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DEPARTMENT OF CIVIL ENGINEERING

CENTRE FOR TRANSPORT STUDIES

Using Spatial Multi-Criteria Analysis as an Appraisal Tool for Bus Rapid Transit Trunk and Feeder Routes

A Case Study in the City of Tshwane, South Africa

A DISSERTATION IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR A MASTER OF SCIENCE DEGREE IN THE FIELD OF CIVIL ENGINEERING

PREPARED FOR: UNIVERSITY OF CAPE TOWN

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Abstract

Private car use around the world has grown increasingly over the last decades. One effect of this is traffic congestion, which results in various detrimental environmental, economic and social impacts. Public transport has been identified as an effective solution to congestion. In South Africa, investment into public transport has led to the implementation of full and partial Bus Rapid Transit (BRT) systems. The policy and implementation measures of these BRT systems have been modelled, to varying degrees, according to Colombia's TransMilenio BRT. However, BRT systems in South Africa have not been as successful as TransMilenio. Failures of South African BRTs can be traced back to many reasons, one of which is an inadequate conduction of an *ex ante* appraisal. This dissertation intended to close a literature gap on the use of *ex ante* appraisal in South African transport projects. At the time of composing this thesis (February 2017), South Africa did not have a standard appraisal tool for the selection of appropriate transport projects and road-based public transport routes. This resulted in systems that were not designed in context and, hence, underperformed for the context in which they were implemented. The contextually insensitive design of BRTs and the effects thereof constituted the conceptual departure point for this research. Accordingly, this dissertation aimed to explore Spatial Multi-Criteria Analysis (SMCA) as a viable appraisal tool for BRT routes. The City of Tshwane formed the study area of the investigation.

SMCA is a decision-support tool that combines multi-criteria analysis (MCA) and geographic information systems for evaluating decision problems whose criteria and alternatives have spatially explicit dimensions. This method was chosen over traditional appraisal tools such as MCA and cost-benefit analysis as it is more suited to routing problems. Suitable evaluation criteria were identified from five themes that were chosen from international and local trends: equity, transport efficiency and economic, social and environmental impact. Ultimately, composite suitability maps were generated according to the aforementioned themes, and optimal trunk and feeder routes were extracted by means of a vector-based network analysis.

Four trunk and four feeder routes were quantitatively and qualitatively analysed. The quantitative analysis of the route involved determining the average impedance, route length and travel time of a route. The qualitative analysis involved determining if the optimal routes had changed to current or planned city routes. On average, trunk routes obtained a higher average impedance than feeder routes. All optimal routes differed to some degree from planned city routes.

Following the determination of optimal routes, an uncertainty analysis showed that trunk routes were more sensitive than feeder routes. The sensitivity analysis also showed that the transport efficiency theme criteria were the most sensitive criteria, causing the highest mean average impedance change of all criteria. Transport efficiency criteria are thus the most important criteria in finding optimal routes. The method of research adopted in this study can be reproduced in any contemporary South African city with plans for BRT. Furthermore, the method of research can be improved upon by investigating standard evaluation criteria to be included in an SMCA routing problem to ensure a uniform appraisal standard.

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List of Symbols and Acronyms

BRT	Bus Rapid Transit
CBA	Cost-Benefit Analysis
CoT	City of Tshwane
CSS	Contextually Sensitive Solution
DoT	Department of Transport
DSS	Decision Support System
EU	European Union
GIS	Geographic Information Systems
IAP	Interested and Affected Parties
IRPTN	Integrated Rapid Public Transport Network
ITS	Intelligent Transport Systems
km	Kilometre
km/h	Kilometre per hour
MBT	Minibus Taxi
MCA	Multi-Criteria Analysis
min	Minutes
NMT	Non-Motorised Transport
OEI	Overview Effects Infrastructure
PT	Public Transport
ROW	Right-of-Way
RSA	Republic of South Africa
SA	Sensitivity Analysis
SDSS	Spatial Decision Support System
SMART	Simple Multi-Attribute Rating Technique
SMCA	Spatial Multi-Criteria Analysis
TUT	Tshwane University of Technology
UK	United Kingdom
USD	United States Dollar

WTP	Willingness-to-Pay

1 Introduction

1.1 Subject of Dissertation

This dissertation focuses on the appraisal of public transport (PT) interventions. Specifically, this research intends on investigating the viability of using an *ex ante* appraisal method called Spatial Multi-Criteria Analysis (SMCA) on Bus Rapid Transit (BRT) routes. The aim is to appraise BRT trunk and feeder routes that are equitable, environmentally sustainable, economically viable, and socially appropriate, while simultaneously meeting intended transport functions. The City of Tshwane (CoT) forms the study area of this research. The appraisal technique developed in this dissertation could possibly serve as a Spatial Decision Support System (SDSS) for BRT routes in the CoT, and other contemporary South African cities

1.2 Background to Investigation

Historically, PT in African cities was and continues to be dominated by the informal minibus taxi (MBT) industry (UITP, 2008). In an attempt to provide a formal and scheduled PT service, African cities such as Lagos (Bakare, 2017), Dar es Salaam (Scruggs, 2017), Addis Ababa (Nadi, 2017) and Johannesburg (Masondo, 2010) have all invested in BRT systems. In South Africa (RSA), specifically, these BRT systems have been modelled (to varying degrees) according to the success of Colombia's TransMilenio in terms of design and policy formulation (Wood, 2014). However, South African BRT systems are not experiencing the same success as TransMilenio. BRT in RSA is characterised by low ridership and high operational costs, consequently leading to a high dependency on subsidies. In addition, most cities are behind schedule in terms of implementation (Macanda, 2017). In this regard, it is hypothesised that the failure of BRT in RSA can be attributed to BRT not being designed in the RSA context and for the RSA context.

Transportation infrastructure investments impact a society in the environmental, socio-economic and, in some cases, political sphere (Black, 2006). In order for a transportation project to adequately meet its prescribed goals without having substantial detrimental impacts on society and the environment, a comprehensive, transparent *ex ante* appraisal is required. *Ex ante* appraisal can be regarded as an investigation into the economic, environmental, social etc. feasibility of alternative solutions to a transportation problem (Baehr, n.d.). An *ex ante* appraisal is a key component in ensuring that contextually sensitive and appropriate transport solutions are implemented. Without a comprehensive appraisal, transport planners and stakeholders run the risk of choosing alternatives that are contextually inappropriate for the intended socio-economic, environmental and political status of the target location. As such, transportation interventions that are not contextually designed do not efficiently serve their transportation purposes or the objectives of stakeholders. In this regard, SMCA has been identified as an appraisal tool that has the potential to successfully incorporate context in transportation projects.

1.2.1 Background to Method of Research

Traditional appraisal methods on selecting transport interventions have included Environmental Impact Assessment, Cost Benefit Analysis and Multi-Criteria Analysis (Bristow & Nellthorp, 2000; Vickerman, 2000; Tsamboulas, 2007; Bin Kamis, 2014). Cost-benefit analysis is a microeconomic framework which uses monetary values to express measured impacts as a total monetary amount (Bristow & Nellthorp, 2000). MCA can be regarded as a tool for the appraisal of different alternatives where several stakeholders' inputs and priorities are considered to produce a common output (Tsamboulas, 2007).

While cost-benefit analyses and multi-criteria analyses have their advantages, and have been proven to provide reliable results, they all share a common shortfall: the inability to incorporate the crucial spatial component of transportation projects. These methods are unable to evaluate transport projects in their spatial entirety whilst simultaneously considering the needs of all stakeholders. SMCA has emerged as an alternative decision support tool that addresses this shortcoming (Aliyu & Ludin, 2015). SMCA has been used as an environmental assessment tool in the construction industry to monitor building performance (Ruiz & Fernández, 2009), and for the site selection of a local park in Italy (Zucca, Sharifi & Fabbri, 2008). In the field of transport, SMCA has been used for a high-speed rail tracking design (De Luca, Dell'Acqua & Lamberti, 2012), to evaluate student travel behaviour (Kamruzzaman *et al.*, 2011) and in road planning (S. S. Keshkamat, Looijen & Zuidgeest, 2009; Beukes, Vanderschuren & Zuidgeest, 2011). However, SMCA is yet to be used in the application of BRT routing. SMCA was chosen as the preferred method for this research as it addresses the spatial transport, environmental, and socio-economic components that must be considered in transport route planning.

In this regard, this research used SMCA and a vector-based network analysis to find optimal BRT trunk and feeder routes in the CoT. Optimal routes are routes that achieve the lowest possible cumulative impedance, or cost, against an array of evaluation criteria and weighting schemes. The SMCA component of this research was used to generate a composite suitability map from the evaluation criteria. This map informs the areas of high and low suitability for the network analysis component. The vector-based network analysis component was used to compute a least-cost algorithm, and consequently, optimal routes, based on the composite suitability map generated in the SMCA component. The method of research followed can be summarised into four stages (Figure 1-1):

i) *Criteria selection and data acquisition*: appropriate spatial evaluation criteria were identified from international and local literature;
ii) *Geo-spatial data handling*: spatial criteria were weighted and standardised to form composite suitability maps. The vector-based network analysis was also performed in this section.
iii) *Computation of results*: optimal routes were mapped and compared to existing or planned routes; and
iv) *Analysis*: sensitivity analyses were conducted to determine sensitive criteria and sensitive routes.

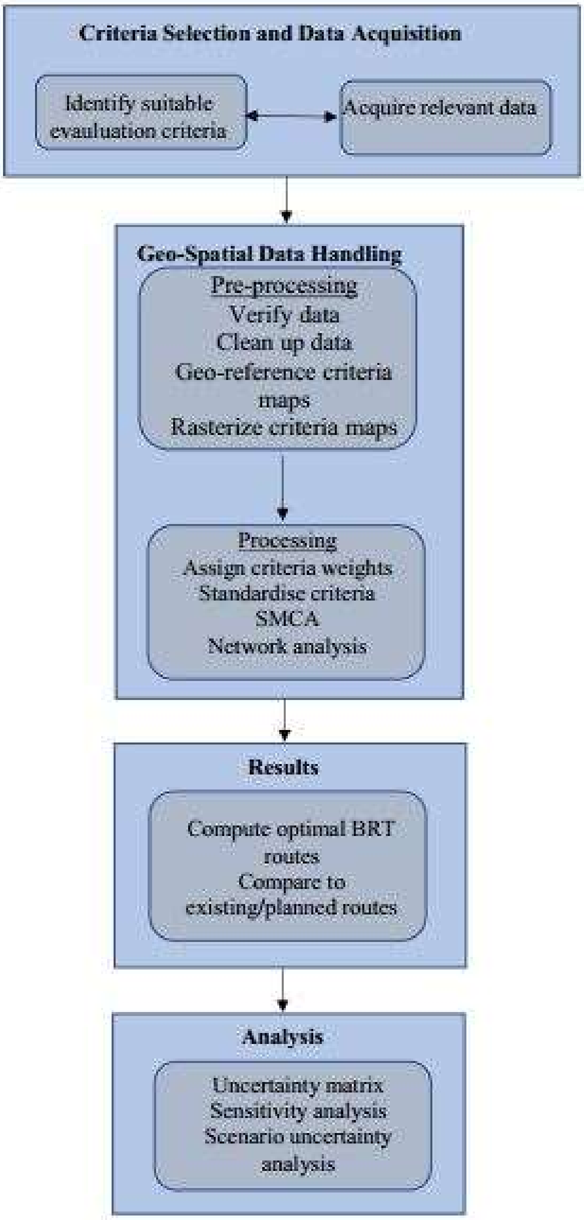


Figure 1-1: Flow Chart of Method of Research

1.2.2 Background to Study Area

Located in Gauteng, the City of Tshwane, previously known as Pretoria, is the capital city of South Africa. Tshwane has a population of 2.9 million people (Frith, 2011). The CoT has an employment rate of 27.7%, which is slightly lower than the national average, and a skewed income distribution (Stats SA, 2011b). Additionally, various threatened plant species, animal species and ecosystems are located within the Municipality. The context of the CoT is described in greater detail in Chapter 5.

According to the Public Transport Strategy (DoT, 2007a), the CoT is one of the 12 cities that have been targeted for implementation of an Integrated Rapid Public Transport Network

(IRPTN). The CoT was chosen as the study area of this research, as BRT is still in its early implementation stage. As such, there exits potential for practical implementation of the results. Phase I of the BRT system, A Re Yeng, was launched in November 2014. Phase I consists of two trunk routes between Pretoria Central and Soshanguve, and Pretoria Central and Mamelodi. The feeder system consists of six feeder lines. Phase II, which is to connect Pretoria Central and Wonderboom, was expected to be complete in 2017 but is several months behind schedule (Macanda, 2017).

1.3 Gap Statement and Research Justification

Due to the impacts transportation interventions may possibly inflict on a society and the environment, decisions on how to invest in them become extremely important. Countries such as the Netherlands, Germany, the United Kingdom (UK) and Japan all have standard appraisal techniques for transport projects that are funded in some part by the government (Bristow & Nellthorp, 2000; Morisugi, 2000; Vickerman, 2000). These countries are all characterised with well-developed, efficient PT systems. The appraisal techniques used by these nations ensure decision makers have full information when prioritising certain transport projects over others. These countries prove that having a standard, robust, appraisal method ensures that the contextually correct transport alternative is selected (Bristow & Nellthorp, 2000). In contrast, South Africa does not have a standard transport appraisal tool, and thus faces a myriad of transportation problems, many of which can be traced back to contextual inappropriateness.

1.3.1 Gap Statement

There exists a knowledge gap in the appraisal of public transportation projects implemented in contemporary South African cities. Furthermore, a review of the literature and various government gazettes and legislations suggests that RSA does not have standard appraisal methods for selecting public transport interventions. Very little information exists as to why certain public transport interventions are chosen, and what the alternatives were. In addition, RSA does not have standard evaluation criteria against which all public transportation alternatives are judged. This research aimed to fill the research gap and advocate for standard appraisal methods and criteria within the RSA public transport context.

1.3.2 Research Justification

The implications of RSA not having a standard appraisal tool for public transportation tool are evident in the *status quo* of PT. RSA is characterised by a fragmented, uncoordinated PT system (Oxford, 2013). Current transport solutions are contextually inappropriate and often do not serve their intended purposes and the objectives as set out by stakeholders. The investigation into an SDSS with the capability to integrate spatial features for South African public transport projects has the potential to change these shortcomings. Such an appraisal tool would aid provincial and local governments in their decision-making processes, and allow for public transport interventions that are equitable, environmentally sustainable, socially acceptable and economically viable.

Further justification for this research stems from similar work done by then doctoral candidate Ignatius Schutte (2010). Schutte, in realising the lack of a standard appraisal tool for selecting South African transport projects, attempted to create one by combining the best elements of MCA and CBA and contextualising them to the context of The CoT. While Schutte rightfully mentioned the importance of including spatial models in the appraisal framework, his work focussed on MCA and CBA only. It can be argued the inclusion of an SMCA as opposed to MCA would have made Schutte's appraisal tool more comprehensive as transport interventions are fundamentally spatial.

Lastly, this research has the potential to provide governmental planning authorities with the necessary tools to select appropriate routes for BRT systems, and thus make BRTs more successful in this country. In addition, this dissertation could serve to highlight methods of providing reliable, sustainable and contextually appropriate public transport in South African cities.

1.4 Aims and Objectives of Dissertation

1.4.1 Aim of Dissertation

Accordingly, the aim of this dissertation is to investigate the importance of contextual appraisal by using SMCA to find optimal BRT trunk and feeder routes in the CoT.

1.4.2 Objectives of Dissertation

The aim of this research may be obtained by meeting the following research objectives:

i) Explore the best practices from traditional appraisal methods used in transport;
ii) Conduct an extensive literature review on SMCA;
iii) Investigate suitable appraisal criteria for South African public transport projects;
iv) Using suitable software, perform an SMCA on the existing and planned A Re Yeng routes;
v) Compare the proposed BRT routes to existing and future BRT routes within the CoT;
vi) Perform an uncertainty analysis;
vii) Perform a sensitivity analysis to determine impacts of weight selection; and
viii) Suggest an SDSS that can be used for BRT routes within the CoT and other South African cities.

1.4.3 Research Questions

The following research questions must be answered to meet the objectives of this research:

i) What are the suitable evaluation criteria to be included in a contextually sensitive SMCA?
ii) What criteria weighting combinations should be used in the contextualised appraisal tool?
iii) What are the characteristics of the optimal routes? Do the optimal differ from existing or planned routes?
iv) How much sensitivity exists in the SDSS?
    a. How much sensitivity is there in the evaluation criteria?

    b. How much sensitivity is there in the routes?
  v) What are the limitations of this SDSS?

1.5 Scope and Limitations

Geographically, the scope of this proposed research was limited to the City of Tshwane. Four trunk routes and four feeder routes form the scope of this investigation.

This research was limited by data availability, e.g. availability of Geographic Information Systems (GIS) data, traffic data etc. Only the available data could form part of the evaluation criteria. Quality of the data obtained, both from the CoT and open source, provide an additional limitation. Most data was obtained from Open Source and consequently required editing. Furthermore, time constraints prevented the conduction of a stakeholder engagement, which would have been useful for determining criteria weights. The effect of this was minimised through a sensitivity analysis. Finally, the financial feasibility of the routes could not be determined as it would require intricate financial modelling, which is outside of the scope of this investigation.

1.6 Structure of Dissertation

Following this introduction, a literature review will be provided over three chapters in a top-down approach. The first chapter of the literature review, Chapter 2, will discuss the differences of PT in the developed and developing world. The aim of this chapter is to show the causality of good appraisal techniques on successful BRT implementations. Chapter 3 will introduce traditional appraisal methods historically used in transportation projects. The final chapter of the literature review, Chapter 4, provides a detailed analysis of SMCA. Included in this chapter are approaches and practical applications.

Following the literature review chapters, Chapter 5 provides a description of the study area. This chapter describes the context in which BRT routes in the CoT must be appraised to be deemed contextually appropriate. Such a description is paramount in selecting appropriate evaluation criteria and parameters.

Chapter 6 expands on section 1.2.1 by providing further detail into the method of research adopted.

Chapters 7 and 8 present the results of the optimal routes and the uncertainty analyses, respectively.

Concluding remarks about the aims and objectives of the dissertation, and recommendations for future work with SMCA, are provided in Chapter 9.

2 Comparing BRT in Developed and Developing Cities

Chapter two aims to outline major differences of BRT implementations in developed and developing cities. This chapter begins by describing the role of PT and why the correct selection of a PT intervention can only occur after a comprehensive *ex ante* appraisal. Thereafter, the case for BRT as a viable PT intervention is presented. Two examples of BRT systems are provided for developed and developing cities. The objective of this comparison is to outline how BRT can exist in any context, provided it is designed for that context.

2.1 The role of Public Transport

Urbanisation is occurring at an unprecedented rate, especially in the developing world. While this is advantageous to socio-economic statuses and standards of living, the detrimental effects of urbanisation cannot be ignored. Such effects include a drastic reduction of natural land, thereby endangering various plant and animal species, increasing global pollution levels, and increasing congestion (Bloom, Canning & Fink, 2008). The sharp rise in global congestion levels can be attributed to increasing private car usage over the last few decades. The number of motorised vehicles grew from approximately 75 million in 1950 to 675 million in 1990, 80% of which being used primarily for private transport (Steg, 2003). This translates to a vehicle growth rate of 964% in that period. Traffic congestion is not only a nuisance for individual travellers, but also undermines the economic competitiveness of cities (Hartgen & Fields, 2009).

In addition to decreasing economic productivity, congestion generates various environmental and social problems. Environmental issues associated with congestion concern the emission of substances such as CO_2, which contributes to global warming, as well as substances that cause smog and acid precipitation. Furthermore, scarce raw materials and energy are needed to manufacture and use cars, leading to an over-exploitation of resources. In the social aspect, car usage is detrimental to urban quality of life as it is noisy, releases unpleasant odours, causes local pollution and yields traffic accidents (Steg, 2003). As such, research has shown congestion, and ultimately, the negative impacts of unsustainable private car usage, can be effectively mitigated through public transportation (Banister, 2008; Woodcock *et al.*, 2009).

Public transport is the collective term for all modes of transport available to the public, irrespective of private vehicle ownership (Abreha, 2007). These modes of transport include trains, buses, vanpools and their variation (Litman, 2011). Public transport is the key to addressing congestion and the effects thereof, as PT is seen as a sustainable and environmentally sensitive transport solution to congestion problems (Krygsman, Dijst & Arentze, 2004). So crucial is PT that governments invest considerable amounts of money into it.

Investment into public transport, plays an important role in a society's economy, social climate, political sphere and natural environment. The selection of an appropriate transportation project is thus one of the most important planning activities encountered by a government (Shang, Tjader

& Ding, 2004). Transportation investments that are not holistically appraised are at risk of failing. PT interventions fail, *inter alia,* by failing to meet the transport needs of passengers through delays, poor reliability and low quality of service. PT modes also fail through failing to recover enough money through fare collection, thereby relying heavily on subsidies. Proper selection of a transportation intervention can only occur once every alternative has been critically assessed against an array of appropriate assessment criteria (Geurs, Boon & Van Wee, 2009; Browne & Ryan, 2011). The correct selection can only occur following a comprehensive, contextually sensitive *ex ante* appraisal.

Appraisal is the third step in the project lifecycle (Figure 2-1). Often incorrectly used synonymously with evaluation, an appraisal is a tool that assesses, *inter alia,* the financial, economic, environmental, and social viability prior to project implementation. An assessment, or appraisal, provides feedback on performance strengths, areas of improvement and insights (Baehr, n.d.). What is crucial in an appraisal is the exploration and assessment of project alternatives (University of London, 2014).

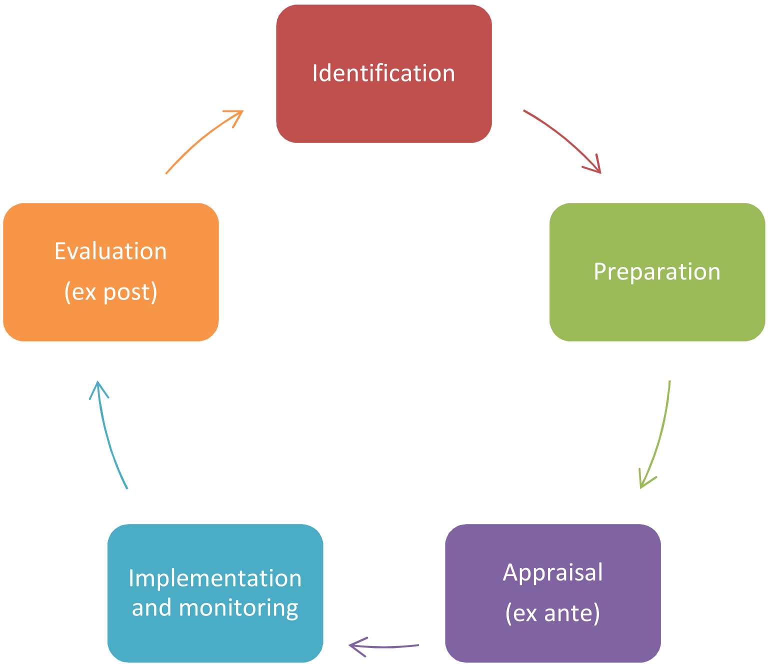


Figure 2-1: The Full Project Lifecycle
Source: University of London (2014)

According to van Zonneveld (2006), some of the key elements, or assessment criteria, that are included in a robust appraisal are the following:

i) Economic and financial viability;
ii) Environmental and social compatibility;
iii) Investment cost;
iv) Technology and design;
v) Legal framework; and

vi) Eligibility.

The first item on the list is a deciding factor in whether or not a project is implemented. A project cannot be implemented if it is not financially viable, despite how many other benefits it achieves. Emphasis is resultantly placed on economic and financial viability.

It is opined that "contextual appropriateness" is an item that should be placed on the list, and with high priority. Contextually sensitive planning in the appraisal process allows a transport project to thrive in the spatial-political and spatial-economic context in which it is to be implemented. Failure to contextualise transport projects results in adopting a 'copy and paste' attitude towards planning, and eventually, implementation. A common PT implementation across many different contexts has been BRT (Levinson *et al*., 2002; Wirasinghe *et al*., 2013).

2.2 The Case for BRT

2.2.1 Description and overview

BRT may be defined as a bus system that, through segregated right-of-way (ROW) infrastructure, services, limited stops and information technologies, provides efficient, cost-effective urban mobility (Hensher & Golob, 2008; Hidalgo & Gutiérrez, 2013). BRT is a popular mode of transport as it provides the capacity to meet high passenger volume demands, and has fixed infrastructure that can be built quickly and incrementally, at a fraction of rapid- or light rail costs (Levinson *et al*., 2002; Wirasinghe *et al*., 2013). Around 164 countries around the world use some form of BRT, 100 of which are in the developing world (Global BRT Data, 2017).

The first full BRT corridor in the world was developed in Curitiba, Brazil in 1982 (Matsumoto, 2006). Curitiba's experience inspired other cities to implement BRT corridors: Quito, Ecuador (1996), Los Angeles, USA (1999), Bogotá, Colombia (2000), Mexico City, Mexico (2003), Jakarta, Indonesia (2004) and Istanbul, Turkey (2008) (Matsumoto, 2006; Hidalgo & Gutiérrez, 2013). Bogota's BRT system has controversially been termed a state of the art BRT system, with many cities around the world modelling their BRTs according to Bogota's (Gilbert, 2008). Bogota's BRT success can be attributed to accompanying policy measures than ensured BRT was prioritised over and more convenient than private vehicles (see section 2.4.1).

2.2.2 Features of BRT

BRT systems have defining features that distinguish them from regular bus services (Larwin, Gray & Kelley, 2007):

i) *ROWs:* BRTs operate on different types of lanes, ranging from fully separated at-grade lanes to mixed flow lanes. Fully separated at-grade lanes are differentiated with distinctive paving;
ii) *Stations:* Station platforms are usually at the same height as BRT vehicle floors. This not only improves boarding and alighting times, consequently increasing passenger capacity, but also ensures that mobility-impaired passengers may board/alight easily. In addition,

BRT stations may also be intermodal PT interchanges, although this would require the use of an integrated fare system;

iii) *Vehicles:* BRT vehicles typically have low floors and multiple wide doors, making boarding and alighting easier. Furthermore, the exteriors are usually branded with designs consistent to that of stations;

iv) *Fare collection:* Fares can be collected on-board upon entering the vehicle, pre-paid prior to entering the vehicle. The latter is preferred to the former due to it being more efficient and lower risk of fare evasion;

v) *Intelligent transport systems (ITS):* ITS includes real-time passenger information, such as the arrival time of the next vehicle or arrival time at the next stop;

vi) *Service:* BRT services are frequent, with operating hours ranging from 18-24 hours in well-developed systems. Headways are shorter, but typically on trunk routes; and

vii) *Route structure:* BRT routes are simple, with convenient structures between trunk and feeder routes. Station locations are usually coordinated with land use plans and major activity centres.

2.2.3 Advantages of BRT

BRT systems are often selected over other PT modes for the following reasons:

i) *High ridership:* Due to the wide, multi-door low-floor buses and seating configurations, BRT is capable of carrying a significantly higher number of passengers per hour per direction than other road-based PT (Chang *et al.*, 2004; Hidalgo & Gutiérrez, 2013). Rail-based PT is the only other mode capable of carrying more passengers per hour per direction;

ii) *Capital cost effectiveness:* BRT infrastructure costs per kilometre a fraction of that of rail. Rail systems with similar capacities can cost three to ten times more per kilometre (Hidalgo & Gutiérrez, 2013). Low operating costs become particularly attractive for developing cities with limited financial resources and high transit dependent populations.

iii) *Operating cost efficiency:* Research has shown that when BRT is introduced into a corridor, corridor performance indicators such as passengers per revenue hour, passenger subsidies and subsidies per passenger kilometre improve (Chang *et al.*, 2004). It is important to note that passenger subsidies and subsidies per passenger kilometre are dependent on item *i)*. The higher the ridership, the fewer subsidies required.

iv) *Incremental implementation:* Unlike rail systems, BRT systems can be built and operated incrementally (Levinson *et al.*, 2002). This is also advantageous to cities with limited financial resources as they will not need large lump sums for capital investments.

v) *Transit-Oriented Development:* BRTs can be designed and integrated into urban environments in ways that stimulate economic development and transit design (Levinson *et al.*, 2002)

2.2.4 Limitations of BRT

It is easy to regard BRT as a miracle solution for cities with limited financial resources and high transit dependant populations. Vuchic (2005) states that dedicated bus lanes cannot be implemented without strict enforcement due to the lawlessness posed by private vehicle drivers. Furthermore, it is not uncommon to see BRT infrastructure deteriorating early. Additionally, BRT cannot fully succeed as a stand-alone system; its effectiveness depends on integration with other modes such as non-motorised transport (NMT) (Matsumoto, 2006). However, this limitation is not unique to BRT. Finally, BRT has also been criticised for crowdedness (Hidalgo & Gutiérrez, 2013).

BRT is used extensively throughout the world in various forms. As such, its prominence makes BRT a viable subject for exploring the effects and importance of context.

2.3 BRT in Developed Cities

This section will discuss the BRTs in Adelaide, Australia and London, Canada. Adelaide's BRT, which has the longest guided busway in the world, is considered to be a successful BRT. It is characterised by a high patronage and a contracting system that minimises the need for subsidies (Bray & Scrafton, 2000; Bray & Wallis, 2008). In contrast, London's BRT, although yet to be built, has been heavily criticised for being contextually inappropriate.

2.3.1 The Case of Adelaide, Australia

Adelaide has a unique BRT system called the O-Bahn, which uses guided busway infrastructure (Figure 2-2), priority lanes and mixed traffic lanes (Government of South Australia, 2015). The guided busway section of the O-Bahn, which links the north-eastern suburbs to Downtown Adelaide, was opened in 1986 and completed in 1989. The guideway system is comprised of concrete tracks 6.2 m wide, and protruding lateral guidewheels that connect to the concrete track. The buses can either operate manually on the guideway tracks, mixed vehicle and priority lanes, or automatically on the guided tracks. The grade-separated guideway tracks allow the buses to reach speeds of 100 km/h, greatly reducing the journey time (Transportation Research Board, n.d.).

Figure 2-2: O-Bahn Bus on Guided Concrete Tracks
Source: Taylor (2006)

As a medium-sized city with a population of just over 1 million, a bus system was not the first choice for Adelaide's growing mobility problems in the north-east corridor (Bray & Scrafton, 2000; Taylor, 2006; Transportation Research Board, n.d.). In the 1960s, rapid urbanisation called for freeways to be built to handle traffic growth. Transport planners began preserving ROW in the plans for these freeways. By the 1970s, however, growing concerns over environmental quality and energy consumption brought the freeways into disrepute, and only one was eventually built. With no transport interventions made, the effects of urbanisation worsened: travel time from the outskirts of the north-eastern suburbs to the city centre were over an hour (Cervero, 1998). An *ex ante* CBA appraisal showed that the most viable solution to the north-eastern corridor would be light rail transit (LRT) (Cervero, 1998; Bray & Scrafton, 2000). The outcome of the appraisal favoured LRT over a bus system as LRT would occupy less ROW, making it more cost effective. Furthermore, the LRT had a higher passenger capacity, and would emit less air and noise pollution. LRT was also perceived by transport planners to be the more comfortable option. However, officials reverted to a conventional bus way when plans indicated that LRT would be financially unviable. The O-Bahn was consequently approved after a delegation travelled to Germany to learn the technology. Two economic *ex ante* appraisals favoured the O-

Bahn over LRT (Cervero, 1998). The environmental and transport efficiency appraisals also favoured the O-Bahn over LRT.

The environmental appraisal showed that either the O-Bahn or LRT would be built in an environmentally sensitive corridor. The planned route for both systems would follow the Torrens River (Cervero, 1998; Bray & Scrafton, 2000; Wilson, Bray & Scrafton, 2010). The Torrens River Valley, which was heavily neglected at the time, has a riverbed made of problematic, unsteady alluvial soils. These soils would be unable to handle the heavy moving loads of LRT. Effective engineering led to the design of precast track elements and sleepers that rested on piers, which proved to be adaptable to the unstable soil conditions (Cervero, 1998). The O-Bahn transformed the once littered, inaccessible Torrens River into an aesthetically pleasing, accessible linear park (Bray & Scrafton, 2000; Wilson *et al.*, 2010). In addition, the noise concerns regarding the O-Bahn were adequately mitigated because the guided concrete tracks do not emit high noise levels. Furthermore, the buses have the potential to run on electricity, thereby addressing energy concerns (Taylor, 2006).

A transport efficiency appraisal also revealed that BRT was a preferred option to LRT. LRT has a higher passenger capacity than buses, which was a key consideration in choosing LRT over busways initially. However, the guided busway neutralises some of the advantages that LRT would have by providing the same advantages through its ROW mechanism: fast travel speeds, uninterrupted travel, greater reliability and improved comfort (Taylor, 2006). Moreover, the O-Bahn out-performs LRT in adaptability. Since the buses can operate on guided concrete rails, priority and mixed traffic lanes, the need for intermodal transfers is reduced. Lastly, the system can be built and operate incrementally (Transportation Research Board, n.d.).

Due to its financial, environmental and transport benefits, BRT in Adelaide can be regarded as a Contextually Sensitive Solution (CSS) to Adelaide's transport problems. In contrast, the planned BRT system for London, Canada, cannot be regarded as a CSS.

2.3.2 The Case of London, Canada

On the 15th of May 2017, the final routes for London's 560 million Canadian Dollar BRT were finalised, making it the largest ever infrastructure project in London's history (Maloney, 2017aa; Maloney, 2017bb). The BRT was selected as a viable solution to London's transport challenges, which include an inadequate PT system, congested arterial roads, bottlenecks at major intersections and a lack of a safe NMT network (Moretti, 2017). London's BRT will comprise of four routes and 35 stations. There will be 24 buses operating on a high frequency schedule. It will take approximately 10 years to build the entire four corridors of 24 km of lanes and 35 stations required to operate BRT (Stacey & Maloney, 2017). While it is evident that a transport intervention was needed for London, the proposed BRT routes have been a cause for concern for many interested and affected parties (IAPs).

There were justified concerns that the planned routes are not culturally appropriate. Lamberink (2017) argues that parts of the route are planned to pass through the Downtown Heritage Conservation District, possibly impacting heritage during construction. Moreover, construction of the routes could uncover historical artefacts as the routes could potentially pass through unmarked graves near St. Paul’s Cathedral and St. Peter’s Basilica. The response by London transport planners was to undertake a more detailed heritage analysis as routes are designed. This solution is problematic as it is reactive rather than proactive. Areas of significant cultural heritage should inform routes, instead of routes being designed and checked for cultural heritage post design.

The proposed routes also raised concerns for business owners in Downtown London. Business owners argued that Downtown London had recently started to boom economically, and constructing BRT lanes on two key streets could threaten future financial gains. These concerns resulted in London City Council approving the development of two alternative routes (Ghonaim, 2017). In this case, it can be argued that the routes were economically inappropriate as possible negative impacts on a growing economic hub were not considered. Business owners were correct to raise their concerns, but their concerns were short-sighted. In the short-term, construction of BRT lanes could be detrimental to business owners in Downtown London, as key streets within this area would have to be closed to the public. However, in the long-term, having BRT in these streets could cause Downtown businesses to gain traction, especially if stops are strategically placed. The economic impact of BRT for Downtown business owners was consequently not deliberated in adequate detail.

The London BRT is a good example of why contextually sensitive planning is crucial. The problem with London’s BRT lies in the routes chosen, and not the BRT itself. In the context of London, the proposed routes are culturally and economically inappropriate. Consequently, the proposed routes have been strongly opposed by IAPs. London’s lack of contextual appropriateness can be attributed to poor public participation in the appraisal stage (Stacey & Maloney, 2017). Had public participation been conducted to an acceptable level, routes may could have been planned in a more contextually appropriate manner. The advantage of London, however, is that BRT is still in the planning phases. As such, routes can be re-designed by considering the context first instead of post-design, thus implementing a CSS.

2.4 BRT in Developing Cities

Section 2.4 will analyse the BRT systems of Bogotá, Colombia and Johannesburg, South Africa. These two BRT systems were chosen as Johannesburg’s BRT policy and operations were strongly modelled according to Colombia’s. Consequently, the two systems are comparable to approximately the same standard, and the importance of contextual *ex ante* appraisal can be emphasised.

2.4.1 The Case of Bogotá, Colombia

Like many cities in developing countries, Bogotá was characterised by a chaotic, inefficient and environmentally unsustainable public transport system prior to the implementation of TransMilenio. In 1998, 22 000 buses transported 72% of the urban population on 639 different bus lines. Additionally, 670 000 private cars transported only about 19% of the population. A rapid population growth rate of 3% per annum contributed to the inadequacies of the already strained PT system. Moreover, the PT system in Bogotá was dominated by the informal sector, with hundreds of "one man companies" competing for each single passenger. This phenomenon became known as the "Penny War" (Figure 2-3). This consequently resulted in traffic jams, rapid deterioration of transport infrastructure, environmental pollution and a high number of accidents. Traffic deaths rose from 1 089 in 1991 to 1 387 in 1995, with most of the victims being pedestrians and cyclists (Müller, 2014).

Figure 2-3: An Example of the "Penny War"
Source: Muller (2014)

With the public transport system evidently failing, the government of Colombia was facing pressure to transform the Bogotá's PT system, which eventually resulted in TransMilenio. Nevertheless, TransMilenio was not the first option for eradicating Bogotá's notorious traffic and urban congestion. Plans for an 18 mile stretch of rail had been in discussion for 5 decades. Costs were expected to be in the region of 168 million United States Dollar (USD) per mile (Sharp, Quarter & Stout, 2014). Yet following Curitiba's successful BRT implementation, only 3 years passed between the initial planning and first implementation phase for TransMilenio (Sharp *et al*., 2014). Financial viability and political preference resulted in the selection of BRT over rail.

TransMilenio Phase I was a fraction of the cost of the proposed rail, at a cost 9.4 million USD per mile (Sharp *et al*., 2014). An estimated 43 000 passengers per hour in total are served on TransMilenio's 106 km of trunk lanes and 663 km of feeder routes (Hidalgo, Lleras & Hernández, 2013; Hidalgo & Muñoz, 2014)..

In terms of system design, a canopied bus station was installed every 500 m along trunk lines, increasing accessibility. To save staff and infrastructure costs, the stations were placed in the middle of the street, thus serving both directions. Furthermore, the method of fare collection is through a contactless smart card, which is pre-loaded with money, thereby reducing boarding times on buses. On average buses operate at a 2-minute interval on peak routes during an operational period of 05:00 am to 11:00 pm on Mondays to Saturdays, and 06:00 am to 10:00 pm on Sundays and holidays. Once completed, TransMilenio will feature 388 km of trunk roads, connecting the whole urban area. The government of Colombia aims for 80% of the urban population to use the system on their way to and from work (Müller, 2014). The system design, through its accessible stations, integrated fare collection method and long operating hours, optimises transport efficiency.

TransMilenio operates on a public-private-partnership (PPP). The public domain provided the required infrastructure, while the private domain provides the buses and fare collection infrastructure. This agreement stemmed from incumbent bus operators who were in opposition to TransMilenio, citing fear of job loss as their reasons. Post negotiations, 59 out of 64 of the original bus companies became shareholders (Turner, Kooshian & Winkelman, 2012). Seven contractors operate the buses that serve the trunk route, and several operate the feeder route. Such a partnership has introduced an element of competition within the system, accordingly reducing the need for government subsidies. In order to erradicate the Penny War among service operators, operators were paid according to the number of kilometres travelled as opposed to the number of passengers transported. To avoid unemployment and possible riots as a result of the eradication of the old system, drivers are only permitted to work 6 hours per day, corresponding to three drivers per bus per day (Müller, 2014). Evidently, the socio-economic standing of Bogotá was well incorporated into the planning and operations of TransMilenio. In addition to the measures mentioned, TransMilenio was synchronised with urban development measures to achieve certain social objectives as outlined by the government. Social housing was constructed along the Metrovivienda Corridor. Tercer Milenio Park was constructed in El Cartucho, which used to be the most dangerous quarter in central Bogota, in order to alleviate crime (Müller, 2014). NMT planning was a further intervention that complimented TransMilenio.

Traffic and parking lanes were removed and replaced with dedicated bus and pedestrian lanes. The bicycle facilities extend beyond the bus station, with over 300 km of bicycle lanes featuring in Bogotá. The share of daily bicycle trips has seen the modal share increase from 0.9% in the 1990's to 4% in 2014. Private vehicle usage was simultaneously deterred with the promotion of bicycle lane use. Through a licensing tag system, forty percent of cars are banned from the central streets during the peak periods daily. The ban extended to the circulation of private vehicles older than 10 years during peak periods. It was envisaged that full coverage of TransMilenio would be provided by 2016 due to citizens agreeing to completely abstain from individual car traffic in peak periods (Cervero, 2014; Müller, 2014). It can be argued that the prohibitive measures adopted against cars were aimed towards encouraging equitable road and transport use.

As the literature suggests, TransMilenio had excellent short- and long-term planning which attributed to a contextually appropriate, successful bus system. TransMilenio has successfully incorporated accessibility, mobility, socio-economic problems and equity into its appraisal, and consequently, design and operations. The significance of TransMilenio's success can truly be appreciated when juxtaposed to a less successful BRT system that occurs in a similar context.

2.4.2 The case of Johannesburg, South Africa

South Africa's political history is not so different to that of Colombia's: both countries have a history of colonisation, violence and inequality South Africa's liberation happened over 150 years after Colombia's (Minster, 2017). As such, Colombia was able to introduce PT interventions decades earlier than SA. Africa's first BRT was launched only in the new millennium in the form of Johannesburg's Rea Vaya.

Like Colombia, SA's public transport system was in a poor state. The effects of an unregulated service were felt through an oversupply of MBT's, reckless driving by taxi drivers, and increasing road safety issues (Venter, 2013). MBT's account for three times more fatalities than cars (Hazen, 2014) While SA did not experience the Penny Wars like Columbia, the nation did experience taxi wars, which were territorial wars against operating bodies. This war led to the deaths of taxi drivers, and often times, passengers (Khosa, 1992). With the *status quo* no longer feasible, and the 2010 Fifa World Cup looming, the South African Government was obliged to intervene.

After learning of the successes of TransMilenio, the South African Government made the decision to provide BRT as a leading transport mode. To formulate the policy around BRT, various decision-makers visited Curitiba and Bogota for the purposes of policy tourism. Policy tourism occurs when local stakeholders travel elsewhere to learn and mimic best practices and form the basis of their policy frameworks. In South Africa, these tours have become a standard method through which knowledge is gained from international contexts. The first visit made by the Johannesburg Municipality was from 23 August to 1 September 2006. Among the travelers were two of the largest MBT associations in Johannesburg. Upon returning, the local government approved the implementation of Phase 1 of a BRT project in principal. A second visit to Bogota included representatives from 17 of the 18 MBT companies potentially affected by the roll-out of Phase 1. A key outcome of this was that many of the MBT operators who were initially opposed to BRT were enlightened to the potential benefits of BRT. Another positive outcome of the study tour was that it created an environment where city officials and MBT associations could negotiate, which was not the case before (Wood, 2014). Although Phase 1 of the BRT system was inevitable, the study tour facilitated stakeholder negotiations, which allowed for a more seamless implementation of the system. The South African government should thus be lauded for their active engagement with MBT associations throughout the planning phase.

Phase 1 comprised of a single 25 km trunk route between Soweto, a large township, and Ellis Park, which is east of the CBD (McCaul & Ntuli, 2011; Venter, 2013). It was complimented by an inner-city distribution route, five feeder routes within Soweto, and an internal route to Soweto that makes use of some of the trunk route (Figure 2-4). Rea Vaya made use of 27 BRT stations along the trunk route and 143 buses in total (McCaul & Ntuli, 2011).

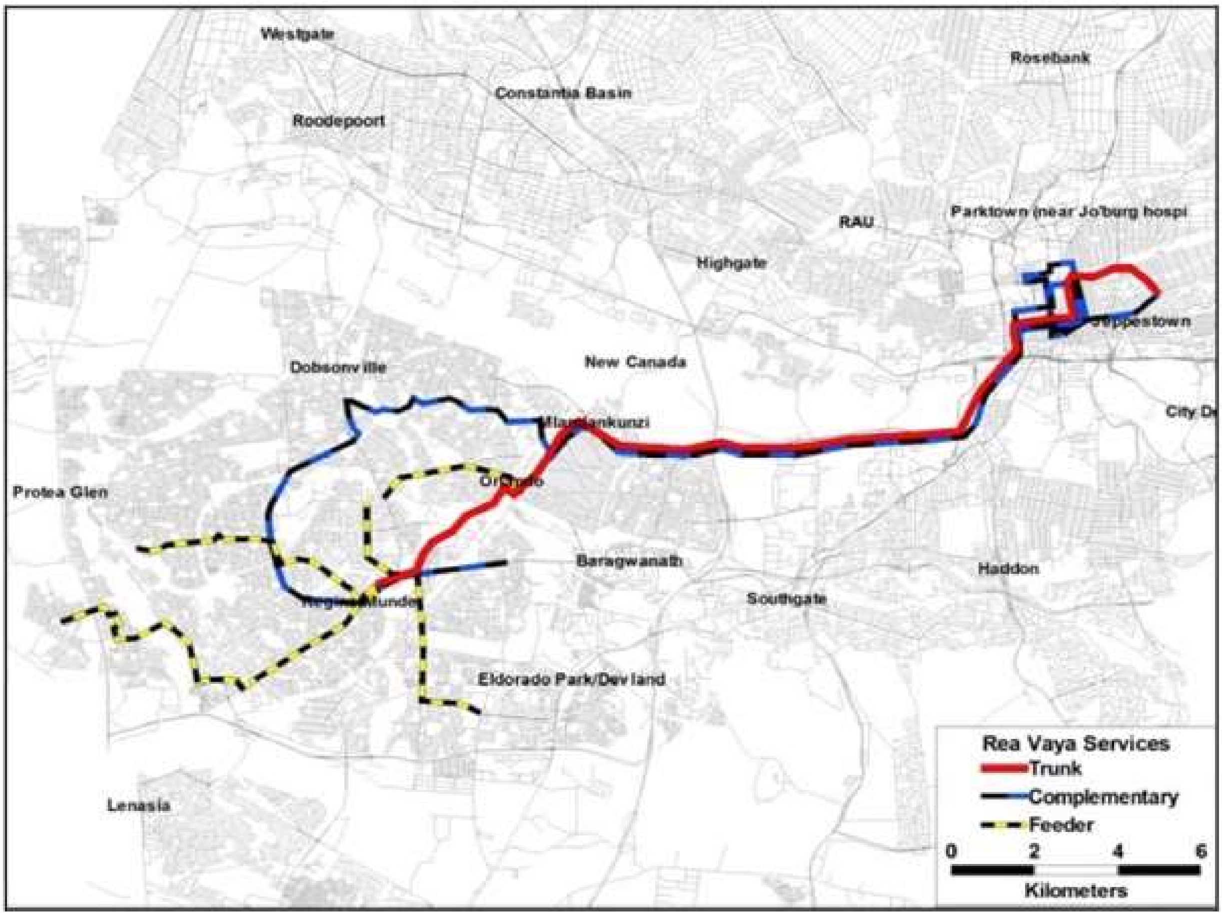


Figure 2-4: Rea Vaya Phase 1 Routes
Source: McCaul and Ntuli (2011)

Rea Vaya was implemented on a smaller scale than TransMilenio. The trunk route also featured stations in the middle of the road serving both directions and dedicated bus lanes (Figure 2-5).

Figure 2-5: Rea Vaya Dedicated Bus Lane and Station
Source: Seco Construction Project Managers (2017)

Phase 1 implementation faced great resistance from MBT associations (mostly prior to the study tours, but post tours as well). Aware of the social complexities of implementing BRT, government proposed that as compensation for withdrawing their taxis from competing routes, MBT stakeholders would become operators of the BRT system. As it was the heads of taxi associations that embarked on the study tours, the resistance originated from taxi drivers. The months leading to the launch of the system were thus plagued with threats of mass action and violence. MBT drivers blocked off roads in protest, with fears that Rea Vaya would leave them with no income (McCaul & Ntuli, 2011). After extensive negotiations, over 300 taxi operators eventually relinquished their businesses to become owners (and some, employees) of a new operating company. The company was given a 12-year contract to operate trunk and feeder services (Venter, 2013). While the socio-economic aspects were adequately appraised, there is no further evidence in the literature for the basis of an economic, transport and any other applicable appraisal.

Rea Vaya and TransMilenio share several similarities: both systems started off with a single trunk route and some feeder services. Both systems have dedicated bus lanes. In addition, governing bodies ensured any employment and future income loss were compensated for by making the existing service providers shareholders and bus operators. Yet, the statistics point out that TransMilenio is outperforming Rea Vaya. TransMilenio is self-sustaining and has a ridership that leads to overcrowding (Müller, 2014). In contrast, Rea Vaya is dependent on subsidies and does not have enough passenger numbers to justify its implementation (Maqutu, 2015). As it stands, Rea Vaya is not a CSS.

The author contends that Rea Vaya, and other BRT systems within RSA, are underperforming because of inappropriate contextual application. South African BRT systems have their policies adapted largely from South American policies adopted from the policy tours conducted. This results in policies that are, for the most part, geographically, socio-politically, economically and financially not suited for local use. The author further contends that policy formulation is contextually inappropriate because the *ex ante* appraisal process used to firstly, select BRT as a PT mode, and secondly, plan and design BRT, is itself contextually inappropriate.

2.4.3 The Need for Contextual PT Appraisal in a South African Context

Sections 2.3 and 2.4 show how BRT can exist in many different contexts, and how the successful BRTs are those planned in context. Adelaide is a medium-sized developed city. London, Canada is a relatively small developed city (The Canadian Press, 2017). Bogotá and Johannesburg are both large developing cities, with Bogotá approaching mega-city status (Stats SA, 2011a; Kotkin, 2013). All these cities have unique *inter alia* environmental, socio-economic and financial standings. In all four cases, however, the basis for selecting BRT was driven mostly by financial and economic factors.

RSA's metropolitan cities are planned for BRT implementation, including City of Tshwane, Cape Town and Rustenburg (DoT, 2007a; DoT, 2007b). To a certain extent, these systems are modelled according to the successes of TransMilenio. In the hope of achieving the same success as TransMilenio, transport planners adopted the same policy used to implement TransMilenio. It can be argued that policy makers did not take due diligence in the planning process of BRT implementations by contextualising TransMilenio to a South African setting. Policy formulation in Bogota occurred under different a political, spatial, economic and social context. More attention was required when transferring and mutating that policy across borders (Wood, 2015). Resultantly, Rea Vaya is not experiencing the same success as TransMilenio.

The author posit that context-sensitive designing and planning in the transportation field has not been at a satisfactory level in RSA. Apart from research by Beukes *et al.* (2011), no reference has been made to the technique of applying CSSs to transportation in RSA specifically. South African transport interventions must consider, *inter alia,* the unique environmental, economic, financial and socio-political climate in RSA instead of copying transport solutions from aboard almost *verbatim*. Referring to the situation of Rea Vaya, CSS could have played a role in reducing the severity of disputes between stakeholders. Additionally, a contextually sensitive appraisal was needed to ascertain financial viability, methods on increasing transport efficiency, and environmental preservation. A contextually sensitive appraisal was not only required in the selection of BRT as a main mode of transport, but in the selection of BRT routes as well.

2.5 Résumé

Chapter two aimed to outline major differences of BRT implementations in developed and developing cities. Firstly, this chapter described the need for public transport: rapid urbanisation and the negative effects thereof on the environment, traffic conditions and the economy. This showed the importance of PT investment, and was a prelude to how the correct PT investment can only occur following a contextually sensitive *ex ante* appraisal.

The second sub-section of this chapter highlighted BRT as a PT intervention, outlining its features, advantages and shortcomings. Countries with high transit dependent populations and limited financial resources have taken to using BRT as a PT intervention as it has a high capacity and relatively low capital costs. Due to its worldwide prominence, BRT is a viable subject for exploring the effects and importance of context. BRT was subsequently analysed in two developed cities and two developing cities. The comparison demonstrated how BRT can exist in different contexts. Adelaide's O-Bahn is a successful BRT due to its contextually sensitive appraisal and resulting contextually appropriate application. In contrast, London's BRT, although yet to be built, has been heavily criticised for being contextually inappropriate, and rightfully so. London's BRT routes threatened to destroy archaeological artefacts and compromise the financial gains of local business owners.

The two developing cities analysed were Bogotá and Johannesburg. As is the case for Adelaide, Bogotá's TransMilenio can attribute its success to contextually sensitive appraisal. TransMilenio has successfully incorporated accessibility, mobility, socio-economic problems and equity into its appraisal, and consequently, design and operations. With the hope of emulating TransMilenio's success, policy tours to Columbia were conducted by various stakeholders. Subsequently, South Africa planned Rea Vaya without comprehensively applying the South

African context to TransMilenio. The results thereof are a struggling BRT system would not be operational without the help of subsidies.

In conclusion, Chapter 2 showed how BRTs can be applied in different contexts, and how the basis of success is contextually sensitive planning stemming from contextual appraisal. The need for contextual PT appraisal in the South African context is reiterated: South African transport interventions must consider, *inter alia,* the unique environmental, economic, financial and socio-political climate in RSA instead of copying transport solutions from aboard almost *verbatim*. Failure to do so results in expensive PT systems that heavily depend on subsidies and do not meet the transport needs of stakeholders

3 Traditional Appraisal Techniques in Transport

Various *ex ante* appraisal tools are used in transportation planning. This section will serve to highlight two of the most common methods in public transport planning: Cost-Benefit Analysis and Multi-Criteria Analysis. Examples on countries that use these two methods in transportation planning are subsequently provided. Thereafter, appraisal techniques used in South Africa are discussed briefly. As decision-making is not an exact science, methods of incorporation uncertainty in the decision-making process are explained in conclusion.

The development of appraisal techniques in transport came in the late 1960s and early 1970s. The context for appraisal back then was assigning monetary values to time and safety benefits. Eventually, appraisal methods were developed for small projects such as new sections of road (Nijkamp, Ubbels & Verhoef, 2003). CBA's are commonly used in the United Kingdom, the Netherlands, Germany and the United States (Vickerman, 2000; Bin Kamis, 2014). Although Japan also uses CBA as an appraisal tool for transportation projects, the CBA acts as a supplementary tool to Multi-Criteria Analysis, which is the main method (Morisugi, 2000).

3.1 Cost-Benefit Analysis

According to Nijkamp Ubbels and Verhoef, (2003), Cost-Benefit Analysis (CBA) is the most widely used *ex ante* appraisal technique in transport. CBA is a microeconomic framework which uses monetary values to express measured impacts as a total money amount (Bristow & Nellthorp, 2000). CBA is based on perfect markets in which the market prices reflect the marginal willingness to pay (WTP) of a society for certain goods and services.

3.1.1 History and Framework of CBA

The earliest case of CBA being used to appraise public investment comes from Dupuit (1844). Dupuit posited the idea that a capital investment project's net advantages could be measured in terms of utility gains (Schutte, 2010). Thereafter, CBA was the most frequently used method in the 1980s. During the 1990s, this traditional policy analysis was judged to be out of date because of its prime focus on economic efficiency and its failure to adapt to the requirements of different stakeholders. CBA then experienced a resurgence since the year 2000 in the form of a renewed version of the method, also called the social cost-benefit analysis. This version includes all benefits and costs that go beyond business decisions by measuring multi-dimensional aspects such as sustainability, ethics and other social values (Haezendonck, 2008). However, in the 1970s, Germany used a CBA which may be considered to have contained social aspects. The appraisal tool consisted of operation and time costs, infrastructure costs and external costs such as accidents, noise and pollution, which may be interpreted as social impacts (Rothengatter, 2000).

The CBA framework is based on achieving net social benefits. Benefits may be measured in terms of consumers' willingness-to-pay (WTP), and costs may be measured in terms of opportunity costs (Schutte, 2010). WTP measures how much consumers are prepared to pay for a certain good. It forms the economic value judgment in a CBA (Sunstein, 2007). Opportunity costs are defined as money lost when one alternative is chosen over another (Pettinger, 2017). The difference between the sums of goods judged according to WTP and opportunity cost gives the net social value of a project. Should the difference be positive, the project has benefits that exceed opportunity costs, and *vice versa*.

It should be noted that the CBA framework suggested by Shutte (2010) is applicable to both a private sector economic evaluation and a public sector evaluation. It is important to differentiate the two in an appraisal process so that a project is implemented for the correct reasons (Table 3-1):

Table 3-1: Differences Between Private Sector and Public Sector CBA

Financial Analysis in Private Sector	Public Sector CBA
Maximise stakeholder wealth	Maximise social welfare
Focus is on interest of stakeholders	Focus is on entire community
Analysis based on current market prices	Analysis is based on shadow prices

Source: Schutte (2010)

To reiterate, the evolution of CBA changed the focus from a historically economic analysis, to an all-inclusive, economic and social CBA. Broad-based CBA includes applying various environmental, health and safety criteria to economic and transport criteria (Weisbrod, Lynch & Meyer, 2009). Schutte and Brits (2012) developed a matrix for classifying CBAs according to broad-based and narrow-based criteria (Figure 3-1):

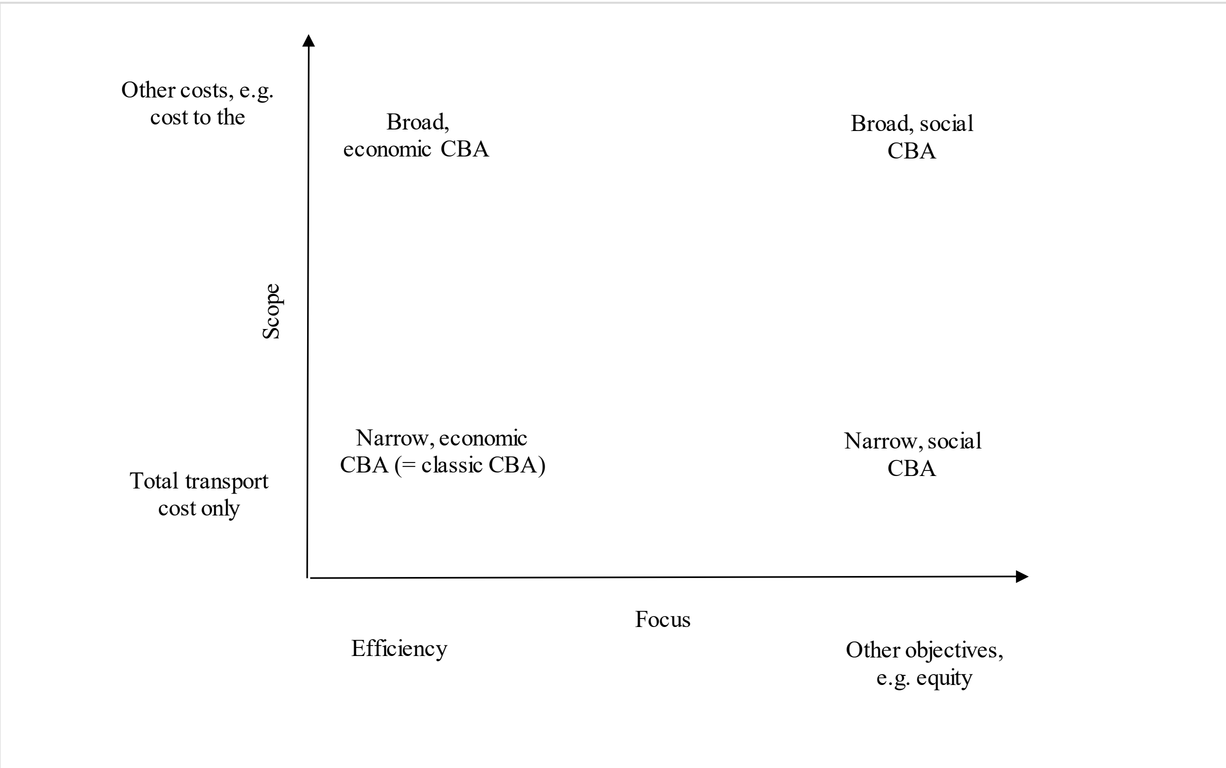


Figure 3-1: Broad- and Narrow-based CBA Matrix
Source: Schutte and Brits (2012)

For an *ex ante* transport appraisal, both the narrow and broad economic and social CBA should be considered. This will ensure a project is evaluated in its entirety prior to implementation. A purely economic CBA, whether it be broad or narrow, should only be adopted in an *ex post* evaluation, as it is inadequate for an *ex ante* appraisal. However, it is important to note the difficulty in incorporating social impacts into a CBA. Social impacts can take on many forms and vary from location to location (Odgaard, Kelly & Laird, 2006).

3.1.2 Analytical Procedures

At the most fundamental level, CBA involves assessing whether a transport project's benefits outweigh its costs. Schutte (2010) identifies three approaches to CBA:

i) Least cost approach;
ii) Maximisation of net benefits approach; and
iii) Investment approach.

Least Cost Approach

This approach makes use of the Equivalent Uniform Annual Cost (EUAC) and Present Worth of Cost (PWoC) techniques. The EUAC method looks at the annual discounted costs which accrue over the lifetime of a project (Albahrani, 2014) (Equation 1):

$$EUAC = P/\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

……….Equation 1

Where:

P = Present worth of a project;
i = Discount rate; and
n = Number of years in project lifespan.

The PWoC can be calculated by rearranging Equation 1 to find P. The techniques used in the Least Cost Approach do not involve a comparison of alternatives. The alternative selected is the alternative with the lowest EUAC or PWoC.

Maximisation of Net Benefits Approach

This approach allows for the comparison of alternatives; namely the planned intervention(s) and the null alternative. According to Bin Kamis (2014), the following steps are conducted in a Maximisation of Net Benefits Approach so as to reach a conclusion about whether the benefits outweigh the costs:

i) Alternative projects should be specified;
ii) Decide on the stakeholders and their benefits and costs to be counted;
iii) Catalogue the impacts and select the measurement indicators. In this step, the physical impact categories and measurement indicators are listed;
iv) Predict and quantify impacts over the lifecycle of the project;
v) Convert all impacts into a currency. A major limitation of CBA lies within this step;

vi) Costs and benefits are to be discounted to present values. The reasons for this are that there is an opportunity cost in the resources used in the project, and most people consume in the present rather than in the future. Impacts are discounted by multiplying their monetary values by the discount rate (Equation 2):

$$PV = V_{(B|C)} * (1 + r)^{(-n)}$$

……….Equation 2

Where:

PV = Present value
$V_{(B|C)}$ = Monetary value of cost or benefit
r = Discount rate
n = Lifespan of project (usually in years, depending on the time frame of r)

vii) Compute the Net Present Value (NPV) of each alternative. This is done by subtracting the sum of the discounted costs from the sum of the discounted benefits. The alternative with the highest, positive NPV is the one that is selected. An alternative approach would be to calculate the Benefit-Cost ratio (BCR), which is the sum of the discounted benefits divided by the sum of discounted the costs for each alternative. As with the NPV, the higher and more positive the BCR, the better the alternative. The BRC should ideally be more than one for a project to be implemented;

viii) Conduct a sensitivity analysis. This step is important as it tests how sensitive the estimations are to assumptions and inferences; and

ix) Make a recommendation. Analysts must use results obtained in vii) and viii) to make a recommendation on the solution that best fits stakeholders' interests.

Arguably, the most difficult step of the methodology is step v). This step relies on many assumptions, e.g. the monetary value of a human life saved. The advantages of using CBA include the output being a monetary value that stakeholders and decision-makers can understand, and the avoidance of double-counting impacts through currency conversion (Bin Kamis, 2014).

Investment Approach

The investment approach, which uses the Internal Rate of Return (IRR), is adopted from the private sector. The IRR is the minimum discounting rate required to make a return on investment. It is found by solving for r in Equation 2, and equating the NPV to 0 (Schutte, 2010). Using the IRR is problematic when the NPV is negative, which a large portion of transportation projects are in the initial stages. In addition, the lifespan of a project greatly influences the IRR; the shorter the project, the greater the IRR. This can produce misleading results. The investment approach should thus not be the sole approach used in an *ex ante* appraisal of transportation projects. The investment approach should rather be used as a complementary approach if used at all.

3.1.3 Applications of CBA

The most common appraisal tool in European Union (EU) member states is CBA. Key appraisal criteria include travel time savings, safety, environmental impacts and employment (Bristow & Nellthorp, 2000). The Netherlands uses a CBA that is arguably regarded as a state-of-the-art CBA, as the CBA considers the largest variety of criteria (Mouter, Annema & van Wee, 2013). More specifically, the Netherlands and the UK are two leading European countries in terms of the effects included in a transport *ex ante* CBA and the standardisation of these effects. The Dutch system, called the Overview Effects Infrastructure (OEI), was established in 2000 and became the mandatory method of evaluating proposed major infrastructural plans that are funded by the government. The OEI contains three evaluation categories: direct effects (reliability benefits and travel time), indirect effects (more efficient housing and labour markets), and external effects (environmental impacts and traffic safety) (Geurs *et al*., 2009). In addition to the OEI arguably considering the largest variety of criteria, criteria are also all monetised. The Danish system monetises all criteria too (Table 3-2), yet the Dutch appraisal system is more sophisticated. For example, Denmark uses guideline monetary values for appraising PT delay, whereas the Netherlands measures and quantifies delays directly. (Odgaard *et al*., 2006).

Table 3-2: Elements of a CBA by Country

Country	Impacts: Construction costs	Disruption from construction	Costs for maintenance, operation and administration	Passenger transport time savings	User charges and revenues	Vehicle operating costs	Benefits to goods traffic	Safety	Noise	Air pollution -local/regional	Climate change	Indirect socio-economic effects
Austria	green	green	green	green	green	green	green	green	green	green	green	orange
Belgium	green	green	green	green	green	green	green	green	orange	orange	orange	orange
Denmark	green	green	green	green	green	green	green	green	green	green	green	green
Finland	green	orange	green	green	green	green	green	green	green	green	green	orange
France	green	orange	green	green	green	green	green	green	green	green	orange	green
Germany	green	orange	green	green	orange	green	green	green	green	green	green	green
Ireland	green	green	green	green	green	green	green	green	orange	orange	orange	orange
Netherlands	green	green	green	green	green	green	green	green	green	green	green	green
Sweden	green	orange	green	green	green	green	green	green	green	green	green	green
Switzerland	green	orange	green	green	green	green	green	green	green	green	green	green
UK	green	green	green	green	green	green	green	green	orange	orange	orange	green

Key: [green] Included with a monetary value; [orange] Measured quantitatively, qualitatively or not included

Source: Odgaard, Kelly and Laird (2006)

Although the Netherlands is the only country to monetise all impacts listed in Table 3-2, Geurs, Boon & Van Wee (2009) argue that social impacts have been underexposed in the Netherlands, and the UK CBA has a broader spectrum of social impacts than the Netherlands. It can be hypothesised that only social impacts that can be monetised are included in the Dutch CBA. The UK system covers a much wider range of impacts because social impacts are measured through qualitative assessments (Vickerman, 2000).

The United Kingdom used to use a CBA method called COBA for proposed highways. Construction and maintenance costs were compared against time savings, fuel and non-fuel vehicle operating costs, and accident savings. Externalities, however, were not monetised in COBA. Environmental impacts, noise, visual intrusion etc. were merely described accordingly. Resultantly, decision-makers had to balance the monetary benefits of a proposed highway with the descriptive assessments of any externalities (Willis, Garrod & Harvey, 1998). The lack of quantifiable externalities introduces room for bias within the decision-making process in COBA. Subsequently, COBA was found to be biased towards projects which generated major reductions in accident costs and time savings. In addition, it excluded environmental impacts and economic impacts on surrounding areas. Authorities concluded that COBA was too narrow in scope, and consequently introduced a refined appraisal framework called New Approach to Appraisal (NATA). NATA introduced previously excluded elements from COBA in a more formal manner through a one page Appraisal Summary Table (AST) (Vickerman, 2000). There are five main impacts included in the AST: environment, safety, economy, accessibility and integration. Monetised items include direct effects, accidents, noise impacts and carbon emissions (Geurs *et al*., 2009). Despite the improvements made, NATA (and OEI, for that matter) has been criticised for excluding equity considerations. In contrast, the German CBA effectively considers the distribution of impacts across different population groups (Bristow & Nellthorp, 2000).

Germany uses a CBA called the Federal Transport Infrastructure Plan. The main evaluation criteria in the CBA include reduction of transport costs, changes of infrastructure maintenance cost, and improvements in traffic safety. Externalities include improvements in accessibility, environmental impact and spatial effects (Hayashi & Morisugi, 2000). A highlight of the Federal Transport Infrastructure plan is that it uses detailed and explicit procedures of including impacts on different regions within the country to address equity concerns. For instance, the existent economic problems of former East Germany are prioritised through employment impacts being given extra weighting. Employment (in the construction and implementation phases) is forecast and monetised. The UK method omits employment all together (Bristow & Nellthorp, 2000). Due to the implementation of contextually sensitive appraisal through the incorporation of equity considerations, the German CBA should be regarded as a strong contender for a state-of-the-art CBA.

Outside of the EU, The United States recommends the use of CBA for transport appraisal. The CBA may be expanded to include equity impacts. Criteria included in the CBA include travel time and cost savings, safety, induced demand, environmental pollution and noise. Other externalities such as land use impacts, economic impacts and development impacts are described but not included in the CBA as they affect travel demand (Hayashi & Morisugi, 2000). In this instance, the exclusion of land use, economic and development impacts is agreeable as it ensures that double-counting is avoided.

3.1.4 Shortcomings of CBA

While CBA may be the most widely used and accredited appraisal tool in transport, it is not without its shortcomings. At the forefront of these shortcomings is the conversion of certain impacts into a currency. The literature indicates that CBA has disputable methods of converting soft variables, or non-quantifiable impacts into money, or sometimes leaves these effects out of the calculation altogether, such as in the case for UK's COBA (Mackie & Preston, 1998; Beukers, Bertolini & Te Brömmelstroet, 2012). Examples of these soft variables include the monetary value of time and of environmental degradation or improvement.

Social impacts are often underexposed in CBAs. Due to time and budget constraints, these impacts are difficult to quantify or monetise. Furthermore, inadequate data collection methods and lack of research and appropriate evaluation tools make social impacts difficult to monetise (Geurs *et al.*, 2009). In addition, the high variety of social impacts makes it difficult to ensure that a full range of social criteria is included in a CBA.

The selection of a discount rate is also a contentious issue in CBA. The chosen discount rate strongly affects the ranking of projects selected. Selecting a discount rate becomes difficult because markets are imperfect, especially with regards to public goods. Additionally, no single stable interest rate is applicable throughout the economy and over time (Nijkamp *et al*., 2003). As such, it can be concluded that there is a great deal of uncertainty that lies within the discount rate. CBAs should thus be complimented with an uncertainty analysis to verify results (see section 3.3.).

Due to these inadequacies, it was necessary to develop a framework that was able to incorporate and assess multiple, often conflicting criteria which are usually difficult to quantify (Bin Kamis, 2014). Another appraisal tool, multi-criteria analysis, addresses some of these shortcomings.

3.2 Multi-criteria analysis

Multi-criteria analysis (MCA) has evolved as a multi-objective decision tool for situations in which a single-criterion approach is incapable of providing the required assessment framework, due to usually conflicting criteria (Bin Kamis, 2014). MCA can be regarded as a tool for the appraisal of different alternatives, when several stakeholders' inputs and priorities are considered to produce a common output. What MCA has in its favour is the fact that it can be used with contradictory evaluation criteria, which CBA cannot (Tsamboulas, 2007). Schutte (2010) has outlined five advantages of using MCA as a decision-making tool:

i) MCA is capable of directly involving stakeholders;
ii) Both qualitative and quantitative data can be used in the appraisal framework;
iii) MCA is a multi-disciplinary approach as it captures the complexity and entirety of projects;
iv) It facilitates an interactive learning process. Stakeholders are obliged to consider the opinions of other stakeholders; and
v) MCA is less susceptible to bias than WTP methods as people are more comfortable expressing preferences in the form of weights.

3.2.1 Analytical Procedures

MCA makes use of weights and scores that are applied to the various criteria for evaluation. The criteria to be weighted can either be based on well-defined quantifiable attributes that are easy to weight, or the attributes can be non-measurable, making it difficult to assign weights (Barfod & Salling, 2015). The methodology of an MCA is slightly more complex as it contains many different approaches, as quantitative and qualitative data is systemically analysed. According to Macharis *et al,* (2009) and Bin Kamis (2014), the following steps are included in a classical MCA analysis, despite the approach used:

i) Problem definition;
ii) Generate alternatives and identify stakeholders;
iii) Develop a set of criteria and evaluation matrix: the identified criteria are assigned weights. These weights reflect the importance of each criteria to the relevant stakeholders;
iv) General evaluation of alternatives: in the fourth step, various constraints are constructed for each criterion. Thereafter, a final score, usually between 0 and 1, is determined for each criterion in a process called standardisation. Criteria are prioritised and ranked for all alternatives;
v) Sensitivity analysis: as this method makes use of weights, it is common to do a sensitivity analysis of the criteria weights chosen. This is done to eliminate the subjectivity in the decision of weights and make the selection process more transparent; and
vi) Implementation: the best performing alternative is chosen using the basic approach (Figure 3-2):

$$\begin{array}{ll} & \begin{array}{cccc} \text{criteria} & C_1 & C_2 & \cdots & C_n \\ \text{(weights} & w_1 & w_2 & \cdots & w_n) \end{array} \\ \text{alternatives} & \text{———————————} \\ X = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}_{m \times n} \end{array}$$

Figure 3-2: Basic Approach to MCA
Source: Wang et al. (2009)

A decision problem of *m* alternatives and n criteria can be summarised in a decision-making matrix (Figure 3-2). X_{mn} represents the performance value of the n^{th} criteria of the m^{th} value, and w_n is the weight of criteria *n* (Wang *et al.*, 2009).

The six steps previously outlined form the core of the several types of approaches that can be implanted when performing an MCA. Simple Multi-Attribute Rating Technique (SMART), Analytical Hierarchy Process (AHP) and Swing Weights are well established approaches in determining criteria weights (Barfod & Salling, 2015).

Simple Multi-Attribute Rating Technique

SMART is a method originally used by Ward Edwards in 1971 (Edwards & Barron, 1994). This model assigns different scores to alternatives and direct weights to criteria. In order to use this method, a high-level knowledge of the alternatives and criteria to be assessed is required. This method should thus only be used when measurable attributes can be identified for the criteria (Barfod & Salling, 2015). With this method, criteria weights are assigned directly, usually on a scale of 0-100, or a natural scale of the number of criteria (Valiris, Chytas & Glykas, 2005; Rahim, 2016). The advantage of the SMART method is that it is independent of the number of alternatives, since the ratings of alternatives are not relative. Therefore, adding alternatives will not change the final score of the original alternatives (Valiris *et al*., 2005). However, this method is susceptible to bias and subjectivity as weights are directly assigned. Stakeholder engagement on the determination of criteria weights is thus mandatory with this method.

Analytical Hierarchy Process

The AHP was first developed by Saaty (1977). It consists of taking a complex decision-making process and organising it into a hierarchical structure. At the top of the hierarchy is the objective of the decision-making process. The second level of the hierarchy consists of the evaluation criteria. Sub-criteria and attributes, which aid in describing the decision process in greater detail, are located from the third to the penultimate level of the hierarchy. The last level of the hierarchy consists of decision alternatives (Tudela, Akiki & Cisternas, 2006).

The criteria weights are computed in a pairwise comparison matrix. A nine-point scale is used to ascertain the relative importance of each criteria. The matrix is an n x n matrix, where n represents the number of criteria considered. Every entry a_{ij} represents the relative importance of the i^{th} criteria to the j^{th} criteria (Saaty, 2005). Every pair must satisfy the following condition in the normalised matrix:

$$a_{ij} * a_{ji} = 1$$

……….Equation 3

The nine-point scale shows degrees of importance of one criterion over another for every odd number (Table 3-3):

Table 3-3: Explanation of 9-Point Scale

Value of a_{ij}	Explanation
1	*i* is equally as important as *j*
3	*i* is moderately more important than *j*
5	*i* is strongly more important than *j*
7	*i* is very strongly more important than *j*
9	*i* is extremely more important than *j*

Adapted from Beukes (2011)

Intermediate values of 2, 4, 6, and 8 can also be used. Following the computation of the matrix, matrix *A,* the normalised matrix $A_{normalised}$ should be computed by finding the Eigenvector of matrix A (Saaty, 2005).

Judging the relative importance of criteria is a subjective process. The AHP should thus be employed when stakeholder engagement is possible and mandatory. A stakeholder vote on the relative importance of criteria weights will remove subjectivity and bias. Additionally, AHP should be complemented with a sensitivity analysis on the weights.

Swing Weights

Barford and Salling (2015) consider this method the most accurate, but also the most difficult. As with AHP, this method is also based on comparison. It involves comparing the swing of the worst value of a criterion to the best value of the same criterion, to the swing of worst value to the best value of another criterion. The most severe swing difference is given the most importance (Dodgson *et al*., 2009). For example, consider two transport alternatives A1 and A2. For the capital cost criteria, the difference between A1 and A2 is small, say R 2000 for a R 5 billion budget. For the travel time criteria, the difference is remarkable: A2 reduces 3 times as much travel time as A1. Travel time criteria would thus be given a higher weighting than capital cost criteria. This intra-criterion comparison thus makes the swing weights method the most accurate.

3.2.2 Applications of MCA

In the EU, Austria, Belgium and Greece all make use of MCA in the evaluation of transport projects. However, a CBA is still contained in all three of these countries (Bristow & Nellthorp, 2000). In addition, Japan also makes use of an MCA. Japan's transport appraisal tool covers impacts such as regional economic impacts, the project's contribution to achieving minimum living standards and global and local environmental impacts (Morisugi, 2000). Weights are assigned to criteria based on results from WTP analyses (Hayashi & Morisugi, 2000). In making use of WTP to determine criteria weights, Japan subsequently incorporates CBA methods into an MCA. However, the appraisal tool states that the result of the CBA section can only inform whether or not an alternative can be listed as a candidate for implementation. The ranking and subsequent selection of alternatives must be based on the MCA results (Morisugi, 2000).

3.2.3 Shortcomings of MCA

Despite many methods being available for determining the weighting of a criterion, this aspect of MCA remains one of its major weaknesses. The methods in place are still susceptible to subjectivity and stakeholder bias. In addition to weighting, another shortcoming of MCA that it is a potentially time-consuming practice, as it requires a large number of working calculations for which specific input data is necessary (Rothengatter, 2000). However, it can be argued that CBA is also time-consuming as a considerable number of working calculations are required, especially for soft variables that are quantified.

Lastly, as MCA is so dependent on stakeholders and the information that they share, it is not uncommon to see stakeholders reluctant to share their knowledge or provide biased information to strengthen their power (Bin Kamis, 2014). Subjectivity in the weights is usually addressed through a sensitivity analysis.

Drawing from the literature, CBA and MCA are worthy appraisal tools for transportation interventions. The output of a CBA is expressed in monetary terms, which can be understood by the layman. Hence, MCAs strength lies in its ability to appraise quantitative and qualitative criteria. While most countries use either one or the other, Nijkamp Ubbels and Verhoef (2003) rightfully argue that the two can work best when used in a complementary system. For example, CBA techniques are often faced with the problem of incorporating qualitative externalities. Often, these externalities are merely described in a CBA, and the physical description is taken into account when evaluating the CBA results. Accordingly, MCA is capable of evaluating both types of data in the appraisal framework. Furthermore, CBA is often criticised for its weak incorporation of stakeholder engagement. In contrast, MCA is reliant on stakeholder engagement. The problem thereafter is with the integrity of stakeholders.

While both appraisal tools are suitable for transportation projects, their suitability for PT routing problems is questionable. A common weakness of both CBA and MCA is that the spatial component of transport projects is not adequately addressed. If CBA and MCA were to be used in the appraisal of PT routes, the routes would need to be pre-determined and presented as alternatives. CBA and MCA could not be adequately used as an appraisal tool to create new routes.

3.3 Transport appraisal in South Africa

South Africa currently does not have an *ex ante* appraisal method for selecting transportation interventions. Selection of transport interventions is governed by the intervention's adherence to various laws and statutes, such as the National Land Transport Transition Act (NLTTA) (Act 22 of 2000). The NLTTA states that land transport planning, which is all road- and rail-based transport, must be integrated with land development processes (Schutte, 2010). Part 7 of the Act provides an array of objectives that land transport must meet (DoT, 2000). These objectives can be regarded as evaluation criteria for the selection of a land transport intervention. The Act does not provide methods on achieving these objectives, or which objectives are more important than others if applicable.

Naude *et al.* (2005) posit that a lack of an appraisal method caused the Council for Scientific and Industrial Research (CSIR) to undertake research into frameworks for the appraisal of transport interventions. While the appraisal framework focused on the South African context, it drew on experiences and practices from other middle-income countries, particularly those with high income inequality. The proposed framework, which was still to be tested imperially, is based on the British New Approach to Transport Appraisal. It was contextualised by focusing on addressing developmental issues relevant to the South African context, such as empowerment and poverty reduction. Twelve years later, however, there is no evidence in the literature of this appraisal framework. It is unclear as to how far this research had progressed and why it was discontinued.

3.4 Incorporating Uncertainty

The decision-making process is not an exact science; it is subject to many uncertainties, e.g. uncertainty in criteria weights or currency conversion. Uncertainties play such a crucial role in the decision-making process that a section into the investigation of uncertainties is warranted. This section will serve to discuss uncertainty analyses in detail. Included in this section will be a definition and justification for an uncertainty analysis. Thereafter, various methods of approach are discussed. To conclude this section, the approach to be used in this dissertation is provided.

3.4.1 Defining Uncertainty

Uncertainties are a guarantee in any decision-making process, especially processes that use models. If decision-making models are to provide a complete, effective decision support tool, all uncertainties encountered at every level of the decision-making process must be considered. At a basic level, uncertainty may be defined as the occurrence of incomplete knowledge or information about a subject. According to Walker *et al*. (2003: 8), uncertainty is "any departure from the unachievable ideal of complete determinism". Eastman (1999) and Chen *et al.* (2011) associate uncertainty with risk. These authors rightfully argue that, in a decision-making context, uncertainties in the decision rule(s) and in the evaluated criteria infer that there is some risk the final decision(s) will be incorrect.

In a more GIS context, Eastman (2001) stated that uncertainty analyses are required to address the following questions:

- Were all relevant criteria considered?
- Were the chosen criteria assigned correct weights?
- Is there a measurement error that exists?
- Is the GIS data aggregated in an appropriate manner?
- How likely is the multi-criteria model to be wrong?

- o What are the limitations on the conclusions based on the degree of incorrectness of the model?

3.4.2 Three Dimensions of Uncertainty

The questions stated above provide the departure point from which an uncertainty analysis is to be conducted in this dissertation. To do so, however, uncertainty must be unpacked in the context of this research. As evidenced by the literature, the definition of uncertainty is open-ended. *Prima facie,* the referenced authors have no overlap in their definitions of uncertainty. Ascough II *et al.* (2008) and Mosadeghi *et al.* (2013) confirm this premise in their papers. What resulted from this ambiguity was an uncertainty classification matrix, designed to classify and identify uncertainty in a structured manner (Walker *et al*., 2003; Warmink *et al*., 2010; Mosadeghi *et al*., 2013). More specifically, it is developed as "a tool by which to get a systematic and graphical overview of the essential features of uncertainty in relation to the use of models" (Warmink *et al*., 2010: 1519). For model-based decision support exercises, Walker *et al*. (2003) distinguish three dimensions of uncertainty in their uncertainty matrix:

i) *Location* of uncertainty: also known as the source of uncertainty, this is where uncertainty occurs in the model;
ii) *Level* of uncertainty: the level of uncertainty refers to how much knowledge there is within the model. It is where the uncertainty occurs along the spectrum of the unachievable goal of deterministic knowledge and the extreme of total ignorance; and
iii) *Nature* of uncertainty: this refers to why the uncertainty exists. Is it due to the imperfection of decision-makers' knowledge, or the variability of the subject being appraised?

Ideally, any uncertainty present in an appraisal model should be described according to the three dimensions. Sources of uncertainty are described as follows (Walker *et al*., 2003; Refsgaard *et al*., 2007; Mosadeghi *et al*., 2013):

i) *Context uncertainty:* this includes uncertainty about the external third-party effects that form the context for the subject being appraised. These third-party effects include economic, environmental, political, technological and social effects;
ii) *Model structure uncertainty:* this is conceptual uncertainty relating to incomplete understanding of modelled processes in comparison to reality;
iii) *Model technical uncertainty:* this uncertainty arises from the computer implementation of the model, e.g. hardware and/or algorithm errors;
iv) *Input uncertainty*: uncertainty relating to the input data, i.e. evaluation criteria;
v) *Parameter uncertainty:* uncertainty in the criteria parameter values selected; and
vi) *Model output uncertainty*; uncertainty in the results of the evaluation model.

As can be inferred from the list above, uncertainties occur at every level of the decision-making process. This becomes problematic as uncertainty analyses are only conducted at the end of the appraisal process. A spectrum of determinism is used to illustrate the second dimension of uncertainty, the level of uncertainty (Figure 3-3):

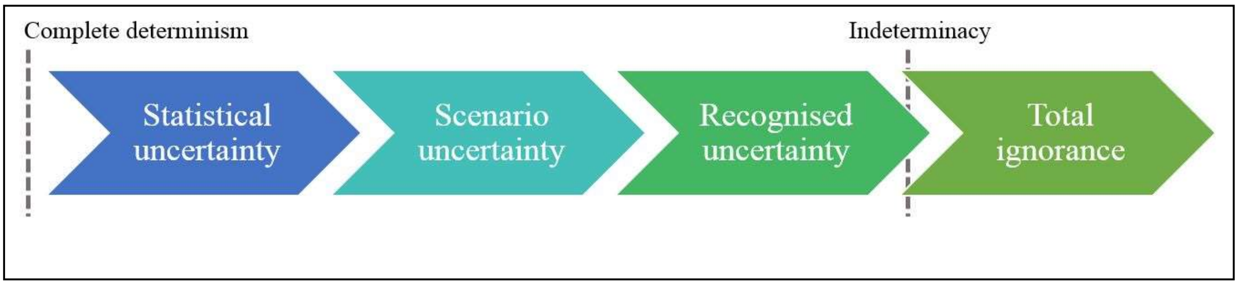


Figure 3-3: Spectrum of Determinism
Source: Walker et al. (2003)

Statistical uncertainty, the most common type, is any uncertainty that can be quantified in statistical terms. This level of uncertainty is applicable to any location within the model (Refsgaard *et al*., 2007; Warmink *et al*., 2010). Scenario uncertainty recognises that there is a range of possible outcomes, but cannot statistically determine the probability of any one outcome (Mosadeghi *et al*., 2013). Recognised uncertainty, or recognised ignorance, is the first stage of ignorance obtained about the subject being appraised. Recognised ignorance can further be classified into reducible ignorance and irreducible ignorance. Reducible ignorance may be eliminated from a study by conducting further research to achieve better understanding. Irreducible ignorance is the term used when further research cannot produce additional knowledge (Walker *et al*., 2003). Total ignorance is an extreme type of ignorance where decision makers have no knowledge, and they cannot obtain more knowledge as they do not know what they do not know. It is for this reason that Warmink *et al*. (2010) and Moadeghi *et al*. (2013) have omitted total ignorance from the spectrum of knowledge, and have in place included qualitative uncertainty before recognised uncertainty. This type of uncertainty addresses uncertainty that cannot be nominally quantified in measurable variables. Qualitative uncertainty is present in expert opinions, linguistic probabilities etc. In a multi-criteria analysis, this type of uncertainty becomes increasingly important to consider as some of the evaluation criteria may be qualitative. Analysing this type of uncertainty, however, would be difficult to do. It would need to be a qualitative assessment.

There is some divergence in the literature with regards to determining the nature of uncertainty. Walker *et al*. (2003), Refsgaard *et al*. (2007) and Mosadeghi *et al*. (2013) all distinguish between epistemic uncertainty and variability uncertainty. Epistemic uncertainty relates to the uncertainty due to perfect knowledge. Variability uncertainty, also known as stochastic or ontological uncertainty, is the inherent uncertainty due to human behaviour, social, economic, cultural factors etc. Warmink *et al*. (2010) distinguish three natures of uncertainty: epistemic, natural variability, as previously mentioned, and ambiguity. Ambiguity is “the simultaneous presence of multiple equally valid frames of knowledge” (Warmink *et al*., 2010: 1521). The authors acknowledge that Walker *et al*. (2003) have included this nature of uncertainty as part of epistemic uncertainty, which implies that gathering more knowledge will reduce uncertainty. In practice, however, this is not always true; gathering more knowledge does not always converge to a single truth. Moreover, seldom times where more knowledge may lead to more uncertainty. It is for this reason that Warmink *et al*. (2010) have considered it as its own nature of uncertainty, and rightfully so.

With the typology of uncertainty delineated, a decision-maker can use the uncertainty matrix to classify all uncertainties in a model (Table 3-4). However, there are no instructions provided as to how to complete the matrix. As such, it can be assumed that the evaluator is at liberty to complete the matrix as they see fit.

Table 3-4: Uncertainty Matrix

Location of Uncertainty		Level of Uncertainty				Nature of Uncertainty		
		Statistical Uncertainty	Scenario Uncertainty	Qualitative uncertainty	Recognised Uncertainty	Epistemic uncertainty	Stochastic uncertainty	Ambiguity
Context	Natural, technological, economic, social, political							
Inputs	System data							
	Driving forces							
Model	Model Structure							
	Technical Model							
	Parameters							
Model Outputs								
Model Outcomes								

Source: Refsgaard et al (2007)

3.4.3 Methods for Uncertainty Analysis

There are many methods available for conducting uncertainty analyses. Chen *et al*. (2011) distinguish between three main approaches: probabilistic methods, indicator-based methods and fuzzy logic. Uusitalo *et al*. (2015) outline four approaches to evaluating uncertainty in deterministic decision support tool models: expert assessment, model sensitivity analysis, model emulation and temporal or spatial variability in the deterministic models. Refsgaard *et al*. (2007) discuss 12 methods of conducting uncertainty analysis, with error propagation equations, scenario analysis, stakeholder involvement and the uncertainty matrix being the most notable. The following methods have been selected for critique as they are considered most applicable to multi-criteria decision problems:

- Sensitivity analysis;
- Scenario uncertainty;
- Error propagation; and
- Stakeholder engagement; and

A sensitivity analysis examines the stability of a model by determining the quantitative or qualitative variation in output when input parameters are varied, either individually or combined (Delgado & Sendra, 2004). In a multi-criteria decision-making model, a sensitivity analysis would be most applicable to the selected weighting scheme. Common methods of sensitivity analyses include Monte Carlo Analysis, sensitivity indices, regression or correlation methods, variance-based techniques and one-at-a-time (OAT) methods. These methods are most commonly applied to test criteria sensitivity by changing criteria values, changing the relative importance of criteria and changing criteria weights (Y. Chen, Yu & Khan, 2010). Traditionally, incremental changes are applied to weighting schemes, most commonly, one criteria at a time (Carver, 1991). This is a shortcoming of traditional sensitivity analyses as varying one criteria weight at a time is not indicative of reality; it is misleading as it overlooks potential interactions that may exist when varying all or some weights simultaneously. Butler *et al.* (1997) addressed this shortcoming by presenting a simulation approach for high dimensional sensitivity analyses of criteria weights. They applied a simultaneous weight-change approach to ascertain the sensitivity in weights for an MCA conducted to determine the best technology to dispose of the US stockpile of weapons-grade plutonium. Another key weakness in sensitivity analyses is that they only address uncertainties in the input variables of the model, and not the uncertainty of the model itself (Uusitalo *et al*., 2015). The MCA model is deemed to be sensitive if the output value changes more than the change in input value. Apart from proving the degree of robustness for MCA models, sensitivity analyses may also give insight into which evaluation criteria require further research to reduce uncertainty and which criteria are redundant and may be removed from the evaluation process.

Scenario analysis involves creating plausible outcomes, either qualitatively or quantitatively, to forecast possible outcomes with changes input variables (Swart, Raskin & Robinson, 2004; Postma & Liebl, 2005). In addition to scenarios being characterised as either qualitative or quantitative, scenarios are distinguished into two main groups: descriptive scenarios and normative scenarios. Descriptive scenarios describe possible outcomes from current trends and conditions. Normative scenarios are constructed to lead to a possible decision that is assigned a specific subjective value by decision-makers (Swart *et al*., 2004). While scenario analyses are effective in highlighting crucial uncertainties, this type of uncertainty analysis does have a blind spot. Scenario analyses are unable to deal with complex trends as the trends tend to often be systematically excluded on the basis of appearing to be logically impossible or inconsistent during the scenario-building process (Postma & Liebl, 2005). As scenario analyses are based on hypothetical outcomes, decision-makers should seek the opinions of experts and stakeholders during the scenario-building process. This will strengthen the uncertainty analysis.

Unlike sensitivity analyses, error propagation techniques address errors at various stages in an MCA model. Error propagation considers the uncertainties of different measured variables and computes them in an additive or multiplicative model (Harvard University, 2007). For additive and multiplicative error propagation equations to be used, the uncertainties must have Gaussian distributions and the uncertainties for non-linear models must be relatively small (standard deviation divided by mean is less than 0,3). Additionally, the uncertainties must have no significant covariance (Refsgaard *et al*., 2007). Error propagations are an important factor to consider in spatial decision models. Depending on the function used (additive or multiplicative), the magnitude of errors can increase quite rapidly during raster overlay (Siska & Hung, 2001). An advantage of error propagation in spatial models is that the errors can be spatially represented on GIS maps, allowing the decision maker to visually establish which areas are more uncertain than others.

Stakeholder engagement is a crucial component of MCAs. During the decision-making process, stakeholders are involved in various stages to decide on project specifications, criteria to consider, and oftentimes, criteria weights. In terms of uncertainty analysis, stakeholder analysis is used to reduce uncertainty by engaging stakeholders to add more knowledge, especially from non-scientific sources. Stakeholder engagement is found to be lacking when stakeholders are asked to comprehend more complex or abstract concepts. Another shortcoming of stakeholder engagement is that it is often difficult to ensure equitable representativeness (Refsgaard *et al*., 2007; Uusitalo *et al*., 2015). Stakeholder analysis is a strong tool to address qualitative uncertainty. A further potential weakness is a weak computational capability that will make it difficult to deal with uncertainty in a statistical manner.

3.4.4 Selecting the Appropriate Uncertainty Analysis Method

Different types of uncertainty analyses are useful at various stages of a decision-making process. For example, an uncertainty matrix would be the best tool in the identification step, and sensitivity analysis or error propagation could be used in the evaluation process. It is for this reason that this dissertation will employ three uncertainty analysis methods: uncertainty matrix, sensitivity analysis and scenario uncertainty.

An uncertainty matrix will be used in the preliminary stage to identify and characterise sources of uncertainty. This will be a purely qualitative assessment. It will provide decision makers with insight on the limitations of the spatial MCA model. The computational component of the uncertainty analysis will feature in the sensitivity analysis. In this process, the effect of weight changes through different themes will be examined by comparing the final results to the reference case where all weights are given the same importance. Finally, scenario uncertainty will be included to represent how results would change had various stakeholders been incorporated into the decision-making process.

Due to time and financial constraints, it is unfeasible to conduct stakeholder engagement. Stakeholder engagement would involve identifying and consolidating all relevant stakeholders, including transport authorities, protected population groups and taxi operators. As such, this could prove to be cumbersome. The integration of three approaches will provide a holistic overview of the uncertainties in the SMCA model used in this dissertation.

3.5 Résumé

The aim of Chapter 3 was to outline the two most common *ex ante* appraisal methods in transport: cost-benefit analysis and multi-criteria analysis. This chapter described the framework, analytical procedures, applications and shortcomings of both methods. It then proceeded to describe the appraisal tool used in RSA. Lastly, a section on uncertainty was deemed necessary as both methods are susceptible to uncertainty in many forms.

CBA, which is the most widely used tool, is a microeconomic framework which uses monetary values to express measured impacts as a total money amount. The CBA framework is based on achieving net social benefits. Benefits may be measured in terms of consumers' WTP, and costs may be measured in terms of opportunity costs. CBA uses EUAC, PWoC, NPV, BCR and IRR in its analytical procedures. CBA has been criticised for the methods adopted to convert soft variables, or non-quantifiable impacts into a currency. Additionally, the selection of a discount rate is often a contentious issue in CBA practices because markets are imperfect, especially with regards to public goods. Additionally, no single stable interest rate is applicable throughout the economy and over time.

MCA can be regarded as a tool for the appraisal of different alternatives, when several stakeholders' inputs and priorities are considered to produce a common output. What MCA has in its favour is the fact that it can be used with contradictory evaluation criteria, as opposed to CBA which cannot. MCA is also capable of adopting both qualitative and quantitative criteria into its evaluation procedure. MCA uses weights instead of currency for measuring the effects of impacts. Technique such as SMART, AHP and swing weights are common methods used for determining criteria weights. Despite so many methods for determining the weighting of criterion being available, this aspect of MCA remains one of the major weaknesses of MCA due to its subjectivity. Additional shortcomings of MCA include stakeholder bias and a tedious, time-consuming method. CBA and MCA share a common weakness in terms of incorporating spatial factors effectively. It can thus be concluded that MCA and CBA are unsuitable for PT route appraisal.

CBA's are commonly used in the United Kingdom, the Netherlands, and the United States. Japan uses an MCA supplemented by a CBA. In RSA, there is no standard appraisal method. Transport projects are selected according to their adherence to certain laws and statutes. The objectives depicted in the laws and statutes form what could be considered as evaluation criteria. No indication is provided as to how to achieve the objectives, or which objectives are more important.

Since decision-making is not an exact science and is subject to uncertainty, a comprehensive uncertainty analysis is required. Uncertainty may be defined as the occurrence of incomplete knowledge or information about a subject. This dissertation will make use of an uncertainty matrix, a sensitivity analysis and a scenario uncertainty analysis. An uncertainty matrix classifies uncertainties encountered at every level of investigation. A sensitivity analysis is used to determine the uncertainty in criteria weights. Finally, a scenario uncertainty analysis represents how results would change had various stakeholders been incorporated into the decision-making process. These three uncertainty analyses were chosen on the basis for being the most suitable for this research given various constraints. Additionally, these three uncertainty analyses will be able to provide a holistic view of all uncertainties and sensitivities at every stage of this SDSS, from conceptualisation to the results.

4 Spatial Multi-Criteria Analysis

As stated in Chapter 3, CBA and MCA are inappropriate tools for appraising PT routes due to their inadequate spatial component. Subsequently, SMCA has evolved as an appraisal tool that, *inter alia,* is capable of informing PT routes. This chapter pertains to the framework and fundamental approach of SMCA. Thereafter, examples of SMCA being used as an appraisal tool in transport are then provided. Lastly, criteria to be included in an SMCA are described.

4.1 Framework of SMCA

Spatial decision problems often involve a substantial set of alternatives and multiple, conflicting evaluation criteria. Such problems inevitably lead to an integration of GIS and MCA in the formulation of GIS-MCA or SMCA (Malczewski, 2006). Additionally, Spatial Cost-Benefit Analysis (SBCA) models exist too (de Moel, 2013; Weig, 2017). Nevertheless, SBCA is not as popular as SMCA as SMCA has a greater capability of incorporating spatial criteria.

What sets SMCA apart from MCA is that the alternatives of SMCA are geographically defined or have spatial consequences. The decision on one or more alternatives is made from a given set of appraisal criteria as determined by decision-makers. SMCA is thus dependant on two key considerations (Ascough II *et al*., 2002):

i) *The GIS component*: This includes data acquisition, data manipulation on a spatial platform, etc; and
ii) *The conventional MCA componen*t: Weighting of spatial criteria, Aggregation of spatial criteria and decision makers' preferences. The SMCA process can be diagrammatically summarised in a hierarchy (Figure 4-1):

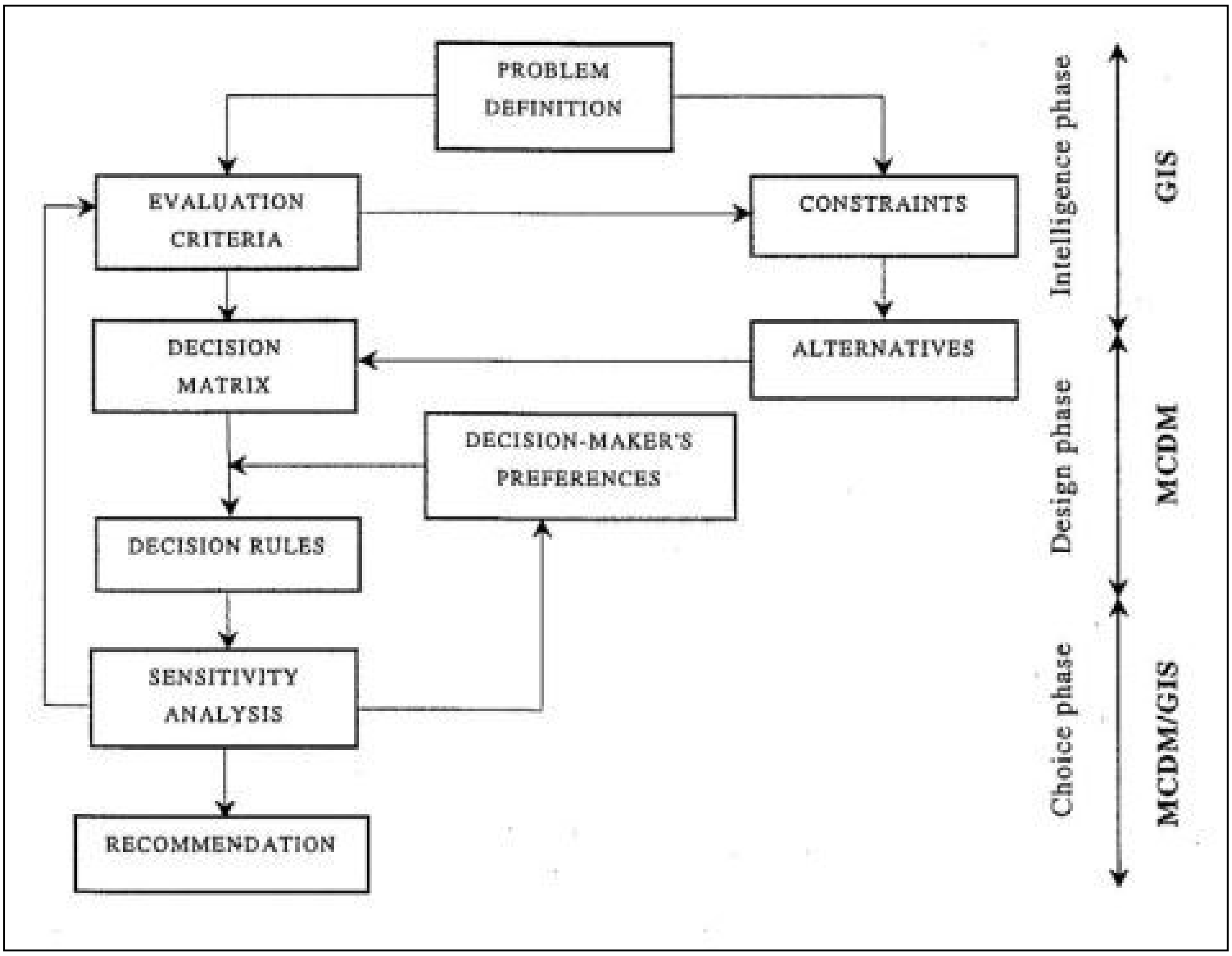


Figure 4-1: Hierarchy of SMCA Process
Source: Malczewski (2006)

The first hierarchy level, the intelligence phase, consists of data gathering and processing (Figure 4-1). The problem is defined, and evaluation criteria and constraints are formed according to spatial objectives. The decision matrix and alternatives overlap with both GIS and MCA constraints. This overlap is justified because while alternatives are geographical in nature, they are also nested in an MCA framework as more than one alternative exists. The second hierarchy comprises of standard MCA components, while the last tier is a combination of both GIS and MCA components.

Early works in SMCA by Kalogirou (2002), Chen *et al.* (2010), Chen *et al.* (2011) and Feizizadeh & Blaschke (2013) traditionally considered land suitability problems. The land suitability problems ranged from selecting land for agricultural production in Tabriz County, Iran (Feizizadeh & Blaschke, 2013), to finding a suitable location of land for a river catchment in Tamar Catchment, UK (Y. Chen *et al.*, 2010). SMCA has further been researched in the work of environmental planning (Diamond & Wright, 1988; Chiquetto & Mackett, 1995; Li, Brimicombe & Ralphs, 2000; Elbir *et al.*, 2010). Furthermore, SMCA has been used extensively as a decision support tool in traffic and transport applications, more of which will be discussed in section 4.3.

The variety of the applications of SMCA indicate the usefulness and versatility of SMCA as a SDSS.

4.2 Fundamental Approach to SMCA

The fundamental SMCA approach can be divided into the GIS approach and MCA approach.

4.2.1 GIS Approach

SMCA is different to conventional MCA due to the GIS components of SMCA. These components comprise of three parts (Malczewski, 2006):

i) Raster- and vector- based data;
ii) Explicit and implicit spatial criteria; and
iii) Explicitly and implicitly spatial alternatives.

Raster- and Vector-Based Data

SMCA is reliant on spatial data stored in maps. The maps can either be in raster format or vector format. Raster data files make use of a grid-cell data structure (Figure 4-2). With this structure, the geographic area under consideration is divided into equal cells which are identified by row and column (Buckey, 1997a; QGIS, 2014a). A specific geographical region is contained in each grid cell or pixel (QGIS, 2014a). The value of a pixel depicts one feature such as height or density (Buckey, 1997a; QGIS, 2014a).

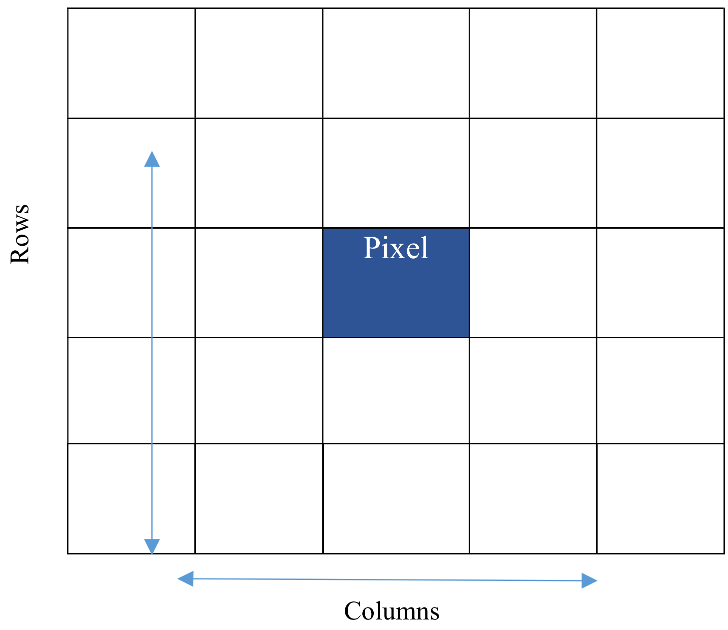


Figure 4-2: Depiction of a Raster Dataset

Adapted from QGIS (2014a)

Vector data makes use of vectors that contain x-, y- and sometimes z-coordinates to represent features (Buckey, 1997b; QGIS, 2014b). Vector data is stored in attributes that describe vector features using text or numerical information (QGIS, 2014b). Through attributes, vector data can thus store information on more than one feature as opposed to raster data, which can only store information on one feature. Vectors are made from vertices which can form points, or join to form polylines or polygons (Figure 4-3):

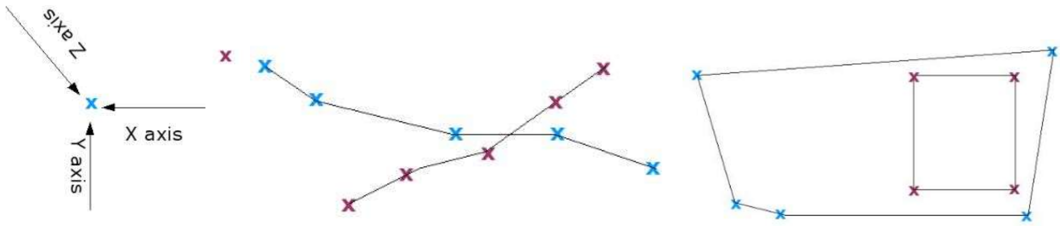


Figure 4-3: Point, Polyline and Polygon Vectors
Source: QGIS (2014b)

Raster maps are often used in SMCA because their continuous nature and one-attribute storage make them suitable for mathematical modelling and other quantitative analysis functions. Multiple raster maps are combined in an additive or multiplicative function to make one composite suitability map. A composite suitability map is an output raster map that is the weighted combination of input criteria maps. Each pixel in the composite suitability map corresponds to the suitability scores of the corresponding pixels in the input maps. Consequently, a higher pixel score in a composite suitability map pertains to a higher degree of suitability, and *vice versa* (Khalil, 2012). Vectors are unable to make composite suitability maps, and resultantly, must be converted to rasters when used in an SMCA.

Explicit and Implicit Spatial Criteria

Explicit criteria are criteria that are fundamentally spatial (Malczewski, 2006). The most common explicit spatial criteria are location, proximity and direction criteria (Rinner & Heppleston, 2006). One example of a location criteria is the density of roads located in a desirable city. The roads would be represented by polylines, and polygons would represent desirable or undesirable locations.

Proximity to desirable facilities is usually depicted as benefit criteria, and proximity to undesirable facilities as cost criteria. Accordingly, proximity values must be standardised through a linear or non-linear standardisation function (see 4.2.2). Direction criteria are incorporated when one location affects the other, and this effect is based on direction. For example, houses located close to an airport may be affected by noise pollution, depending on typical take-off and landing directions (Rinner & Heppleston, 2006).

Implicit spatial criteria use geographic features to extract information that is spatially representative of those criteria (Ceretta, Panaro & Poli, 2016). Examples of implicit spatial criteria include ecological integrity indices, cost of disposing solid waste and equitable income distribution (Malczewski, 2006; Ceretta *et al*., 2016). Implicit and explicit spatial criteria need not be evaluated in separate SMCAs, as they are not mutually exclusive. SMCA decision software are often capable of incorporating both explicit and implicit spatial criteria.

Explicit and Implicit Spatial Alternatives

The definition of explicit and implicit spatial alternatives follows that of explicit and implicit spatial criteria. Explicit alternatives are alternatives which are spatial in nature, e.g. site locations, land suitability, routing problems. Implicit alternatives are not spatial in nature. Instead, their implementation has spatial implications (Malczewski & Rinner, 2015). In contrast to explicit and implicit spatial criteria, explicit and implicit spatial alternatives are mutually exclusive; alternatives in a SDSS may either be spatially implicit or explicit.

4.2.2 MCA Approach

Following the selection and processing of vector and raster data and determination of explicit and implicit spatial alternatives, SMCAs take on a traditional MCA approach. The explicit and implicit spatial criteria must be standardised, weighted and aggregated using traditional MCA methods.

Standardisation

Standardisation involves translating all criteria input values to a common scale, usually between 0 and 1[1]. There are many linear and non-linear standardisation techniques available. The most common standardisation tool is the linear transformation, also known as maximum. Equation 4 and Equation 5 outline the mathematical procedure involved in standardising criteria according to the linear standardisation method.

For a benefit:

$$s_i = \frac{v_i}{v_{max}}, i = 1, \ldots, m$$

……….Equation 4

For a cost:

$$s_i = 1 - \frac{v_i}{v_{max}} + \frac{v_{min}}{v_{max}}, i = 1, \ldots, m$$

……….Equation 5

Where:

s_i = Standardisation value of criterion *i;*
v_i = Value of criterion *i;*
v_{max} = Maximum criteria value;
v_{min} = Minimum criteria value; and
m = Number of criteria.

Adapted from ILWIS (2010a)

[1] Scales of 0-1 are common in decision-making problems due to their simplicity. A scale of 0-100 is also acceptable.

Weighting

Following standardisation, weights must be applied to criteria. The MCA weighting methods outlined in Chapter 3 are applicable methods for applying weights to spatial criteria. If weights are assigned directly, the weights must be normalised (Beukes, 2011) (Equation 6):

$$W_i = \frac{w_i}{\sum_1^m w_i}, 1, \dots, m$$

………Equation 6

Where:

W_i = Normalised weight of criterion *i;* and

w_i = Applied weight of criterion *i.*

Aggregation

Finally, weighted criteria must be aggregated to find the value of every alternative. The aggregation process creates one composite suitability map. Using the results obtained from Equation 3 to Equation 6, scores for alternatives are computed (Beukes, 2011) (Equation 7):

$$A_i = \sum_{i=1}^{m} W_i \cdot s_i, i = 1, \dots, m$$

………Equation 7

This dissertation will follow the procedures outlined in section 4.2. A mix of vector and raster data will be used to form evaluation criteria. Some criteria are spatially explicit, while others are spatially implicit. As this dissertation is a transport routing problem, all alternatives will be spatially explicit.

4.3 SMCA in Transport

The literature documents several instances where SMCA has been used in transport. Section 4.3 examples where SMCA has been in transport policy formulation, bicycle facility planning, road safety and transport routing.

Arampatzis *et al.* (2004) presented a computer-integrated evaluation tool for the appraisal of transport policies. The objective of the SDSS tool was to realistically model the Greater Athens multimodal transport network and assist transport planners in developing policies that enhance the efficiency of transport supply. Criteria on efficiency included improving energy and environmental side effects. The two policy alternatives involved prohibiting half the private cars from entering the region or reducing 50% of the parking spots in the region. These alternatives are spatially implicit, as are the evaluation criteria. The GIS component of the tool was used mostly as a data repository and user interface.

SMCA has been used in the appraisal of bicycle facility planning in the city of Wisconsin, USA. Traditional bicycle facility analysis practices either engrossed the supply side or demand side, but not both. Recognising that this placed a severe limitation on sustainable multi-modal transport planning, Rybarczyk and Wu (2010) developed a SDSS tool that integrates both demand- and supply-based criteria. The tool used the criteria to develop a bicycle facility planning method using GIS, MCA and exploratory spatial data analysis (ESDA). The GIS and ESDA component were used to explore the spatial patterns of bicycle facilities, and potentially suggest new patterns.

In the field of road safety, Fuller *et al.* (2003) used a raster-based SMCA to determine risk along several road segments within the Hoppi Reservation, Arizona. In their research, risk was defined as the likelihood of a crash occurring. The criteria used to determine risk included proximity to intersections, gradient of the land, curvature of the road and proximity to washes. A linear weighted function was used as the weighting scheme, which allowed weights to be adjusted incrementally in steps of 0.05 and 0.10. A sensitivity analysis was conducted on the weights, where both the weights and the weighting method for each criterion were varied. This research did not present alternatives as it was a location problem; the objective was to locate areas of high risk so that transport planners may provide interventions to mitigate risk. Location decision problems occasionally do not contain alternatives; but instead, produce alternatives. This is the nature of this dissertation.

4.3.1 SMCA in Transport Routing Problems

For the last few decades, GIS and land suitability mapping methods have been used to assist transport planners in route selection problems (Jankowski & Richard, 1994). Planning a road network or transport route in GIS is advantageous as it allows one to take the impedance of each segment of a route into account. Impedance is defined to be a measure of the cost or resistance that a road user experiences as they traverse through a specific road segment. The higher the impedance, the greater the resistance to movement (Niaraki & Kim, 2009; Kamruzzaman *et al*., 2011). Impedance models are thus required in addition to GIS analysis when performing a spatial *ex ante* appraisal for a network analysis or route determination. Normally, road segment impedance is determined as a one-dimensional variable such as distance, speed or traffic (Niaraki & Kim, 2009). In order to personalise these models to include desired criteria, planners have attempted to integrate multi-dimensional factors using SMCA (Kamruzzaman *et al*., 2011). Keshkamat, Looijen and Zuidgeest (2009) make use of a line-raster extraction impedance algorithm. The algorithm extracts the suitability scores (determined from the composite suitability map) beneath each road segment, and inverts the scores to form a segment impedance (Kamruzzaman *et al*., 2011) (Equation 8):

$$LMW = \frac{\sum_{i=1}^{n}(l_i * v_i)}{L}$$

………Equation 8

Where:

LMW = line weighted mean suitability score;
l_i = length of line segment i covering a certain raster cell;
v_i = suitability value of the raster cell underlying that line segment; and
L = Total length of the road segment of which the line segment forms part.

Keshkamat (2007) used the procedure outlined to suggest an optimal route to link Warsaw to the Lithuanian border in the Via Baltica region of Poland. An alternative route was required as the government-proposed route had detrimental environmental impacts that were deemed unacceptable by authorities. A stakeholder engagement allowed Keshkamat to compute four different policy routes based on stakeholder weights. Keshkamat's SMCA was conducted on a program called ILWIS, which this dissertation also makes use of due to its powerful SMCA component.

The literature provides a further example in SMCA-based route selection through Atkinson *et al*. (2005). In response to critiques that previous route selection methods were too subjective, the authors proposed a GIS-based DSS for determining a least-cost-path (LCP) for an all-weather route that incorporates MCA. LCP is synonymous with impedance. Evaluation criteria were adopted from environmental considerations, engineering literature and available spatial data. Criteria weights were obtained using Saaty's pair-wise comparison method.

Spatial multi-criteria analyses are susceptible to spatial uncertainties. Measurement and taxonomic errors are inherent to spatial data. Furthermore, selection of weights is also an issue with SMCA as it is with MCA due to subjectivity. Although sensitivity analyses have been developed for SMCA's, the most critical shortcoming of the procedures is the lack of insight they provide into the spatial aspects of weight sensitivity (Feick & Hall, 2004). There thus exists a need and potential research opportunity for developing robust spatial sensitivity analysis methods for SMCAs.

4.4 Selecting Suitable Criteria for an SMCA

The criteria selected to inform decisions about various possible BRT route locations form the core of this research and thus play a pivotal role in the results. Accordingly, the criteria to feature in an SMCA should not be arbitrarily selected, as this will affect the validity of the results. The selected evaluation criteria are derived from common public transport objectives internationally and nationally. The common objectives of public transportation are summarised below (HDR Alaska, 2002; Litman, 2017):

- To provide equal transport opportunities to all users, especially captive users, thus ensuring an equitable society;
- Environmental protection by reducing transport-based CO_2 emissions;

- Improving health, safety and security through reducing the risk of injury, illness and death resulting from detrimental transportation modes;
- Improving the quality of life for both transport users and non-users through a safer, healthier environment; and
- Maximising the economic activity of a country.

In the National Land Transport Strategic Framework (NLTSF) the Department of Transport's goal is to create "an integrated and efficient transport system supporting a thriving economy that promotes sustainable economic growth, supports a healthier life style, provides safe and accessible mobility options, socially includes all communities and preserves the environment" (DoT, 2017: 133). Additionally, the NLTSF states that transport systems in South Africa must be sustainable. In order to achieve sustainability, transport systems must encompass four pillars (DoT, 2017):

- Environment;
- Society;
- Culture; and
- Economy.

With international and national transport goals described, this research can be contextualised further by outlining local transport goals. In their Comprehensive Integrated Transport Plan, the CoT stated that their transport vision is to provide a transport system that is "developed to support a sustainable city" (CoT, 2015b: 6). Furthermore, their transport mission is to "develop a transport system that positions the Capital City to meet the economic and social needs of its citizens" (CoT, 2015b: 6). To meet their vision and mission, the CoT has outlined the following goals:

- "Plan and develop a transport system that improves accessibility and mobility whilst enhancing social inclusion;
- Provide a fully integrated public transport system;
- Develop a transport system that drives economic development;
- Improve the safety and security of the transport system;
- Develop a transport system that reflects the image of the city;
- Develop an efficient, effective, development oriented public transport system that integrates land use and public transport plans;
- Develop a transport system that is environmentally sustainable". (CoT, 2015b: 6).

From the common transport objectives, national transport goal and the CoTs objectives, common, overarching themes for PT systems can be inferred: environmental protection, public health improvement, equitable transport opportunities, and safe and secure transport options. As such, five criteria themes were chosen that the author best believed would encompass national and local transport objectives, thereby adequately representing the context of the CoT. The five themes chosen as evaluation criteria are as described follows:

- *Transport efficiency*: the BRT trunk and feeder routes must be selected in such a way that mobility and accessibility are optimised;
- *Equity*: transport opportunities must be equitable; parts of the population that require PT as a necessity (mostly low-income individuals) must be prioritised first;
- *Economic impact*: public transportation systems should ideally enhance the economy through job creation and job accessibility. Furthermore, PT systems should not demand exorbitant implementation costs;
- *Environmental impact*: PT must decrease total transport-induced energy demand as well as preserve the surrounding environmental features; and
- *Social impact*: the chosen BRT routes should ideally follow social landmarks such as schools, recreational areas and places of worship so as to eliminate social exclusion.

It is worth mentioning that the common transport objectives, national transport goal and the CoTs objectives do not provide explicitly spatial goals and objectives. Instead, spatial implications can be extracted from these objectives. The criteria themes selected are both explicitly and implicitly spatial. Environmental and social impact criteria themes are explicitly spatial, while the remaining themes are implicitly spatial.

4.5 Résumé

The objectives of Chapter 4 were to outline the components of SMCA and highlight its uses in the field of transportation. The chapter started by describing the framework and fundamental approach to SMCA. Thereafter, suitable evaluation criteria to be included in an appraisal tool were provided. Finally, the criteria to be included in this dissertation were justified.

Spatial decision problems often involve a substantial set of alternatives and multiple, conflicting evaluation criteria. Such problems inevitably lead to an integration of GIS and MCA in the formulation of GIS-MCA or Spatial Multi-Criteria Analysis (SMCA). The fundamental SMCA approach can be divided into the GIS approach and MCA approach. The GIS approach comprises of three components: raster- and vector-based data, spatially implicit and explicit criteria, and spatially implicit and explicit alternatives. The traditional MCA approach comprises of standardising, weighting and aggregating the spatially implicit and explicit criteria.

The literature documents several instances where SMCA has been used in transport. Examples where SMCA has been in transport included policy formulation, bicycle facility planning, road safety and transport routing.

Section 4.3 described the process of using SMCA as a DSS for transport routing problems. Planning a road network or transport route in GIS is advantageous as it allows one to take the impedance of each segment of a route into account. Impedance is defined to be a measure of the cost or resistance obtained through traversing a specific road segment. This section is particularly important as it highlights the SMCA approach to be used in this research. The appraised BRT routes will be those that follow the path of least impedance.

The final section of Chapter 4 pertained to selecting suitable criteria to be used in an SMCA. There were 5 criteria groups derived from international and local literature: transport efficiency, equity, environmental impact, social impact and economic impact. The criteria groups were chosen as the author best believed the criteria would encompass national and local transport objectives, thereby adequately representing the context of the CoT.

5 The Context of CoT: A Description of the Study Area

To provide contextually sensitive BRT routes to the CoT, the context of this city must be defined. Included in the context definition are Tshwane demographics, roads and transport status, economic standing of the CoT, and the current environmental status. Understanding the context of the CoT is paramount in selecting contextual evaluation criteria and parameters.

5.1 Location of the Study Area

Located in Gauteng, the City of Tshwane is the administrative capital of South Africa. It is one of five municipalities in Gauteng Province. The CoT has coordinates of -25.11°N, 29.10°E, -26.08°S, and 27.89°W according to the Hartebeeshoek 1994 coordinate system (Figure 5-1):

Figure 5-1: CoT and Surrounding Metropolitans
Source: Municipalities of South Africa (2017b)

The CoT municipality, highlighted in blue (Figure 5-1), covers an area of 6 368 km^2 (Municipalities of South Africa, 2017a). The municipality is made up of 14 traffic analysis zones (TAZs) (Figure 5-2):

Figure 5-2: CoT Traffic Analysis Zones
Source: Author's own

TAZs are demarcated, contiguous, homogenous areas that represent trip origin and destination (O-D) points in transport modelling. TAZs are delineated according to socioeconomic and demographic information (You, Nedović-Budić & Kim, 1998). Of the 14 TAZs in the CoT, two TAZs are considered extremely rural and thus do not form part of the analysis: Nokeng tsa Taemane and Kungwini. The TAZs to the west of the orange border will feature in the analysis (Figure 5-2).

5.2 Demographics

Understanding the demographics of Tshwane allows planners to prioritise public transport modes and public transport routes for people that need PT, e.g. captive riders, disabled riders, vulnerable population groups etc. TAZs that are highly populous and low-earning should be prioritised with affordable PT.

5.2.1 Population

The last census conducted in 2011 indicated that the CoT had a population of 2 921 488, making it the fifth most populous city in RSA. In the ten years leading up to the census, the population grew at a rate of 3.1% p.a. The population density is 464 persons/km^2 (Stats SA, 2011b), which according to world standards, is very low. A low population density consequently results in longer PT-trip lengths (Lombard *et al.*, 2007). In comparison, Lagos has a density of 12 700 persons/km^2, Paris 3 800 persons/km^2 and Tokyo 4 300 persons/km^2 (Cox, 2012). As such, these are all cities with better PT systems and utilisations. When compared to other South African cities, the CoT has a relatively low population density too. The population density in Cape Town is 1 350 persons/km^2 (World Population Review, 2017a), and further North, Johannesburg has a population density of 2 900 persons/km^2 (World Population Review, 2017b). Despite Cape Town and Johannesburg having relatively higher densities than the CoT, PT quality in these cities is still lagging behind acceptable standards (Walters, 2014).

5.2.2 Income

A concerning 44.3% of individuals in the CoT do not earn any income. In addition, 10% earn below the poverty line, which is roughly R500 per month (Stats SA, 2011b; Nicolson, 2015). Furthermore, 60,7% of households earn 50% of the total Tshwane income (Figure 5-3):

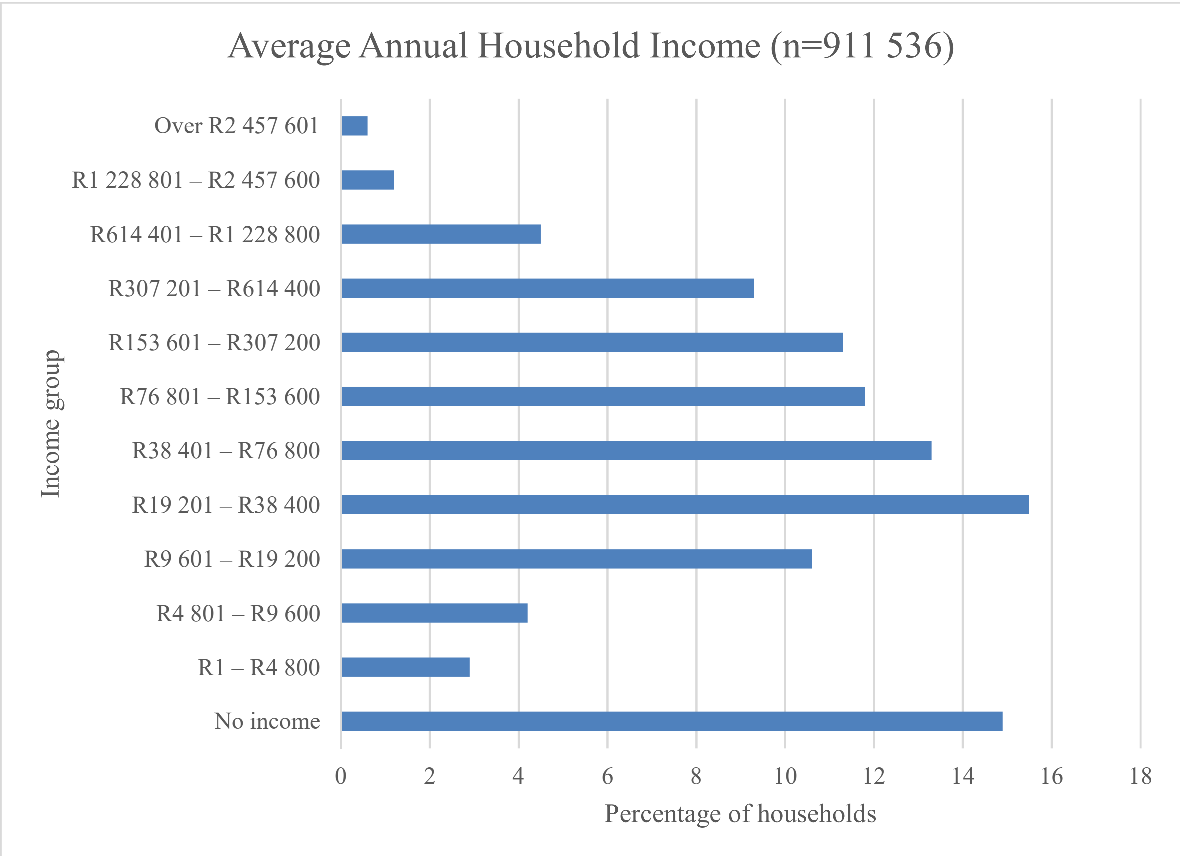


Figure 5-3: Average Household Income in the CoT
Source: Stats SA (2011b)

It can be concluded that the majority of the Tshwane population live in poverty or close to poverty. This fact emphasises the need for affordable, inclusive transport solutions that do not marginalise already marginalised population groups.

5.3 Roads and Transport

Being the national capital, the CoT has a well-established road network. Furthermore, only 23% of all trips made in the CoT are PT trips, which is below the DoTs 60% target (DoT, 2007b; Gauteng Provincial Government, 2016).

5.3.1 Roads and Road Status

The CoT follows an extensive road network hierarchy with 5 classes of roads (Table 5-1):

Table 5-1: Road Categories and Function

Road Category	Name	Function
Class 1	Primary distributor	Mobility
Class 2	Regional distributor	Mobility
Class 3	District distributor	Mobility and accessibility
Class 4	District collector	Accessibility
Class 5	Access road	Accessibility

Source: Gauteng Provincial Government (2012)

SANRAL is responsible for all national roads, and Tshwane Municipality is responsible for all municipal roads. Municipal roads consist of a few Class 2 roads, and all Class 3 to Class 5 roads. The CoT has 5 209 km of surfaced municipal roads and 2 231 km of gravel municipal roads (Table 5-2):

Table 5-2: Road Share in the CoT

Municipal Road	Type of Road	Share of Road (km)
Paved roads	Primary roads	937.6
	Secondary roads	667.2
	Tertiary roads	989.7
	Minor tertiary roads	2 552.4
Unpaved roads	Secondary roads	89.2
	Main tertiary roads	89.2
	Minor tertiary roads	2 052.5

Adapted from Gauteng Provincial Government (2012)

Approximately two thirds of surfaced municipal roads prioritise accessibility (Table 5-1 and Table 5-2). While this is beneficial to providing equal transport opportunities to all, it negatively impacts travel time. Unpaved roads are unsuitable for PT interventions as they require full upgrades, thus greatly increasing the cost.

5.3.2 Public Transport Status Quo

On average, 26% of all morning trips made in Gauteng are PT trips (Gauteng Provincial Government, 2016). Minibus taxis (MBT) are the most widely used mode of public transport throughout Tshwane. Approximately 20% of all education- and work-based public transport trips are made by bus (Figure 5-4):

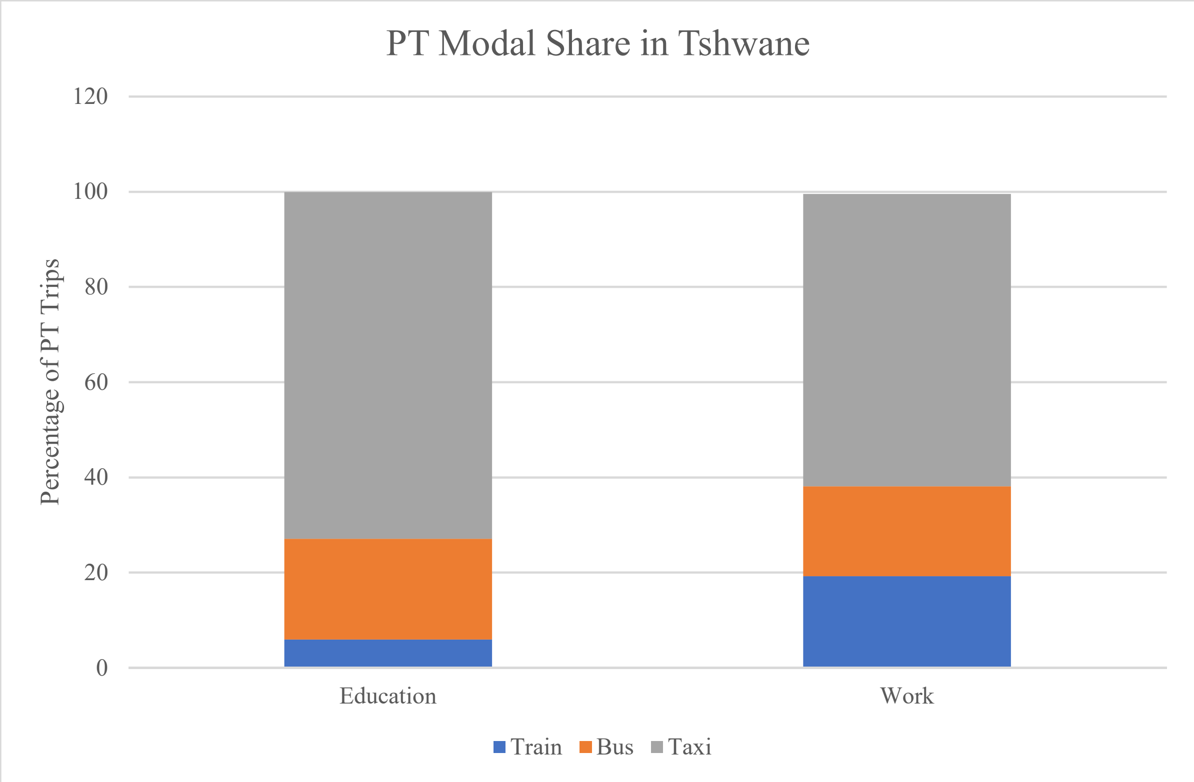


Figure 5-4: PT Modal Share for Education and Work Trips Made in Gauteng
Source: Stats SA (2014b)

There is great potential to develop PT in the CoT so that public transport trips increase in general, and bus trips in particular. PT should thus be prioritised and improved to obtain the 60% modal share target set out in the Transport Action Plan.

Rail services in the CoT comprise of Metrorail and Gautrain. There are three Gautrain stations in Tshwane: Hatfield, Centurion and Tshwane Central. A feasibility study conducted by Gautrain revealed plans of extending Gautrain to Mamelodi (Mbanjwa, 2016). The extension to Mamelodi will greatly improve the accessibility of the region.

The Public Utility Transport Corporation (PUTCO) has traditionally supplied scheduled bus services across Gauteng. However, in 2015, PUTCO announced plans to discontinue their services in Tshwane, among other Gauteng regions (Mrototo, 2015; Ndlovu, 2015). Interestingly, this announcement came a year after the implementation of A Re Yeng Phase I. PUTCO removing their services led to a greater passenger market that A Re Yeng could tap into. Tshwane Municipality also operates scheduled, subsidised bus services called the Tshwane Bus Service. However, a 2006 survey revealed that Tshwane Bus Services provided a poor quality of service.

Buses were often late or did not turn up at all, drivers would often deviate from assigned routes, drivers would skip bus stops, and drivers were rude and sometimes drove recklessly (Govender & Bateman, 2006). Tshwane Bus Services is still in operation, despite the implementation of A Re Yeng. Both bus services are owned by the CoT Municipality. In this regard is unclear as to how the two services do not compete with one another, or which bus service is given priority if applicable.

A Re Yeng Phase I was launched in December 2014 (CoT, 2016b). The first phase consisted of a 7 km trunk route with seven median stations that connected the CBD to Hatfield. Feeder routes connected Hatfield to Groenkloof, Pretoria West, and Steve Biko Hospital. A Re Yeng was initially met with opposition by the public, who raised congestion, safety and noise concerns. These concerns, however, stem from misinformation as PT often solves congestion, safety and noise problems. A further design concern was the preservation of heritage assets such as jacaranda trees, historical buildings and underground artefacts (Knopjes, 2016).

To support employment, local SMMEs were deployed for sub-contracting jobs for a minimum value of 25% of the works (Knopjes, 2016). In this regard, it can be deduced that some sort of context was considered in the planning process. What is not evident was if context was considered in a systematic manner.

5.4 Environment

Environmental factors should be considered when implementing a sustainable public transport solution, as construction tends to degrade the environment.

5.4.1 Critical Biodiversity Areas

Critical biodiversity areas cover 26% of the CoTs surface area (CoT, 2016a), and include the Tshwane Nature Reserve, the Apies River and Nootgedacht Dam (CoT, 2015d). Critical biodiversity areas may be represented by ecosystem protection levels which calculate the proportion of biodiversity targets met for each vegetation type that features in the area (CoT, 2016a) (Figure 5-5):

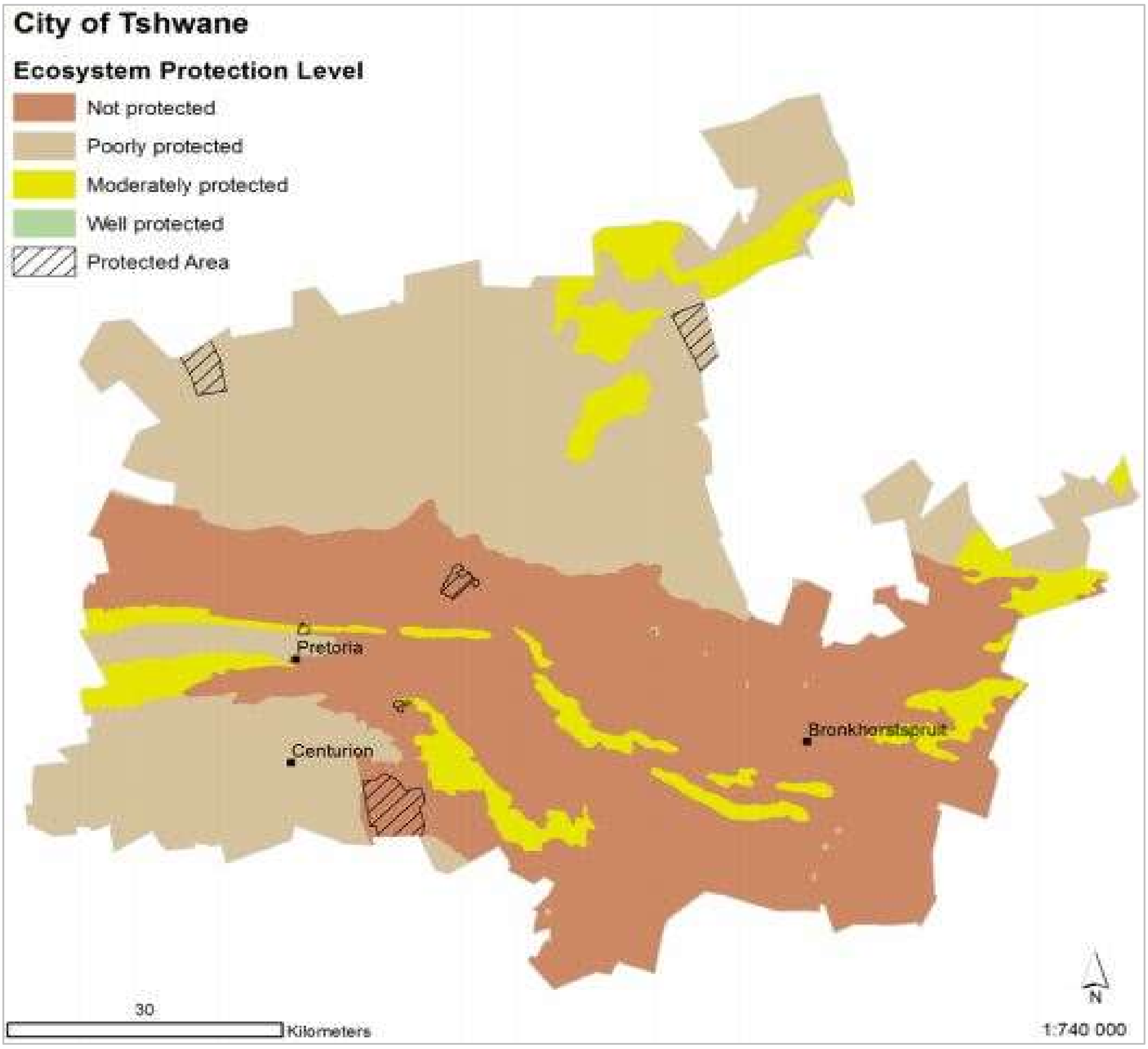


Figure 5-5: Map of Ecosystem Protection Level in the CoT
Source: CoT (2016a)

Most of the land area is either not protected or poorly protected (Figure 5-5). A key consideration is that some moderately protected areas fall within the city centre and urban areas, which may negatively impact construction as these areas should be avoided.

5.4.2 Ecologically Sensitive and Protected Areas

The CoT is located within the grasslands biome, which is one of seven biomes in RSA. A high proportion of rare and threatened species, as well as threatened ecosystems fall within this biome. At least 35 plant species, 15 animal species and 15 nationally listed ecosystems in the CoT are classified as threatened (CoT, 2016a). From this information, it is evident that the environment has a key role to play in transport planning and thus cannot be compromised.

5.4.3 Freshwater

The quality of the CoTs diverse rivers and wetlands is largely polluted by industrial and mining activity. Resultantly, 83% of wetland ecosystems and 58% of river ecosystems in the CoT are categorised as threatened (CoT, 2016a). The effects of compromised freshwater systems include a decrease in water quality, prominence of water borne diseases and a change in natural water flow regimes (Figure 5-6):

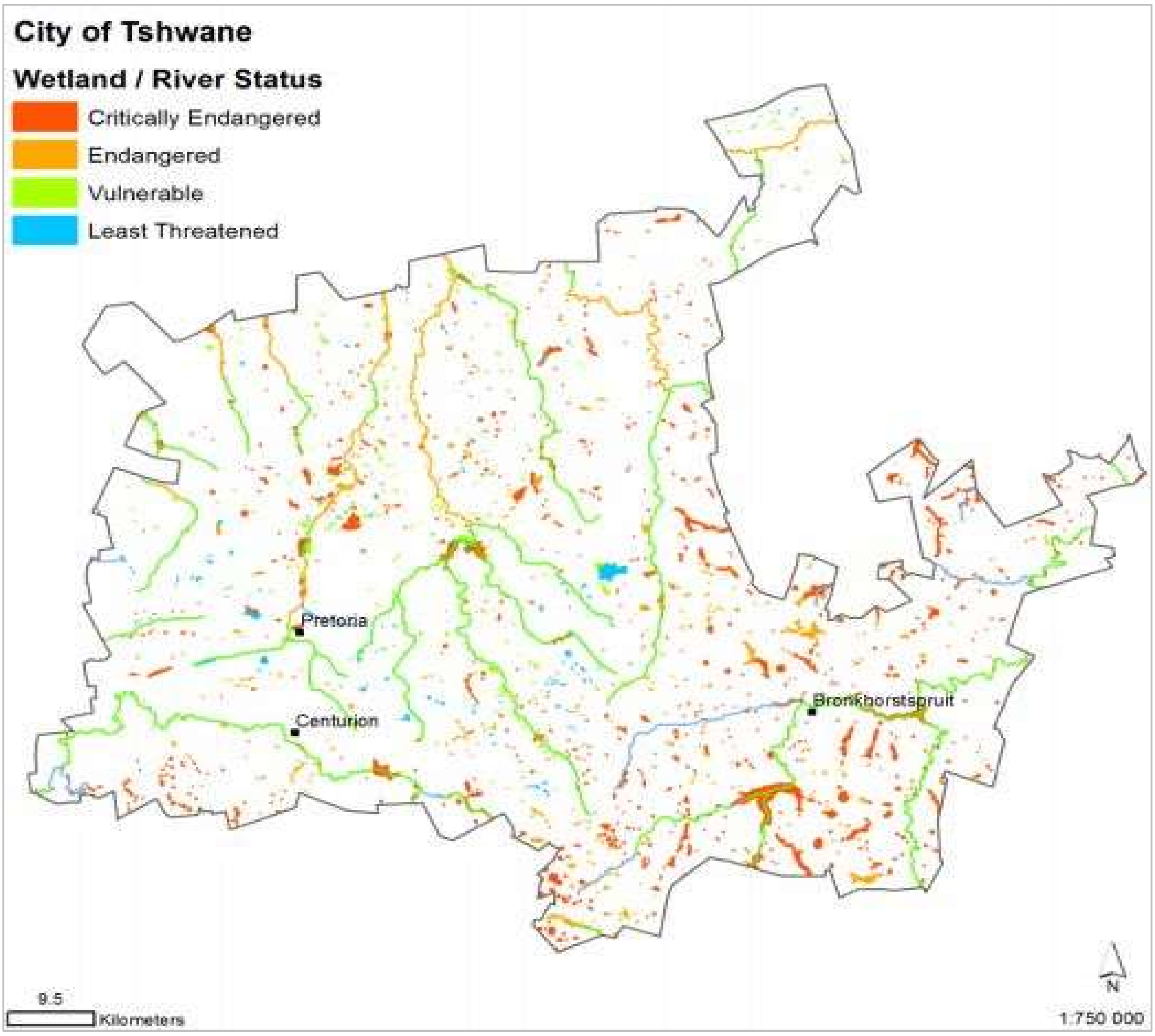


Figure 5-6: CoT Freshwater Status
Source: Baig (2012)

Vulnerable, endangered and critically endangered wetlands and rivers are widespread throughout the CoT (Figure 5-6). As a result, it would be difficult to plan BRT routes that avoid these rivers and wetlands completely. Therefore, construction methods adopted should ensure that the ecological integrity of vulnerable, endangered and critically endangered wetlands remains intact.

5.5 Economic Activity

Between 1997 and 2011, the CoT was the fastest growing economy in RSA (Stats SA, 2011b). Economic activity will be contextualised according to employment and gross value added.

5.5.1 Employment

At 24.2%, the CoT has an official unemployment rate slightly less than the national rate of 27.7% (Stats SA, 2011b). A high unemployment rate has affordability and economic viability implications on public transport. Those who are unemployed are least likely to own a car and consequently rely on NMT and PT to look for work. Additionally, 32% of the working population in the CoT rely on public transport to get to work (Stats SA, 2014b). It can be concluded that affordable public transport in the CoT plays an important economic and social role for both employed and unemployed citizens.

5.5.2 Gross Value Added

Gross Value Added (GVA) measures the monetary value of goods and services produced by a region or sector to an economy (Nayak, 2017). The CoT has a significant impact on both the provincial and national economy. In 2014, the CoT contributed 25% to Gauteng's economy, and 9% to the national economy. Furthermore, the CoTs economic output grew more than the national average at 4,0% p.a. between 2010 and 2014 (CoT, 2015a). The benefits of a good GVA include increased productivity and per capita earnings. A transport system should thus be designed to complement areas of high production to ensure these trends continue.

5.6 Résumé

The aim of Chapter 5 was to contextualise the study area with the goal of selecting the correct evaluation criteria and parameters. The CoT was contextualised in terms of demographics, roads and transport, the environment and economic activity. The CoT is located in Gauteng and forms one of five municipalities. Tshwane is the fifth most populous city in RSA. Its low population density of 464 persons/km^2 indicates that PT-trip lengths are at risk of being significantly longer than cities with higher densities, such as Lagos and even Johannesburg. In addition to having a low population density, most of the population of Tshwane live in poverty or close to poverty. This fact emphasises the need for affordable, inclusive transport solutions that do not marginalise already marginalised population groups.

The CoT has a well-developed road network. Approximately two thirds (4 209.3 km) of Tshwane roads prioritise accessibility as opposed to mobility. While this is beneficial to providing equal transport opportunities to all, it negatively impacts travel time. It can thus be concluded that implemented BRT routes should find an equitable balance of both accessibility and mobility roads.

Only about 26% of all morning trips made in Gauteng are made by PT. Incumbent PT services include Metrorail, Gautrain, MBTs and Tshwane Bus Services. There thus exists a need for integration across all modes of PT; BRT routes should not compete with existing PT routes. The extremely low service quality of Tshwane Bus Services justified the need for A Re Yeng. Among the complaints for Tshwane Bus Services were delays, reckless driving and rude drivers. Tshwane Bus Services and A Re Yeng are both municipal bus services. It is cumbersome for both services to exist simultaneously. Tshwane Bus Services should instead be dissolved into A Re Yeng.

The CoT has a number of sensitive environmental issues which have the potential to affect the construction of BRT routes. Critical biodiversity areas cover 26% of Tshwane's surface area. In addition, the CoT is located within the grasslands biome, within which a high proportion of rare and threatened species, as well as threatened ecosystems fall. Furthermore, 83% of wetland ecosystems and 58% of river ecosystems in the CoT are categorised as threatened. Construction methods adopted should thus ensure that the environmental integrity of the CoT remains uncompromised.

At 24.2%, the CoT has an official unemployment rate less than the national rate of 27.7%. Additionally, 32% of the working population in the CoT rely on public transport to get to work. It can be concluded that affordable public transport in the CoT plays an important economic and social role for both employed and unemployed citizens.

6 SMCA Route Optimisation on BRT Routes in Tshwane

Chapter 6 described the method of research followed in obtaining optimal BRT trunk and feeder routes for the CoT. This research makes use of SMCA and a vector-based network analysis to find low impedance routes. As outlined in Chapter 1, the method of research followed can be categorised into four stages: criteria selection and data acquisition, geo-spatial data handling, results and analysis.

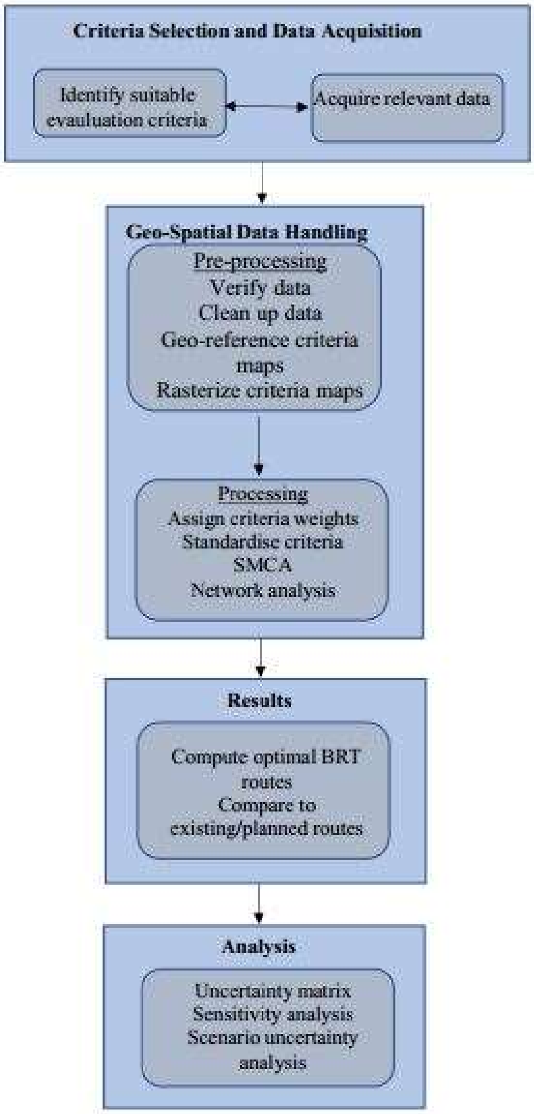


Figure 6-1: Flow Chart of Method of Research

6.1 Software Used

Various software was consulted throughout the research:

- *Microsoft Excel:* implicit spatial data was prepared through EXCEL, as this data was not available in GIS shapefiles.
- *ArcGIS 10.2:* explicit spatial data was prepared and processed in ArcGIS. Furthermore, the network analysis was also performed on ArcGIS;
- *ILWIS 3.31:* the SMCA component of this research was conducted in ILWIS, as ILWIS has a powerful SMCA function that is capable of many methods of weighting and standardisation; and
- *Geospatial Modelling Environment (GME):* GME was used to process the composite suitability maps so that they may be used in the network analysis.

6.2 Criteria Selection

Individual criteria were selected upon finalising the criteria themes described in section 4.4. The criteria were either classified as a spatial benefit, a spatial cost or a spatial constraint. A benefit is a criterion that has a positive contribution to the final output; the more of that criterion there is, the better the output. Contrastingly, a spatial cost is a criterion that has a negative contribution to the final output; the less of the criterion there is, the better the final output. A spatial constraint represents a criterion that signals areas that are completely unsuitable in the final output. Constraints will always get a pixel value of zero.

An array of criteria themes and different criterion for every criteria theme were identified. Each criterion is classified as either a spatial benefit, a spatial cost or a constraint. In addition, the selection of each criterion is justified (Table 6-1):

Table 6-1: Criteria Selected for SMCA

Criteria Theme	Criterion	Justification	Data Source
Equity	Household density	*Spatial benefit. L*ower income households tend to be located in high density residential areas. A greater portion of the population is thus served when BRT routes are located in high density areas.	CSIR
	Household income	*Spatial cost.* The 2013 Household Travel Survey showed that lower income groups have less access to private vehicles than higher income groups (Stats SA, 2014a). Lower income groups are thus more dependent on public transport and should be prioritised accordingly.	openAfrica
	Unemployment rate	*Spatial benefit.* Lack of transportation is often a hindrance to accessing work opportunities. A step in creating an equitable society would be to provide affordable, efficient public transport to areas that experience high unemployment. Furthermore, providing PT to high unemployment areas can increase the employment rate through job provision, i.e. BRT lane construction, station operators etc.	openAfrica
	Vulnerable road users	*Spatial benefit.* Vulnerable road users were categorised as people who were either the age of 5 or over the age of 65, as they are people who would most likely require assistance when using road-based PT.	2013 National Household Travel Survey (NHTS)
	Disabled users	*Spatial benefit.* Disabled users need to be prioritised as they are often marginalised from PT systems. Universal design in public transportation infrastructure is an important aspect of creating equitable societies.	2013 NHTS
Transport efficiency	Demand for bus services	*Spatial benefit.* The higher the current demand, the more efficient a BRT route would be, as fare recovery would be higher.	2013 NHTS
	Demand for BRT services	*Spatial benefit.* The higher the current demand, the more efficient a BRT route would be, as fare recovery would be higher.	2013 NHTS
	Proximity to existing PT stops and stations	*Spatial benefit.* In order to create an IRPTN, the proposed BRT routes should be located as close in proximity as possible to existing PT stops and stations.	MapCruzin
	Proximity to Metrorail	*Spatial benefit.* The closer the BRT routes are planned to Metrorail, the greater the chance of creating an IRPTN.	MapCruzin
	Proximity to Gautrain	*Spatial benefit.* The closer the BRT routes are planned to Gautrain, the greater the chance of creating an IRPTN.	MapCruzin
	Proximity to existing traffic infrastructure	*Spatial benefit.* Existing traffic infrastructure includes signalised and non-signalised intersections. These locations represent areas where traffic calming measures are already in place.	MapCruzin

Criteria theme	Criterion	Justification	Data source
Transport efficiency	Presence of suburban roads	*Spatial benefit.* Suburban roads represent a high level of accessibility, and as such, BRT routes should follow these routes to promote transport efficiency.	MapCruzin
	Presence of arterial roads	*Spatial cost.* Arterial roads represent a low level of accessibility.	MapCruzin
Environmental impact	Formally protected areas	*Spatial constraint.* Formally protected areas include fauna parks, game reserves etc. These areas represent significant ecological importance and should thus be disturbed as little as possible.	South African National Biodiversity Institute (SANBI)
	Biodiversity protection level	*Spatial cost.* This criterion has areas classified as either low, medium or high protection. The higher the protection level, the more the area should be preserved.	SANBI
	Fire risk	*Spatial cost.* This criterion is classified as either low, medium or high risk. BRT routes should avoid high fire risk areas due to potential damage that might be inflicted should there be a fire.	SANBI
	Distance from waterways	*Spatial cost.* BRT routes should be located away from natural waterways to preserve water quality.	SANBI
Social impact	Proximity to schools	*Spatial benefit.* The greater the access to schools, the lesser the degree of social exclusion.	MapCruzin
	Proximity to places of worship	*Spatial benefit.* The greater the access to places of worship, the lesser the degree of social exclusion.	MapCruzin
Economic impact	Gross value added	*Spatial benefit.* Economic impact is optimised when BRT routes follow areas of high production.	CSIR
	Employment rate	*Spatial benefit.* Productivity in an economy can be optimised if more work trips are made by PT and not private vehicles.	openAfrica
	Demand for BRT services	*Spatial cost.* The lower the demand, the more money subsidies will be required.	2013 NHTS
	Demand for bus services	*Spatial cost.* The lower the demand, the greater the amount of subsidies required.	2013 NHTS
	Residential roads	*Spatial cost.* Residential roads represent low category roads and as such have low bearing capacity. These roads will require upgrading and constant maintenance if they are to support loads from BRTs.	MapCruzin
	Arterial roads	*Spatial benefit.* Arterial roads are high category roads with high bearing capacity. Money will be saved as these roads do not require reconstruction to increase the bearing capacity.	MapCruzin
	Proximity to existing traffic infrastructure	*Spatial cost.* Signalised and non-signalised intersections may need to be upgraded to accommodate BRT lanes.	MapCruzin

The criteria depicted in Table 6-1 are a function of the literature, as well as a function on the available data. There is no limitation as to how many criteria can be included in an SMCA. The more criteria included, the more comprehensive the analysis is. The criteria in Table 6-1 thus represent data that was found to have shapefiles for ArcGIS analysis, or data in which spatial features could be extracted.

Some criteria which formed part of the initial criteria list, such as crime hotspots and road accident zones, had to be omitted from the final criteria list. BRT routes and stations near crime hotspots have a potential role to play in the alleviation of crime. However, the data on crime incident reports was too disaggregate and generic; it displayed how many crimes were reported to specific stations. To be able to include crime data in the SMCA, the geographic locations of crimes is preferred to stations where crimes were reported. This type of data requires as much disaggregation as possible for it to be an accurate determinant in a routing analysis problem.

6.3 Pre-Processing of Spatial Data

Pre-processing was required to verify the spatial data obtained in GIS shapefile format. The GIS shapefiles were obtained in three different formats: continuous, discreet and line data. Continuous data comprised of polygon shapefiles. Discreet data comprised of point data that represented the locations of objects such as schools or bus stops. Line data consisted of roads, railway lines and waterways. As such, pre-processing was required to ensure all data obtained formed a continuous surface in the form of a polygon (see 6.3.2), so that a continuous composite suitability map could be created.

6.3.1 Data Verification

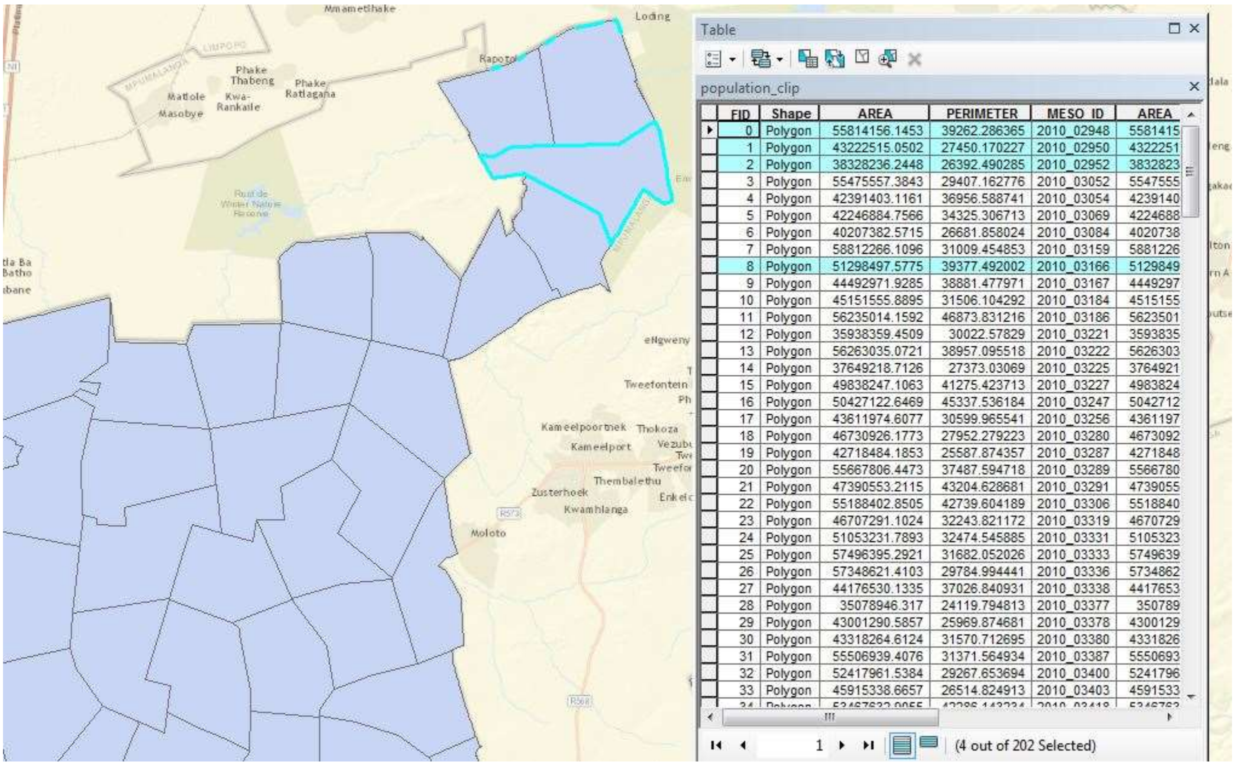
Open source data was used in this research. Although most data was sourced from credible sources such as SANBI and CSIR, verification was still necessary in order to eliminate faulty shapefiles. Demographic data was verified by adding up the population of the enumeration areas and cross-referencing that total with the total Tshwane population quoted in the 2011 household census. The data obtained from the NHTS did not need to be verified as it was obtained directly from the source. To verify other spatial data, the data in question was overlaid onto street maps or earth maps. This ensured that the locations of schools, railway lines, arterial roads etc. could be verified.

6.3.2 Preparation of Continuous Data

Most of the polygon shapefiles obtained included data for the entire surface of South Africa. Processing data at this level would not only be time consuming, but could also lead to aggregation errors. In this regard, a Tshwane TAZ shapefile was thus used as a mask polygon for the geographical extent of the CoT. Any polygon that fell outside of the borders of the study area was thus trimmed to the mask polygon shape using the “clip” tool in ArcGIS. The TAZ shapefile originally contained the name, identification number and coordinates of each TAZ within the CoT.

Household Density

The household density shapefile was obtained at a national level. Data for this shapefile was stored in small polygons that depict Small Enumeration Areas (SEAs). The clip tool was used to remove polygons that fell outside of the CoT borders. A shortcoming of the clip tool is that it includes polygons that do not fall entirely within the borders of the mask polygon. Any part of a line of a polygon that touches the borders of the mask polygon will result in the whole polygon's data being included in the clipped polygon. This is highly inaccurate as it conveys false information. Resultantly, each polygon within the newly clipped polygon was further scrutinised, and polygons that were incomplete were discarded (Figure 6-2):



FID	Shape	AREA	PERIMETER	MESO_ID	AREA
0	Polygon	55814156.1453	39262.286365	2010_02948	5581415
1	Polygon	43222515.0502	27450.170227	2010_02950	4322251
2	Polygon	38328236.2448	26392.490285	2010_02952	3832823
3	Polygon	55475557.3843	29407.162776	2010_03052	5547555
4	Polygon	42391403.1161	36956.588741	2010_03054	4239140
5	Polygon	42246884.7566	34325.306713	2010_03069	4224688
6	Polygon	40207382.5715	26681.858024	2010_03084	4020738
7	Polygon	58812266.1096	31009.454853	2010_03159	5881226
8	Polygon	51298497.5775	39377.492002	2010_03166	5129849
9	Polygon	44492971.9285	38881.477971	2010_03167	4449297
10	Polygon	45151555.8895	31506.104292	2010_03184	4515155
11	Polygon	56235014.1592	46873.831216	2010_03186	5623501
12	Polygon	35938359.4509	30022.57829	2010_03221	3593835
13	Polygon	56263035.0721	38957.095518	2010_03222	5626303
14	Polygon	37649218.7126	27373.03069	2010_03225	3764921
15	Polygon	49838247.1063	41275.423713	2010_03227	4983824
16	Polygon	50427122.6469	45337.536184	2010_03247	5042712
17	Polygon	43611974.6077	30599.965541	2010_03256	4361197
18	Polygon	46730926.1773	27952.279223	2010_03280	4673092
19	Polygon	42718484.1853	25587.874357	2010_03287	4271848
20	Polygon	55667806.4473	37487.594718	2010_03289	5566780
21	Polygon	47390553.2115	43204.628681	2010_03291	4739055
22	Polygon	55188402.8505	42739.604189	2010_03306	5518840
23	Polygon	46707291.1024	32243.821172	2010_03319	4670729
24	Polygon	51053231.7893	32474.545885	2010_03331	5105323
25	Polygon	57496395.2921	31682.052026	2010_03333	5749639
26	Polygon	57348621.4103	29784.994441	2010_03336	5734862
27	Polygon	44176530.1335	37026.840931	2010_03338	4417653
28	Polygon	35078946.317	24119.794813	2010_03377	350789
29	Polygon	43001290.5857	25969.874681	2010_03378	4300129
30	Polygon	43318264.6124	31570.712695	2010_03380	4331826
31	Polygon	55506939.4076	31371.564934	2010_03387	5550693
32	Polygon	52417961.5384	29267.653694	2010_03400	5241796
33	Polygon	45915338.6657	26514.824913	2010_03403	4591533

Figure 6-2: Example of Inaccuracy of Clip Tool

The purple area represents the SEAs that make up the extent of the CoT (Figure 6-2). The table to the right of the study area is called the Attribute Table. In the column titled FID, numbered items 0-2 are line items that have been included in the clipped polygon, despite being incomplete polygons. Such items had to be deleted. In contrast, numbered item 8, also highlighted, is a completely contained polygon, all of which were contained in the analysis.

To verify that no data was omitted, the attribute table was exported to EXCEL. The total number of households was summed, and this was cross referenced to the total number of households in the CoT as quoted in the 2011 census conducted by StatsSA. The number of households in the attribute table matched the total number of households in the census.

Household Income

Household income data was processed in the same manner as household density. The data originates from a household census shapefile.

Employment and Unemployment Rate

A population shapefile obtained from openAfrica contained demographic data that included populations of different races, level of education achieved and employment status. The employment status included the total number of people employed, unemployed and discouraged workers. The employment rate is a better indication of employment than an absolute figure, and was calculated by dividing the number of employed people by the labour force (Equation 9):

$$Employment\ rate = \left(\frac{E}{E+U}\right) * 100$$

……….Equation 9

Where:

E= Number of people employed; and
U=Number of people unemployed;

The unemployment rate was obtained simply by subtracting the employment rate from 100. This data was also obtained at a national level and consequently had to be clipped to the borders of the CoT.

Vulnerable Road Users and Disabled Users

Microsoft Excel was used to derive this data from the population file of the NHTS. This information was available at a TAZ level, and the total number of vulnerable road users and disabled users was merely aggregated. It was observed that the total number is too absolute, which consequently conveys distorted information. Relative comparisons were made across TAZ levels by dividing the number of vulnerable road users and disabled users by the total population of the TAZ. The results were translated to GIS by adding columns to the attribute table of the CoT TAZ shapefile and adding the results of each TAZ to the corresponding row.

Demand for Bus and BRT Services

The demand for bus and BRT services was obtained from the household file of the NHTS and was also available at a TAZ level. Absolute figures were used for this data, as passengers per day are always quoted in absolute figures. As with vulnerable road users and disabled road users, the data was transferred from EXCEL to ArcGIS by editing the attribute table of the CoT TAZ shapefile.

Formally Protected Areas

This data was available at a national level and consequently had to be clipped to the boundaries of the study area. The polygons in this shapefile were disaggregated; the polygons did not form a continuous surface. As ILWIS requires a continuous surface, the data had to be merged with the TAZ shapefile. This was achieved using the “Merge” function of ArcGIS. In order for the

SMCA to extract the correct data from the new polygon, the attribute table had to be amended again. This was done in ILWIS, as it allowed a "True/False" function to be used. This function was used as the criteria is a constraint, and polygons that contain either a True or the False value can be blocked while the other value is allowed to pass. All formally protected areas were assigned the True value. True values were subsequently blocked. The remainder of the polygon, which was the TAZ polygon, was assigned the False value.

Biodiversity Protection Level

This data was found to be at an aggregated, national level. Some of the polygons were discarded as they were found not to be completely enclosed within the study area boundaries. Other polygons were discarded because they were situated in other provinces. This is a limitation on the ArcGIS tool. Post clipping, the data was imported into ILWIS, where the attribute table was further amended. The data contained three protection levels: poorly protected, moderately protected and highly protected. A column was added in the attribute table in which polygons were ranked to an ordinal scale with values of 1,2 or 3[2] for poorly, moderately and highly protected respectively.

Fire risk area

This shapefile followed the same processing as biodiversity protection level. The polygons were classified as either low-risk, moderate-risk or high-risk areas. A ranking scheme of 1-3 was applied respectively.

Accordingly, all polygons were uploaded into ILWIS where they were geo-referenced and rasterised according to the relevant attributes in the attribute tables.

6.3.3 Preparation of Discreet Data

Due to a lack of surface continuity, discreet data proved to be slightly more complicated and more tedious to process than continuous data. With this data type, the distance from the points was the basis of the evaluation. Various ArcGIS tools such as Euclidean Distance, multiple ring buffers and Krigging were experimented with to represent the distance to these points. All were found to be inaccurate. Service Areas, which is a Network Analyst tool, was deemed to be the most appropriate tool. As this is a routing problem, service areas are the most accurate tool as service areas determine parts along a road network that are a specified distance from a point of interest. Multi-ring buffers and Euclidean Distance do not incorporate road networks into their analysis. The resulting distance barriers are depicted by polygons (Figure 6-3):

[2] Any numbers could have been chosen, as long as an ordinal ranking scheme was formed. The numbers 1,2, and 3 were chosen for simplicity.

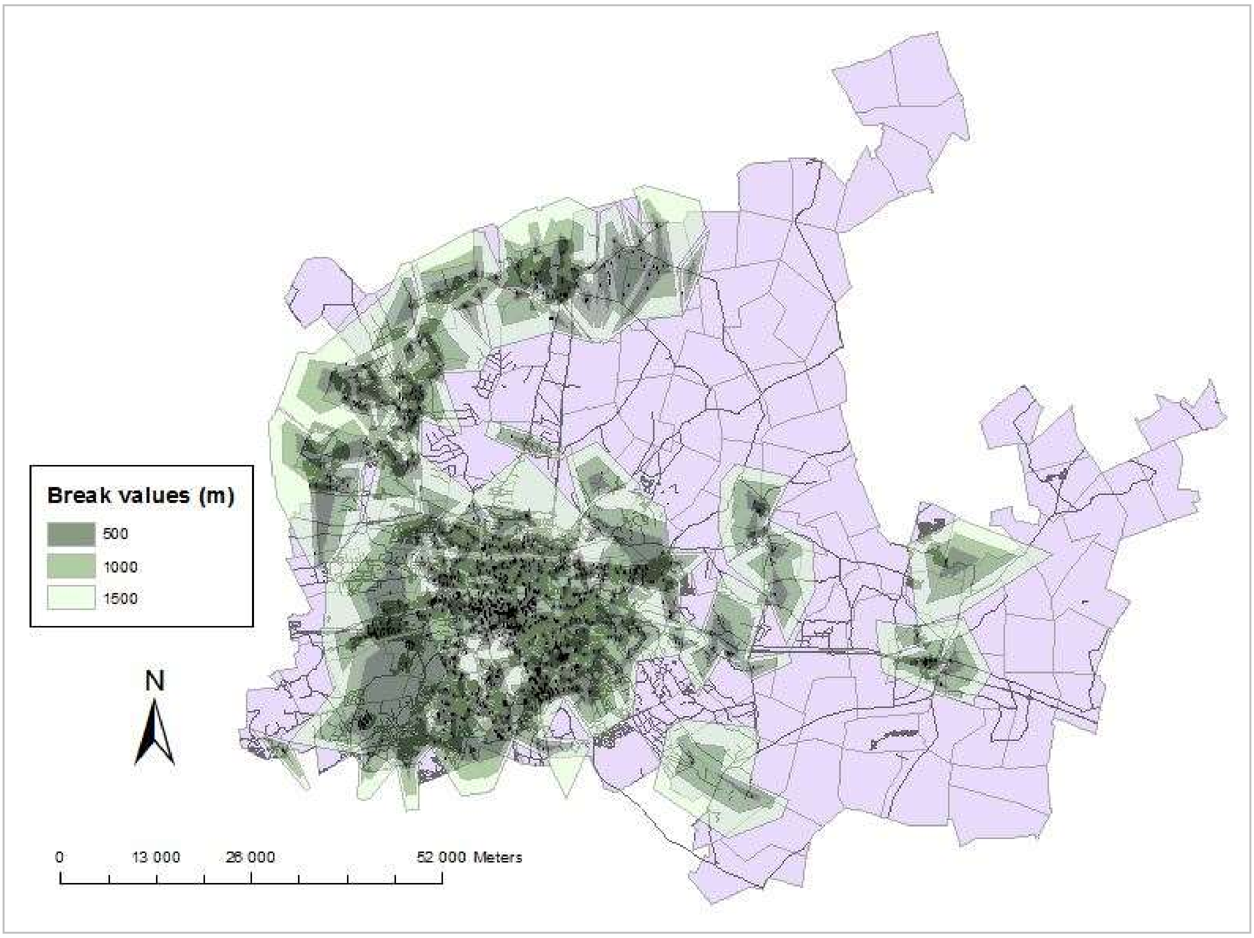


Figure 6-3: Service Area of Schools

The polygons formed from the service areas do not cover the entire study area as the distances are fixed up to a distance of 1500 m, which is small in comparison to the study area (Figure 6-3). Once again, the Merge tool was used to create a full, continuous surface. In ILWIS, the attribute tables were all amended by inserting a ranking column. The closest distances were ranked the highest (which is a rank of one). Polygons that fell outside of the break values, i.e. not within the service areas were ranked zero. Public transport stops, traffic infrastructure, locations of schools and places of worship had various break distances in their analysis (Table 6-2):

Table 6-2: Description of Discreet Data Processing

Item	Description	Break Distances (m)	Justification
Public transport stops	Bus stations, bus stops, taxi ranks, train stations	100, 500, 1000, 1500	Transit stops should ideally be within 1 km of dwellings as it takes approximately 15 minutes for an able-bodied person to walk this distance (CSIR, 2000; Bruun, 2013). Although people tend to walk significantly longer distances (Bruun, 2013), but these distances, especially in developing countries were excluded from the analysis to prioritise shorter, inclusive distances.
Traffic infrastructure	Signalised and non-signalised intersections	100, 300, 500	Traffic infrastructure will rarely need to be upgraded beyond 100 m of an intersection. An analysis of up to 500 m was included should queue jumper lanes be required.
Locations of schools	Basic and higher education institutions	500, 1000, 1500	These distances are based on a walking time of maximum 25 minutes. Walking times to transit stops should be minimised so as to minimise total travel time.
Locations of places of worship	Places of worship across all faiths	500, 1000, 1500	The justification for location of schools applies in this case too.

6.3.4 Preparation of Line Data

The Service Area tool does not work for line shapefiles. Consequently, multiple ring buffers were used for this data type. Multiple-ring buffers are similar to service areas in that polygons representing different distances are created around the lines of interest. Where multiple rings differ, and are subsequently inadequate to service areas, is that the distance buffers are independent of the road network. Multiple-ring buffers create distance buffers regardless of any physical barriers, which does not accurately indicate which parts of the route are affected (Figure 6-4):

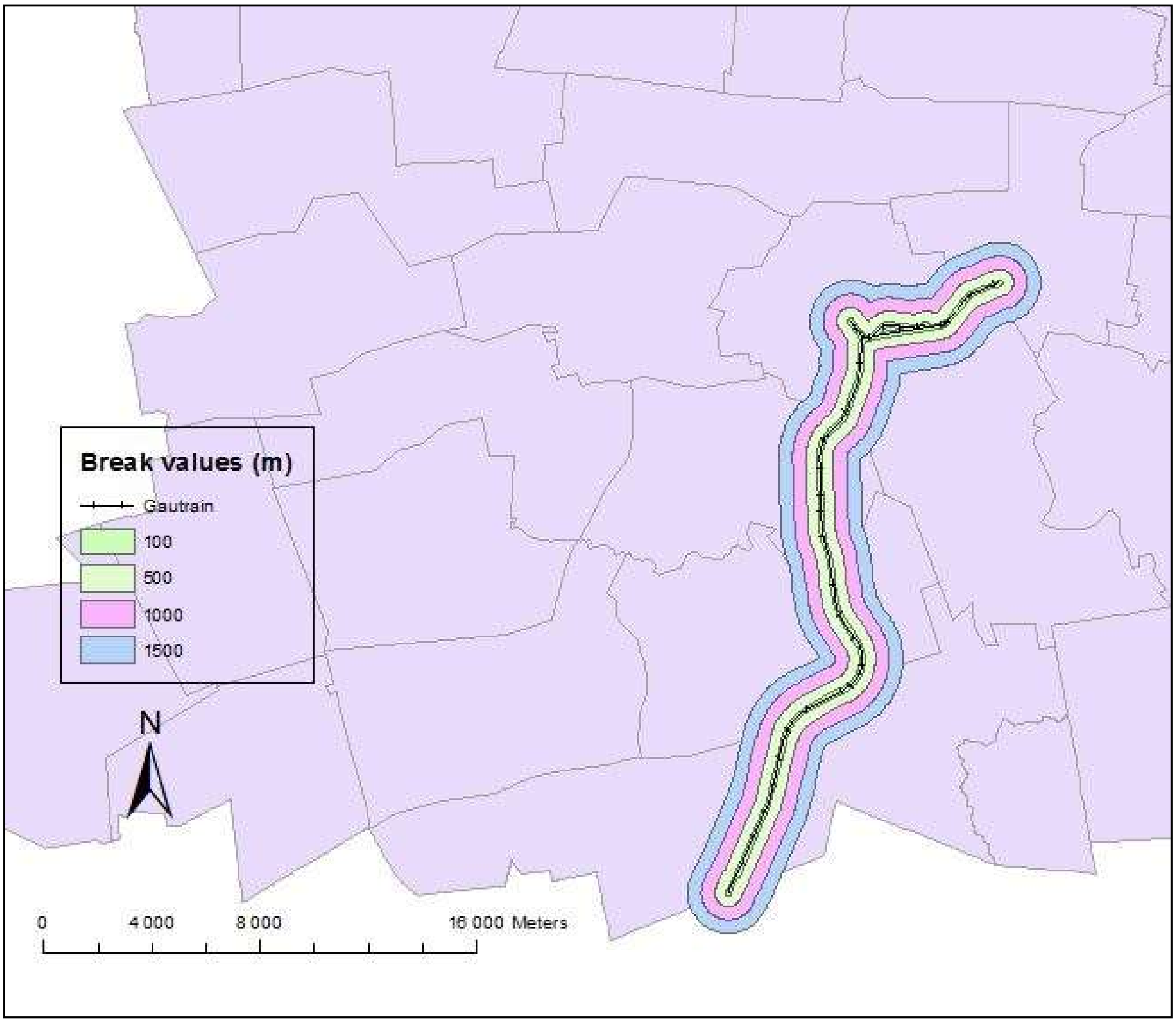


Figure 6-4: Multiple Ring Buffer Around Gautrain

There were five line shapefiles in the dataset. Metrorail, Gautrain and Waterways all used multiple-ring buffers (Table 6-3):

Table 6-3: Description of Line Data

Item	Break Distance (m)	Justification
Distance to Metrorail	100, 500, 1000, 1500	Short walking trips should be encouraged in order to promote an integrated public transport network. Consequently, walking trips should be as short as possible.
Distance to Gautrain	100, 500, 1000 1500	The above justification applies in the instance of Gautrain.
Distance to waterways	100, 500, 1000, 1500	A maximum distance of 1500 m was chosen to reduce the effects of construction on ground water seepage.

For the remaining two line shapefiles, which are arterial and residential roads, 100 m single buffers were made from the roads. This buffer distance was chosen as it ensured that at no more than two pixels were influenced by the presence of the overlying road segment, which would have been an over-estimate.

In addition, travel speeds were allocated to the road shapefile so that the travel speed of the optimal route could be deduced. Travel speeds were informed by road design speed standards within RSA (Table 6-4):

Table 6-4: Travel Speed per Road Category

Road Category	Travel Speed (km/h)
Primary highways	100
Secondary highways	80
Tertiary highways	60
Residential Road	30

6.4 Spatial Multi-Criteria Analysis

Following GIS pre-processing, the data was ready for processing in ILWIS Academic 3.31. ILWIS is a GIS that is capable of processing both vector and raster data. Although ArcGIS has a multi-criteria function called “Map Algebra” that allows the weighted combination of multiple rasters, ILWIS was chosen for its superior SMCA capabilities. ILWIS allows the evaluator to sort the data into criteria trees and provides various standardisation and weighting options. All input data into ILWIS was vector data, which simplified the processing required. A new coordinate system file was created in ILWIS that matched the coordinate system used in ArcGIS. This ensured that composite suitability raster files that are imported back into ArcGIS are correctly geo-referenced and overlap the study area. With all raster files completed and correctly geo-referenced, a criteria tree could be formed (see Section 6.4.1).

A pixel size of 100 m by 100 m was selected for the grid size in the raster files. The selection of this cell size was based on the observation that data accuracy was maintained without sacrificing processing time. A pixel size of 100 m by 100 m produced 1190 rows and 1346 columns for the CoT.

6.4.1 Criteria tree

A criteria tree is an organisational map of main criteria and their sub-criterion. In a criteria tree, all criterion can be standardized and weighted (Figure 6-5). The criteria tree followed the same organisation outlined in Table 6-1.

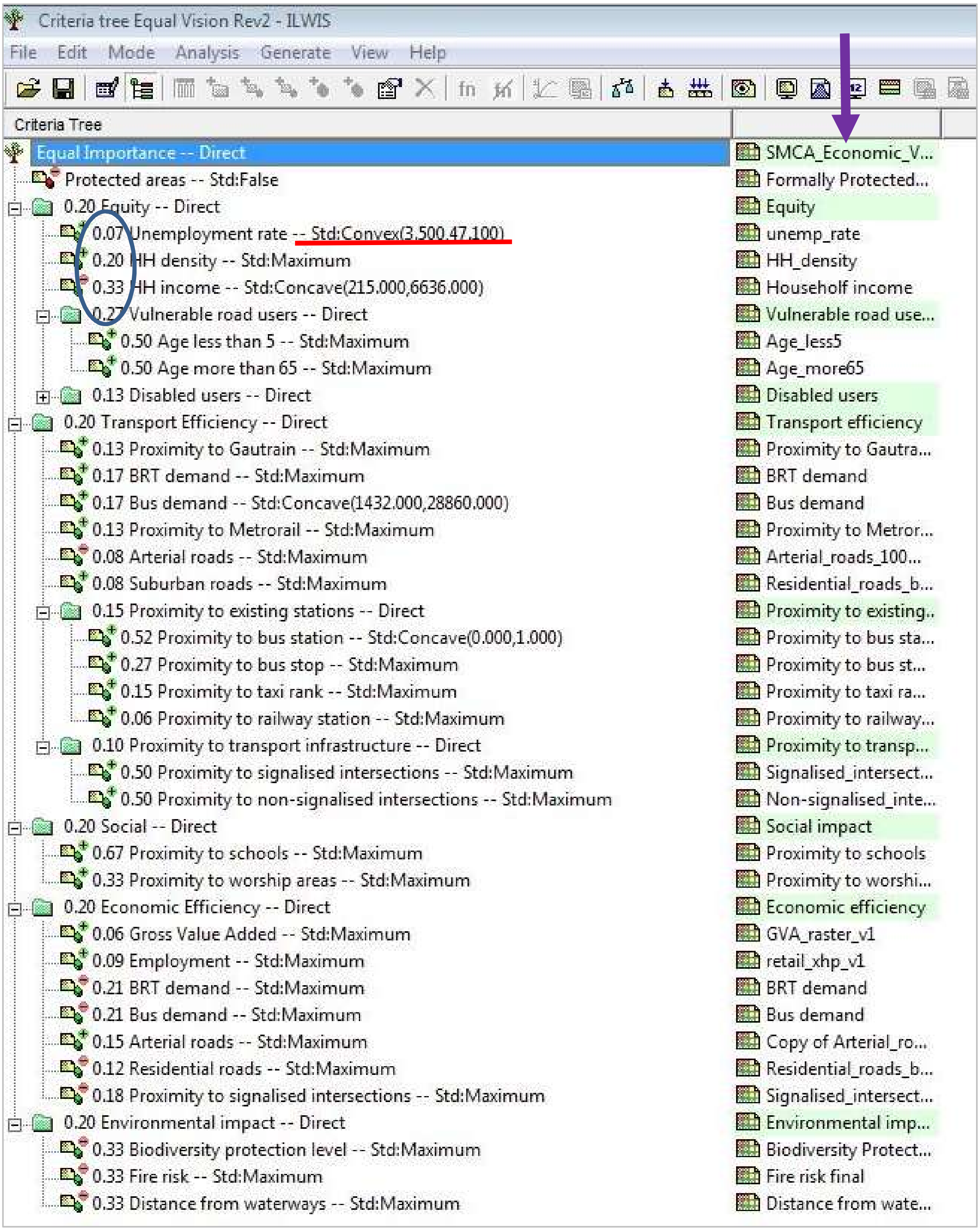


Figure 6-5: Screenshot of Criteria Tree

The criteria tree contains five main criteria and 35 criterion branches representing the sub-criteria. Each of the criterion branches forms a suitability map. The method of standardisation is found in the information on the right of the criteria name (underlined in red). The numbers next to the criteria on the left (circled in blue) depict the weighting of every criteria. The column on the right (indicated with a purple arrow) depicts the processed raster maps used for every criteria. The weighted summation of the 35 suitability maps produced one composite suitability map.

6.4.2 Standardisation

Standardisation is the process of translating pixel values from their original scores into values between 0 and 1[3], where 0 represents complete unsuitability and 1 represents maximum suitability. The standardisation methods used were either maximum (for benefits), minimum (for costs), convex or concave. Maximum and minimum standardisations transfer the original pixel scores onto a linear scale. For benefits, the largest score was scaled to one, and all other scores were divided by the maximum. The minimum standardisation process was slightly more complex (Equation 10):

$$V_i = 1 - \frac{v_i}{v_{max}} + \frac{v_{min}}{v_{max}}$$

.........Equation 10

Where:

V_i = Standardisation value of criterion i;
v_i = Original score for criterion i;
v_{min} = Maximum pixel score obtained within the criterion; and
v_{max} = Minimum pixel score obtained within the criterion.

Concave and convex standardisation techniques were used when it was decided that criteria values should not be linearised (Table 6-5). A linear relationship assumes an equal rate of increase or decrease between pixel values, which translates to a linear change in suitability. For some criteria, it was decided that suitability did not increase linearly, but at an exponential rate. For example, suitability scores of people living below the poverty line should be exponentially higher than people who live affluently because of the effects of poverty. The x values depict pixel scores and the y values depict standardisation values.

[3] The scale 0-1 is the scale used by ILWIS. Any linear scale will do, such as 0-100.

Table 6-5: Critical standardisation Values and Justification for Concave and Convex Criteria

Criteria	Standardisation Technique	Critical Values	Justification
Household income	Concave	*x_1 = 215.0 y_1 = 1.0 x_2 = 500.0 y_2 = 0.945 #x_3 = 6636.0 y_3 = 0.0	The poverty line is $1.25/day (Nicolson, 2015), which translates to approximately R500/month. Those that live below the poverty line thus receive an exponentially higher standardisation score.
Unemployment rate	Convex	x_1 = 3.5 y_1 = 0.0 x_2 = 24.2 y_2 = 0.25 x_3 = 47.1 y_3 = 1.0	In the CoT, the unemployment rate is 24.2% (Stats SA, 2011b), which was used as the benchmark for 75% of the standardisation scores.
Bus demand (for transport efficiency)	Concave	x_1 = 1432.0 y_1 = 0.0 x_2 = 10000.0 y_2 = 0.75 x_3 = 28860.0 y_3 = 1.0	A demand of under 10000 passengers/day would best be served by minibus-taxi, hence a high y-value for y_2.
Proximity to bus station	Concave	x_1 = 0.0 y_1 = 0.0 x_2 = 0.60 y_2 = 0.70 x_3 = 1.0 y_3 = 1.0	In the processing stage, the lowest distances were given higher rankings. Distances were ranked from 0-1. A value of 0.6 corresponds to a distance of 1 km, giving the first kilometre increased importance.

* Represents the minimum output value and # represents the maximum output value.

6.4.3 Weighting

The ultimate step in producing suitability maps was to assign weights to the criteria. As no stakeholder engagement was conducted, the academic solution was to assign all criteria equal weights. This is the reference case. Each of the five criteria themes thus received a weight of 0.20. However, individual criterion within each criteria theme were assigned different weights as some criteria were logically more important than others in the context of PT routing.

The weighting method used is a direct method, which was chosen over Pairwise and Rank Order. Pairwise, which uses AHP, requires comparisons to be made over the perceived degree of importance of one criteria over another. This subsequently requires stakeholder engagement and expert opinions for the sake of accuracy, and was thus deemed unsuitable. The rank order method has two alternative weighting methods which both use complicated formulae (ILWIS, 2010b). The direct approach was thus chosen for its transparency and simplicity. For each criteria theme, the sub-criteria were assigned a ranking of 1-*n*, where *n* represents the number of sub criterion.

With the weights assigned and criterion standardised, a composite suitability map could accordingly be generated (Figure 6-6). The final standardised value of each pixel was made up of the sum of the corresponding pixel score of each criterion, multiplied by the criterion weight. The weighted composite suitability map was exported to ArcCatalog to be re-assigned the GIS coordinate system.

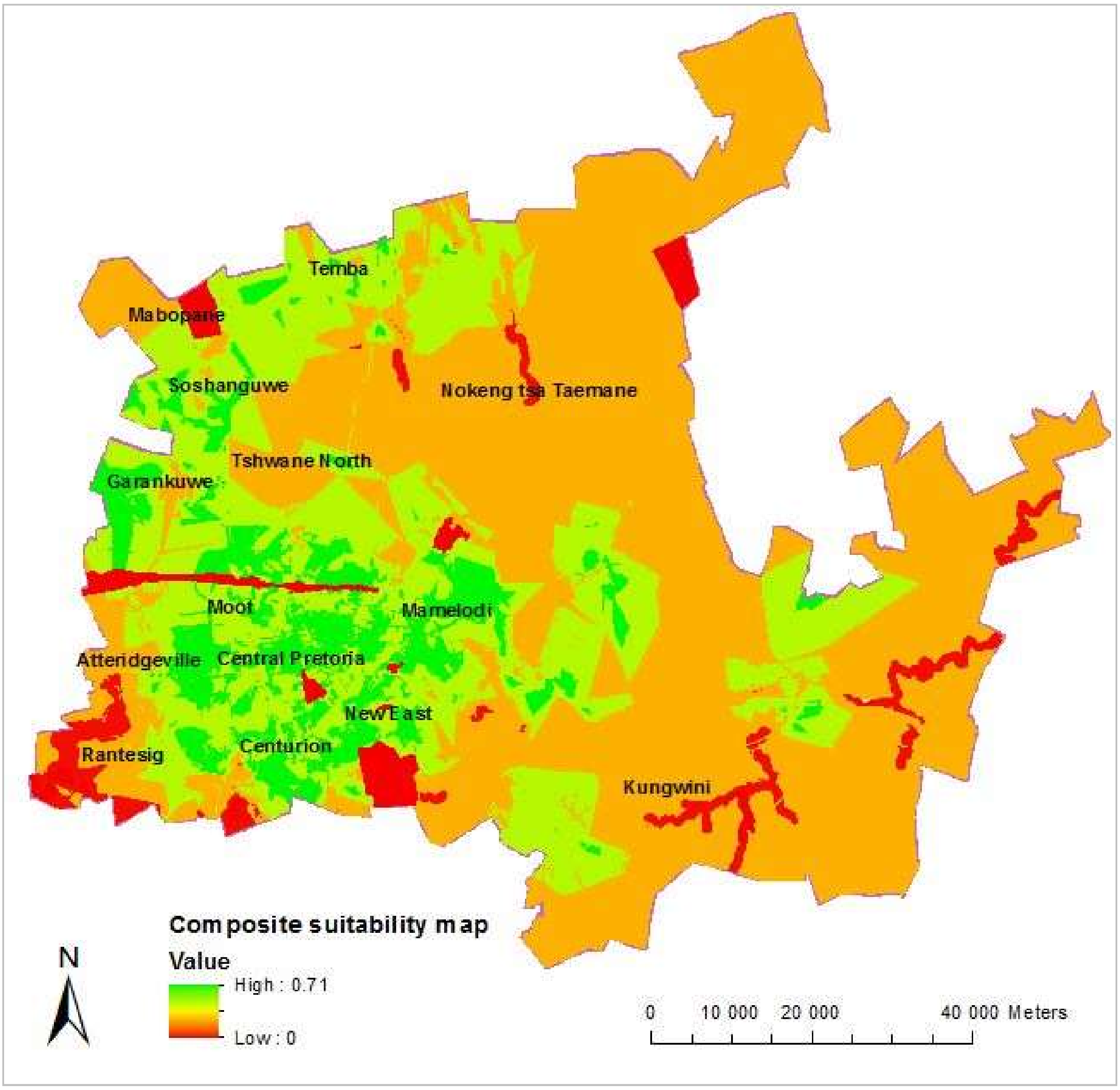


Figure 6-6: Composite Suitability Map of Reference Case

Areas of high suitability are depicted by green, and areas of low suitability by red (Figure 6-6). A minimum suitability score of 0 was obtained due to the presence of constraints in the form of formally protected areas. The suitability score of each pixel informs the cost of travel along each pixel. Costs, or impedances, were calculated in the network analysis section.

By changing criteria themes, four additional composite suitability maps were produced. Criteria theme weights were changed to indicate scenarios that depict preferences for stakeholders had a stakeholder engagement taken place. The routes produced from this weight change were called “scenario routes”. The four scenario themes were: environmental impact, social impact, transport efficiency and equity. For each scenario theme, the highest weight was given to the corresponding criteria theme.

6.5 Network Analysis

Four trunk routes and four feeder routes were analysed in this research. The network analysis section involved the following steps:

i) Suitability maps were converted from asc format to tiff format so that they could be read in the Geospatial Modelling Environment (GME) program;
ii) Along each road segment, GME was used extract the LWM suitability scores from the composite suitability maps using function "isectlinerst". LWM, originally introduced in section 4.3.1, is reproduced as show (Equation 11):

$$LWM = \frac{\sum_i^n (l_i * s_i)}{L}$$

……….Equation 11

Where:
l_i = Length of road segment i;
s_i = Suitability value of the pixel underlying road segment i; and
L = Total length of road of which road segment forms part;

iii) The road shapefile was opened in GIS with the added LWM values. In the attribute table, the mean impedance ω_i was calculated as shown (Equation 12):

$$\omega_i = \frac{1}{LWM}$$

----------Equation 12

iv) In ArcCatalog, a network dataset was built from the road network with the impedance as the cost attribute;
v) The network dataset was uploaded into ArcGIS, which allowed the use of the "New Route" tool;
vi) For each route, the corresponding stops were added. The stops were either taken from existing BRT stops supplied by the CoT, or from A re Yeng's future BRT plans;
vii) After the LWM inverse was set as the impedance factor in the analysis settings, the route was determined; and
viii) The new routes were compared to existing routes where the existing route was available.

6.6 Sensitivity Analysis

A sensitivity analysis was required to test the robustness of the results, as well as reveal where sensitivities in the SDSS occurred. A qualitative and quantitative sensitivity analysis was conducted. The qualitative sensitivity analysis included an uncertainty matrix and a scenario uncertainty evaluation. The quantitative uncertainty analysis involved changing one criteria at a time by a certain amount, and observing whether the results changed by more than the criteria weight change. If the results changed by more than the criteria weight change, the corresponding criteria was judged to be sensitive. In addition, if the route changed due to the weight change, the route was judged to be sensitive.

6.7 Challenges Encountered and Limitations of the SDSS

Every decision model is subject to challenges and limitation. The following were encountered in this research

i) The original road shapefile was incompatible with the Network Analyst tool. The Network Analyst tool could not solve any routes. It was discovered that there were not enough junctions along the road, and as a result, and the road segments were too long. Consequently, the route solver could not enter a road at any point along the road. Initially, AutoCAD was used to split the line segments, but as there were over 18 000 line segments, this proved to be a tedious process. Thereafter, road segments were split in ArcGIS using the “Split line at vertices” tool. As the road layer had no junctions yet, a preliminary network dataset had to be built, as this creates junctions. The junctions were used as split points on the old road layer to create a new road layer. The new road layer, with 56 000 elements, proved to be successful and allowed each route to be solved;
ii) A lack of O-D data meant that the original bus stops planned by the CoT had to be followed. This took away a creative element in the research, as the stop placements significantly affect the route. However, while some creativity was lost, accuracy was maintained as the stops are derived from a presumably extensive travel demand analysis conducted by the CoT. Otherwise, the most important element of the research was upheld, which was optimal routing; and
iii) Only one cost attribute could be considered: impedance. This meant that routes formed did not take distance, and subsequently, travel time, into consideration. The inability to incorporate multiple impedances and subsequently rank them is a major shortcoming of the Network Analyst tool.

6.8 Résumé

This chapter delineated the method of research followed in order to find optimal BRT trunk and feeder routes in the CoT. The chapter started by providing the evaluation criteria used in this research and the justification for those criteria. There were 5 criteria groups derived for this research: transport efficiency, equity, environmental impact, social impact and economic impact. For each criteria group, sub-criteria are selected. The chapter proceeds to discuss how the spatial data collected was validated, as most of the data used is open-source data. Thereafter, methods of pre-processing vector data encountered in this dissertation are provided in depth. The vector data consisted of three types: continuous, discreet and line data. With the spatial data prepared, the SMCA process is described in three sections: forming the criteria tree, standardising the data and assigning criteria weights. All of the aforementioned steps were necessary in producing a composite suitability map which was used in the network analysis section to find optimal routes. With the optimal routes mapped and the corresponding impedances collected, sensitivity analyses are conducted to ascertain the robustness of the results, as well as were uncertainties lie in the model. The three sensitivity analyses conducted are an uncertainty matrix and scenario uncertainty analysis, which are qualitative, and a quantitative uncertainty analysis in the weights.

To conclude the chapter, challenges encountered in the SDSS and shortcomings of the model are provided. A major shortcoming of the SDSS is that the Network Analysis tool in ArcGIS does not allow for the consideration of more than one cost factor, i.e. both impedance and travel time. As such, optimal routes do not take travel time into account in addition to minimising impedance.

Another limitation encountered was the unavailability of an O-D matrix, which meant original bus stops planned by the CoT had to be followed. This took away a creative element in the research. However, accuracy was maintained as the stops are derived from a presumably extensive travel demand analysis conducted by the CoT. Otherwise, the most important element of the research was upheld, which was optimal routing

7 Optimal BRT Trunk and Feeder Routes of the CoT

Following the research method outlined in Chapter 6, optimal BRT trunk and feeder routes of the CoT could be computed and mapped (Figure 7-1). This chapter begins by presenting the routes obtained for the reference case, when all criteria were given the same weighting. Each route is described, and a map of the route is presented. The route is also graphically compared to existing routes or planned routes where possible. Thereafter, route characteristics are quantitatively presented for each route. In section 7.3, results of the four scenario analyses are presented. The chapter concludes with a ranking of all routes based on their average impedance across the reference case and four scenarios.

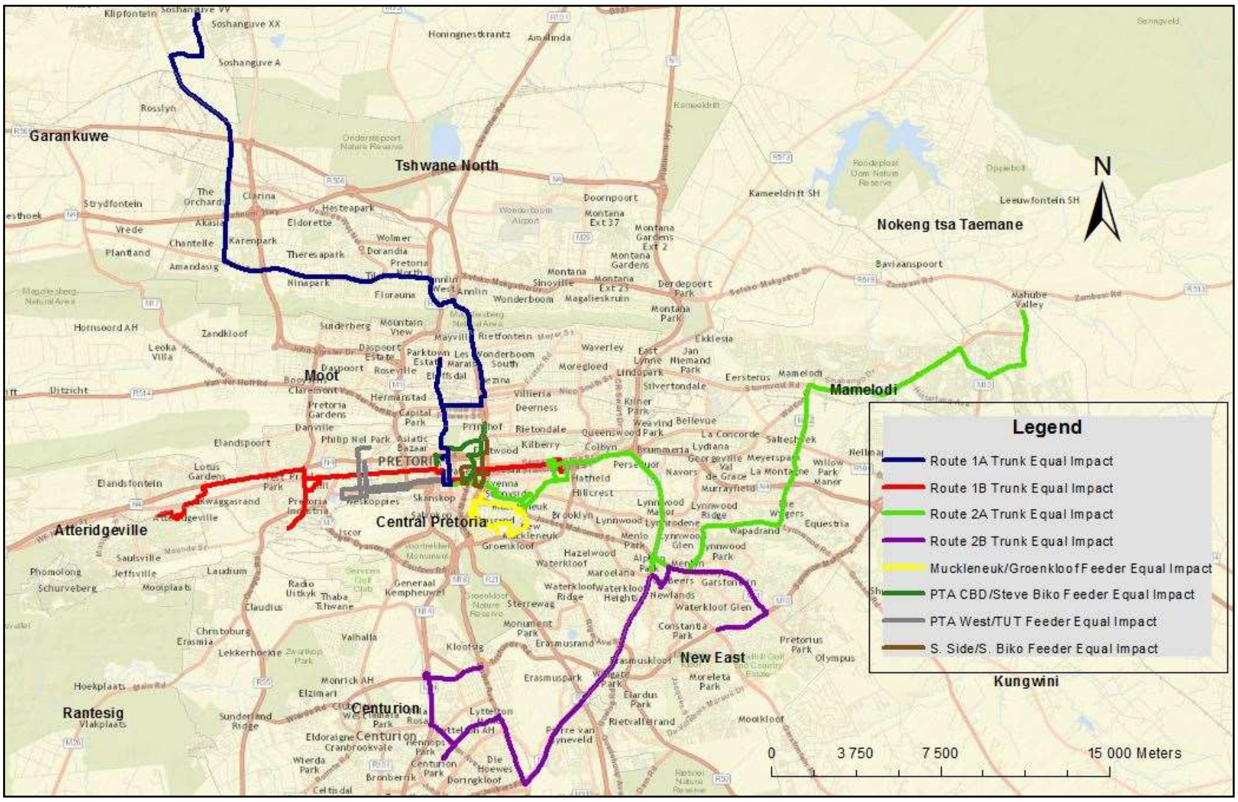


Figure 7-1: Overall View of Trunk and Feeder Routes

The weighted summation of all criteria produced a composite suitability map. The green areas represent areas of high suitability, and the red areas represent areas of low suitability (Figure 7-2):

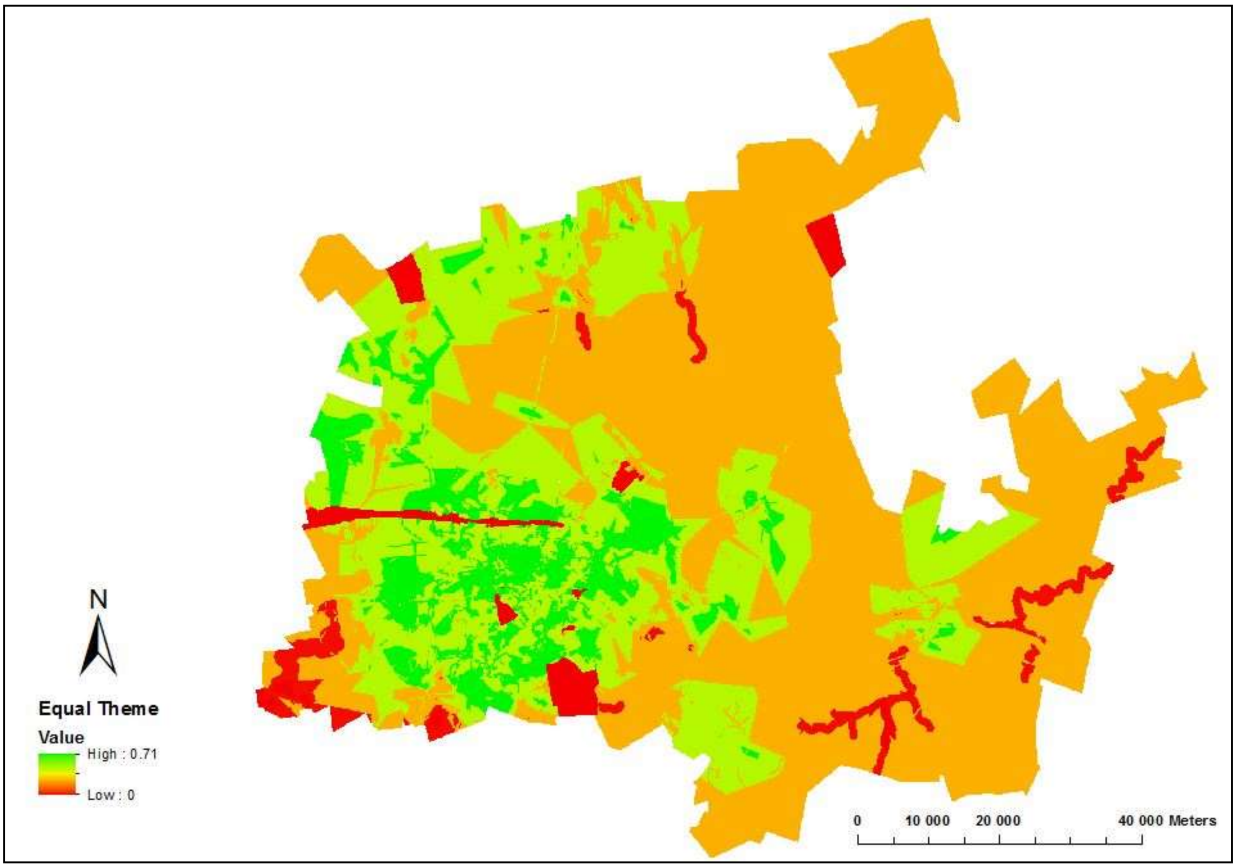


Figure 7-2: Composite Suitability Map for Reference Case

7.1 Optimal Trunk Routes

As mentioned in Chapter 1, optimal routes are routes that achieve the lowest possible cumulative impedance (or cost) against an array of evaluation criteria and weighting schemes.

7.1.1 Trunk 1A

Trunk 1A is to connect the CBD to Soshanguve via the Wonderboom.

Route Description

Trunk 1A begins in a northerly direction from Church Square. It follows Thabo Sehume Street until Anton Lembede Bus Station, where it joins the R101. The route follows that road until Stop 5, where the bus will be required to make a U-turn to join the M5 via the M8. At Pretoria North, the route joins the R533 where it passes Wonderpark Shopping Centre. It then joins the M20 where it passes Akasiaboom Train Station and concludes near Kopanong Station (Figure 7-3):

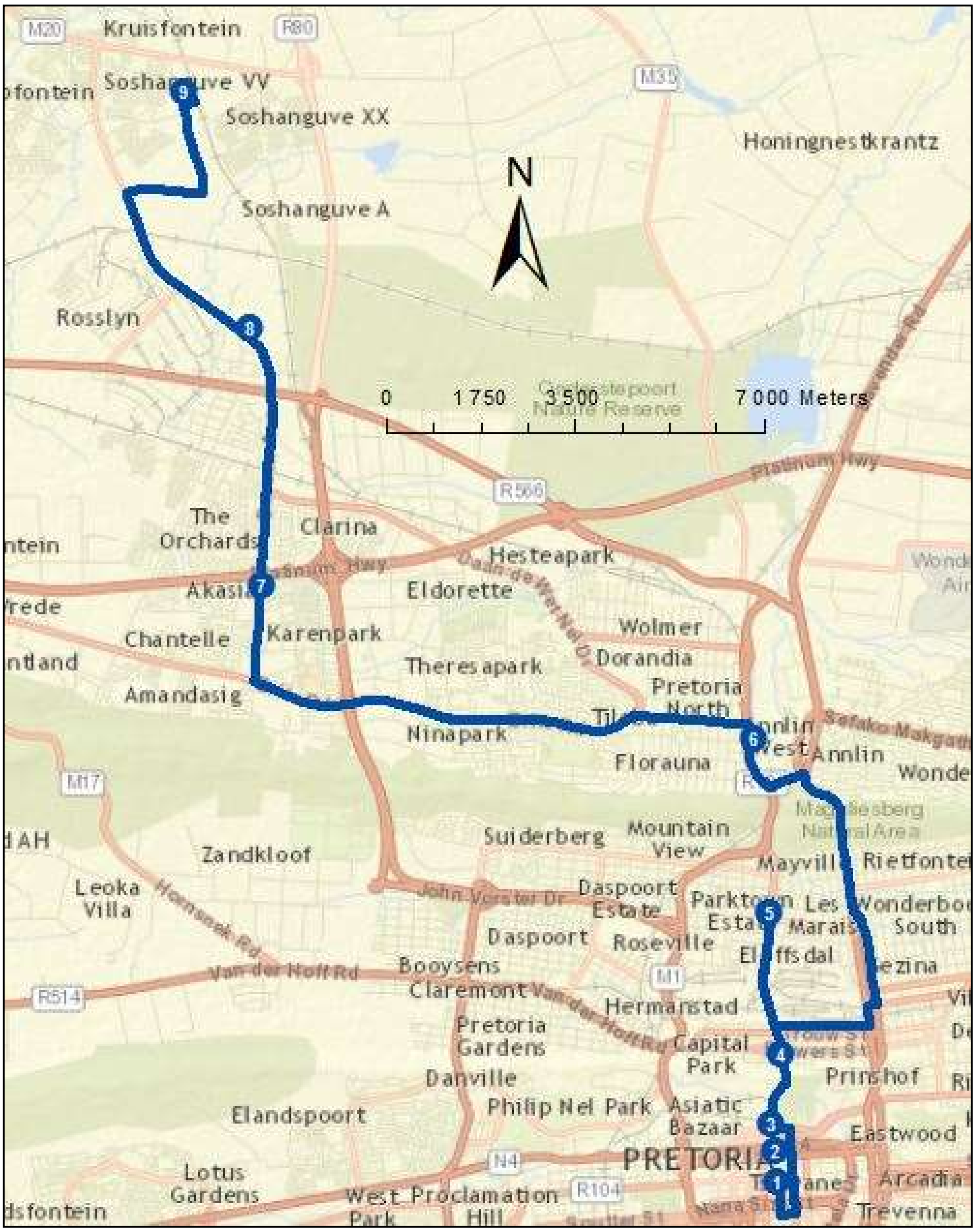


Figure 7-3: Trunk 1A Route and Stops

For this route, the first five stops were available from the CoT. The remaining four stops were taken from the CoTs Spatial Development Framework (CoT, 2012).

Comparison to Actual Route

Only a section of the route was available as GIS data for Trunk 1A. The route differs from Stop 1, where it follows the R101 all the way to Stop 5 (Figure 7-4):

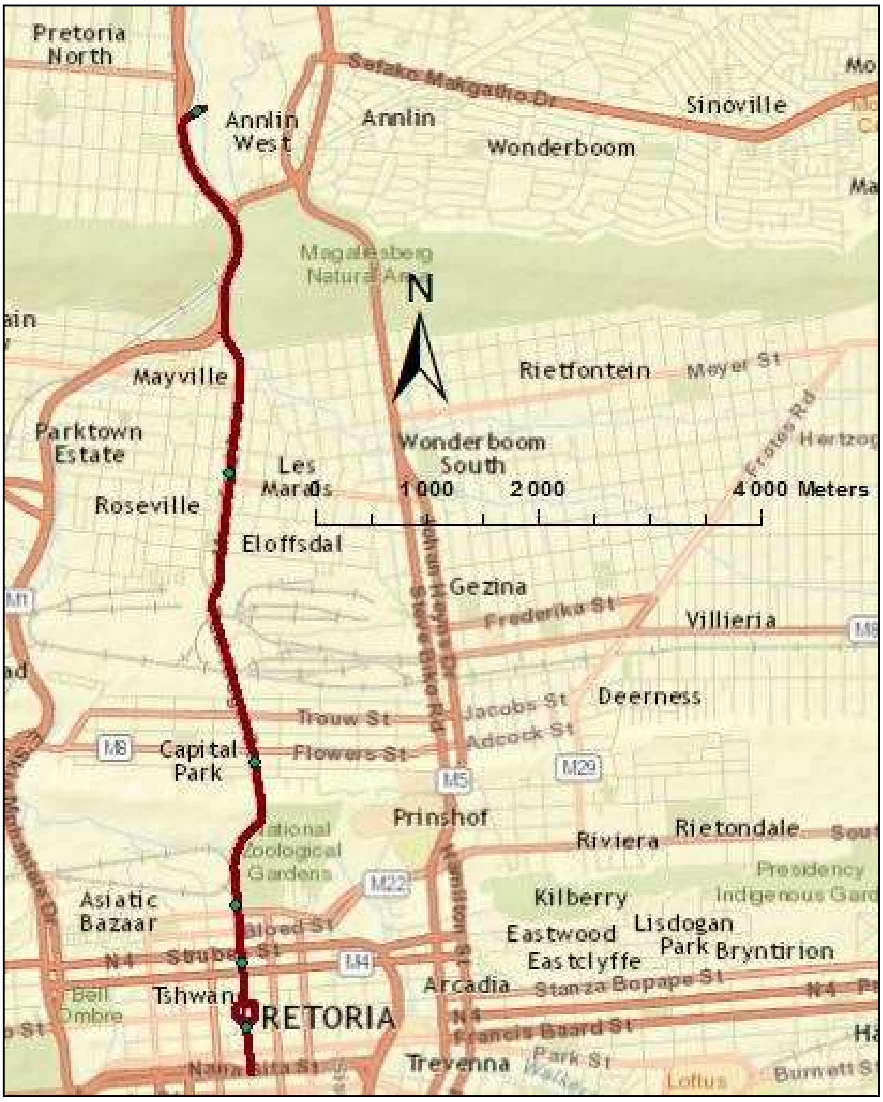


Figure 7-4: Trunk 1A Actual Route and Stops

Route Characteristics

The route characteristics for Trunk 1A are summarised as follows:

Route length: 37 733.1 m
Total impedance: 157.018
Average impedance: 4.161/km
Travel time: 94.0 min

7.1.2 Trunk 1B

Trunk 1B is an East-West route that connects Atteridgeville to Hatfield.

Route Description

The route begins at Atteridgeville Terminal and follows the N4 and R55 to Nywerheid Station. Thereafter, the route follows the R104 until the CBD, where it joins the M2 until it terminates at Hatfield Station (Figure 7-4):

Figure 7-5: Trunk 1B Route and Stops

Comparison to Actual Route

GIS data was not available to create a route and make a comparison for Trunks 1B and 2B. Furthermore, map images were not available on the CoTs BRT website. Consequently, the route may be compared to the red route (Figure 7-6) and yellow stops (Figure 7-7):

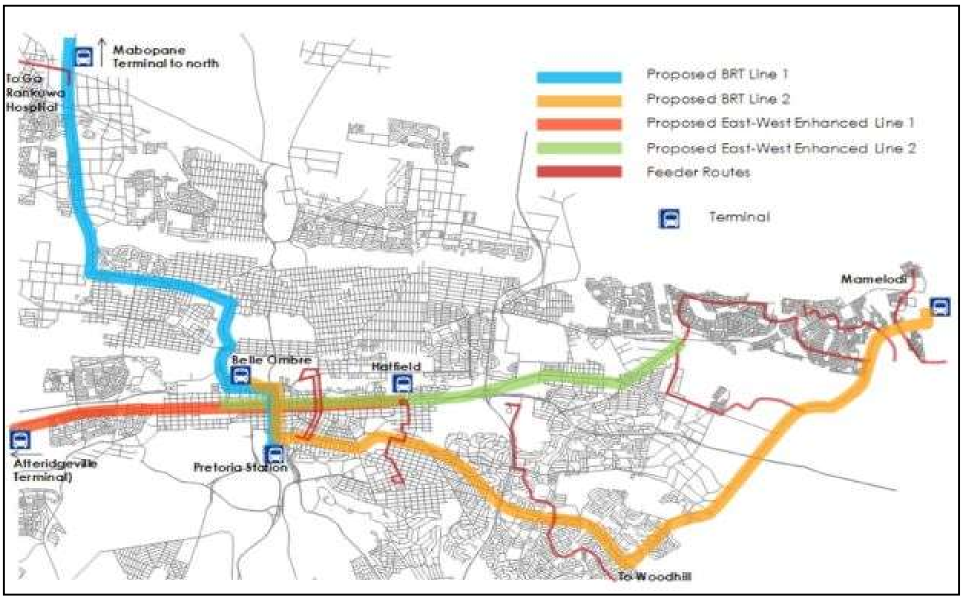


Figure 7-6: Planned Trunk Corridors
Source: Gauteng Provincial Government (2012)

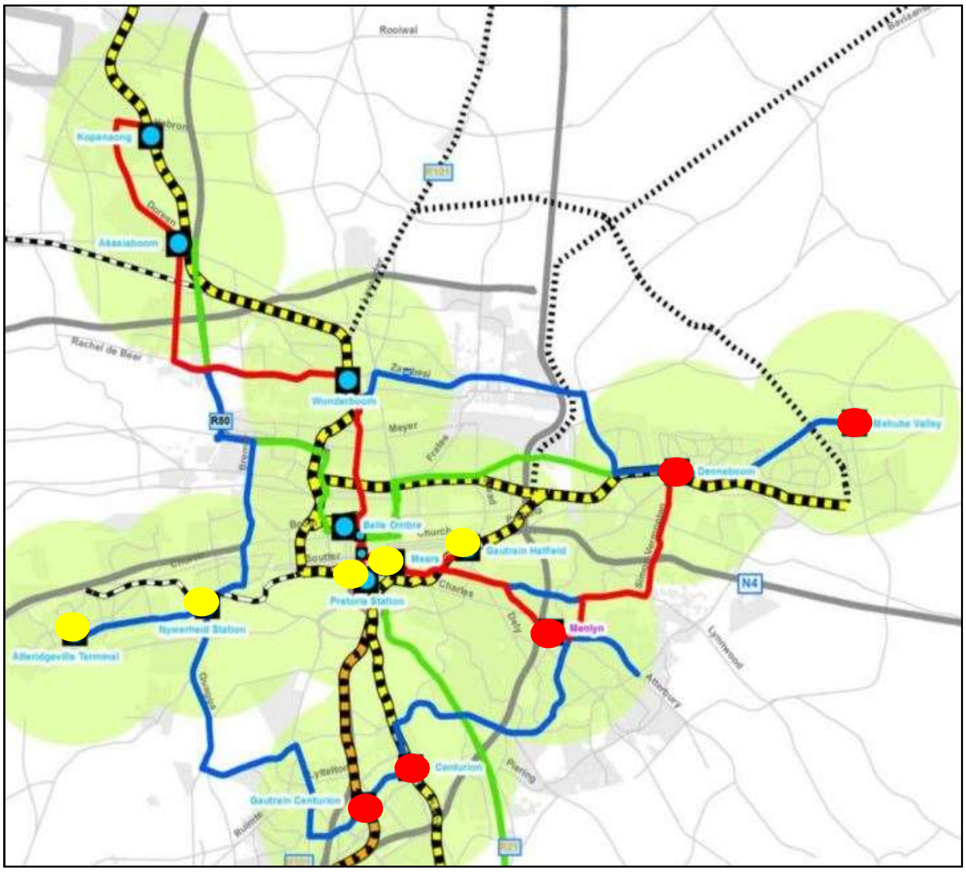


Figure 7-7: Planned Trunk Routes and Stops
Source: CoT (2012)

Route Characteristics

The route characteristics for Trunk 1B are summarised as follows:

Route length:	25 680.0 m
Total impedance:	127.064
Average impedance:	4.948/km
Travel time:	94 min

7.1.3 Trunk 2A

Trunk 2A is also an East-West route. It connects the CBD to Mahube Valley in Mamelodi.

Route description

Beginning in Church Square, the route follows Park Street until it reaches the Hatfield Station. Thereafter, the route follows the N4, N1 and M11 where it stops at Menlyn Shopping Centre. From the M11, the route turns left onto the M33, right onto the M6, left onto the M12 and right onto the M8 until it stops at Denneboom Station. It continues on the M8 until it reaches the R513, whereupon it turns right. The route proceeds left onto the M10 until it culminates at Mahube Valley (Figure 7-8). The first 9 stops of the route were available as shapefiles from the CoT.

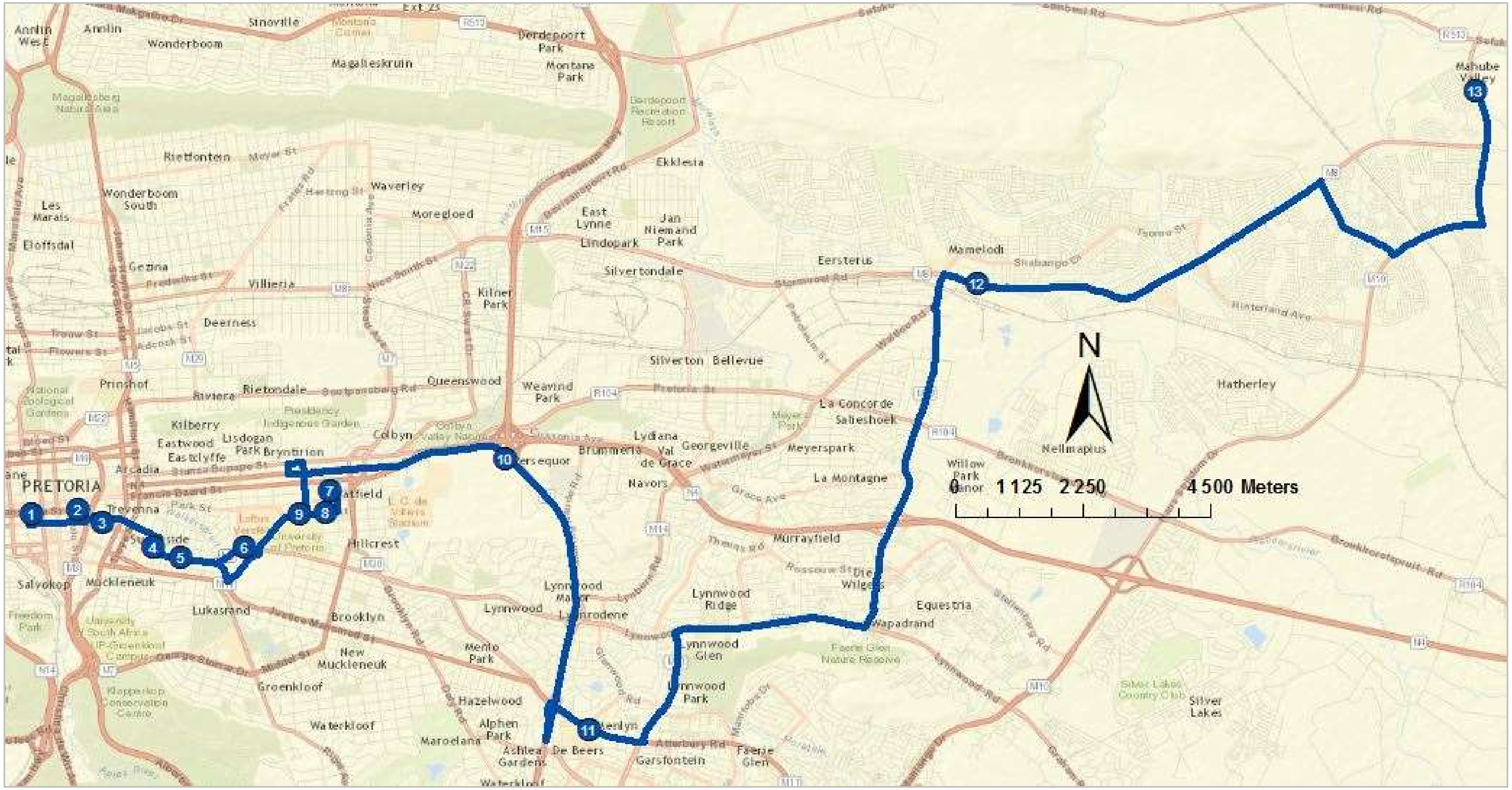


Figure 7-8: Trunk 2A Route and Stops

Comparison to Actual Route

The only section of Trunk 2A that was available for comparison was the section between the CBD and Hatfield. The actual route starts off on the M2, whereas the optimal route starts off on Visagle Street. There are noticeable differences between the optimal route and actual route, especially between Stops 7 and 9 (Figure 7-9):

Figure 7-9: Trunk 2A Actual Route and Stops

Route Characteristics

The route characteristics for Trunk 2A are summarised as follows:

Route length:	44 652.7 m
Total impedance:	223.475
Average impedance:	5.005/km
Travel time:	117.6 min

7.1.4 Trunk 2B

Trunk 2B is a North-South route connecting New East with Centurion.

Route Description

The route starts off close to the intersection of the M10 and M30 freeways. It moves North up the M10 to turn left onto the M11, past Menlyn Shopping Centre Stop. Thereafter, the route turns left onto Lois Avenue, right onto the M30 and follows the N1 until Doringkloof. The route off-ramps onto the M18 towards Lyttelton Manor and then left onto the M25 where there is a stop at the Centurion Gautrain Station. The route proceeds to follow the M34 to join the N14 until it off-ramps onto the M10 to end at Kloofsig Train Station (Figure 7-10):

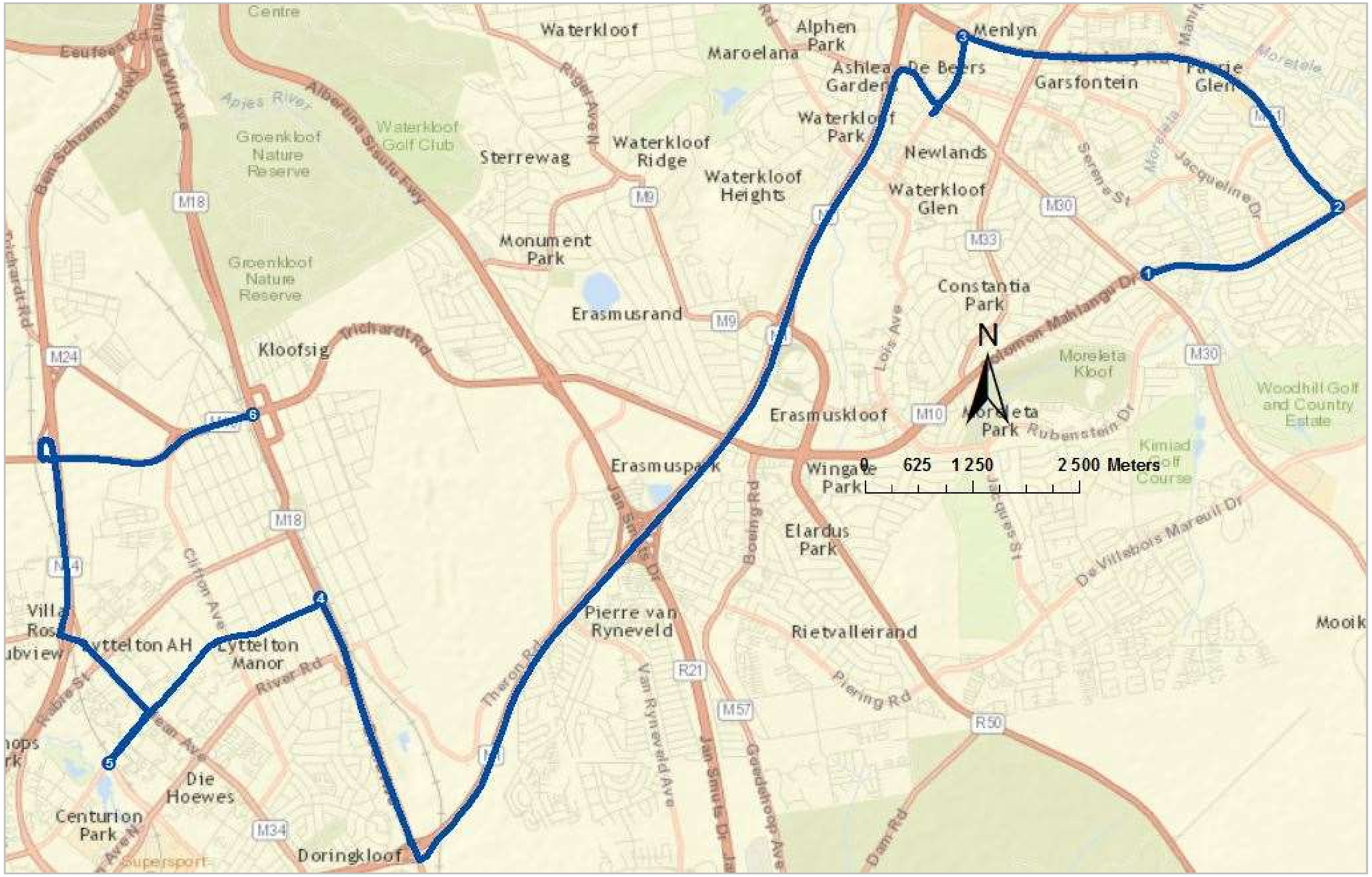


Figure 7-10: Trunk 2B Route and Stops

Comparison to Actual Route

Trunk 2B must be compared to the orange route (Figure 7-6) and red stops (Figure 7-7) as GIS data or map diagrams were not available.

Route Characteristics

The route characteristics for Trunk 2B are summarised as follows:

Route length:	31 076.8 m
Total impedance:	130.783
Average impedance:	4.208/km
Travel time:	47.1 min

7.2 Optimal Feeder Routes

7.2.1 S Side/Steve Biko Feeder

The S. Side/ Steve Biko Feeder services Arcadia, connecting the suburb to the Tshwane District Hospital.

Route Description

The route begins at the Nana Sita Bus Station on the M3. From there, it joins the M6 via Kotze Street and makes a right turn onto Sisulu Street. A right turn is made onto the R104, where the route continues until the M3. The route proceeds to the M5 until Capital Park Bus Station, whereupon a U-turn is made. The route culminates on the intersection of the M5 and M22 at Arcadia Bus Stop (Figure 7-11):

Figure 7-11: S. Side/Steve Biko Feeder Route and Stops

Comparison to Actual Route

The optimised S. Side/Steve Biko Feeder route follows a slightly more intricate path than the planned route. Noticeable differences occur around Stops 1 and 10 (Figure 7-12):

Figure 7-12: S. Side/Steve Biko Feeder Actual Route and Stops
Source: CoT (2015c)

Route Characteristics

The route characteristics of the S. Side/Steve Biko Feeder are summarised as follows:

Route length:	7 753.6 m
Total impedance:	51.153
Average impedance:	6.855/km
Travel time:	20.1 min

7.2.2 CBD/Steve Biko Feeder

This feeder route is intended to connect the University of Pretoria to the CBD.

Route Description

The first stop of the route lies along the R104, which is WF Nkomo Street. The route follows the M18 and proceeds to turn onto the N4 after the second stop. Two left turns are made onto Thabo Sehume Street and the M22 respectively. Thereafter, the route follows the M22 until Capital Park Bus Station, where a U-turn is made and the route joins the M5. A left turn is made onto the N4 to service two stops. The route then proceeds onto the M6 before making its concluding turn onto the M3, where it ends at Nana Sita Bus Station (Figure 7-13):

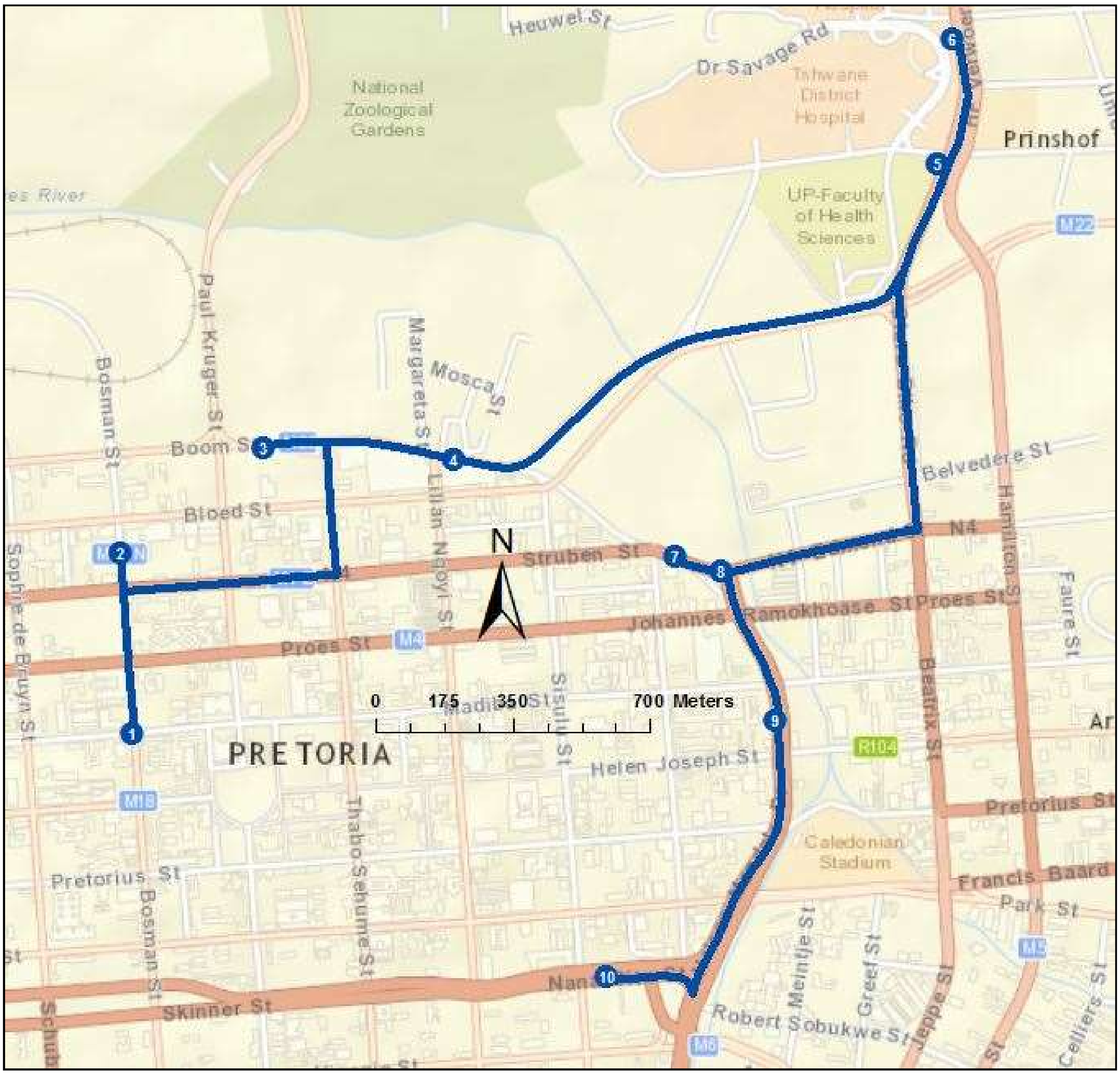


Figure 7-13: CBD/Steve Biko Feeder Route and Stops

Comparison to Actual Route

This route differs from the intended route from Stops 2 to 4. It must be noted that stops from S. Side/Steve Biko have been added in Figure 7-14, which is why the route in Figure 7-14 appears to have more stops than the optimal route.

Figure 7-14: CBD/Steve Biko Feeder Actual Route and Stops
Source: CoT (2015c)

Route Characteristics

The route characteristics are summarised as follows:

Route length:	6 763.3 m
Total impedance:	62.039
Average impedance:	9.173/km
Travel time:	21.6 min

7.2.3 Pretoria West/TUT Feeder

This route connects the main campus of Tshwane University of Technology (TUT) to what was formerly known as Pretoria West.

Route Description

The route begins in Central Tshwane and proceeds in a westerly direction on the M2. The route makes a loop on Zeiler Street before turning right onto Carl Street then right onto Buitenkant Street. From Buitenkant Street, the route turns right back onto the M2, left onto Rebecca Street and right onto Staatsartillerie Road. This road is followed until it intersects with Technikon Pl Street. At this intersection, a U-turn is made and the route follows Staatsartillerie Road, Rebecca Street, the M2 until it stops at the same station in Central Tshwane (Figure 7-15):

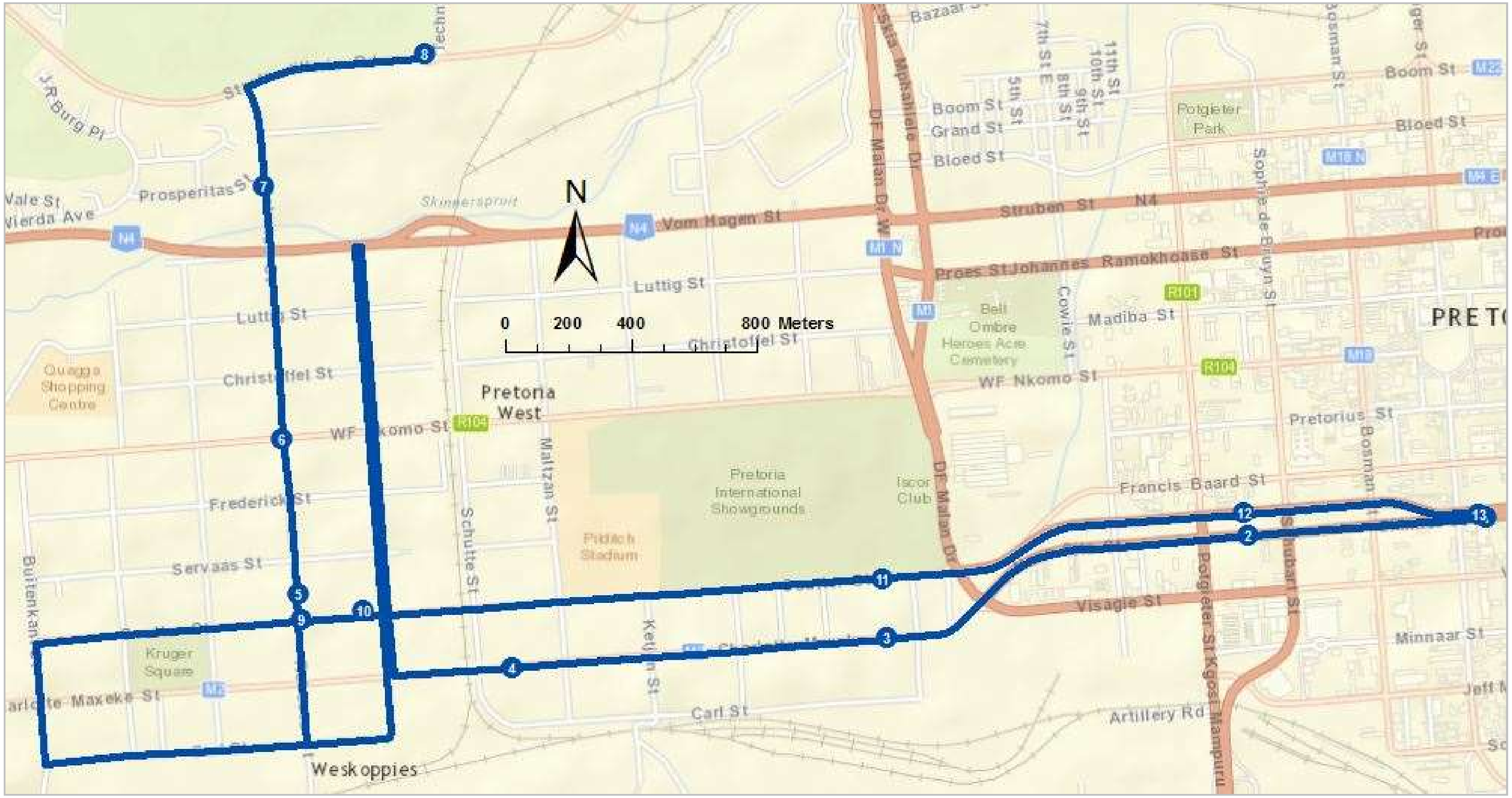


Figure 7-15: Pretoria West/TUT Feeder Route and Stops

Comparison to Actual Route

The most notable difference on this route is the loop that is made on Zeiler Street in the optimised route (Figure 7-16). The loop adds to the travel time and distance of the route, without servicing a stop. This is evidence of the limitations of the SDSS; the inability to incorporate more than one cost factor in the network analysis so that both impedance and travel time are optimised.

Figure 7-16: Pretoria West/TUT Feeder Actual Route and Stops
Source: CoT (2015c)

Route Characteristics

The route characteristics for Pretoria West/TUT Feeder are summarised as follows:

Route length:	16 277.5 m
Total impedance:	58.442
Average impedance:	3.590/km
Travel time:	54.0 min

7.2.4 Muckleneuk/Groenkloof Feeder

The Muckleneuk/Groenkloof Feeder connects Sunnyside and Muckleneuk, servicing travellers wishing to go to the University of South Africa (UNISA).

Route Description

The route begins at Justice Mahomed Bus Stop on the M5. It enters the M11 and Stops at Unisa Sunnyside Bus Stop. The route continues on the M11 until it ramps onto the M3 freeway.

Thereafter, it off-ramps onto Willow Road. It makes a loop on Ridge Street, Troye Street and Mears Street, right until Unisa Bus Stop on Willem Punt Avenue. The route makes a turn to stop at Tuks Groenkloof Stop on Leyds Street. A U-turn is made on this stop and the route follows Sibelius Street and Dr Lategan Road, past Steger Stop and Quinns Stop. After Sibelius Street, the route follows the M9, makes a loop on Klip, Ormonde and John Streets before entering the M11 and concluding on the M5 (Figure 7-17):

Figure 7-17: Muckleneuk/Groenkloof Feeder Route and Stops

Comparison to Actual Route

The actual route (Figure 7-18) varies considerably from the optimised route (Figure 7-17):

Figure 7-18: Muckleneuk/Groenkloof Feeder Actual Route and Stops
Source: CoT (2015c)

Route Characteristics

The Muckleneuk/Groenkloof Feeder route characteristics are summarised as follows:

Route length:	9 244.1 m
Total impedance:	79.351
Average impedance:	8.584/km
Travel time:	39.6 min

7.3 Scenario Routes

In an MCA, it is seldom found that all criteria are considered equal. Various stakeholders and Interested and Affected Parties would be consulted in a multi-criteria decision model to create a robust weighting scheme. Due to time and budget constraints, stakeholder engagement was not possible in this research. Alternatively, scenarios were created to represent the interests of different stakeholder and ascertain how the routes would change should their weighting schemes be implemented. With five criteria groups, there were over 120 possible weighting combinations to choose from. The final scenario weighting schemes were chosen on their probability of being critical weighting schemes (Table 7-1):

Table 7-1: Weighting Schemes for Scenario Routes

		Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Criteria	Transport efficiency	0.33	0.27	0.27	0.27
	Economic efficiency	0.27	0.33	0.07	0.07
	Equity	0.13	0.20	0.33	0.20
	Environmental impact	0.20	0.13	0.13	0.33
	Social impact	0.07	0.07	0.20	0.13

7.3.1 Scenario Composite Suitability Maps

Composite suitability maps were produced for all four scenarios (Figure 7-19 to Figure 7-22):

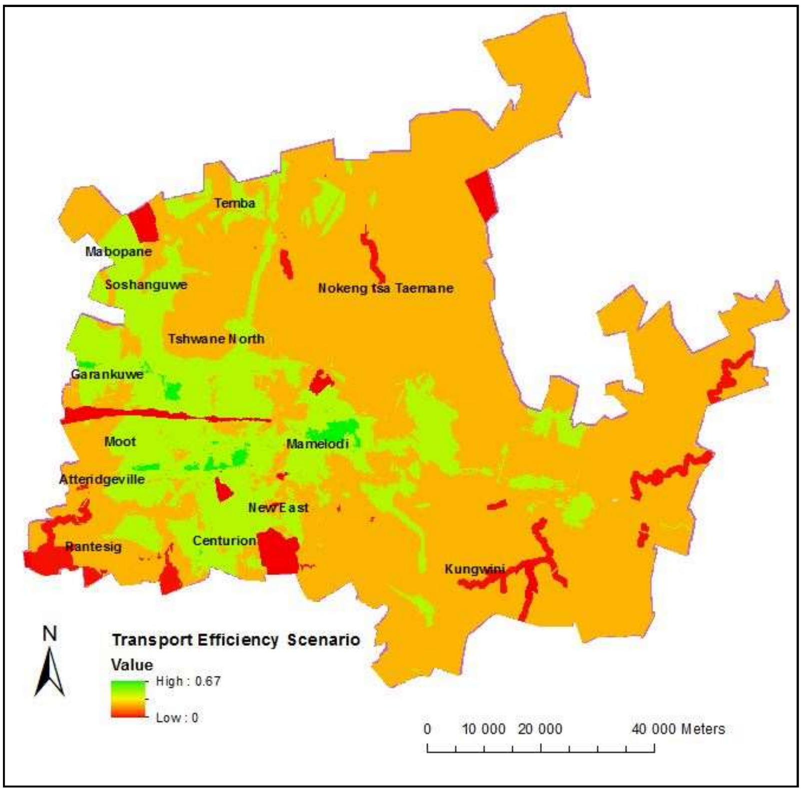


Figure 7-19: Transport Efficiency Scenario Composite Suitability Map

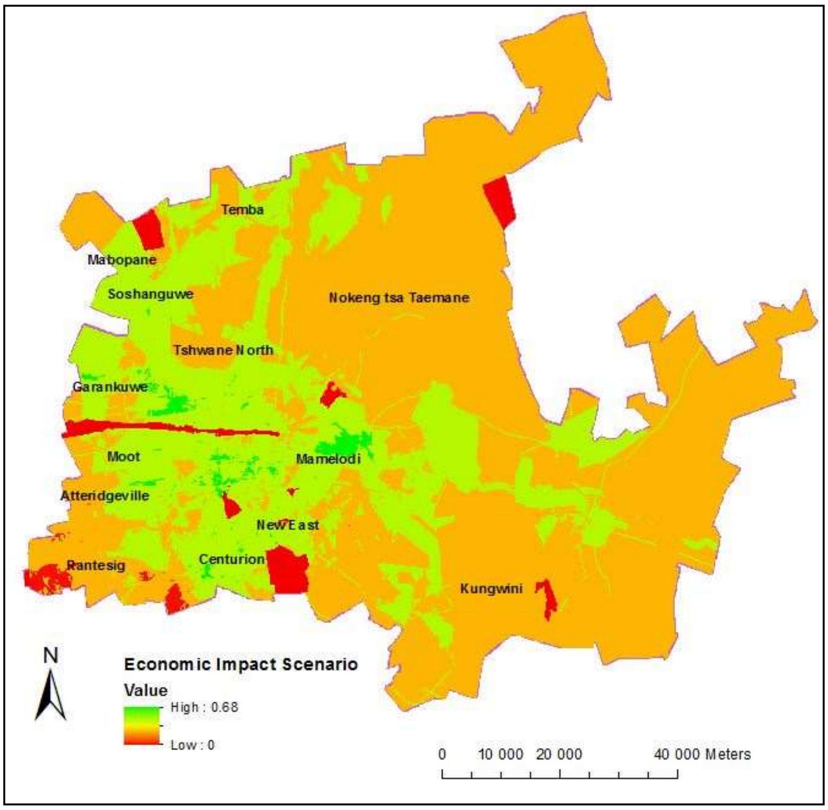


Figure 7-20: Economic Impact Scenario Composite Suitability Map

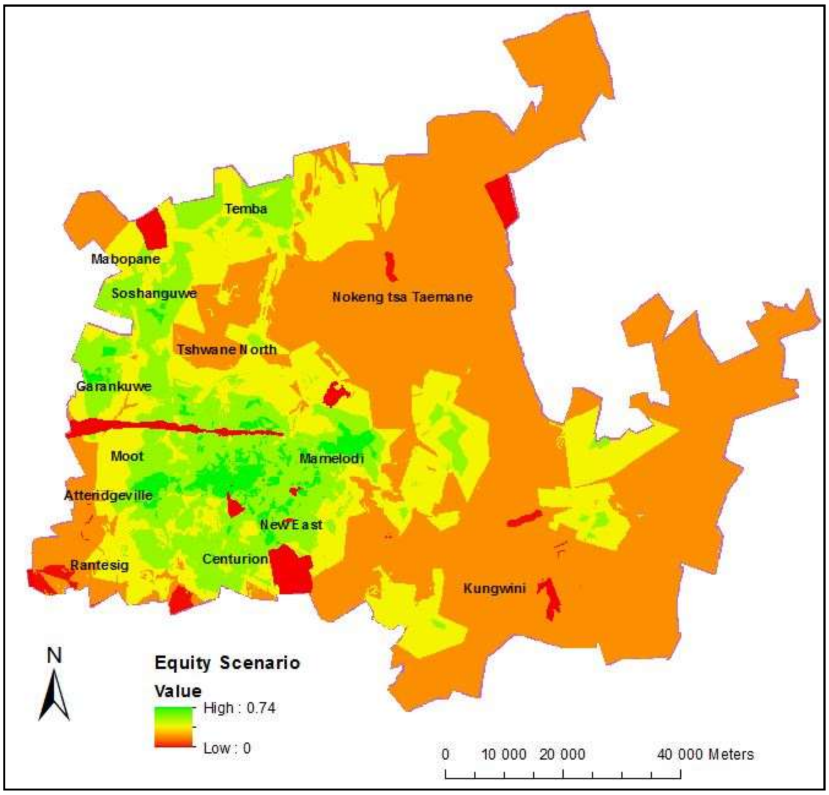


Figure 7-21: Equity Scenario Composite Suitability Map

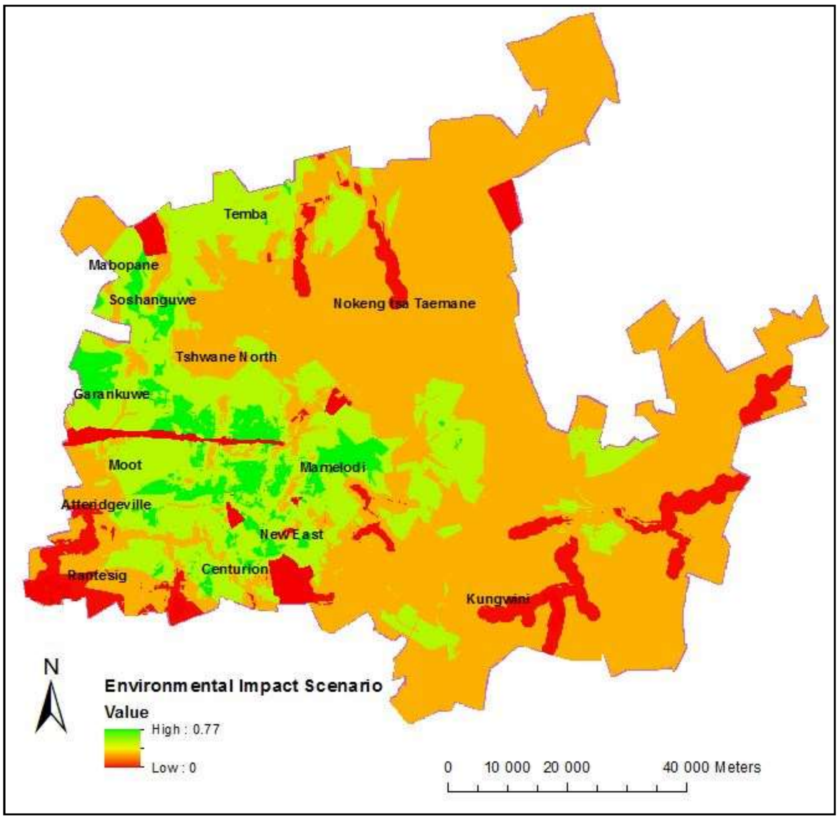


Figure 7-22: Environmental Impact Scenario Composite Suitability Map

A common feature of all four composite suitability maps is that the areas around Centurion, Central Tshwane, New East, Mamelodi and Garnakuwa obtain high suitability scores. In the transport efficiency suitability map (Figure 7-19), residential areas obtain high suitability scores. Central Tshwane scores highly in the economic impact scenario suitability map (Figure 7-20). In the equity scenario map (Figure 7-21), the poorer communities of Temba, Soshanguve, Garankuwa and Mamelodi score very highly. Lastly, the areas around waterways obtain a low score in the environmental impact scenario map (Figure 7-22).

The weighting schemes shown in Table 7-1 were applied to all eight routes, and the results obtained are as follows:

7.3.2 Trunk 1A

With all scenario routes, there is an aversion to follow the R101 from Stop 1 to Stop 2, indicating high impedance in that area (Figure 7-23 and Figure 7-24):

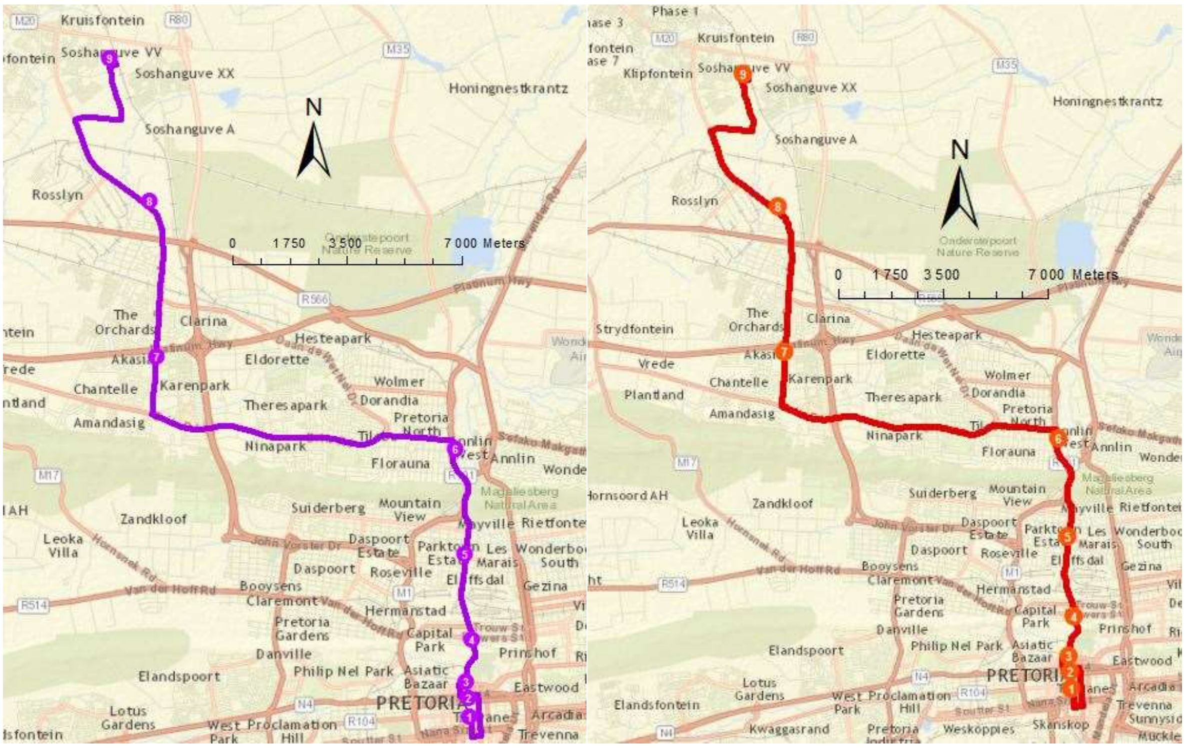


Figure 7-23: Trunk 1A Transport Efficiency and Economic Impact Scenario Routes on the Left and Right Respectively

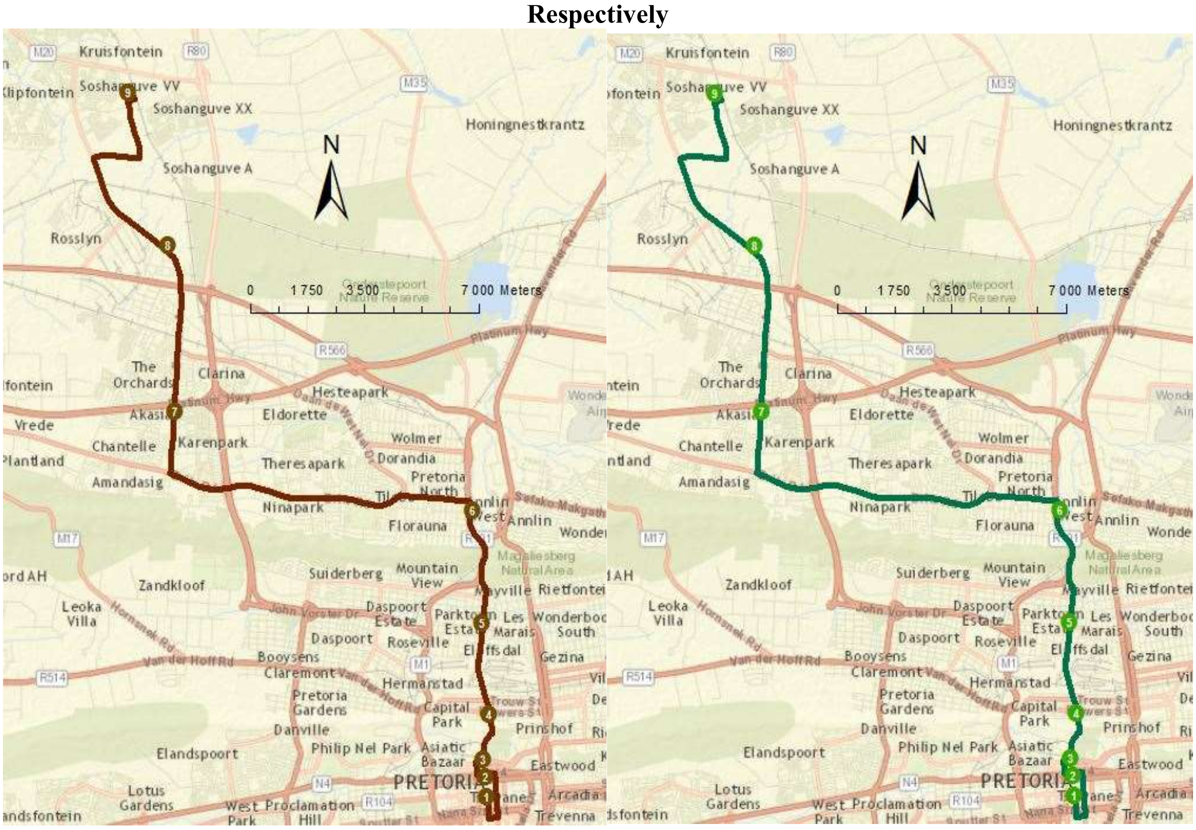


Figure 7-24: Trunk 1A Equity and Environmental Impact Scenario Routes on the Left and Right Respectively

The routes follow the R101 all the way to Stop 6. Thereafter, all scenario routes follow the same roads to Stop 9 as those described in the equal weighting route in section 7.1.1. This is significant as it indicates robustness in that section of the route. The route from Stops 6 to 9 remain the same despite the weighting scheme applied. Scenario routes were compared to the reference route in terms of impedance, total length, travel time and average impedance (Table 7-2):

Table 7-2: Trunk 1A Scenario Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Efficiency Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	157.018	128.925	154.494	161.013	144.047
Total length (m)	37 733.054	31 048.071	31 048.071	31 048.071	31 048.071
Travel time (min)	94.0	76.5	76.5	76.5	76.5
Impedance/km	4.161	4.152	4.976	5.186	4.639

All four scenario route have the same route length and travel time, indicating that they follow the same path. Furthermore, the travel time decreases by 17’30’’. It would thus be worth implementing one of the scenario routes over the equal impact route. The transport efficiency route would be a fair implementation as it has the lowest average impedance of all routes.

7.3.3 Trunk 1B

Trunk 1B scenario routes did not experience major route changes (Figure 7-25 and Figure 7-26)

Figure 7-25: Trunk 1B Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

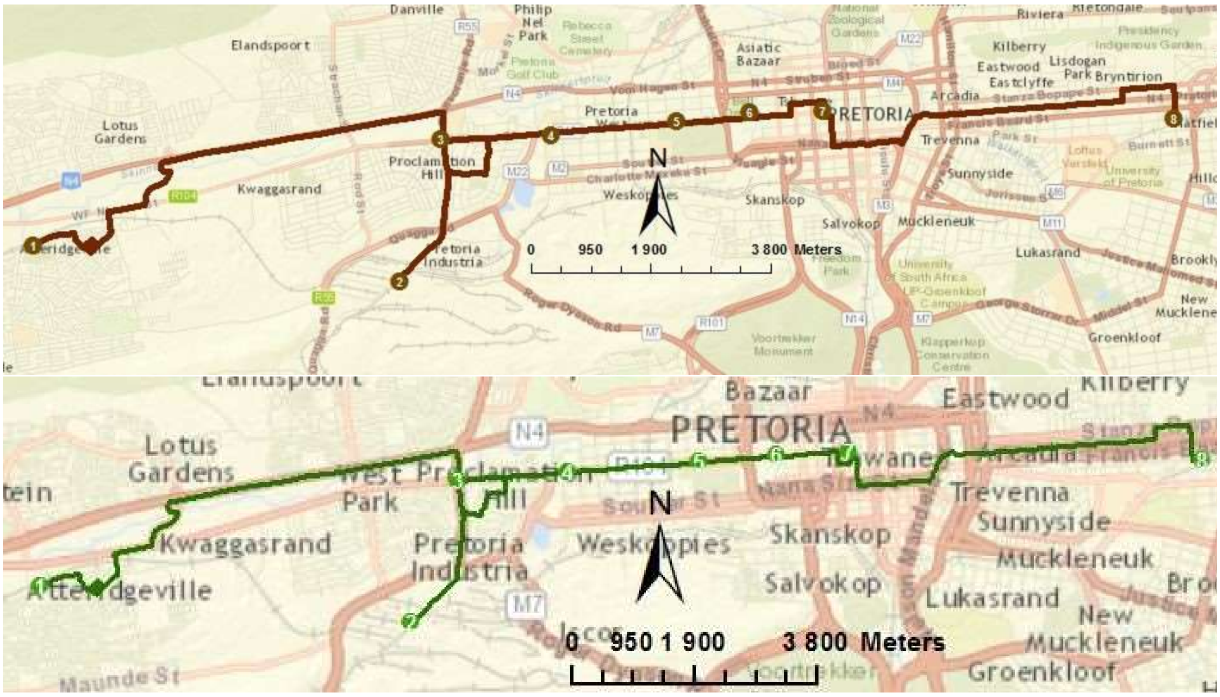


Figure 7-26: Trunk 1B Equity and Environmental Impact Scenario Routes on the Top and Bottom Respectively

The most significant changes in all four routes occur around Stops 6 and 7, and shortly after Stop 7. The environmental impact scenario route deviates from Stop 3 (Figure 7-26). The route characteristics show that every scenario route differs from the reference case route (Table 7-3):

Table 7-3: Trunk 1B Scenario Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	127.064	140.006	142.464	130.363	131.652
Total length (m)	25 679.956	26 031.793	26 891.950	26 026.589	26 334.633
Travel time (mins)	94.0	97.2	95.5	97.3	93.5
Impedance/km	4.948	5.378	5.298	5.009	4.999

From the maps depicted in Figure 7-25 and Figure 7-26, as well as the data from Table 7-3, it is evident that all routes for Trunk 1B follow different paths. This is an indication of high sensitivity to different weighting schemes. As such, the route cannot be judged to be robust.

7.3.4 Trunk 2A

Scenario routes obtained for Trunk 2A do not display any differences from one another (Figure 7-27 and Figure 7-28):

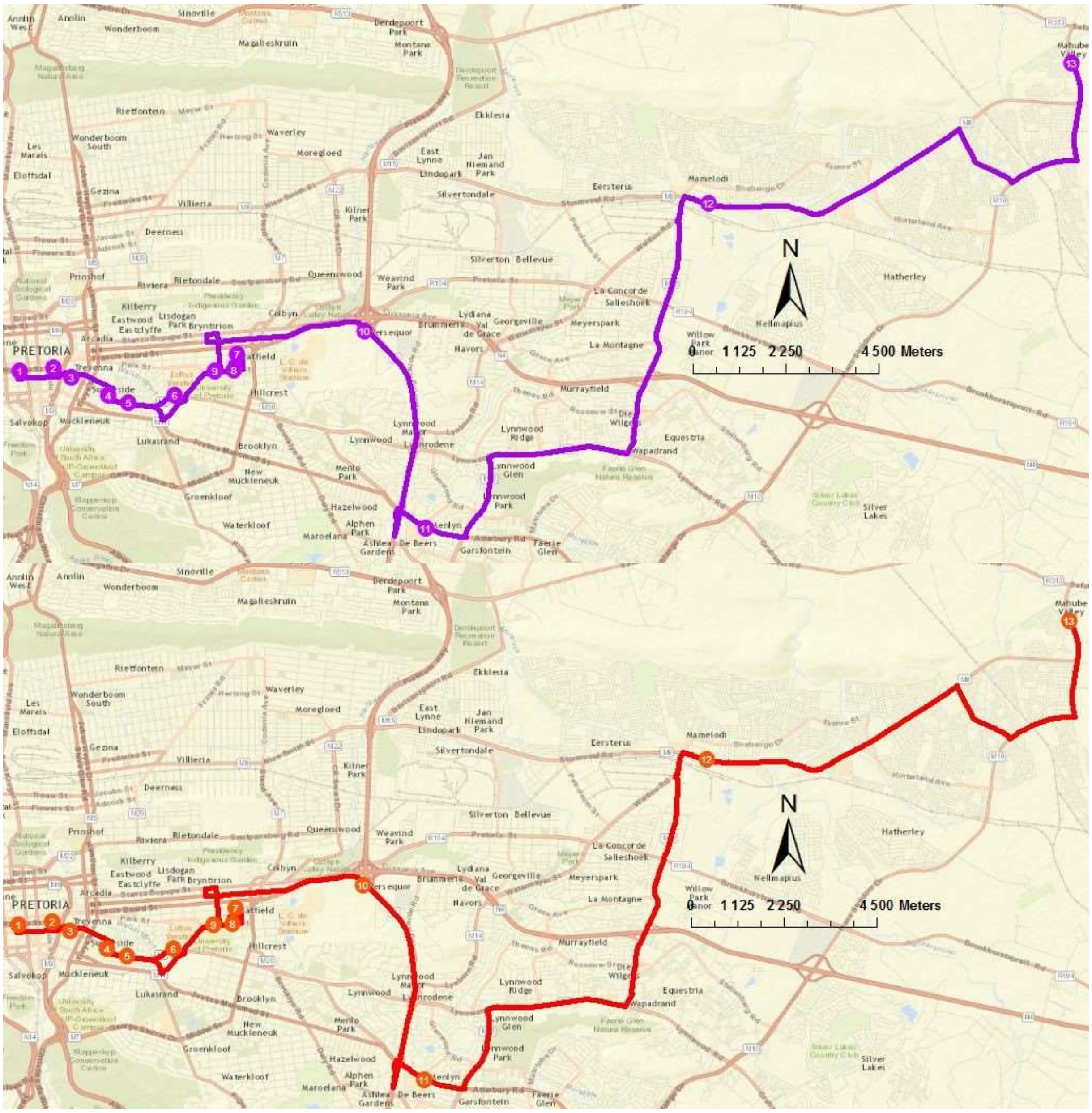


Figure 7-27: Trunk 2A Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

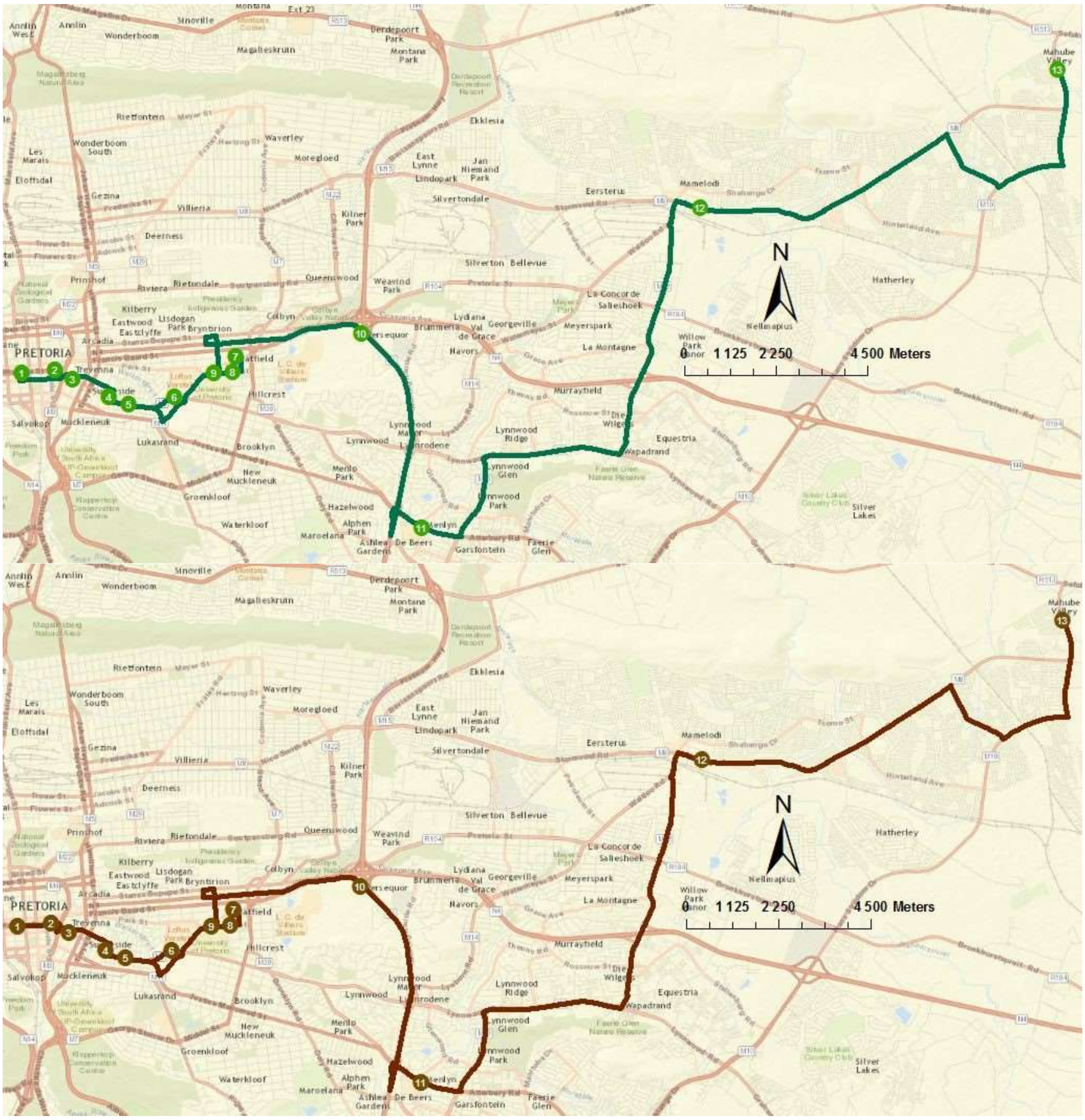


Figure 7-28: Trunk 2AEquity and Environmental Impact Scenario Route on the Top and Bottom Respectively

The differences among all routes are minor, which is evident in the average impedance values obtained (Table 7-4):

Table 7-4: Trunk 2A Scenario Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	223.475	253.355	249.059	236.715	232.117
Total length (m)	44 652.742	44 646.971	44 646.971	44 628.532	44 652.742
Travel time (mins)	117.6	117.6	117.6	117.7	117.6
Impedance/km	5.005	5.675	5.578	5.304	5.198

The equal theme route and environmental impact scenario route are identical. The same applies for the transport efficiency and economic impact scenario routes. The mean impedance is 5.352/km, and all results fall within two standard deviations of the mean. The equal theme route obtained the lowest average impedance, thus performing the best.

7.3.5 Trunk 2B

For Trunk 2B, the transport efficiency and economic impact scenario routes are identical to each other (Figure 7-29). Likewise, the equity and environmental impact scenario routes are, identical to each other (Figure 7-30):

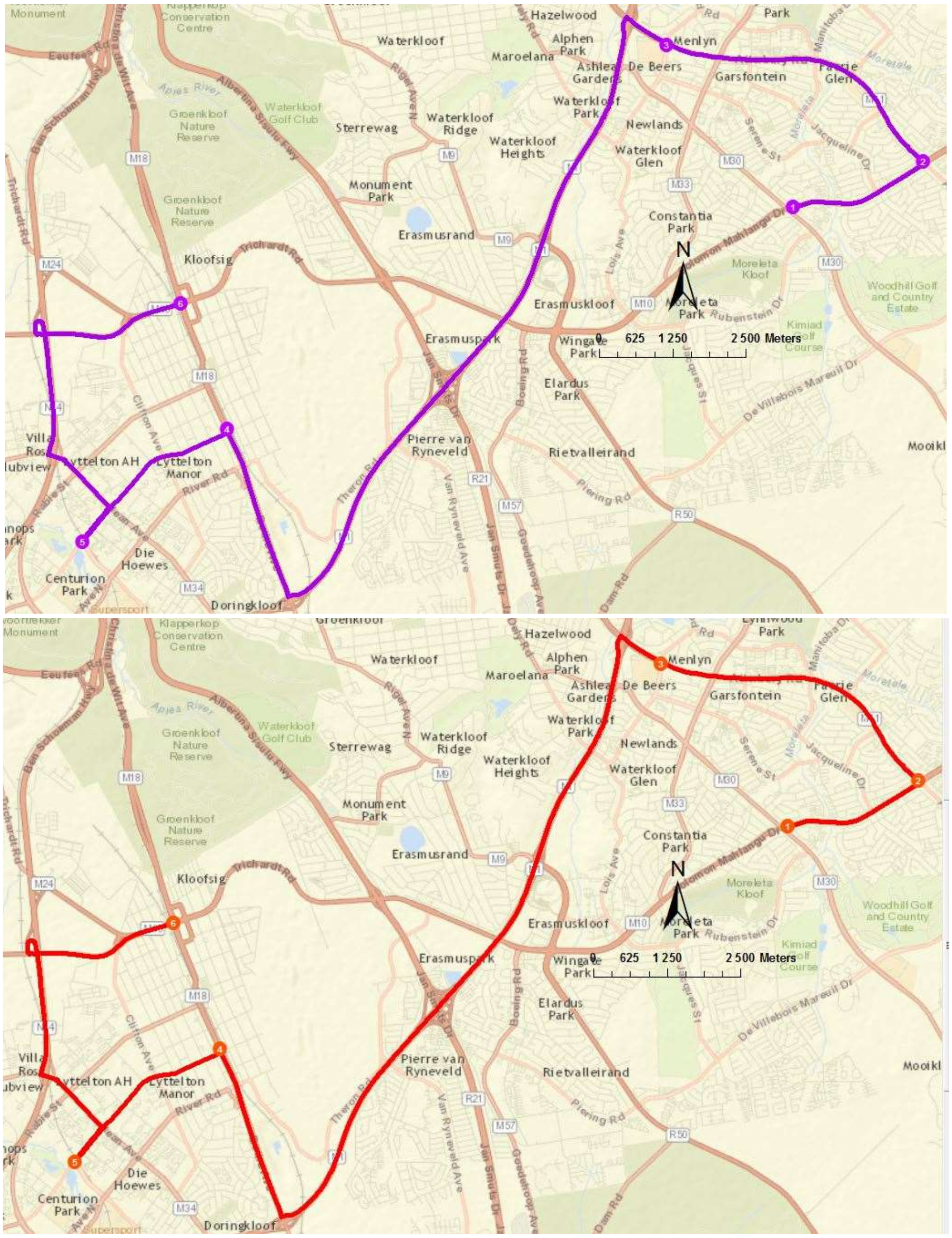


Figure 7-29: Trunk 2B Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

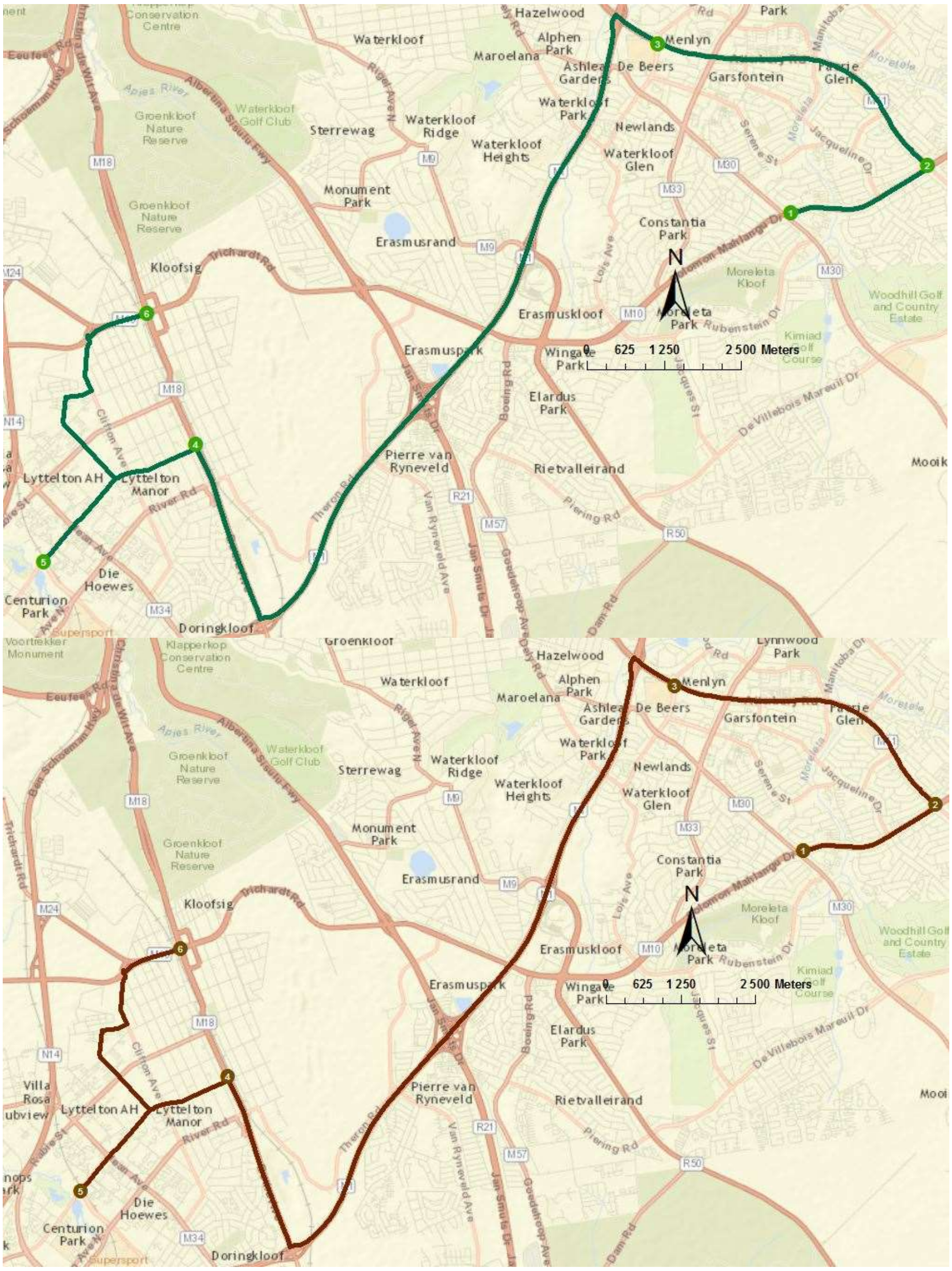


Figure 7-30: Trunk 2B Equity and Environmental Impact Scenario Route on the Top and Bottom Respectively

Apart from the transport efficiency and economic impact scenario routes, all scenario routes differ from the reference case (Table 7-5):

Table 7-5: Trunk 2B Scenario Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	130.783	136.534	123.926	129.715	130.430
Total length (m)	31 076.832	30 638.136	30 638.136	29 306.496	29 306.496
Travel time (mins)	47.1	55.9	55.9	57.3	57.3
Impedance/km	4.208	4.456	4.045	4.426	4.451

While the equal theme route is the longest, it has the shortest travel time of all four scenario routes. It can be deduced that the equal theme route makes use of higher class routes more than the scenario routes.

7.3.6 S Side/Steve Biko Feeder

This feeder route remains unchanged, except in the economic impact and environmental impact scenario routes on the approach to Stop 10 (Figure 7-31 and Figure 7-32):

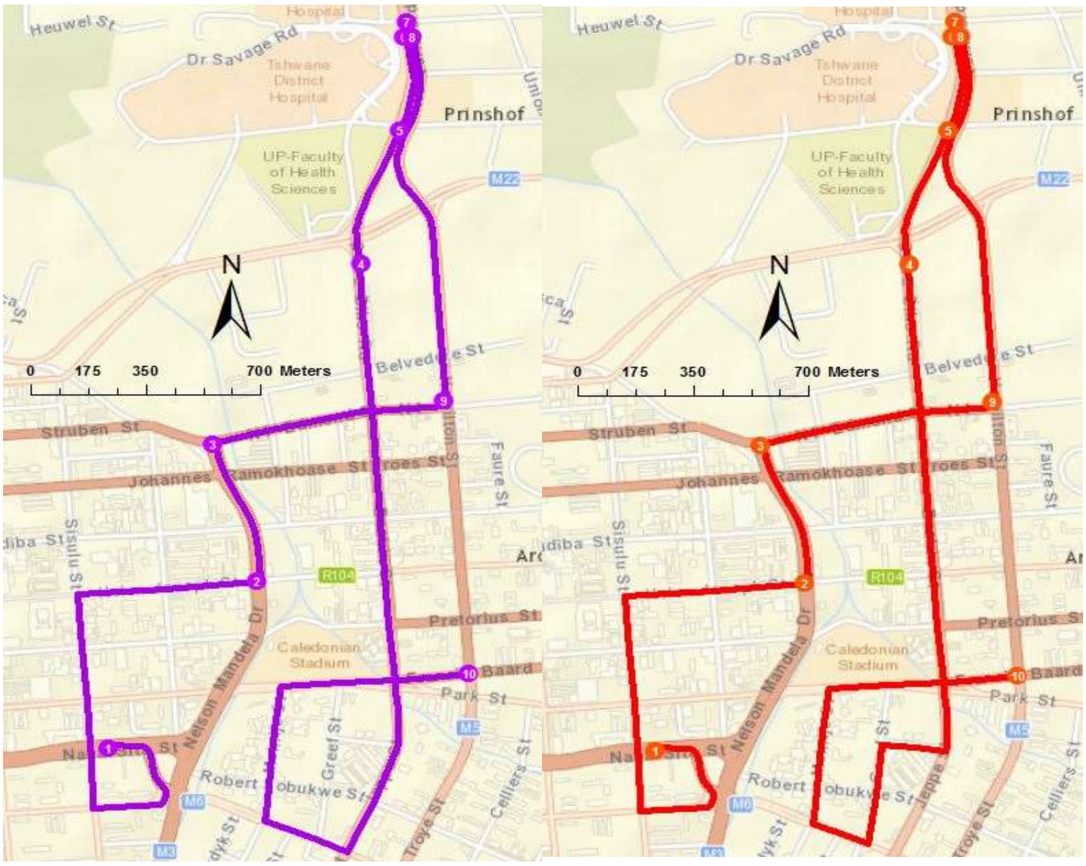


Figure 7-31: S. Side/Steve Biko Feeder Transport Efficiency and Economic Impact Scenario Routes on the Left and Right Respectively

Figure 7-32: S. Side/Steve Equity and Environmental Impact Scenario Routes on the Left and Right Respectively

The equal theme, transport efficiency scenario and equity scenario routes are all identical to one another, indicating some degree of robustness. The economic and environmental impact routes are identical to one another as well (Table 7-6):

Table 7-6: S. Side/Steve Biko Feeder Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	53.153	60.384	58.665	54.239	59.917
Total length (m)	7 753.590	7 753.590	7 801.736	7 753.590	7 801.736
Travel time (mins)	20.1	20.1	20.3	20.1	20.3
Impedance/km	6.855	7.788	7.520	6.995	7.680

The equal theme route obtained the shortest route and travel time, along with the transport efficiency scenario route and the equity scenario route. Where the equal theme route obtains an advantage over the other routes is in its low average impedance. Therefore, the S. Side/Steve Biko feeder route to be implemented should be the equal theme route.

7.3.7 CBD/Steve Biko Feeder

For the CBD/Steve Biko Feeder route, all scenario routes remain unchanged from the reference route (Figure 7-33 and Figure 7-34):

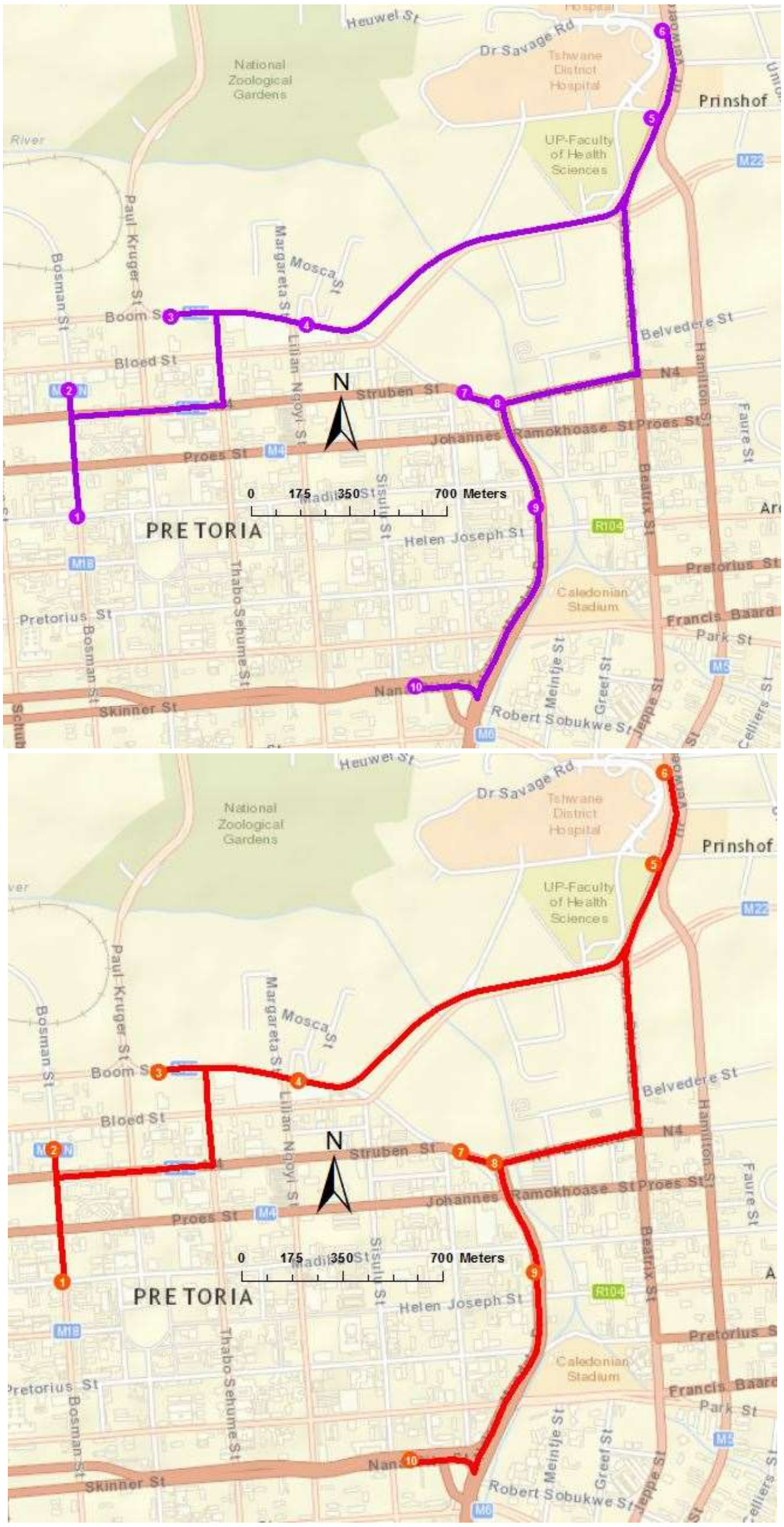


Figure 7-33: CBD/Steve Biko Feeder Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

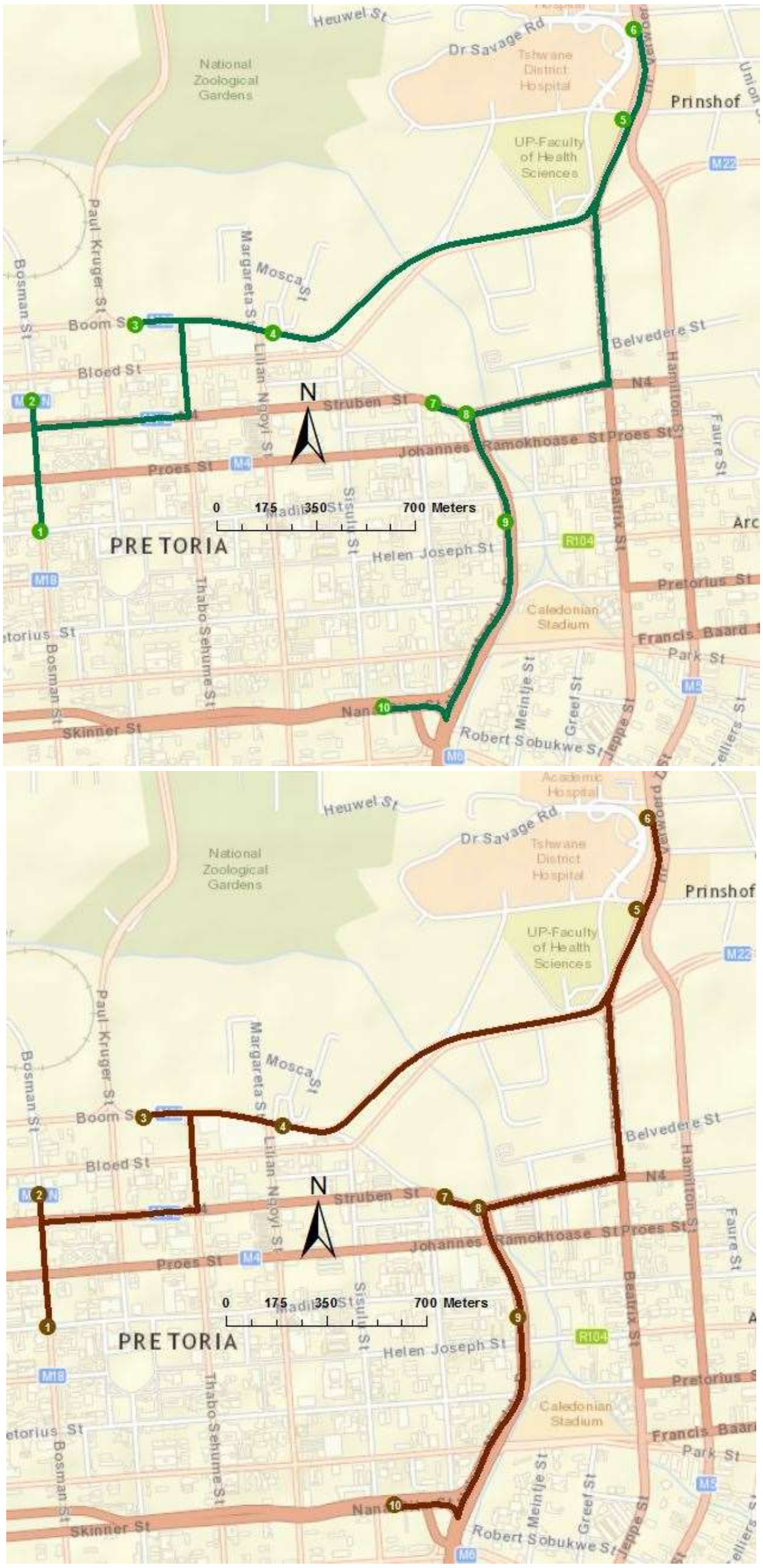


Figure 7-34: CBD/Steve Biko Feeder Equity and Environmental Impact Scenario Route on the Top and Bottom Respectively

The PTA CBD/Steve Biko route has a good travel time of 21.6 minutes (Table 7-7). The equal theme route obtained the lowest average impedance and consequently performed the best.

Table 7-7: PTA CBD/Steve Biko Feeder Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	62.039	69.991	68.114	63.344	67.589
Total length (m)	6 763.252	6 763.252	6 763.252	6 763.252	6 763.252
Travel time (mins)	21.6	21.6	21.6	21.6	21.6
Impedance/km	9.173	10.349	10.071	9.366	9.994

A change in criteria weights did not change the route characteristics (Table 7-7). It can be concluded that the PTA CBD/Steve Biko Feeder is a robust route. As such, this route can thus be implemented with confidence as is. The mean average impedance is 10.289/km and all average impedances lie within two standard deviations of the mean, indicating low variance.

7.3.8 Pretoria West/TUT Feeder

The only Pretoria West/TUT scenario route that changed from the reference route was the Equity scenario route, after Stop 4 Figure 7-35: Pretoria West/TUT Feeder Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively (Figure 7-35 and Figure 7-36). The change in route added 847 m to the equal theme route (Table 7-8):

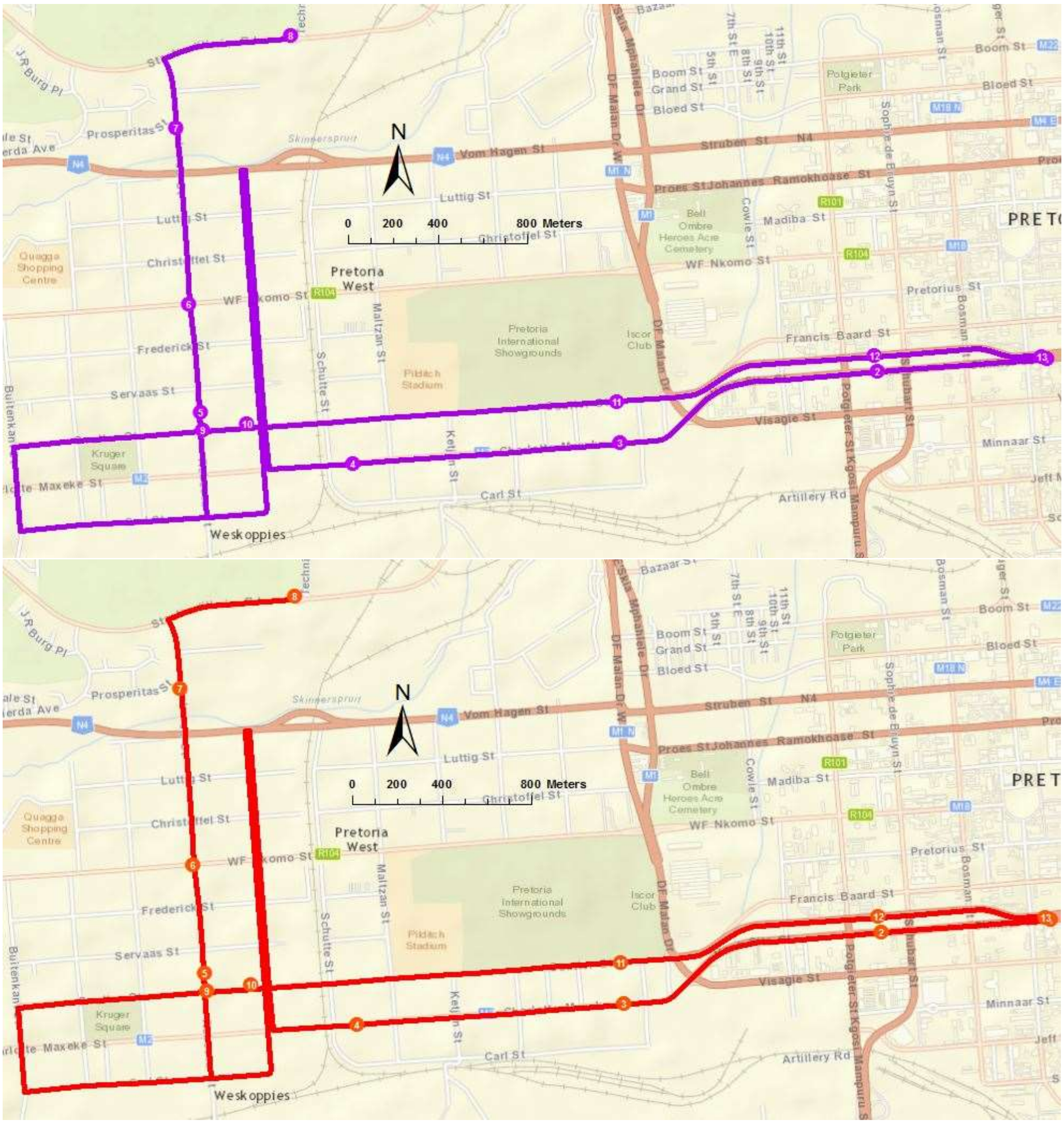


Figure 7-35: Pretoria West/TUT Feeder Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

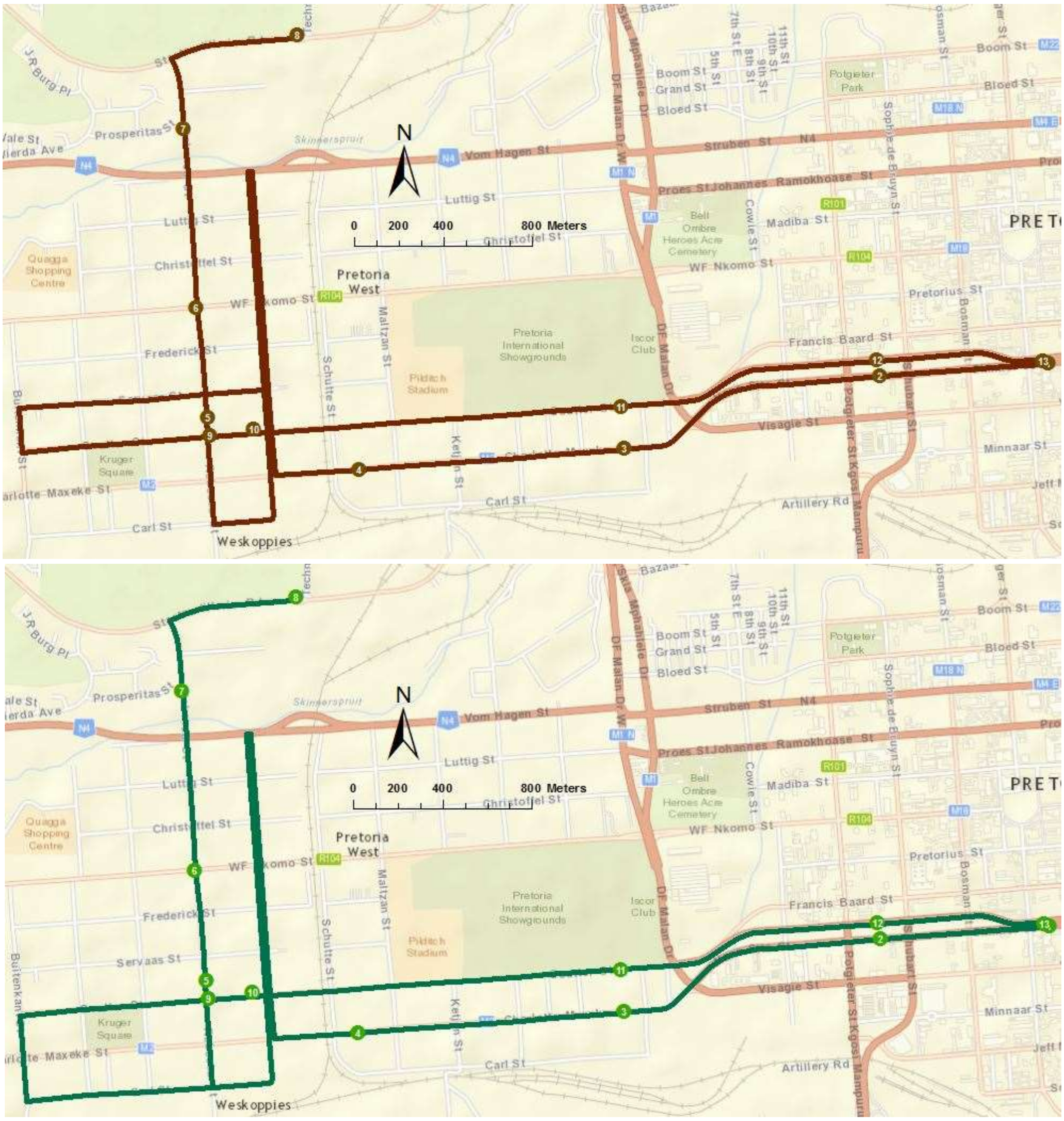


Figure 7-36: Pretoria West/TUT Feeder Equity and Environmental Impact Scenario Routes on the Top and Bottom Respectively

A high travel time of 54 minutes indicates that the Pretoria West/CBD feeder routes make use of many lower order, accessibility roads (Table 7-8):

Table 7-8: Pretoria West/TUT Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	58.442	66.472	67.822	57.799	61.004
Total length (m)	16 277.503	16 277.503	16 277.503	17 124.495	16 277.503
Travel time (mins)	54.0	54.0	54.0	54.6	54.0
Impedance/km	3.590	4.084	4.167	3.375	3.748

The PTA West/TUT feeder route performs relatively consistently across the equal theme and scenarios. The mean average impedance is 3.793/km, and all average impedances fall within two standard deviations of the mean, indicating low variance within the route.

7.3.9 Muckleneuk/Groenkloof Feeder

While the routes remain relatively similar, slight variances occur between Stops 11 and 12 (Figure 7-37 and Figure 7-38):

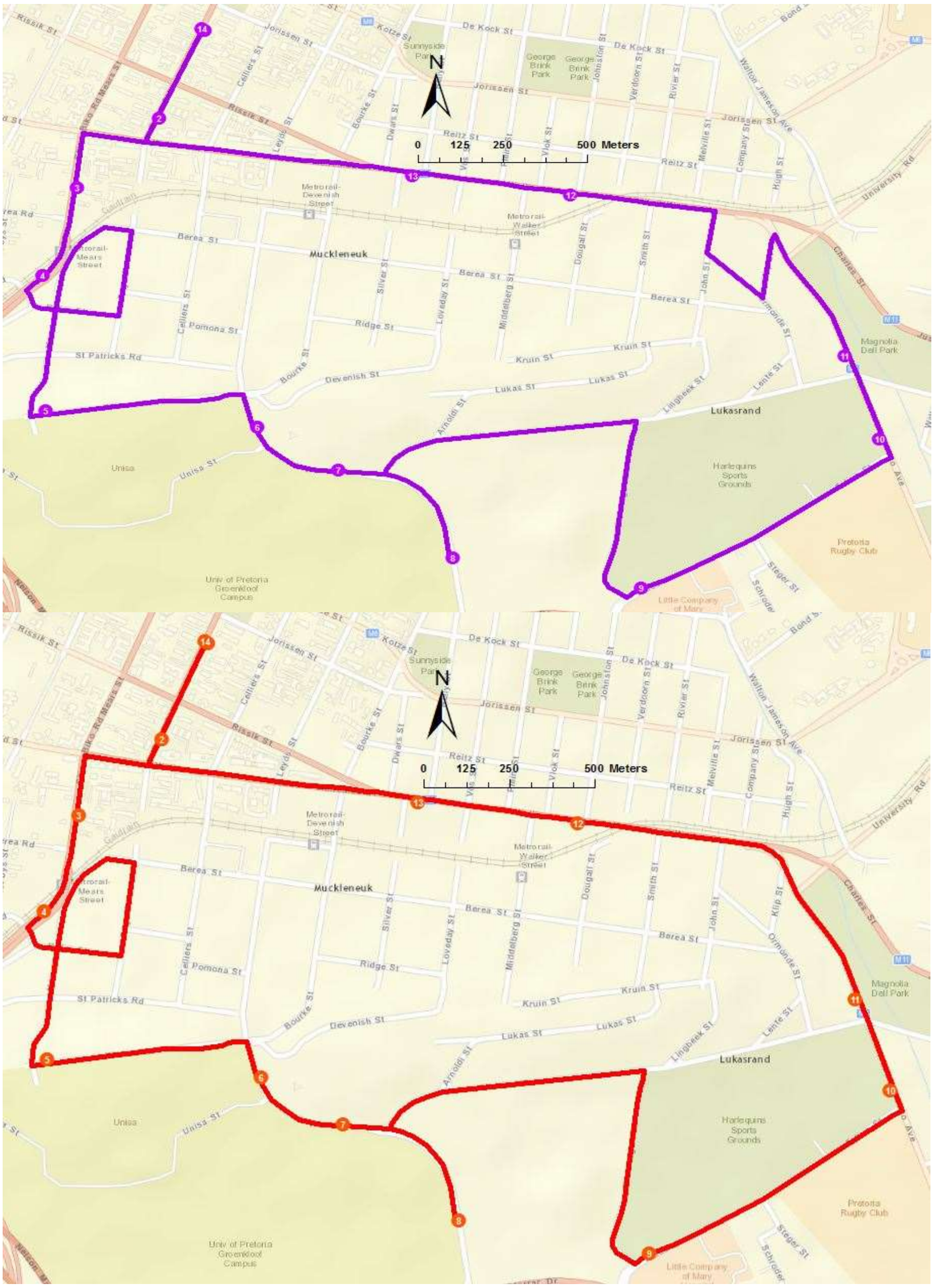


Figure 7-37: Muckleneuk/Groenkloof Feeder Transport Efficiency and Economic Impact Scenario Routes on the Top and Bottom Respectively

Figure 7-38: Muckleneuk/Groenkloof Feeder Equity and Environmental Impact Scenario Route on the Top and Bottom Respectively

The most optimal route is the equity scenario route, which obtained the lowest average impedance of 8.298/km. In addition, the travel time is a minute longer than the fastest route, which is the environmental impact scenario route (Table 7-9):

Table 7-9: Muckleneuk/Groenkloof Feeder Route Characteristics

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Impedance	79.351	84.185	83.719	76.711	81.720
Total length (m)	9 244.096	9 244.096	8 915.841	9 244.096	9 046.920
Travel time (mins)	39.6	39.6	39.0	39.6	38.6
Impedance/km	8.584	9.107	9.390	8.298	9.033

7.3.10 Ranking of Routes

For the equal theme and scenario routes, routes were ranked in terms of average impedance. This ranking allows one to critique how each route performs when a certain weighting scheme is adopted. In addition, the ranking shows which routes should be prioritised if a scenario were to be implemented.

Trunk 2B proved to be the best performing route, ranking first in 60% of the cases. Trunks 2B and 1A both share the overall second spot ranking. The route that ranked third in 80% of the cases is Trunk 1B. Trunk 2A consistently ranked last. For the feeder routes, the ranking remained consistent (Table 7-10):

Table 7-10: Ranking of Routes

	Equal Theme	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Rank	**Trunk routes**				
1	Trunk 1A	Trunk 1A	Trunk 2B	Trunk 2B	Trunk 2B
2	Trunk 2B	Trunk 2B	Trunk 1A	Trunk 1B	Trunk 1A
3	Trunk 1B	Trunk 1B	Trunk 1B	Trunk 1A	Trunk 1B
4	Trunk 2A	Trunk 2A	Trunk 2A	Trunk 2A	Trunk 2A
	Feeder routes				
1	Pretoria West/TUT	Pretoria West/TUT	Pretoria West/TUT	Pretoria West/TUT	Pretoria West/TUT
2	S. Side/Steve Biko	S. Side/Steve Biko	S. Side/Steve Biko	S. Side/Steve Biko	S. Side/Steve Biko
3	Muckleneuk/Groenkloof	Muckleneuk/Groenkloof	Muckleneuk/Groenkloof	Muckleneuk/Groenkloof	Muckleneuk/Groenkloof
4	CBD/Steve Biko	CBD/Steve Biko	CBD/Steve Biko	CBD/Steve Biko	CBD/Steve Biko

7.4 Résumé

Chapter 7 pertained to the results obtained during the application of an SMCA to BRT trunk and feeder routes in the CoT. Results were represented diagrammatically in the form of route maps, and quantitatively in the form of route characteristics. Where available, optimal reference case routes were compared to existing or planned routes. All the 6 routes that were comparable were found to vary to some degree from existing or planned routes, thereby indicating that the existing or planned routes are not optimised against the selected evaluation criteria. Thereafter, the chapter proceeded to present the results of the scenario routes in the same manner of that of reference case routes. Scenario routes represent possible outcomes had a stakeholder engagement been possible.

In conclusion, all routes were ranked in terms of average impedance over the reference case and the four scenarios. For trunk routes, Trunk 1A performed the best in 60% of the cases. It can thus be concluded that Trunk 1A is a robust, low-cost route. Trunk 2A performed the worst in 100% of the cases. In this regard, it can be concluded that Trunk 2A is a high-cost route, and is the least optimal of all trunk routes. Feeder routes performed consistently for all five cases, indicating high robustness against various weighting schemes. Their ranking, from best to worst is Pretoria West/TUT, S. Side/Steve Biko, Muckleneuk/Groenkloof, and CBD/Steve Biko.

8 Route Uncertainty Analyses

Uncertainty is defined as the occurrence of incomplete knowledge or information about a subject (Ascough II *et al*., 2008). In this dissertation, an uncertainty analysis was used to categorise uncertainties encountered at every level of the investigation, and to compute occurrences of sensitivities within the routes and within the criteria. A taxonomy of uncertainties encountered is presented through an uncertainty matrix. Thereafter, sensitivities in the evaluation criteria and routes are presented diagrammatically and quantitatively through a sensitivity analysis, and qualitatively through a scenario uncertainty analysis.

8.1 Taxonomy of Uncertainty

Uncertainty encountered at every stage of the research, from the problem definition to results, can be qualitatively expressed in an uncertainty matrix. Recall, the uncertainty matrix classifies uncertainty according to three dimensions (Walker *et al*., 2003):

i) *Location* of uncertainty: This is where the uncertainty occurs in the model, i.e. conception stage, results etc.;
ii) *Level* of uncertainty: This refers to how much knowledge exists within the evaluation model. It is where the uncertainty occurs along the spectrum of the unachievable goal of deterministic knowledge and the extreme of total ignorance; and
iii) *Nature* of uncertainty: This refers to why the uncertainty exists. Is it due to the imperfection of evaluator's knowledge, or the variability of the subject being appraised?

The first location of uncertainty lies in the context of the SMCA model. There exists a slight level of ambiguity in external factors, such as political, environmental, social and economic circumstances that form the context of this research. These circumstances have the potential to change daily and can thus never be expressed with 100% confidence. Uncertainty may then be found in the evaluation criteria used, which form the inputs of the SMCA model. While extensive research was carried out to formulate evaluation criteria, there will always be a certain level of indeterminacy generated from data sources. Thereafter, uncertainties are to be found the actual SMCA model. These uncertainties lie in the form of the SDSS itself arising from errors in the computer implementation. Lastly, uncertainties lie in the results of the SMCA model. These can be computed statistically, graphically and scenario-wise (Table 8-1). A high degree of uncertainty is demonstrated with +++, a moderate degree of uncertainty with ++, and a low degree of uncertainty with +.

Table 8-1: Uncertainty Matrix

Location of Uncertainty		**Level of Uncertainty**				**Nature of Uncertainty**		
		Statistical Uncertainty	Scenario Uncertainty	Qualitative uncertainty	Recognised Uncertainty	Epistemic uncertainty	Stochastic uncertainty	Ambiguity
Context	External political, environmental, economic and social circumstances that define context of research problem		+++		* (reduceable)			++
Inputs	System data: Criteria maps		+	+	+		+++	
	Driving forces: Scenario variables and policy variables		+++					+
Model	Model Structure: Uncertainty about the SMCA model	+	+++	+++				
	Technical Model: Uncertainty about the computer implementation of the model	+++ Quantifiable uncertainty of weights	+++		+			
	Parameters: Uncertainty related to parameter values of criteria		+++	++			+ Uncertainty, due to human behaviour	
Model Outputs: Uncertainty due to all the above		+++	++	+++ Expert opinions		++	+	++

8.2 Sensitivity Analysis

A sensitivity analysis (SA) of criteria weights was conducted, and the effects thereof mapped. A sensitivity analysis was conducted for each criteria theme, making five sensitivity analyses in total. For each sensitivity analysis, the weight of the corresponding criteria theme was changed by 30% from 0.20 as obtained in the reference case, to 0.50. The weights of the remaining five criteria decreased from 0.20 to 0.125 to ensure that the sum of the weights was 1.0 (Table 8-2). The following criteria form the standard against which sensitivity is assessed:

i) Determining whether a change in the weighting scheme caused a change in the route followed; and
ii) Determining whether an increase of 30% in a criteria theme weight caused a change of more than 30% in the average impedance of the reference case routes.

Routes that did not meet either of the above criteria were classified as not sensitive. Routes that met either one of the criteria were classified as moderately sensitive, and routes that met all the criteria were classified as highly sensitive.

Table 8-2: Sensitivity Analysis Weighting Scheme

		Transport Efficiency SA	Economic Impact SA	Equity SA	Environmental Impact SA	Social Impact SA
Criteria	Transport efficiency	0.50	0.125	0.125	0.125	0.125
	Economic impact	0.125	0.50	0.125	0.125	0.125
	Equity	0.125	0.125	0.50	0.125	0.125
	Environmental impact	0.125	0.125	0.125	0.50	0.125
	Social impact	0.125	0.125	0.125	0.125	0.50

8.2.1 Transport Efficiency SA

Suitability scores for this SA improved slightly from the maximum score of 0.71 to 0.72 (Figure 8-2). Recall that the minimum suitability score will always be zero due to the presence of constraints in the evaluation criteria. The composite suitability scores for reference case (Figure 8-1) is repeated for comparison's sake.

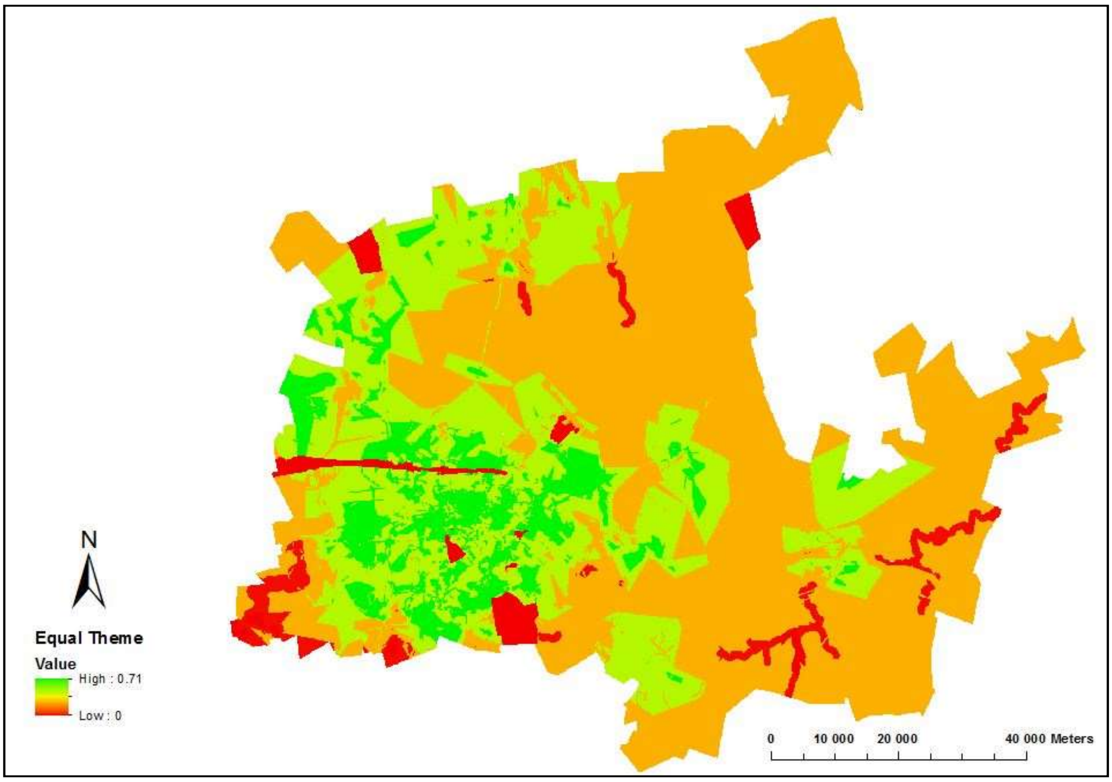


Figure 8-1: Equal Theme Composite Suitability Map

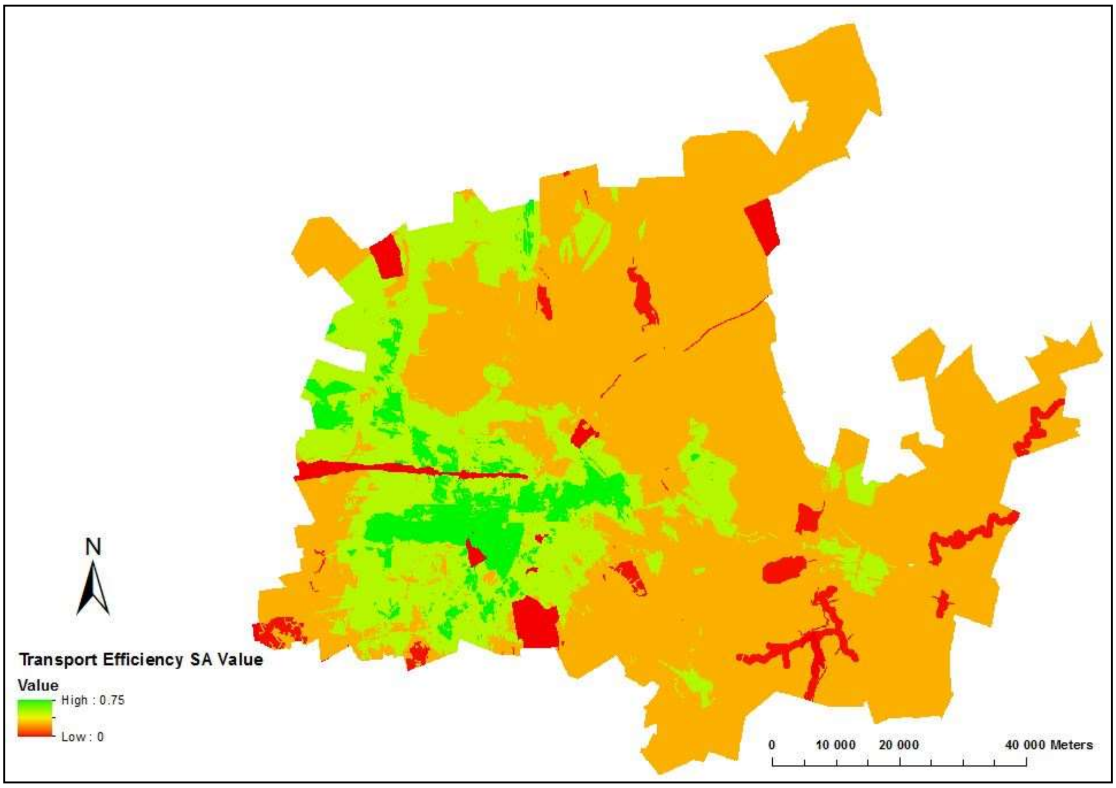


Figure 8-2: Transport Efficiency SA Composite Suitability Map

While the highest suitability score increased slightly from the reference case to the transport efficiency SA, the total area of high suitability decreased (Figure 8-2). Prioritising the transport efficiency criteria has resulted in less land being suitable for BRT routes.

Routes obtained from the sensitivity analyses overlay the reference case routes so that route sensitivity may be determined (Figure 8-3 to Figure 8-10):

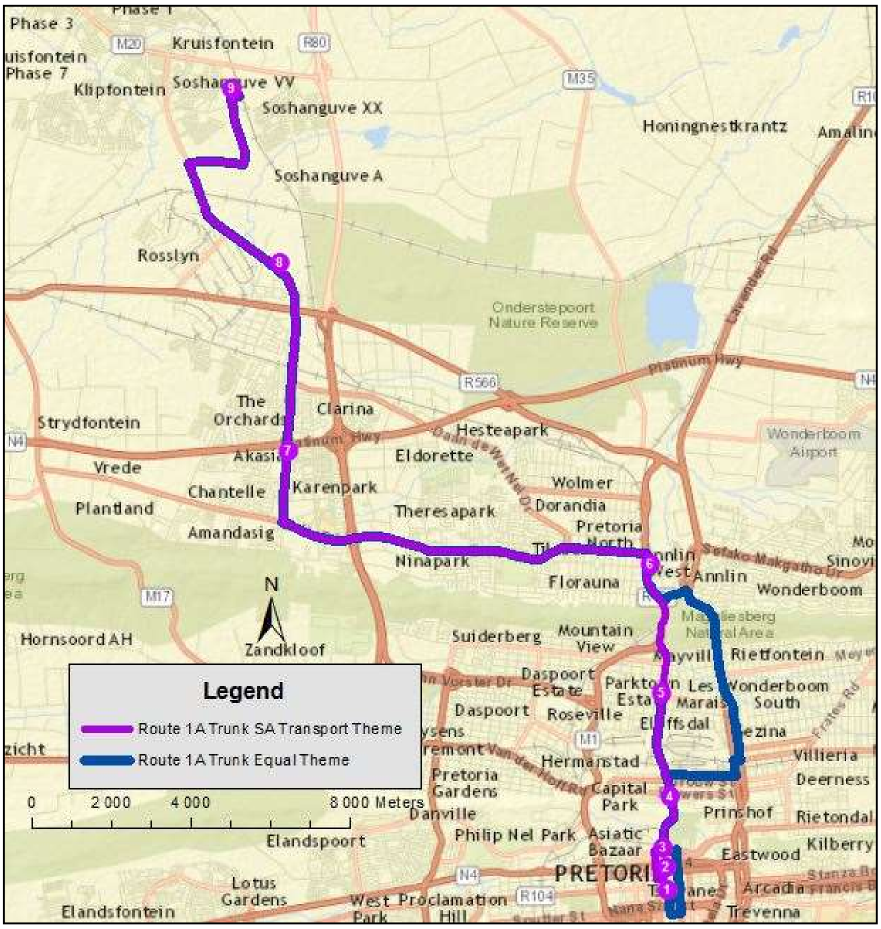


Figure 8-3: Trunk 1A Transport Impact SA

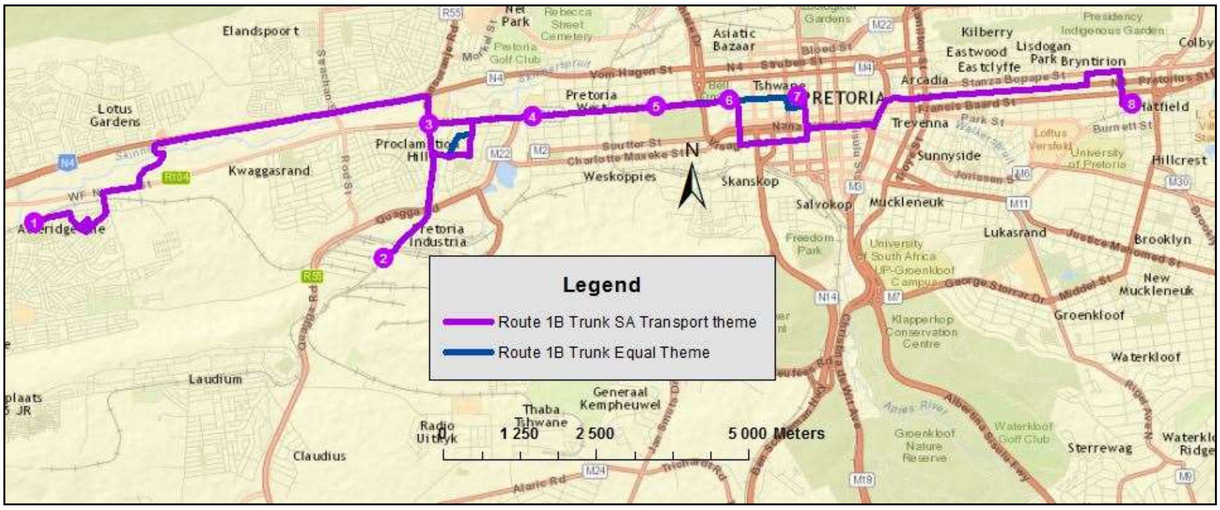


Figure 8-4: Trunk 1B Transport Impact SA

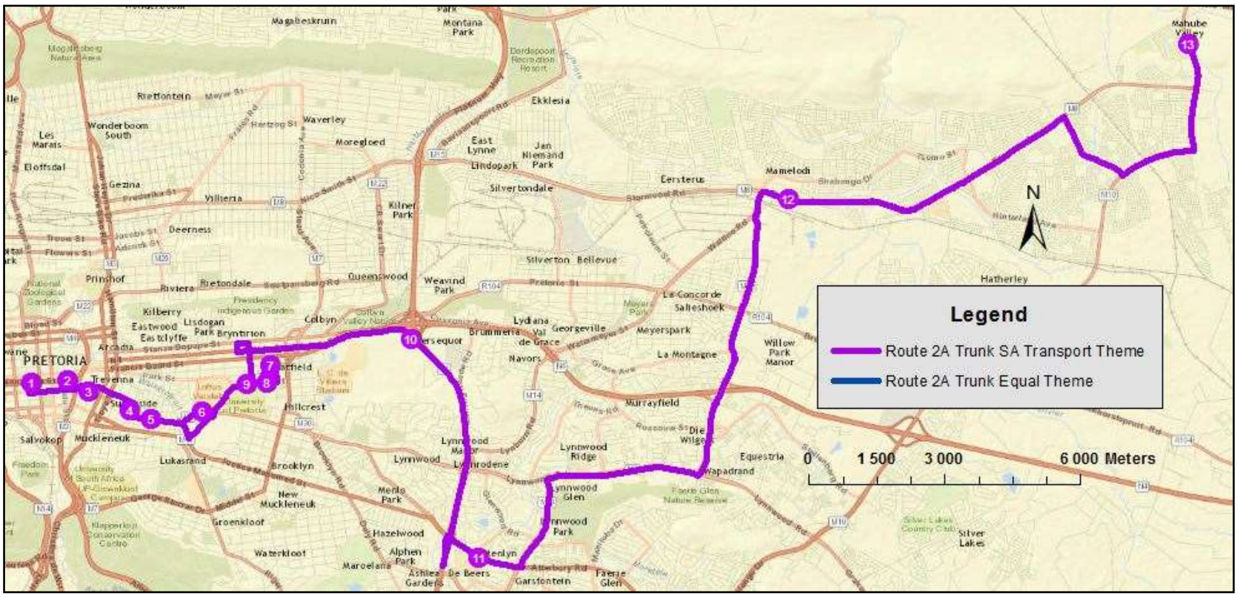


Figure 8-5: Trunk 2A Transport Impact SA

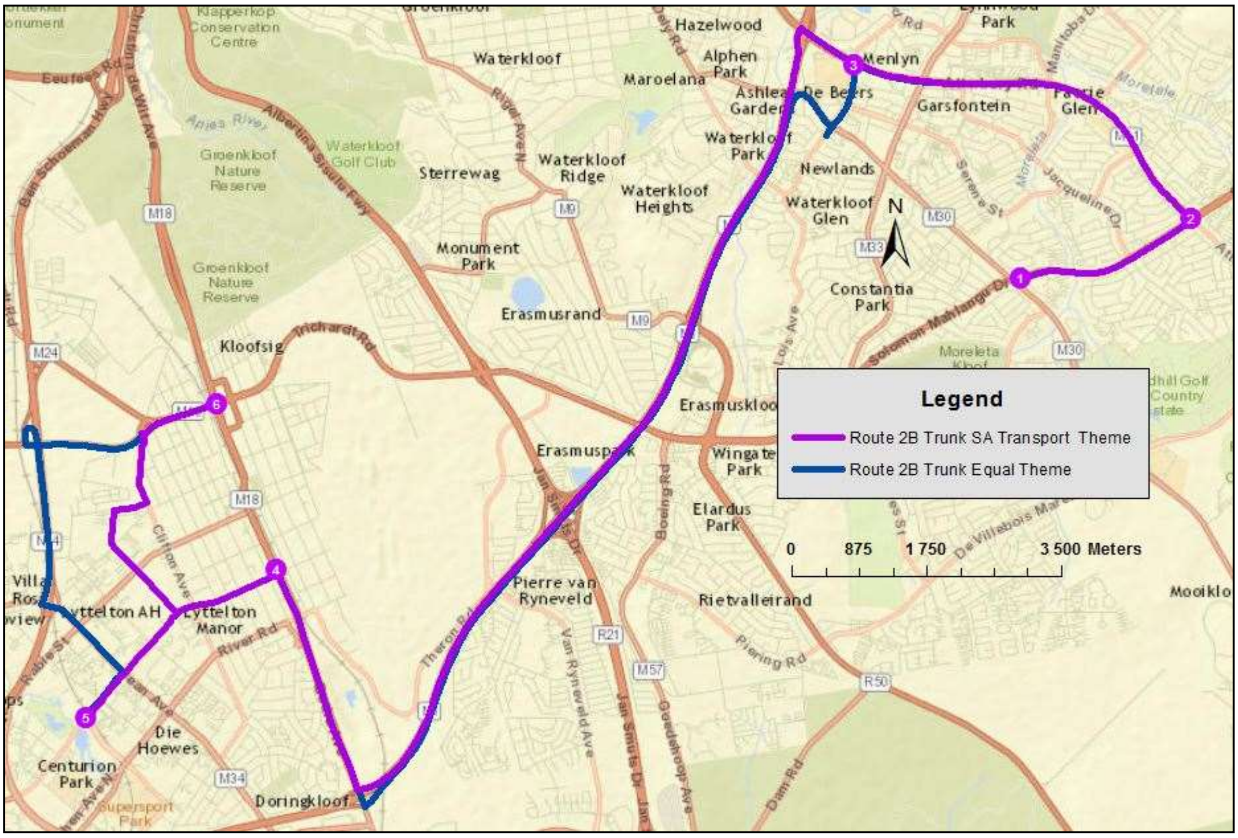


Figure 8-6: Trunk 2B Transport Impact SA

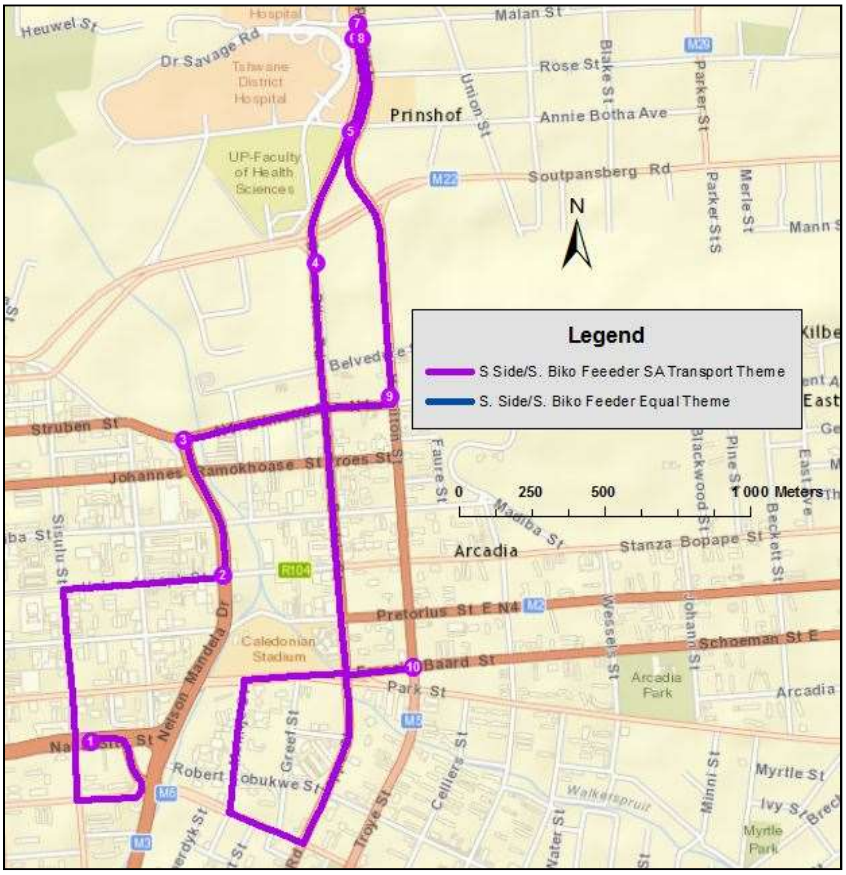


Figure 8-7: S. Side/Steve Biko Feeder Transport Impact SA

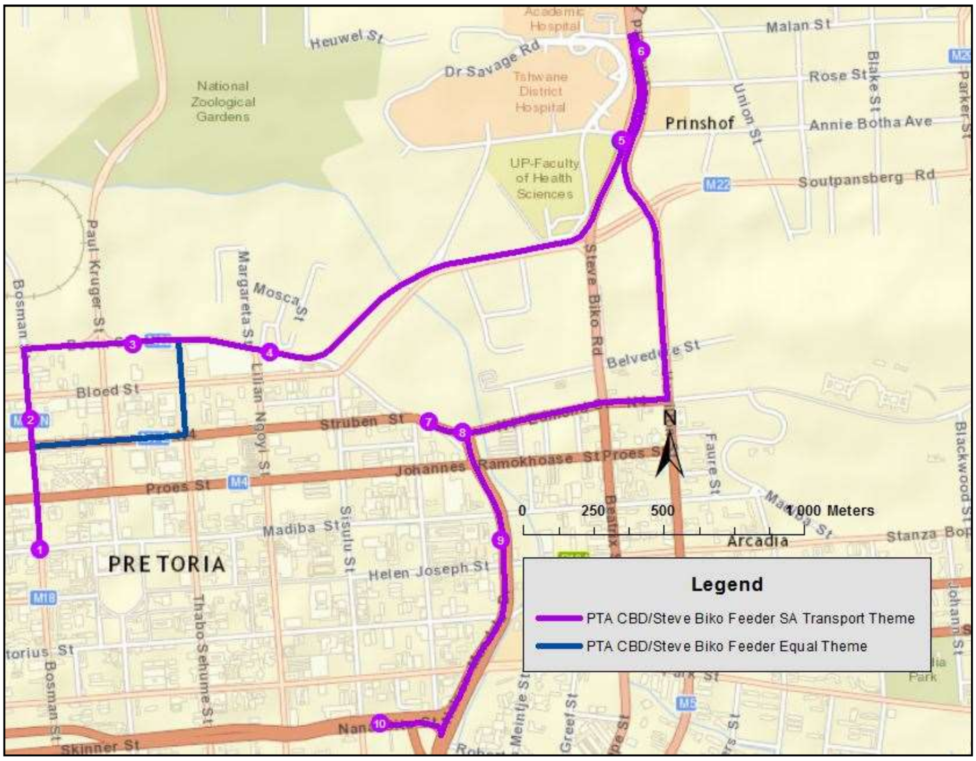


Figure 8-8: CBD/Steve Biko Feeder Transport Impact SA

Figure 8-9: Pretoria West/TUT Feeder Transport Impact SA

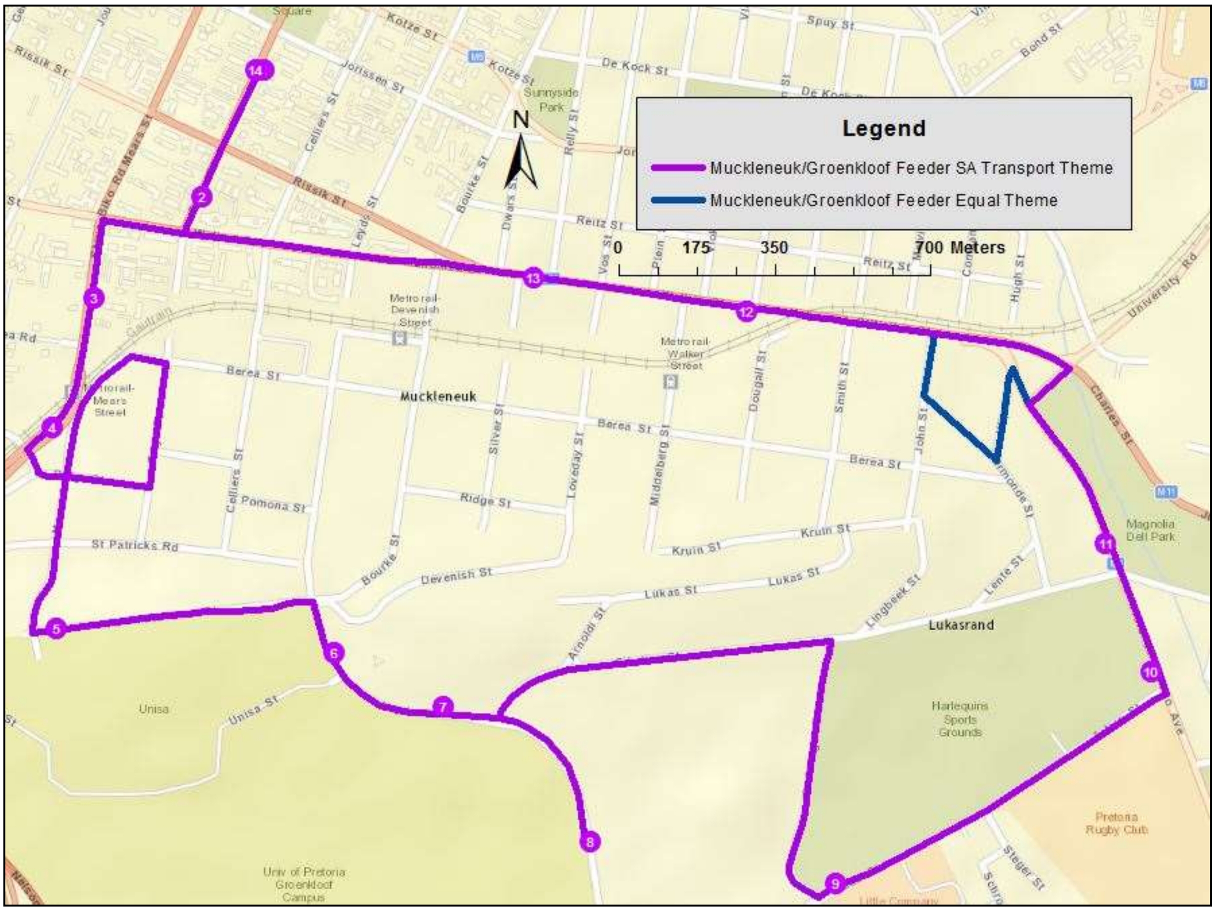


Figure 8-10: Muckleneuk/Groenkloof Feeder Transport Impact SA

Trunk 2A, S. Side/Steve Biko Feeder and Pretoria West/TUT Feeder routes are not sensitive to a change in transport efficiency criteria weights, whereas the remaining routes are. A quantitative assessment shows that 50% of all routes moderately change with a change in transport efficiency criteria (Table 8-3):

Table 8-3: Route Characteristics for Transport Efficiency SA

	Trunk 1A	**Trunk 1B**	**Trunk 2A**	**Trunk 2B**	**S. Side/Steve Biko Feeder**	**CBD/Steve Biko Feeder**	**Pretoria West/TUT Feeder**	**Muckleneuk/Groen-kloof Feeder**
Impedance	169.718	142.651	142.651	265.163	62.211	75.536	61.701	76.901
Total length (m)	30 109.147	26 891.950	26 891.950	44 646.971	7 753.590	6 634.957	16 277.503	9 047.233
Travel time (mins)	76.2	95.5	95.5	117.6	20.1	21.3	54.0	38.7
Impedance/km	5.637	5.305	5.305	5.939	8.024	11.385	3.791	8.500
% Change of Impedance/km	35.46%	7.21%	7.21%	18.67%	17.04%	24.11%	5.58%	-0.98%
Degree of sensitivity	High	Moderate	None	Moderate	None	None	Moderate	Moderate

The only route that obtained a change in average impedance more than 30% is Trunk 1A (Table 8-3). In addition, a route change occurred from this sensitivity analysis. Consequently, Trunk 1A can be categorised as highly sensitive to a change in transport efficiency weights. The Muckleneuk/Groenkloof Feeder experiences a negative change in average impedance. This simply translates to the average impedance decreasing from the reference case, which is equivalent to a more optimal route.

8.2.2 Economic Impact SA

The maximum suitability score increases by 5% to 0.76. The areas of high suitability have decreased significantly from the equal vision map. The areas of high suitability mostly follow arterial roads (Figure 8-11):

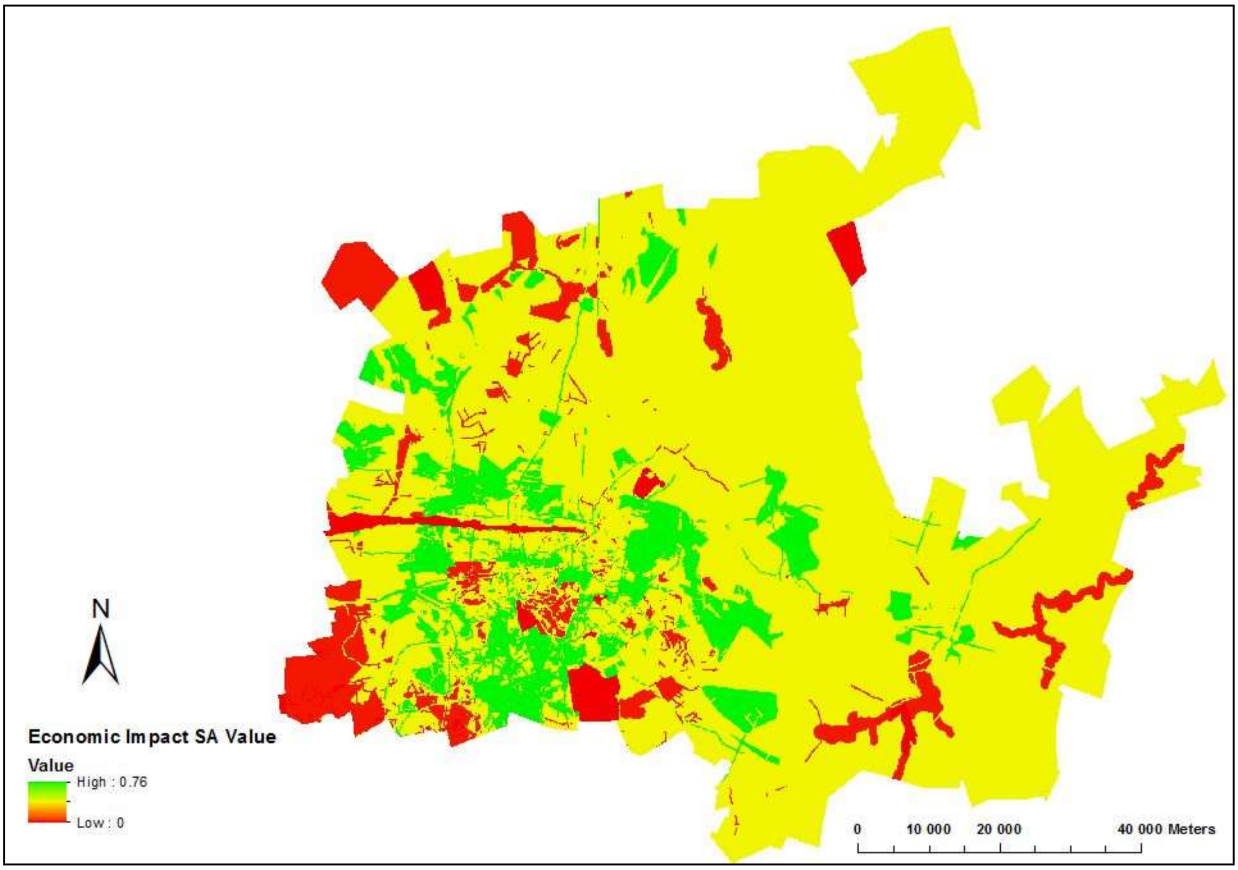


Figure 8-11: Economic Impact SA Composite Suitability Map

To avoid repetition, only routes with significant changes from the reference case routes will be presented. Routes that do not change significantly from the reference case may be found in Appendix A. The most severe economic impact SA routes were Trunks 1A and 1B, and the PTA CBD/Steve Biko Feeder route (Figure 8-12 to Figure 8-14):

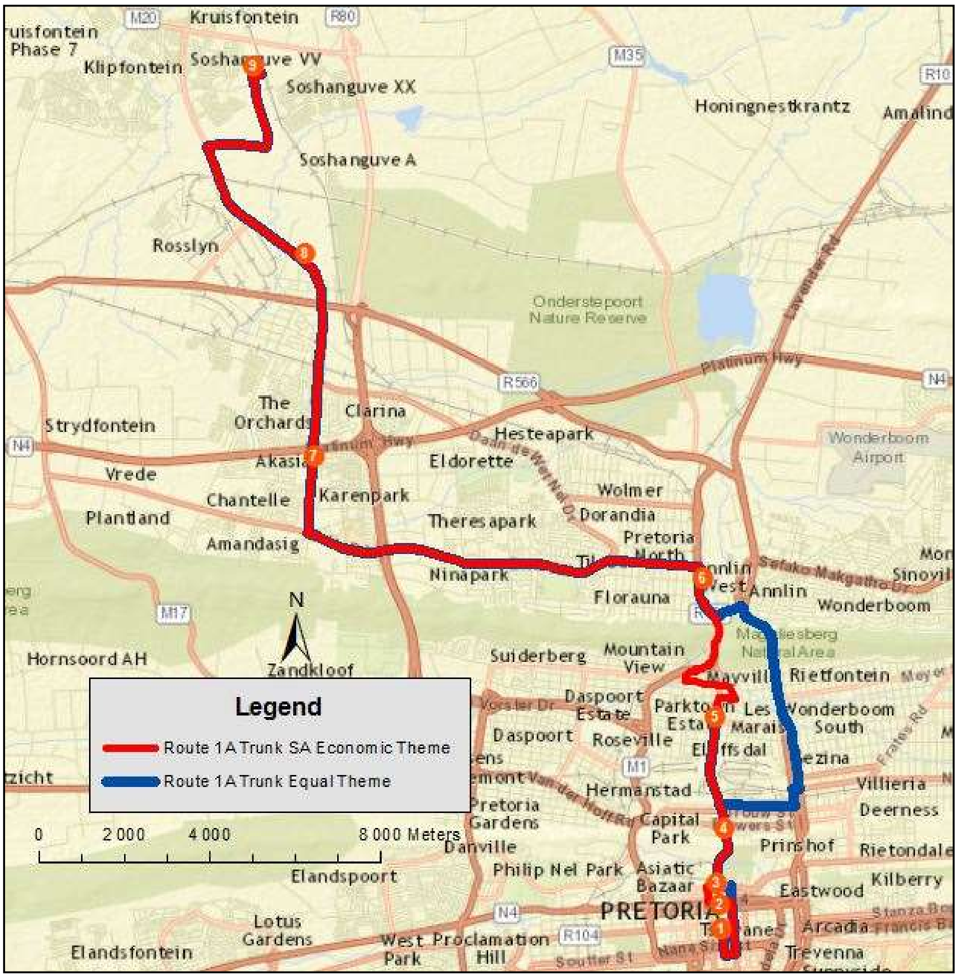


Figure 8-12: Trunk 1A Economic Impact SA

Figure 8-13: Trunk 1B Economic Impact SA

Figure 8-14: PTA CBD/Steve Biko Feeder Economic Impact SA

Feeder routes S. Side/ Steve Biko and Pretoria West/TUT are the only two routes that do not obtain a route change due to the economic impact SA (Table 8-4):

Table 8-4: Route Characteristics for Economic Impact SA

	Trunk 1A	Trunk 1B	Trunk 2A	Trunk 2B	S. Side/Steve Biko Feeder	CBD/Steve Biko Feeder	Pretoria West/TUT Feeder	Muckleneuk/Groen-kloof Feeder
Impedance	149.395	144.244	240.311	110.516	57.708	69.328	69.130	91.247
Total length (m)	32 631.025	25 318.867	44 628.532	30 638.136	7 753.590	6 722.976	16 277.503	8 915.841
Travel time (mins)	77.7	118.7	117.7	55.9	20.1	21.0	54.0	39.0
Impedance/km	4.578	5.697	5.385	3.607	7.443	10.312	4.247	10.234
% Change of Impedance/km	10.02%	15.14%	7.59%	-14.29%	8.57%	12.42%	18.29%	19.23%
Degree of Sensitivity	Moderate	Moderate	Moderate	Moderate	None	Moderate	None	Moderate

There are no routes that exceed the 30% benchmark for the economic impact sensitivity analysis (Table 8-4). Consequently, two thirds of the routes obtained a moderate degree of sensitivity. At -14.29%, Trunk 2B experiences a significant improvement in average impedance.

8.2.3 Equity SA

The equity theme composite suitability map did not vary too much from the equal theme composite suitability map. The maximum score changed from 0.71 to 0.72. Furthermore, the areas of high and low suitability did not change significantly. Areas of extremely high suitability decreased in the equity composite suitability map (Figure 8-15):

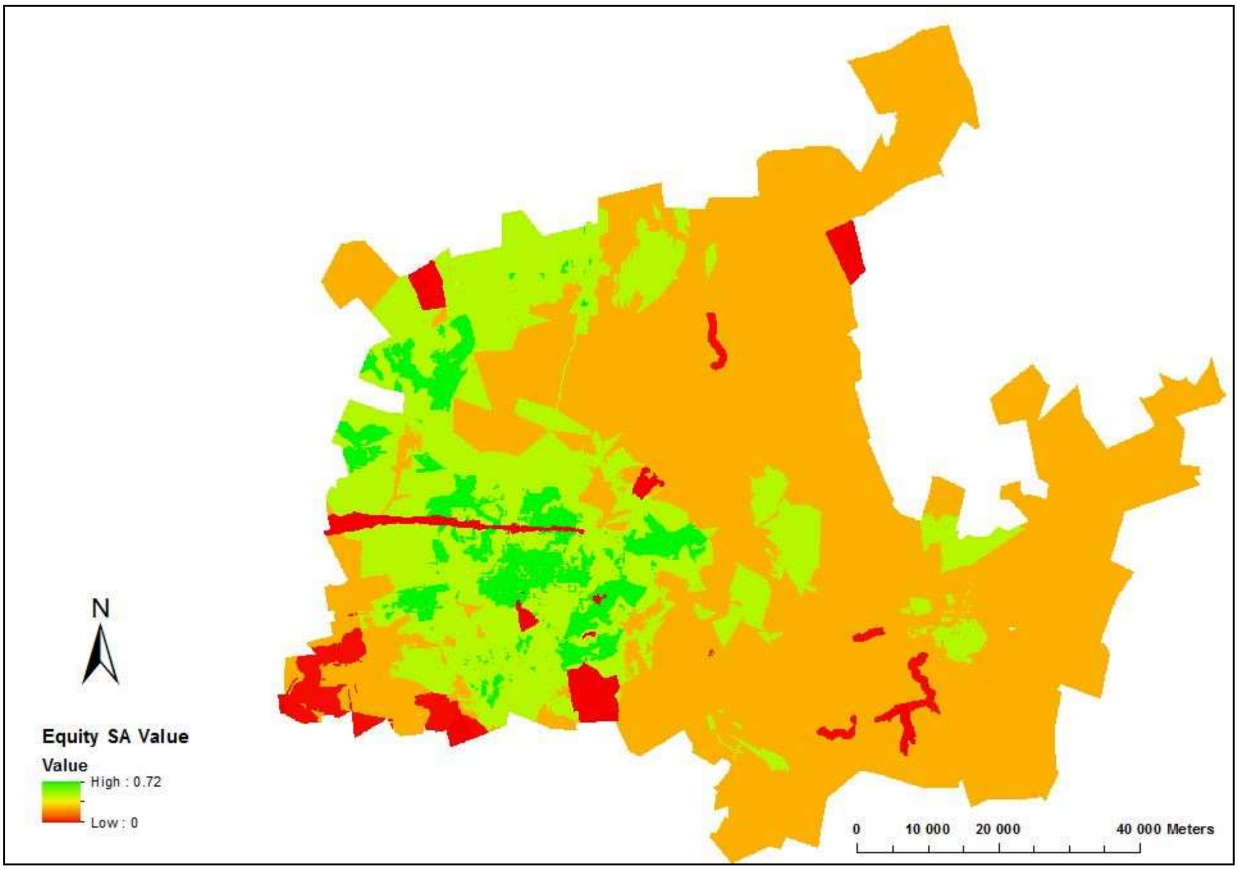


Figure 8-15: Composite Suitability Map for Equity SA

The only two routes that changed significantly for the equity SA were Trunks 1A and 1B (Figure 8-16 and Figure 8-17 respectively):

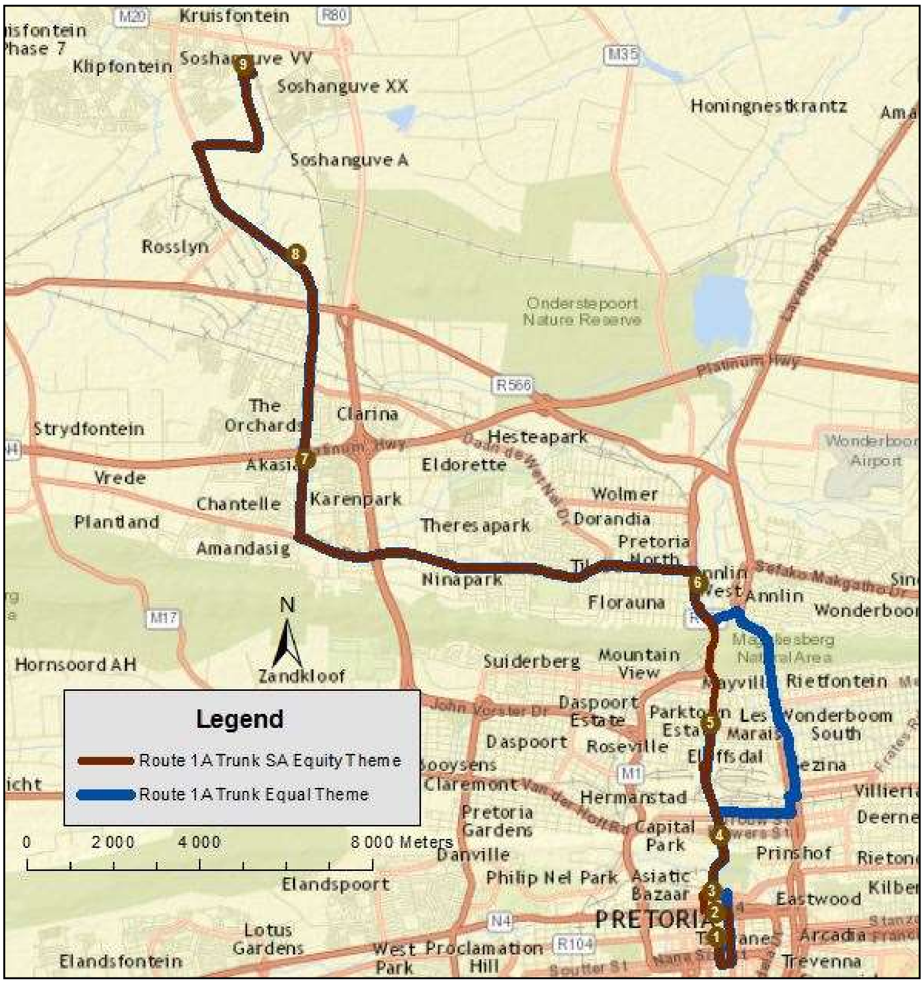


Figure 8-16: Trunk 1A Equity SA

Figure 8-17: Trunk 1B Equity SA

For the equity SA, the feeder routes S. Side/Steve Biko, CBD/Steve Biko and Pretoria West/TUT do not experience any route changes with a change in criteria (Table 8-5):

Table 8-5: Route Characteristics for Equity SA

	Trunk 1A	Trunk 1B	Trunk 2A	Trunk 2B	S. Side/Steve Biko Feeder	CBD/Steve Biko Feeder	Pretoria West/TUT Feeder	Muckleneuk/Groenkloof Feeder
Impedance	154.138	131.575	226.309	119.353	51.574	61.807	58.673	79.671
Total length (m)	33 768.092	27 013.141	44 524.892	30 638.136	7 753.590	6 763.252	16 277.503	8 915.841
Travel time (mins)	79.9	99.0	121.4	55.9	20.1	21.6	54.0	39.0
Impedance/km	4.565	4.871	5.083	3.896	6.652	9.139	3.605	8.936
% Change of Impedance/km	9.69%	-1.56%	1.56%	-7.43%	-2.97%	-0.38%	0.40%	4.10%
Degree of sensitivity	Moderate	Moderate	Moderate	Moderate	None	None	None	Moderate

The equity SA has no routes that exceed the 30% threshold. Furthermore, the average impedance percentage changes are all relatively low, with the maximum being under 10%. The equity SA has a high number of negative average impedance changes, meaning that route optimisation improves by prioritising equity criteria.

8.2.4 Environmental Impact SA

With the environmental impact SA, it is evident that there are more areas of high suitability throughout the municipality (Figure 8-18):

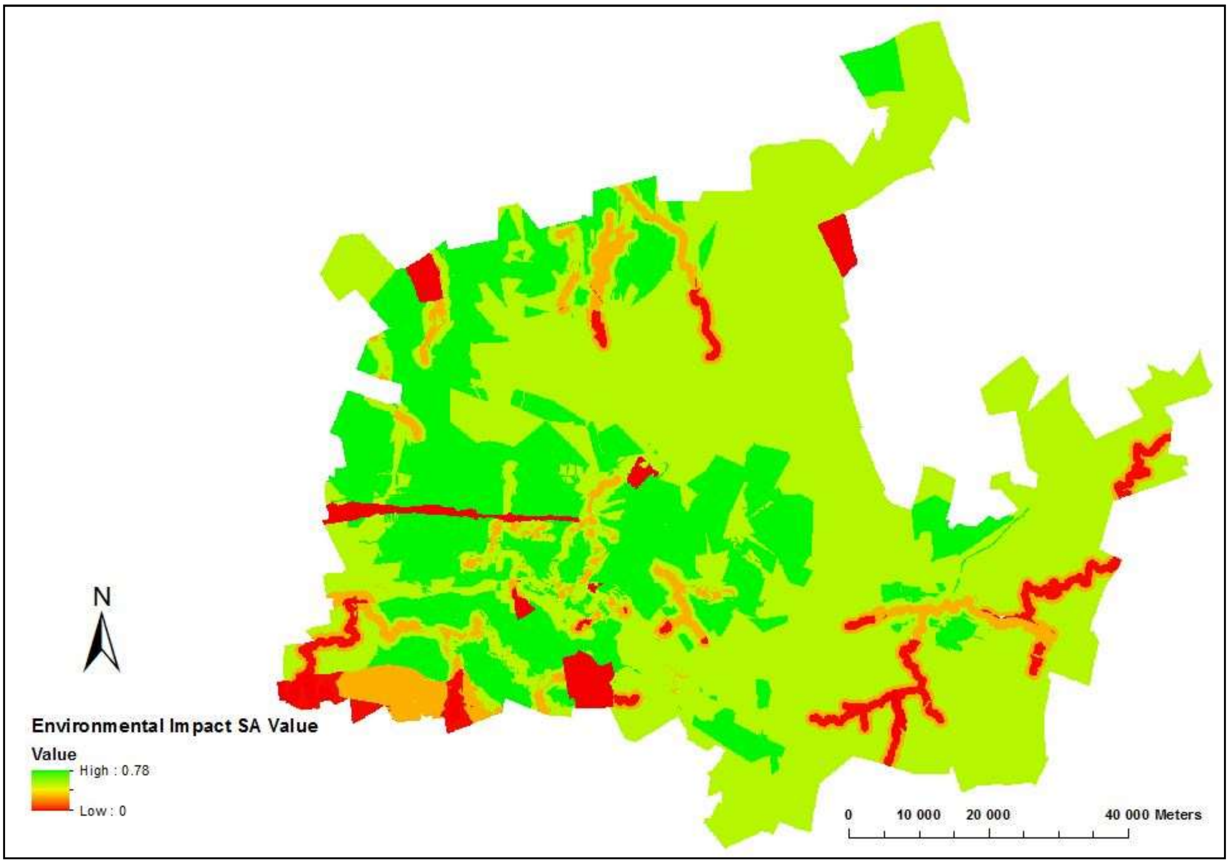


Figure 8-18: Environmental Impact SA Composite Suitability Map

Trunks 1A and 2B, and the Groenkloof/Muckleneuk Feeder obtained significant route changes (Figure 8-19 to Figure 8-21):

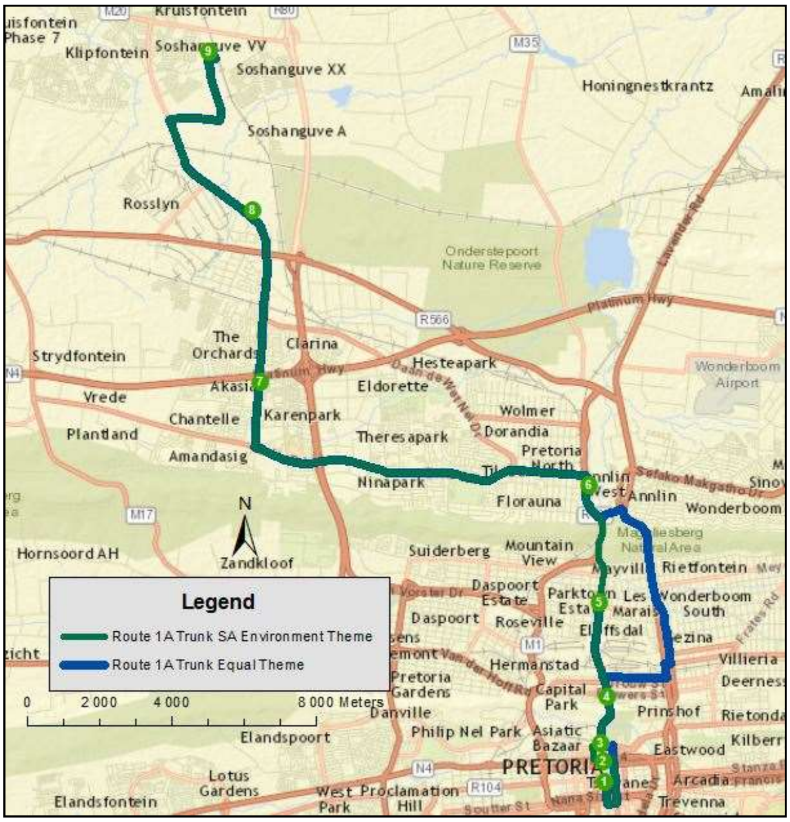


Figure 8-19: Trunk 1A Environmental Impact SA

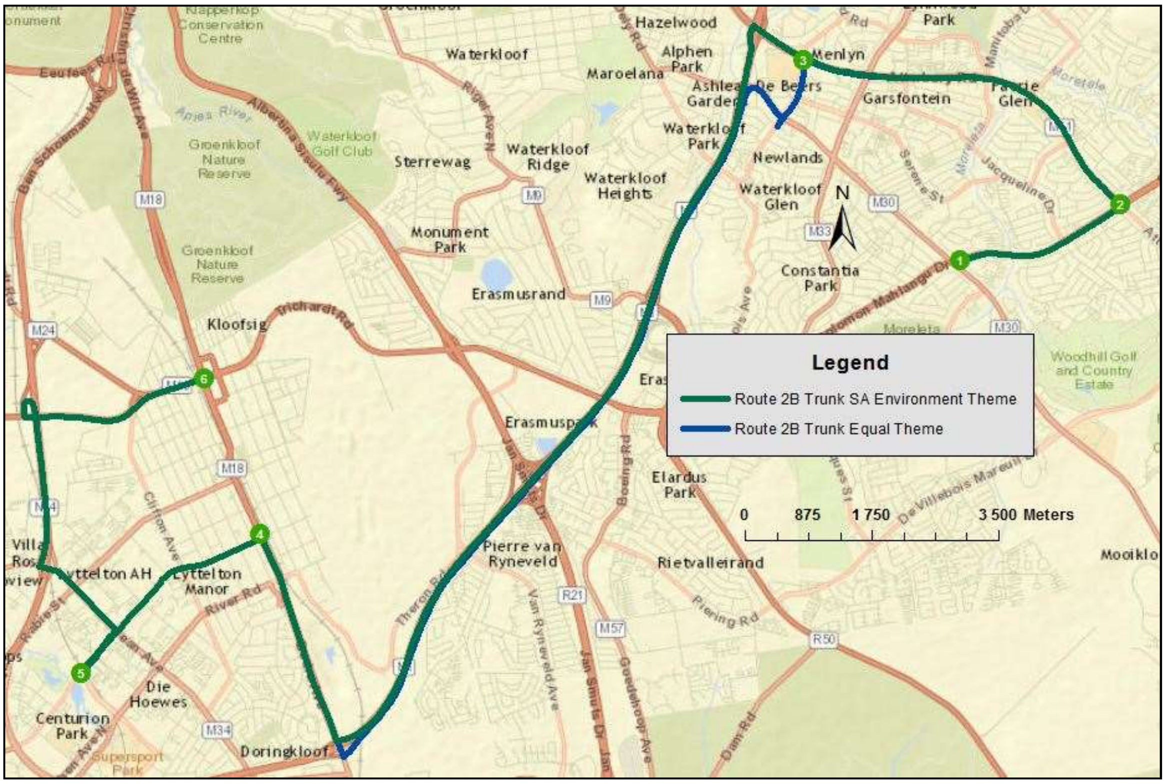


Figure 8-20: Trunk 2B Environmental Impact SA

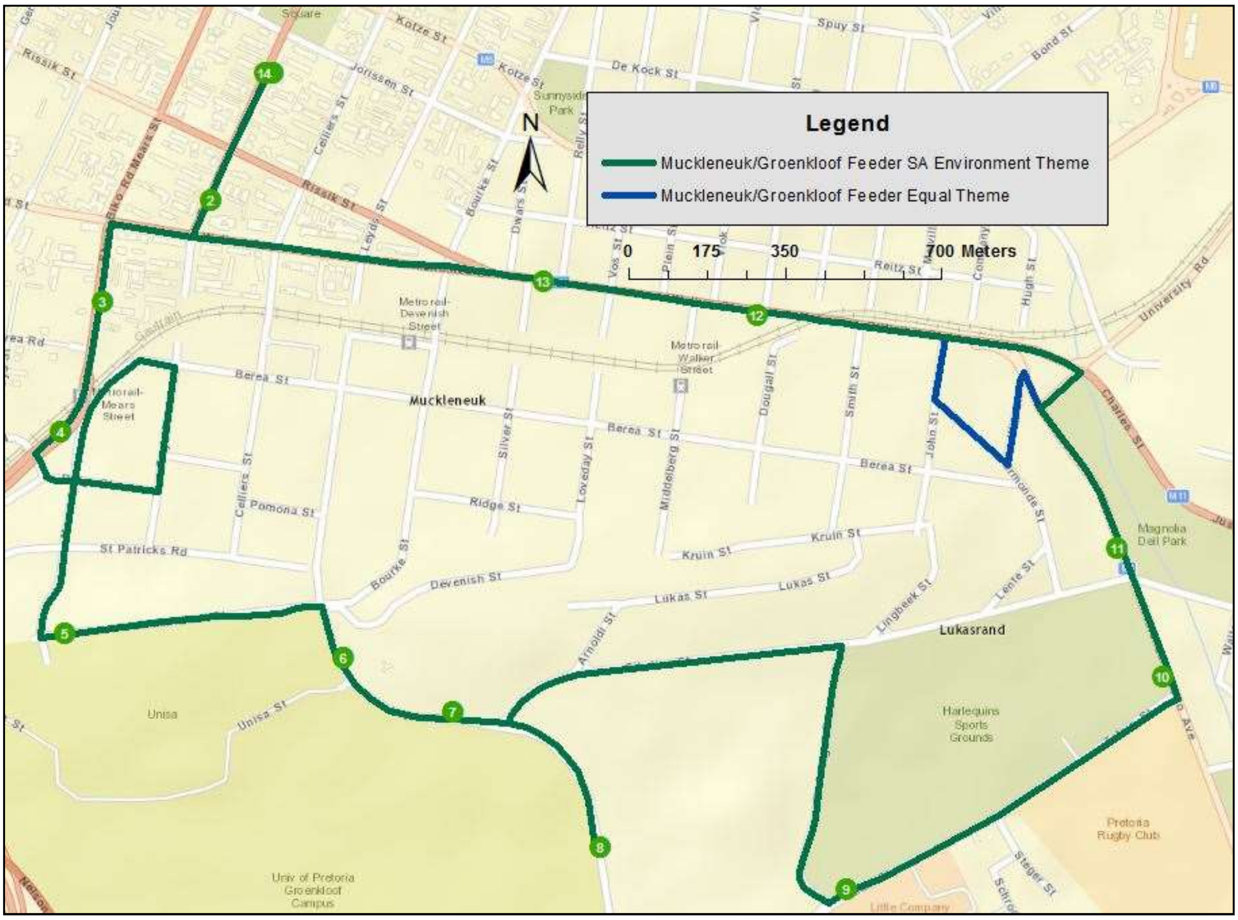


Figure 8-21: Muckleneuk/Groenkloof Feeder Environmental Impact SA

Environmental impact criteria are relatively insensitive, as 83% of the routes remained unchanged (Table 8-6):

Table 8-6: Route Characteristics for Environmental Impact SA

	Trunk 1A	Trunk 1B	Trunk 2A	Trunk 2B	S. Side/Steve Biko Feeder	CBD/Steve Biko Feeder	Pretoria West/TUT Feeder	Muckleneuk/Groen kloof Feeder
Impedance	135.627	129.699	225.473	117.311	57.816	69.018	64.254	86.605
Total length (m)	31 098.823	25 679.956	44 467.278	30 638.136	7 753.590	6 763.252	16 277.503	9 047.233
Travel time (mins)	76.6	94.0	117.3	55.9	20.1	21.6	54.0	38.7
Impedance/km	4.361	5.051	5.071	3.829	7.457	10.205	3.947	9.572
% Change of Impedance/km	4.80%	2.07%	1.32%	-9.02%	8.77%	11.25%	9.95%	11.52%
Degree of sensitivity	Moderate	None	None	Moderate	None	None	None	Moderate

There are no routes within the environmental impact SA that experience a change of over 30% in the average impedance values.

8.2.5 Social Impact SA

The social impact composite suitability map increased significantly from the reference case, with the maximum score increasing from 0.71 to 0.82. Areas of low suitability also increased significantly from the reference case (Figure 8-22):

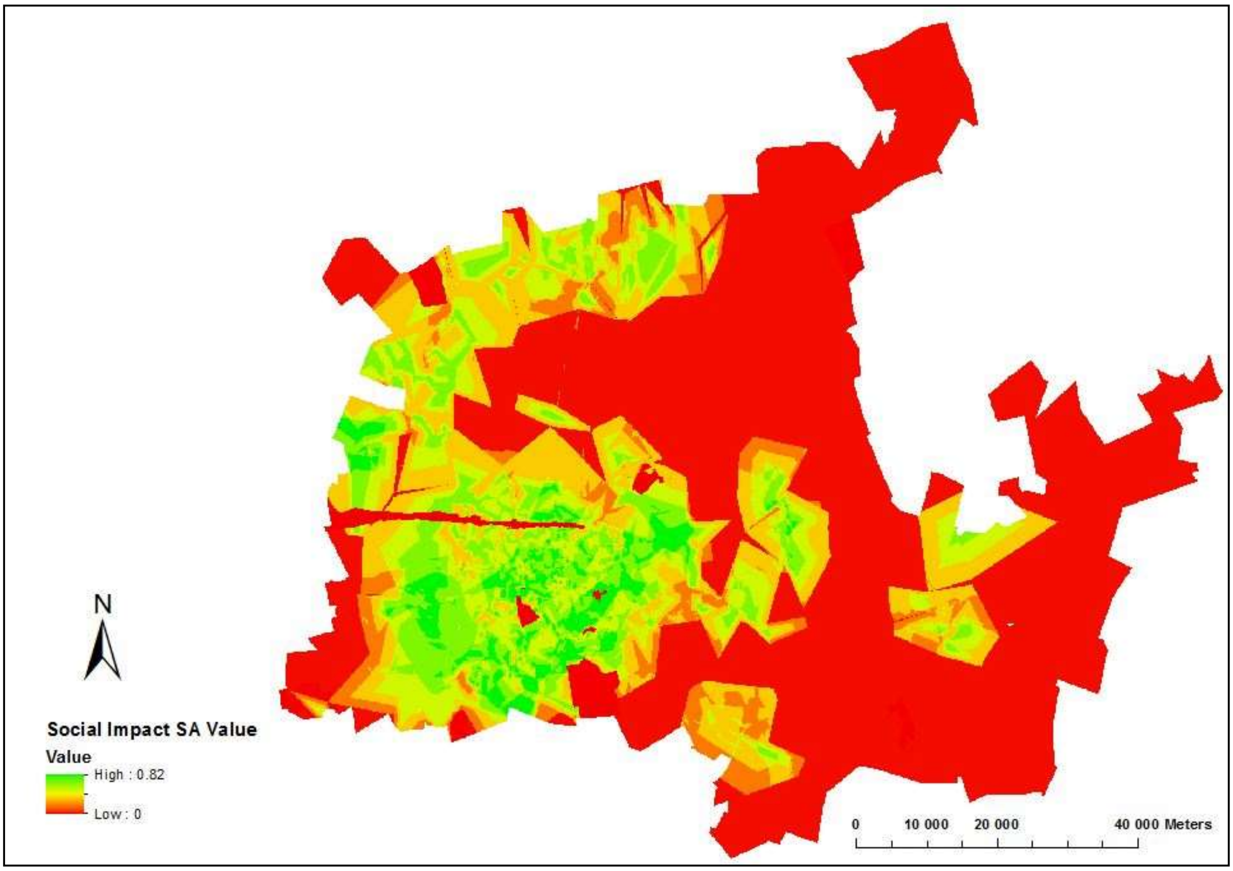


Figure 8-22: Social SA Composite Suitability Map

As in the case of the transport efficiency, economic impact, equity and environmental impact SAs, Trunk 1 deviated from the reference case in the social impact SA. Additional routes include Trunks 1B and 2A (Figure 8-23 to Figure 8-25):

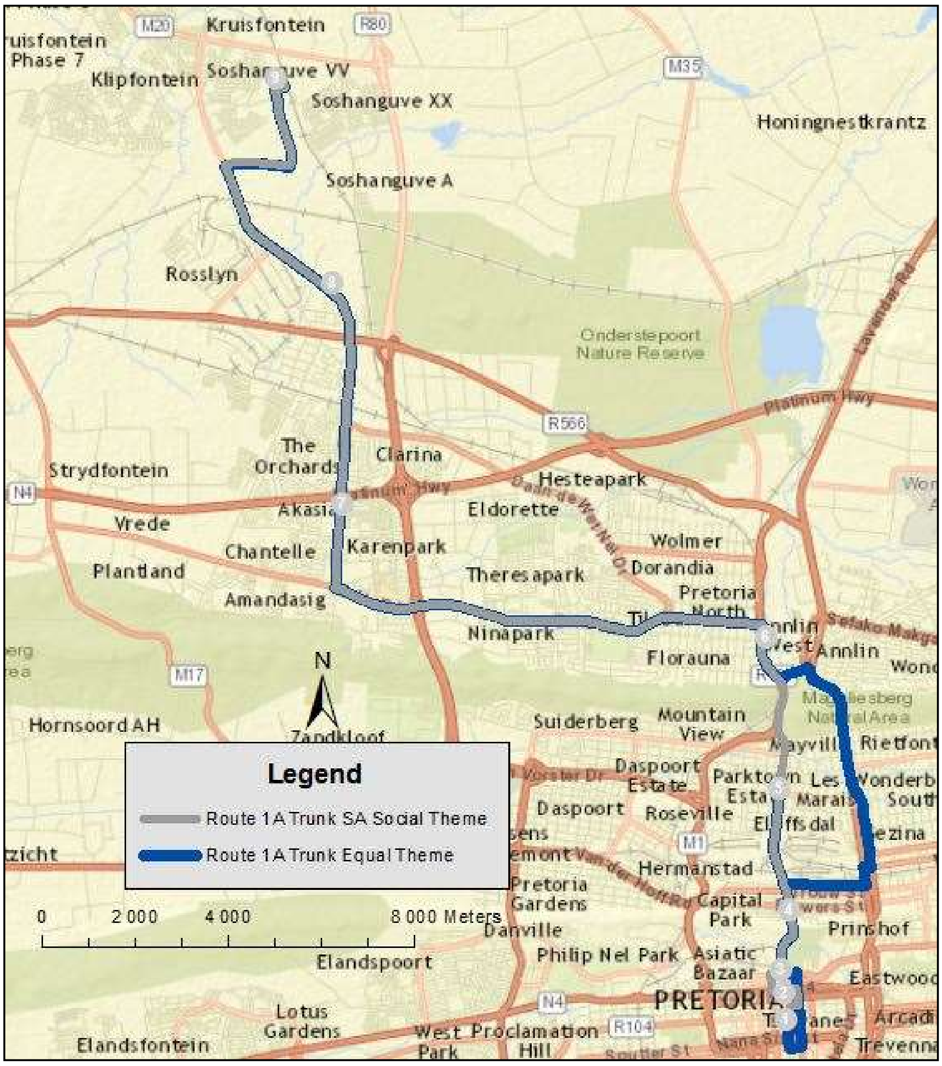


Figure 8-23: Trunk 1A Social Impact SA

Figure 8-24: Trunk 1B Social Impact SA

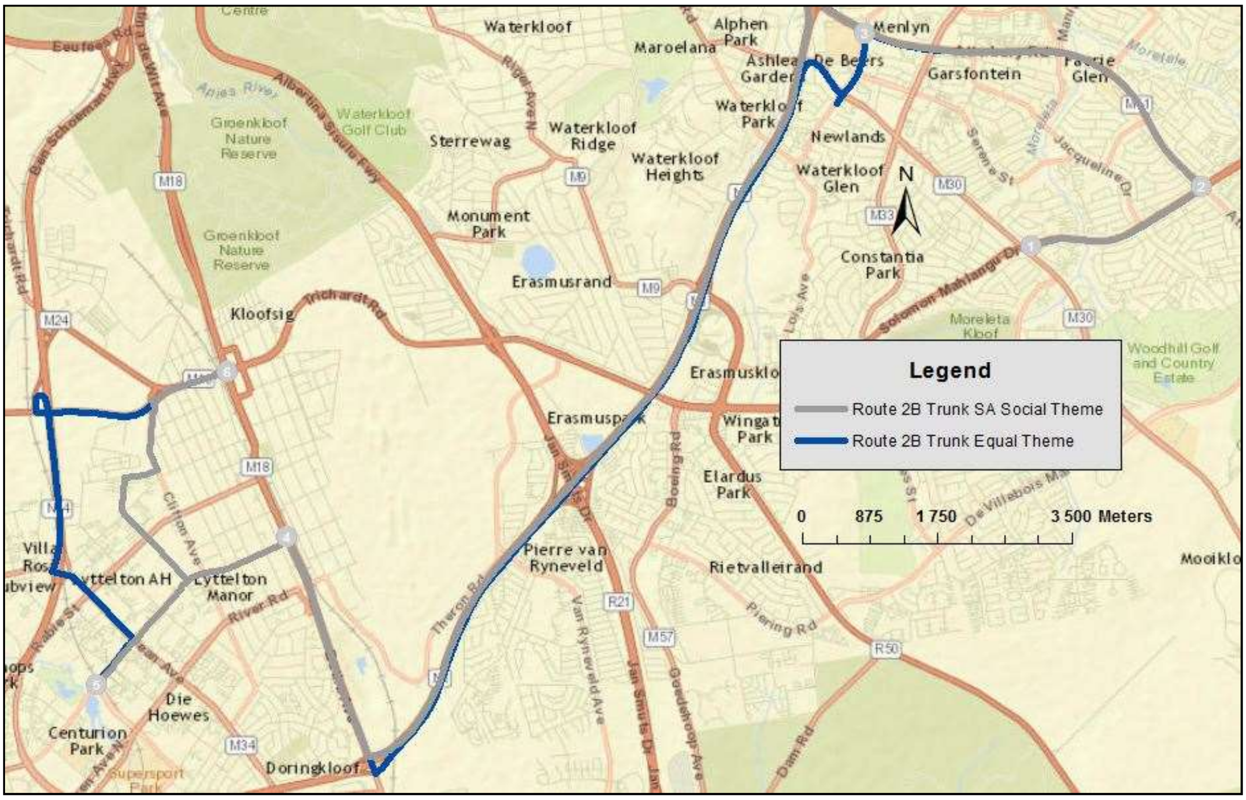


Figure 8-25: Trunk 2A Social Impact SA

Three feeder routes remain unchanged with the implementation of a social impact SA: S. Side/Steve Biko, CBD/Steve Biko and Pretoria West/TUT, and are thus not sensitive to social impact criteria (Table 8-7):

Table 8-7: Route Characteristics for Social Impact SA

	Trunk 1A	Trunk 1B	Trunk 2A	Trunk 2B	S. Side/Steve Biko Feeder	CBD/Steve Biko Feeder	Pretoria West/TUT Feeder	Muckleneuk/Groenkloof Feeder
Impedance	129.647	128.221	211.075	109.616	52.320	63.640	55.399	70.451
Total length (m)	29 956.959	25 251.260	44 628.532	29 306.496	7 753.590	6 763.252	16 277.503	8 915.841
Travel time (mins)	74.116	119.463	117.3	57.277	20.1	21.6	53.982	38.972
Impedance/km	4.328	5.078	4.730	3.740	6.748	9.410	3.403	7.902
% Change of Impedance/km	4.00%	2.62%	-5.50%	-11.12%	-1.57%	2.58%	-5.21%	-7.95%
Degree of sensitivity	Moderate	Moderate	Moderate	Moderate	None	None	None	Moderate

No routes obtained a change in average impedance that is greater than the change in weights. Six out of eight routes experience a negative change in average impedance. This may be attributed to a significantly higher composite suitability score (Figure 8-22).

The figures and tables outlined in Section 8.2 allows for the most sensitive routes and the most sensitive criteria to be determined. The trunk routes are more sensitive than feeder routes as they experienced more route changes. This may be attributed to the fact that the trunk routes are longer than the feeder routes and, hence, have a higher probability of sensitivity occurring somewhere along the route. Trunk 2B is the most sensitive of the trunk routes. Its route changes in all five scenarios, and it also has the highest mean percentage change of average impedance. In all five sensitivity analyses, S. Side/Steve Biko Feeder and Pretoria West/TUT feeder remain unchanged. These are also the two shortest routes in the analysis. The CBD/Steve Biko Feeder route remains unchanged in the equity, environmental impact and social impact sensitivity analyses (Table 8-8):

Table 8-8: Mean Absolute Change in Average Impedance per Route

Route	Mean % Change of Average Impedance
Trunk 1A	12.80%
Trunk 1B	5.72%
Trunk 2A	6.93%
Trunk 2B	15.59%
S. Side/Steve Biko Feeder	7.78%
CBD/Steve Biko Feeder	10.15%
Pretoria West/TUT Feeder	7.88%
Muckleneuk/Groenkloof Feeder	8.75%

Additionally, evaluation criteria may be ranked according to the average sensitivity caused across all routes (Table 8-9):

Table 8-9: Average Sensitivity of Evaluation Criteria

Criteria	Average Sensitivity (goal = 30%)
Transport efficiency theme	16.89%
Economic efficiency theme	13.19%
Equity theme	5.07%
Social impact theme	7.34%
Environmental impact theme	3.51%

The transport efficiency criteria are the most sensitive criteria of the SMCA model, with an average change of 16.89% in average impedance. This correlates to transport efficiency criteria being the only criteria group to cause a change of over 30% in average impedance for one of the routes. The economic efficiency sensitivity analysis is the second most sensitive criteria, which correlates to it only having two routes unchanged. The least sensitive evaluation criteria are the environmental impact criteria. The criterion in this group caused a low change in average impedance of 3.51%, and had five out of eight routes remain unchanged.

8.3 Scenario Uncertainty

Many different route outcomes are possible depending on the scenario implemented. As discussed in Chapter 7, scenarios were created to represent the interests, and subsequently, weighting schemes, of various stakeholders had they been consulted. With the results of the scenario analysis already provided in Chapter 7, it is unnecessary to reproduce them here. Instead, a summary has been provided (Table 8-10). An input value of "Yes" means that the route changed from from the reference case route, and "No" means that the route remained unchanged.

Table 8-10: Effect of Route Changes on Reference Routes Due to Scenario Uncertainty

	Transport Efficiency Scenario	Economic Impact Scenario	Equity Scenario	Environmental Impact Scenario
Trunk 1A	Yes	Yes	Yes	Yes
Trunk 1B	Yes	Yes	Yes	No
Trunk 2A	Yes	Yes	Yes	No
Trunk 2B	Yes	Yes	Yes	Yes
S. Side/Steve Biko Feeder	No	Yes	No	Yes
CBD/Steve Biko Feeder	No	No	No	No
Pretoria West/TUT Feeder	No	No	Yes	No
Muckleneuk/Groenkloof Feeder	No	Yes	No	Yes

Like the sensitivity analysis, the results from the scenario uncertainty analysis shows which routes are most sensitive, and which scenarios and their corresponding criteria are most sensitive. The trend encountered in Section 8.2 of trunk routes being more sensitive than feeder routes continues in the scenario uncertainty analysis. Of all four trunk routes, only two routes remained unchanged: Trunks 1B and 2A, and both for the environmental impact scenario. Trunks 1A and 2B experienced a route change in every scenario, indicating a high susceptibility to weight change. The most robust feeder route was the CBD/Steve Biko Feeder, for which all routes remained unchanged from the reference case. This feeder is followed by Pretoria West/TUT, which only changed route for the equity scenario.

In terms of scenarios, economic impact scenario is the most sensitive, causing route changes in six of eight routes. This is followed by equity, where five of eight routes changed. Environmental impact and transport impact scenarios both cause route changes in half of the routes.

8.4 Additional Uncertainty Considerations

The methodology used in this research supports two additional uncertainty analyses that were considered, but not pursued, for reasons stated below:

i) *Incremental sensitivity analysis:* to compute this SA, weights would be changed incrementally until the routes changed. The goal of this approach is to determine how much flexibility exists in the certainty of criteria weights before a weight change causes a change in routes. As there are five criteria groups and eight routes, this could prove to be an extremely tedious process; and

ii) *Standardisation sensitivity analysis:* ILWIS makes use of five different standardisation techniques, three of which are used in this dissertation. The standardisation methods used for every criterion, and the combination in which they are used within the criteria tree, provide a degree of uncertainty. The possibility that a change in results could occur should there be a change in the combination of standardisation techniques used cannot be ignored. This type of analysis was also not pursued because of the myriad of standardisation techniques that could be applied to the 34 criteria. The process was thus also judged to be too tedious to pursue.

8.5 Résumé

Chapter 8 served to discuss the uncertainty of all reference case routes obtained in Chapter 7. Firstly, uncertainties encountered at every stage of the research method were classified in an uncertainty matrix. Scenario uncertainty was a common level of uncertainty at every location, due to there being a range of possible outcomes whose probability cannot be statistically determined.

According to the sensitivity analyses, trunk routes were found to be more sensitive than feeder routes. Trunk 2B, which obtained the highest mean average impedance change of 16% for a 30% weight change, was found to be the most sensitive of the trunks. Furthermore, trunk 2B experienced a route change in all five scenarios. Subsequently, Trunk 2B is the most sensitive route as it is highly susceptible to weight changes. Trunk 1B was the least sensitive trunk with a mean average impedance change of 6% for a 30% weight change. Feeder route S. Side/Steve Biko remained unchanged in all five analyses and had the lowest mean average impedance change of all routes of 8%. It can be concluded that S. Side/Steve Biko is the least susceptible route to weight changes. CBD/Steve Biko Feeder obtained the highest mean average impedance change of 10% but remained unchanged in four scenarios, making it moderately sensitive

The SA also showed that the transport efficiency theme criteria were the most sensitive criteria, causing a mean average impedance change of 17% across all 8 routes. It can thus be concluded that transport efficiency criteria are the most important criteria in determining optimal routes. Environmental impact criteria are the least sensitive, and subsequently the least critical criteria, with a mean average impedance change of 4%. This corresponds to the environmental impact SA having the highest number of unchanged routes at five.

The scenario uncertainty analysis confirmed that trunk routes were more sensitive than feeders. Only two trunks remained unchanged in one scenario: Trunks 1B and 2A. All other trunks changed for every scenario. The CBD/Steve Biko Feeder never experienced a route change. The economic impact scenario, and correspondingly, economic impact criteria, was found to be the most sensitive, causing route changes in six of the eight routes. Environmental impact and transport impact scenarios were the least sensitive scenarios.

In conclusion, there were many methods in which an uncertainty analysis could have been conducted in this research, some more appropriate than others. For instance, an incremental SA could have been adopted to show how much flexibility exists in the certainty of criteria weights before a weight change causes a change in routes. In addition, an SA could also have been conducted on the standardisation techniques employed. Both these uncertainty analyses were omitted from this research as their high computational requirements would prove to be a tedious process.

9 Conclusions and Recommendations

This closing chapter aims to provide conclusions and recommendations on the research conducted. Firstly, conclusions are drawn on the aims and objectives of the dissertation. Answers to the research questions are also provided. Lastly, recommendations to improve the research and recommendations on further research are provided.

9.1 Conclusions to Study

The aim of this dissertation was to use suitable criteria in an SMCA to find optimal BRT trunk and feeder routes in the CoT. Optimal routes are routes that achieve the lowest possible cumulative impedance against an array of evaluation criteria and weighting schemes. The purpose of the dissertation was to address the knowledge gap that exists in PT appraisal in South Africa, and subsequently advocate for a standardised, robust appraisal tool. Such an appraisal tool in the South African context would serve to ensure that transportation projects are designed for the context in which they are applied, thus making them contextually appropriate, and ultimately, more successful. Contextually sensitive PT projects are those that are, *inter alia,* environmentally sensitive, financially and economically viable, equitable and socially appropriate.

9.1.1 Research Questions

The objectives of the dissertation as outlined in Chapter 1, were met by answering the following research questions.

What are the suitable evaluation criteria that should be included in a contextually sensitive SMCA?

International literature (HDR Alaska, 2002; Litman, 2017) and local literature (CoT, 2015b; DoT, 2017) presented four common pillars which transport projects must encompass to be deemed sustainable: environment, society, culture and economy. From these four pillars, five criteria themes were deduced:

- Transport efficiency;
- Environmental impact;
- Economic impact;
- Equity; and
- Social impact.

All five criteria themes contained individual criterion. In total, the SMCA comprised of 26 criteria. The 26 criteria all formed suitability maps which were used to create one composite suitability map.

What weighting combinations should be used in the contextualised appraisal tool?

It was not possible to conduct a stakeholder engagement to ascertain the relative importance of criteria. As such, all criteria were given equal importance for the reference case, which is the academic solution. Hence, the criteria themes all had a weighting of 0.20. However, Individual criterion within the criteria groups were not assigned equal weighting. Weighting was assigned on the basis of perceived importance.

A scenario weighting scheme was formed to mimic the results of a stakeholder engagement had one taken place. Four scenarios were analysed: environmental impact, transport efficiency, economic impact and equity. There were 120 possible weighting schemes. The weighting schemes chosen for the scenario routes represent those judged to be most critical (Table 9-1):

Table 9-1: Scenario Weights

Scenarios		Transport Efficiency	Economic Impact	Equity	Environmental Impact
Criteria	Transport efficiency	0.33	0.27	0.27	0.27
	Economic efficiency	0.27	0.33	0.07	0.07
	Equity	0.13	0.20	0.33	0.20
	Environmental impact	0.20	0.13	0.13	0.33
	Social impact	0.07	0.07	0.20	0.13

What are the characteristics of optimal routes? Do they differ from existing or planned routes?

Optimal routes were analysed according to route length, travel time, impedance and average impedance (Table 9-2):

Table 9-2: Optimal Route Characteristics

	Impedance	Total Length (m)	Travel Time (mins)	Impedance/ km	Route Change from Current/Planned Route?
Trunk 1A	157.018	37 733.1	94.0	4.161	Yes
Trunk 1B	127.064	25 680.0	94.0	4.948	N/A
Trunk 2A	223.475	44 652.7	117.6	5.005	Yes
Trunk 2B	130.783	31 076.8	47.1	4.208	N/A
S. Side/S. Biko Feeder	53.153	7 753.6	20.1	6.855	Yes
PTA CBD/Steve Biko Feeder	62.039	6 763.3	21.6	9.173	Yes
PTA West/TUT Feeder	58.442	16 277.5	54.0	3.590	Yes
Muckleneuk/Groenkloo f Feeder	79.351	9 244.1	39.6	8.584	Yes

Trunk 1B and 2B could not be compared to actual routes as GIS maps were unavailable. From Table 9-2, all the implemented and planned routes deviate from the optimal routes. It can be concluded that the implemented or planned routes are not optimal routes. Furthermore, on average, the trunk routes have a lower average impedance than the feeder routes, as the longer length .

How much sensitivity exists in the SDSS?

A quantitative sensitivity analysis allowed sensitive routes and sensitive criteria to be determined. A sensitivity analysis was conducted for each criteria theme, making five sensitivity analyses in total. For each sensitivity analysis, the weight of the corresponding criteria theme was changed from 0.20, as obtained in the reference case, to 0.50. The weights of the remaining five criteria decreased from 0.20 to 0.125 to ensure that the sum of the weights was 1.0.

The SMCA revealed that there is a considerable amount of sensitivity in the model. Uncertainties encountered in the model were computed qualitatively and quantitatively. In the qualitative analysis, uncertainties encountered at every stage of the research methodology were classified in an uncertainty matrix. Scenario uncertainty was a common level of uncertainty at every location, due to there being a range of possible route outcomes whose probability could not be statistically determined.

A qualitative scenario uncertainty analysis was conducted based on the scenario routes. This analysis involved judging whether the scenario weights (Table 9-2) caused the reference case routes to change.

a) How much sensitivity is there in the evaluation criteria?

The sensitivity analysis showed that the transport efficiency theme criteria were the most sensitive criteria, causing a mean average impedance change of 17% for a 30% weight change across all 8 routes. It can be concluded that for this SDSS, transport criteria are thus the most critical criteria in obtaining optimal routes. Environmental impact criteria are the least sensitive with a mean average impedance change of 4% across all routes. This corresponds to the environmental impact sensitivity analysis obtaining the highest number of unchanged routes at five.

In contrast, the scenario uncertainty analysis revealed that the economic impact scenario, and correspondingly, economic impact criteria, was found to be the most sensitive scenario, causing route changes in six of the eight routes. Consequently, both the transport efficiency and economic impact criteria are sensitive criteria in this SDSS. Environmental impact and transport impact scenarios were the least sensitive scenarios. From the sensitivity analysis and scenario uncertainty analysis, it can be concluded that the environmental impact criteria are the most robust criteria and least critical in obtaining optimal routes.

b) How much sensitivity is there in the routes?

Sensitivity in the routes was judged against two parameters:

i) Determining whether a change in the weighting scheme caused a change in the route followed; and
ii) Determining whether an increase of 30% in a criteria theme caused a change of more than 30% in the average impedance of the reference case routes.

According to the sensitivity analyses, trunk routes were found to be more sensitive than feeder routes. This can be attributed to their longer lengths which subsequently increase the probability of sensitivities occurring along the route. Trunk 2B was found to be the most sensitive trunk route. Trunk 2B obtained the highest overall mean average impedance change of 16% for a 30% weight change and experienced a route change in all five uncertainty analyses. It can be concluded that Trunk 2B is the most susceptible route to weight changes and subsequently, the least robust trunk route. Trunk 1B was the least sensitive trunk with a mean average impedance change of 6% for a 30% weight change. Feeder route S. Side/Steve Biko remained unchanged in all five analyses and had the lowest mean average impedance change of all routes of 8%, making it the least sensitive and most robust feeder route. Of the feeder routes, CBD/Steve Biko Feeder remained unchanged in four of the five scenarios, making it a robust route

The scenario uncertainty analysis confirmed that trunk routes were more sensitive than feeder routes. All trunks, bar 1B and 2B, changed for every scenario uncertainty analysis. The CBD/Steve Biko Feeder never experienced a route change, making it insensitive to criteria weights and relatively robust.

What are the limitations of the SDSS?

The major limitation of this SDSS lies in the fact that only one cost attribute could be considered: impedance. This meant that routes formed did not take distance, and subsequently, travel time, into consideration. As such, some of the routes appraised have long travel times. An ideal solution would have been one where multiple cost attributes could be incorporated through a ranking system. This would allow impedance to be optimised first and foremost, then travel time.

9.2 Recommendations of Study

Recommendations are made to the study in terms of how the research may be improved, and how it may further be applied.

9.2.1 Recommendations for Improvements to Research

This research on finding optimal BRT routes using SMCA may be improved upon in the following ways:

- Developing a comprehensive weighting scheme through a questionnaire completed by stakeholders. Such a questionnaire would allow for the relative importance of weights to be determined and applied though an AHP; and
- Applying a financial analysis to the results to determine the financial feasibility of the routes, as well as stages of implementation according to budget constraints.

9.2.2 Recommendations for Further Applications of SMCA in Transport Routing

The method of research used in this dissertation is reproducible: it can be applied as is to any contemporary South African city with plans for BRT. The method of research adopted in this study can also be applied to any form of road-based transport, such as scheduled bus services and MBTs. The following recommendations are provided for the purposes of reproducing this research within contemporary South African cities:

- Investigate suitable evaluation criteria to be included in an SDSS. This uniformity will ensure that all routing problems are judged to the same standard;
- Create a spatial database of all criteria identified to be included in the SDSS. This will eliminate dubious data obtained through open source; and
- Develop a South African SDSS model to analyse all road-based transport routing problems which can be used by all planning authorities. A local model will reduce the amount of computing required to find optimal routes. The model can be calibrated to include standardisation techniques and weighting schemes applicable to a South African context.

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11 Appendices

11.1 Appendix A: Chapter 8-Route Uncertainty Analyses

In this section, routes from the SA that experienced significant changes from the reference case routes will be presented.

Economic Impact Routes

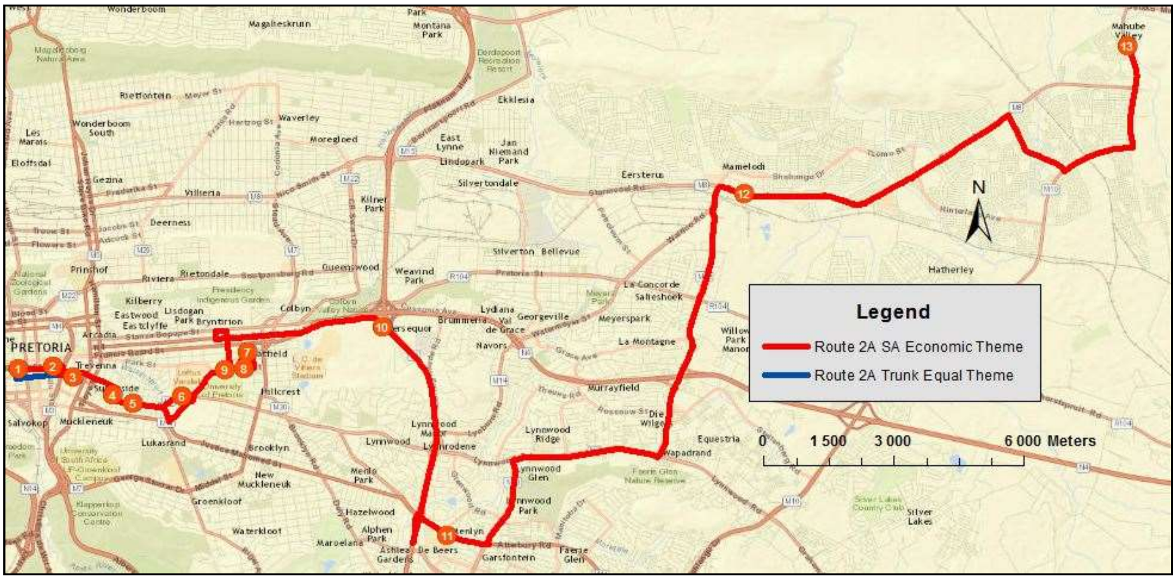

Figure 11-1: Trunk 2A Economic Impact SA

Figure 11-2: Trunk 2B Economic Impact SA

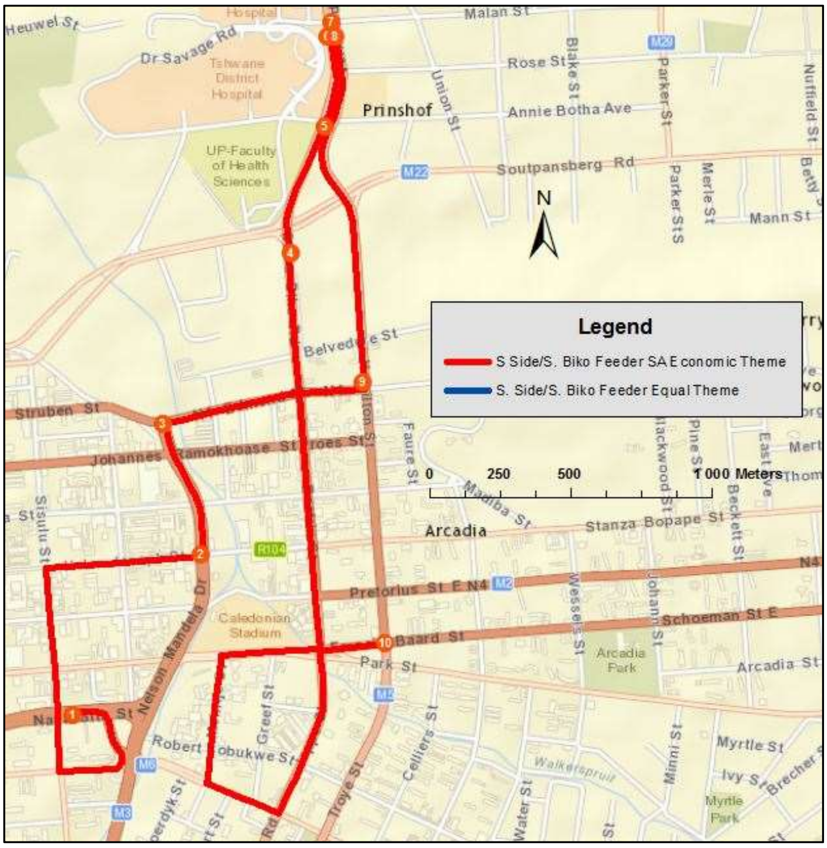

Figure 11-3: S Side/Steve Biko Feeder Economic Impact SA

Figure 11-4: Pretoria West/TUT Feeder Economic Impact SA

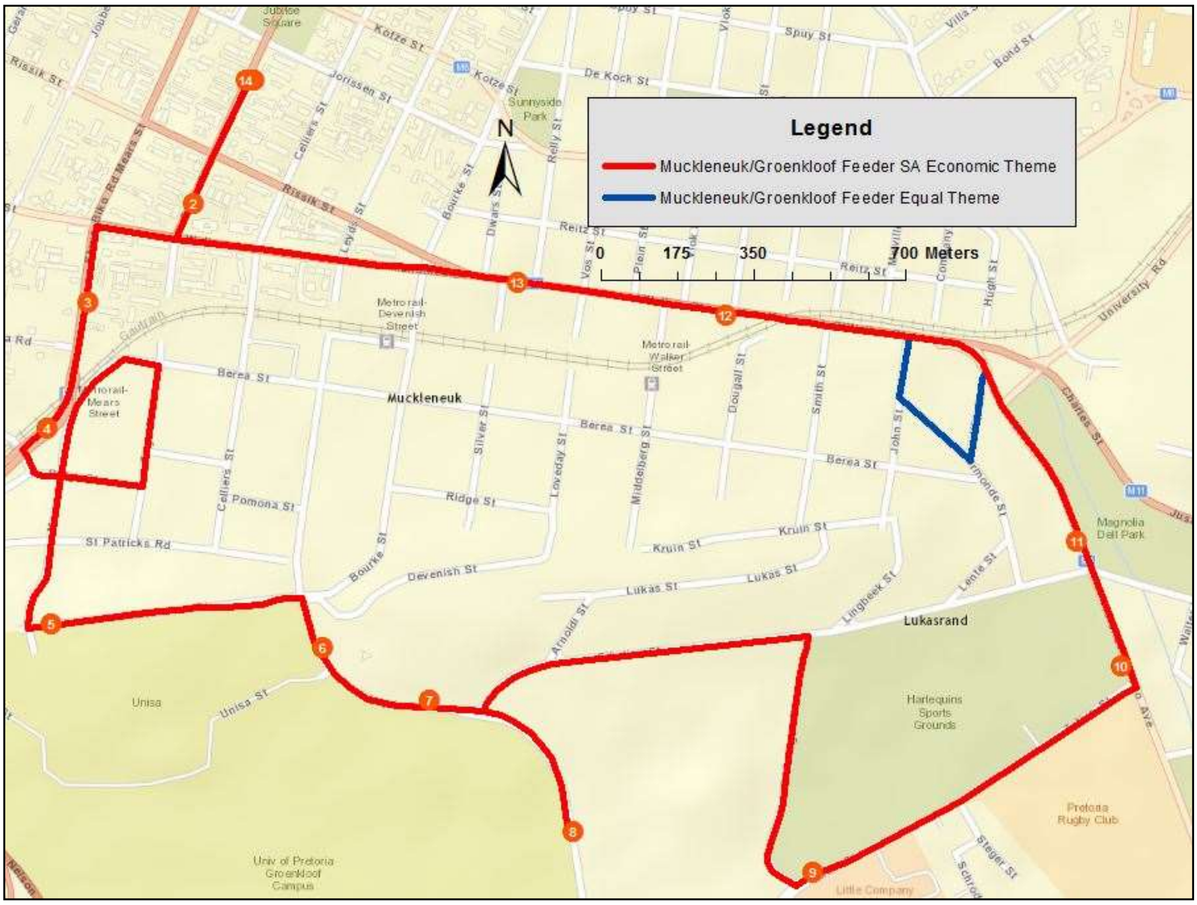

Figure 11-5: Muckleneuk/Groenkloof Feeder Economic Impact SA

Equity SA Routes

Figure 11-6: Trunk 2A Equity SA

Figure 11-7: Trunk 2B Equity SA

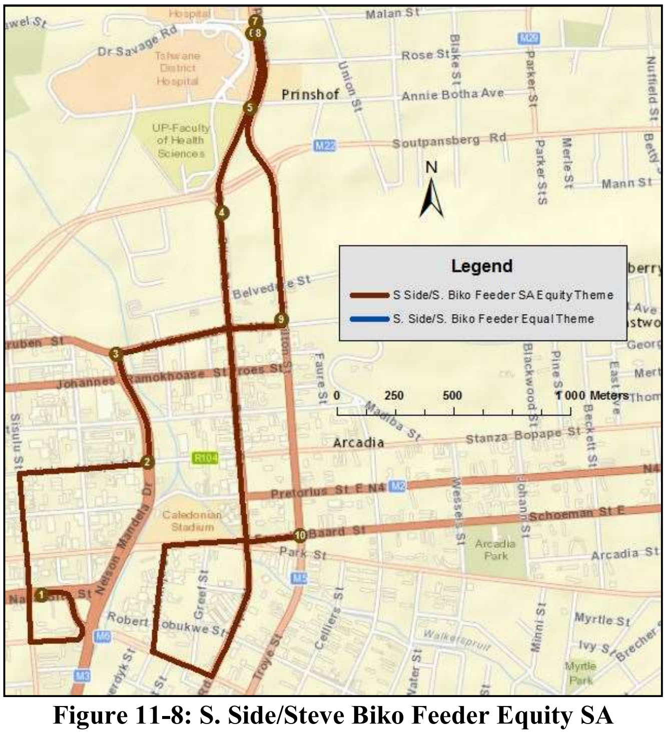

Figure 11-8: S. Side/Steve Biko Feeder Equity SA

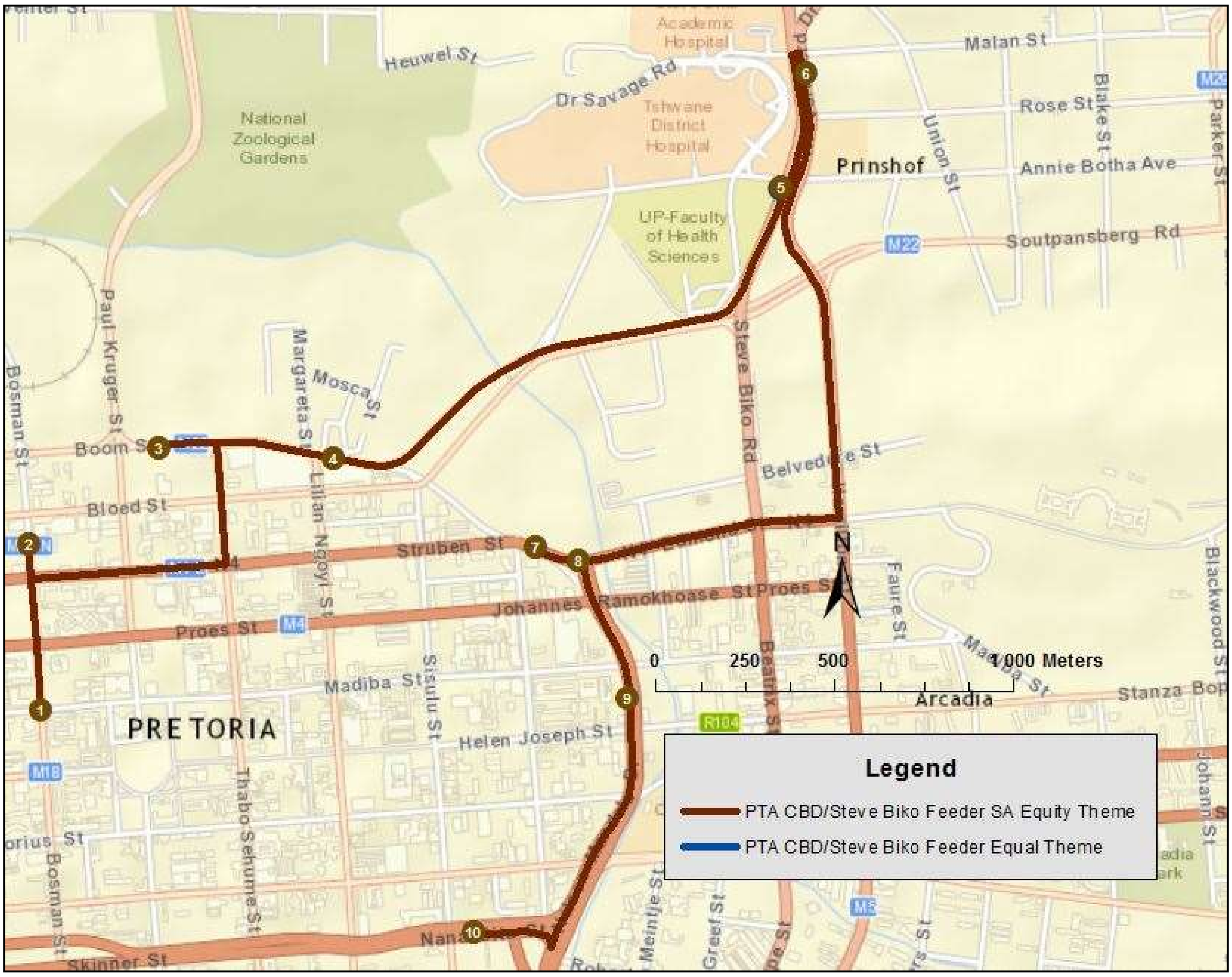

Figure 11-9: CBD/Steve Biko Feeder Equity SA

Figure 11-10: Pretoria West/TUT Feeder Equity SA

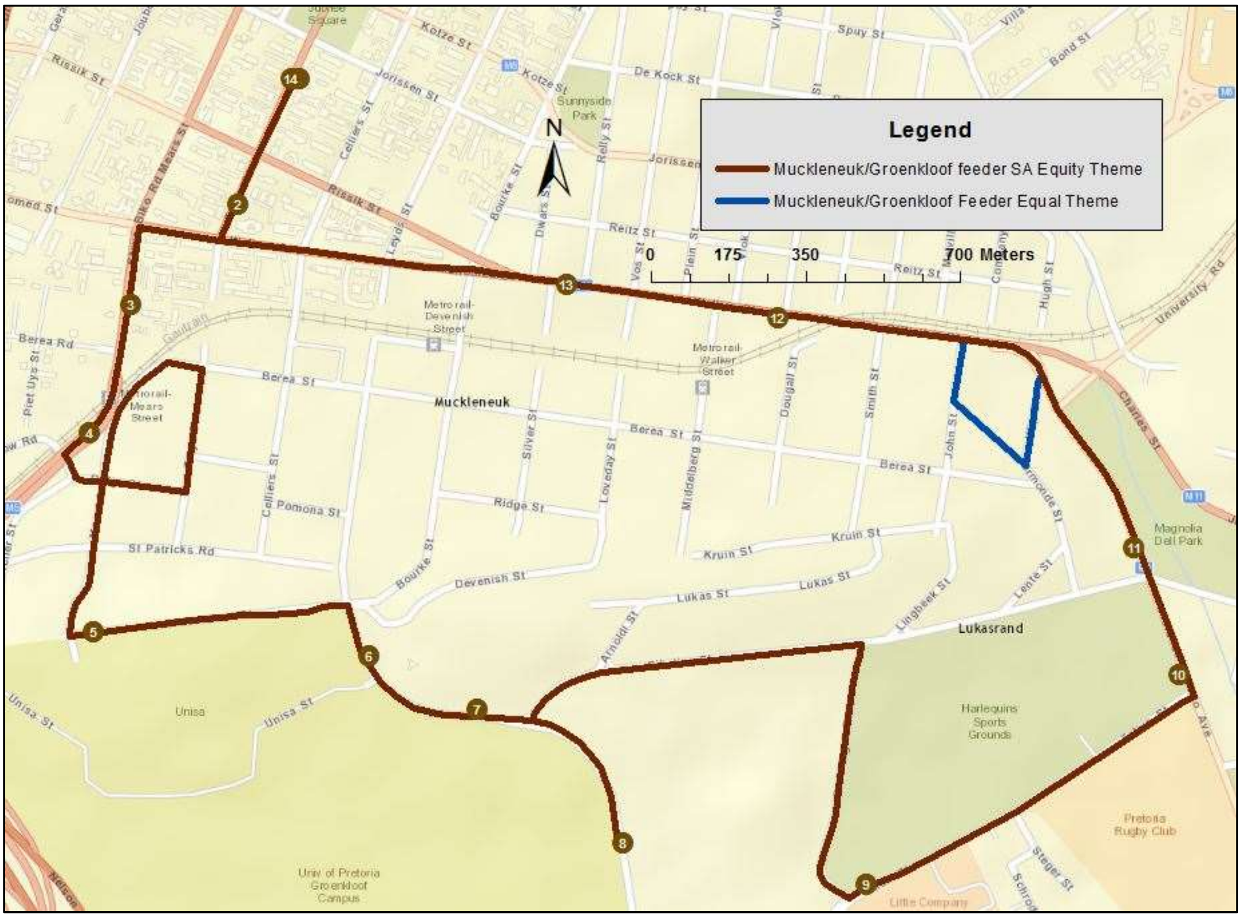

Figure 11-11: Muckleneuk/Groenkloof Feeder Equity SA

Environmental Impact SA Routes

Figure 11-12: Trunk 1B Environmental Impact SA

Figure 11-13: Trunk 2A Environmental Impact SA

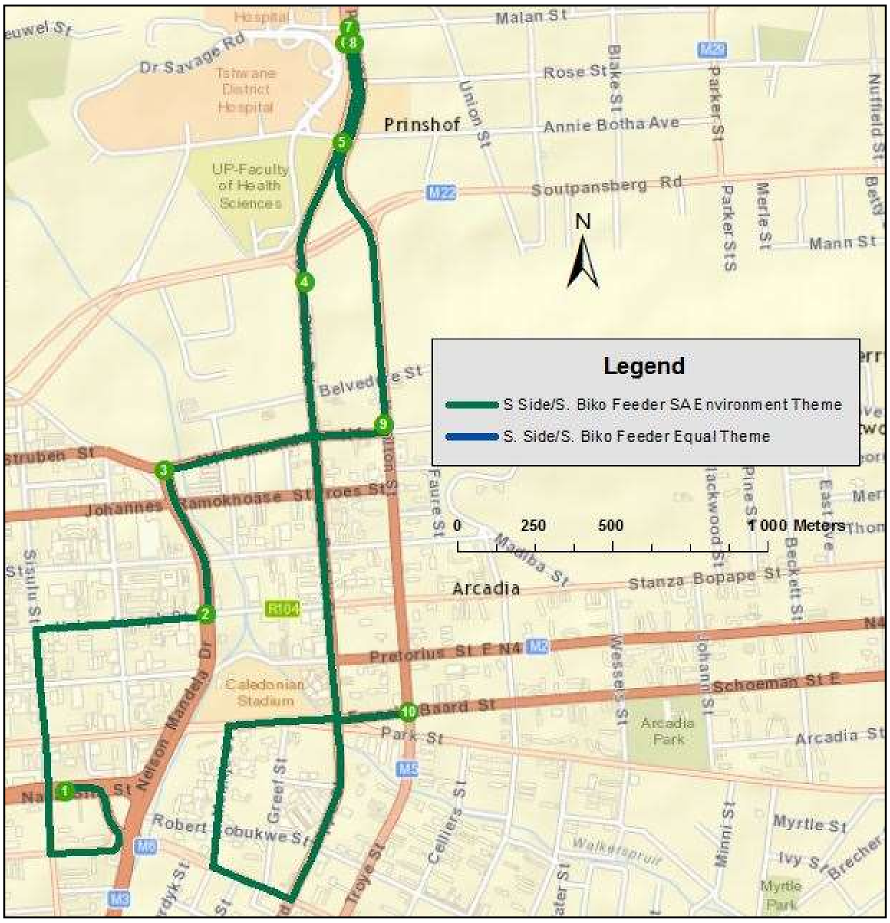

Figure 11-14: S. Side/Steve Biko Feeder Environmental Impact SA

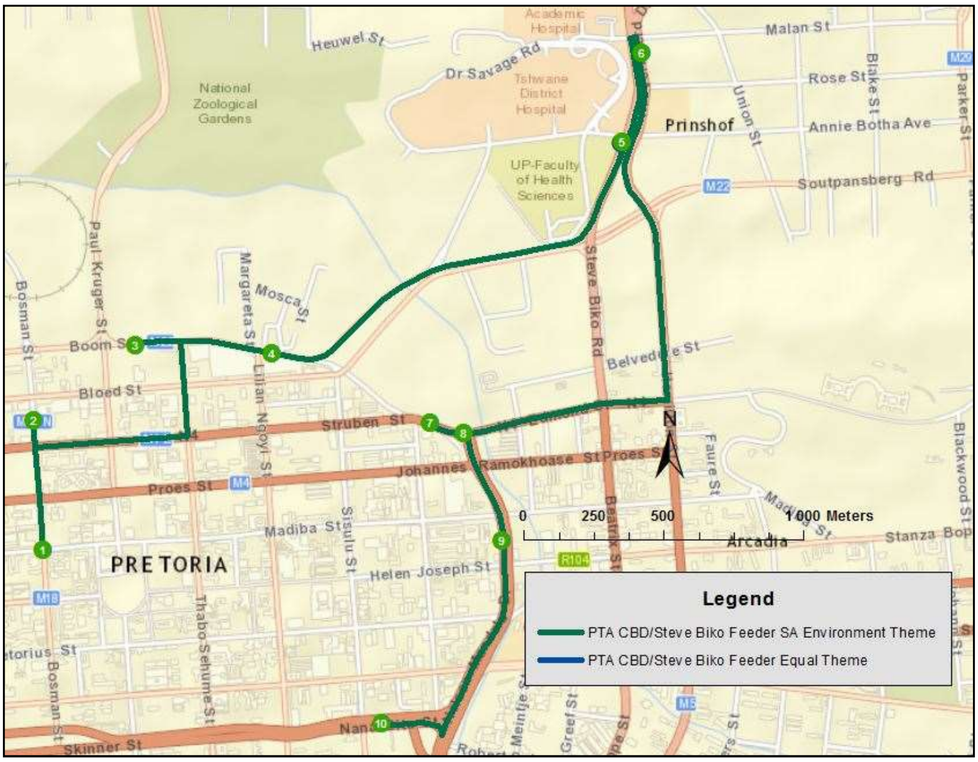

Figure 11-15: CBF/Steve Biko Feeder Environmental Impact SA

Figure 11-16: Pretoria West/TUT Feeder Environmental Impact SA

Social Impact SA Routes

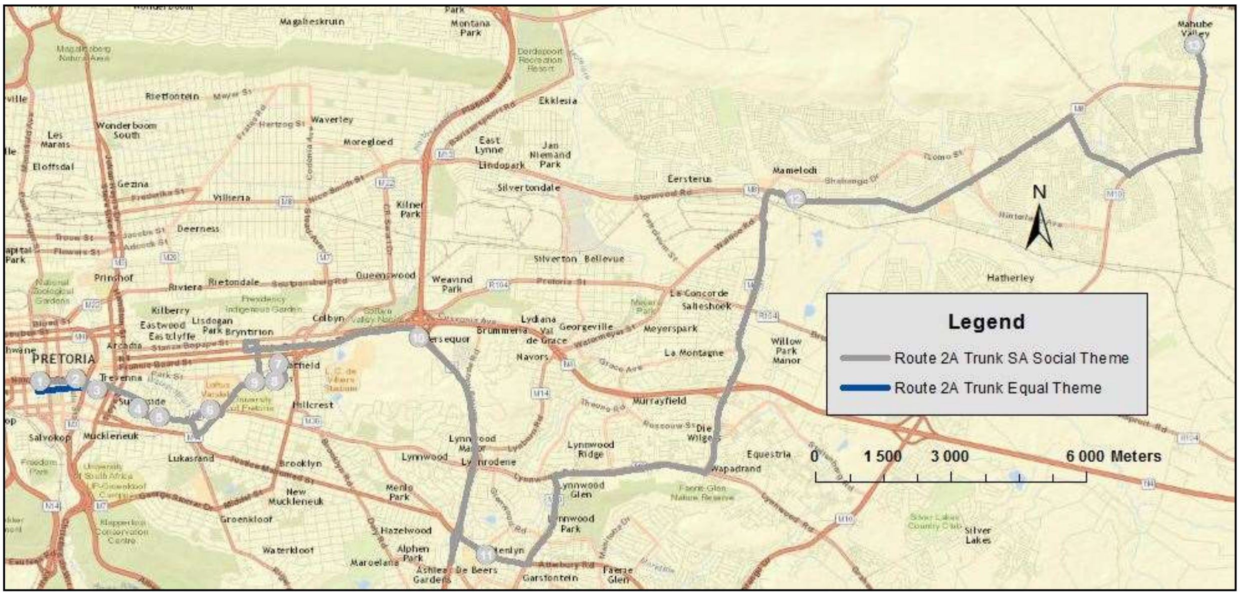

Figure 11-17: Trunk 2A Social Impact SA

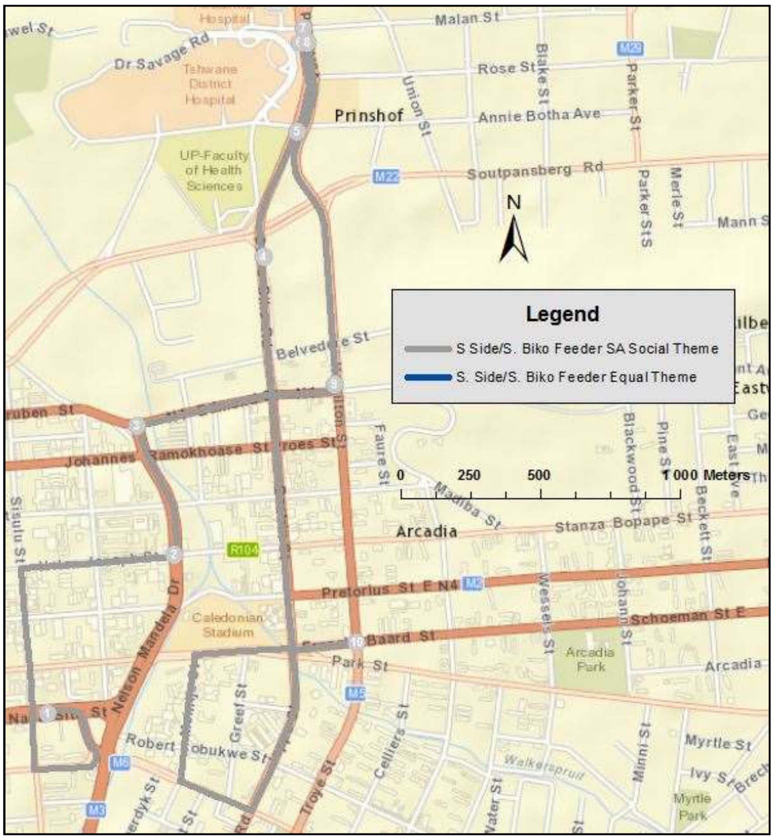

Figure 11-18: S. Side/Steve Biko Feeder Social Impact SA

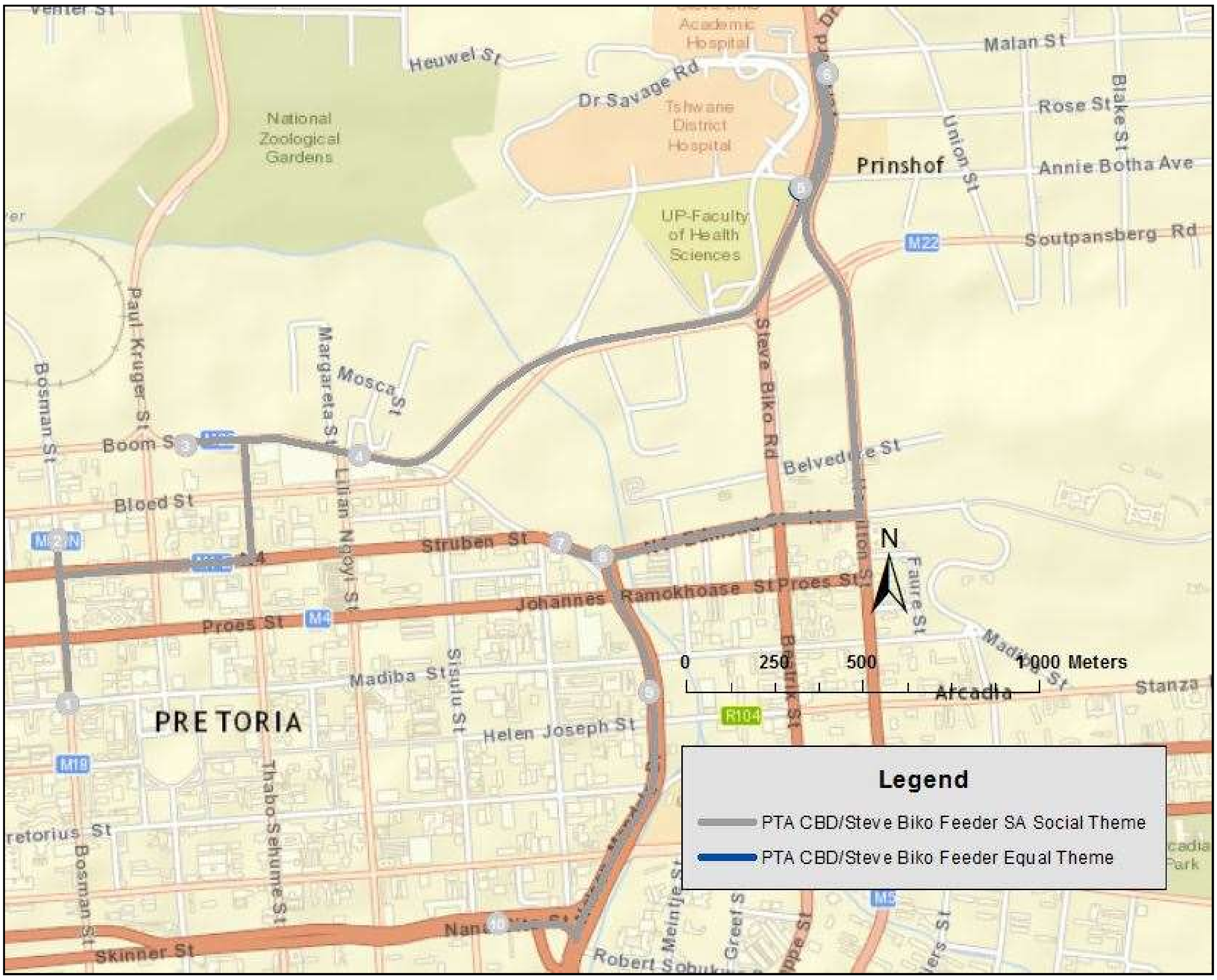

Figure 11-19: CBD/Steve Biko Feeder Social Impact SA

Figure 11-20: Pretoria West/TUT Feeder Social Impact SA

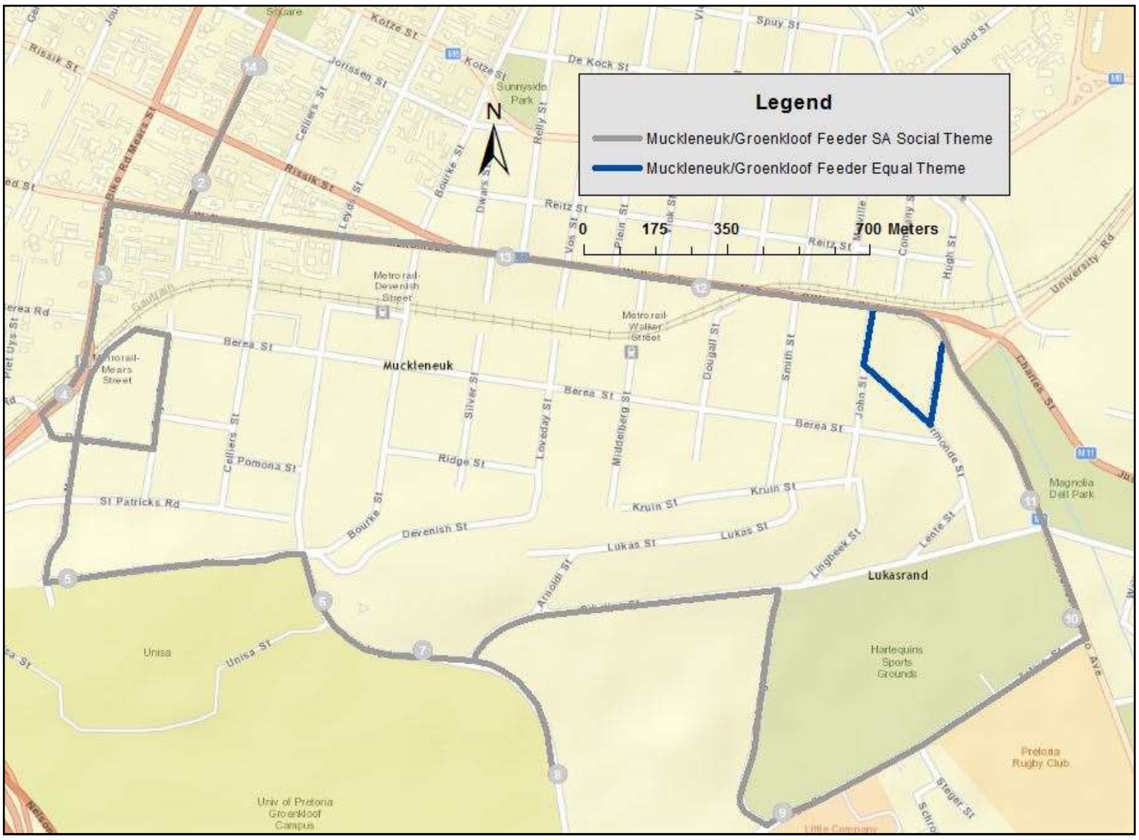

Figure 11-21: Muckleneuk/Groenkloof Feeder Social Impact SA

11.2 Appendix B: Ethics Clearance Form

Appendix removed to avoid exposing signatures of the relevant parties online.

Figure 11-22: Copy of EBE Ethics Clearance Form