UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

DEPARTMENT OF CIVIL ENGINEERING

A 120 credit dissertation submitted in partial fulfilment of the requirements for the degree

of

Master of Science in Engineering

Investigating the relationships between land use characteristics, public transport network features and financial viability at a corridor scale

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October 2016

Acknowledgements

My utmost appreciation is for my supervisor, Professor Roger Behrens, for introducing me to the field that has become my passion and all of the guidance that has allowed me to chart my path into it. The immense independence that you were willing to give me with my research, both related to this dissertation and to my many other projects, cannot be overstated in its importance. The myriad of detours that I took has allowed me to find my place within this profession, and I equally valued your guidance when I ventured too far from the path. Your exemplary standard of work, and insightful critique of mine, has raised the quality of my research far beyond my expectations. I will be eternally grateful for the opportunities you have afforded me and the ambition I now have to attain ever greater goals.

To my co-supervisor, Emeritus Professor Romano Del Mistro, our few, brief meetings were far more valuable than you are aware. Your models, upon which mine is based, provided the structure from which I could confront this daunting line of investigation. Furthermore, your technical critique of my research method always came at the opportune time, when I could not see the forest for the trees.

I would like to thank the National Research Foundation and the Southern Transportation Centre for Development for all of the funding that made this research a reality. To the admin staff within the Department of Civil Engineering and the Postgraduate funding office, thank you for tolerating my administrative ineptitude, I would have been lost without your assistance.

Finally, heartfelt gratitude to my colleagues, friends and family for keeping me sane; I would not have had the strength or focus to persevere through the tough times without all of you.

Plagiarism declaration

“I know the meaning of plagiarism and declare that all the work in the documents, save for which is properly acknowledged, is my own.”

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Abstract

The successful integration of public transport and land development planning is likely to be central in determining how effectively the cities in the ‘global south’ manage the mounting pressures from rapid urbanization, population growth and rising income inequality. While a number of Sub-Saharan African cities, particularly in South Africa, have commenced large scale public transport reform, little research has been undertaken to date on appropriate public transport-land use integration in these contexts. As a result, both of the initial phases of BRT corridor implementation, in Cape Town and Johannesburg, have been found to be financially unsustainable in their current urban forms. The major decisions regarding the design of land use environments and public transport networks, in the context of rapidly developing cities, still occur without due consideration for each other.

The aim of this study is to investigate the relationships between land use characteristics, network features and viable public transport services in the South African context and at a corridor scale. The study utilises a public transport corridor operating cost model that was created to simulate the effects of variation in four land use characteristics (population density, density distribution, land use mix and destination accessibility) and two public transport network features (mode technology and service configuration) on the financial viability of services. The corridor operating cost model consists of cascading land use, transport and costing sub-models for which the output of one supplies the input of the next.

Gross population density was found to have the weakest causal relationship with financial viability. Density distribution was shown to have a very significant effect on the average passenger trip length, and financial viability as a result. When the majority of the population is articulated adjacent to the public transport trunk corridors, at a higher density, far fewer inefficient feeder services are required. Additionally, the chosen non-motorised transport mode for those accessing the trunk service directly had a considerable effect as the higher speed of bicycles increases the catchment area within which a feeder service is usually not required. Bicycle-based density articulation was able to halve the total cost of the public transport network in one of the cases, relative to the conventional pedestrian-based variety. Land use mix had a strong connection to public transport financial viability, through substantial effects on peak passenger volume. The final land use characteristic, destination accessibility, was represented by distance to the Central Business District (CBD), as well as dictating the length of the transport corridor. It was found to have a substantial influence on financial viability and affordability, especially in the context of a distance-based fare system.

Passenger volume is the key determinant of mode technology choice and is influenced by population density, as well as the other three land use characteristics to a lesser degree. Low population densities intuitively favour smaller vehicles, while high densities or economies of scale promote the use of suburban rail and other capital intensive modes. Long public transport corridors with unsupportive land use environments favour larger vehicles, such as the BRT and non-BRT articulated bus modes. Fewer of these large vehicles are required to meet the demand and they can efficiently operate over longer distances than their smaller competitors. Whereas, short corridors and supportive land use environments favour the space priority that the conventional and articulated BRT modes possess. The higher speed that the segregated lanes allow the vehicles to reach over the shorter route distance also decreases vehicle requirements due to the higher rate of trips per hour per vehicle. The trunk-feeder and direct service configurations reacted similarly to the changes in land use characteristics, when the optimum modes are chosen to minimise costs. The results of the study suggest that a detailed land use development plan is necessary for each major public transport corridor, with unique targets for population density, density articulation and land use mix. It also demonstrated that, in the South African context, to achieve a high public transport modal split and sustainable public transport service requires high population densities, high articulation, mixed land uses, small corridor catchment areas and minimal feeder services.

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Glossary of Terms

Adaptive cities – Cities that have adapted their urban structure in order to support a desired public transport system

Adaptive transit – Cities that have used innovation and technology to adapt the features of their public transport systems to serve a desired urban structure, usually dictated by an unrestricted real estate market

Articulated density – Strategically distributed population and/or employment density across an urban area with regard to public transport trunk service stations

Densification target – A target for population and/or employment density whose attainment is believed would result in a desired outcome

Density articulation – A measure of the level of articulated density in a specified area

Density gradient – A mathematical description of the decrease in population and/or employment density from a core economic node, usually the Central Business District, to the edge of the urban area

Dysfunctional density – A density that is too high for an automobile-dependent city and but is not distributed along linear corridors in a public transport friendly manner (UN-Habitat, 2013:87)

Euclidean zoning – A land use zoning system that separates primary uses, such as residential and commercial

Global South – Developing countries

Gross population density – The average number of people residing in an urban area, per unit of area, including the space dedicated to transport, utilities and public uses

Hybrid cities – Cities that have adapted the features of their public transport systems as well as their urban structure in order for them to support each other

Land use entropy – The level of homogeneity of land use within a given area or census tract

Mohring effect – The observed phenomenon in which increased demand on a public transport system, marginally increases its supply, and therefore improves the level of service for all the users of the system

Net population density – The average number of people residing in an urban area, per unit of area, excluding the space dedicated to transport, utilities and public uses

Network design – The overarching structure of the public transport system at a metropolitan or corridor scale

Network effect – Conception that public transport services planned as a seamless and integrated network can generate higher levels of patronage than those planned as individual routes because of the added support for unexpected trip making behaviour which planners might not have predicted (Dodson, 2011)

Peak-to-base ratios – The ratio between the peak demand on a public transport service and the average demand during the off-peak periods

Public transport viability – Public transport is suggested to be generally viable if it is affordable, effective and both socially and economically sustainable.

Public transport financial viability – Public transport is suggested to be financially viable if it has attained sustainable levels of public sector subsidy.

Seat turnover – The concept of short passenger trips allowing a single seat to serve multiple passengers during the length of one vehicle trip

Threshold density – The minimum population and/or employment density within the catchment area of a public transport service that is likely to assure its financial viability

Threshold ridership – The minimum passenger demand or ridership on a public transport service that is likely to assure its financial viability

Transport corridor – One or more primary transport facilities that constitute a single pathway for the flow of people and/or goods between activity centres, as well as the adjacent land uses and supporting street network (Williams, 2000:2)

Transit Oriented Development - Mixed-use, compact, pedestrian-friendly development organized around a public transport trunk station (Suzuki et al., 2015)

Abbreviations

B-TOD - Bicycle-Based Transit Oriented Development

BRT - Bus Rapid Transit

CBD - Central Business District

CITP - Comprehensive Integrated Transport Plan

GDP – Gross Domestic Product

HCPPT - High Coverage Point-to-Point Transit

IRPTN - Integrated Rapid Public Transport Network

LRT - Light Rail Transit

MCD - Millennium Cities Database

OD - Trip Origin and Destination

SIA - Station Influence Area

T-F - Trunk-Feeder

TAD - Transit Adjacent Development

TAZ - Traffic Analysis Zone

TOD - Transit Oriented Development

1 Introduction

1.1 Research motivation

Many cities in the 'global south' face mounting pressures from rapid urbanization, population growth and rising income inequality (Parnell & Oldfield, 2014). The successful integration of public transport and land development planning is likely to be central in determining how effectively these cities manage these pressures. Some research – associated with the advent of bus rapid transit (BRT) systems – into how best to integrate public transport and land development planning has been undertaken in Latin America and Asia (Cervero & Dai, 2014; Kash & Hidalgo, 2014; Lindau, Hidalgo & de Almeida Lobo, 2014; Cervero, 2013; Suzuki, Cervero & Iuchi, 2013). While a number of Sub-Saharan African cities, particularly in South Africa, have commenced with large scale public transport reform, little research has been undertaken to date on appropriate public transport–land use integration in these contexts.

The initial phases of BRT corridor implementation in South African cities have highlighted the importance of supportive urban forms in facilitating public transport services that are no longer dependent upon unsustainably high operating subsidies. The City of Cape Town's 2014 review of its Comprehensive Integrated Transport Plan (CITP), for instance, states that "*[t]he operational requirements to run road-based public transport…in the current urban form of Cape Town, are proving to be financially unsustainable*" (CoCT, 2014):11). The City of Johannesburg has come to similar conclusions in its Rea Vaya Phase 1C Sustainability Study (CoJ, 2013). Clearly a better understanding of the prerequisite land use conditions for high quality public systems is required, and technology choices should be made with due regard to the prevailing urban form.

1.2 Research background

The coalescing of land use and public transport planning has been suggested as fundamental to creating sustainable urban development, moderating climate change and increasing the mobility of the urban poor (Suzuki, Cervero & Iuchi, 2013). There is a long history of integrating land use and transport planning, spurred on by a pioneering survey of land use conditions during the Chicago Area Transportation study of 1956 (cited in Mees, 2010a). However, the integration of land use and public transport planning at the detailed corridor level is far less frequent. The major decisions regarding the design of land use environments and public transport networks still occur without due consideration for each other, especially in the context of rapidly growing developing cities. The incongruity of public transport systems in relation to the prevailing land use conditions is one of the leading threats to their financial viability.

According to Suzuki, Cervero & Iuchi (2013), the developed cities that have achieved the successful integration of their land use and public transport at the metropolitan planning level, utilised one of three approaches. The ‘adaptive cities’ method involves choosing a desired, high-efficiency public transport service and changing the city’s land use environment aggressively to support it. The ‘adaptive transit’ method allows an unrestricted real estate market to determine the land use environment, and the public transport service is optimised to the resulting conditions. Finally, the ‘hybrid cities’ method significantly adapts both the land use structure and the public transport services of a city in order to support each other.

However, even in developed cities, the relationship between the land use environment and public transport financial viability at the more detailed corridor scale is far more complex. When analysing the land use environment, it can be described by a set of transport-related characteristics; each having a unique effect on the financial viability of public transport services. Population density has been widely accepted by city planning authorities, and much of the land use-transport viability literature, as an important land use prerequisite, resulting in the formulation of density targets and densification policies (Jones, 2014; Cervero, 2013; Ewing & Cervero, 2010; Newman, 2006; Newman & Kenworthy, 1989). Other land use indicators, such as land use mix and destination accessibility, have also been posited as a requirement for the attainment of viable public transport (Suzuki, Cervero & Iuchi, 2013; Naess, 2012; Ewing & Cervero, 2010; Kockelman, 1997). Another land use indicator, density distribution, has now come to the fore as a potential new determinant for public transport supportiveness (Suzuki, Cervero & Iuchi, 2013; Zhang, 2007). Each of these characteristics are suggested to have varying impacts on the potential financial viability of a public transport network and, where relevant, should influence the process of its design.

The level of land use consideration given during the design of public transport networks is, firstly, dependent upon which of the two primary approaches to design is chosen: computational or empirical. Although, irrespective of the choice, few studies have included land use characteristics as optimisation variables when designing public transport networks, and of those found, population density is often the only characteristic analysed (Chen, Li & Lam, 2015; Wang, 2008). Furthermore, in these studies, the structural features of the public transport networks are rarely variable despite their effect on land use integration potential and service viability under diverse land use conditions. Structural features, such as the confluence of routes into corridors, the different mode technologies and the service configurations within these corridors, have all been suggested to affect the capacity for land use integration and the resulting costs of the public transport services (Suzuki et al., 2015; Suzuki, Cervero & Iuchi, 2013; Jara-Díaz, Gschwender & Ortega, 2012; Guerra & Cervero, 2011).

1.3 Problem statement and research objectives

In response to high urbanization rates in developing countries, many city authorities are embarking upon large scale public transport improvement programmes. Supportive land use environments will be necessary to reduce operating subsidies to within sustainable limits for these developing economies.

Previous studies have shown links between land use characteristics and public transport financial viability, as well as the effect of certain network features on financial viability, but the relationships between them have not been studied comprehensively and not in the context of a developing city. Therefore, the aim of this study is to investigate the relationships between land use characteristics, network features and public transport financial viability at a corridor scale, within the context of a generic South African city. This study will attempt to determine the complementary or discordant relationships between land use characteristics and network features, in terms of financial viability.

The key research objectives of this dissertation are:

- To investigate the effect of population density, density distribution, land use mix and destination accessibility on public transport financial viability when analysed in isolation from each other.
- To identify any financially beneficial or complementary relationships that may exist between the four land use characteristics and if any discordance may occur.
- To ascertain the extent to which the choice of mode technology and service configuration affect the financial viability of a public transport service under different land use conditions.
- To explore how the integration of land use and public transport, at the corridor level, affect the metropolitan planning policies in South Africa and planning policies abroad.
- To determine what manner of land use characteristics and network features could produce viable public transport in a generic South African urban context.

1.4 Dissertation outline

The body of this dissertation is structured into 6 chapters of which this introduction is the first. Chapter 2 reviews relevant literature and identifies the contemporary theories in land use-public transport financial viability research. It begins by defining the meaning of 'viability' as it pertains to public transport services and this study. Three approaches to the metropolitan scale integration of land use and transport planning are then summarised to form an overview of the aggregate land use-transport relationship. The scale of the land use environment is then reduced, to investigate the connection between individual land use characteristics and public transport financial viability on a more detailed level. Literature on the relationships of four land use characteristics is reviewed: population density; density distribution; land use mix and corridor length. Approaches to public transport network design are assessed as well as their varying levels of land use consideration. The public transport corridor as an element of the network structure is then analysed with regard to its prominence in many planning ideologies and its importance to land use-transport integration. The two most significant network design decisions, based on previous studies, are then evaluated and their connection to the land use environment is determined. The chapter concludes with an overview of land use-transport interaction in the South African policy environment.

Chapter 3 analyses the general land use-public transport viability relationship using secondary empirical data collated from 128 cities spread across the world. It establishes the effect of population density on public transport mode share, subsidy requirements and the monthly transport expenditure of the users according to empirical data. The analysis highlights correlations between density and public transport viability that can then be critically compared to the results of model simulations.

Chapter 4 outlines the functions and the process of the public transport corridor cost model that was created to analyse the effects of the four land use characteristics and the two network features on the financial viability of the public transport services. The chapter gives an overview of the spatial structure of the corridor model, the layout of the analysis zones and the dimensions of the corridor itself. The corridor operating cost model consists of three cascading models with the output of one supplying the input of the next. The details of the land use, transport and costing sub-models are then explained and discussed.

Chapter 5 illustrates the results of five land use scenarios in which one or more of the land use characteristics are varied to determine their effect on the financial viability of the public transport services. It follows with an analysis of the impact that mode technology choice has on financial viability under different land use conditions.

Chapter 6 draws conclusions based on the results of the study, and suggests some possible implications of these conclusions on the transport and city planning policies of South African and international cities. Finally, recommendations are made regarding public transport and land use corridor design, and fruitful avenues of further research in this field are explored.

2 Literature review

2.1 Introduction

The primary aim of this research is to investigate the relationships between land use characteristics, network features and public transport financial viability in the context of a South African urban transport corridor. The literary base that has formed around the integration of land use and transportation in urban planning is well established; and bolstered by a burgeoning library of empirical studies. However, far less common are studies attempting to integrate the fundamental attributes of a land use environment into the design process of a public transport corridor, especially with the goal of financial viability maximisation. The purpose of this chapter is to review this established literary base and critically analyse the studies that do test transport financial viability under these relationships at the corridor scale.

This review of the literature commences by exploring the meaning of viability in the context of public transport services (Section 2.2) in order to define the medium by which this study will analyse the relationships. Section 2.3 then examines the three approaches, posited by Suzuki, Cervero & Iuchi (2013), through which the successful integration of land use planning and public transport design can lead to system viability at the metropolitan scale.

Section 2.4 explores the proposed effects of land use characteristics on public transport service viability at a more detailed scale. Within the land use environment, there are individual land use characteristics with different effects on the financial viability of public transport services. The relationship between each characteristic and the public transport service it influences is not understood as comprehensively, and few studies have analysed these relationships in isolation. This section investigates studies relating to the effects of four land use characteristics on public transport service viability.

Section 2.5 studies the potential connections between the features of a public transport network and its financial viability under different land use conditions. Sub-section 2.5.1 evaluates the magnitude of land use consideration given by the two major methodologies for the design of public transport corridor services: computational and empirical. Sub-section 2.5.2 then investigates the role of a public transport corridor as a structural feature and its importance for land use-transport integration. The final sub-section suggests the two most important corridor scale network features and evaluates their connection to the land use environment.

This chapter concludes with a contextualisation of the argument through an overview of land use-transport interaction in the South African policy environment, the land use related transport objectives and transport related land use targets.

2.2 Public transport financial viability

Public transport is suggested to be generally viable if it is affordable, effective and both socially and economically sustainable. To be both affordable and economically sustainable, a public transport service needs to be financially accessible to the majority of the population, especially captive users, while minimizing public sector subsidies to within sustainable limits (UN-Habitat, 2013). In this study, the financial viability of a public transport system or service represents the sustainability of the subsidies. Henceforth, public transport viability will refer to its financial viability unless stated otherwise.

Public transport subsidisation is supported by a range of justifications, which Ubbels et al. (2001) suggests fall into three main arguments. Firstly, the subsidization of public transport offsets the under-priced external costs of private transport use to society, such as pollution, congestion, environmental externalities and road safety risks (Vickrey, 1963). Secondly, the large fixed costs and small variable costs related to a public transport system mean that the marginal cost is low and the system benefits from economies of scale. Similarly, the 'Mohring effect' dictates that the increased demand on a public transport system, increases the supply, although marginally, and improves the level of service for all the users of the system (Mohring, 1972). Finally, public transport subsidies allow the poorest members of society to access public services and economic opportunities through affordable fares and income redistribution effects (Serebrisky et al., 2009). Therefore, the societal benefits of public transport subsidies are suggested to outweigh the financial costs, especially in developing cities where the proportion of poor, captive users is higher.

Public transport subsidies are ubiquitous in developed cities, in order to create viable public transport, but less so in developing cities where fisci are more constrained and paratransit services are dominant (Del Mistro & Behrens, 2014). The magnitude of subsidization is often dependent on the financial liquidity of the national government or the local transport authority (Mees, 2010b). As developing cities, such as those in South Africa, scale up their formal public transport systems, minimizing operating subsidies becomes an increasingly important goal. Therefore, the concept of public transport service viability is variable. Developing cities have a larger proportion of poor, captive public transport users, which means higher levels of subsidy are required. But the transport authorities suffer from a poverty of funding that they can allocate to subsidization, whether the subsidies are warranted or not. Minimizing the level of subsidy required is therefore equally, if not more, important in developing cities than those of the developed world.

2.3 Land use-transport integration at the metropolitan scale

It has been suggested that there are three main approaches to integrating land use and public transport at the metropolitan scale with the aim of improving its viability (Suzuki, Cervero & Iuchi, 2013). The first approach, 'Adaptive cities', is said to be the most common reaction to a discordance between public transport and the land use environment. It involves the adaption of the urban structure of the city in order to support a desired public transport system. The second approach, 'Adaptive transit', uses innovation and technology to adapt the features of the public transport system to serve a desired urban structure, usually dictated by an unrestricted real estate market. The final approach, 'Hybrid cities', adapts both its urban structure and the features of its public transport service until viability is attained. This section will critically analyse each of the three approaches, their advantages and disadvantages.

2.3.1 Adaptive cities

'Adaptive cities' have allowed large scale transit infrastructure to dictate settlement patterns and urban growth in order to achieve desired spatial and societal objectives. Commonly, this has manifested as Transit Oriented Development (TOD), which is defined as:

> *"Compact, mixed-use, pedestrian-friendly development organized around a transit station. TOD embraces the idea that locating amenities, employment, retail shops, and housing around transit hubs promotes transit usage and non-motorized travel" (Suzuki et al., 2015).*

Adaptive cities tend to have a dominant Central Business District (CBD) with much of the remaining economic activity concentrated around the transit nodes, in a "string of pearls" development pattern (Suzuki, Cervero & Iuchi, 2013). Examples of adaptive cities are Copenhagen; Stockholm; Seoul and Tokyo. Adaptive cities maintain the viability of their public transport systems through the efficiency of a high-capacity trunk service network and the optimised travel patterns of the dense, mixed use communities (OECD, 2012). In the Scandinavian cases, the compactness of the satellite communities was so high that they were able to place protective greenbelts between them (Suzuki, Cervero & Iuchi, 2013). This allowed the residents to enjoy the benefits of a suburban lifestyle without the associated urban sprawl and large environmental footprint. Although, the Scandinavian cities can sustain this suburban compactness, in part, due to their small populations relative to the average city in a developing country. Most of these adaptive cities have followed a detailed development masterplan as they've grown and adhered to strict land use-transport strategies that have spanned decades.

2.3.2 Adaptive transit

On the opposite end of the urban planning spectrum, 'adaptive transit' is public transport that adapts to an unsupportive land use environment created by an unregulated private real estate market (Suzuki, Cervero & Iuchi, 2013). In order to be competitive in this environment, public transport has emulated the service features of the private automobile, through the use of smaller vehicles with increased demand responsiveness and flexibility (Salazar Ferro & Behrens, 2015).

In many wealthier developed cities, unrestricted housing markets tend toward suburban development patterns and rampant urban sprawl, which some believe is a sign of affluence and economic progress (OECD, 2012). Hence, the origins and destinations of the transport trips are fairly evenly distributed throughout an urban area. The decentralization of economic opportunities into the residential areas leads to arbitrary tangential movement instead of the conventional movement toward the major economic nodes that public transport services utilize to achieve economies of scale (Mees, 2010b). This has resulted in the exploration of High Coverage Point-to-Point Transit (HCPPT) which utilises technological advances and innovative service structures (Cortes, 2003). It could be argued that a new example of HCPPT are the number of mobile application-based rideshare services, such as Uber, Lyft, and SideCar, that have enjoyed exponential growth in cities throughout the world (Xu et al., 2015). Their superior technology, speed and directness mitigate some of the conventional negative externalities associated with formal public transport in unsupportive environments.

In poorer developing cities, unrestricted housing markets tend toward large, single-storey informal settlements, often on the periphery of the urban area (Golub, Behrens & Salazar Ferro, 2012). The rapid, unregulated and dynamic growth of some developing cities has favoured public transport services with similar traits. Paratransit services have come to dominate the public transport sector in the developing cities of the Global South. They have remained resilient to public sector efforts to formalise public transport services and adapted to ever more complex urban environments (Salazar Ferro & Behrens, 2015). As they evolve to be more formalised enterprises and start to borrow from the technological advances of the new HCPPT services, paratransit will become even more adaptive to the environment in which it operates.

2.3.3 Hybrid cities

Adaptive cities are public transport utopias but require decades of planning to shape urban development as it is occurring. Therefore, the model is unsuitable for the developed cities whose urban development has already sprawled without restriction. Conversely, it is equally incompatible with the rapid growth rates and lack of regulatory control seen in many developing cities. Adaptive transit is no more of a solution due to the inefficiency of its public transport systems and the unsustainable urban form it serves. A spectrum of solutions between the two models is required to meet the needs of most cities.

Hybrid cities have invested sufficiently in TOD to sustain efficient public transport, while simultaneously adapted their public transport to the existing inefficient land use patterns. As the cities have not been master-planned but still contain significant TOD, the hybrids usually develop a polycentric structure linked by high-capacity public transport trunk service corridors (Suzuki et al., 2015).

The hybrid city model could explain the recent popularity of Bus Rapid Transit (BRT) in developing cities as it can achieve much higher capacities and efficiency than paratransit services but remains more flexible and demand responsive than suburban rail and metro services (Suzuki, Cervero & Iuchi, 2013). However, despite BRT being touted as a hybrid city-inspired panacea, especially for developing cities, it has failed to attain viability in many urban contexts.

An understanding of the fundamental relationships between specific characteristics of the land use environment and the many decisions involved in public transport network design would be required to determine the optimal level of adaption of each. The following section explores the relationships that the four predominant land use characteristics in transport literature have with the viability of public transport services.

2.4 Land use characteristics

The link between urban form and public transport viability has been identified by transport and spatial planning practitioners for more than a century. The financial viability of New York City's Interborough Rapid Transit (IRT) system, for instance, was predicated on the stimulation of transit supportive urban development around the new stations (Ward & Zunz, 1997). Transport and spatial planning practitioners have been trying to analyse the way in which land use characteristics affect public transport viability, and gained real traction with Zupan and Pushkarev's book, *Public transportation and land use policy*, in 1977 (Marshall & Banister, 2007). Zupan and Pushkarev created a set of "land use thresholds" that they determined would be required to make different modes of public transport financially viable (Badoe & Miller, 2000). The land use factors that were deemed significant were residential density, distance to the CBD and size of the CBD (Pushkarev, 1977).

Since their study, the list of land use characteristics with a significant influence on travel has evolved to become known as the '5 Ds'. Ewing & Cervero (2010) performed a meta-analysis of the relevant literature, finding 62 studies that analysed at least one of the D characteristics. The 5 Ds are *density*; *diversity*; *design*; *destination accessibility* and *distance to transit*. Of the 5 Ds, the following two characteristics are not directly relevant to a study on land use characteristics and public transport viability.

Design represents the urban design of the areas surrounding the public transport stations. Public transport supportive urban design, through the creation of pedestrian-oriented environments, differentiates TOD from the unsupportive Transit Adjacent Development (TAD) (Zhang, 2007). Although it has been found to have a significant effect on public transport ridership, it is more a characteristic of urban design than one of land use.

Distance to transit is usually a measure of the average shortest path to a public transport stop or station from a residence or place of employment. It describes the street pattern of the neighbourhoods or the station density of the public transport service (Ewing & Cervero, 2010). Neither of these factors are within the scope of this study; for an investigation of the relationship between population density and station density see Chen, Li & Lam (2015); Sivakumaran et al. (2014).

The remaining D characteristics, *density*, *diversity* and *destination accessibility*, as well as one new characteristic, are investigated in the following sections to determine their relationships to public transport service viability.

2.4.1 Population density

Population *density* is defined in this study as the number of people residing within a specified area, per unit of area. Population density affects the volume of passengers, or ridership, that utilise a public transport service (Newman, 1989). Championed by Newman and Kenworthy in the 1980s, density has garnered most of the attention in the land use-transport interaction research. Their research spawned a host of investigations which have yielded a broad literary base for this relationship. Extensive literature reviews have been done by UN-Habitat (2013); Ewing & Cervero (2010); Stead (2001) and others. From the studies done, the majority are in agreement that population density is the most significant spatial factor in determining public transport viability.

The connection between population density and public transport viability is purported to be through the concepts of 'threshold ridership' and 'threshold density'. Threshold ridership is the volume of passengers that a public transport service requires to be financially viable. Ridership is largely dependent upon access to the system, which is derived from the generalised cost and the user's proximity to a public transport station or stop (Wang, 2008).

It is claimed that every public transport user is also a pedestrian, which is why the maximum proximity of a user is often assumed to be the maximum distance a user is willing to walk to the point of access (Mees, 2010b; Murray et al., 1998). The maximum proximity delineates the extent of the effectual catchment area from which passengers are likely to utilise the public transport stop. Therefore, most of the passengers that are required to meet the threshold ridership of the service will live or work within the collective catchment area of its stops, and those of its feeder services. Consequently, the number of users that are likely to utilise the service, from within the catchment area, is fundamentally dependent on population density (Wang, 2008). The threshold ridership will then have an accompanying threshold population density that is based on the modal split of the area. Although, the public transport modal split is also dependent upon population density. The high level of congestion and short passenger trip lengths associated with high density cities favour public transport mode technologies (UN-Habitat, 2013).

If user costs are kept relatively constant, the threshold ridership is based on the financial cost of operating the service. Therefore, a higher threshold ridership can be representative of a public transport service that is more modern, efficient and of higher quality than the local alternative modes (Murray et al., 1998). To maximise quality-of-service but remain financially viable, a public transport service needs to have a threshold ridership that is equal to the number of passengers that are likely to utilise it (Wang, 2008). This means that an expensive, high capacity subway system, with a very high threshold ridership, will require an equally high population density to remain viable. In summary, population density is said to put the 'mass' in mass transit, increasing the patronage of a service and leading to viability through the economies of scale (Guerra & Cervero, 2012).

The primary focus of the population density research, relevant to the objectives of this study, has been the estimation of the magnitude of density required to attain viable forms of different public transport systems: the 'density threshold' (Renne & Ewing, 2013). Various authors have posited density thresholds specific to public transport modes, levels of service and urban contexts that assure service viability (Guerra & Cervero, 2011). Many of these thresholds are derived from the empirical analysis of existing public transport systems and their respective urban contexts. Pioneering empirical population density thresholds ranging from 30 persons per ha (p/ha) (Kenworthy & Newman, 1989) to 100 p/ha (Manual, 1956) have shaped the debate on urban form and public transport viability for decades (Mees, 2009). Even though Kenworthy and Newman's (1989) threshold is based on a more comprehensive multinational study, the data was exclusive to developed cities.

There are numerous methods and units for measuring population density. 'Gross population density', the persons per hectare (p/ha) for an entire area, and 'net population density', the p/ha for residential land only, are among the most common. Gross and net residential densities are calculated in a similar manner: using residential dwellings units per hectare (Suzuki, Cervero & Iuchi, 2013).

2.4.2 Density distribution

The distribution of density across space is a recent addition to the group of urban form indicators. It has elements of *density*, *distance to transit* and *destination accessibility*. Strategically distributed density with regard to public transport trunk service stations is referred to as 'articulated density' (Suzuki, Cervero & Iuchi, 2013), or 'differentiated density' in the Chinese literature (Zhang, 2007). Articulated density derived from the research into compact city development patterns and the concept that sustainable urban developments need to be dense, and proximate to both each other and mobility nodes (OECD, 2012).

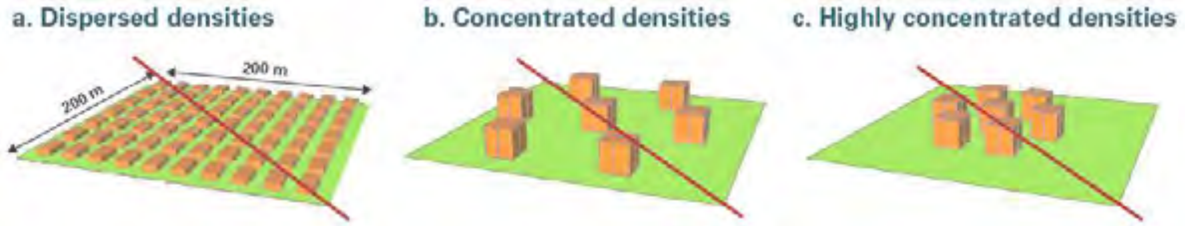

Figure 1: Density and proximity in regard to a public transport trunk service (Suzuki, Cervero & Iuchi, 2013)

In Figure 1, each of the three examples has the same gross population density and the red line represents a public transport trunk service. The 'dispersed density' example illustrates that the population density is evenly distributed throughout the urban area. This form of density is prevalent in cities like Los Angeles, USA and has become known as 'dysfunctional density' (UN-Habitat, 2013). As a result, Los Angeles has the highest gross-base metropolitan population density in the US as well as the highest per capita vehicular travel and the highest congestion. It has been determined that the densities are “too high for a car-dependent city and are not organized along linear corridors in a public transport friendly manner” (UN-Habitat, 2013:87).

When ‘highly concentrated densities’ occur around public transport trunk service stations, it is known as articulated density. Therefore, this form of density is essential for the creation of TOD. A notable example of articulated density is Curitiba, Brazil; it leverages its relatively low gross population density to maintain an efficient and unsubsidised public transport network (Lindau, Hidalgo & Facchini, 2010). The distribution of density can affect public transport viability through its impact on average passenger trip lengths and the proportion of public transport users within walking distance of the trunk service route (Suzuki, Cervero & Iuchi, 2013). The higher the proportion of users accessing the trunk service stations directly, the lower the number that are required to take the less efficient and less viable feeder services. To a large degree, the effect of articulated density hinges on the benefits of decreased feeder service reliance.

As articulated density relies on increased trunk service station access, its footprint has been assumed to be the walking distance radius from a trunk service station. However, other non-motorised modes can also be used as the basis for the TOD area; most notably, the bicycle. Lee, Choi & Leem (2015) have recently suggested that bicycle-based TOD (B-TOD) can extend the spatial influence of a trunk service station and overcome many of the criticisms of conventional TOD. The Station Influence Area (SIA) for pedestrian access was determined by preceding studies to be approximately between 0.5 and 1km, drawing predominately from studies in the developed city context (Kim & Nam, 2013). When compared to an SIA for cyclist access of approximately 1.8 - 4km, B-TOD could cover up to 6300% more area than conventional TOD without altering the public transport service. An example of this

Figure 2: Station Impact Area by access distances in Seoul, South Korea (Lee, Choi & Leem, 2015)

would be that the proportion of Seoul, South Korea's urban area covered by the collective SIA of its trunk service stations would increase from 29.9% using conventional TOD to 93.6% using B-TOD, illustrated in Figure 2 (Lee, Choi & Leem, 2015).

To date, no measure could be found for the level of articulated density or the degree to which the density of a city is strategically distributed with regard to public transport trunk services. Conventional density distribution metrics, such as the 'density gradient', exclusively use the CBD or other urban planning features as the point of reference (Bertaud & Malpezzi, 2003).

2.4.3 Land use mix

The land use mix, or *diversity*, refers to the spread of land uses and their level of interaction within a given area (Ewing & Cervero, 2010). Land use mix has an influence on public transport viability through its effect on trip length and the degree of seat turnover achieved by a vehicle during a completed trip. In the past, Euclidean (single-use) zoning practices segregated residential areas from the pollution generated by industrial facilities and major retail environments (Cervero, 1991). Despite the advent of modern, non-polluting industries and retail developments, the segregation of land uses persists in many cities as an anachronism (Newman, 2006). The more fine-grained the mix of land use types, the closer an average resident is to the nearest place of employment, retail and other amenities, which leads to a higher percentage of short public transport trips (Manaugh & Kreider, 2013).

This is important for the viability of public transport systems as shorter trips are generally more expensive per kilometre for the passenger, but passengers make a greater number of trips as the cost of each trip is low (Newman, 2006). Shorter trips also mean that more passengers can use the same seat on a vehicle through the duration of the route, increasing vehicle productivity: this is the concept of seat turnover. Vehicles satisfying more trips at a higher per kilometre fare, substantially increases the revenue of a public transport service (Newman, 2006). Furthermore, the differing periods of peak demand for different land uses mean that the passenger volumes on proximate public transport routes will be more evenly spread throughout the day and week, and 'peak-to-base' ratios will be reduced (Suzuki, Cervero & Iuchi, 2013). The peak-to-base ratio represents the magnitude of demand during a public transport system's temporal peak in comparison to the average demand in the off-peak hours (Nielsen, 2005).

In South Africa, the Apartheid spatial planning ideology resulted in unique spatial patterns that have formed unidirectional demand profiles and high peak-to-base ratios in the public transport services (van Ryneveld, 2010). The peak-to-base ratio represents the magnitude of demand during a public transport system's temporal peak in comparison to the average demand in the off-peak hours (Nielsen, 2005). These two factors are perceived as fundamental reasons for why the creation of effective and viable public transport in South Africa has been so difficult. Both factors are linked to land use mix and the distribution of employment opportunities. Land use mix could significantly improve the viability of public transport services in South African cities but very little research into the characteristic has been conducted.

Regarding the context of a developing city, Zegras (2010) found relatively modest effects of land use mix on travel behaviour in Santiago de Chile compared to most developed cities, which may be due to the larger effects from income and distance to the CBD. A study by Haque et al. (2013) suggests that there is a significant land use imbalance between urban zones in the city of Sylhet, Bangladesh, which has a significant effect on trip patterns. While Saghapour (2013) observed that increasing land use diversity in Shiraz City, Iran, reduces trip lengths but does not significantly affect private vehicle usage. These studies illustrate the varied nature of land use mix's effects in the context of different developing cities. There was no study found that analysed the impact of land use mix on public transport viability in a developing city.

The metrics for land use mix come in the form of land use indices, such as 'entropy', 'dissimilarity', 'variability' and 'concentration', among others (Bordoloi et al., 2013). The indices require detailed land use information on a local scale and are not easily comparable (Manaugh & Kreider, 2013). Some developed cities have begun to set land use mix targets in an effort to improve public transport travel patterns and viability. Land use 'entropy' is currently the most commonly used index and quantifies the homogeneity of land use within a given area or census tract (Bordoloi et al., 2013). Equation 1 utilises the proportional area of the different land uses to determine an index score, but does not account for their distribution pattern nor the likelihood of significant interaction between them (Manaugh & Kreider, 2013).

Equation 1: Entropy Index Equation (Kockelman, 1997)

$$\boldsymbol{Entropy = \Sigma_j P_j \times \frac{\ln(P_j)}{\ln(J)}}$$

Pj = the proportion of total developed area of jth land-use category found in the study area,
J = total number of land uses under consideration

2.4.4 Destination accessibility

Destination accessibility characterises the ease with which one can access one's trip destination and, in the regional context, has been represented in previous studies by the distance to the CBD (Ewing & Cervero, 2010). Despite appearing as a characteristic in Pushkarev's (1977) original set of land use thresholds, it has not received the popularity in the literature that population density and land use mix hold. In regard to travel behaviour, distance to the CBD is found to have a significant influence on car ownership and average trip length (Naess, 2012). The CBD of monocentric cities contains a majority of the employment opportunities, meaning that distance to the CBD often determines the distance between the trip's origin and destination (Naess, 2012). Even though density and land use diversity were found to have significant effects in the model of automobile ownership and use in Santiago de Chile by Zegras (2010), distance to the CBD was found to have a considerably larger estimated impact.

Additionally, the size of a public transport corridor's catchment area is dependent upon its length and that of its feeder services. The larger the catchment area, the smaller the level of population density necessary to generate a certain amount of demand on the service. Therefore, reducing the catchment area would allow one to increase the population density while maintaining the same peak passenger volume and level of public transport infrastructure. As intense densification is often occurring on cheaper land at the periphery of rapidly growing developing cities – while the majority of the economic opportunities remain within the CBD and other historic economic centres – the length of the public transport corridors serving these captive users become exceptionally large. An example is the 35km Phase 2 BRT trunk corridor in Cape Town, South Africa which will commence construction in 2016 (Transport for Cape Town, 2014). Similarly, in Indonesian cities, the average BRT route is approximately 30 km in length and the demand pattern is radial, terminating at the CBD (Ernst & Sutomo, 2010).

From a meta-analysis of past empirical studies, distance to the CBD is purported to have one of the strongest influences on travel behaviour and private vehicle use (Ewing & Cervero, 2010). However, the indicator usually represents the distance from the CBD of each individual neighbourhood instead of the average distance for all neighbourhoods. This means that the indicator is empirically correlated with many of the 'D' characteristics through residential self-selection (Cao, Mokhtarian & Handy, 2009). Residential self-selection is the notion that residents of a neighbourhood may use a certain transport mode or travel pattern, not because of the influence of the surrounding land use environment, but because of its predilection to their preconceived preferences regarding them (Chatman, 2014). This confusion around correlation and causality permeates through the land use-transport interaction empirical studies and remains one of the largest barriers to their use in public transport network design.

2.5 Public transport network design

Public transport network design refers specifically to the intensive coordination of public transport services to create the 'network effect'. Efficient and well-designed public transport networks will not simply emerge from a mesh of uncorrelated overlapping routes. These networks require detailed design through the application of an ordered set of planning strategies and techniques (Dodson, 2011).

The overarching structure of the public transport system at a metropolitan or corridor scale is described as the 'network design' (Nielsen, 2005). In the past two decades, there has been an increasing level of recognition in transport planning literature that public transport operates most efficiently and successfully when it has been designed as a unified network instead of a set of individual routes designed in isolation (Wright & Hook, 2007).

2.5.1 Network design methodologies

There are two main methodologies for the study and design of public transport network features: computational and empirical. The computational methodology simulates public transport services through econometric and mathematical models to optimise their features. The empirical methodology analyses existing case studies; using institutional knowledge and international best practice principles to guide public transport service design.

2.5.1.1 Computational methodology

The computational methodology encompasses the research dedicated to optimising the design of public transport networks through the use of mathematical and econometric models and equations. In 1925, Patz became the first person to generate a transport network model for the purpose of line optimisation (Patz, 1925). A simple network of 10 nodes in a tree formation was used and it was solved using basic linear programming (Quak, 2003). Subsequent models have grown exponentially in complexity and size.

Guihaire & Hao (2008) have compiled a comprehensive review of the mathematically based models that have been created since 1925 to solve a part of the public transport network design process. They found that 69 approaches have been taken and answer varying combinations of the public transport network design, frequency setting and scheduling problems. For the models addressing the network design problem, the input variables were deemed to be the topology of the area and the transport demand, in the form of an origin-destination matrix. No mention is made of any models that include contextual data, such as land use patterns or socio-economic attributes.

One notable mathematical model that was absent from the review, is that of the High Coverage Point-to-Point Transit (HCPPT) concept which was discussed in the ‘adaptive transit’ section (2.3.2) of this review (Cortes, 2003). Neumann & Nagel (2012) continued the adaptive transit research by modelling demand responsive services in a ‘survival of the fittest’ approach reminiscent of paratransit systems in developing countries. Since the review, a number of important studies have been produced that have progressed the state of the art. Fernández, de Cea & Malbran (2008) built a metropolitan level model to compare the current transport system of Santiago, Chile against a restructured alternative. The existing system of demand responsive, direct services with different operators was modelled in comparison to a new integrated system with a hierarchical structure of specialist services. Their study began to analyse the effect of service configuration and other network structure choices on the viability of the resultant system. It was found that the operating costs of the restructured system would be significantly lower than the existing system. These cost savings would then allow the transport authority to implement important modernization measures without increasing subsidies or fares.

Vickrey (1955) and Mohring (1972) were the first to analyse the bus optimisation problem from an economic perspective, including ideas such as economies of scale and fare revenue maximisation.

They found that the frequency should be proportional to the square root of the number of passengers that are to be carried on the bus line. Glaister (1986; 1985) then began analysing the effects of competition and deregulation on urban bus systems. He found that it would be more financially feasible for cities to introduce smaller vehicles, such as minibuses, along routes and allow them to compete against each other, rather than the existing system of large buses in a heavily regulated system. Gronau (2000) furthered this line of research by suggesting that a bus line should have two different services catering to patrons with different values of time. For a full review of the issues in public transport economics see Gwilliam (2008).

Jara-Díaz & Gschwender (2003a) produced a paper proposing a general microeconomic model for the operation of public transport. The study reviewed the previous literature on econometric models for public transport systems and compared the new model against those of Mohring, (1972), Jansson, (1980) and others. It was found that the square root rule remained relevant for frequency in their model but it became proportional to the cube root of demand when line spacing was taken into account. Later, Jara-Díaz & Gschwender (2009) tried to determine why observed bus services utilised vehicles that were too large and frequencies that were too low. They posit that financial restraints on the operator affects the system in a similar way to the diminishment of the value of users' time and results in these sub-optimal characteristics.

Jara-Díaz & Gschwender (2003) also conducted an econometric analysis on the service configuration choice of public transport corridors, comparing a direct service system to that of a trunk-feeder service. In a simplified model, they determined that financial preference for either structure depended on many different variables. The most significant of these variables were related to the relative value of in-vehicle and waiting times, as well as the distribution and magnitude of the demand along the trunk service corridor. This research was expanded to analyse the addition of complementary, substitute or exclusive lines, and the demand conditions under which routes involving transfers are preferable (Jara-Díaz, Gschwender & Ortega, 2012).

Wang (2008) conducted one of the few mathematically-based approaches to public transport network design that analysed its viability with due consideration for land use characteristics. The study investigated the effect of density on the feasibility of rail services within an idealised metropolitan area. The distribution of density was allocated using the saturation gradient method, in which the density of trip origins is highest in the CBD and tapers following an exponential function moving outward. Sensitivity analyses were completed with different exponential functions to ascertain its effects on rail service viability. In this study, the density distribution function dictates the footprint of the city; the length of the service; the station spacing and the service headway. An iterative, mixed-integer linear programming approach was taken to identify the globally-constrained solutions. Minimum population densities in the range of 175 to 398 p/ha were needed to create a subsidy-free rail system for different density gradient functions. Although, it was found that these minima were predominantly affected by the length of the corridor. As mentioned in Section 2.2, subsidies for public transport services are ubiquitous in developed cities, as they can induce far greater returns for society and the local government. Therefore, a subsidy-free public transport system would not be the desired outcome for most network design processes. Additionally, very few cities have achieved a metropolitan gross population density above 200 p/ha, so the posited density thresholds would not be suitable targets for South African cities (Kenworthy & Laube, 2001). Furthermore, the relevance of this study is limited by the assumptions that all trips are destined for the Central Business District (CBD) and that the distribution of population density follows an exponential profile, both of which are incompatible with many rapidly growing developing cities.

Sivakumaran et al. (2014) is the only study found that explores the effect of density distribution on public transport viability which identifies the stations as the point of reference. The study is also based on an idealised urban profile, except rectangular in shape and with a uniform grid road network. It uses a continuum approximation model, which has a small number of continuous input functions such as spatial and temporal distributions of demand or station and line separations. The model appraises user costs based on travel time and agency (authority) costs based on infrastructure, fleet and operating costs. The study also includes a mode technology choice between conventional bus, bus rapid transit (BRT) and rail. Analyses then calculate the most viable mode technology for a range of densities and corridor lengths. The analysis of particular relevance is that of the distribution of demand density. The urban profile is set as a square with a length (*L*) and width (*W*) of 20km. The demand density (ρ), which is the gross trip origin density, is set as 250 trips/km^2-hr and the local average wage (μ) is \$20/hr. μ is then used to convert all costs to travel time minutes by assuming that the average wage is also the monetary value of user time. The trip density is distributed in order to account for articulated density. An area of $2d_{max}^2$ is set around the trunk service station as its station influence area, and named the TOD

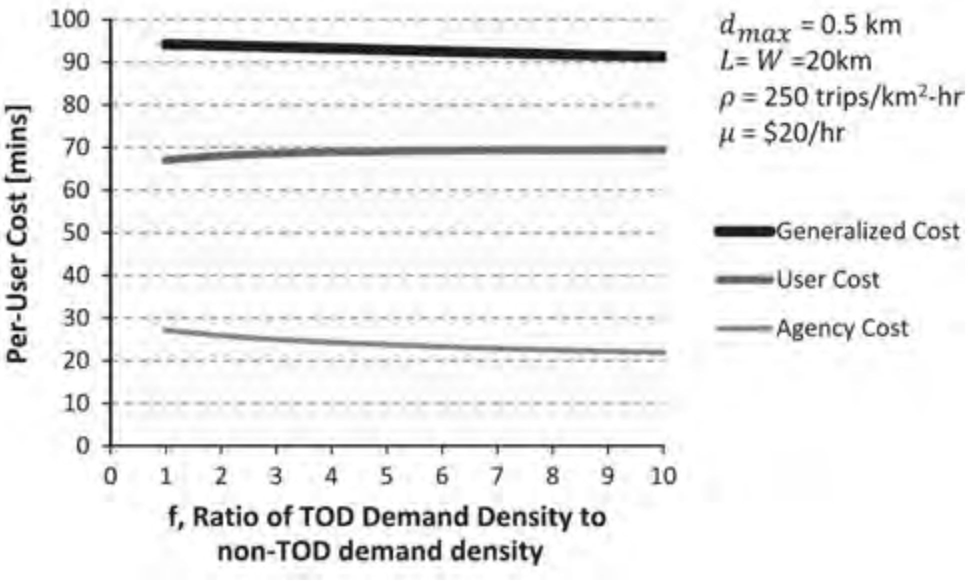

Figure 3: Relationship of cost components to trip-making density distribution (Sivakumaran et al., 2014)

zone, with d_{max} designated as the radius to the furthest extent of the TOD zone from the trunk service station. d_{max} was chosen based on a review of TOD area definitions and acceptable walking distances used in previous studies. The overall trip density is then held constant as the ratio (f) of the trip density in the TOD zone to the density outside the TOD zone is increased. Figure 3 illustrates that a very weak relationship is found between the TOD density ratio and the per-user cost components. However, the analysis does not include feeder services as it focuses on TOD. It has been argued that the most significant financial effect of articulated density is through the change in feeder service demand; highlighting the major difference between articulated density and TOD (Suzuki, Cervero & Iuchi, 2013). The absence of feeder services could account for the weak relationship seen and demonstrate the importance of promoting articulated density as well as TOD.

The most relevant study, for the objectives of this dissertation, is by Chen, Li & Lam (2015), who analyse the mode technology choice problem by optimising network features to maximise the social welfare of a public transport corridor for a range of population densities. The model optimises the transit line length, number of stations, station spacing headway and fare price. The corridor connects the CBD to the suburbs, wherein the public transport service utilises a flat fare structure and linear elastic demand density function to determine the social welfare of three different mode technologies: Bus Rapid Transit (BRT); Light Rail Transit (LRT) and Metro. The input variables for each mode, in the study by Chen, Li & Lam (2015), are:

1. Average vehicle speed;
2. Average dwell time;
3. Fixed operating cost;
4. Variable operating cost;
5. Fixed station cost;
6. Variable station cost;
7. Fixed line costs;
8. Variable line costs;
9. Capacity of the vehicles.

Social welfare is posited to be a combination of the consumer surplus of the users and the net profit of the transport authority. The consumer surplus is derived by subtracting the price that the users pay from the price that they were willing to pay. This model breaks from the idealised urban context norm and is applied in the context of five Chinese cities. The length of the corridor is fixed at 30km. Figure 4, illustrates the social welfare of the three modes against population density and the critical points at which a new mode becomes preferable. For reference, the population density of the five Chinese cities, from which the input data was derived, are also represented in the Figure 4. The density at which LRT is preferable to BRT in terms of social welfare is 110p/ha, and metro becomes preferable at a density of 144 p/ha.

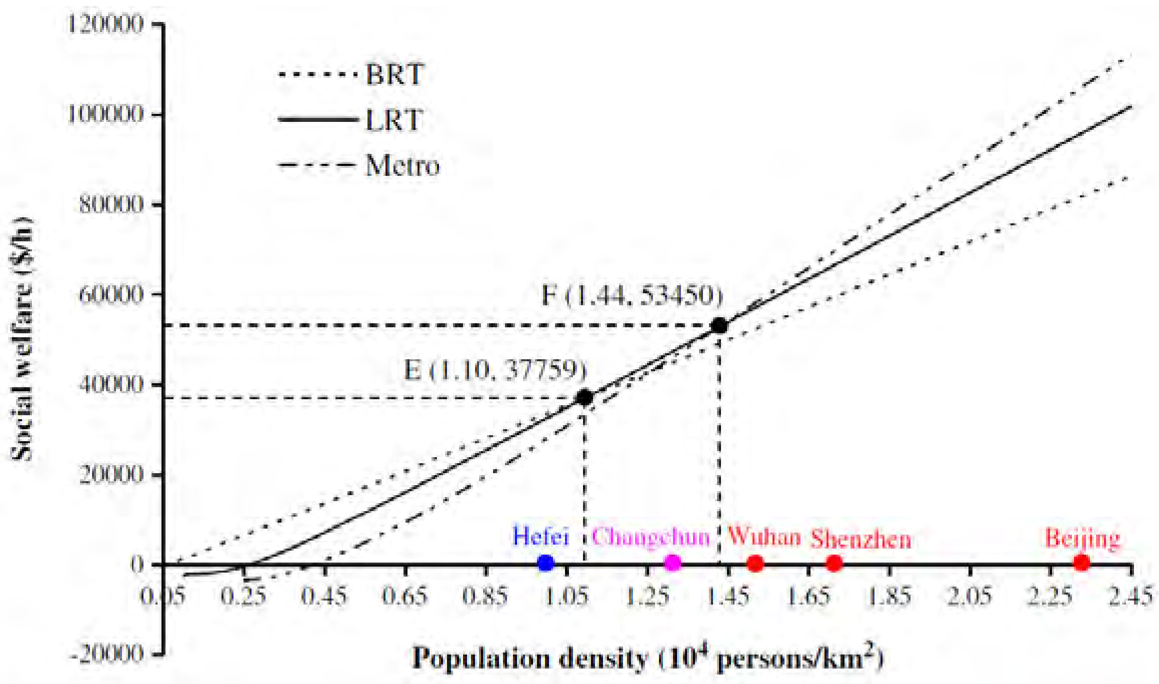

Figure 4: **Change of social welfare with population density for BRT, LRT and metro technologies (Chen, Li & Lam, 2015)**

The limitations of this study lie in the simplicity of the corridor. All of the trips terminate in the CBD, meaning that no land use mix nor trip destination diversity is taken into account. There were no feeder services and the distribution of density was not analysed. Overall, the analysis of the connection between public transport viability and density at the corridor scale is significant, but an increase in the complexity of the corridor and the land use environment is required to start fundamentally understanding their relationship.

2.5.1.2 Empirical methodology

The empirical methodology to public transport network design is that of the transport practitioners and engineers. In its purest form, it uses extensive institutional knowledge and experience in the field of transport system design to create "best practice guides" for other practitioners to base their decisions upon. Many transport practitioners tend to focus on the technological choices and infer correlations from empirical case studies instead of optimisation through modelling (Mees, 2010b). This is especially true in developing cities where data limitations constrain the accuracy of computational methods.

One of the most utilised best practice guides was produced by Vuchic (1981), titled *Urban public transportation; systems and technology*. It has been used as a reference guide to aid in the design of public transport systems, giving definitions of network features and mode technology options. The subsequent book, *Urban Transit: Operations, Planning, and Economics*, then began to outline the best practices for developing an entire public transport service in a holistic manner (Vuchic, 2005). Neither, place much prominence on the land use environment as a determinant for the decisions regarding the features of a public transport system.

In the same year, Nielsen (2005) and others produced a five book series named the *HiTrans Best Practice Guides*, including *1. Public transport and land use planning* and *2. Public transport - Planning the networks*. The book series was funded by the European Commission's Interreg IIIB North Sea Programme for use by participating cities and transport authorities in the United Kingdom and multiple Scandinavian countries. The series covered the basics of trying to plan a public transport network in varying situations, both concisely and simply enough for the general public to grasp. They expanded on this work in the following years with literature confronting the theories behind their best practice guide and some of the common pitfalls that practitioners encounter (Nielsen & Lange, 2008; Nielsen et al., 2006).

After the work by Nielsen, more specific guides began appearing that addressed the specific choices faced when designing for a particular public transport mode. One guide that has gained noted popularity investigates the process of developing a successful Bus Rapid Transit (BRT) service (Wright & Hook, 2007). The guide would undoubtedly have influenced the South African metropolitan transport authorities during the design phase of their own BRT systems. However, the guide promotes the 'adaptive city' approach, wherein a mode and accompanying technology has been chosen first, and the urban form is adapted to fit the network structure of the service. In fact, most of the best practice guides dedicate very little consideration to the nature of the operating environment and assume that the existing spatial structure will change into one that is supportive. The best practice guides do not address the effects of land use characteristics on the viability of the public transport service but are still commonly used in the public transport network decision-making process.

In developed cities, many transport practitioners have progressed beyond the limitations of both the computational and empirical methodologies of public transport network design by combining elements of both. Modern transport and land use modelling software, such as EMME 4 and UrbanSim, can utilise large empirical datasets and institutional knowledge to examine public transport options in the context of these cities (Linke, 2008). However, these models do not often examine the fundamental relationships between land use and public transport viability, and are rarely used in the context of a developing city.

2.5.2 Public transport corridor

The investigation of adaptive and hybrid cities revealed the prominence of spatially-dominant, high-capacity, public transport corridors serving their mono- and polycentric economic nodes. A transport 'corridor' is defined as:

> "*one or more primary transportation facilities that constitute a single pathway for the flow of people and goods within and between activity centres, as well as the abutting land uses and supporting street network*" (Williams, 2000:2).

If designed and planned well, public transport corridors become the spatial context in which TOD is most likely to thrive, and evolve into an ameliorating network (UN-Habitat, 2013). The adapted Scandinavian cities have utilised a 'pearls on a string' structure of intensifying TOD around the stations of their rail corridors to significant effect, attaining high ridership levels while minimising subsidies (UN-Habitat, 2013). Copenhagen, Denmark even centred the city's masterplan on its five rail corridors, which famously became known as the 'finger plan' (Suzuki, Cervero & Iuchi, 2013).

Curitiba, Brazil is one of the best planned and most sustainable hybrid cities due to its successful public transport oriented corridors (Lindau, Hidalgo & Facchini, 2010). Curitiba has followed a plan for urban form adaption since 1965 while concurrently adapting its bus network to create the concept of BRT (Rabinovitch, 1996). Figure 5 illustrates Curitiba's hierarchical trinary road system for their transport corridors that place dedicated BRT lanes in the centre of the structural axis. The articulated density concept is then implemented with high density, mixed use developments abutting the structural axis and facilitating pedestrian access, with development decreasing in density and land use mix when moving away from the public transport service.

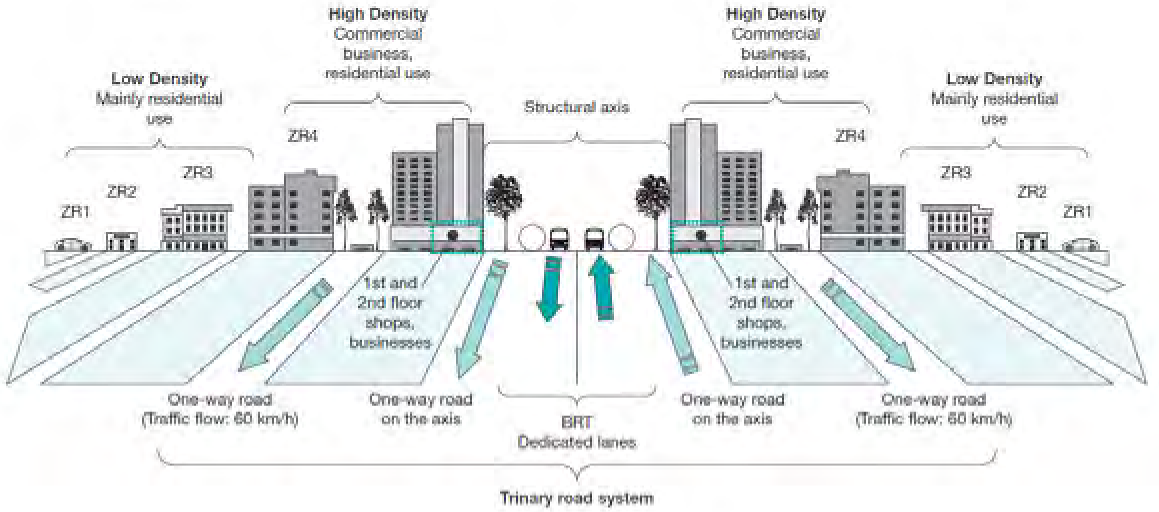

Figure 5: A cross-section of the BRT trunk corridors in Curitiba, Brazil (UN-Habitat, 2013)

Transport and urban development corridor planning concepts have also dominated South African planning ideologies in previous decades (Del Mistro & Buthelezi, 2001). For example, Johannesburg's latest spatial vision for the city calls for 'Corridors of Freedom' to be created, which are "*well-planned transport arteries linked to interchanges where the focus will be on mixed-use development - high-density accommodation, supported by office buildings, retail development and opportunities for leisure and recreation*" (Ogra & Ndebele, 2014:540). The importance of public transport corridors for land use-transport integration is reiterated in the spatial development plans of all the major South African cities.

2.5.3 Network features

Based on the review of public transport network design studies, the two most important decisions for the features of a public transport service are the choice of mode technology and the type of service configuration. This section reviews the relationship that each feature has with the viability of the public transport service and the surrounding land use environment, according to previous studies.

2.5.3.1 Mode technology

Urban public transport modes have greatly different technical, operational and financial characteristics, and a thorough understanding of the interaction with their operating environment is required for sound urban transportation planning (Vuchic, 2007). The choice of mode technology is important for public transport service viability because it has significant effects on the capital costs related to the associated infrastructure and the fare pricing that can be justified (Sivakumaran et al., 2014). The mode technology decision is typically case specific but often made without due consideration for the operating environment.

As mentioned in Section 2.4.1, the viability of a specific transport mode is believed to rely on a threshold ridership, or threshold density, being met. In the search for operational appropriateness, density thresholds have been posited for individual mode technologies in many studies, and some have been collated from the literature by Jones (2014) in Table 1. These thresholds postulate that their attainment will ensure some form of viability for the related transport services.

2.5.3.2 Public transport service configuration

The decision around service configuration, specifically regarding direct service and trunk-feeder service, is usually dependent upon the mode technology decision. In South African cities, the direct service configuration is associated with lower quality paratransit services, and trunk-feeder service configuration is associated with the newer BRT systems (Salazar Ferro & Behrens, 2015). This has resulted in unfair connotations applied to each and clouded judgment regarding the service configuration decision (Del Mistro & Bruun, 2012).

Figure 6: Diagrammatic structure of a Trunk-Feeder (left) and a direct (right) corridor service configuration (After (Bruun, 2013)

Table 1: Synthesis of population density thresholds for different mode technologies in the international literature (After Jones, 2014)

Type of transit service	Level of service / infrastructure	Net density (du/ha)	Net density (persons/ha)	Gross density (du/ha)	Gross density (persons/ha)	Author
Bus	Minimum Service, ½ mile between routes, 20 buses/day	10	24	7	17	Pushkarev & Zupan (1982)
		10 - 15	24 - 36	7 - 10	17 – 24	Institute of Transport Engineers (1989)
	Intermediate service: ½ mile between routes, 40 buses/day	18	43	12	29	Pushkarev & Zupan (1982)
		18 - 20	43 - 48	12 - 13	29 - 31	Institute of Transport Engineers (1989)
		18	43	12	29	Marcia Lowe (1992)
		25	60	17	40	Sacramento Rapid Transit (1987)
	Frequent service: ½ mile between routes, 120 buses/day	38	91	25	60	Pushkarev & Zupan (1982)
		40	97	27	65	CATS (1956)
		18 - 38	43 - 91	12 - 25	29 - 61	Snohomish County Trans. Authority (1989)
Light Rail	5 minute peak headways / $25 million per mile Light rail service according to Cervero & Guerra (2011)	23	55	15	36	Pushkarev & Zupan (1982)
		23	55	15	36	Institute of Transport Engineers (1989)
		23	55	15	36	Marcia Lowe (1992)
		25	60	17	40	Sacramento Rapid Transit (1987)
		25	60	17	40	Barton-Ashman Associates (1990)
				14	35	Cervero & Guerra (2011)
	$50 million per mile			33	80	Cervero & Guerra (2011)
	$75 million per mile			52	125	Cervero & Guerra (2011)
	$100 million per mile			70	168	Cervero & Guerra (2011)
Rapid Transit	5 minute peak headways	30	72	20	48	Pushkarev & Zupan (1982)
Commuter Rail	20 trains/day	3 - 5	7 - 12	2 - 3	5 - 7	Pushkarev & Zupan (1982)
Heavy Rail	$100 million per mile			10	23	Cervero & Guerra (2011)
	$150 million per mile			23	55	Cervero & Guerra (2011)
	$200 million per mile			38	90	Cervero & Guerra (2011)
	$250 million per mile			52	125	Cervero & Guerra (2011)
	$500 million per mile			124	298	Cervero & Guerra (2011)

Figure 6 illustrates a diagram of the structural differences between a trunk-feeder service (left) and a direct, trunk-branch service (right) when operating along a corridor from the suburbs towards the CBD at the bottom. A direct service is one that conveys a user directly from their point of origin to their point of destination, with no or as few transfers as possible. The advantages of this configuration are the time savings due to fewer transfers, and lower infrastructure costs due to less stations and smaller vehicles. The disadvantages are lower operational efficiency, negative effects on congestion and a lower average speed (Bruun, 2013). Trunk-feeder services use smaller, feeder vehicles to convey passengers from their origin points to a transfer station on the nearest trunk route (Nielsen, 2005). At the station, users transfer to larger, trunk vehicles that often have dedicated right-of-way. The advantages are a higher efficiency in operation, being able to size vehicles more closely to the demand, and higher service quality, due to economies of scale allowing the operation of higher quality services on the trunk service route (Wright & Hook, 2007).

Previous studies have attempted to determine which operating conditions affect the choice between the service configurations from a microeconomic perspective. Jara-Díaz, Gschwender & Ortega (2012) determined that having the majority of the demand along the trunk route, favoured the trunk-feeder service configuration and vice versa. Del Mistro & Bruun (2012) found that the trunk-feeder service configuration is favoured when there is one destination catchment, a low peak-to-base ratio and a relatively low peak passenger volume; in the case of a transport corridor in Cape Town, South Africa.

2.6 The land use-transport relationship in the South African policy environment

This section investigates the connections between land use characteristics and public transport viability acknowledged and expressed in the South African transport policy environment. First, the local vision of public transport viability is explored through the many transport policies and then an investigation of how the policies believe land use characteristics can play a role in its attainment. Five major public transport objectives outlined in the policies are then acknowledged as essential to achieving the vision of viability and dependent upon an aspect of the land use environment. Finally, public transport viability related land use targets are identified for five South African cities.

2.6.1 Defining viable public transport and supportive land use conditions

Post-1994, South Africa has produced transport policies that advocate affordable, equitable, efficient and sustainable public transport. The first of these policies, the *White Paper on National Transport Policy*, stipulated that the provision of public transport services should support economic and social development strategies whilst remaining economically sustainable (DoT, 1996). The *Moving South Africa* policy document set a goal to ensure that public transport systems generate enough revenue to cover all operation and maintenance costs (Republic of South Africa, 1998). More recently, the *Public Transport Strategy* is seeking to establish modern, efficient, high quality public transport systems, for both captive and choice users, that will be affordable, financially sustainable and accessible to most urban inhabitants (DoT, 2007). Therefore, South African transport policies envision viable public transport as affordable, car-competitive and independent of public transport operating subsidies. However, when the *Public Transport Strategy* (DoT, 2007) was written, it was still believed that bus rapid transit (BRT) could achieve these three principles. Subsequently, the metropolitan transport authorities have realised that BRT functions far less efficiently in the land use context of South African cities than in its birthplace of Latin America (CoCT, 2014). Consequently, the benchmark of creating subsidy-free, car-competitive public transport systems has been temporarily lowered, even though the national policy is yet to be updated to reflect this new policy position.

All of the policy documents identify land use change as an important tool to achieve the objectives that have been set for public transport viability. The *White Paper on National Transport Policy* and *Moving South Africa* were insistent on the need to address low-density developments, spatially dislocated settlements and urban sprawl, in order to overcome the public transport challenges that the country faced (Republic of South Africa, 1998; DoT, 1996). The *White Paper* also stated that public transport travel time and distance should be limited to 40 km or one hour in each direction, highlighting the significance of destination accessibility. The corridor planning notions gave emphasis to intensive densification along 'development corridors' to ensure more efficient public transport travel patterns (Republic of South Africa, 1998; DoT, 1996). The *National Land Transport Transition Act* promoted densification through infilling as an addition to the high density development corridors (Republic of South Africa, 2000). Finally, the *Public Transport Strategy* suggested the proactive channelling and regulation of land use to secure the viability and sustainability of the public transport networks (DoT, 2007). Although, the most succinct articulation of the relationship is in the *White Paper on Western Cape Provincial Transport Policy*:

> *"To produce a transport system which is truly efficient, viable and affordable, and is sustainable into the future, it will be necessary to adopt policies on containment, densification and mixed land use, leading to a fundamental restructuring of the land use system in order to reduce the demand for movement. In addition, appropriate legislation will be established at the national and provincial levels to ensure that transport and spatial development are integrated and that land use development proposals are subject to an approved land use/transport policy framework."* (Western Cape Department of Transport and Public Works, 1997).

The transport policy environment in South Africa is strongly in favour of the integration of land use and public transport planning but limited mention is given to public transport network or corridor design. Population density, land use mix and destination accessibility are acknowledged, in some form, as necessary to achieve viable public transport but no instruction is given for how they are to be included in the public transport decision-making process. The integration of land use and transport remains at the level of national, provincial or, in some cases, metropolitan planning policy. This can even be seen in the connection between national public transport viability objectives and metropolitan land use targets, which are explored in the subsequent two sections.

2.6.2 Land use related public transport viability objectives

The South African transport policies have posited that the progressive adaption of the urban land use environment has the ability to foster a viable and successful public transport network. This ability of land use adaption to accomplish public transport objectives is rooted in the connections that the objectives have to land use characteristics. The following sections explore five fundamental objectives stated within the South African transport policies, to facilitate the creation of viable public transport, that have been identified to rely on one or more land use characteristics. Understanding how these objectives can be met through changes in the urban form is essential to estimating useful targets for the land use characteristics.

2.6.2.1 Coverage

The *Public Transport Strategy* aims to have 85% of a South African metropolitan city's population within 1km of an Integrated Rapid Public Transport Network (IRPTN) trunk or feeder service (DoT, 2007). The distance of 1km was set by the *White Paper on National Transport Policy* as the desirable maximum walking distance to a public transport service in a metropolitan area (DoT, 1996). This distance represents the *distance to transit* principle, delineates the catchment area that was referred to in relation to population density and is the base value for the station influence area (SIA) which affects TOD. Coverage, through a distance to transit limit, also determines route density and ridership which have significant effects on infrastructure costs and fare revenue.

2.6.2.2 Quality-of-service

Two further objectives of the *Public Transport Strategy* are that trunk corridors operate with 5-10 minute headways during the peak period and for a minimum period of 16 hours (DoT, 2007). Achieving these objectives for quality-of-service will increase the operating costs of the services which will need to be met by increasing the supportiveness of the land use environment. Specifically, the more constant temporal demand distribution associated with mixed land use would be required to increase utilisation of the extended operating hours.

2.6.2.3 Modal split

One of the goals set by the *White Paper on National Transport Policy* is achieving a public transport motorised mode share of 80% for all weekday motorised trip purposes (DoT, 1996). This goal would only be met by high quality, efficient, car-competitive public transport systems that generally have high infrastructure requirements. A land use environment, in which 80% of all weekday motorised trips utilise public transport as the preferred mode, would be exceedingly public transport supportive and probably need to positively leverage all relevant land use characteristics. Doubt has been cast around whether a public transport mode split of 80% is possible under prevailing conditions; a more realistic goal of 60% has been suggested as the likely maximum that can be achieved and maintained (Masemola et al., 2013).

2.6.2.4 Subsidy

The minimisation or elimination of public sector subsidies toward public transport system operations is stated as an aim of the IRPTNs in the *Public Transport Strategy* (DoT, 2007). This is a key objective in achieving the policy vision of viable public transport. However, very few public transport systems operate without financial support from the public sector; only those in exceptionally conducive land use and cultural conditions can attain profitability for their services (Suzuki, Cervero & Iuchi, 2013).

2.6.2.5 Monthly transport expenditure

The *White Paper on National Transport Policy* has stipulated that commuters should spend less than 10% of their disposable income on transport (DoT, 1996). The utilisation of distance-based fare systems means that trip length is a significant determinant in transport expenditure. All four land use characteristics have been linked to reduced trip distance by placing trip origins closer to trip destinations.

Based on the public transport viability objectives of the South African national transport policies and their strong links to a supportive land use environment, one would expect detailed and aggressive land use characteristic targets at the metropolitan scale to aid in achieving these ambitious goals. The following section outlines the land use characteristic targets of five major South African metropolitan cities.

2.6.3 Public transport viability related land use targets

As noted in the sections reviewing population density (2.4.1) and mode technologies (2.5.3.1), land use targets and thresholds are guidelines for achieving viable public transport through a supportive land use environment. However, the international research into targets and thresholds has been dominated by population density and the same is true in South African cities. Despite the lack of relevant studies strongly linking population density to public transport service viability in rapidly growing developing cities, discussed in Section 2.4.1, the cities are still being touted as fertile environments for viable public transport systems due to their dense urban forms (OECD, 2012). This has led to assurances from international development and research agencies that some advanced public transport systems can be subsidy-free in the context of a dense developing city (Del Mistro & Bruun,

Table 2: Gross population density targets of selected South African cities (after Jones, 2014; Turok, 2011)

Geographic areas	South African city / municipality				
	City of Cape Town	City of Tshwane	City of Johannesburg	Nelson Mandela Bay	eThekwini
Existing gross population density					
City wide urbanised area (p/ha)	40 - 47	28 - 35	43	21 - 23	35 - 39
Targeted gross population density					
City wide urbanised area (p/ha)	83	-	-	78	79
Public transport trunk routes (p/ha)	208	150	232	238	209

2012). As a result, dense cities can be complacent about the viability of new public transport infrastructure and less dense developing cities, such as those in South Africa, have implemented gross population density targets to improve the viability of their public transport systems (Jones, 2014). Densification targets have been set by many South African cities, five of which are summarised in Table 2. After decades of support for gross population density as a primary indicator of sprawl and public transport use, its significance is now being questioned in some international literature (Eidlin, 2010). In recent studies on the built environment and travel behaviour, other regional-scale land use characteristics have been found to have larger impacts on households' car use than population density (Guerra, 2013; Boarnet, 2011; Ewing & Cervero, 2010; Brownstone & Golob, 2009). One of the very few empirical studies on this relationship in the context of a developing city, Zegras (2010), found that the effect of dwelling unit density in Santiago de Chile was not significant. In contrast, Guerra (2013) observed a significant and increasing effect of population density on car use in Mexico City. Overall, the results of studies using the context of a developing city seem to be inconclusive. This casts further doubt on the prominence of density as an indicator for public transport viability in rapidly growing developing cities and on the potential success of densification policies to reduce unsustainable subsidy levels.

2.7 Summary and conclusion

The primary aim of this research is to investigate the relationships between land use characteristics, network features and public transport viability in the context of a South African public transport corridor. The purpose of this chapter was to review the established base of literature around the integration of land use and transportation in urban planning, and to investigate the studies that test this relationship through the medium of transport viability, at the corridor scale. The chapter set out to define transport viability in the South African context, and examine methods for which this viability could be attained through the successful integration of land use and transport planning at the metropolitan scale. The chapter sought to identify the effects that the major relevant land use characteristics have on public transport services and the degree of consideration given to these effects by studies committed to the successful design of these services. Accordingly, the chapter aimed to assess the importance of the role that the public transport corridor plays in facilitating land use-transport integration. Finally, the discussion was to be contextualised through an overview of land use-transport interaction in the South African policy environment.

A public transport service is said to be generally viable if it is affordable, effective and both socially and economically sustainable. To be both affordable and economically sustainable, a public transport service needs to be financially accessible to the majority of the population, especially captive users, while minimizing public sector subsidies to within sustainable limits. In this study, the financial viability of a public transport system or service represents the sustainability of the subsidies. Public transport subsidisation is ubiquitous in developed cities and its net positive effect on society is supported by multiple complementary arguments. However, as developing cities scale up their formal public transport systems, minimizing operating subsidies becomes an increasingly important goal. Therefore, the concept of public transport viability is political, and represents the trade-off between the societal need for public subsidies and the financial capacity of the governing authority to afford them.

Suzuki, Cervero & Iuchi (2013) posit that there are three main approaches to integrating land use and public transport at the metropolitan scale with the aim of improving its viability. The 'Adaptive cities' approach involves the adaption of the urban structure of the city in order to support a desired public transport system. The 'Adaptive transit' approach uses innovation and technology to adapt the features of the public transport system to serve a desired urban structure, usually dictated by an unrestricted real estate market. The 'Hybrid cities' approach adapts both its urban structure and the features of its public transport service until viability is attained. The suitability of each approach depends of the commitment of the city to sustainable public transport and the ability of the planning authority to shape development growth.

At a more detailed scale, the list of land use characteristics with a significant influence on travel has evolved to become known as the '5 Ds': *density*; *diversity*; *design*; *destination accessibility* and *distance to transit*. Of the 5 Ds, *design* and *distance to transit* are not directly relevant to a study on land use characteristics and public transport viability. Population *density*, persons per unit area affects the volume of passengers, or ridership, that utilise a public transport service. It is suggested to be a prerequisite to attaining viable public transport, which is demonstrated through the density thresholds and targets that have become very popular.

Density distribution is a recent addition to the group of land use indicators and articulated density represents population density that is distributed strategically with regard to public transport trunk services. It can affect public transport viability through its impact on average passenger trip lengths and feeder service reliance. Articulated density is believed to have a strong relationship with TOD and public transport service viability.

Land use mix, or *diversity*, refers to the spread of land uses and their level of interaction within a given area. Land use mix has an influence on public transport viability through its effect on trip length and the flow pattern of public transport trips. It positively affects viability by increasing fare revenue while decreasing infrastructure requirements.

Destination accessibility is represented in the regional context by the distance to the CBD, and has a significant influence on car ownership and average trip length. Mathematical modelling studies have found public transport service viability to depend heavily on the length of the corridor when terminating in the CBD. The exceptionally long average distances to the CBD seen along the public transport corridors of many developing cities – primarily due to the intense densification that is occurring on cheaper land at the periphery – reduce the productivity of the vehicles.

For the design of public transport corridor services, there are two competing methodologies with varying levels of land use consideration: computational and empirical. The computational approach encompasses the research dedicated to optimising the design of land use and public transport networks through the use of mathematical and econometric models. The reviewed studies posited a varied range of population densities that predict viability under different conditions. Wang (2008) found minimum population densities in the range of 175 to 398 p/ha were needed to create a subsidy-free rail system for different density gradient functions. Sivakumaran et al. (2014) determined that articulated density has a very weak relationship with per-user cost components but did not include feeder services or the effect of articulated density on their reliance. Chen, Li & Lam (2015) found that the density at which LRT is preferable to BRT in terms of social welfare is 110p/ha, and metro becomes preferable at a density of 144 p/ha, in five Chinese cities.

Empirical studies use extensive institutional knowledge and experience in the field of transport system design to create "best practice guides" for other practitioners to base their decisions upon. The best practice guides do not address the effects of land use characteristics on the viability of the public transport service but are still commonly used in the public transport network decision-making process.

A public transport trunk service corridor, as a structural feature, is very important for land use-transport integration. If designed and planned well, public transport corridors become the spatial context in which TOD is most likely to thrive, and evolve into an ameliorating network. Strong public transport corridors have been used to create viable public transport in many cities despite having low population densities and other indicators of an unsupportive land use environment.

Based on the review of public transport network design studies, the two most important decisions for the features of a public transport system are the choice of mode technology and the type of service configuration. The choice of mode technology has significant effects on the capital costs related to the associated infrastructure and the fare pricing that can be justified. In the search for operational appropriateness, density thresholds have been posited for individual mode technologies in many studies. The decision over service configuration, specifically regarding direct service and trunk-feeder service, is usually dependent upon the mode technology decision. A direct service is one that conveys a user directly from their point of origin to their point of destination, with as few transfers as possible. Trunk-feeder services use smaller, feeder vehicles to convey passengers from their origin points to a transfer station on the nearest trunk route.

The transport policy environment in South Africa is strongly in favour of the integration of land use and public transport planning but little mention is given for public transport network design. Population density, land use mix and destination accessibility are acknowledged, in some form, as necessary to achieve viable public transport but no instruction is given for how they are to be included in the public transport decision-making process. Many objectives underpinning the creation of viable public transport in the national transport policies have been identified to rely on one or more land use characteristics. However, only population density targets have been set by five of South Africa's largest cities.

Little research has been conducted into the relationships between land use characteristics, public transport features and viability, especially at the corridor scale. Population density has garnered most of the attention in the land use-transport interaction research. Targets, thresholds and analyses for other land use characteristics are rare, particularly in the developing cities. An empirical analysis of the relationship between land use characteristics and public transport viability indicators is required to determine the observed significance of the connections described by the literature. Relevant metrics for the level of articulated density and land use mix need to be investigated in order to accurately test their effects on viability. Detailed investigation of the three other land use characteristics could yield similar benefits for land use-transport policy formulation that the research into population density has.

Mathematically-dominant, cost optimisation models appear to be at the vanguard of this research field. Currently, the models have only addressed the effects of population density, density distribution, mode technology choice and service configuration options on public transport service viability. A model that tested all four of these characteristics simultaneously, as well as land use mix and destination accessibility, could draw more meaningful and comprehensive conclusions. Additionally, evaluating the relationships at the corridor scale would allow more detailed analyses and implementable recommendations.

3 Secondary data analysis

3.1 Introduction

In order to better understand the empirical relationships between land use characteristics and public transport viability, described in the literature, an analysis was conducted on metropolitan scale secondary data to determine the strength and consistency of these connections. Additionally, it gave the opportunity to test the congruence between the metropolitan density targets of the five South African cities with three of the South African national public transport objectives. As with the research studies and the land use targets, the available data on land use characteristics linked to public transport is dominated by gross population density.

Metropolitan scale public transport and land use data is still not readily available for many cities, especially those in the developing world. Therefore, the Millennium Cities Database (MCD) compiled by Jeffrey Kenworthy and Felix Laube is the most comprehensive database of city-specific transport indicators to date, despite its reference year being 1995 (Kenworthy & Laube, 2001). For this analysis, the MCD has been supplemented with data compiled by Paul Mees and the online Transit Oriented Development database, which have reference years of 2006 and 2010 respectively (CTOD, 2011; Mees, 2010a). The unavailability of relevant data is also the reason that only three of the South African national public transport objectives can be tested. The transport data on South African cities was collated by Jones (2014), and supplemented with population density data from Turok (2011).

3.2 Public transport mode share

The following analyses explore correlations between gross population density and public transport motorised mode share, public sector subsidy requirements and average monthly household expenditure on transport. The gross population density targets for the entire urbanised area of the South African metropolitan cities, ranging from 78 to 83 p/ha, are represented on each graph as the 'Densification target'. The shaded region to the left of the densification target illustrates the increase in population density that needs to occur for the city with the lowest current population density, Nelson Mandela Bay (21-23 p/ha). The red markers represent the existing gross population density range of the five South African cities. The blue shaded region illustrates a range of values that would satisfy one of the South African national public transport policy objectives. The blue markers represent the international cities that met the analysis criteria and for which data on that relationship was available. The threshold between a developed and a developing world city was assumed to be a GDP/capita of $10,000 in 1995.

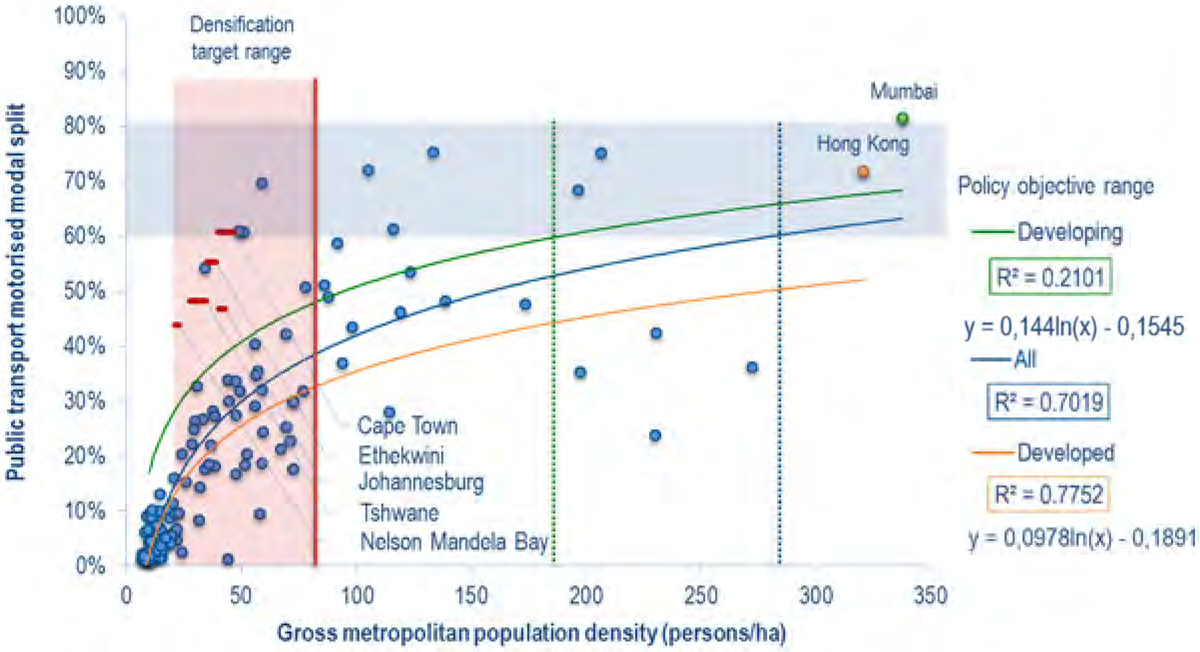

Figure 7: Public transport motorised modal split and gross population density relationship, for all weekday trip purposes, for various cities (n=24 developing world cities, n=104 developed world cities) (Source: CTOD, 2011; Mees, 2010a; Kenworthy & Laube, 2001)

The first analysis assessed the empirical relationship between gross base population density and public transport motorised mode share, illustrated in Figure 7. A strong positive relationship appears which concurs with the results of many previous empirical studies done on this relationship. A logarithmic description of the increase in public transport mode share with increasing gross metropolitan population density is accurate for developed cities, represented by an R^2 value of 0.77 (equation displayed). However, the nature of this relationship is not as clear in the smaller sample of developing cities, achieving an R^2 value of only 0.21. This much weaker empirical correlation supports the doubt cast, in Section 2.4.1, on population density as an effective indicator of public transport viability in the context of a rapidly developing city. Many low income residents in developing cities, like those in South Africa, are captive to the public transport market, removing the option of choosing private transport even at very low population densities. Similarly, the low quality of some public transport modes deters choice passengers at high population densities. These factors, in addition to the issues around data availability, are why developing cities have often been excluded from the empirical studies of this relationship.

The observed relationship suggests that the motorised mode share policy objective of 80% for public transport is high, with only Mumbai having attained it at a population density of 337 p/ha. When the more realistic goal of 60% public transport mode share is tested, posited by Masemola et al. (2013), the average city that achieves this would have a population density of 280 p/ha, or 190 p/ha for the average developing city. One of the South African cities, Cape Town, has already achieved a public transport motorised mode share of 60%, due to its large base of captive users and an extensive trunk rail network (Maunganidze & Del Mistro, 2012). Of the developed cities, only Hong Kong has a mode share of more than 60%, at a density of 320 p/ha. This highlights the fact that significantly higher population densities are needed to maintain the same public transport mode share when a higher proportion of residents are choice users. The metropolitan population density targets set by the South African cities would need to double, if not triple, to attain or maintain a mode share of 60% as the proportion of captive users declines.

3.3 Public sector subsidisation

The second analysis, presented in Figure 8, investigates the empirical relationship between population density and the proportion of annual operating costs that are subsidised by the public sector. The analysis only includes cities with a public transport mode share of more than 15%. This is due to the subsidy requirements of small or disused public transport systems being susceptible to non-land use related factors, such as fare policies, minimum allowable levels of operation, overcrowding and paramount social objectives. An R^2 of 0.21 describes a weak relationship, but subsidisation levels do decrease on average with increasing population density. The analysis illustrates that the empirical relationship between density and the financial viability of public transport systems is not as clear or dominant as the literature describes. The relationship is especially weak in developing cities.

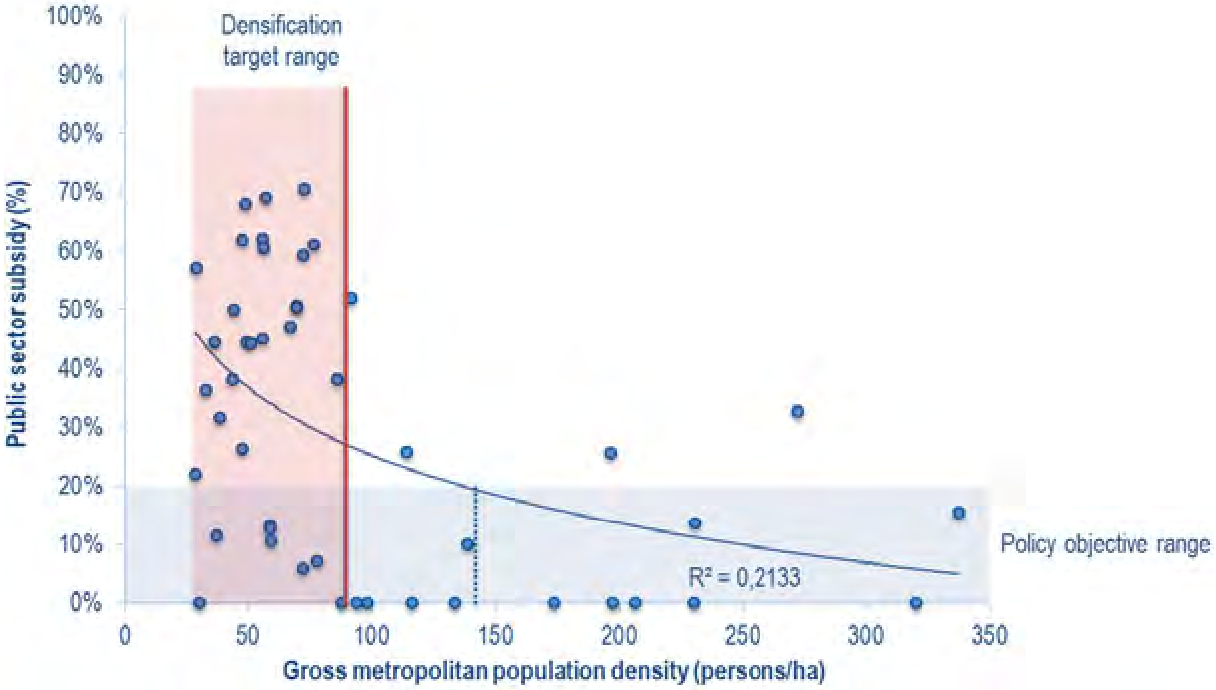

Figure 8: Operating cost subsidy and gross population density relationship in cities with public transport motorised mode share of more than 15% (n=47) (Source: CTOD, 2011; Mees, 2010a; Kenworthy & Laube, 2001)

The South African national transport policy objective for public sector subsidisation is minimisation or elimination. Eleven cities in the dataset have no operating cost subsidisation. Of these, only Curitiba, Brazil has a population density that is lower than the targets set by the South African cities, i.e. 34p/ha. Curitiba was highlighted in the literature review for its ‘hybrid city’ nature, dominant public transport trunk service corridors and high level of articulated density. In regard to articulated density, Curitiba has developed a population density of up to 330 p/ha along its public transport trunk corridors, which has been attributed with the financial success of its BRT network (Bertaud, 2002). Additionally, the bidirectional flow of passengers along the mixed use corridors generates a seat occupancy of 71% throughout the day (Kenworthy & Laube, 2001). Curitiba demonstrates the possibility that a low gross metropolitan population density (34 p/ha) can be an unfair representation of the population density within the station influence areas of its public transport services. The data suggests that the average city would reach a 20% cost subsidisation level at approximately 140 p/ha. Therefore, it is likely that South African cities would require a gross metropolitan population density above this to eliminate subsidies, if articulated density and transit oriented development are not heavily prioritised.

3.4 Monthly expenditure on transport

The final analysis is on the relationship between population density and monthly household expenditure on transport, illustrated in Figure 9. The R^2 values show that the relationship is both weak and complex but a downward trend with increasing density is observable. The high GDP/capita of cities in the developed world generally means the monthly household expenditure on transport is relatively low by comparison, which reduces their sensitivity to the effects of population density. Monthly expenditure on transport is also a poor indicator of public transport viability in developed cities as overriding social objectives can promote fare-capping policies, even at low densities, by allowing public sector subsidies to increase. Therefore, Figure 9 displays only the individual plots of cities in the developing world.

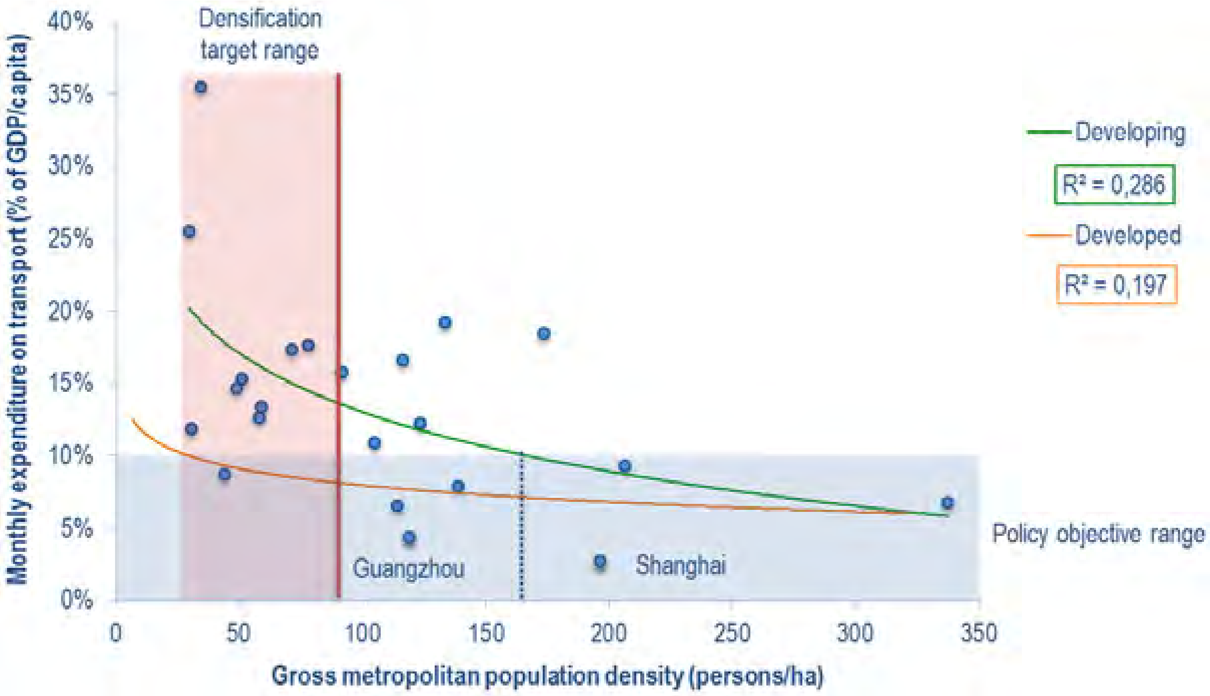

Figure 9: Monthly household expenditure spent on transport vs gross population density for various cities (n=24 developing world cities, n=82 developed world cities) (Source: CTOD, 2011; Mees, 2010a; Kenworthy & Laube, 2001)

The South African national public transport policy objective states that the monthly household expenditure on transport must be less than 10% of disposable income. Due to a lack of available data, GDP/capita is utilised as a proxy for disposable income. To prevent any user from spending more than 10% of their income on transport, the average household expenditure would have to be significantly lower. Only two developing cities have average household expenditures on transport that are less than 5% of GDP/capita, Guangzhou and Shanghai, with population densities of 119 and 196 p/ha respectively. The data suggests that the average city in the developing world would only decrease aggregate monthly household expenditure on transport below 10% of GDP/capita at a population density of approximately 170 p/ha.

3.5 Summary and conclusion

The main objective of this study is to investigate the relationships between land use characteristics, network features and public transport financial viability in the context of a South African public transport corridor. The aim of this chapter was to explore and examine the empirical relationships between land use characteristics and general public transport viability, described in the literature. Furthermore, it attempted to determine the congruence between the objectives set out in South Africa's national public transport policies and the population density targets set by the metropolitan planning authorities in five local cities.

The availability and comparability of metropolitan transport and land use data severely constrained the scope of the empirical analyses. The Millennium Cities Database (MCD) was the most comprehensive, relevant and recent source of data for most cities despite having a reference year of 1995. The MCD also had a very limited set of cities from developing countries, which is representative of the starkly different magnitude of knowledge related to the land use-transport relationship in developed and developing city contexts.

Notwithstanding the age and skew limitations of available datasets, empirical analysis of international city data suggested that metropolitan population densities in the order of 140-190 p/ha will be required to achieve the objectives set out in South African national public transport policies relating to three aspects of public transport viability. The current gross densification targets determined by South African cities – in the order of an increase from current metropolitan densities of ±40 p/ha to ±80 p/ha – are insufficiently high to achieve the policy objectives. It highlights the discordance between public transport and land use planning at different scales of government.

This empirical analysis also suggests that strategic articulated densities may enable viable public transport to be achieved in cities with relatively low metropolitan population densities. It is therefore of strategic importance that South African cities focus on public transport corridor densification through proactive transit oriented, land use development, in addition to promoting higher metropolitan densities.

Despite meaningful analysis of secondary data in this chapter, the outlined constraints regarding data availability, especially for the cities of developing countries, severely limit more detailed and insightful empirical investigation. Additionally, the review of the literature and preceding studies in Chapter 2 identified uncertainty relating to the causality of the effects that land use has on public transport viability, observed in the empirical data. It is posited that greater understanding can be garnered through the advancement of the line of research utilising computational models to simulate the land use-transport relationships. Building on the robust base of mathematical and econometric models created to test these relationships, a more comprehensive model could be created that also begins to test their interdependence. With the ability to hold other variables constant, a clearer perspective could be gained on the true causality of land use's purported impacts on the viability of public transport systems.

4 Research method

4.1 Introduction

As discussed in Chapter 1, the primary aim of this research is to investigate the relationships between land use characteristics, network features and public transport viability in the context of a South African public transport corridor. From the analysis of secondary data discussed in Chapter 3, it was determined that this investigation could not be conducted empirically, especially in the South African context. Therefore, a decision was made to simulate the relationships that the study is attempting to investigate. This chapter describes the spreadsheet-based, public transport corridor operating cost model that was created to simulate the effects of varying land use environments and public transport network features on the viability of the services.

The chapter begins with an overview of the spatial structure of the corridor model, the layout of the analysis zones and the dimensions of the corridor itself. The structural differences between the routing of the two service configurations requires two separate variants of the model. Figure 10 illustrates that the corridor operating cost model consists of three different sub-models with the output of one supplying the input of the next. The data requirements for the land use sub-model will be outlined, as well as the process and worksheets for which this data is input. The land use sub-model is explained and the output of zonal trip productions and attractions are identified, for input into the transport sub-model. A brief description of the gravity method follows, which is the process used to calculate the trip patterns and volumes based on the productions and attractions. The trips are assigned to routes and the demand on each route during the peak hour becomes the key input for the costing sub-model. Contextual data from a South African city is then utilised to derive a detailed costing for each of the public transport service routes in the corridor. The process is then repeated with a new set of land use characteristics in an iterative manner. The sub-headings of sections 4.2, 4.3 and 4.4 correspond to the name of the worksheet in the respective sub-model that is being discussed. The output indicators that have been chosen to represent the viability of the public transport system in each simulation are the final output of the model. This model uses elements from a previous model developed by Del Mistro & Bruun (2012): a single route, corridor operating cost model.

4.2 Corridor model spatial structure

The spatial structure of the model represents a single public transport corridor in the context of a South African city. Due to the previously monocentric nature of South African cities creating a legacy of isolated, radial public transport trunk routes (Parnell & Oldfield, 2014), the model represents a triangular transport corridor terminating at the Central Business District (CBD), illustrated in Figure 11. The length of the trunk service corridor (black line) is 20 km, which is comparable to the 15 km of

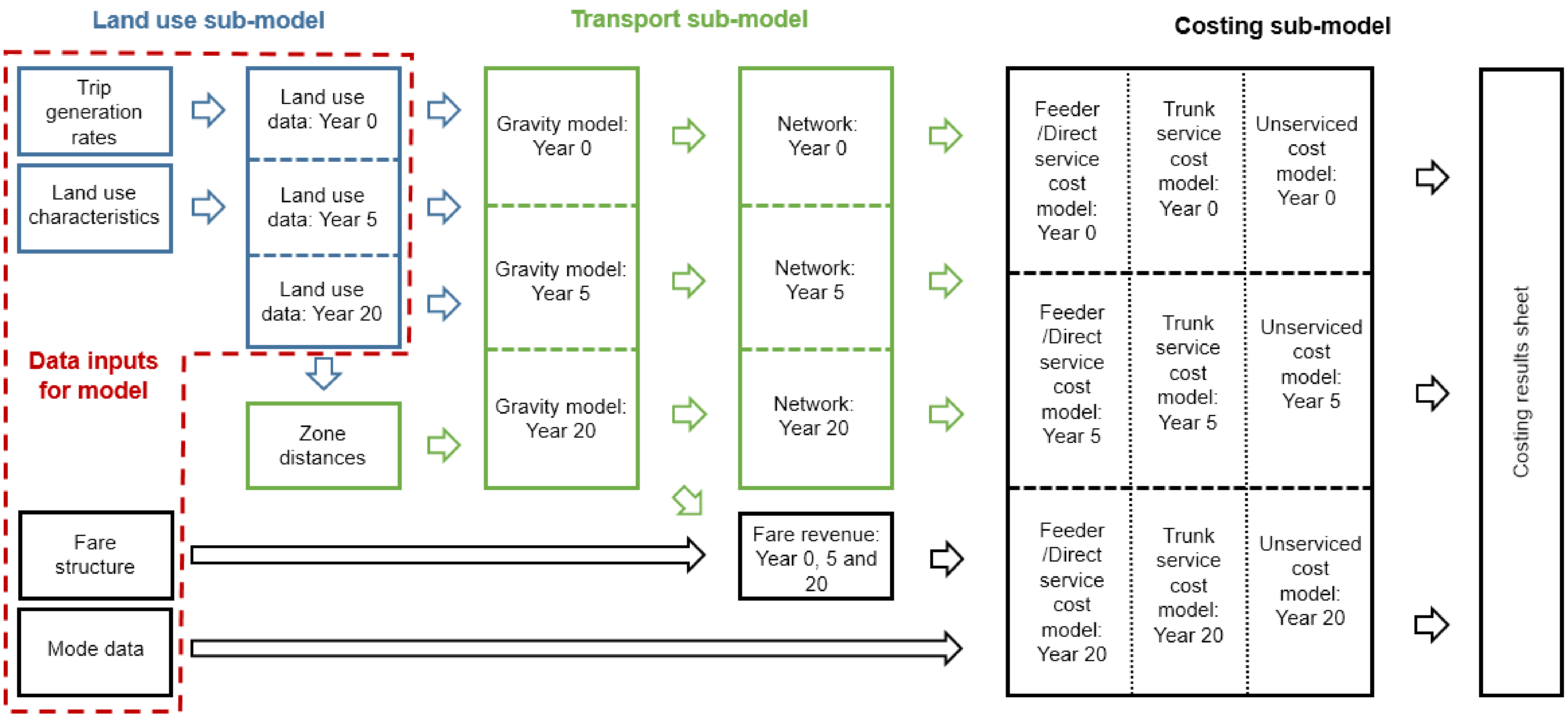

Figure 10: Diagram of the modelling architecture, showing the three interconnected sub-models, that constitutes the corridor operating cost model

Cape Town's Phase 1A and 25.5 km of Johannesburg's Phase 1A BRT trunk service corridors (www.brtdata.org, 2015).

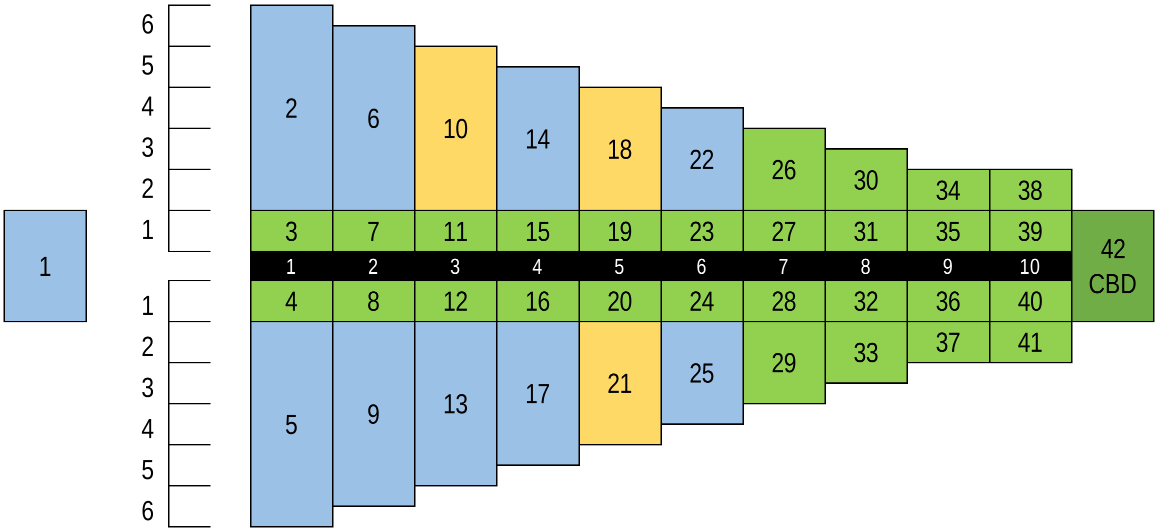

Figure 11: TAZ layout of the simulated transport corridors

The catchment area of the corridor is divided into 42 Traffic Analysis Zones (TAZs), each with specific land use types and characteristics. In Figure 11, the green zones, called the TOD zones, represent areas that are within sufficient proximity to the trunk service route to negate the need for an additional feeder service, i.e. an average of less than 2km from the zonal centroid. Outside of these zones, the maximum allowable walking distance is 1km; as is the width of the zones either side of the trunk route. The length of each zone ranges from one to five kilometres, visible on the scale in the figure, and their 2km width is derived from the maximum allowable walking distance. These distances conform to the guidelines of the South African national *Public Transport Strategy* (DoT, 2007) and the *White Paper on National Transport Policy* (DoT, 1996). The blue zones represent areas that require feeder or non-trunk direct services, where zone 1 represents external trips from the surrounding peri-urban area. The beige zones represent the portions of the corridor catchment area that are not served by feeder services despite their proximity to the trunk service being too great for pedestrian access. These zones improve the realism of the model as the coverage of a transport system is often less than 100%. The *Public Transport Strategy* aims to achieve 85% coverage of a metropolitan city area, in accordance, this model achieves 83.6% coverage (DoT, 2007). Note that the black zones represent the segments of the public transport trunk service and do not generate or attract any passenger trips.

4.2.1 Trunk-feeder service routing

The trunk-feeder service model is comprised of one trunk service route (thick black line) and ten feeder service routes (thin red lines), illustrated in Figure 12. On feeder service routes, all trips are assumed to start or finish at one of the two terminal points as capacity for the feeder service is determined by the theoretical peak volume.

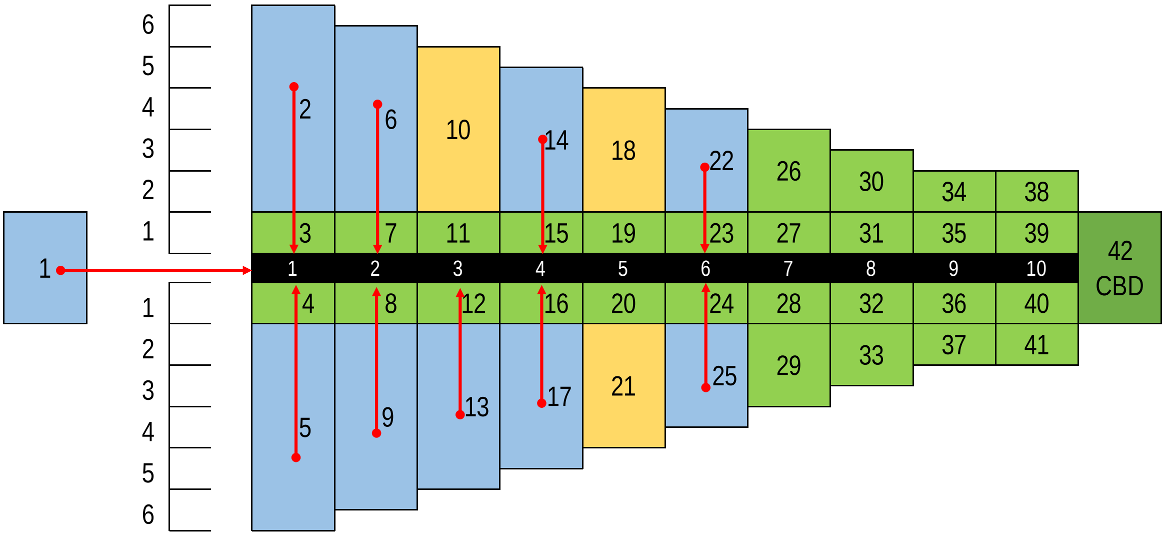

Figure 12: Route layout of the simulated trunk-feeder service transport corridor

4.2.2 Direct service routing

For comparability, each of the same blue zones is given a direct route to either end of the trunk service corridor. This is to limit the number of transfers required; one of the biggest differences between the two types of service configuration. Figure 13 illustrates the routes leading toward the CBD and Figure 14 illustrates those leading away from the CBD.

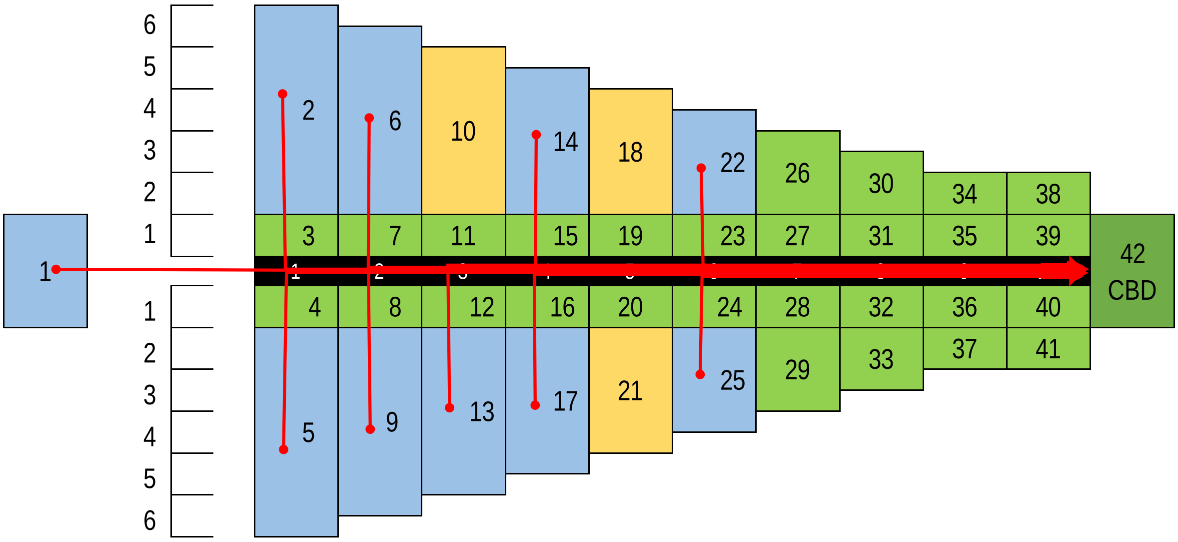

Figure 13: Layout of routes leading toward the CBD in the simulated direct service transport corridor

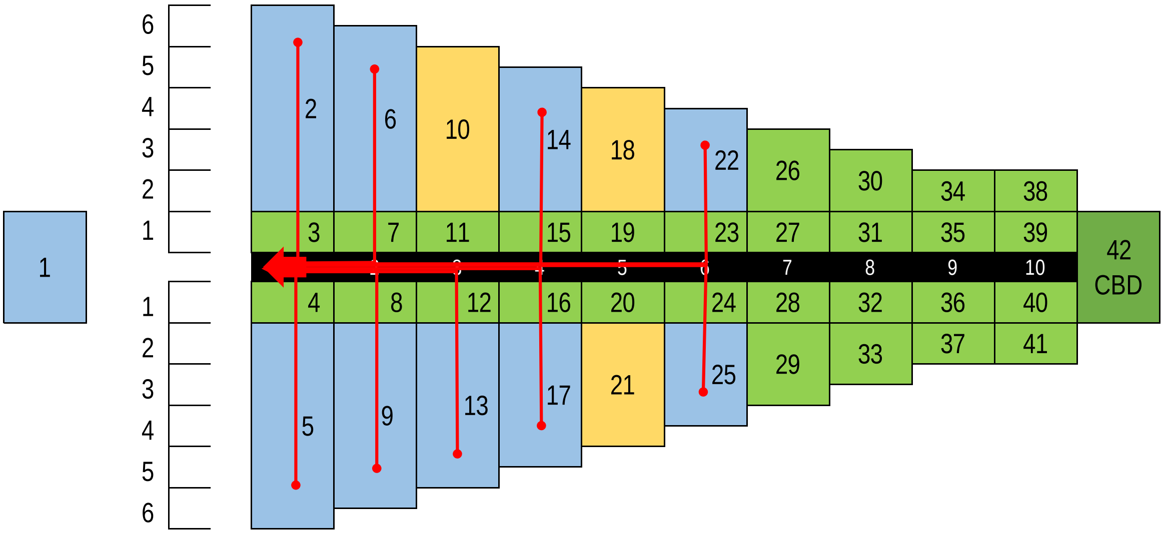

Figure 14: Layout of routes leading away from the CBD in the simulated direct service transport corridor

4.3 Land use sub-model

The land use sub-model utilises the land use characteristics set for each of the TAZs, trip generation rates and additional contextual data to determine the number of public transport trips produced by and attracted to each TAZ. The land use sub-model consists of five worksheets, each of which requires the input of data:

1. *Trip generation rates*
2. *Land use characteristics*
3. *Land use data year 0*
4. *Land use data year 5*
5. *Land use data year 20*

4.3.1 Trip generation rates

The trip generation rates estimate the number of passenger trips likely to be produced by an area based on local empirical data. The rates are input for four land use categories: residential; business; industrial; and commercial. For the South African context, the trip generation rates were sourced from Table 3.3 of the South African Trip Data Manual, created by the Committee of Transport Officials (COTO, 2012). Table **3** highlights the trip generation rate per land use category per unit of area for the AM Peak period as well as the proportion of those trips that are produced rather than attracted.

Table 3**: Trip generation rates of the four land use categories (COTO, 2012)**

Land use	Unit	% AM production	AM Peak Trip Rate
Residential	Dwelling unit	75%	0,63
Business	/100GLA m²	15%	2,1
Industrial	/100GLA m²	30%	0,7
Commercial	/100GLA m²	35%	1

(Note: GLA = Gross Leasable Area)

4.3.2 Land use characteristics

The values for three of the land use characteristics are input in this sheet. The value for gross population density is input in p/ha, whereas the values of density articulation and land use mix are input as a percentage. The metrics for these land use characteristics are explained in Sections 5.3.1, 5.3.2 and 5.3.3 respectively. The population density (D_p) also approximates the expected public transport modal split (MS_{Pt}) based on an analysis of the secondary empirical data presented in Chapter 3. The following equation was derived from the analysis in Section 3.2.

Equation 2: Public transport mode share

$$MS_{Pt}\ (\%) = 0{,}1 * Ln(D_p)\ -\ 0{,}2$$

4.3.3 Land use data year 0, 5 and 20

The *Land use data* sheets assign the land use characteristics to the TAZs and calculate the public transport trip productions (*PtP*) and attractions (*PtA*) in each zone for the AM peak period, illustrated in Table 4. Firstly, the size and the centroid co-ordinates of each TAZ is set. The data for the four land use categories, residential; business; industrial; and retail, is added to each TAZ individually. The entire area of each TAZ has been allocated to residential land use as the trip generation of the residential land use category is controlled by the set value of gross population density (D_p) instead of the area devoted to the land use. The total area allocated to each non-residential land use across the corridor has been set to maintain an approximate balance between public transport trip productions and attractions. Therefore, the intensity, or employment density, of these land uses increases linearly with increasing population density (D_p) in order to preserve the balance. The corridor is nominally isolated from outside trips but they can be represented by trips allocated to the outer zones.

The population density and the intensity of the land uses – and therefore the costs associated with the system – are ramped up and averaged over a period of 20 years in order to include the repayment costs of the capital investments. *Land use data year 5* and *Land use data year 20* recalculate

Table 4: Extract from the land use data sheet illustrating the area, trip productions and attractions for each TAZ

Zone	Residential			Commercial			Industrial			Retail		
	Area	PtA	PtP	Area	PtA	PtP	Area	PtA	PtP	Area	PtA	PtP
1	1000	3401	10204									
2	800	2721	8163									
3	200	680	2041	60	1453	256	48	319	137	48	423	228
4	200	680	2041	60	1453	256	48	319	137	48	423	228
5	800	2721	8163									
6	700	2381	7143									
7	200	680	2041	60	1453	256	48	319	137	48	423	228
8	200	680	2041	60	1453	256	48	319	137	48	423	228
9	700	2381	7143									
10	600	2041	6122									

(Note: PtA = Public transport passenger trips Attracted; PtP = Public transport passenger trips Produced) the area, trip productions and attractions in each TAZ for the fifth and twentieth years of the 20 year analysis period respectively.

4.4 Transport sub-model

The transport sub-model is a conventional four-step model, wherein the first step, trip generation, is estimated by the land use sub-model. The second step, trip distribution, is completed by a standard gravity model that translates the zonal trip production and attraction values into a matrix of trip origin and destination (OD) pairs. The third step, mode choice, is not performed as the model is run for all variations of all mode technologies so that analyses on their different levels of viability can be conducted. There is assumed to be no competition between alternative public transport mode technologies when simulating each mode technology. The final step, route assignment, is completed using the proximity of the origin and destination of each OD pair to a specific public transport route. Route options and congestion-related impedance are not accounted for as the public transport service sets capacity to meet the peak passenger volume.

4.4.1 Zone distances

The distance covered by each OD pair in the matrix is calculated by trip length in order to determine the generalised cost of each destination option. The OD trip distance is utilised as an input for the gravity model. The distance of each trip segment is also determined in order to calculate separate fare cost components.

4.4.2 Gravity model

This sheet contains the gravity model that performs the trip distribution calculations for each of the three time periods: year 0, year 5 and year 20. For a description of the standard gravity model see Masucci et al. (2013). The zone distance matrix becomes a shortest path matrix from which the friction factor is derived. The friction factor accounts for the impedance that a trip encounters from one zone to another and then estimates the probability of that trip occurring. The exponential friction factor ($f(c_{ij})$) in Equation 3 uses OD trip distance as the impedance or generalised cost (c_{ij}) and a beta value (β) of 0.25 to represent travel distance sensitivity.

Equation 3: Exponential friction factor

$$f\left(c_{ij}\right) = e^{-\beta(c_{ij})}$$

The sum of all the friction factors, or the relative probabilities that a trip will occur, is divided by the sum of all trips produced, to determine an expansion factor. The friction factor of each OD pair is then multiplied by the expansion factor to provide a realistic first estimate for the magnitude of trips travelling between each of the zones. The matrix then corrects these estimates based on the calculated data for the total production and attraction values of each zone. The matrix performs this correction nine times, following the Furness method. This leads to a final matrix that approximates the distribution of trips across all of the zones.

4.4.3 Network year 0, 5 and 20

These three worksheets conduct step four of the transport sub-model, route assignment. The trips are assigned to the proximate routes and the peak demand on each route is calculated to set a minimum capacity for the required services. The number of trips per OD pair are also multiplied by their OD distance. The sum of which is then divided by the total number of trips, to determine the average trip length.

In the trunk-feeder service model, the trips originating from or destined to non-TOD (blue and beige) zones are allocated to the nearest of 13 feeder routes, each serving one specific zone. The maximum volume between the trips entering the zone and those leaving the zone is taken as the peak passenger demand on that feeder route. Every trip that uses a segment of the trunk route is assigned to that segment and the trunk service peak passenger volume constitutes the highest demand on any segment irrespective of direction.

In the direct service model, route assignment and passenger demand estimation is more complex. This is due to the fact that the two routes leaving each non-TOD zone require separate peak passenger demand values and their shared infrastructure requiring a joint demand value to size its capacity. Therefore, trips are allocated separately to the 13 direct routes travelling toward the CBD and the 13 direct routes travelling away from the CBD. The maximum of the combined trips entering and leaving each zone for both routes is then set as the capacity requirement for the infrastructure. Due to seat turnover on the trunk corridor, spaces on these routes become available as passengers reach their destinations or transfer to other routes. Consequently, the trips originating in the TOD zones can fill up the available spaces and maintain high levels of vehicle productivity. The ‘Route demand’ represents the demand on each of the trunk segments from the non-TOD zones that is satisfied by the direct service routes. The ‘Non-route demand’ is the passenger volume from the TOD zones which needs to be filled into the spaces on the existing direct service routes. The ‘Route capacity’ determines the existing capacity on each trunk segment from the 26 non-trunk direct service routes, based on the mode that is most viable for them in total. The ‘Spare route capacity’ is the number of spaces available due to the seat turnover that can be filled. As the demand from the TOD zones is often too great for the spare capacity of the 26 non-trunk direct services, one further service is created which only operates along the trunk corridor. The peak passenger volume of this ‘Trunk direct service’ determines its capacity and mode choice separately to the other routes to represent a complementary, dual-mode direct service system, running in parallel.

As an example, let 37 trips be the total number of trips on one of the Trunk segments that collectively originate from non-TOD zones. Therefore, the ‘Route demand’ on that trunk segment is 37 trips. Then, let the total capacity of all the direct services originating in non-TOD zones and passing through that trunk segment be 50 spaces, this is the 'Route capacity'. Consequently, there are then 13 spaces on the non-TOD direct service vehicles that aren't being utilised when they pass through that trunk segment, this is the 'Spare route capacity'. As a result, 13 trips originating in TOD zones that need to pass through that trunk segment can be accommodated on the non-TOD direct service vehicles. Finally, let the total number of trips from the TOD zones that need to pass through that trunk segment be 30 trips. Of these 30 trips, 13 can be accommodated on the non-TOD direct service vehicles; the remaining demand for the 17 trips must then be met by introducing a 'Trunk direct service'.

4.5 Costing sub-model

The costing sub-model utilises the peak passenger demand on each route to determine the operational and infrastructural requirements for each of the modes. The sub-model derives a range of operating, management, fleet and infrastructure costs for the 20 year analysis period. The refurbishment and replacement cycles for the vehicles and related infrastructure are based on local South African services. The costs are based upon local mode specific operational and costing data. Costs are calculated separately for every feeder, direct and trunk service route, as well as the private vehicle, park-and-ride costs for those zones that are not served by public transport. Fare pricing is based on local South African fare structures and calculated annually for the analysis period. The key costing and viability indicators are then collated and summarised in the costing results sheet for analysis.

Table 5: An example of the operational performance data for each of the mode technologies (Source: Del Mistro, 2013)

MODE	1	2	3	4	5	6	7
	Minibus	Conventional bus	Articulated Bus	Bus BRT	Articulated bus BRT	Suburban rail	Private car
Travel speed CBD/Commercial in peak (km/h)	20	15	15	20	20	43	30
Travel speed Arterial in peak (km/h)	40	30	30	45	45	48	50
Travel speed Freeway in peak (km/h)	55	50	50	60	60	60	75
Stop spacing (km): CBD/Commercial	0.5	0.5	0.5	0.5	0.5	1.6	100
Stop spacing (km): Arterial/Inner section	1.0	1.0	1.0	1.0	1.0	2.5	100
Stop spacing (km): Freeway/Outer areas	2.0	2.0	2.0	2.0	2.0	5.0	100
Acceleration: (m/s^2)	1.3	1.4	1.3	1.5	1.4	1	1.5
Deceleration: (m/s^2)	2	2	2	2	2	1.5	2
PRE-PAID: Passenger handling time(sec/pass)	20	8	8	4	4	0	0
ON-BOARD: Passenger handling time(sec/pass)	20	19	19	4	4	0	0
Vehicle Stopped Time/stop (sec)	0	0	0	0	0	30	0
Time spent to turn vehicle (min)	0	1	2	1	2	4	0
Additional time spent to turn vehicle (min/coach)						0.44	
Maximum volume/Capacity ratio	0.85	0.85	0.85	0.85	0.85	0.85	1
Vehicle capacity/coach (standing allowed)	13	80	120	85	120	191	1.3
Vehicle capacity/coach (standing is not							

4.5.1 Mode data

Operational performance and costing data for the six public transport modes and one private mode used in Del Mistro & Bruun's (2012) study were updated and supplemented with data sourced from government and parastatal agency publications. Table 5 illustrates some of the operational performance data used for each of the mode technologies. The costing data includes the capital and maintenance costs of the vehicles, infrastructure requirement costs and contract or management costs among others. Data on externalities was also collated, such as energy consumption and resultant pollution levels.

4.5.2 Fare structure

The fare structure of each public transport mode was approximated to resemble the fares in Cape Town, South Africa. As all of the fares in Cape Town are distance-based, the fare structures were separated into a base fare and a variable fare that, together, is the closest approximation of the fare prices found in each of the source documents. The largest difference in fare, at any distance, between the existing fares and the stated approximation is 14%. The fare prices, collated in Table 6, are represented in South African Rand: R1 = €0.056 = $0.063 (18/05/16).

Table 6: Distance-based fare structure for each mode

Mode	Base fare	Variable fare	Source
	R	R/km	
Suburban rail	8	0,15	http://www.capemetrorail.co.za/Communication/External_Communication/20120629_Metrorail_monthly_tickets_concession_remains.pdf
Conventional bus	5	0,4	http://gabs.co.za/fares-tickets/
Minibus	6	0,8	http://www.capetown.gov.za/EN/TRAVELSMART/Pages/Minibustaxis.aspx
BRT	6,3	0,16	http://myciti.org.za/docs/1302/NewFaresCalculator-02_694x_crop_90.jpg

4.5.3 Fare revenue year 0, 5 and 20

The fare revenues of the trunk, feeder and direct services are calculated for each mode technology and time period. The distance-based fare structure calculates a fare for each trip segment based on the length of the segment and then sums to a total trip fare value. The base fare is only included once per trip, irrespective of the number of trip segments, in accordance with South African best practice. The fare revenue is accumulated separately for the trunk, feeder and direct services per mode and input into the costing worksheets.

4.5.4 Cost feeder

In both models, the demand on each service route during the peak hour is extrapolated to represent the demand over an entire day before costing. This is done using South African temporal demand data. The proportion of the total day's trips that are undertaken during the peak hour must be determined or estimated. It is assumed that there are two further peak hours of lesser severity throughout the day, for which the proportion of trip demand must also be discerned for each direction. The remaining proportion of trips is then split evenly over 14 off-peak hours, summing to a total operating time of 17 hours per day. The duration of operation and number of peak hours is contextual data and is representative of public transport operations in South African cities. The full day and peak hour demand volumes, along with the mode and zone distance data, are utilised to calculate 152 cost components and other indicators relating to the public transport service. Each indicator is evaluated for each of the 20 years within the analysis period and for each mode technology. The cost components include operating, capital and maintenance costs of the vehicle fleets; way infrastructure; terminals; stops; stations and depots, among others. Contract management costs and predetermined operator profit are also included. There is a separate cost sheet for each of the 13 feeder services.

4.5.5 Cost direct

A complexity with modelling direct services is calculating the operating and capital costs for each route, individually. The operating costs are directly attributed to each route but the infrastructure, and therefore much of the capital costs, are shared. To overcome this problem, three service route cost sheets were created for each of the non-TOD zones. The three routes departing from each non-TOD zone are: the two operating routes (right and left) travelling toward and away from the CBD, and a notional third route that only travels as far as the trunk service route. Therefore, using Route 2 as an example, worksheet ‘Direct 2 R’ is used to calculate the operating costs of the service travelling from zone 2 toward the CBD and worksheet ‘Direct 2 L’ calculates the operating costs of the service travelling away from the CBD. The notional third route, ‘Direct 2 C’, calculates the capital costs of the shared infrastructure between zone 2 and the trunk service. Therefore, it was given the sum of the demand leaving or entering the non-TOD zone, for the other two routes.

4.5.6 Sum feeder/Directs

In the trunk-feeder service model, the feeder and trunk services are evaluated as separate collective systems with regard to mode technology choice. Therefore, to compare the viability of the modes for the feeder services as a collective, the cost components of the 13 routes need to summed or averaged, which is performed in the ‘sum Feeder’ worksheet. The same logic is applied to the direct service model, but due to the complexity of the route costing structure three provisional and one final summation exercise is done. The cost components of the direct routes leading toward the CBD are aggregated in ‘sum Directs R’; the components of the routes leading away from the CBD are aggregated in ‘sum Directs L’ and the capital cost components of the notional third route are aggregated in ‘sum Directs C’. The cost components of all three summations are then selectively aggregated in ‘sum Directs’ according to the nature of the component.

4.5.7 Sum unserviced

The unserviced, non-TOD zones (beige zones in Figure 11) represent the areas of a transport corridor for which a feeder service is required but not supplied due to financial or other reasons. These areas have been represented as three cohesive non-TOD zones, however, in a real corridor the areas would usually occur randomly as small parcels of land throughout the non-TOD zones. The absence of a feeder service option would necessitate the prospective public transport users to commute by private vehicle to the nearest public transport station. Therefore, worksheet ‘sum Unserviced’ aggregates the cost components of those three feeder service routes for the private vehicle mode only. In the direct service model, only the operational and capital cost components of the notional third route are aggregated for the three unserviced zones as the passengers transfer to the trunk service at the nearest station. At the trunk service station, the trips are then represented as TOD trips and either filled into the existing spare capacity or added to the demand on the trunk direct service route.

4.5.8 Cost/sum trunk

In the trunk-feeder service model, the cost components of the trunk service are calculated as one service with no need for aggregation. However, in the direct service model, to account for the shared infrastructure required on the trunk segment of each route, a notional trunk service route has to be created that allows the cost model to calculate the magnitude of the infrastructure required by all the non-trunk direct services along the trunk corridor. The notional trunk service route functions in the same way as the notional third route from each non-TOD zone. The operational costs for the trunk direct service are calculated in worksheet ‘sum Trunk Nett’, only satisfying the demand over and above the spare capacity of the other direct routes. The capital costs of all the non-trunk direct services in the trunk corridor are then calculated in ‘sum Trunk Gross’, using the total demand of all the routes to determine the shared infrastructure costs. The different cost components are then selectively aggregated in ‘sum Trunk’ according to the nature of the component.

4.5.9 Costing results sheet

Depending on the simulation scenario, the costing results sheet is named: *Cost Den*; *Cost ArtDen*; *Cost ArtDen B-TOD*; *Cost LMix*; *Cost All*; *Cost All Half-dist or Cost Mode*. These sheets present some outputs of the costing and transport sub-models for comparison and analysis.

4.6 Corridor cost model limitations

The public transport corridor operating cost model was created to investigate the relationships between land use characteristics, network features and public transport viability on a more detailed level. The purpose of the model is to explore the trends and general relationships between a larger set of interdependent variables than has been tested previously. As a result of the increased complexity regarding the relationships of the variables, the processes within the sub-models needed to be significantly simplified. This means that the margins for error in the quantitative values of the results will be higher than in precedent studies for which the set of variables was smaller. However, an aim of this study, and its potential contribution to literature, will be a greater understanding of the nature of these relationships and not individual results for a particular set of land use characteristic values.

Furthermore, the context of the model is a generalised South African public transport corridor that has specific, and sometimes unique, traits. Conclusions and deductions on general trends can be inferred but detailed investigation is still necessary in different contexts. Even within the South African context, spatial patterns and operational features can differ greatly between cities or public transport corridors. The some of the many limitations and assumptions necessary to run this model are listed below:

- The trip generation rates are specific to the South African context.
- The spatial structure of the transport corridor was assumed to be triangular, terminating at a major economic node.
- The public transport trips originating and terminating in zones that did not have feeder services were assumed to park and ride, rather than shifting away from public transport entirely.
- The inclusion of only four land use types (Residential, Commercial, Industrial and Retail) limited the nuance of the land use environment that could be represented in each zone.
- Light rail could not be included in the study due to a lack of contextually relevant data on capital and operating costs.
- The beta value for the transport sub-model was set at 0.25; sensitivity analyses were run on each scenario with beta values ranging from 0 to 0.5 and none of the results deviated by more than 4%.
- Public transport modes were limited only by theoretical capacity, therefore the space required for additional lanes and passing lanes was assumed to be available.
- Vehicles were assumed to travel at a constant, contextually relevant, average speed, irrespective of demand upon the service.
- All trips were assumed to originate and terminate at the centroid of the traffic analysis zones.
- The temporal demand profile of the local context was used and remained constant.
- The repayment period for capital expenditure was assumed to be less than 20 years.

With regard to the set of significant indicators for public transport service viability, two indicators are beyond the scope of the corridor cost model: temporal demand variability and user travel time. The simplified structure of the model prevented the inclusion of these two indicators, which could fundamentally change the measure of service viability in certain conditions. The public transport modal share, utilised in the model, is dependent upon an empirical relationship with gross population density, derived from metropolitan scale data for an international set of cities predominantly from developed countries. Finally, active competition between public and private transport modes, based on their relative utility, is not accounted for within the motorised modal split.

4.7 Summary and conclusion

This chapter aimed to describe the spreadsheet-based, public transport corridor operating cost model that was created to simulate the effects of varying land use environments and public transport network features on the viability of the services in the South African urban context. The chapter began with an overview of the spatial structure of the corridor model, the layout of the analysis zones and the dimensions of the corridor itself.

The corridor operating cost model consists of three different sub-models with the output of one supplying the input of the next. The land use sub-model utilises the land use characteristics set for each of the TAZs, trip generation rates and additional contextual data to determine the number of public transport trips produced by and attracted to each TAZ. The transport sub-model is a conventional four-step model except that the first step, trip generation, is estimated by the land use sub-model. The trip distribution is estimated by a standard gravity model that translates the zonal trip production and attraction values into a matrix of OD pairs. The trips are assigned to routes by proximity and the demand on each route during the peak hour becomes the key input for the costing sub-model.

Contextual data from a South African city is then utilised to derive a detailed costing for each of the public transport routes in the corridor. The process is then repeated with a new set of land use characteristics in an iterative manner. The output indicators that have been chosen to represent the viability of the public transport system in each simulation are the final output of the model. The model has simplified many of the processes involved in public transport service modelling and costing in order to test a larger set of interdependent variables, including the land use variables. The model was designed to foster a greater understanding of the nature of these relationships and not individual results for a particular set of land use characteristic values.

5 Results and discussion

5.1 Introduction

The primary aim of this research was introduced in Chapter 1 as an investigation of the relationships between land use characteristics, network features and public transport viability at a detailed corridor level. The method of investigation is the simulation of a set of scenarios using a public transport corridor operating cost model, described in Chapter 4. This chapter explains how each scenario was tested, illustrates the results of the simulations, and then discusses and interrogates these results on the grounds of meaning and consequence.

The chapter begins with an overview of the output indicators from the model that were chosen to represent public transport viability in the analyses. The first scenarios analysed are for the four land use characteristics in Section 5.3. The relationship between public transport viability and each characteristic is analysed in isolation at the corridor scale. Once the effects of the individual characteristics are determined, their interconnections are explored. The results of these analyses are presented for both service configurations in each scenario due to the structural differences in their modelling processes and for direct comparability in a wide range of land use environments. The chapter concludes with an evaluation of the impact that different mode technologies have on the viability of their services under a variety of land use conditions, in Section 5.4.

5.2 Indicators of public transport viability

From the output of the model, five indicators of public transport viability were chosen for analysis related to land use characteristics: total cost; authority cost; operator cost; average trip length; and peak passenger volume.

In Section 2.2, the literature review found that generally viable public transport was said to be affordable, effective and both socially and economically sustainable. Effectiveness is dependent upon the level of service provided by the public transport system. To ensure a minimum limit for effectiveness, constraints have been placed on maximum headways and walking distances. Additionally, as the features of the public transport corridor optimise to the surrounding conditions, the resulting service should be the most appropriate variant for the operating environment. Therefore, the three remaining criteria must be represented to assess public transport service viability.

The primary component of economic sustainability is the nett cost of the system to the city. The nett cost is dependent upon the total cost of the public transport services and the subsidies required to meet them. However, as discussed in Section 2.2, the need for public transport subsidies and their availability often do not align. A poorer city minimises fare cost to maintain affordability, which increases the subsidies required, but the equally poor transport authority may not have the financial liquidity to fund the subsidies. As a result, the magnitude of subsidies given to public transport services and fare revenue collected can have a weak relationship with the cost of the most appropriate public transport system. Therefore, due to the subjectivity of fare revenue generation and subsidy availability, the total cost of a public transport service is posited to be the most consistent indicator of its viability. Hence, the transport mode or modes generating the lowest total cost to operate the trunk route and the collection of non-trunk routes, respectively, are chosen as the most appropriate simulation of a transport system under each set of land use characteristic values.

Though, the potential fare revenue generation and subsidy requirement of a public transport service within its local context is still a significant factor in the decision-making processes of the transport authority. The authority cost represents the nett cost of the system to the transport authority, which is the total cost minus the expected revenue collected. The authority cost includes the operating subsidies as well as loan repayments on capital investments. The model uses the gross cost contracting arrangement, whereby the operator is guaranteed a certain amount of profit over and above their expenses, and the financial risk of the system rests with the authority. The shortfall between the operator's costs, including predetermined profit, and the fare revenue is then met by the authority through a subsidy.

The cost to the operator is also significant as it can affect the social sustainability of the public transport system. If the cost of being a public transport operator is too high, market entry and contestability would be detrimentally affected. A majority of South African public transport trips are currently being serviced by small-scale operators who would find difficulty in competing in a high cost environment (Schalekamp & Behrens, 2010).

The fares have been set to the existing fare prices of South African public transport services at the time of investigation in order to ensure relative affordability. However, the dominant fare collection system used in South Africa, and many other developing cities, calculates the fare based on distance travelled. Therefore, the affordability of the fares is directly dependent upon the distance that the average user needs to travel. Furthermore, distance-based fare systems penalize shorter trips through a base fare. This means that average trip length not only affects affordability but also fare revenue.

The peak passenger volume on the trunk route determines the capacity requirements for the corridor, and is often the determinant for the choice of mode technology. The required capacity and mode technology, in turn, determines much of the capital and operating costs of the service. The peak passenger volume and mode capacity limits also prevent overcrowded but otherwise viable public transport services from being presented as appropriate solutions.

5.3 Land use scenarios

In the land use scenarios, the effects of three land use characteristics are first tested in isolation of each other: population density, density distribution and land use mix; thereafter, combining density distribution and land use mix to ascertain their complementarity. The final analysis is of destination accessibility, as changing this land use characteristic inherently affects the other three.

The preceding studies have drawn many connections between these land use characteristics and the success of public transport services. Population density is posited to have very strong control over the mode technology choice and financial health of the proximate transport services. However, some of the literature and the secondary empirical data analysis, in Chapter 3, have cast doubt on the significance of this relationship in developing cities. Section 2.4.2 outlined that the level of articulated density has recently been suggested to have a significant effect on public transport viability, as well as the average distance that a user is likely to travel. Similarly, Section 2.4.3 evaluates the claims that land use mix affects trip length and the patterns of passenger flow through increased seat turnover. Lastly, from the literature reviewed in Section 2.4.4, destination accessibility is thought to influence trip length and public transport modal share. These theories, derived from empirical studies, will be critically compared against the results of the corridor cost model to help establish the underpinnings of these relationships and generate a clearer image of their direct effects.

5.3.1 Population density

The population density scenario simulations explore the effect of gross corridor population density on public transport system viability. The test range was between two and 400 p/ha spread evenly across the corridor area, though only the relevant ranges have been illustrated in each scenario. The land use distribution approximated a generic South African city with a strong CBD, allocating 50% of the trip destinations to the CBD and the remaining destinations along the trunk route. The non-residential land use activity was increased with population density to balance the trip origins and destinations. The allocated land use areas remained constant, resulting in the total population of the corridor increasing linearly with increasing density. As the costs of the system naturally increase with the number of users, they are difficult to compare for different values of population density. Hence, the total, authority and operator costs are represented as monetary values per passenger trip served.

Figure 15 illustrates the three cost indicators for the simulated transport system at each value of population density; as does Figure 16 for the trip length and passenger volume indicators. The upper limit of the displayed density values is 100 p/ha, as the peak passenger volume for one of the trunk service segments at 100 p/ha is 82 892 persons per hour per direction (p/h/d), which is beyond the capacity of all non-rail transport systems. Furthermore, the total cost, authority cost, operator cost and average trip length are observed to remain relatively unchanged for higher density values in this representation of a South African public transport corridor.

A significant amount of the literature reviewed in Section 2.4.1 posits that each transport system, and specifically each mode, has a threshold density that is required for it to be efficient and viable. Additionally, each mode is constrained by a passenger volume capacity limit which negates its

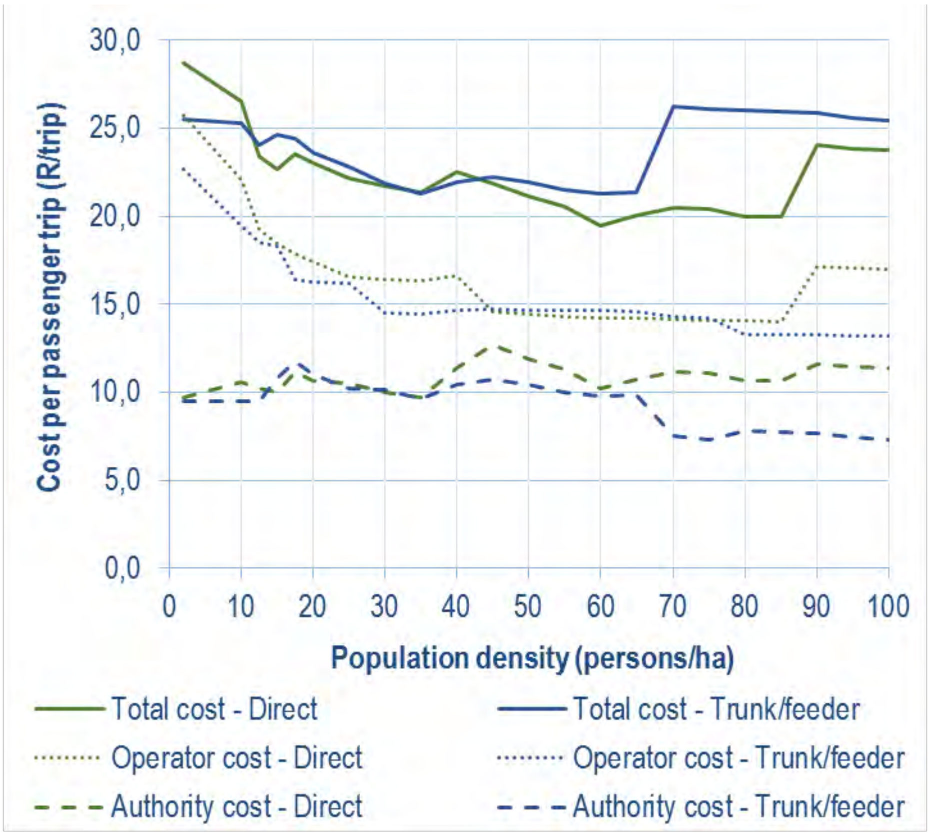

Figure 15: Cost components when varying population density on a 20km corridor

use at higher volumes. The effect of the density thresholds and capacity limits can be seen in the stepped nature of the cost components in Figure 15. An example is the sharp increase in total cost for the Trunk-Feeder (T-F) service model at a population density of 70 p/ha, which is due to the trunk service having to choose the suburban rail mode due to the large passenger volume. Similarly, for the direct service model, suburban rail is chosen by the trunk service at 90 p/ha for the same reason. The fact that the trunk service hits the passenger capacity limit in direct service model at a higher population density than in the T-F model is due to the direct service model's parallel services adding additional capacity to the trunk route.

However, attaining the threshold densities does not seem to have a significant effect on the systems' viability, in this case. The total cost, per passenger, decreases marginally with increasing density but incurs stepped increases again every time the public transport mode reaches its capacity limit. The differences in the cost components between the results of the direct and trunk-feeder service models are also slight. The structure of the generic South African transport corridor seems to favour the direct service configuration, based on the marginally lower total cost. However, the local fare structure is expected to generate a larger revenue for the T-F configuration, potentially leading to lower authority costs in the South African context.

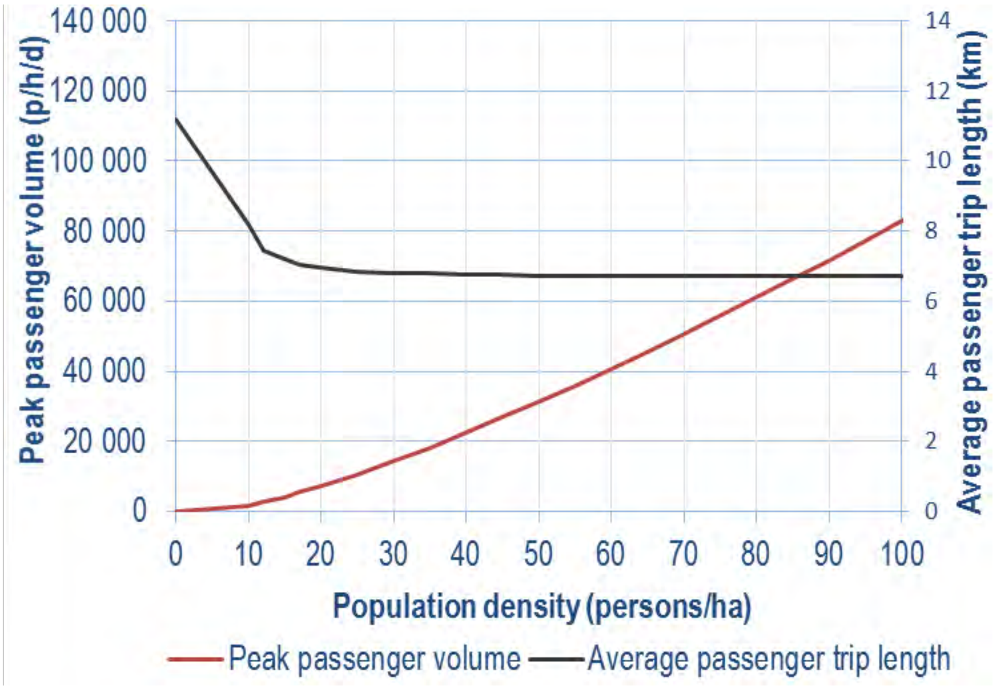

Figure 16: Average passenger trip length and peak passenger volume when varying population density on a 20km corridor

The weak relationship between gross population density and public transport cost per passenger trip suggests that achieving the metropolitan density targets set by the South African cities will not significantly improve the financial situation of their public transport systems. In fact, due to the large catchment area of the average South African transport corridor, attaining the modest density target of 80 p/ha would result in a peak passenger volume of 61 026 p/h/d. The potential capacity of the BRT systems being built in these cities is 25 000 – 35 000 p/h/d, with the theoretical modal maximum being 45 000 p/h/d. Therefore, if one of the new BRT corridors resembles the one simulated in this scenario, the BRT system will reach capacity constraints well before the density target is reached. This could have serious ramifications for South African cities, and many others that believe attaining density targets will rescue financially unsustainable public transport services.

The average trip length is not substantially affected by density and the initial decrease at very low population densities is due to small fractions of trips accompanying OD pairs with large distances having to be rounded up to full trips. However, the potential effect of population density on the trip distribution sub-model's distance decay function, due to congestion and other externalities, is not accounted for. The peak passenger volume rises linearly with increasing density.

5.3.2 Density distribution

Measures for density distribution, thus far, have primarily utilised geographic reference points unrelated to the public transport network or focussed on the level of Transit Oriented Development (TOD) adjacent to trunk service stations. Neither of which adequately address the effect of density distribution on feeder service reliance, a major positive effect of articulated density. Therefore, a measure needed to be derived through the examination of density distribution patterns across different cities. In this study, ‘Density articulation’ is proposed as a measure for how strategically the population density is distributed over the metropolitan area with regard to public transport trunk service proximity. Curitiba is purported to be an exemplar of high articulated density, owing to its high proportion of residences within walking distance of its trunk service network (Suzuki, Cervero & Iuchi, 2013). In South African cities, the poor majority occupy cheap land at relatively higher densities on the periphery of the city (Maunganidze & Del Mistro, 2012). This would represent low density articulation. The suggested measure for density articulation is the percentage of the urban area’s total population that lives within walking distance of the trunk service route, given a specified gross population density. At a percentage of zero, the entire corridor population lives in the non-TOD (blue and beige) zones of Figure 11, closer to South Africa’s current urban situation. At a percentage of 100, no person lives outside of the TOD (green) zones.

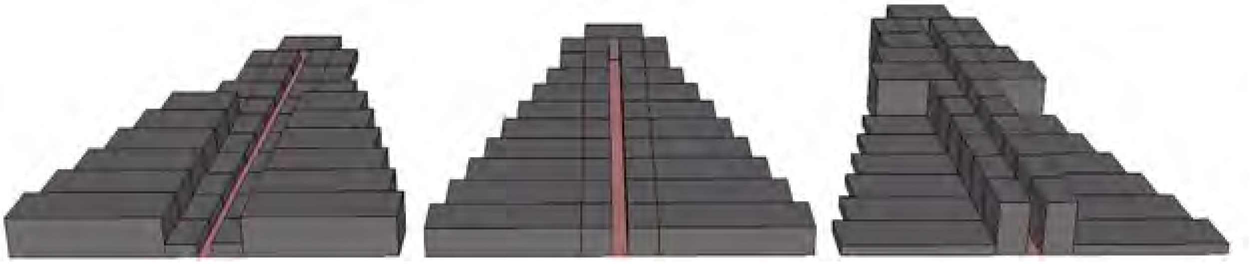

Figure 17: Orthographic projection of 20% (left); 43% (centre) and 80% (right) density articulation on the simulated corridor representing population density as height

The concept of density articulation is illustrated in Figure 17, using the generic South African corridor and a gross population density of 50 p/ha. In the centre of the illustration, the density is evenly spread over the catchment area, representing a density articulation of approximately 43%. To the left, a density articulation of 20% is applied, showing that the majority of the population is in the TAZs that require feeder services. Due to the prevalence of suburban housing and peripheral townships, this situation has a close resemblance to the current South African context. The illustration on the right has an 80% level of density articulation, resulting in a reduced demand for feeder services.

5.3.2.1 Pedestrian-based density articulation

The density articulation scenario simulations vary the distribution of population while keeping the distribution of other land uses constant. The land uses associated with trip attraction maintain the same distribution pattern as they had in the population density scenario simulations in order to ease comparison and retain the representation of a radial network. Population density was set at 50 p/ha, as the peak passenger volume in the population density scenario was 31 242 p/h/d, which is within the operating capacity of both semi-rapid bus and suburban rail. For the analysis of conventional, pedestrian-based density articulation, the TOD and other walking catchment areas originally described in section 4.2 are utilised. These areas are illustrated in Figure 17.

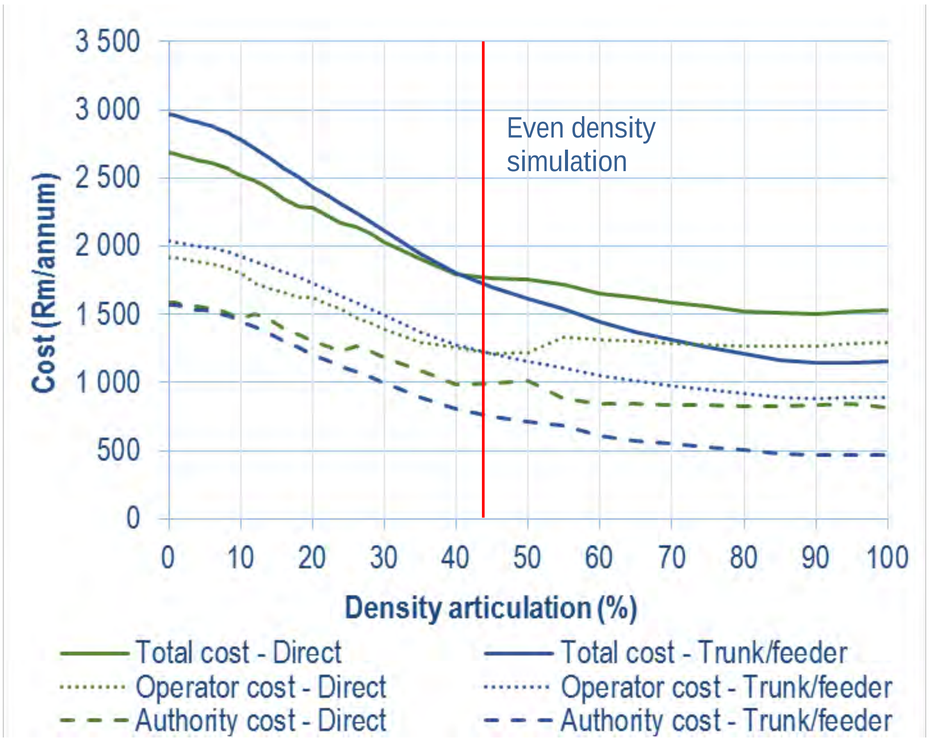

Figure 18: Cost components when varying density articulation on a 20km corridor

Figure 18 illustrates the effect of density articulation on the three cost indicators for a 20km trunk corridor and highlights the point at which an evenly spread density profile is reached. The even density simulation describes the point at which the population density is constant across the entire transport corridor, as was the case in every one of the population density simulations in Section 5.3.1. This point serves as the point of commonality and comparison for transport corridors, when the allowable access distance and feeder service structure is changed. In this scenario, density articulation appears to have a larger direct effect on the cost components of the public transport services than that of population density. The total cost decreases by 61% and 43% for the T-F and direct models respectively, across the range of density articulation values. In the T-F model, as density articulation increases, the reliance on feeder services diminishes until the minimum allowable level is reached. In the direct service model, the increase in density articulation causes a decrease in the demand for the non-trunk direct services. Eventually, only the trunk direct service is operating at higher than minimum allowable levels. The structure of the direct service configuration means that the non-trunk direct services are much longer than the feeder services in the T-F configuration. Hence, the non-trunk direct services are more expensive to operate at lower passenger volumes and, consequently, high levels of density articulation favour the T-F service configuration. Similarly, at low levels of density articulation, the non-trunk direct services accommodate the higher non-TOD passenger volumes with larger, more efficient vehicles and eliminate the necessity of the trunk direct service. Whereas, the T-F service model is also required to operate larger vehicles but on the shorter, less productive feeder routes. The results echo those of Jara-Díaz, Gschwender & Ortega (2012), which found that having a majority of the demand along the trunk route – possibly as a result of high density articulation – favours the trunk-feeder service configuration.

In the context of a South African transport corridor, and accounting for the potential local fare revenue, it appears that the trunk-feeder configuration is marginally more cost-effective at all levels of density articulation in this case. The authority cost decreases by 71% and 49% across the range of density articulation values. However, this study does not take into account the time cost to the user of having to transfer when accessing the trunk route. Additionally, this model has one major destination catchment zone (CBD), which Del Mistro & Bruun (2012) claim can favour trunk-feeder service configurations.

Based on this simulation, the highest possible trunk service walking catchment (TOD) gross population density that can be achieved is approximately 100 p/ha, well below the public transport trunk corridor density targets of the South African cities presented in Table 2 (which range between 150 and 238 p/ha). To achieve the highest density target (238 p/ha) within the green TOD zones in this simulation, at 100% density articulation, would require an average population density of at least 100 p/ha across the corridor. Additionally, this level of population density would result in a peak passenger volume above 100 000 p/h/d on one of the trunk corridor segments, which is beyond the capacity limit of most public transport systems.

The operator cost of the scenario simulations decrease in near parallel with the total cost, for increasing levels of density articulation. The decrease in use of the less efficient feeder and non-trunk direct routes contributes to a 56% and 32% drop in costs borne by the operators for the T-F and direct configuration respectively. Although, the operator cost in the direct service model decreases only at lower values of density articulation, after 55% it remains relatively constant. This is primarily due to the transition of the non-trunk direct services to operationally less efficient, smaller modes.

The average passenger trip length decreases by 68% over the range of density articulation, shown in Figure 19. This is important in South Africa, with the prevalence of distance-based fare systems, as the cost per average trip will decrease without changing the fare structure. The initial decrease in peak passenger volume at low values of density articulation is due to some of the origins of the trips now being closer to the CBD than their destinations and the flow of passengers away from the CBD beginning to rise. The effects of the growing bi-directional flow are then offset after 40% density articulation by the increased public transport modal split in the TOD zones associated with their rising population densities.

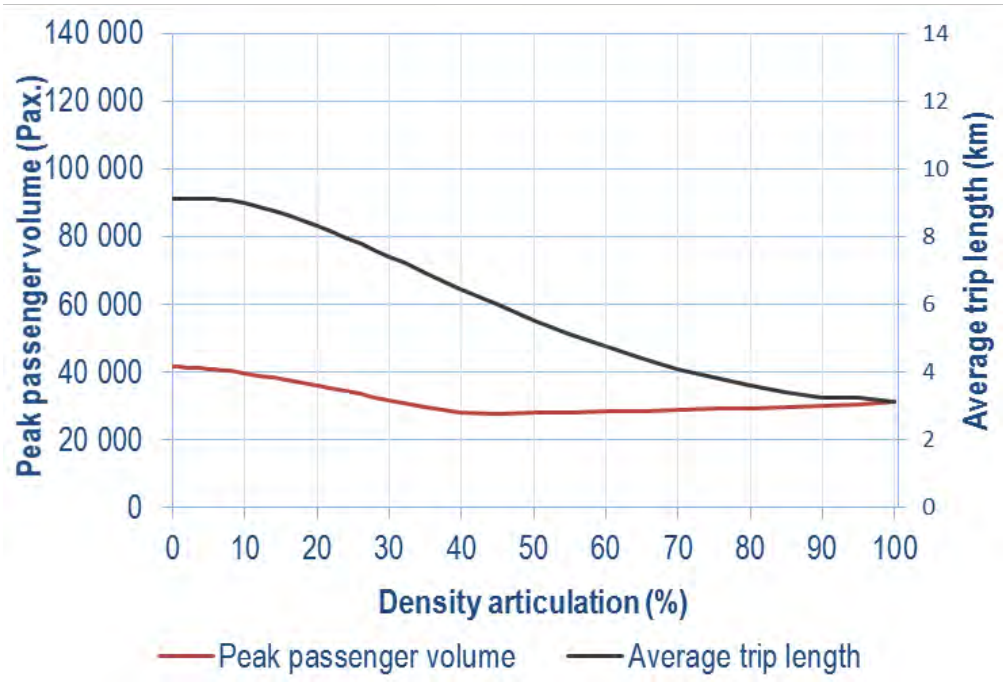

Figure 19: Trip length and peak passenger demand when varying density articulation on a 20km corridor

5.3.2.2 Bicycle-based density articulation

Density articulation is based primarily on reducing the reliance on feeder services, therefore, the area of articulated density is dependent upon the station influence area (SIA) of the trunk service stations. The SIA of the trunk service stations in the other simulation scenarios is based upon the maximum walking distance prescribed by the South African national transport policies. However, if a strong cycling culture could be fostered, the SIA of the trunk service stations could expand to a distance for which the average user is willing to cycle. Lee (2015) has investigated this type of bicycle-based transit oriented development (B-TOD) and its potential effects on the SIA of Seoul, South Korea’s subway system. As with pedestrian-based TOD, there is a host of different values for the acceptable distance that a public transport user is willing to travel in order to access a public transport trunk station. See Lee (2015) for a list of common values ranging from 1km to 10km. For this scenario, the B-TOD area is set to include any point within 3km of the trunk service route. All other aspects of the pedestrian-based density articulation scenario were kept constant. The result of the increased SIA for the trunk service route is that the proportion of the total corridor area that does not require a feeder service – effectual TOD area – increases from 43% to 78%.

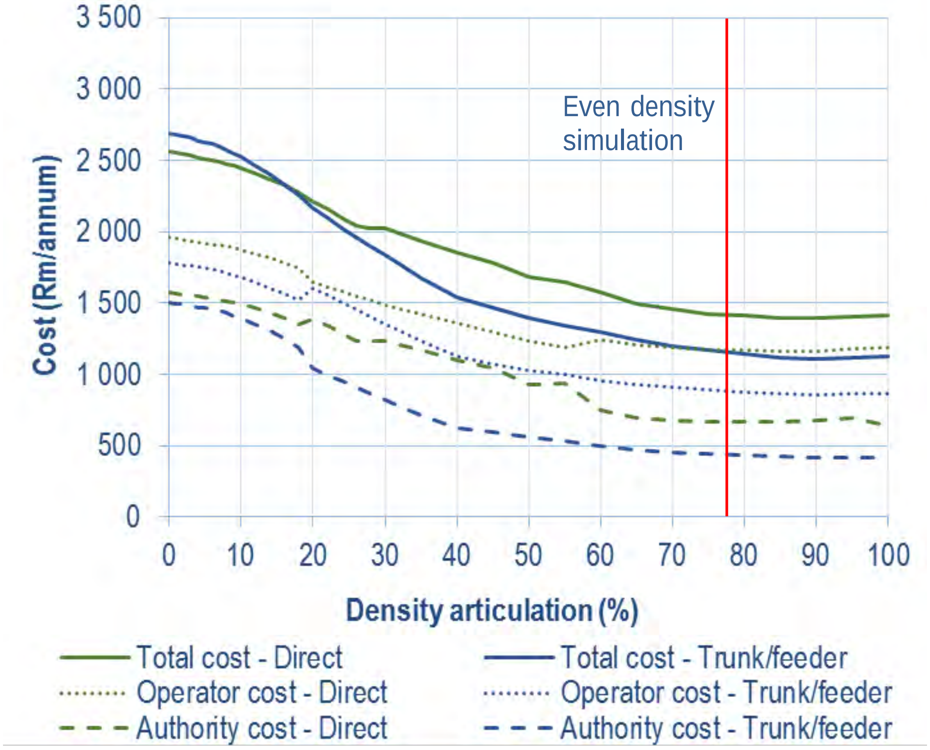

Figure 20: Authority and operator cost when varying bicycle-based density articulation on a 20km corridor

The effect of the bicycle-based scenario simulations on the three cost components, in Figure 20, appears to be marginally more significant than the pedestrian-based density articulation scenario. The average total cost of the public transport services is 10% and 4% lower than the pedestrian-based scenario for the trunk-feeder and direct service configurations respectively. However, due to the change in the proportional area that is categorised as TOD, the two figures cannot be compared directly. To determine the effect of density articulation with conventional TOD and B-TOD requires one to analyse two scenario simulations with the same land use characteristics. In the pedestrian-based scenario, the land use simulation with evenly spread population density has a density articulation of approximately 43%. Whereas, the exact same land use simulation in the bicycle-based scenario has a density articulation of approximately 78%, illustrated on Figure 20. This is due to the higher proportion of the B-TOD area, and illustrates the relative nature of a density articulation level. When comparing the results of these two analyses with identical land use conditions, the benefits of B-TOD become clear.

The total cost for the B-TOD scenario is 33% and 20% lower for the trunk-feeder and direct service configurations respectively. Furthermore, the authority cost, in the South African context, is expected to be 42% and 33% lower for the trunk-feeder and direct service configurations respectively. This means that a transport authority could theoretically halve its annual subsidy amount just by promoting cycling access to the stations of its trunk services, without changing the land use environment. This could have a major impact on transport policy as land use change can often take decades to achieve, whereas cycling promotion and infrastructure implementation are relatively fast and low cost. Although, the cost of the cycling infrastructure required to create B-TOD has not been included in the cost calculations for this scenario.

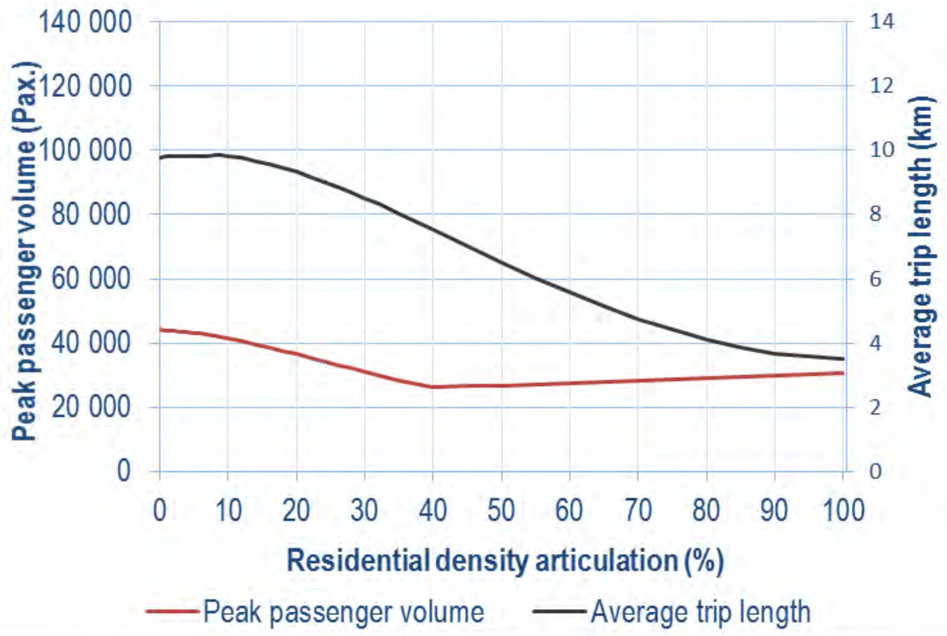

Figure 21: Trip length and peak passenger demand when varying bicycle-based density articulation on a 20km corridor

Moreover, one of the main factors for the financial success of a B-TOD based trunk service is the reduction in area that lacks access to public transport. A significant proportion of the areas that were previously unserved by feeder services are within the 3km B-TOD area. The prospective public transport users in those areas have been modelled to shift from park-and-ride to bicycle access, leading to substantial savings for the transport authority.

Overall, the authority cost decreases 58% and 45% for the T-F and direct service models respectively, across the range of density articulation values. The marginally greater positive effect of density articulation in the B-TOD scenario compounds the viability increases from the B-TOD itself. In Figure 21, the peak passenger volume is almost identical to that of the pedestrian-based scenario, in Figure 19, with it being marginally lower due to a higher proportion of residents being within the TOD areas, which are areas with higher trip attractions, meaning fewer inter-zonal trips are required. The average trip length remained higher in the B-TOD scenario than the pedestrian-based scenario, due to the decreased perceived cost of access that the bicycle mode allows.

5.3.3 Land use mix

The land use mix scenario tests the effects that changing the level of diversity of land uses in an area has on the viability of the public transport system. To negate the effects of land use articulation, the non-residential land uses were distributed evenly among the TAZs, irrespective of proximity to the trunk service route. At a land use mix of 0%, all of the non-residential land uses are situated in the CBD, representing a monocentric city with segregated land uses. At a land use mix of 100%, each zone has a proportion of the non-residential land uses that is equal to its relative area, including the CBD. The rationale for this method is derived from Equation 1, the equation for land use 'entropy' (see Kockelman, 1997), which calculates land use diversity based on the proportion of their respective developed areas. The population density of the land use mix scenario was also set at 50 p/ha to retain continuity and comparability.

The results of the simulations show a marked decrease in the cost components in Figure 22, for both service configurations. The total, authority and operator costs for the direct service configuration decreases 54%, 67% and 57% respectively, across the range of land use mix. Similarly, the total, authority and operator costs for the trunk-feeder service configuration decreases 48%, 67% and 50%. The results correlate with the positive effects on vehicle efficiency described in the literature. The posited effect on average trip length, by seat turnover, is demonstrated through a 37% decrease between the unmixed and fully mixed land use simulations. While significant, the decrease is not as substantial as the density articulation scenario simulations. In contrast, the effect of land use mix on peak passenger volume, shown in Figure 23, is much more significant than that of density articulation. The peak

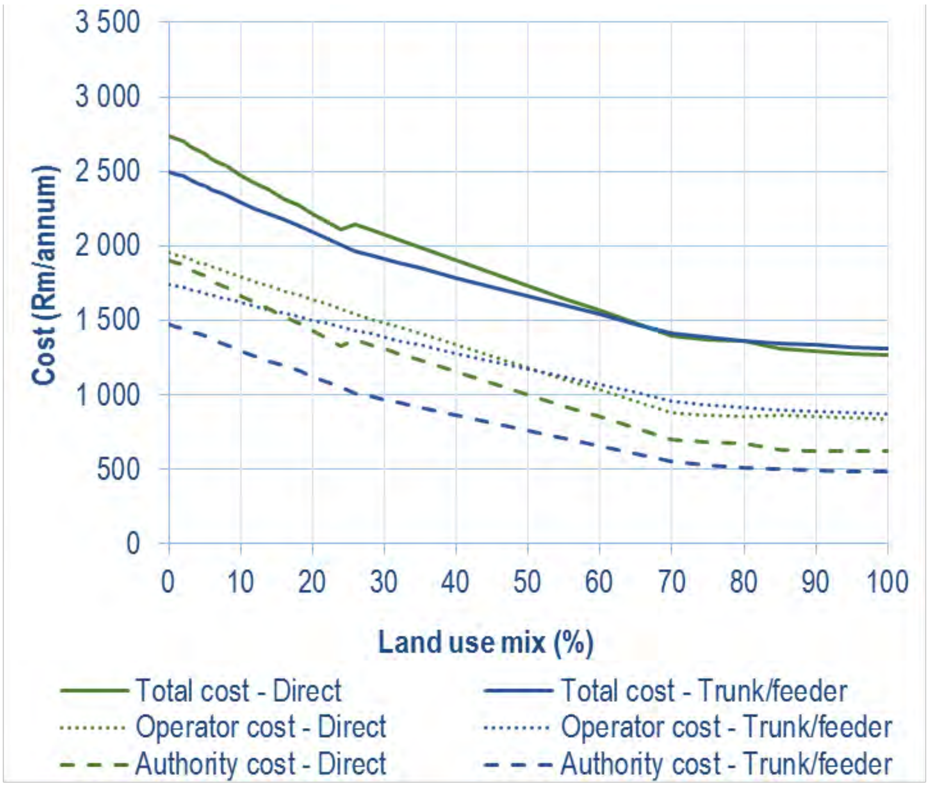

Figure 22: Cost components when varying land use mix on a 20km corridor

passenger volume decreases 67%, from 46 193 p/h/d to just 15 429 p/h/d. It is observed that this decrease is indeed due to increased bi-directional flow and seat turnover. As more trip ends are further from the CBD than their origins, the flow on the trunk route begins to even out. Furthermore, as trip destinations are increasingly available within the same TAZ as the origin, fewer trips along the trunk route are required.

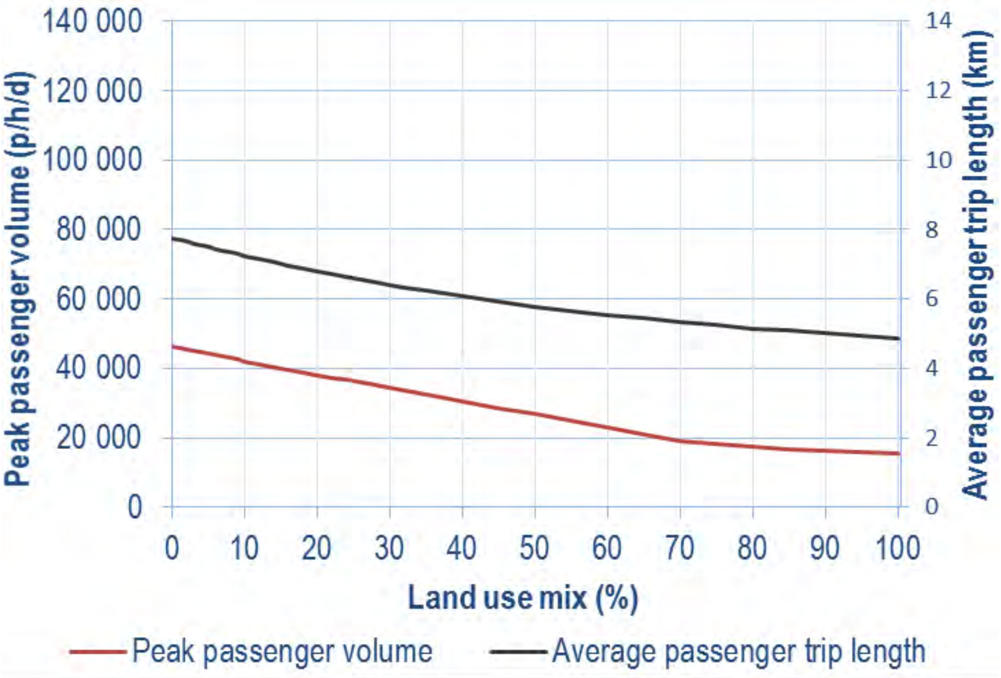

Figure 23: Trip length and peak passenger demand when varying land use mix on a 20km corridor

The apartheid spatial planning practices in South Africa's history have resulted in fragmented cities with segregated land uses and even less mixing of income groups. It has made land use mix particularly difficult and has been identified by the cities as one of the main causes of the financial distress that their public transport systems encounter. The effect of land use mix on bi-directional flow would allow the same amount of passengers to be served by substantially less infrastructure and a significantly smaller fleet. These are direct cost savings that substantially improve the viability of a public transport service. Prioritizing land use mix to the same extent as has been done with density could fundamentally alter the operating environment and financial sustainability of many South African public transport corridors.

5.3.4 Land use mix and density articulation

It was noted in Section 3.3 that the effects of density articulation and land use mix can be complementary, which gave rise to a scenario in which both indicators were tested simultaneously. The same percentage scale was used for density articulation but the method for distributing the non-residential land uses in the land use mix scenario was modified. As density articulation moves prospective users toward the trunk service route, non-residential land uses are likely to follow. Therefore, as land use mix increases, the area of non-residential land uses will increase only in the TOD zones, adjacent to the trunk service route. At 100% land use mix and density articulation, all land uses, including residential, are distributed evenly along the trunk service route in proportion to zone size. The population density was maintained at 50 p/ha.

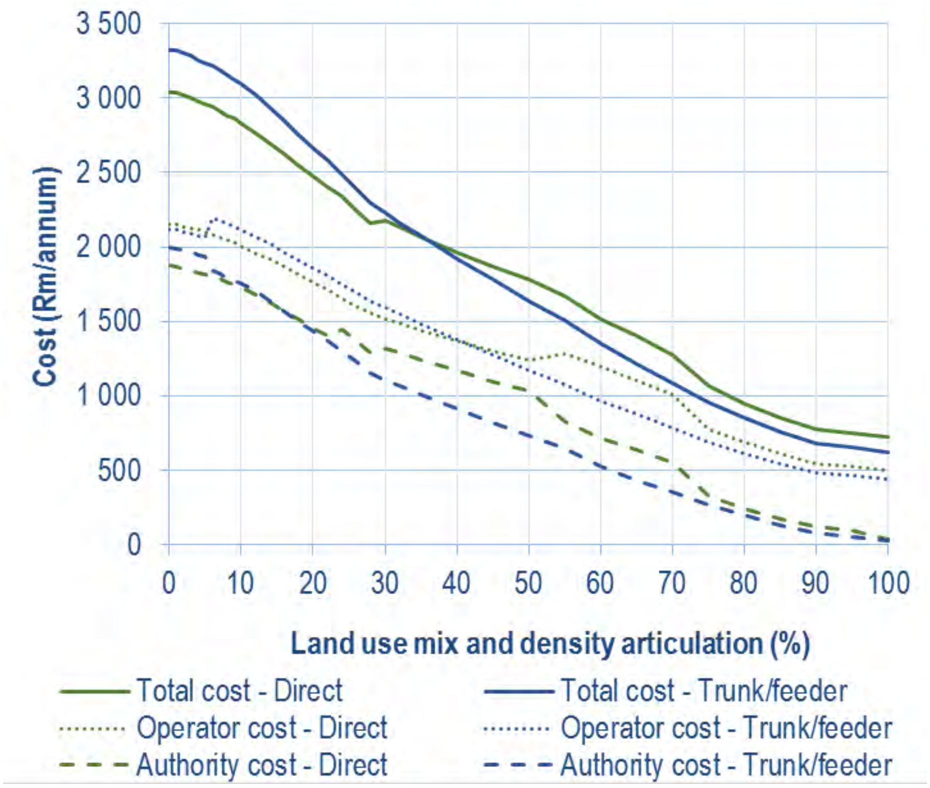

Figure 24: Cost components when varying land use mix and density articulation on a 20km corridor at 50 p/ha

In Figure 24, the magnitude of the effect to the cost components of both service configurations is larger than that of each individual land use characteristic. The total cost for the trunk-feeder and direct service models both decreased from above R3 billion annually to less than R1 billion. Additionally, the potential decrease in authority cost for the South African context could be from around R2 billion down to almost zero, across the test range. This is achieved at a relatively low corridor density of 50 p/ha and a trunk length of 20km. It demonstrates that, by leveraging the effects of just these two characteristics, even moderate population densities are not an absolute requirement to operate viable public transport systems.

In Figure 25, the peak passenger volume decreases in a very similar fashion to the land use mix scenario, reiterating a lack of significant effect by density articulation. However, the average trip length drops 74% over the test range, from 10.9 km to 2.8 km, highlighting one of the factors for which the land use characteristics complement each other. Based on the current fare data from Cape Town, the fare for the average trip by minibus would decrease from R14 to R6 due to the change in trip distance exhibited in this scenario. This would result in a saving of at least R4000 per annum for a daily commuter.

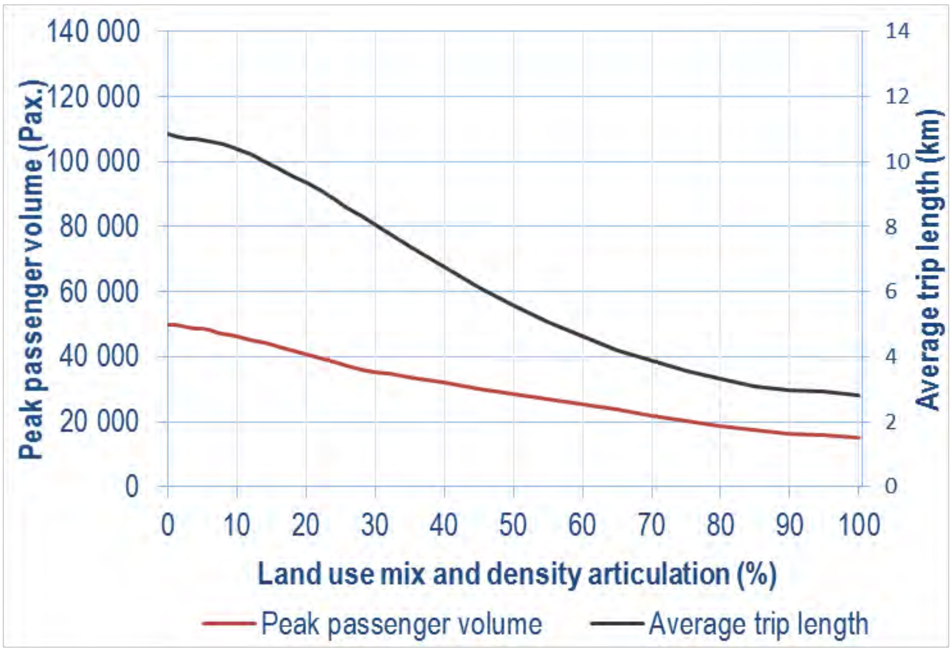

Figure 25: **Trip length and peak passenger demand when varying land use mix and density articulation on a 20km corridor**

At a density of 50 p/ha – substantially below the metropolitan density targets of three major South African cities – a land use mix and density articulation of at least 40% is required just to bring the peak passenger volume under the maximum capacity limit of a full specification, spatially segregated BRT system. Thus, for a transport corridor of this size, densification policies in isolation will result in severe congestion and will not significantly improve the viability of the transport system. Furthermore, the peak passenger volume is also the barrier to increasing the public transport modal split by restricting population density to around 50 p/ha. The corridor trunk length of 20 km creates a very large catchment area which magnifies the problems of low land use mix. Reducing the corridor length and catchment area could begin to remove these barriers.

5.3.5 Destination accessibility

The principle of destination accessibility is often presented as either job accessibility or distance to the CBD. As land use mix is already accounting for the metric of job accessibility, focus was placed upon testing distance to the CBD. The indicator chosen to represent the characteristic is corridor length, which linearly increases a zone’s distance to the CBD as it increases. To test this indicator, the scenario halves the length of the corridor, which will also determine to what extent a smaller catchment area can allow a public transport system to sustain a higher population density, and the resulting effect on its viability. The trunk route length is 10 km and the catchment area is one third of the original, wherein the population density has been increased to 100 p/ha.

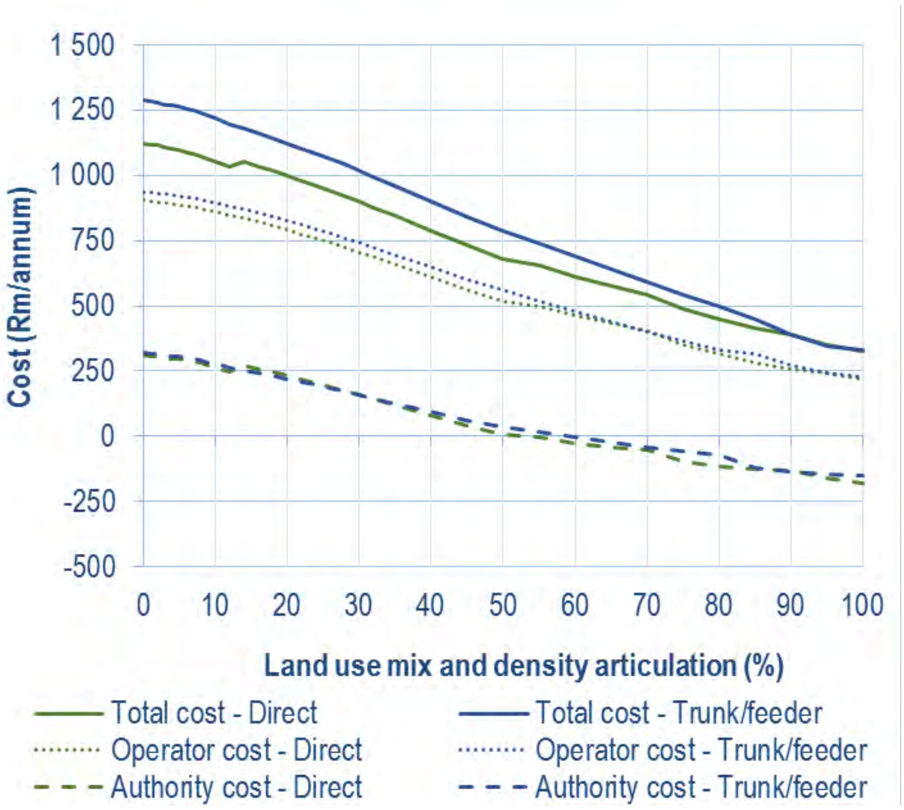

Figure 26: Cost components when varying land use mix and density articulation on a 10km corridor at 100 p/ha

As the width of the corridor was reduced in proportion to the decrease in its length, a higher percentage of the total area is now within the TOD zones. This means that the percentage of the catchment area that requires a feeder service decreases from 56% to 28%. As a result, the effect of leveraging density articulation to increase the gross population density of the TOD zones is greatly diminished. This is the reason for the slightly gentler decline in the cost components with increasing levels of density articulation and land use mix, seen in Figure 26.

When analysing the relationship between density articulation and catchment area it was noted that the South African urbanised city area densification targets are around 80 p/ha, and trunk corridor densification targets are around 200 p/ha (see Table 1). To achieve the 120 p/ha disparity in the two figures, even with a catchment area proportional to that of a 30 km corridor, a density articulation of at least 70% would be required. This assumes that the policy requirement of 85% coverage is upheld. A service similar to the one described would be unviable and generate demand well above the operating capacity of most public transport systems. A fine balance is needed between corridor catchment area, land use characteristics and public transport operating capacity.

Due to the triangular shape of the corridor catchment area, halving the corridor length and doubling population density means that the 10km scenario at 100 p/ha has two-thirds of the catchment population that the 20km scenario has. However, as the public transport modal share is dependent upon population density, the average number of passenger trips served is actually 6% higher for the 10km scenario than the 20km scenario.

In Figure 26, the total cost of the public transport services decreases 74% and 71% for the trunk-feeder and direct service configurations respectively. Furthermore, in the South African context, the potential cost to the transport authority of the direct service system could reach zero at a land use mix and density articulation of approximately 55%, whereas under the same conditions the authority cost for the 20km corridor would be R827 million per annum. The same is true for the trunk-feeder service configuration at a land use mix and density articulation of approximately 60%. The authority costs of the two configurations converge toward the 100% density articulation and land use mix level at around R150 million profit per annum.

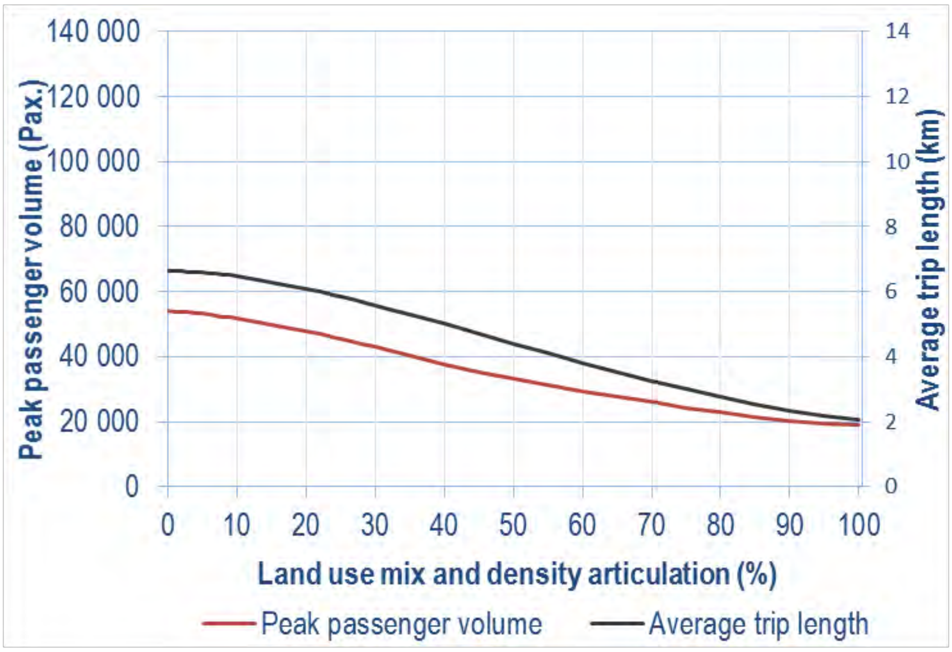

Figure 27: Trip length and peak passenger demand when land use mix and density articulation on a 10km corridor

As expected, due to the shorter corridor, Figure 27 illustrates that the average trip length is much lower than that of the previous scenarios. However, it still decreases by 69% to 2 km across the range of the indicator, showing that the magnitude of the effect by the land use characteristics is not dependent on corridor size. Despite the higher average population density, the peak passenger volume decreases 65% over the test range and descends to within the operating capacity of range South African BRT at 45% land use mix and density articulation.

5.4 Public transport network features

In the public transport network feature scenarios, further analysis is performed with the specific aim of investigating the effect that mode technology choice and service configuration choice have on public transport viability under different conditions. The viability of the six public transport modes will be evaluated for trunk, feeder and direct services under generic South African land use conditions as well as a scenario with a far more supportive land use environment.

Preceding studies have drawn many connections between the prevailing land use conditions and the appropriateness of public transport network features. Each public transport mode is posited to have a threshold population density dependent upon its operating costs and the fare prices it can justify. Smaller, more demand responsive vehicles are suggested to be better suited to unsupportive land use environments, while larger, more capital intensive systems require intensive TOD to remain viable. These theories, derived from empirical studies, will be critically compared against the results of the corridor cost model to help establish the underpinnings of these relationships and generate a clearer image of their direct effects.

Throughout the scenarios, the mode with the lowest total cost for each set of land use characteristics is chosen. In each simulation, the trunk, feeder, trunk direct and non-trunk direct services each have a separate mode chosen on this basis. Therefore, in both of the following scenarios, four analyses have been conducted, representing the two mode choices made by each of the service configuration models. The total cost per passenger trip segment is represented for every public transport mode at each value of population density, until the peak passenger volume surpasses the mode's capacity limit.

5.4.1 Trunk-feeder service configuration

The first scenario to be analysed is the original population density scenario described in Section 5.3.1 and illustrated in Figure 15. Figure 28 illustrates the average total cost, per trunk service passenger trip segment, by public transport mode for the trunk-feeder service configuration. The cost components in Figure 28 and Figure 17 are not identical as the average total cost per passenger trip represents multiple trip segments, including feeder and park-and-ride segments related to the unserved zones. The viability of the service improves with increasing population density for most transport modes in both the trunk and feeder services. In this generic South African scenario, the viability of each trunk service mode does not change significantly after a population density of 50 p/ha is reached. At population densities of less than 20 p/ha, the capital costs of vehicles, stations and other associated infrastructure result in a very high cost per passenger trip for most modes. The exceptions, minibus and conventional bus, can utilize existing roadways and require very little additional infrastructure. The total cost of these two modes increases initially as the major infrastructure investments are demand dependent. Between 18 and 25 p/ha, the capacity of articulated buses overcomes their capital vehicle cost, and makes them the most viable trunk service mode under these land use conditions. Beyond 25 p/ha, the demand on the trunk service warrants the space priority that the articulated buses in a BRT system are given. Due to the inefficient structure of a generic South African public transport corridor, the capacity limit of BRT is reached at a relatively low population density of 65 p/ha. At higher densities, suburban rail is the only viable public transport mode for the trunk service, irrespective of its higher cost.

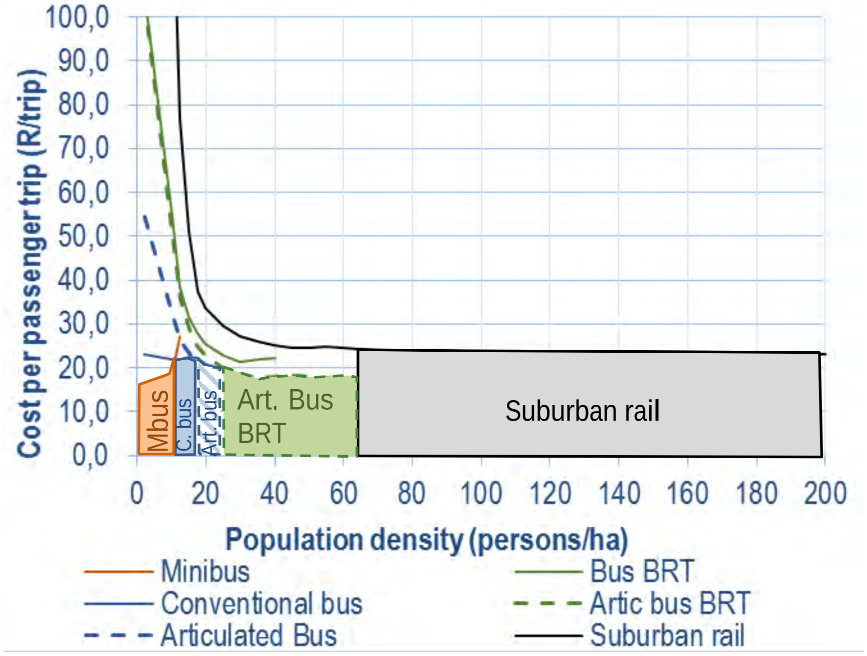

Figure 28: Effect of population density on the total cost of different modes for the trunk component of a feeder-trunk public transport system along a 20km corridor under generic South African land use conditions

Figure 29 illustrates that a higher population density is required for the feeder service modes to overcome their initial capital costs, and reach the minimum cost per passenger trip segment, than those of the trunk service. This is due to feeder services requiring similar levels of infrastructure to trunk services for each mode to operate despite lower levels of demand at each value of population density. Even the minibus mode shows an initial improvement as its minimal required capital investments are utilized more productively. However, the lower levels of demand also stave off the demand dependent infrastructure investments, making minibus the most viable feeder service mode, in this case, for all densities lower than 40 p/ha. After this, conventional bus is the preferred mode at values of up to 80 p/ha and the two BRT modes are preferred beyond this. However, Bus BRT then reaches its volume capacity limit at a population density of 180 p/ha.

Despite the positive relationship between population density and viability for most individual public transport modes, the cost per passenger trip segment of each mode plateaus at relatively high rates and at moderate levels of density. This is due to the inherent inefficiency in the structure of a generic South African transport corridor. The low levels of seat turnover and bidirectional flow, as well as the length of the corridor, prevent an affordable fare from ever covering the marginal operating cost, even at high population densities. Therefore, the average additional trip or increase in population density would be detrimental to the financial health of a public transport system under these conditions. This finding is contrary to the fundamental belief in the literature that public transport viability can improve through the economies of scale.

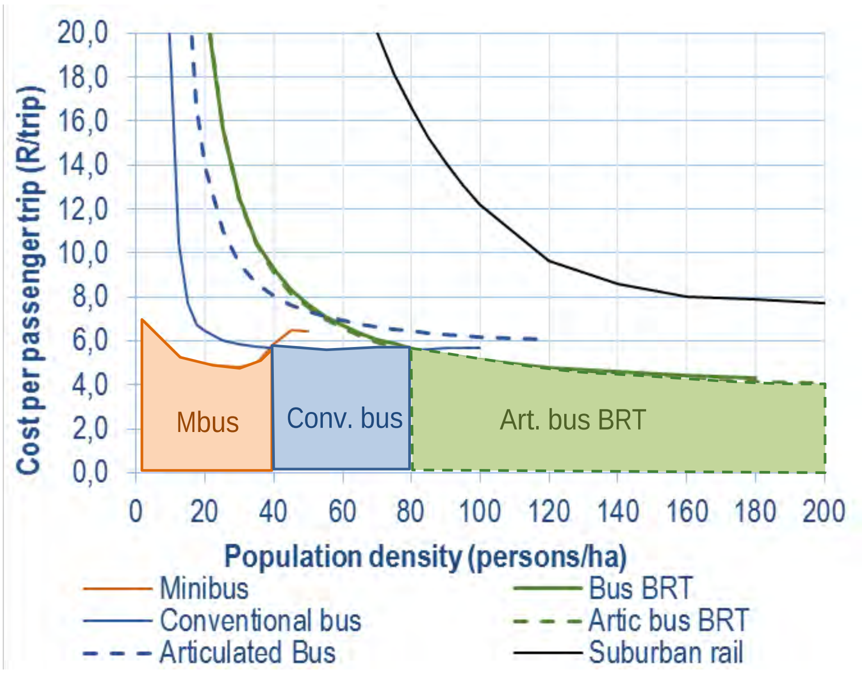

Figure 29: Effect of population density on the total cost of different modes for the feeder component of a feeder-trunk public transport system along a 20km corridor under generic South African land use conditions

The second scenario analysed is one that is very public transport supportive and a possible goal for South African public transport corridors. The corridor length has been reduced from 20km to 10km, and the density articulation and land use mix have been set to 80%. This scenario examines how each public transport mode is affected by a more supportive operating environment.

Figure 30 illustrates the total cost per passenger trip segment of a trunk service with different modes at a range of population densities. The population density at which each mode reaches its volume capacity limit is significantly higher than the previous scenario due to the more efficient passenger flow pattern decreasing congestion on the trunk route. At very low densities, the minibus mode can utilize the existing infrastructure to maintain low costs per passenger trip. However, the additional facilities required to meet the rising demand increases the costs as population density increases. Though, the minibus can maintain the lowest cost per passenger trip segment up until a population density of 20 p/ha, almost double the value of the previous scenario. This is due to the smaller catchment area and bi-directional flow of the mixed land use containing the peak passenger volume within its optimal operational limits.

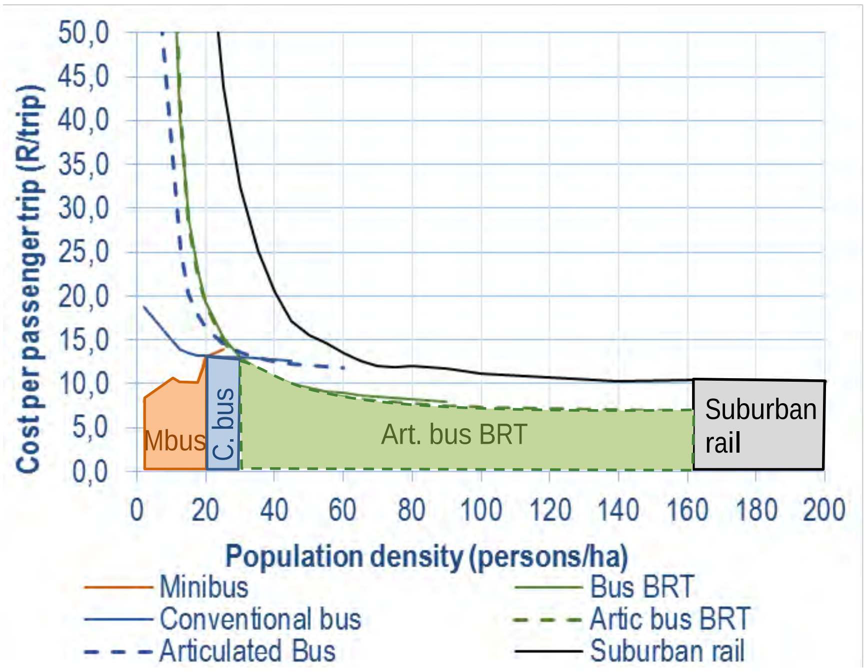

Figure 30: Effect of population density on the total cost of different modes for the trunk component of a feeder-trunk public transport system along a 10km corridor with 80% density articulation and 80% land use mix

An interesting note is the convergence of the larger bus modes at higher densities. In the first scenario, Figure 28, when the volume capacity limits are set aside, the conventional bus and bus BRT modes converge to a similar cost per passenger trip segment. The same convergence is seen between the conventional and BRT articulated bus modes. It suggests that in an unsupportive land use environment, with a long corridor, the size and efficiency of the vehicle plays a more significant role. Whereas, in Figure 30, the two conventional bus modes converge, as do the two BRT modes. This suggests that in a more supportive land use environment with a shorter corridor, the speed and productivity of the segregated lanes make a larger impact. Additionally, the supportive land use environment allows the articulated bus BRT mode to operate at more than twice the density of the previous scenario.

The feeder service in Figure 30 requires even higher population densities to overcome the initial capital costs related to operating the service. The shorter corridor length reduces the proportion of the catchment area requiring feeders and the high level of density articulation places very few OD pairs within the non-TOD area. The result is low levels of passenger demand on the feeder services, even at high levels of population density. The low demand makes the minibus mode appropriate at densities as high as 70 p/ha and explains the relatively high levels of population density required by the other modes to be competitive.

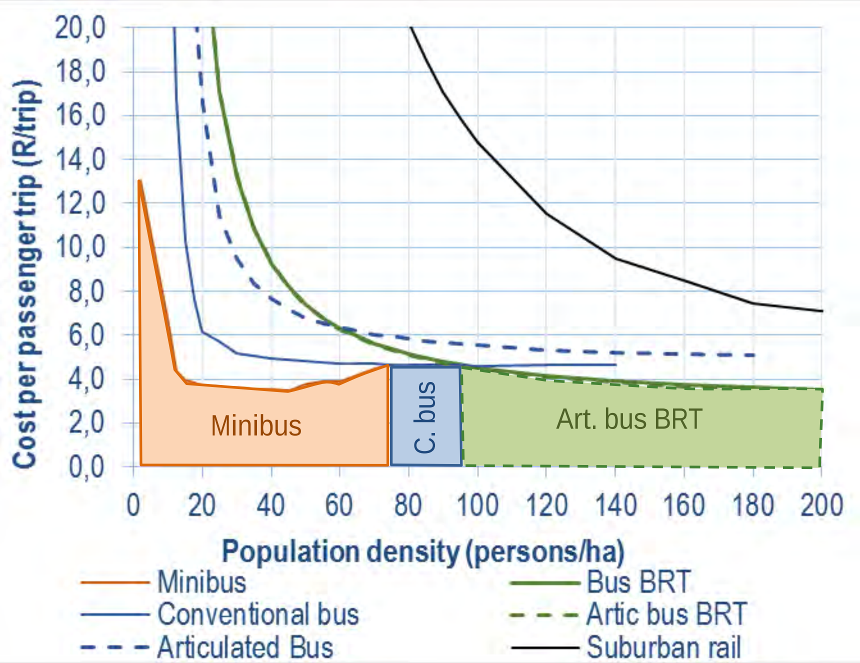

Figure 31: Effect of population density on the total cost of different modes for the feeder component of a feeder-trunk public transport system along a 10km corridor with 80% density articulation and 80% land use mix

5.4.2 Direct service configuration

The same two scenarios were tested in the direct service model. Only the non-trunk direct services have been analysed as the trunk direct service just meets the shortfall between their capacity and the demand along the trunk route. Thus, the demand on the trunk direct service is inconsistent and the mode choice is not significantly dependent on the surrounding land use conditions.

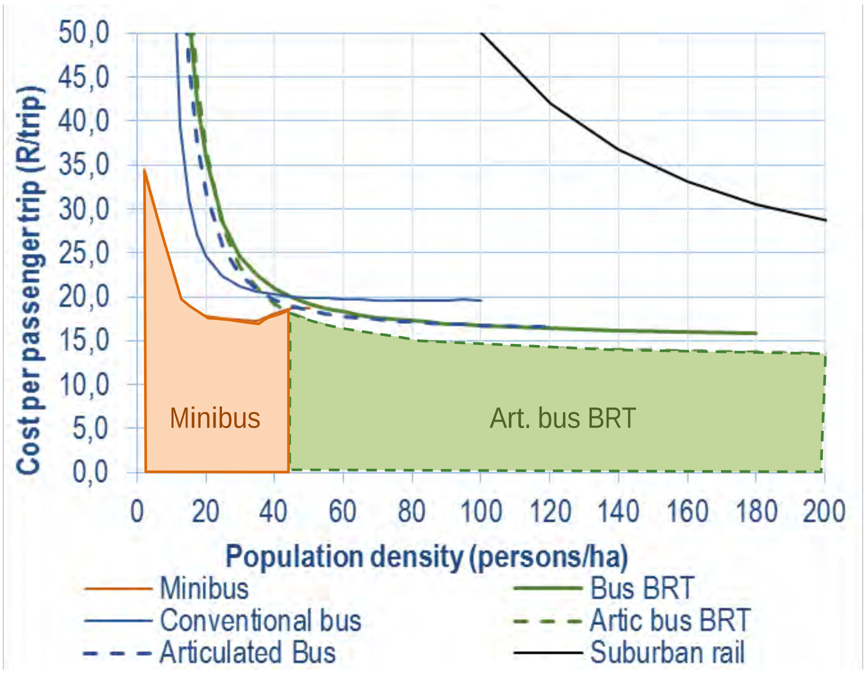

Figure 32: Effect of population density on the total cost of different modes for the non-trunk direct services of a direct public transport system along a 20km corridor under generic South African land use conditions

The analysis of the generic South African corridor scenario shows dominance, in terms of viability, of the minibus mode for a larger range of population densities. The minibus is the financially preferred mode up to 45 p/ha. Above this density, the long corridor and unsupportive land use environment, again, favours the size and efficiency of the articulated BRT bus form. Similarly, the articulated conventional bus is significantly more viable than its unarticulated counterpart. However, a dissimilarity to the trunk-feeder service configuration is the absence of the competitiveness of the suburban rail mode. The immense infrastructure requirements of rail cannot be justified on any of the longer direct service routes, even when leveraging the economies of scale.

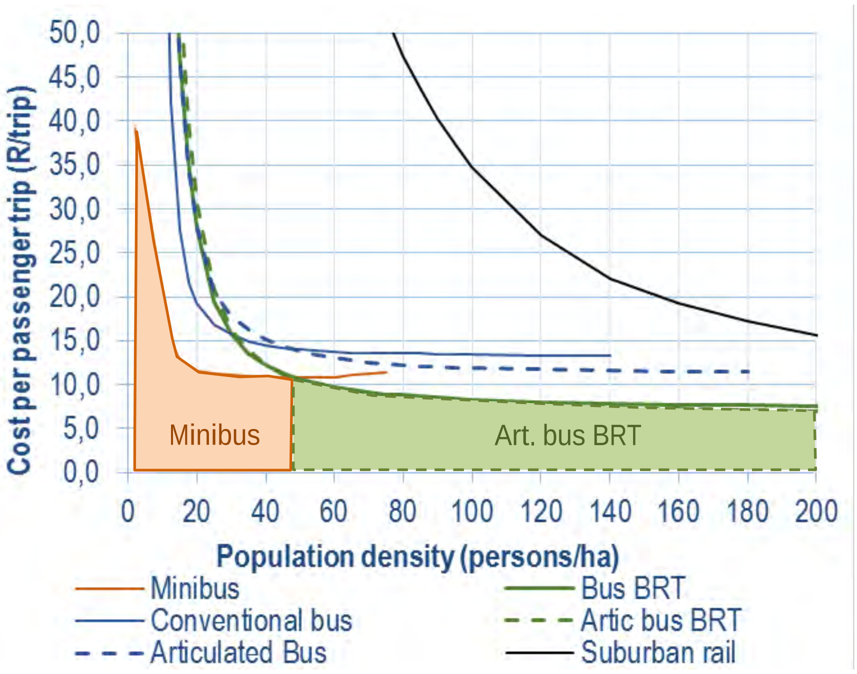

Figure 33: Effect of population density on the total cost of different modes for the non-trunk direct services of a direct public transport system along a 10km corridor with 80% density articulation and 80% land use mix

The second scenario in the direct service model is significantly more viable for each of the public transport modes. In similarity to the previous scenario, the cost effectiveness of the minibus mode is only surpassed by the articulated BRT mode at a population density of 45 p/ha. However, in contrast, the conventional BRT bus mode is equally competitive, reiterating the suitability of space priority in public transport supportive land use environments.

5.5 Summary and conclusion

This chapter illustrated and discussed the most relevant and significant results of the study in relation to the set objectives. The effects of population density, density articulation, land use mix and destination accessibility on public transport service viability were analysed in isolation of each other. Population density was found to have the weakest direct relationship with viability, but retained a strong influence on public transport ridership. Density distribution, through the suggested indicator of density articulation, was shown to have a very significant effect on the average passenger trip length, and viability as a result. Bicycle-based density articulation appears to have considerable benefits over the conventional pedestrian-based form, halving costs in some cases. Land use mix affected the average passenger trip length and, to a higher degree, the peak passenger volume, which, in turn, produced a strong connection to public transport viability. Finally, destination accessibility, through the indicator of corridor length, has illustrated a substantial influence on profitability and affordability, especially in the context of a distance-based fare system.

Passenger volume is the key determinant of mode technology choice and is influenced by population density, as well as the other three land use characteristics to a lesser degree. Low densities favour smaller vehicles, while economies of scale promote the use of suburban rail and other capital intensive modes. Long corridors and unsupportive land use environments favour the efficiency of larger vehicles, such as the conventional and BRT articulated buses. Whereas, short corridors and supportive land use environments favour the increased speed and productivity of the space priority that the BRT modes possess. On average, the costs related to the trunk-feeder and direct service configurations are very similar. It is only the distribution of density that has a significant influence on the choice of configuration. Higher proportional demand along the public transport corridor favours the trunk-feeder service configuration, and higher demand on the periphery of the corridor favours the direct service configuration.

6 Conclusion

6.1 Introduction

The primary aim of this study was to investigate the relationships between land use characteristics, network features and viable public transport services at a corridor scale. The study intended to use the South African context as a stage for the investigation in order to draw recommendations from the results for the South African policy environment.

The first objective of the study was to investigate the effect of population density, density distribution, land use mix and destination accessibility on public transport viability when analysed in isolation of each other. The second was to identify any financially complementary relationships that exist between these four land use characteristics and any occurrence of discordance. The third objective sought to ascertain to what extent the choice of mode technology and service configuration affects the viability of a public transport service under different land use conditions, and to verify if these choices influence each other when optimising the system to minimise costs and subsidies. The fourth objective was to explore how this integration of land use and public transport at the corridor level would affect metropolitan planning policies, in South Africa and abroad. The final objective was to determine a set of land use characteristics and network features that could produce viable public transport in a generic South African context.

The following section will contain the conclusions that can be drawn from the results on the relationships. Then, a discussion on the implications of these conclusions for South African and international metropolitan planning policies. Finally, gaps in the literature and the results of this study will be identified for which further study is needed.

6.2 The relationships between land use characteristics, network features and viable public transport services

Based on a review of the available literature, it is believed that this study is one of the first to examine the effect of land use characteristics and network features on a public transport system simultaneously, allowing interdependent effects to be examined. The land use-public transport viability literature is heavily dominated by gross population density in studies, targets and data. An analysis of secondary data revealed a strong correlation between population density and some of the indicators of public transport viability. This analysis echoed the results of a majority of the studies, which tended also to be empirically based. However, the existence of outliers such as Curitiba, Brazil brought into question whether the relationship was in fact causal or just a strong correlation. The analysis also highlighted the disparity between the South African national transport objectives and the metropolitan land use targets.

The design and integration of land use and public transport at the corridor scale is suggested as a possible solution to this disparity.

The four land use characteristics were tested against public transport viability in a corridor operating cost model, in isolation of each other. In the population density scenario simulations, very little effect on the viability of the public transport system was observed when all other variables were held constant. Even when accounting for the unusual South African urban context, this contradicts many of the empirical studies done on the relationship. Unlike in this simulation, the varying corridor catchment areas and density distribution patterns of the comparable cities, in the empirical studies, are not accounted for. This attributes some of the effects of destination accessibility and density articulation to population density. Therefore, the majority of the effects on viability seem to be correlated with population density but not caused by it. Population density as an isolated characteristic seems to be a poor indicator of public transport viability, especially in the South African context.

Density articulation appears to have a much stronger relationship with public transport viability. Small improvements in density articulation could have substantial positive impacts on public transport operations, even at low urban gross population densities. The substantial effects of density articulation on average passenger trip length would also positively affect affordability for systems with distance-based fares. Achieving higher population density would magnify the effect of density articulation even further. However, this is predominantly true for large catchment areas, where density itself is limited by the operational capacity of the public transport service. In smaller catchment areas, where the TOD zones make up a majority of the entire corridor, density articulation becomes less effective as a measure of viability. This highlights an inherent inverse relationship between the level of density articulation and corridor length. Bicycle-based TOD (B-TOD) also inherently increases the level of density articulation due to the proportion of the corridor covered by TOD being dramatically increased. Consequently, the positive effects of an increased trunk service station influence area can halve the public transport costs in some cases, without changing the land use environment.

The results of the land use mix scenario simulations for the South African context mirror the effects on trip length and passenger flow posited by the literature. All of the factors contribute to a strong relationship between land use mix and the viability of the public transport system, as well as for the transport authority and for smaller operators. Density articulation and land use mix are directly complementary through their significant effects on average passenger trip length and peak passenger volume respectively. Even at low population densities, their complementarity has the potential to create a viable public transport system. Therefore, these two land use characteristics are fundamental to creating meaningful TOD and a supportive land use environment.

Destination accessibility, through the indicator of corridor length, is found to have a very significant impact on public transport viability. This is a worrying observation for South African cities, whose legacy of Apartheid city planning has created some of the highest average public transport trip lengths in the world. Reducing the size of the catchment area allows density to increase without the associated increase in peak passenger volume. Destination accessibility, through the indicator of corridor length, has a complementary relationship with population density and land use mix, as well as naturally increasing the level of density articulation due to its impact on catchment area.

The appropriate choice of mode technology appears to be largely dependent upon the service configuration and supportiveness of the land use environment. Population density does appear to be the strongest determinant of mode choice preference but, as stated, density articulation; land use mix and corridor length govern the viability of the modes. At low population densities, the minimal capital requirements of the minibus and conventional bus modes take preference, especially if no additional facilities are necessary. As more infrastructure and capital investment is required by each successive mode, a proportionally higher population density is needed for them to become the most viable option. Therefore, density thresholds, including those in the literature, are only reference guides to mode suitability and not targets for viability as has been suggested. Within the bus modes, it was noted that long, land use-unsupportive transport corridors favour the larger, more efficient articulated vehicles while short, supportive corridors favour the speed and productivity of BRT’s segregated lanes. This theory is in direct conflict with the current plans of South African cities to provide dedicated BRT infrastructure on some 30-40km trunk service routes.

6.3 Policy implications and recommendations

The study has drawn some interesting connections between land use characteristics, public transport network features and service viability at the corridor scale. The first implication for policy is the identification of a disparity between South African national transport objectives and metropolitan land use targets. The importance of the public transport corridor for land use-transport integration shows the need for a fundamental understanding of the corridor level land use-transport relationships and their unique connections in each major public transport corridor.

The study has highlighted the dominance of gross population density in this field of research and the problems with placing it at the core of a land use policy. The prominent empirical density thresholds that have influenced densification targets and policies in developing cities may not be relevant to their urban contexts. Without due consideration for the other measures of land use supportiveness, density targets could lead to negative impacts on viability if densification occurs in an unsustainable manner. Density articulation and land use mix targets, which are currently lacking for developing cities, would directly improve the financial sustainability of the public transport systems within the areas for which they are met. However, the density articulation targets are dependent upon the corridor catchment area and the proportion of that area that falls within the Station Influence Area (SIA) of its trunk service stations. The population density targets are also dependent on the catchment area, as well as the passenger volume capacity limit of the public transport service. This means that the planning and policy focus needs to change, depending on the characteristics of the corridor. Therefore, it is suggested that a detailed land use development plan is created for each major public transport corridor, with unique targets for population density, density articulation and land use mix. Efforts to reduce the length of the public transport corridor and increase the SIA of the trunk service stations could then be integrated into the adaptable land use targets.

The choice of mode technology should also reflect the nature of the land use environment within the corridor and be cognisant of how its suitability will change as the land use targets are achieved. The choice over service configuration seems to be more complex. For South African transport authorities it will be accompanied by further important questions: Would a marginal gain in viability associated with trunk-feeder services be worth the risk of pricing smaller, poorer operators out of the market? Can the smaller operators be amalgamated and supported to competitively compete for larger trunk service operating contracts?

At the very least, the policy environment should now be aware that to achieve a high public transport modal split and sustainable public transport service requires high densities, high articulation, mixed land uses, small catchment areas and minimal feeder services.

6.4 Avenues of further study

Many important questions arose during this investigation that were beyond the scope of this study or were not sufficiently answered by the results. A key area of further study will be a more detailed analysis of the correlation and causation relationships that density shares with public transport viability. Additionally, a further investigation is needed to refine and empirically apply the density articulation metric to cement its place as a relevant indicator for public transport viability and the supportiveness of the land use environment. Part of the investigation should seek to incorporate employment density into the density articulation metric and understand its significance. There may be potential to combine the metrics of population density, employment density and density articulation to create a more descriptive indicator for public transport viability.

One of the key avenues of investigation, especially for South African cities, that the study was unable to incorporate within its scope was the effect of land use characteristics on the temporal variability of public transport service viability. An investigation of this topic would seek to understand the impact that each land use characteristic has on a public transport service's temporal demand profile and, more broadly, its peak-to-base ratios.

A further indicator that would have improved the study is the addition of travel time to estimate a user's generalized cost in order to determine the trade-off between viability and user experience under different land use conditions. Expanding user cost beyond affordability to encapsulate user experience would give more nuanced and contextualised results.

The study has also failed to garner sufficient insight into the service configuration decision to give recommendations based on the nature of the local land use environment. Additionally, how the decision would be affected by other network decisions such as the establishment of a paratransit–public transport hybrid structure needs to be investigated.

Finally, to understand the land use-transport connection in a more detailed and contextualised manner, the model would need to move toward case study analyses based on empirical data. A case study analysis would inherently require a more complex version of the model, capable of representing realistic traffic analysis and Transit Oriented Development zones rather that rectangular approximations. A Geographic Information System (GIS) overlay to the model would significantly increase the accuracy of the potential effects of land use characteristics on the financial viability of the public transport services. Furthermore, the scale of the operating cost model being a public transport corridor was very useful in simplifying its complexity and focussing on the fundamentals of the relationships. However, a case study would benefit from a metropolitan-scale analysis due to the unique interconnections between different public transport corridors within a city. Empirical data would be required for each of the land use characteristics, per traffic analysis zone, in order to approximate the status quo. The most recent data for the operating and capital costs of each public transport mode would be necessary, and estimations for any modes that are not yet in use. Similar data is necessary for the fare structure of each mode, and estimations on how that structure may change due to changes in the level of public transport provision. A full case study, at the metropolitan scale, in one of South Africa’s cities, is the logical continuation of this research to deepen the understanding of land use and transport relationships in the context of developing cities.

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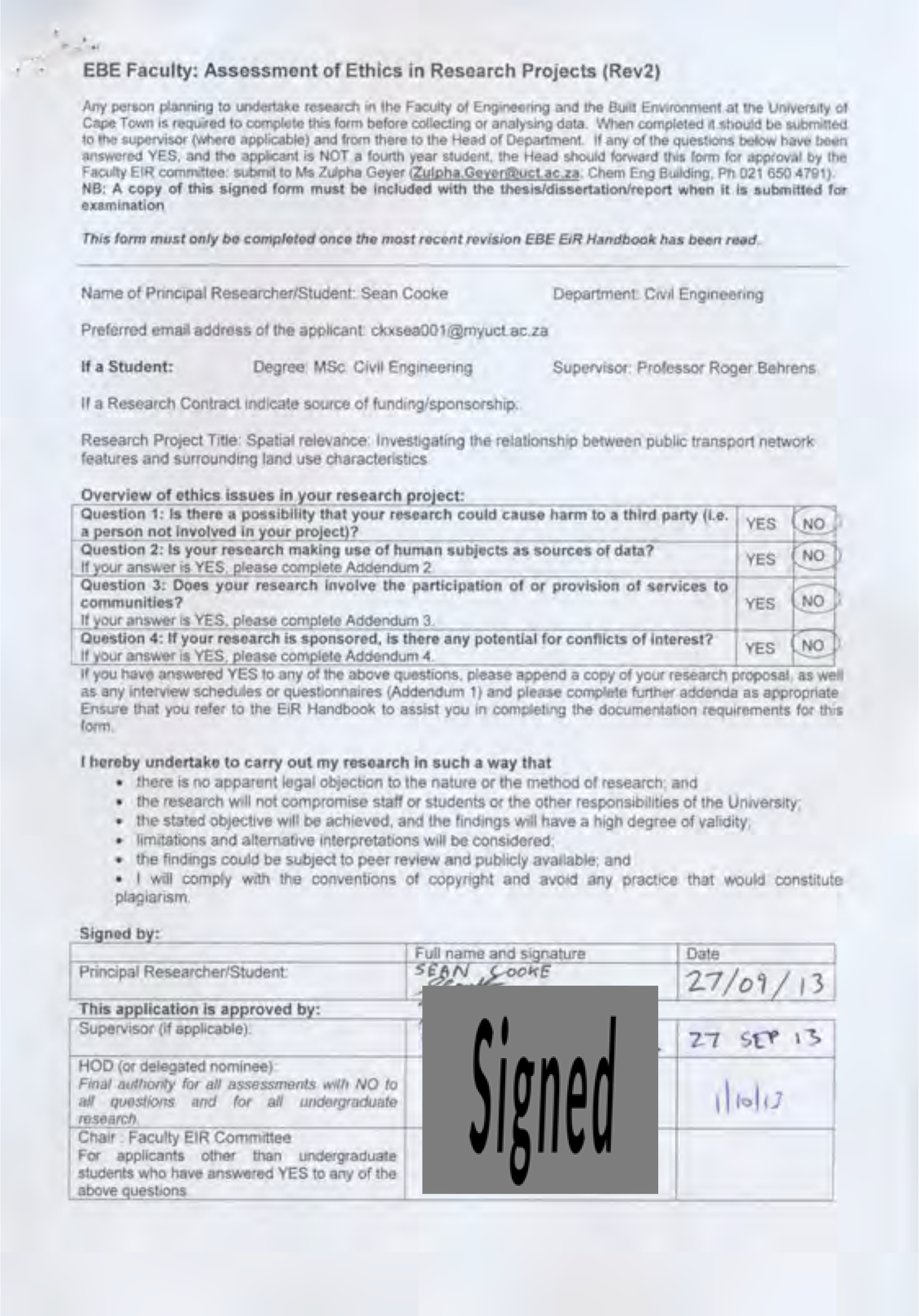
8 Appendices

8.1 Appendix A: Ethics clearance



EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).
NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination

This form must only be completed once the most recent revision EBE EiR Handbook has been read.

Name of Principal Researcher/Student: Sean Cooke   Department: Civil Engineering

Preferred email address of the applicant: ckxsea001@myuct.ac.za

If a Student: Degree: MSc. Civil Engineering   Supervisor: Professor Roger Behrens

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Spatial relevance: Investigating the relationship between public transport network features and surrounding land use characteristics

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	[✓ NO]
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	[✓ NO]
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	[✓ NO]
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	[✓ NO]

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EiR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	SEAN COOKE	27/09/13

This application is approved by:

Supervisor (if applicable):	Signed	27 SEP 13
HOD (or delegated nominee): *Final authority for all assessments with NO to all questions and for all undergraduate research.*		1/10/13
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions		