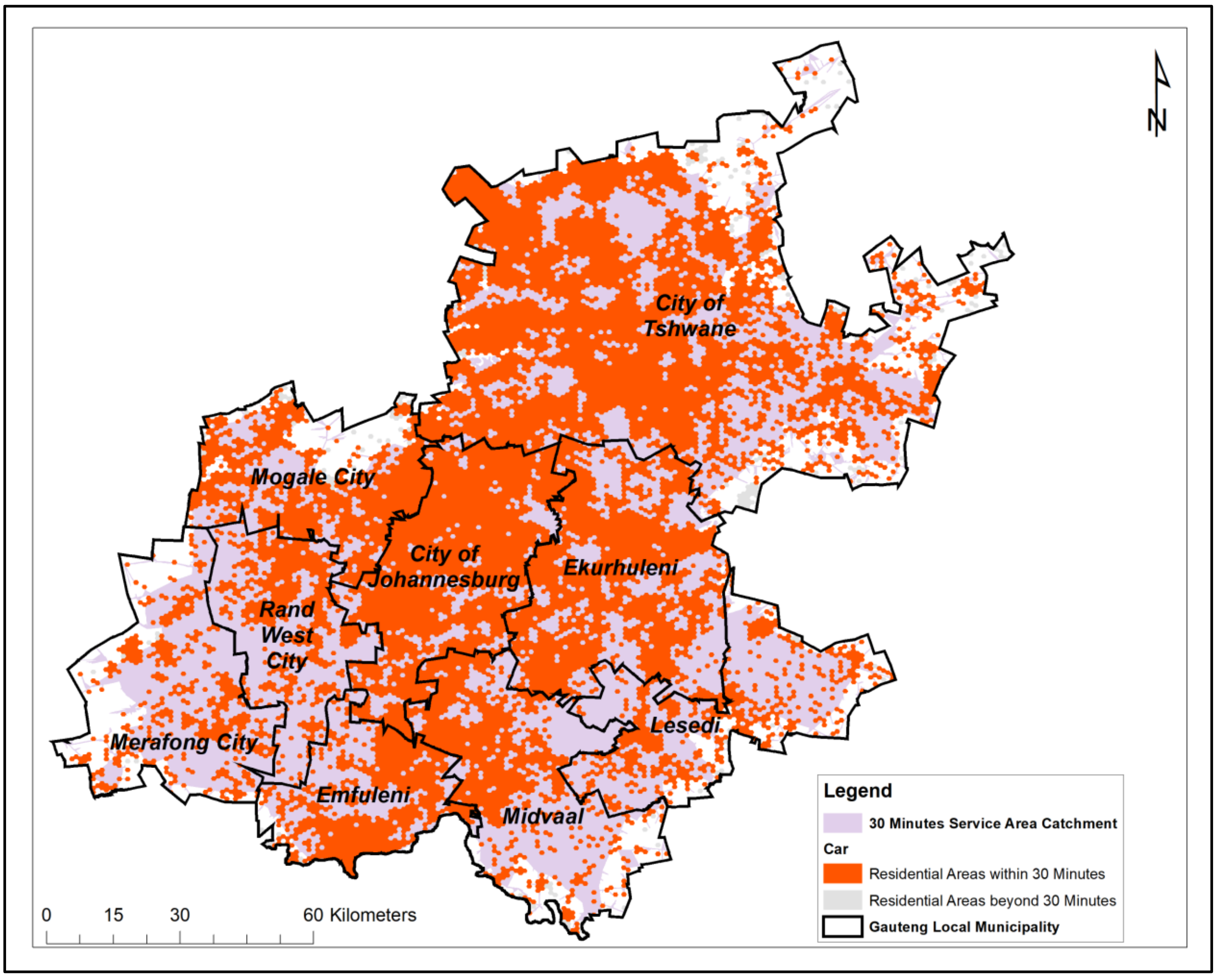


Figure D_7: Residential areas within a 30 minutes catchment area of places of work.

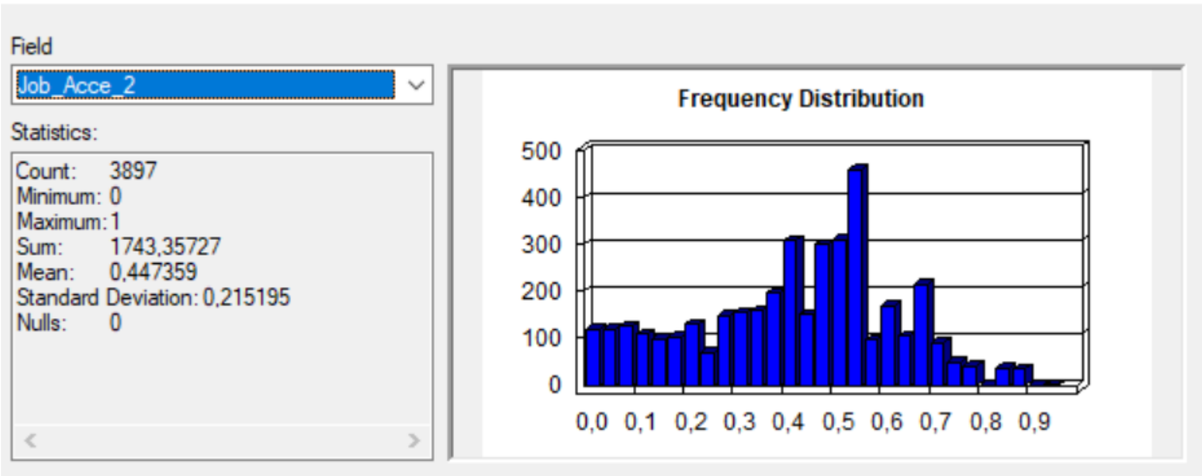


Figure D_8: Frequency distribution plot for the job accessibility scores.

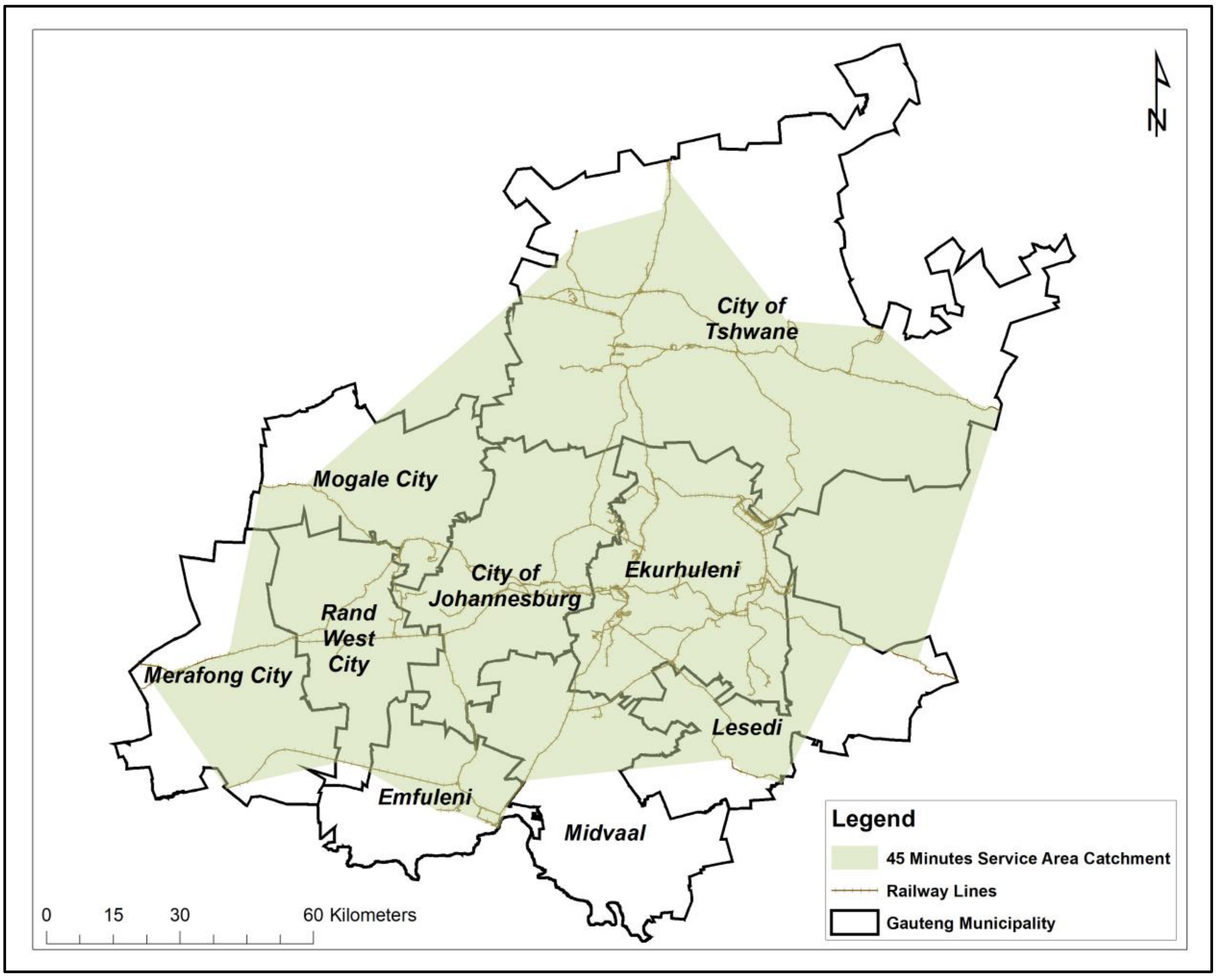


Figure D_9: Service area travel-time for places of work accessible within 45 minutes using rail.