A Proof of Concept Investigating the Support of Densification through the Planning and Implementation of Road Infrastructure in the South African Context

by
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Declaration

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Dedication

This thesis is dedicated to my parents (Mr and Mrs Govender), my supervisor (Professor Marion Sinclair), mentor (Mr Alan Robinson) and family and friends who provided me with support and guidance throughout my academic career.

Abstract

In recent decades, the metropolitan areas of Johannesburg and Pretoria in South Africa have expanded rapidly. It is expected that the trend will continue in the future. Planning and implementation of road infrastructure, controlling urban sprawl, compact city layouts, jobs-housing balance, mobility in around urban areas and the viability and efficiency of public transport systems within and around regions have been an ongoing concern for transportation planners. These elements are inter-dependent and form the principles in creating a compact city. With ongoing refinements, they can eventually be the key to achieving "The Future City". The "Future City" concept, currently being developed in Europe (for example Barcelona Superblocks) enshrines the concept of "live, work and play" in areas within proximity of each other. Although urban design paradigms are shifting, it is argued that approaches to strategic transportation planning can facilitate the Future City by ensuring shorter trip lengths, higher gross-population densities in cities and efficient public transport systems are achieved. The aim of this study is to develop a proof of concept to investigate the support of densification through the planning and implementation of road infrastructure in the South African context. A linking idea to this concept tests the question of "Are we spending our road infrastructure budget correctly?". The main outcomes of this study are:

- A set of synthesized deterrence functions for trips on the Gauteng Freeway Improvement Project (GFIP) road network;
- Graphical representations of congestion on the GFIP road infrastructure resulting from the assignment of the different synthesized deterrence functions;
- Resulting trip lengths and trip times from the assignment of each synthesized deterrence function to the GFIP network; and
- Economic Benefit/Disbenefit in terms of travel time for the base year and design year per scenario tested.

The objective of this study is to demonstrate that shorter trips and densification can be supported through the planning and implementation of road infrastructure, which can in turn promote the viability of the Future Cities concept.

The research methodology estimates the deterrence function for the existing trip distribution on the GFIP network and uses that function to develop synthesized deterrence functions to test various trip distribution scenarios. Synthesized trip matrices, produced from each synthesized deterrence function, were assigned to the GFIP road network to obtain comparable trip lengths, travel times and congestion levels. All transport modelling was completed using the Simulation and Assignment of Traffic in Urban Road Networks (SATURN) software. A brief economic study relating to the economic benefit/disbenefit in terms of travel time was completed for each scenario to determine the optimal solution.

The results from this study demonstrate that intelligent planning of road infrastructure can achieve the following:

- Reduced urban sprawl;
- Altered driver behaviour in terms of route choice and trip lengths;
- Better managed regional expansion;
- Increased residential density and mixed-use areas which are supported by an efficient public transport system;
- Smaller road infrastructure budgets; and
- An improved social experience of urban living.

The study has resonance for all cities where urban sprawl is seemingly unstoppable.

Word Count: *496*

Keywords—Compact Cities, Densification, Road Infrastructure Planning, Transportation Modelling

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Opsomming

In Suid-Afrika, het die metropolitaanse gebiede van Johannesburg en Pretoria vinnig gegroei oor die afgelope dekades. Na verwagting sal hierdie neiging voortduur in die toekoms. Die beplanning en implementering van padinfrastruktuur, gekontrolleerde stedelike verspreiding, kompakte stedelike uitlegte, balans tussen werkgeleenthede en behuising, mobiliteit in stedelike gebiede en die lewensvatbaarheid en doeltreffendheid van openbare vervoerstelsels in en rondom streke, is 'n deurlopende bekommernis vir vervoerbeplanners. Hierdie elemente is onderling afhanklik en vorm die beginsels vir die skepping van kompakte stede. Die voortdurende verfyning van hierdie elemente, kan uiteindelik lei tot die sleutel vir die bewerkstelling van “The Future City”. Die "Future City" konsep, wat tans in Europa ontwikkel word (byvoorbeeld Barcelona Superblocks), omskryf die konsep van "live, work and play" in gebiede wat naby mekaar geleë is. Alhoewel stedelike ontwerpparadigmas verander, word dit aangevoer dat benaderings tot strategiese vervoerbeplanning die “Future City” kan ondersteun deur korter reislengtes, hoër bruto bevolkingsdigthede in stede en doeltreffende openbare vervoerstelsels te verseker. Die doel van hierdie studie is om 'n bewys van konsep te ontwikkel tot die ondersteuning van verdigting deur die beplanning en implementering van padinfrastruktuur in die Suid-Afrikaanse konteks te ondersoek. Die skakelidee van hierdie konsep toets die vraag: "Bestee ons, ons padinfrastruktuurbegroting optimaal?". Die kern uitkomstes van hierdie studie sluit in:

- 'n Stel gesintetiseerde afskrikfunksies vir reise op die “Gauteng Freeway Improvement Project (GFIP)” padnetwerk;
- Grafiese voorstellings van opeenhoping op die GFIP padinfrastruktuur as gevolg van die toewysing van die verskillende gesintetiseerde afskrikfunksies;
- Resulterende reislengtes en reistye vanaf die toewysing van elke gesintetiseerde afskrikfunksie aan die GFIP netwerk; en
- Ekonomiese voordeel / nadeel ten opsigte van die reistyd vir die basisjaar en die ontwerpjaar per toets.

Die doel van hierdie studie is om aan te toon dat korter reistye en stedelike verdigting ondersteun kan word deur die beplanning en implementering van padinfrastruktuur, wat op sy beurt die lewensvatbaarheid van die “Future Cities” konsep kan bevorder.

Die navorsingsmetodologie bepaal die afskrikfunksie vir die bestaande reisverspreiding op die GFIP netwerk en gebruik die funksie om gesintetiseerde afskrikfunksies te ontwikkel om verskillende reisverspreidingscenarios te toets. Gesintetiseerde ritmatrikse, ontwikkel uit elke gesintetiseerde afskrikfunksie, is aan die GFIP padnetwerk toegeken om vergelykbare

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reislengtes, reistye en opeenhopingsvlakke te bepaal. Alle vervoermodellering is uitgevoer met behulp van “Simulation and Assignment of Traffic in Urban Road Networks (SATURN)” sagteware. 'n Ekonomiese studie, rakende die ekonomiese voordeel / nadeel ten opsigte van reistye, is vir elke scenario uitgevoer om die optimale oplossing te bepaal.

Die resultate van hierdie studie toon dat intelligente beplanning van padinfrastruktuur die volgende kan bereik:

- Vermindering in stedelike verspreiding;
- Verandering in bestuurdergedrag ten opsigte van roete keuse en reislengte;
- Verbetering in streeksuitbreiding bestuur;
- Verhoogde woondigtheid en gemengde gebruiksareas wat ondersteun word deur 'n doeltreffende openbare vervoerstelsel;
- Kleiner padinfrastruktuurbegrotings; en
- 'n Verbeterde sosiale ervaring van stedelike lewe.

Die studie sal aanklank vind tot stede waar stedelike verspreiding oënskynlik onstuitbaar is.

Woordtelling: 472

Sleutelwoorde — Kompakte Stede, Verdigting, Padinfrastruktuurbeplanning, Vervoermodellering

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List of Abbreviations

CBD	Central Business District
COC	Central Operations Centre
CTO	Comprehensive Traffic Observation
GFIP	Gauteng Freeway Improvement Project
ID	Identity
IRR	Internal Rate of Return
Kph	Kilometers per hour
LG	Lane group
LUTI	Land Use Transport Interaction
MS-DOS	Microsoft Disk Operating System
NPV	Net Present Value
OD	Origin-destination
ORT	Open Road Tolling
pcu	Passenger Car Unit
PPP	Public Private Partnership
SANRAL	South African National Roads Agency (SOC) Limited
SATURN	Simulation and Assignment of Traffic in Urban Road Networks
TLFD	Trip Length Frequency Distribution
VDF	Volume Delay Function
VOC	Vehicle Operating Cost
VOT	Value of Time
Vph	Vehicles per hour

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1 Introduction and Background

1.1 Introduction

Despite research done by transportation planners and researchers such as Sieg, Landre, Cooke and Behrens, indicating that the jobs-housing balance in areas is important in achieving shorter trip lengths and more affordable transit costs, development trends still continue to expand away from city and economic centres. The consequence of this development trend is sprawl. Sprawl cities are categorized as those that have been developed and extended towards the outer limits of the city (Sieg and Landre, 1991). Sprawl can be explained simply as having "non-compact, scattered pockets of urban development which alternate with tracts of undeveloped land" (Sieg and Landre, 1991). Controlling urban sprawl has proven to be a challenge for many transportation planners around the world. According to Yusuf and Allopi*,* the majority of cities in South Africa are expanding through developments (housing, leisure and industrial land uses) beyond the existing urban periphery. This has also been highlighted by Sieg and Landre in their study, published in 1991, of the "*Measurement of Residential Sprawl in the Johannesburg Metropolitan Area"*. They have indicated through simulations of the Johannesburg metropolitan residential areas, that the occurrence of sprawl will decrease when the density of the city itself is increased.

Significant amounts of funding are required for transport infrastructure (Robinson, 2017). High mobility roads are a key example of road infrastructure pertaining to the South African context as well as this research project. The quality specifications of high mobility roads are very strict which means that the construction and maintenance costs for these roads are high (Robinson, 2017). The problem of having new developments located further from the periphery of the city is that longer high mobility roads will need to be constructed to connect these developments to the city centres (Cooke and Behrens, 2014). This in turn results in an increased cost in road infrastructure, public transport infrastructure, an increase in commuter costs, longer trip lengths and an increase in delay experienced by road users.

Albert Einstein once said: "The definition of insanity is doing the same thing over and over again but expecting different results". The manner in which transportation planning has been executed over the past decades confirms this statement. Despite the debates around land use patterns, the importance of jobs-housing balance, the importance of good integration of land use and road infrastructure, and the disadvantages of sprawl; new developments are still planned and located in areas far from city centres. As a result, these cities continue to expand outwards of the city periphery. Consequences, as mentioned earlier, include increased road infrastructure costs as well as increased public transport infrastructure costs, increased commuter costs, longer trip lengths and increased delays experiences by road users. The cycle continues. A comprehensive literature review, on various topics, was completed to gain an understanding of elements in transportation planning and to use the knowledge to identify elements used in transportation planning which prevent us from having the following:

- Shorter trip lengths to places of employment and leisure; and
- A viable and efficient public transport system.

The key findings were as follows:

- Spatial planning in South Africa is poor and has resulted in urban sprawl and an imbalance in jobs and housing. Therefore, people travel great distances for work purposes;
- Our cities have low gross population densities which affect the viability and efficiency of public transport systems;
- The combination of sprawl and low population densities make public transport very expensive to expand, operate and maintain; and
- Continuous expansion and upgrading of freeways only seem to be contributing to sprawl.

The proof of concept tested in this study uses the approach of adding a twist on how transport planning should be approached. The following questions were raised during the study and were tested in the technical section of the study.

- What would happen if we use the planning and implementation of road infrastructure as the driver of urban development?
- What would happen if we forced people to make shorter trips?
- Can we use the above-mentioned elements to support densification which in turn creates a conducive environment for public transport?

The proof of concept effectively proves that by improving the second order road network, through improving the capacity of the existing road network and by introducing infrastructure which encourages and supports public transport, we can encourage densification of cities. The hypothesis is that by improving the second order road network (which links onto the freeway system) developers and businesses will be attracted to the land zones near the improved road network, thereby developing the land zones accordingly. Improving the capacity of the lower order road network will mean that road users will make shorter trips as compared to those if they were to use the freeway. This in turn is predicted to attract people to live, work and play in these areas. This is a method of creating an environment which supports densification. Due to the costs of public transport as well as the costs involved in maintaining the service and reliability of public transport, public transport is popular for short trips. Hence, it is envisaged that the improvement to the second order road network and the densification of land use will produce an environment which is conducive to implementing an economically efficient public transport system.

The trips are estimated based on the generalized cost of travel between zones as well as the trips generated from and attracted to these zones (Robinson, 2017). This mathematical function which estimates trips based on generalized cost is the known as the deterrence function. In this research project the derivation of a deterrence function which mathematically estimates trips, in the origin destination (OD) matrix, based on generalised cost was completed. The importance of this function is to calibrate the trip distribution on the GFIP network.

Trip frequency and traffic flow data was used to develop a strategic transport model using the SATURN software for the Gauteng Freeway Improvement Project (GFIP) network to assess the behaviour of the distance-deterrence function derived for the trips on the GFIP network.

The overall aim of this study is to test a proof of concept to investigate the support of densification through the planning and implementation of road infrastructure in the South African Context.

1.2 Background

In recent decades, the metropolitan areas and surrounding regions, in Gauteng, have been expanding rapidly. Looking at the increase in young professionals and interests expressed by developers in developing available land it is expected that the trend in growth will continue in the future. Careful consideration should be given to the strategic planning and transportation modelling for the future expansion of Gauteng which handles this rapid growth and resulting increase in population.

Planning and implementation of road infrastructure, controlling urban sprawl, compact city layouts, jobs-housing balance, mobility in and around urban areas and the viability and efficiency of public transport systems within and around regions have been an ongoing concern for transportation planners. These elements are inter-dependent on one another and form the principles in creating a compact city and with ongoing refinements can eventually be the key to achieving “The Future City”.

Strategic planning and transport modelling should be done based on achieving the above-mentioned elements thereby creating an environment which is conducive for the implementation of a viable and efficient public transport system.

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The development of a reliable strategic transport model depends primarily on the data inputted and the parameters of the model to reflect the current situation (e.g. current land use and traffic information). The fundamental model traditionally used in developing any strategic transport model is known as the Four Step Model. The four stages included in the model is trip generation, trip distribution, modal split and trip assignment. The trip distribution stage is complicated based on the nature of its behaviour. Trip distribution on a given network is affected by numerous variables such as the attractiveness of a route to a driver, presence toll fees on the route, time of day, route length and experienced travel time. A method of completing the trip distribution stage is through the application of the Gravity Model. The Gravity Model works similarly to Newton's theory of gravity. Deterrence functions (in the Gravity Model) will be used to reflect the spatial separation between zones (origins and destinations) which depicts people's actual trip behaviour when choosing their routes to their destinations based on trip length, time and cost of their journey. Deterrence functions play a key role in trip distribution within a study area through the simulation of trip lengths. Therefore, it is important that the deterrence functions used in any transport model is calibrated such that they correctly reflect the actual trip behaviour/distribution within the study area (Rasouli, 2018).

The aim of this study is to develop a proof of concept to investigate the support of densification through the planning and implementation of road infrastructure in the South African Context. A linking idea to this concept tests the question of "Are we spending our road infrastructure budget correctly?". The study firstly determines the deterrence function for the base year strategic transport model, based on information in the latest available land use and traffic data provided by The South African National Roads Agency Limited (SANRAL), and then generates various synthesized deterrence functions to test their effect on trip lengths and route choice on the Gauteng Freeway Improvement Project (GFIP) network. The main outcomes of this study will be the following:

- A set of deterrence functions for trips on GFIP;
- Graphical representations of congestion on the GFIP road infrastructure resulting from the assignment of the different deterrence functions;
- Resulting trip lengths and trip times from the assignment of each deterrence function to the GFIP network;
- A determination of the Economic Benefit/Disbenefit in terms of travel time for the base year and design year per scenario tested; and
- A simple Economic Evaluation Summary of the Economic Indicators (NPV, IRR) for each project alternative proposed.

For the development of suitable deterrence functions, two of the three forms of the deterrence functions were examined. There are the Exponential and Combined functions. The Gamma function was not examined due to the other two being sufficient for the nature and purpose of this study.

From the analysis of the functions mentioned above, it has been established that the Exponential function is the best suited in replicating the actual trip distribution on the GFIP network. This was determined through an extensive exercise which involved estimating suitable parameters for the deterrence function representing existing trips on the network. This exercise involved estimating parameters in a deterrence function which adjusted a synthesized curve until it matched the distribution curve for existing trips on the network. After this exercise was completed for both the Exponential and Combined functions, it was found that the Exponential function provided a better fit with the distribution curve for existing trips in the network. Therefore, the Exponential function is best suited for the generation of synthesized deterrence functions to test the proof of concept of this study.

As part of testing a proof of concept to investigate the support of densification through the planning and implementation of road infrastructure in the South African Context, a four-step strategic transport model has been developed for the GFIP network using the Simulation and Assignment of Traffic in Urban Road Networks (SATURN) software.

1.3 Methodology and Objectives of the Study

The study methodology will include the following actions:

- A literature review focusing on spatial, social, trip lengths and public transport aspects;
- The literature review will also focus on research done pertaining to the following aspects:
  - Urban Sprawl;
  - Types of City Layouts:
    - The Concept of Urban Spatial Structure and Associated Commuting Patterns
    - Urban Spatial Planning in South Africa (Gauteng)/Past Travel Patterns in Gauteng
    - The Concept of a Compact City
    - Jobs-Housing Balance
  - Requirements for Public Transport Implementation:
    - Relationship between Density and Trip Length
    - Population Density Requirements
    - Infrastructure Requirements

  - The Future City:
    - Features of The Future City
    - Barcelona Superblocks
    - Jewel City in the Johannesburg CBD

The purpose of completing an extensive literature of these topics is to investigate and understand elements in our transportation planning which prevent us from having shorter trip lengths to places of employment and leisure and a viable and efficient public transport system. The knowledge gained from the literature review informs the approach to developing the methodology to be used in testing the proof of concept in this study; i.e. A proof of concept investigating the support of densification through the planning and implementation of road infrastructure in the South African Context.

- A literature review of methods which will enable the achievement of the objective of this research project. The aspects which were research are as follows:
  - Integrated Transportation and Land Use Models;
  - The Four Step Modelling Process;
  - Deterrence Functions;
  - The Furness Method of Balancing Factors;
  - Trip Length Calibration; and
  - Origin-Destination (OD) Trip Matrix Estimation.
- Description of the process followed when updating the 2006 GFIP strategic transport model to the base year (2018) using 2018 land use and traffic data. The statistical component of this study is present in this section of the report;
- Estimation of parameters of the deterrence function to replicate trip distribution on the GFIP network for the base year (2018);
- Develop a methodology to develop synthesized distance-deterrence functions for trip reductions of 10%, 20%, 30% and 40%. Use the synthesized deterrence functions to produce synthesized trip (OD) matrices to test various trip distribution scenarios for the base year (2018) and design year (2038). Use the results to identify resulting road infrastructure upgrade requirements based on congestion levels from the assignment of each synthesized trip OD matrix;
- Repeat the assignment of each synthesized OD trip matrix to upgraded road networks on the GFIP road network:

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  - A scenario whereby the capacity of the second order road network, connecting to the freeways, are upgraded;
  - A scenario whereby the capacity of the freeways is upgraded.
  - Compare the differences in the trip lengths between the scenarios before and after the upgrade to the both road networks; and
  - Complete a simple economic study whereby the economic benefit/disbenefit in terms of travel time for the base year and design year per scenario are compared.
- Provide conclusions obtained from the research project and recommend areas in which further research can be undertaken.

1.4 Research Significance

The objective and nature of this research project is unique because it approaches the planning and implementation of road infrastructure from a different view point. This study focuses on investigating an approach to the planning and implementation of road infrastructure such that densification is supported. One of the key benefits of a densified environment is that drivers are able to make shorter trips on the given network.

This research project develops new knowledge through the application of the <u>proof of concept</u> which demonstrates a method of supporting densification through the planning and implementation of road infrastructure which promotes shorter trip lengths.

The development of a reliable transport model which easily replicates the current traffic patterns of the network is indispensable.

It has been shown that reliable transport models play an essential role in future planning of spatial development, the provision of road infrastructure and traffic management decisions for urban and rural development (Rasouli, 2018).

New knowledge developed through this research project is summarised as follows:

- A trip demand forecast is a critical component in transportation planning to evaluate the future road infrastructure needs for an urban or rural area.
- An efficient method or technique is required to predict and forecast future trip patterns such that accurate and economical road infrastructure planning and decisions can be anticipated and achieved.
- The ultimate outcome of this research study is to develop a distance-deterrence function for trips on the GFIP network. Thereafter the distance deterrence function will be used to

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determine infrastructure requirements as a result of shorter trip lengths. The shorter trip lengths will be achieved by altering the beta value in the deterrence function. It is envisaged that this concept will demonstrate a method of supporting densification through the planning and implementation of road infrastructure which promotes shorter trip lengths. This concept has not been researched or developed in the discipline of transportation planning before. It is intended that this research project can provide some insight to transportation planners regarding the planning and implementation of road infrastructure such that sprawl can be avoided; and instead an environment which supports densification is created. Densification, in turn, is conducive to the implementation of an affordable and economical public transport system.

- The distance-deterrence function developed in this research project contains the variables applicable to the GFIP network. The distance-deterrence function has been calibrated based on the latest traffic and land use information which has been used in the development of the strategic traffic model for the GFIP network.
- The results, conclusions and recommendations obtained through this research project can be used to assist future researchers in establishing strategic traffic models and in developing distance-deterrence functions to inform the planning and implementation of road infrastructure which supports densification and promotes shorter trip lengths in other areas of South Africa.

1.5 Thesis Structure

This research project comprises of the following chapters:

Chapter 1: Introduction and Background to the Research Project

This chapter contains the introduction and background to the research project. This chapter describes the objectives, methodology proposed to achieve these objectives and discusses the significance of this research project.

Chapter 2: Literature Review

This chapter focuses on discussing the findings from the literature published by previous researchers who researched topics related to the objective of this research project; i.e. to test a proof of concept which demonstrates a method of supporting densification through the planning and developing of a road infrastructure which promotes shorter trip lengths. Through the extensive literature review, it was found that there are is no literature which focuses on findings which directly tie in with the objective of this research project. It was therefore concluded that this research project brings in new knowledge which can contribute to and build on the existing

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industry knowledge regarding a concept which enables shorter trips and a densified environment through the effective planning and implementation of road infrastructure. Therefore, the approach to completing the literature review for this research project deviates from the conventional manner in which literature reviews are done for research projects; i.e. building on existing research. The method of completing the literature review for this research project instead focuses on extracting, from prior studies, the relevant components and pieces of information pertaining to aspects which contribute to building the proof concept used to achieve the research objective.

Chapter 3: Methods Essential in Developing and Testing the Proof of Concept

This chapter discusses the various concepts and methods which are essential in the development of the proof of concept. The essential components involved in the development of the proof of concept are as follows:

- Demand Models;
- Land Use Transport Models;
- The Four Step Modelling Process;
- Deterrence Functions;
- Trip Lengths;
- Trip Length Frequency Distribution Functions; and
- Origin-Destination Trip Estimation.

Chapter 4: Data Collection for Model Inputs

In this chapter the input parameters and information used to develop the strategic transport model the Gauteng Freeway Improvement Project (GFIP) for the Base Year scenario (year 2018) will be explained. The land use information, traffic information and the SATURN traffic modelling software was provided by Mr Alan Robinson, a Traffic Engineer and Transportation Modeller from SANRAL.

Chapter 5: Development of the Strategic Transport Model for GFIP

The process followed when developing the strategic transport model, using the SATURN traffic modelling software, is discussed in this chapter. The process followed to calibrate the traffic assignment on the network was a crucial part of developing an accurate strategic transport model and will be discussed in this chapter. The statistical component of this study is also included in this chapter.

Chapter 6: Estimation of a Distance-Deterrence Function for the GFIP Network

In this chapter a detailed discussion is included on the estimation of a distance-deterrence function for trips, for the base year, on the Gauteng Freeway Improvement Project (GFIP) network. A detailed explanation of the process followed to achieve a suitable distance-deterrence function for the GFIP network is included. The various curve-fitting analyses based on different deterrence function forms were also investigated and the respective process and results are included in this chapter.

Chapter 7: Development of a Distance-Deterrence Function for Shorter Trips for the Design Year (2038)

In this chapter the process followed in the development of synthesized distance-deterrence functions and synthesized OD matrices which assign trips with shorter trip lengths will be discussed.

Chapter 8: Case Study: Testing the Performance of the Synthesized Distance-Deterrence Functions

The effectiveness of the synthetic distance-deterrence functions developed in reducing trip lengths on the GFIP network will be tested. The synthetic distance-deterrence function will be applied to the GFIP model, using the SATURN traffic modelling software. The results as to whether this method of planning and developing road infrastructure promotes shorter trips and supports densification will be discussed.

Chapter 9: Testing the Effect of Different Road Infrastructure Improvement Projects on Total Time and Distance Travelled Savings

This chapter focuses on comparing each improvement project alternative with the do-nothing scenario in terms of the economic benefit based on the total travel time and total travel distance saved.

Chapter 10: Economic Evaluation: Investigating the Different Economic Benefits of the Project Alternatives

This chapter presents the approach and results from the simple economic evaluation completed for each project scenario proposed. The economic benefits included are based on generalized cost in terms of total travel time (hours) and total distance travelled (km) by all light vehicles on the network.

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Chapter 11: Conclusions and Recommendations for Further Research

This chapter consolidates the findings and conclusions attained through this research project. The author's recommendations for further research on the topic is outlined in this chapter.

The recommendations for further research in this area of transportation planning and modelling is provided such that this research can be grown and provide greater benefit to industry.

Appendices

All appendices are provided. The appendices include the raw data used for the analysis and development of the strategic transport model and the synthetic distance-deterrence functions.

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2 Literature Review

2.1 Introduction

A comprehensive literature review in the area of transportation planning, spatial planning, trip lengths, transportation modelling and public transport requirements is presented in this chapter. The objective of the literature review is to understand and establish the research already completed in this area. Through the extensive literature review, it is found that there is no literature focusing on findings which directly tie in with the objective of this research project. It was therefore concluded that this research project brings in new knowledge which can contribute to and build on the existing industry knowledge regarding a concept which enables shorter trips and a densified environment through the effective planning and implementation of road infrastructure. Therefore, the approach to completing the literature review for this research project deviates from the conventional manner in which literature reviews are done for research projects; i.e. building on existing research. The method of completing the literature review for this research project instead focuses on extracting, from prior studies, the relevant components and pieces of information pertaining to aspects which contribute to building the proof concept used to achieve the research objective.

It is to be noted that the author has made all endeavors to mention the owners and authors of all material sourced in this chapter, and report as a whole, to the best of her knowledge.

2.2 Urban Sprawl

Urban sprawl is described as unrestricted growth in housing, commercial developments and road infrastructure with minimal consideration of future urban planning (Britannica, 2019). Sprawl is directly proportional to the distance away from the city boundary. This means that sprawl increases as the distance from the city centre increases. There are social and environmental consequences of sprawl in cities and towns which include longer home-work and work-home distances travelled by commuters and larger road infrastructure required to link residential areas to the central business district (CBD) (Cooke and Behrens, 2014). Characteristics of urban sprawl also include pockets of low-density residential areas spread outwards from the CBD of cities and towns, single use zoning and relies heavily on the use of private vehicles for transportation to and from places of work and leisure (Britannica, 2019). In addition to the above-mentioned characteristics of urban sprawl, urban sprawl can also be identified as the spreading out of population without having a well-defined centre. In summary, urban sprawl is the decentralization, discontinuity and segregation of residents. Cooke and Behrens (2014) further explains that a key

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factor contributing to the increase in urban sprawl over the years is the cost of land and property. Market trends indicate that the price of property increases towards the CBD. This in turn contributes to the segregation of commuters according to their level of income. This in summary can be understood that high income earners will most likely reside closer to CBD's of cities and lower income earners will most likely reside further away from the CBD's of cities.

A classic example which demonstrates this trend is the city of Johannesburg. Stieg and Landre (1991) published a research paper title *"The Measurement of Residential Sprawl in the Johannesburg Metropolitan Area"* in which they highlight that a key contributing factor to urban sprawl is the ability of people to afford property based on location. The authors also approach the issue of the increase in urban sprawl from another angle; the angle being road infrastructure. It is understood that urban sprawl is due to affordability of land but this raises the question "What have road authorities done to limit or control sprawl?" Literature published on the subject of urban sprawl, city layouts and spatial planning published by authors various authors (Stieg and Landre (1991), Cooke and Behrens (2014) and Bertaud (2003)) have all highlighted that urban sprawl is continuing to increase. These authors have also emphasized the need for urban and spatial planning to be improved and changed from the current approach being applied in industry. Focusing again on the angle of limiting and controlling urban sprawl through road infrastructure; Stieg and Landre (1991) have stated that urban sprawl was encouraged in the city of Johannesburg when road authorities constructed road infrastructure for main roads which extended outside of the city boundary.

Urban sprawl has a number of negative consequences and the primary consequence which this research project aims to address is the high cost of transportation (infrastructure, maintenance and generalized cost in terms of travel time and distance travelled). Another consequence of sprawl is the high costs of providing services such as sewerage, lights and water to households far from the city centre or other highly densified areas (Stieg and Landre, 1991). It would therefore make sense to concentrate households in areas which are near to city centres and other densified places which contain places of work and access to medical care, educational facilities and other necessary amenities. However, this is not the trend which is being followed by transportation planners.

Planning city layouts such that urban sprawl is limited will allow for services and road infrastructure to be provided to residents in a more economical manner. An added bonus from reducing urban sprawl and creating a more compact city layout is that public transport becomes more accessible to residents and commuters. Subsidies for the provision of public transport service and

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infrastructure becomes easier to provide due to trips being shorter than that in an environment that has increased urban sprawl.

Taking into account the above advantages of limiting sprawl in cities, authors in addition to the ones mentioned emphasize the need to approach transportation planning differently going forward. Research of literature focusing on urban sprawl have indicated that there is interest in reducing and preventing further urban sprawl through better planning of city layouts; i.e. plan and develop and grow city layouts in a more compact manner.

Literature suggests that transportation planning should focus on reducing sprawl by limiting the distance of developments (residential zones) from city centres. In theory through the limitation of sprawl, an environment which supports and encourages densification will be created. An additional benefit of a densified environment is that the average trip lengths between zones will be shorter. The combination of shorter trip lengths between zones and a densified environment supports the implementation of public transport (Cooke and Behrens, 2014). A proof of concept investigating the support of densification though planning and implementation of road infrastructure is the key focus of this research project.

Sieg and Landre (1991) have discussed simulation results for residential developments under different planning policies. Their planning alternatives are summarized below:

- Increase the overall density: This can be explained as renewing the existing fabric of a city by increasing the minimum densities in urban developments.
- Increase Density in Specific Areas: Locate higher density areas along the transportation corridors linking to places of work. These higher density areas should be located where facilities are designed to cope economically with the increase.
- Growth Incentives in Slowly Expanding Areas: This requires growing urban areas which have a lesser density than other urban areas with the aim of balancing the densities of urban areas in Johannesburg. This will assist with a distribution in the city’s population and resources.

Hence, the first step towards densification and improved planning of road infrastructure is to redefine or change the current spatial layout of existing cities.

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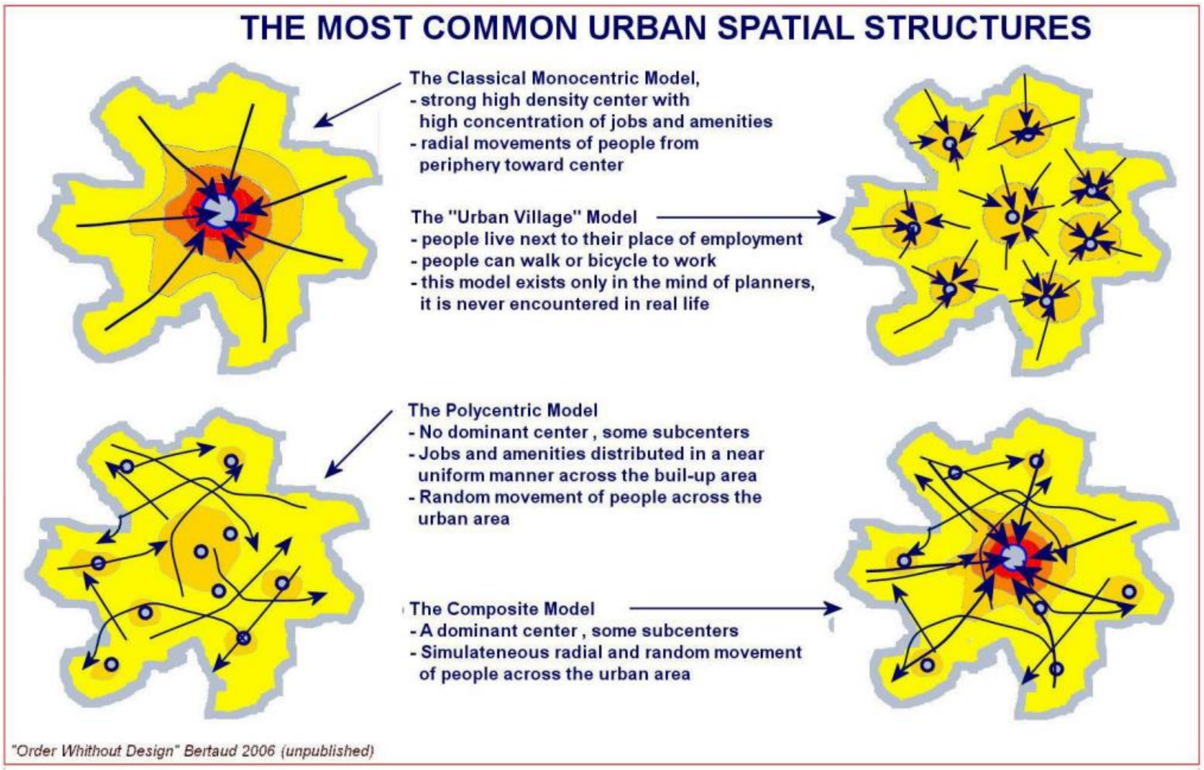
2.3 Types of City Layouts

2.3.1 Concept of Urban Spatial Structure and Associated Commuting Patterns

There are four primary urban spatial structures on which city layouts are based. They are the monocentric model, the urban village model, the polycentric model and the composite model. The figure below illustrates these spatial structures.



"Order Whithout Design" Bertaud 2006 (unpublished)

Figure 2-1: The Most Common Urban Spatial Structures (Lin et al, 2013)

The monocentric model spatial structure has a highly concentrated employment centre. The nature of this type of spatial layout means that residents/employees generally reside in suburbs which are located away from the concentrated economic centre (central business district or CBD). There would therefore be a high number of commuting flows on radial routes towards the centre of the city. This trip pattern is a result of there being many origin zones for work trips (this being the suburban residential areas which are located in a dispersed manner) and a single concentrated destination zone for employment (the CBD).

The urban village model spatial structure can be understood as mini monocentric models in which people live within close proximity to their place of work. The distance from residential areas to places of work is such that it is possible for commuters to cycle or even walk to work.

Unfortunately, this model remains a concept in the minds of transport planners and has never been implemented in real life (Lin et al 2013).

The polycentric model operates similarly to a city with a monocentric spatial structure. The difference being that the commuting patterns are different due to zones relating to job structure being divided throughout the city structure (Lin et al, 2013). A polycentric city has two commuting models. The first model is such that the city has sub-centres of employment (all of a similar size) which generates trips from different areas in the city. The commuting characteristics indicate scattered dispersion of origins and destinations. The second model is similar to the first model except that there is a single sub-centre which is more concentrated and stronger than the other sub-centres (Lin et al, 2013).

The composite model spatial structure exhibits characteristics of the monocentric and polycentric models combined. It has a dominant employment centre surrounded by origins and destinations which are scattered around the dominant employment centre. The nature of commuter trips is radial and random occurring all over the city area (Lin et al, 2013).

The type of urban spatial structure has an influence on trip patterns, trip lengths and modal choice of commuters (Lin et al, 2013). The topic of the extent in which decentralization and polycentric development in metropolitan and urban areas has influenced the commuting patterns of people has been debated over the past twenty years (Lin et al, 2013). According to Lin et al (2013) suburbanisation has played a part in reducing traffic congestion by distributing the traffic demand to routes which have less congestion and which are away from central areas. Lin et al (2013) also highlights that when sources of employment move to suburbs, workers tend to navigate to those locations. This in turn allows workers to benefit from shorter commuting times; i.e. shorter trip lengths as well as less congestion in city centres due to traffic.

2.3.2 Urban Spatial Planning and Past Travel Patterns in South Africa (Gauteng)

The evidence of poor spatial planning in South Africa can be seen in the urban infrastructure. The consequence of this poor spatial planning is the following:

- Imbalance in access to available public transport services;
- Poor connectivity between suburbs, cities and towns; and
- Increased trip lengths for home-work trips.

The public transport infrastructure, in Gauteng, is unable to cater for all income groups (low, middle and high) effectively (Simpson et al, 2014). This is a consequence of urban sprawl stemming from the poor spatial planning in South Africa. It is not economical to operate public transport services over long distances (Lin et al, 2013). Urban sprawl continues to increase in South Africa despite the acknowledgement of its consequences (Simpson, 2014). The reason can be partly based on the spatial planning of cities and towns in South Africa at the initial stage; i.e. high-income earners being able to afford living closer to city centres and lower income earners being able to only afford property further away from the city centres. This resulted in pockets of developments spread outwards from the periphery of the city centre. Over time, further developments adopted the similar trend by either developing a new plot of land or by expanding existing developments. The figure below provides an example of the road infrastructure network in Gauteng as a result of sprawl.

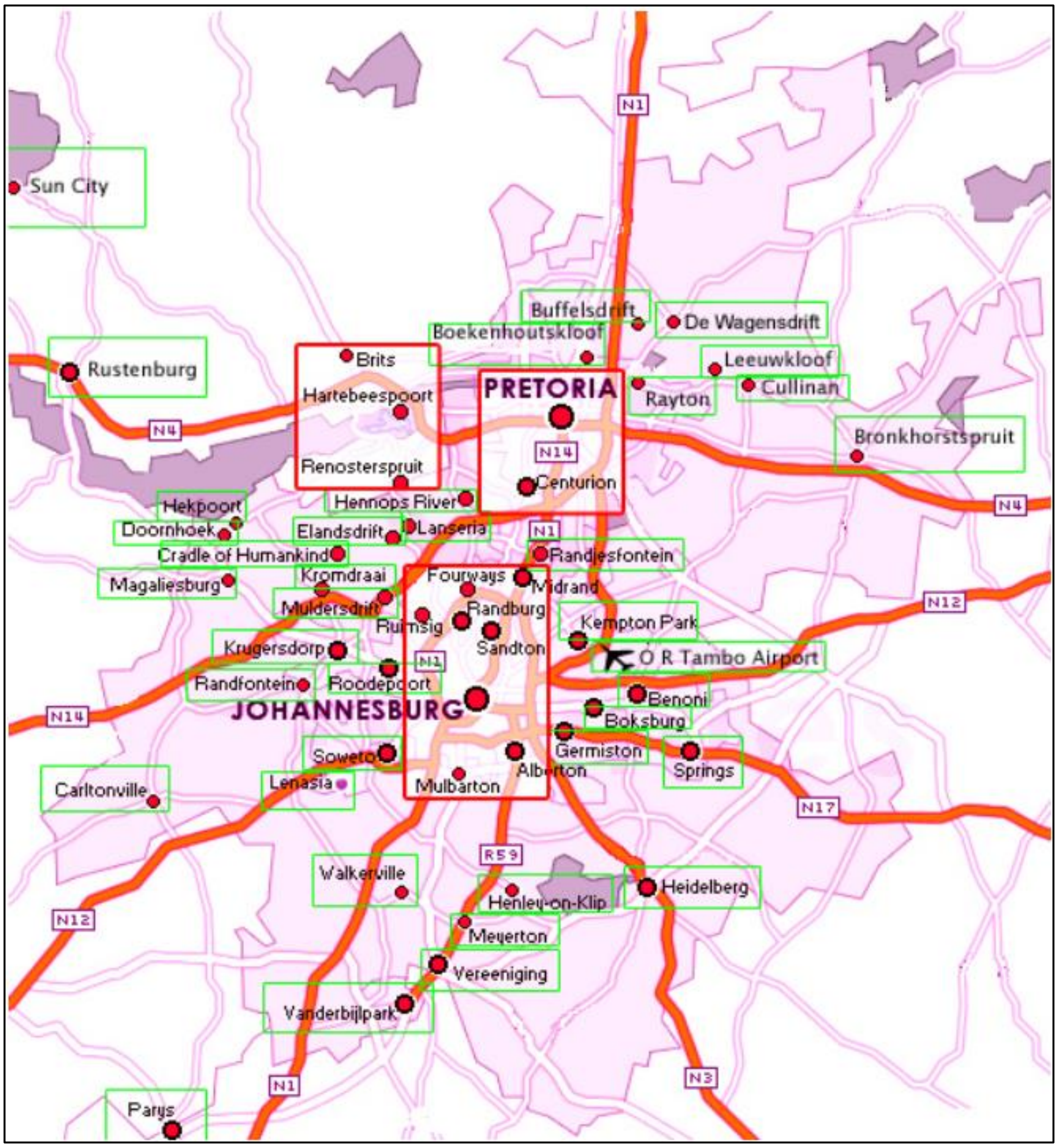


Figure 2-2: Illustration of Road Infrastructure Linking Sprawled Areas (Madbookings.com, 2019)

Low income earners do not have adequate funds to cover both transport and housing costs and therefore seek lower priced housing either on the urban periphery or away from the urban

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periphery. This means that they are now burdened with high transportation costs and limited public transport options (Lin et al, 2013). In the South African context, the available public transport services are mini bus taxis and a limited supply of buses.

The cost of implementing public transport in Gauteng is exceptionally high due to low urban densities and high urban sprawl. Due to the sprawl layout of cities and areas in Gauteng, a formal transport service cannot be implemented. The first step to implementing a formal transport service would be to improve the spatial layout of cities and areas through densification (Yusuf & Allopi, 2004). In theory, a policy which specifies strict limitations and requirements of densification needs to be implemented and monitored.

The rapid expansion of the development of the city region in Gauteng continues to increase. Therefore, the spatial layout of this expansion is a key concern when dealing with providing the required road infrastructure to cater for transportation needs.

It can therefore be concluded that the consequence of urban sprawl in South Africa is summarized as follows (Yusuf & Allopi, 2004):

- Inefficient use of urban land;
- Rural encroachment;
- Dependence on private vehicles;
- Traffic congestion on mobility routes as well as the second order road network; and
- An expensive public transport system.

When considering the consequences and effects that urban sprawl has had on South Africans, it can be concluded that urban sprawl has impacted negatively on their quality of life.

2.3.3 The Concept of a Compact City

2.3.3.1 Introduction

There has been rapid urbanization occurring in many areas throughout the world. Approaches to revive inner cities, such that the ever-increasing population and their corresponding transportation needs are accommodated for, are constantly being reviewed by transportation planners and policy makers (Varma, 2017). As a result, methods of modifying the “modern day city” is being scrutinized. In the past, the basis for planning urban and road infrastructure was “private vehicle” induced mobility (Varma, 2017). The dominant influence of private vehicles has created accessibility for people residing in farther distances. The negative outcome from this is the creation of a low-density urban environment (sprawl) and has left those without private vehicles or access to an affordable public transport service, stranded. Policy makers have recently taken a new approach to the planning of urban and road infrastructure; that being focusing on access to transportation (public transport) and the distribution of network capital (Varma, 2017). These factors in turn result in social exclusion of those living further away from cities and employment centres.

The prime focus of urban development centres around using public transport and walkable (pedestrian friendly) cities in an effective manner (Varma, 2017).

The concepts of 'New Urbanism' and the 'Compact City' have emerged as suitable answers in modifying low density and private vehicle driven urban and road infrastructure, and environments, to achieve the following characteristics:

- Cities and towns with mixed urban densities;
- Neighbourhoods which are well connected;
- Mixed used and diversity;
- Increased densities of cities and towns; and
- Improved quality of life for all income groups through reducing social exclusion of income groups.

The topics of New Urbanism and the Compact City are fairly new in the South African context with limited applications in existence. Some examples include *Century City* in Cape Town and *Melrose Arch* in Gauteng. However, it is to be noted that these developments are suited for high income earners thereby excluding the lower- and middle-income groups. Therefore, these developments operate in isolation to the transportation network and urban infrastructure around them. The capabilities and extents of changes to urban and road infrastructure, such that the concepts of New Urbanism and the Compact City can be implemented, need to be understood. To achieve a complete understanding of how these concepts can be applied to an existing or new city, emerging trends in urban mobility must be considered (Varma, 2017). The effective combination of New Urbanism, the Compact City and urban mobility play a key role in the growth of a city.

2.3.3.2 The Concept of New Urbanism

New Urbanism is a design approach that focuses on designing cities by prioritising people (Varma, 2017). The private vehicle is not completely excluded from the design but rather considered once the needs of people/pedestrians are catered for. The new urbanism approach to designing cities involves some of the following:

- Planning city layouts such that high densities are achieved through closely spaced housing;

- Positioning of stores on streets within walking distances; and
- Providing easy access to public transport services by having facilities positioned regularly along the streets.

The New Urbanism approach to designing the modern city is envisaged to provide people with the opportunity to appreciate the character of the urban environment in a safe manner through suitable pedestrian facilities and an efficient and affordable public transport system. This in turn is predicted to improve the quality of life for people of all income groups (Varma, 2017).

2.3.3.3 The Concept of the Compact City and its Influence on Urban Mobility

The opposite of a city defined as “sprawl” is a city which is compact.

A compact city has the following characteristics:

- Promotes working and living in places which have high densities of living and working spaces;
- Walkable streets and residences and work spaces within walking distances of each other;
- Has an affordable and efficient public transport service and the necessary pedestrian facilities to cater for the movement of people for work or leisure needs;
- A spatial layout such that long distance trips are reduced, and shorter distance trips are promoted; and
- Has a spatial layout which encourages densification and mixed land use.

A compatible relationship exists between the level of compactness of a city and its public transport systems (Varma, 2017). High density urban layouts promote the success of public transport services, reduces the dependency on private vehicles and improves the walkability of a city. The combination of these aspects therefore contributes to a sustainable transport strategy for urban growth in the future (Varma, 2017).

2.3.4 Jobs-Housing Balance

Jobs-housing balance is often misunderstood as a community which is self-contained and self-reliant within which residents eat, play and work. However, this is not the correct description of jobs-housing balance. In fact, jobs-housing balance is a community or area which has a ratio of jobs to houses lying in the range of 0.75 to 1.25 (Cervero, 1989). To accommodate households which have more than one salary earners living together, the upper band of the range can be increased to 1.5 to reflect the modern-day household (Cervero, 1989). A ratio of jobs-housing higher than 1.5 in an area suggests that there is insufficient supply of households to satisfy the demand of the local workforce. The consequence of this leads to the high commute patterns of workers leaving and entering the area. Another consequence of an imbalance in jobs and housing is that workers will need to travel farther than necessary for home-work and work-home trips. This poses additional travel costs onto the worker especially in the cases where an affordable and reliable public transport system is not available.

The above paragraphs can be summarized as follows: the primary reason for workers having long commute times is due to high housing costs and housing shortages closer to places of employment (Cervero, 1989). This is very applicable to the South African context.

Some of the areas close to the Johannesburg CBD are Rosebank, Houghton Estate, Hillbrow and Sandton. These areas are known to be some of the most expensive areas in Gauteng. Therefore, the residents of these areas would most likely be high income earners. Currently, for the year 2019, the average prices of properties in Rosebank, Sandton and Houghton Estate according to *Property24* are as follows:

- Rosebank: Houses = R6 600 000, Apartments = R1 900 000
- Sandton: Houses = R3 150 000, Apartments = R1 250 000
- Houghton Estate: Houses = R6 250 000, Apartments = R2 350 000

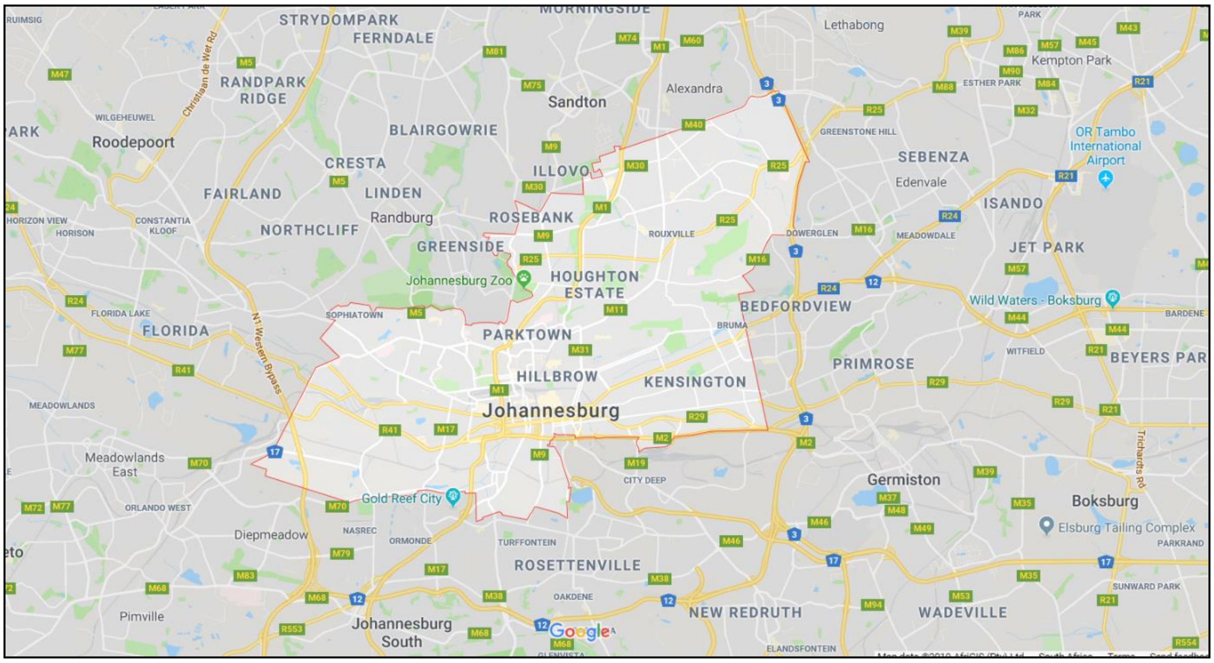

Figure 2-3: Johannesburg CBD (Google Maps, 2019)

These high property prices make it difficult for the average salary earner in Gauteng to be able to live in these areas and therefore close to the Johannesburg CBD (employment centre). According to the article *"This is the Average Salary in South Africa right now"* published by BusinessTech in 2018, the average salary of the workforce in South Africa was R20 860 after tax deductions. An

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employee earning this salary might be able to afford property in the areas mentioned, however this would be possible with very careful financial planning, budgeting and application of home loans. Unfortunately, those earning less than the average salary will most likely not be able to afford a property in these areas. The result of this is that they will need to travel longer distances to their places of work as well as make us of the limited public transport services available. Therefore, a percentage of urban planners are resorting to the relationship between jobs-housing as a method of finding remedies for the phenomenon of growing urban congestion (Lin et al, 2013). The concept of balancing the job-housing relationship can be used to improve urban mobility within and around a city. This can in turn assist with the reduction or limitation of urban sprawl.

Cervero published a paper in 1989 titled "*Jobs-Housing Balancing and Regional Mobility"* where he discusses his findings from an investigation where he studies the effect of an imbalance in the jobs-housing ratio in 42 major subcentres in the United States of America. The areas which had an imbalance in the jobs-housing ratio tended to produce low proportions of pedestrian and cycling trips and conversely, produced high levels of congestion on the second order road network linking onto the highways and freeways. This means that there is a small percentage of people working within the areas they resided in and were therefore travelling further distances to their places of employment. The opposite can be assumed, this being that there was a high influx of workers from other areas entering into these areas via highways and freeways. In the South African context, these longer commutes are also a result of poor spatial planning and urban sprawl. These aspects were discussed in sections 2.2 and 2.3.

Frank and Pivo (1994) conducted empirical studies using the case study of Central Puget Sound Region of Washington State to show that the commuting time and distance of areas which have a jobs-housing balance are lower than those which are imbalanced. Frank and Pivo (1994) also found that the average distance for work trips was shorter by 29% in balanced areas when compared with imbalanced areas.

It is clear that there is a link between the balance in jobs-housing, reduction in home-work trip lengths, congestion levels and the usage of public transport services. The research relating to the balance in jobs-housing also indicates that driver behavior can be linked to the location of jobs; i.e. commute trips tend to move towards places of employment even if these are located further from places of residence.

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2.4 Requirements for Public Transport Implementation

A successful transportation system is an essential component of any country. The public transport system in South Africa includes a rail system, the high-speed Gautrain rail system, buses including two bus rapid transit (BRT) systems (MyCiti in Cape Town and Rea Vaya in Johannesburg) and mini bus taxis which operate throughout the country.

Regardless of these modes of public transport systems being available, public transport still faces numerous challenges in South Africa (Aropet, 2017). These challenges include low ridership and inadequate access to public transport facilities in rural and suburban areas. These challenges are the result of jobs-housing imbalance, spatial segregation due to affordability of property, poor planning of integration of different land uses and poor efforts of densifying cities and employment areas efficiently.

2.4.1 Relationship between Density and Trip Length

Research published by Holz-Rau et al (2013) titled "*Travel distances in daily travel and long-distance travel: what role is played by urban form?"* suggests that distances travelled by commuters residing in areas with a lower population density and which have a lower proportion of mixed land use are longer than the converse.

The relationship between density and trip length has been a common topic in sections 2.3.3 and 2.3.4. To recap, trip lengths have proved to be consistently low in inner city networks (city layouts) which have high densities and mixed land use. Longer trip lengths were found to be consistent in neighborhoods and suburbs with low densities (Varma, 2017).

2.4.2 Population Density Requirements

2.4.2.1 Population Density in Hong Kong: A Public Transport Success Story

The density of an urban city or region affects the number of passengers that is able to use a public transport service (Cooke and Behrens, 2014). User ridership of a public transport service is primarily dependant on accessibility to the public transport system. The accessibility of the public transport system is derived from the generalized cost as well as how close the user is located to a public transport facility (Cooke and Behrens, 2014). It is crucial to remember that all public transport users are also pedestrians. Hence, the spacing and location of public transport facilities must be based on the maximum distance that a pedestrian is willing to walk to get to the relevant facility. The maximum distance (proximity) defines the effective catchment area which has the highest probability of user's utilising the public transport stops or facility (Cooke and Behrens,

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2014). This means that most public transport users will prefer to live and or work within the collective catchment area of a public transport facility. Furthermore, the number of users who are most likely to use the public transport service is fundamentally dependent on the density of the urban development or city (Cooke and Behrens, 2014). The threshold ridership is based on the financial cost of the operation of the service - provided that user costs are kept constant (Cooke and Behrens, 2014). A high quality and efficient public transport system will have a high ridership threshold (Cooke and Behrens, 2014). For a public transport service to be of a high quality and good viability it must have a ridership threshold which equals the number of users (Cooke and Behrens, 2014). This can be explained using the example of a subway system. An expensive subway system with a high ridership threshold will require an equally high urban density to be viable. Urban density can be measured using gross population density and net population density. Gross population density is the number of people per hectare in a city. Net population density is the number of people per hectare in a residential area.

Articulated density is explained as a method of strategically distributing the population density over a metropolitan area with regards to the proximity to public transport or transit-oriented development (Cooke and Behrens, 2014).

Activity intensity can be defined as combining population density and job density as both ends of a trip needs to attain high density levels to significantly effect travel behaviour and the viability of a public transport system (Cooke and Behrens, 2014).

These concepts both focus on moving people closer to places of work. Having people closer to employment centres promotes shorter work trips. The abovementioned concepts also highlight the distribution of the population density such that close proximity to public transport services are achieved. These two methods of densification both demonstrate a strong link to the importance of access to a viable, efficient and affordable public transport system. These concepts link strongly to the objectives of this research study.

To obtain a better understanding of the population density requirements for a successful public transport system, the population density of the public transit systems in ten cities will be considered. According to McKinsey & Company, these ten cities have the most successful public transport cities in the world.

Table 2-1: Urban Densities for the Top Ten City Profiles (McKinsey & Company, 2018)

City	City Population (Millions)	Gross Population Density (people/km^2)	Cars Per 1000 People
Singapore	5.6	8 100	101
Metropolis of Greater Paris	7	9 200	530
Hong Kong	3.3	36 300	63
London	8.4	5 200	213
Madrid	3.2	5 200	563
Moscow	12.4	11 300	341
Chicago	2.7	4 400	436
Seoul	10.1	16 700	308
New York	8.5	10 600	305
Province of Milan	3.2	2 000	518

The public transport system, in each of the above cities, is citywide and consists of the following major modes of public transport:

- Mass transit railway (MTR);
- Trams; and
- Buses.

Lu et al (2018) wrote a paper titled "Commuting Mode Choice in a High-Density City: Do Land-Use Density and Diversity Matter in Hong Kong?" in which the authors discuss that the success of the citywide public transit system can be based on the urban density of Hong Kong.

2.4.2.2 Population Density in South Africa: Current and Targets

The figures for the current gross population densities of cities in South Africa could not be obtained. This can be an avenue for proposed further research.

Therefore, the target densities for urban environments will be considered instead. The efficiency and viability of a public transport system depends on the density targets for a city (Cook and Behrens, 2014). The density targets are based on the minimum population densities founded on operating conditions and travel behaviour of passengers. Metropolitans in South Africa (Cape Town, Tshwane/Pretoria, Johannesburg, Nelson Mandela Bay and eThekwini Municipality) have acknowledged that urban density plays a crucial role in the creation of sustainable urban environments (Cooke and Behrens, 2014). The table below was extracted from a paper, *"A Comparative Empirical Analysis of the Relationship between Public Transport and Land Use Characteristics"* written by Cooke and Behrens (2014).

Table 2-2: Densification Targets Summarised by Five Cities in South Africa (Cooke and Behrens, 2014)

Targeted Areas	**South African City/Municipality**				
	Cape Town (CoCT, 2012)	**Tshwane (CoT, 2012)**	**Johannesburg (CoJ, 2010)**	**Nelson Mandela Bay (NMBM, 2007)**	**eThekwini (eThekwini Municipality, 2013)**
Entire Urbanised City Area (persons/ha)	83	-	29	78	79
Activity Spines (persons/ha)	393	150	-	340	209
Development/Public Transport Trunk Corridors (persons/ha)	208	150	232	238	209

It is encouraging to see that various municipalities around the country have recognised the importance of gross population densities in urban environments in implementing a viable and efficient public transport system. However, limited literature was found documenting municipalities efforts or plans in achieving these density targets.

The following can be deduced from the vast literature relating to land use and successful public transport systems:

- Gross population densities of cities play a key role in the viability and efficiency of its public transport system;
- High frequency short trips play a key role in the viability and affordability of a public transport system; and
- Densified urban cities provide a conducive environment for public transport systems. An added benefit of densified urban cities is that they provide a "walkable" environment for people thereby promoting the use of public transport facilities and discourages private vehicles. The densified and walkable environment makes the use of private vehicles

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unnecessary, expensive and inconvenient. This in turn reduces congestion levels within and around cities.

2.4.3 Infrastructure Requirements

The gross population densities of cities, combined with supporting urban infrastructure, are key components in creating a viable and efficient public transport system. The component of gross population densities in cities has been discussed in the preceding section. This section will focus on the infrastructure component of a public transport system.

Literature titled "*Elements of Success: Urban Transportation Systems of 24 Global Cities"* compiled by Knupter, Pokotilo and Woetzel of Mckinsey & Company, provides a comprehensive study of various transportation systems in selected countries. An implementation guide for public transport was published, in 2019, via an online forum by the *C40 Cities Climate Leadership Group* which includes methods on making public transport an attractive option in cities. The table below summarized the infrastructure requirements for a viable and efficient public transport system which have been extracted from the above.

Table 2-3: Infrastructure Requirements for Viable and Efficient Public Transport Systems (McKinsey & Company (2018), C40 Cities Climate Change Leadership Group (2019))

Infrastructure Requirement	**Example of Successful Implementation**
Users must have easy access to public transport facilities.	Singapore, Hong Kong, Madrid
Bus Routes must be optimized to reduce overlap of routes and improve coverage of the city area.	Houston (United States of America). Reduction in trip overlap increased ridership by 7%.
Location of regular bus stops for improved access.	Barcelona has bus stops spaced at a maximum of 350m. Seattle has a year 2040 strategy to position 73% of households within 800m of frequent transit routes.
Reduce spatial bias by reclaiming road space for public transport for the following infrastructure: • Dedicated bus lanes; • Improved facilities for waiting areas; and • Improved transit terminals	• Hong Kong • Singapore • Madrid • Paris • London • New York

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Examples of public transport in these ten cities are provided on the next few pages (Worldatlas, 2018).

Singapore

Figure 2-4: Public Transport in Singapore (Worldatlas, 2018)

Metropolis of Greater Paris

Figure 2-5: Public Transport in Paris (Worldatlas, 2018)

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Hong Kong

Figure 2-6: Public Transport in Hong Kong (Worldatlas, 2018)

London

Figure 2-7: Public Transport in London (Worldatlas, 2018)

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Madrid

Figure 2-8: Public Transport in Madrid (Worldatlas, 2018)

Moscow

Figure 2-9: Public Transport in Moscow (Moscovery, 2019)

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Chicago

Figure 2-10: Public Transport in Chicago (Tripsavvy, 2019)

Seoul

Figure 2-11: Public Transport in Seoul (Worldatlas, 2018)

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New York

Figure 2-12: Public Transport in New York (Worldatlas, 2018)

Province of Milan

Figure 2-13: Public Transport in Milan (Milanocard, 2019)

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2.5 The Future City

Through the literature review completed in producing this academic research project, the following key conclusions were made;

- In South Africa, transportation planning has not evolved or adopted the techniques and advancement of that in overseas countries such as Singapore, Barcelona, Madrid and Hong Kong;
- Sprawl in South African regions continues despite its consequences being acknowledged by policy makers, decision makes and transportation planners;
- Transportation and urban planning approaches in overseas cities can be used as examples which can be adopted to improve and advance transportation and urban planning in South Africa; and
- Concepts like New Urbanism and The Compact City are being implemented overseas successfully. Methods of integrating these concepts with current transportation and urban planning methods, in South Africa, should be investigated.

This section of this research project focuses on presenting elements of The Future City which could be applicable to the South African context provided that urban planning and public transport systems are improved as discussed in the earlier sections of this Chapter.

2.5.1 Features of The Future City

The Future City will be planned and designed with the pedestrian as the design vehicle. The Future City will comprise of the New Urbanism elements discussed earlier in this report. The Future City will comprise of the following features (Smartcitiesdive, 2019):

- Infrastructure and a city layout which promotes cycling and walking;
- Planning for local hubs. These will allow people to work near to their homes as well as complete their errands. Planning for local hubs assists with keeping trips local and confined. This in turn reduces congestion on the freeways which should be used for purely mobility and only when necessary;
- Introduction of congestion charging. This entails having a tax on fuel for personal travel. This encourages the use of the different public transport modes available;
- Seamless travel which is achieved by effective integration of different public transport modes thereby allowing people to effortlessly change modes during a journey (e.g. hop of a bus and onto the train).

These features have been adopted and implemented, to an extent, by cities in other countries as a method of reducing trip lengths and encouraging densification. A successful project is the Barcelona Superblocks, in Barcelona.

2.5.2 Barcelona Superblocks

The Barcelona Superblocks is an innovative urban development project initiated by the Barcelona City. It is a unique approach to traffic management, promoting cycling and walking and making more city space available to pedestrians (The Conversation, 2019). According to the developers, the model and layout of the Barcelona Superblocks also has health and economic benefits.

The Barcelona Superblocks urban development model consists of large “blocks” each covering an area of 400m by 400m. These “blocks” are created from residential blocks of 150m by 150m (The Conversation, 2019).

The city’s through traffic is accommodated on streets outside the Superblocks and is restricted to a 50 km/hr speed limit (The Conversation, 2019). Private vehicles are banned or restricted to travelling at 20 km/hr inside the Superblocks and pedestrians and cyclists are given priority (The Conversation, 2019).

According to The Conversation (2019), benefits of the Barcelona Superblocks include the following:

- Healthier lifestyle due to the encouragement of walking;
- A more sustainable and economic lifestyle for residents due to the close proximity of work and leisure facilities;
- Improved socializing of residents due to the open and shared space layout of cities within the Superblocks; and
- Fewer fatalities due to the restrictions of the use of private vehicles within the Superblocks.

The images below provide concepts and visual information relating to the Barcelona Superblocks.

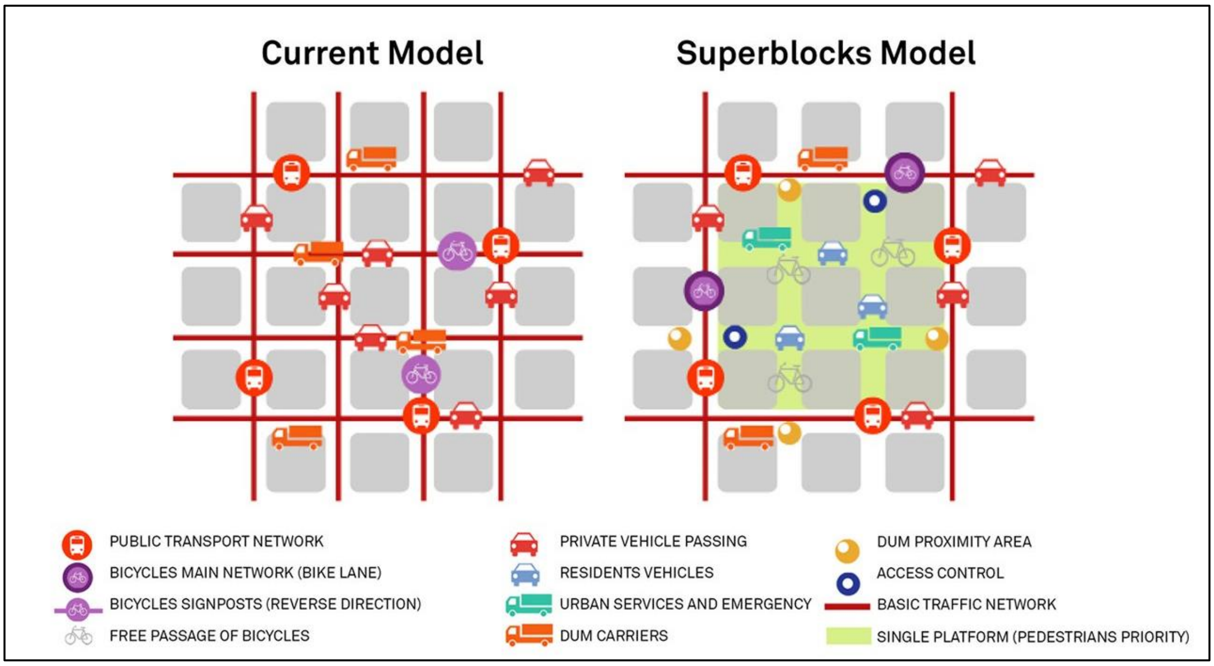

Figure 2-14: Superblocks Model (The Conversion, 2019)

Figure 2-15: Aerial View of the Barcelona Superblocks (The Conversion, 2019)

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Figure 2-16: Walkable and Pedestrian Friendly Streets in the Barcelona Superblocks (The Conversation, 2019)

Figure 2-17: Walkable and Pedestrian Friendly Streets in the Barcelona Superblocks (The Conversion, 2019)

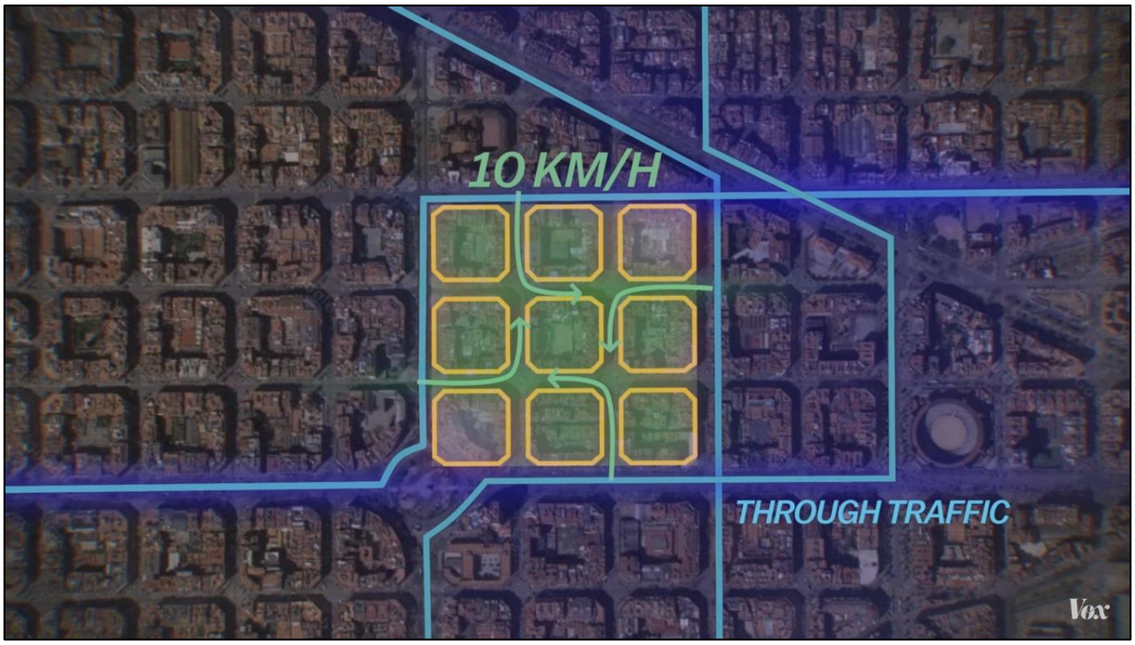

Figure 2-18: Permissible Routes for Through Traffic around the Barcelona Superblocks (The Conversion, 2019)

2.5.3 Jewel City in the Johannesburg CBD

Of recent, 2018, there has been an initiative by a group of property companies (DiverCity which is a partnership of Atterbury and iThemba Property) to redevelop a section of land in the middle of Johannesburg's CBD. The development has some similarities to Barcelona's Superblocks.

The development project will be called "Jewel City" and will be located on Fox Street in the eastern section of the Johannesburg CBD (Writer, 2018).

The project involves redeveloping five of the six existing city blocks and the construction of a new residential building. Th final project will comprise of a mixed-use precinct with approximately 1000 residential units, commercial area of 20 000 m^2, 2800 m^2 of retail space and 750 parking bays (Writer, 2018). Plans to make Fox Street more pedestrian friendly is also included in the project's scope of works. The intention is to create a more vibrant, safe, green and social place for people to enjoy Johannesburg's inner city (Writer, 2018).

According to the developers, the target group of the project is the working, middle-class. The developers claim that the location of the project makes short work and leisure trips possible for residents.

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The images below provide concepts and visual information relating to the Jewel City project.

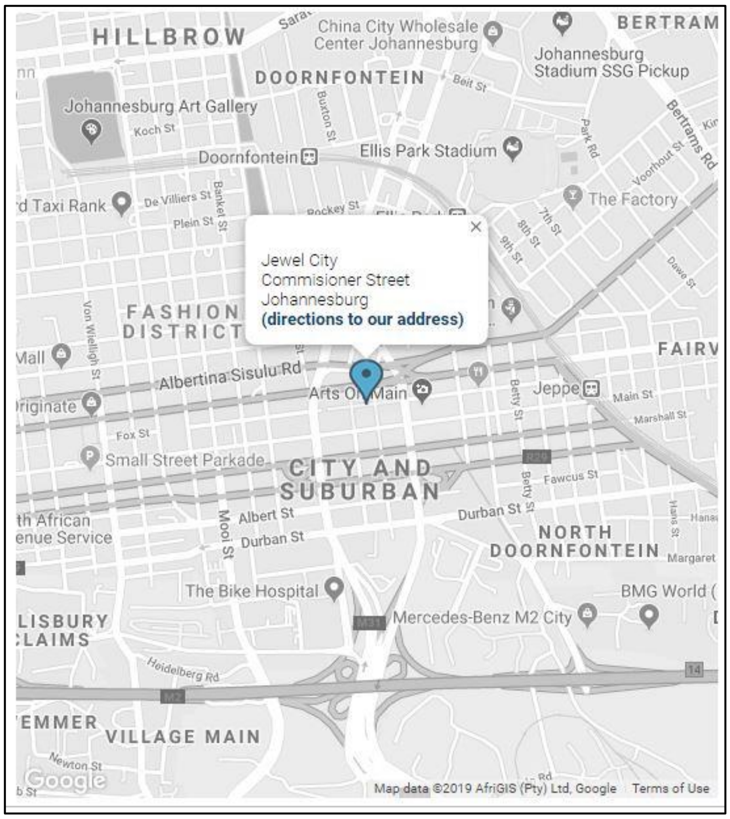

Figure 2-19: Locality Map of Jewel City Development (Atterbury, 2019)

Figure 2-20: Proposed Area of Jewel City Project (Atterbury, 2019)

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Figure 2-21: Proposed Layout of Jewel City Project (Atterbury, 2019)

Figure 2-22: Concept of Jewel City (Atterbury, 2019)

Figure 2-23: Concept of Jewel City (Atterbury, 2019)

Figure 2-24: Concept of Jewel City (Atterbury, 2019)

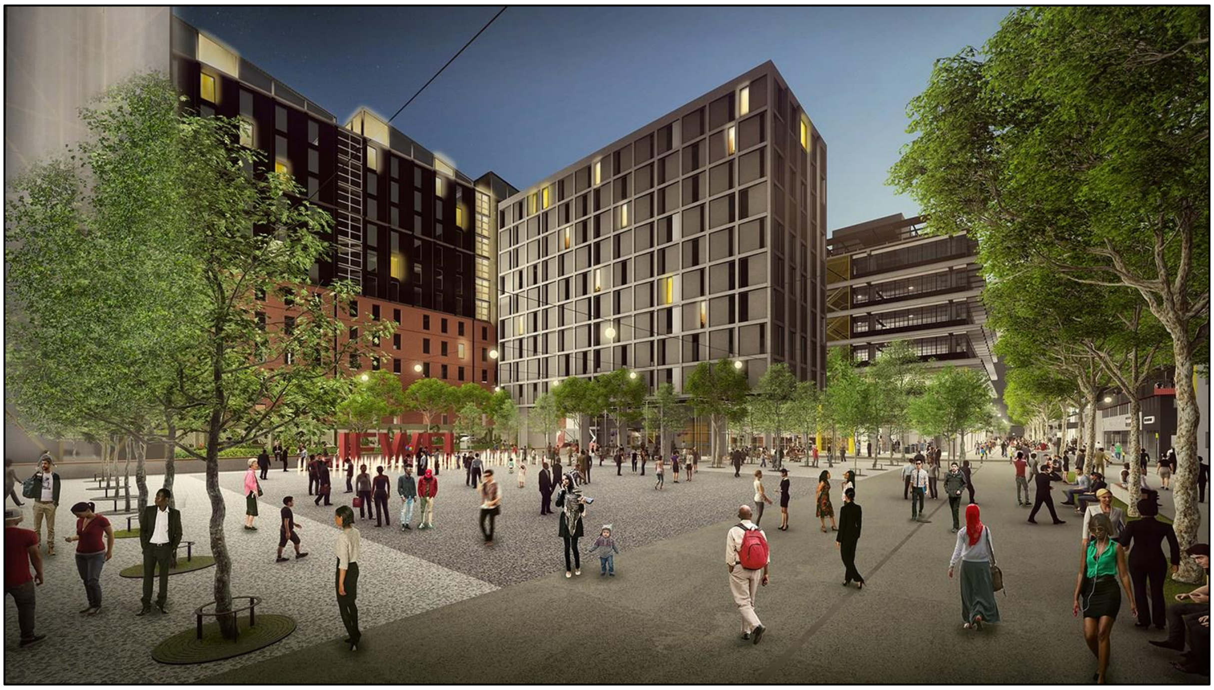

Figure 2-25: Concept of Jewel City (Atterbury, 2019)

2.6 Conclusions and Summary

A comprehensive literature review was presented in this chapter. The focus of the literature review was to gain an understanding of elements in transportation planning and to use the knowledge to identify elements used which prevent us from having shorter trip lengths to places of employment and leisure as well as a viable and efficient public transport system.

The key findings of the literature review were as follows:

- Spatial planning in South Africa is poor and has resulted in urban sprawl and an imbalance in jobs and housing. Therefore, people travel great distances for work;
- Our cities have low gross population densities which affect the viability and efficiency of public transport systems;
- The combination of sprawl and low population densities make public transport very expensive to expand, operate and maintain; and
- Continuous expansion and upgrading of freeways only seem to be contributing to sprawl.

The review of the limited available literature justifies the importance of this research and confirms the importance of densification, shorter trip lengths and a viable and efficient public transport system in every city and region.

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3 Methods Essential in Developing and Testing the Proof of Concept

3.1 Integrated Transportation and Land Use Models

Integrated transportation and land use models are used as a method of representing the reaction (interaction) cycle of transportation and land use in a network (NCHRP, 2018). According to multiple sources NCHRP (2018), Cooke and Behrens (2014), Bertaud (2003), Litman (2019), Lin et al (2013), Levinson (1998), Cervero (1989) and Frank and Pivo (1994) areas (including neighborhoods) which are more accessible are seen as being more desirable regarding choice of location than those seen as less accessible. The choice of location and transportation are interdependent (NCHRP, 2018). To explain this simply, the example of where households and or companies change their location to be in suburbs (residential areas) then the existing trip distribution will change (NCHRP, 2018). The trip distribution will change to reflect the change in origins and destinations in the area/network (Ortúzar and Willumsen, 2011). The change in the distribution of trips will in turn affect the level of congestion experienced on links, between origins and destinations. The relationship and inter-dependency between transport and land use in an area, which affects the behavior of the model, is not a new concept. However, many transportation planners/modelers have ignored this relationship in their models (NCHRP, 2018).

Strategic transport models developed on the basis of integrating transport and land use produce more realistic results than those produced by models which only consider transport and not land use (NCHRP, 2018). Strategic transport models integrating transport and land use are useful in modelling and analyzing different scenarios. The effects on trip distribution, congestion and travel times as a result of re-zoning and densification of areas in the network can be tested (Ortúzar and Willumsen, 2011). This enables decision makers to select the most suitable, financially affordable and economically viable options for projects.

3.2 The Four Step Modelling Process

The four step modelling process is the conventional method used to forecast travel volumes and travel behaviour. This modelling process involves completing four steps. The stages of the four step modelling process is as follows; trip generation, trip distribution, modal split and trip assignment. This sequence is illustrated below:

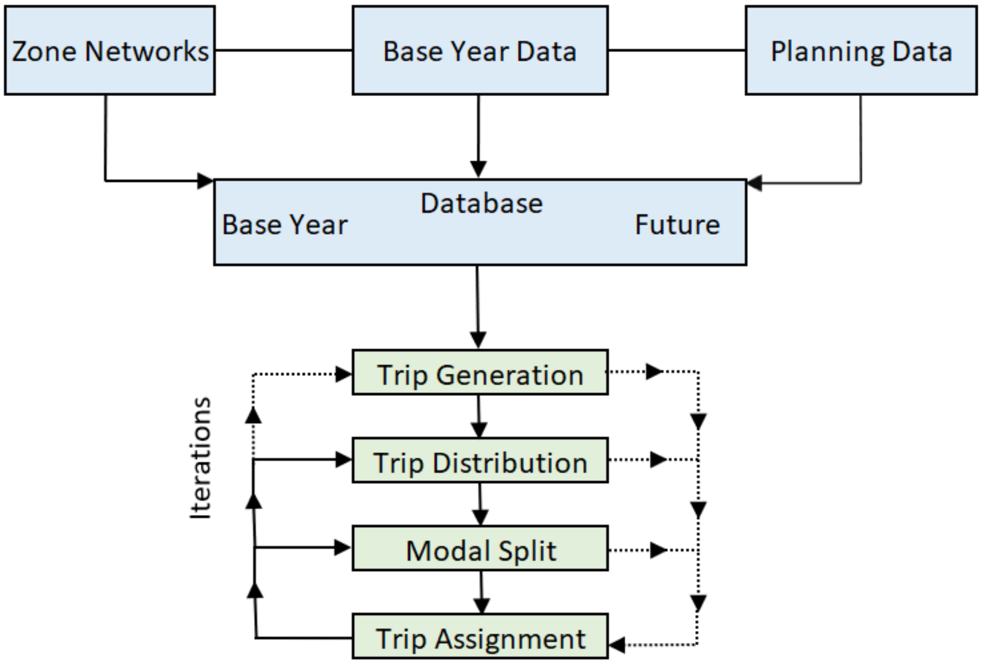

Figure 3-1: The Four Step Modelling Process (Ortúzar and Willumsen, 2011)

The four steps of the modelling process are described as follows:

3.2.1 Trip Generation

The primary objective of the trip generation step of the transport model is to predict the total number of trips generated by the origins (Oi) and attracted to the destinations (Dj) in each zone of the area under study (Ortúzar and Willumsen, 2011). To predict the above-mentioned trips, two models need to be developed, namely a trip production model and a trip attraction model. The trip production and attraction equations can be developed by means of a regression analysis.

Terms which are used in the development process of the trip generation model are explained below.

Trip or Journey: describes one way movement from a point of origin to a point of destination. Trips can be divided into vehicular and person trips. Vehicular trips can be converted to person trips, and vice versa, via a conversion factor. Trips made by persons younger than 5 years and person trips less than 300 meters in distance are usually ignored (Ortúzar and Willumsen, 2011).

Home-based (HB) Trip: A trip where the residence of the traveller is either the origin or destination of the trip (Ortúzar and Willumsen, 2011).

Non-home-based (NHB) Trip: A trip where neither the origin nor destination is the home/residence of the traveller (Ortúzar and Willumsen, 2011).

Trip production: is the home end of a home-based trip or as the origin of a non- home-based trip. (Ortúzar and Willumsen, 2011). Refer to Figure 3-2.

Trip attraction: is the non-home end of a home-based trip or the destination of a non-home-based trips (Ortúzar and Willumsen, 2011).

The figure below illustrates the trips movement as described under these terms.

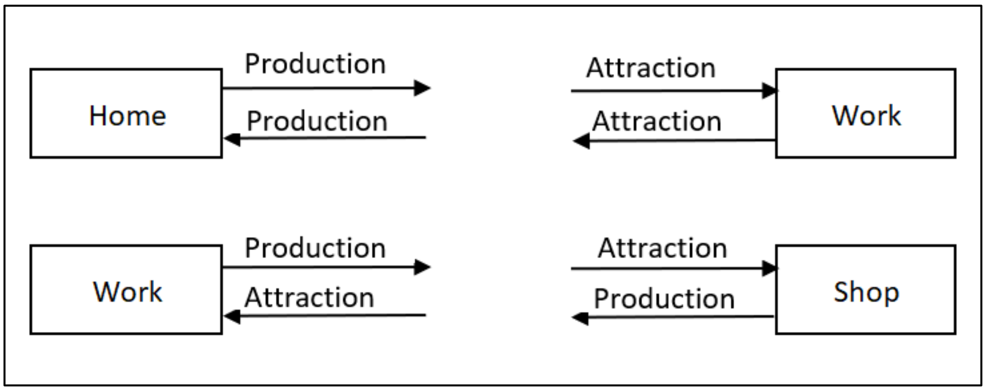

Figure 3-2: Trip Productions and Attractions (Ortúzar and Willumsen, 2011)

3.2.2 Trip Distribution

The primary objective of the trip distribution stage is to determine the number of trips produced by origins and attracted to destinations as per the corresponding zones (Ortúzar and Willumsen, 2011). Trip distribution is calculated as a function of distance and time. It is also dependant on the number of trips expected to occur between two zones. Trip distribution helps us to determine the following; the trip patterns on a network, modes of transport being used on the respective routes (trip patterns of different modes of transport) and congested routes (Ortúzar and Willumsen, 2011). At the trip distribution stage, of the four step modelling process, travel patterns can be represented as a trip matrix. The trip matrix shows all trips made from origins to destinations during a given time period. Another name for the trip matrix is the Origin-Destination (O-D) matrix (Ortúzar and Willumsen, 2011). It is important that the trip distribution on a network is calibrated as accurately as possible. This is to prevent the likelihood of the model distributing traffic volumes in an unrealistic manner. The model must distribute trips (traffic volumes) such that they represent the actual trips occurring on site.

To evaluate the efficiency of the trip distribution, on the road network, two OD matrices must be considered in the process. The first matrix is the OD matrix of the observed trips which were

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recorded on site. The second matrix is the OD matrix of the modelled trips which is produced by the SATURN software.

The purpose of comparing the two trip matrices is to check whether the traffic model is behaving such that the traffic flows in the model correspond to the traffic flows on site (Rasouli, 2018).

The process of comparing the trip distribution volumes produced by the software with the trip distribution volumes observed on site is a method of calibrating the Base Year trip matrix (Rasouli, 2018). The Base Year is defined as the year in which the strategic transport model has been developed and calibrated for (Robinson, 2017). For the purpose of this research project, as well as to correlate with the available land use and traffic information, the Base Year selected is 2018.

Accordingly, the SATURN strategic transport model used in this research project has been calibrated such that the traffic volumes/flows recorded for the Gauteng Freeway Improvement Project (GFIP) was replicated.

The figure below illustrates the movement of trips from origin i to destination j.

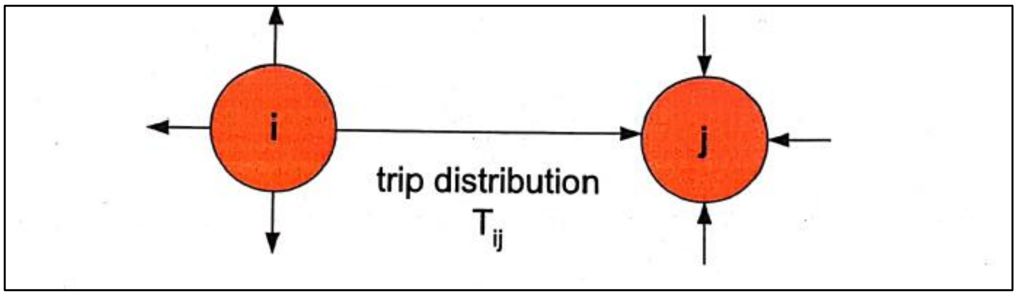

Figure 3-3: Illustration of Trips from Origin i to Destination j

3.2.2.1 The Gravity Distribution Model

The trip distribution model, used in this research project, is based on the Gravity Model to estimate the peak-hour O/D matrix between zones for the future/projected year (2038).

The doubly constraint gravity model is used to develop a strategic transport model as well as to estimate trip distribution on a network (Robinson, 2017). The gravity model is based on Isaac Newton's concept of gravity (Rasouli, 2018). The doubly constraint gravity model will be used to distribute trips on the Gauteng Freeway Improvement Project (GFIP) network in this research project. The equation below illustrates the form of a doubly constraint gravity model:

$$Tij=AiBjOiDj\mathrm{e}^{\beta C} \qquad \text{(Equation 3-1)}$$

Where:

Ai is the balancing constraint to satisfy the row totals for the origin trips (Oi);

Bj is the balancing constraint to satisfy the column totals for the attraction trips (Dj);

C represents the generalised cost of trips between the origin zone Oi and Dj;

B is a constant which is calibrated from survey data.

β is a critical factor in the calculation of the average trip lengths and therefore influences the trip distribution of trips on the network. Hence, β must be calibrated as accurately as possible before it is used in the gravity model (Robinson, 2017). The accuracy of the calibration of β is also crucial in this research project and therefore numerous calibration attempts were completed before achieving a β which was suitable for the trip distribution (distance-deterrence) function on the Gauteng Freeway Improvement Plan (GFIP) network. Once the β value has been determined, it can be manipulated such that different trip lengths and trip distributions can be investigated (Robinson, 2017).

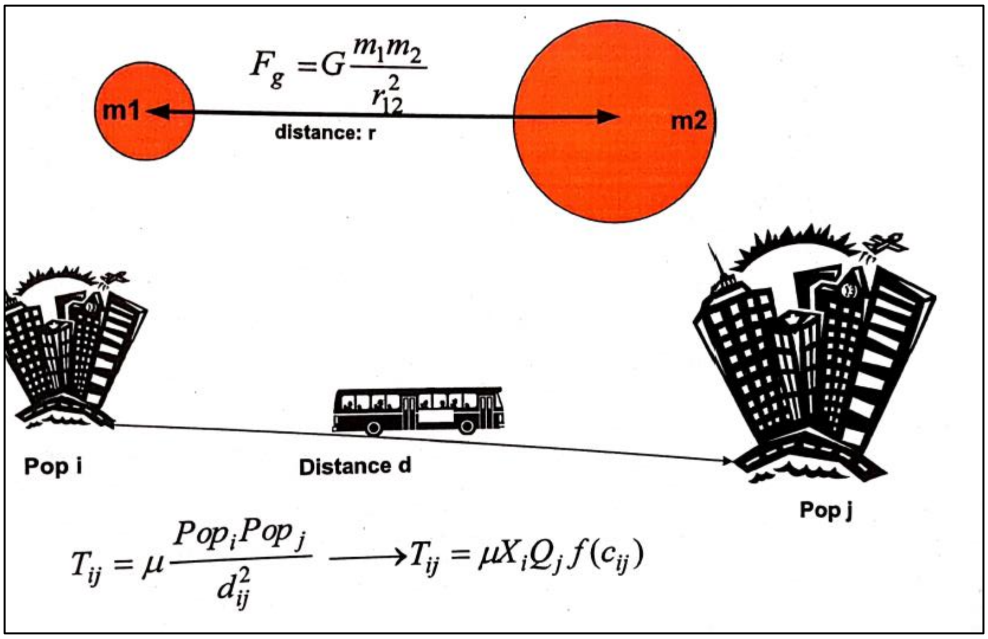

Figure 3-4: Graphical Representative of Trip Distribution Using the Gravity Model

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3.2.3 Modal Split

The primary objective of the modal split stage is to predict the modal split between the number of travellers (person trips) which will select a particular mode of transport offered to them; for e.g. the modal choice model can be used to predict the modal split between car and minibus taxi (Ortúzar and Willumsen, 2011).

The modal choice model is an important part of travel demand models because it influences how transportation planning is done while taking into account spatial planning and future developments which may include public transport infrastructure (Venter, 2018). Public transport plays a key role in policy making and modal choice affects the general efficiency in which people can travel in urban areas, the amount of urban space designated to transport functionality and services, as well as whether a range of mode choice is available to travellers (Ortúzar and Willumsen, 2011). Travelling in public transport enables the road space to be used efficiently, produce fewer accidents and emissions as compared to when personal cars are used by people. If people use public transport, then the level of serviceability of the road will be improved as there will be fewer vehicles on the road space. It is therefore important to develop and use modal choice models, which account accurately for those attributes of travel, which influence the choice of transport mode chosen by travelers (Ortúzar and Willumsen, 2011). The factors which influence the choice of mode chosen by travelers can be categorized as:

- Characters of the Trip maker;
- Characteristics of the Journey; and
- Characteristics of the Transport Facility.

***Note:** The importance of this stage in the four step modelling process has been acknowledged. The modal choice stage of the four step model will unfortunately not be included in the SATURN transport model due to the limitations of the modelling software. The SATURN software does not have the functionality of modelling public transport. Due to time and budget constraints, the acquiring of and adaptation of the GFIP model to another transport modelling software was not possible. Instead the aspect of the modal choice model which highlights an environment suitable for the implementation of a public transport system will be addressed using a theoretical approach based on literature and findings from the outputs obtained from the proof of concept process.

3.2.4 Trip Assignment

The trip assignment stage of the transport model (4 step model) is used by planners in order predict the route that travelers will use. This in essence will provide an idea of what trip demand each route would have. The trip assignment process starts by building a map representing the vehicle and transit network being investigated. This network map illustrates the possible routes which trips could be made from; i.e. the routes which travellers could use. The result of the trip assignment model indicates the routes that all trips will use as well as the traffic volume (person trips that can be converted into vehicle trips where needed) on each link in the network. The trip assignment model is the final stage in the 4 stage model and together with the preceding three stages (trip generation, trip distribution and modal choice models, provides transportation planners with realistic information as well as estimates of trips in a network. This information can be used to evaluate the effects that policies can have on the transport network and system in a network.

3.3 Deterrence Functions

To accurately model trips, while accounting for the impact of distance and time on travel behavior of drivers, a set of friction factors were included in the Gravity Model by researchers over the years (Rasouli, 2018). The Gravity Model in the original form (as per the Equation 3-2) was further generalized by considering that the effect of distance could be more accurately modelled by a decreasing function of the travel cost or distance cost between origin and destination zones (Ortúzar and Willumsen, 2011). This is represented by equation 3-3.

$T_{ij} \frac{\alpha P_i P_j}{D_{ij}^2}$ (Equation 3-2)

Where:

P_i is the population of the area’s origin;

P_j is the population of the area’s destination;

D_{ij} is the distance between origin (*i*) and destination (*j*); and

α is the proportionality factor in trips.distance^2/population^2

$T_{ij} = \alpha O_i D_j f(C_{ij})$ (Equation 3-3)

Where:

O_i is the total trip ends of the area’s origin;

D_i is the total trip ends of the area’s destination;

$f(C_{ij})$ is the generalised function of travel (distance) costs which includes one or more variables for calibration; and

α is the proportionality factor in trips.distance^2/population^2

The function represented in equation 3-3 is called the deterrence function because it signifies the disincentive of drivers travelling as distance (travel time) or cost increases (Ortúzar and Willumsen, 2011). The generalised function can be used in three different forms, as suggested by Ortúzar and Willumsen (2011), which are illustrated below:

$f(C_{ij}) = n * e^{(-\beta C_{ij})}$ exponential function (Equation 3-4)

$f(C_{ij}) = n * C_{ij}^{-n}$ power function (Equation 3-5)

$f(C_{ij}) = n * C_{ij}^{n} e^{-\beta C_{ij}}$ combined function (Equation 3-6)

In the above equations, C_{ij} is the term which has a direct influence on trip distribution on a network (Ortúzar and Willumsen, 2011). This term is known as the generalised cost which is expressed in terms of distance, time or a combination of distance and time (Ortúzar and Willumsen, 2011). The variables n and β are constants in the equation.

The different forms of the generalised function for cost (using different calibration variables) is illustrated in the figure below.

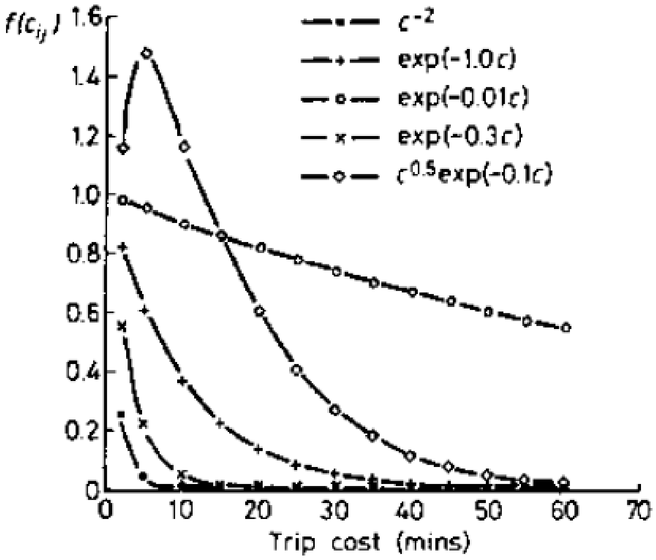

Figure 3-5: Different Forms f the Generalised Function for Cost (Ortúzar and Willumsen, 2011)

3.4 The Furness Method of Balancing Factors

An iterative method of estimating a trip matrix which satisfies both trip-end constraints, or two sets of growth factors, must be used to balance the trips at origins and destinations. The iterative method involves calculating a set of correction coefficients which are applied to rows and columns. Once the corrections have been applied (for each row), each column is summed and compared with the target totals. In the instance where the corrections have been applied to each column, the rows are summed and compared with the target totals. A method of this nature which has been applied in Transportation Modelling is the "*Furness Method"* of balancing factors.

The Furness Method is defined below:

Tij = tij x Ai x Oi x Bj x Dj (Equation 3-7, Ortúzar and Willumsen, 2011)

Where:

Tij is the future (grown matrix)

Tij is the base matrix

Oi is the production values or origin sum

Bj is the error in the columns

Dj is the destination sum attraction

"The most important condition required for the convergence of this method is that the growth rates produce target values Ti and Tj such that":

$\sum_i T_i \sum_j t_{ij} = \sum_i T_j \sum_i t_{ij} = T$ (Equation 3-8, Ortúzar and Willumsen, 2011)

"Enforcing this condition may require correcting trip-end estimates produced by the trip generation models." (Ortúzar and Willumsen, 2011)

3.5 Trip Length Calibration

O_i, D_i and $f(C_{ij})$ are values which differ from region to region and are also dependent on factors, such trip numbers and trip costs, relevant to those regions (Rasouli, 2018). As per *Figure 3-5* each generalised function for cost can be used to represent a different form of the deterrence function for transport modelling. When modelling trip lengths within the study network according to existing conditions, the first challenge lies in selecting the appropriate form of the generalised function for cost. Once the appropriate form of the function is selected, the second challenge lies in finding the values for the constants within the function which can be used to accurately calibrate the trip lengths within the study network according to existing conditions (Rasouli, 2018). For example, if the appropriate form of the generalised function for cost for the study network is equation 3-4, then the constants would be n and β. The exercise of determining the suitable values for the constants is known as the calibration stage of the modelling process (Rasouli, 2018). According to Shrewsbury (2012) the calibration stage of a transport model is a complicated process and he suggests that even though certain analytical methods have been included in some modelling packages, the conventional trial and error methods (first principals) may still be used to determine these constants.

The purpose of the calibration stage of a transport model is to determine, as close as possible, suitable values for these constants such that the transport model's performance is optimized to accurately replicate the trip distribution conditions as per the site observations (Rasouli, 2018). The different components of the transport model can be calibrated using the appropriate method. The different components of the transport model include travel times, queues, travel distance, traffic volumes and trip delay. For the purpose of this research project the friction factors in the Gravity Model will be calibrated and this process is known as the calibration of the trip lengths (Rasouli, 2018). The term 'trip lengths' refers to the actual distance travelled by drivers. Upon completion of the calibration of the friction factors through the determination of values for the constants according to the existing conditions of the study network, the Gravity Model is then considered as being calibrated such that it incorporates the trip lengths of the conditions of the existing trip lengths on the study network (Rasouli, 2018). This means that the Gravity Model can be used to reflect the actual trip lengths on the study network. In the instance where the Gravity Model has been calibrated as accurately as possible, it can be understood that the trip distribution function has been calibrated for different trip purposes. Having a calibrated Gravity Model means that the transport model has been calibrated for trip distribution and therefore means that realistic traffic/ trip distribution can be achieved by the transport model. According to Rasouli (2018) transport modellers in the past approached calibrating process of models by only calibrating parameters for travel time and traffic volumes on road links and focused less on calibrating the trip distribution of the model. This results in the errors being carried through to the following steps of the four-step modelling process (modal split and trip assignment). The consequence of not calibrating the trip distribution is that the transport model will assign trips on the study network unrealistically.

The importance of calibrating the trip distribution function of a study network has been highlighted in the discussion above. Rasouli (2018) published a PhD titled *"Calibrating the Distance-*

Deterrence Function for the Perth Metropolitan Area" in January 2018 which focuses primarily on the calibration of a distance-deterrence function. The calibration of a distance-deterrence function is a crucial key step in achieving the outcomes of this research project. The methodology and findings of the thesis presented by Rasouli (2018) was closely consulted to gain a better understanding of the subject of the calibration of a distance-deterrence function. The aim of the thesis presented by Rasouli (2018) focused on investigating distance-deterrence functions and the calibration of the parameters associated with work trips. The study area was the metropolitan area in Perth. The objectives of the study can be summarized as follows:

- The investigation and documenting of findings from similar studies completed by other researchers;
- The investigation and calibration of different deterrence functions based on the metropolitan area in Perth;
- The development of a transport model for the metropolitan area in Perth;
- The use of appropriate software to calibrate and fit the most suitable deterrence function for work trips within the study area; and
- The investigation of the performance of the deterrence functions (which have been calibrated) using the strategic transport model developed for the metropolitan area in Perth as well as discussion of outcomes.

The author of this research project recognises that, apart from the thesis presented by Rasouli in 2018, there is little existing literature and studies available pertaining to the topic of 'calibrating distance-deterrence functions'. Therefore, the thesis presented by Rasouli in 2018 has been closely referred to in order to achieve a calibrated distance-deterrence function which is required for achieving the outcomes of this research project. It is concluded that due to a deficiency in research in this topic, the material and findings presented in this research project will contribute to industry knowledge.

With the relevant environment adaptations, the methodology and proof of concept used in this research project can be applied to other study areas.

3.6 Origin-Destination (OD) Trip Matrix Estimation

Origin-destination (OD) matrices are an important source of traffic flow (demand) information required for the development of accurate transport models (Doblas and Benitez, 2004). There are three methods to estimate OD matrices:

- Acquiring trip data from home-based, registration plates or roadside surveys;

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- Using a trip distribution model (such as a gravity model); and
- Updating an existing OD matrix by using the most recent traffic counts as measurements of flows on links on the study network.

Doblas & Benitez (2004) consider option ‘a’ as the method which yields results with the highest accuracy. However, the process and requirements of carrying out an extensive survey to acquire the relevant data for accurate OD matrices is very expensive (Robinson, 2017). Option ‘b’ does not provide accurate results and is mainly used for quick calculations (Doblas & Benitez, 2004). The gravity, opportunity and gravity opportunity models use techniques which include entropy maximisation and generalised least squares estimators as well as using a non-linear programming approach using software (Robinson, 2017). Option ‘c’ is the method which has been used frequently over the past two decades and is still the popular method used today (Doblas & Benitez, 2004). Traffic counts can be measured automatically by placing devices such as loop detectors on relevant links on the road network. This makes option ‘c’ advantageous over the others because it eliminates the need for expensive interviews, the manipulation of data, checks and validation (Doblas & Benitez, 2004).

The accuracy of the OD matrix depends on the following:

- The algorithm used in the model for trip distribution (all or nothing trip assignment, equilibrium trip assignment and stochastic trip assignment);
- The method used to estimate the OD matrix;
- The level of reliability and independence of the traffic counts;
- The detail level of the zoning system used to zone the land use in the model; and
- The level of accuracy of the prior trip matrix used as the base matrix in the matrix estimation method selected.

Traffic volumes on links in a road network are dependent on the combination of a trip matrix and route choice of drivers (Ortúzar and Willumsen, 2011). This means that the sum of all OD pairs (on a link) in the OD matrix adds up to the traffic count on the respective link. It is an impossible task to create a unique matrix which has balanced traffic counts for large scale models from only zone connectors as the source. Instead, by using a gravity model or prior matrix combined with zonal trip-end constraints as a starting point and by using entropy maximizing techniques, an acceptable unique matrix solution can be achieved (Robinson, 2017).

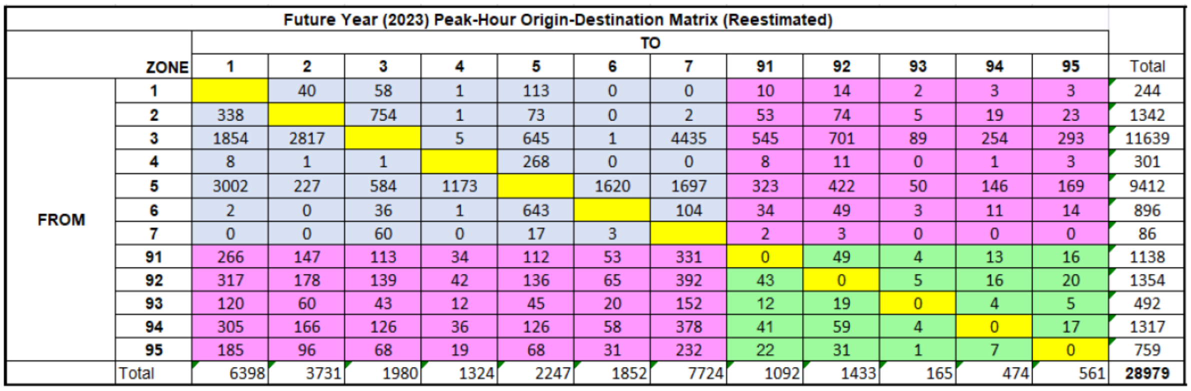
Ortúzar & Willumsen (2011) show that traffic on a section of road (road link) results from the combination of a trip matrix and route choice. This combination of a trip matrix and route choice forms the total origin-destination (OD) pairs which use the specific link within the road network.

The accuracy of the resultant matrix will depend on the volume of traffic counts. The higher the volume of traffic counts then there will be more OD pairs involved in the OD matrix.

The main purpose of obtaining the required data for optimisation of the matrix estimation process is to ensure that:

- The data obtained can be relied on and is consistent;
- The data is independent of each other;
- The amount of data measurements is optimised; and
- The data relates to the least number of OD pairs (Robinson, 2017).

The figure below is an example of a peak-hour OD matrix for a small town.



Future Year (2023) Peak-Hour Origin-Destination Matrix (Reestimated)														
		TO												
	ZONE	1	2	3	4	5	6	7	91	92	93	94	95	Total
FROM	1		40	58	1	113	0	0	10	14	2	3	3	244
	2	338		754	1	73	0	2	53	74	5	19	23	1342
	3	1854	2817		5	645	1	4435	545	701	89	254	293	11639
	4	8	1	1		268	0	0	8	11	0	1	3	301
	5	3002	227	584	1173		1620	1697	323	422	50	146	169	9412
	6	2	0	36	1	643		104	34	49	3	11	14	896
	7	0	0	60	0	17	3		2	3	0	0	0	86
	91	266	147	113	34	112	53	331	0	49	4	13	16	1138
	92	317	178	139	42	136	65	392	43	0	5	16	20	1354
	93	120	60	43	12	45	20	152	12	19	0	4	5	492
	94	305	166	126	36	126	58	378	41	59	4	0	17	1317
	95	185	96	68	19	68	31	232	22	31	1	7	0	759
	Total	6398	3731	1980	1324	2247	1852	7724	1092	1433	165	474	561	**28979**

Figure 3-6: An Example of a Peak-Hour Origin-Destination Matrix (Govender, 2018)

3.7 Summary

This chapter provided an explanation of the essential methods and concepts used in this study to achieve the objectives. The purpose of this chapter is to explain the concepts and methods involved in this study in a simple manner such that the reader is able to understand the content being discussed.

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4 Data Collection for Model Inputs

4.1 Source and Extent of the Traffic and Land Use Data used in the GFIP Traffic Model

The traffic data and land use information relating to the GFIP road network, used to develop the strategic transport model, was provided by the South African National Roads Agency Ltd (SANRAL).

The road network of the Gauteng Freeway Improvement Project (GFIP) extends over approximately 201 km of the freeway in Gauteng. There are 45 structures, with radar technology, erected at a spacing of approximately 10km between them. Figure 4-1 provides an illustration of the road network for GFIP.

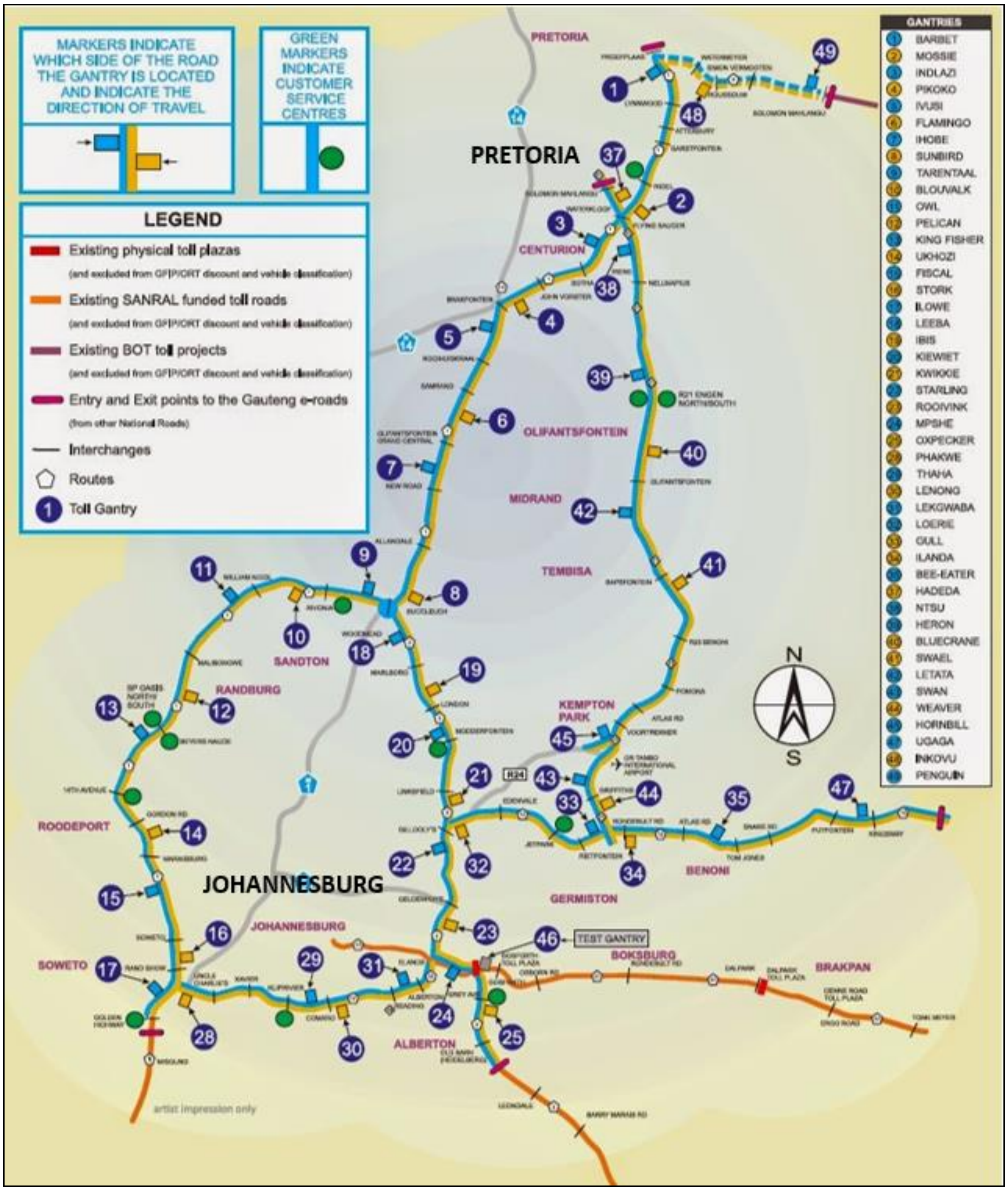

Figure 4-1: GFIP Freeway Layout (SANRAL Toll Strategy, 2019)

4.2 Traffic Data used in the GFIP Strategic Transport Model

The structures with radar technology on the GFIP network have the ability to count and classify vehicles as they pass underneath them. The open road tolling (ORT) equipment then converts the traffic counts (per vehicle class, day of the week and time of day) into traffic flows (per vehicle

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class, day of the week and time of day). This data is then communicated by the ORT equipment to the Central Operations Centre (COC) in Midrand, Johannesburg. SANRAL provided access to the traffic counts database as well as additional traffic counts (obtained from comprehensive observation stations or CTO stations) from on-ramps and off-ramps leading to and away from the GFIP network. The extensive traffic data assisted with the assignment of trips in the strategic transport model for GFIP using the SATURN software.

The 24-hour traffic data obtained from the structures with radar technology and CTO stations contained the following information:

- Traffic volumes for vehicle class A2 (light vehicles) for each lane group;
- Traffic volumes for vehicle class B (short heavy vehicles + 0.5*medium heavy vehicles) for each lane group; and
- Traffic volumes for vehicle class C (0.5*medium heavy vehicles + long heavy vehicles) for each lane group.

The table below presents an extract of the traffic data obtained from the structures with radar technology and CTO stations provided by SANRAL.

The relevant columns for this study are listed and discussed briefly below:

Columns 1 and 7: Contains the CTO station numbers at which traffic counts were collected. This information was important for the updating of the 2006 GFIP Strategic Transport Model. The location of each CTO station, on a Google Earth file, was used to check whether each traffic assignment on the GFIP Strategic Transport Model was realistic. The updating of the traffic assignment based on updated traffic counts was completed using the CTO station location on the Google Earth file, the raw traffic data and the modelled assignments completed by the SATURN software. This process is further explained in the next chapter.

Columns 2 and 8: Represents the lane groups on which the traffic volumes were recorded. This information is important for the traffic assignment process completed during the model update process. Assigning traffic volumes to the incorrect lane group will result in an inaccurate strategic transport model. The resulting consequences of this includes inaccurate locations of high congestion areas, wrong road infrastructure being identified as requiring capacity improvements, incorrect peak periods and incorrect annual average daily traffic (AADT) for the different road sections.

Column 3: Lists the start and end nodes between which traffic volumes move. This is very important in transport modelling as it reflects the direction of traffic movement between nodes.

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This in turn is used to calculate travel delays, identify congestion locations, possible road infrastructure which require capacity improvements, AADT, the different peak periods and is used to develop the origin-destination trip matrix. The origin-destination trip matrix is often used for traffic forecasting and is also used for toll feasibility studies. Therefore, the assignment of traffic volumes to the correct node pair is crucial for in any transport model.

Columns 4 and 5: Lists the start (A) and end (B) nodes, listed in column 3, individually.

Column 6: Provides the traffic volumes per user class as well as the total traffic volume for that particular section of road between the corresponding A and B nodes.

Columns 9, 10 and 11: Provide information relating to the details of the ramps and road sections on which the corresponding traffic volumes move. This is essence provides a partial idea of the origins and destinations of portions of traffic volumes on the network.

Table 4-1: An Extract of the Traffic Data obtained from the structures with radar technology, CTO stations and SANRAL

1	2	3		4	5	6						7	8	9	10	11
* Station	LG	A NODE-B NODE	*	* A NODE	B NODE	UC					Spd					
			*	* Start Hour	7.00	1	2	3		*	4	CTO	LG			
13	1	2713-9873		2713	9873	1211	65	11	1288	*	0	13	1	Paul Kruger Ext	North	To R566 (K8)
13	2	9873-2713		9873	2713	1096	60	17	1172	*	0	13	2	Paul Kruger Ext	South	To Wonderboompoort
33	1	2443-11354		2443	11354	280	17	8	305	*	0	33	1	Doornrandjies	North	To Hartbeespoortdam
33	2	11354-2443		11354	2443	381	9	2	392	*	0	33	2	Doornrandjies	South	To Diepsloot
41	1	10376-10375		10376	10375	1061	50	10	1121	*	0	41	1	Poortview AH(BL)	East	To Ruimsig
41	2	10375-10376		10375	10376	1065	103	24	1192	*	0	41	2	Poortview AH(BL)	West	To Tarlton
45	1	6493-6490		6493	6490	247	28	8	283	*	0	45	1	Tarlton	East	To Krugersdorp
45	2	6490-6493		6490	6493	192	22	7	222	*	0	45	2	Tarlton	West	To Magaliesburg
57	1	9400-3118		9400	3118	1403	37	8	1448	*	0	57	1	Fourways Gardens	North	To Broadacres AH
57	2	3118-9400		3118	9400	1223	39	5	1267	*	0	57	2	Fourways Gardens	South	To Fourways
70	1	5309-3532		5309	3532	367	18	20	405	*	0	70	1	Westonaria North	North	To Randfontein
70	2	3532-5309		3532	5309	538	25	19	582	*	0	70	2	Westonaria North	South	To Vereeniging
72	1	11908-3620		11908	3620	300	14	19	333	*	0	72	1	Westonaria South(BL)	North	To Randfontein
72	2	3620-11908		3620	11908	317	16	16	350	*	0	72	2	Westonaria South(BL)	South	To Vereeniging
86	1	4915-11858		4915	11858	1428	37	55	1520	*	0	86	1	Kliprivier WIM	North	To Alberton
86	2	11858-4915		11858	4915	802	61	51	914	*	0	86	2	Kliprivier WIM	South	To Vereeniging
95	1	5482-9642		5482	9642	164	10	16	190	*	0	95	1	Spaarwater AH	North	To Dalpark
95	2	9642-5482		9642	5482	197	11	4	212	*	0	95	2	Spaarwater AH	South	To Heidelberg
108	1	4116-9203		4116	9203	320	23	3	346	*	0	108	1	Modderfontein Rd(CM)	East	To Birchleigh
108	2	9203-4116		9203	4116	1333	22	9	1364	*	0	108	2	Modderfontein Rd(CM)	West	To Modderfontein
110	1	3985-11523		3985	11523	804	8	5	818	*	0	110	1	Alan Manor	North	To Jhb CBD
110	2	11523-3985		11523	3985	544	6	2	552	*	0	110	2	Alan Manor	South	To Kibler Park
123	1	6445-11299		6445	11299	128	9	13	150	*	0	123	1	Magaliesburg (RH)	East	To Magaliesburg
123	2	11299-6445		11299	6445	134	15	16	165	*	0	123	2	Magaliesburg (RH)	West	To Rustenburg
127	1	5594-12080		5594	12080	135	16	10	161	*	100	127	1	Bronkorstspruit (RM)	East	To Bronkhorstspruit
127	2	12080-5594		12080	5594	155	9	6	170	*	103	127	2	Bronkorstspruit (RM)	West	To Bapsfontein
131	1	2372-11632		2372	11632	366	19	12	397	*	0	131	1	Pyramid (BH)	North	To Bela Bela
131	2	11632-2372		11632	2372	483	19	16	518	*	0	131	2	Pyramid (BH)	South	To Paramid
133	1	5668-10618		5668	10618	222	19	13	254	*	2	133	1	R25 Bapsfontein	North	To Bronkhorstspruit
133	2	10618-5668		10618	5668	299	15	11	325	*	2	133	2	R25 Bapsfontein	South	To Bapsfontein
139	1	11795-11792		11795	11792	222	19	13	254	*	2	139	1	Moloto (BH)	North	To Moloto
139	2	11792-11795		11792	11795	299	15	11	325	*	2	139	2	Moloto (BH)	South	To Pretoria
140	1	2314-2510		2314	2510	1150	29	14	1193	*	0	140	1	Mabopane (CH)	North	To Soshanguve
140	2	2510-2314		2510	2314	1929	39	13	1980	*	0	140	2	Mabopane (CH)	South	To Akasia
141	1	2418-9915		2418	9915	147	11	5	163	*	0	141	1	Wes Moot (BM)	East	To Pretoria
141	2	9915-2418		9915	2418	135	13	5	153	*	0	141	2	Wes Moot (BM)	West	To Brits
151	1	3645-3644		3645	3644	235	12	17	264	*	0	151	1	Glenharvie HSWIM	East	To Johannesburg
151	2	3644-3645		3644	3645	279	21	22	321	*	0	151	2	Glenharvie HSWIM	West	To Potchefstroom

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4.3 Land Use Data used in the GFIP Strategic Transport Model

A brief overview of the model input information, pertaining to the land use information provided by SANRAL, is as follows:

- Trip ends for low, medium and high-income households (for years 2010 and 2015);
- Trip ends for employment activity. These trips have been split into trips pertaining to retail, office, industrial, commercial and local serving trips; and
- Trips made by heavy vehicles categorized into retail, industrial and heavy activity trips.

Table 4-2 represents an extract of the land use trip ends data provided by SANRAL.

The table provides the number of trips for households and employees for the years 2010 and 2015. The data for the year 2015 was used in the 2018 (base year) model. Information for year 2015 was used since newer data could not be obtained within a reasonable timeframe which allowed sufficient time for the completion of this research project.

The trips generated by household (residential) zones have been separated into low, medium and high-income households. This plays a role in forecasting the data for future land use changes and growths.

The trips attracted by employment zones have been separated into categories for retail, office, industrial, commercial and local services. Again, this plays a role in forecasting the data for future land use changes and growths.

These trips relating to the trip generating zones (residential zones) and trip attracting zones (employment zones) were included in the origin-destination trip matrix used in the GFIP strategic transport model to accurately and realistically model trips/traffic volumes between zones.

Table 4-2: An Extract of the Land Use Trip Ends Data provided by SANRAL

TOLL STUDY:		2015						alanr: Input % Low to be included			2010								
Car Ownership Growth	High	0.25%		Medium	1.50%														
Years	5																		
AREA		2015 RESIDENTIAL				2015 BASE YEAR EMPLOYMENT					2010 Residential				2010 BASE YEAR EMPLOYMENT				
Description	Model Zone	Households			+ 10% Low	FORMAL WORKERS					Households			+ 10% Low	alanr: Input % Low to be included			RS	
		High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving	High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving
	Gen Rate	1.519			0.539	0.200	0.600	0.200	0.600	0.200									
2005 Data		666217	1009825	1854567	1195282	543384	924951	680447	59275	416750									
Annual Growth		1.96%	1.97%	0.77%	1.79%	3.51%	3.97%	3.24%	3.44%	1.87%									
		1.34%				3.35%													
TOTALS		733939	1113554	1926905	1306245	645577	1123941	798091	70199	457181	666217	1009825	1854567	1195282	543384	924951	680447	59275	416750
Winterveld	1	52	735	3989	1134	242	50	0	0	603	52	718	4137	1132	242	50	0	0	603
Winterveld	2	470	4002	11772	5179	1026	63	20	0	1663	466	3907	12210	5128	1026	63	20	0	1663
Soshanguve	3	134	2744	8299	3574	93	13	0	0	803	132	2679	8608	3540	82	7	0	0	772
Soshanguve	4	214	7941	11553	9096	81	21	0	0	1447	212	7752	11982	8950	81	21	0	0	1447
Soshanguve	5	1797	11265	8256	12091	718	99	77	0	1414	1780	10997	8529	11850	718	35	77	0	1414
Mabopane	6	1167	7852	10150	8867	3444	405	850	0	1455	1156	7665	10229	8688	3076	405	770	0	1455
Mabopane Prison	7	303	4551	9620	5513	408	162	0	0	993	300	4443	9978	5441	298	52	0	0	701
Soshanguve	8	827	3540	3630	3903	83	11	0	0	756	819	3456	3753	3831	83	11	0	0	756
Soshanguve	9	44	2443	15780	4021	141	146	0	0	1516	44	2385	15739	3959	141	146	0	0	1516
Klip- Kruisfontein	10	105	4628	5406	5168	65	11	0	0	597	104	4517	5607	5078	65	11	0	0	597
Garankuwa Industrial	11	136	3803	11413	4944	1214	80	6168	0	1199	134	3712	11805	4893	884	80	6085	0	1199
Garankuwa	12	178	3715	4423	4158	529	410	0	0	1060	176	3627	4588	4086	183	202	0	0	572
Medunsa	13	12	248	300	278	3	3	0	0	5650	12	242	306	272	2	2	0	0	5648
Itsoseng	14	57	752	7683	1521	88	71	0	0	603	57	734	7821	1517	88	71	0	0	603
Klip- Kruisfontein	15	21	793	5968	1390	91	38	0	0	329	21	774	6178	1392	91	38	0	0	329
Noord van Rosslyn	16	71	925	9040	1829	715	229	0	0	1151	70	903	7963	1700	366	70	0	0	883
Rosslyn	17	0	6	75	13	375	0	35980	0	141	0	6	70	13	374	0	29856	0	140
Wes van Rosslyn	18	0	956	2687	1225	117	88	0	0	234	0	664	0	664	29	22	0	0	49
Suid van Rosslyn	19	35	2365	4695	2834	396	251	0	0	913	35	1717	3820	2099	192	108	0	0	477
Orchards	20	1737	1511	95	1521	179	76	263	0	243	1721	1234	98	1243	143	52	263	0	186
Clarina	21	41	349	83	357	369	7	0	0	81	40	322	86	330	368	6	0	0	79
Klerksoord	22	13	53	95	62	0	0	10579	519	20	13	51	94	61	0	0	7717	278	20
Soshanguve	23	33	1470	6399	2110	16	2	0	0	696	33	1435	6632	2098	16	2	0	0	696
Nuwe Eersterus/Stinkwater	24	0	5112	15339	6646	1117	382	0	0	1761	0	4990	15850	6575	1117	282	0	0	1761
Temba/Dilopye	25	332	3883	12721	5155	882	208	0	0	1718	329	3791	13194	5110	496	80	0	0	1389
Temba/Babelegi	26	116	5797	11486	6946	2218	889	12397	0	1414	115	5659	11864	6846	1862	780	12230	0	1414
Refilwe Block G	27	1	55	1024	157	86	19	0	0	159	1	53	443	98	10	2	0	0	34
Wonderboom Farms	28	63	262	2913	553	52	26	0	0	252	62	256	2958	552	52	26	0	0	252
South of Temba	29	0	1445	10630	2508	298	85	0	0	761	0	1411	10952	2506	159	85	0	0	761
Wonderboom Farms	30	14	52	229	75	1	1	0	0	20	14	51	202	71	0	0	0	0	13
Wonderboom Farms	31	6	25	124	37	1	1	0	0	22	6	24	93	33	0	0	0	0	14

TOLL STUDY:		Difference									2015								
Car Ownership Growth	High											Factor	86.9%						
Years	5																		
AREA		2010-2005 RESIDENTIAL				2010-2005 BASE YEAR EMPLOYMENT					2011 RESIDENTIAL				2011 BASE YEAR EMPLOYMENT				
Description	Model Zone	Households			+ 10% Low	alanr: Input % Low to be included			RKERS		Households			+ 10% Low	FORMAL WORKERS				
		High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving	High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving
	Gen Rate																		
2005 Data		666217	1009825	1854567	1195282	543384	924951	680447	59275	416750	666217	1009825	1854567	1195282	543384	924951	680447	59275	416750
Annual Growth		10.17%	10.27%	3.90%	9.28%	18.81%	21.51%	17.29%	18.43%	9.70%	8.83%	8.93%	3.39%	8.07%	16.34%	18.70%	15.02%	16.01%	8.43%
		6.91%				17.91%					0.98%				2.44%				
TOTALS		67722	103729	72338	110963	102193	198991	117645	10924	40431	725067	1099966	1917429	1291709	632190	1097874	782680	68768	451884
Winterveld	1	0	18	-148	3	0	0	0	0	0	52	733	4008	1134	242	50	0	0	603
Winterveld	2	4	95	-438	51	0	0	0	0	0	469	3989	11829	5172	1026	63	20	0	1663
Soshanguve	3	1	65	-309	34	11	6	0	0	31	133	2736	8340	3570	91	13	0	0	799
Soshanguve	4	2	189	-430	146	0	0	0	0	0	214	7916	11609	9077	81	21	0	0	1447
Soshanguve	5	17	268	-273	241	0	64	0	0	0	1795	11230	8292	12059	718	90	77	0	1414
Mabopane	6	11	187	-79	179	368	0	80	0	0	1166	7827	10160	8843	3395	405	840	0	1455
Mabopane Prison	7	3	108	-358	73	111	110	0	0	292	303	4537	9667	5504	394	147	0	0	954
Soshanguve	8	8	84	-123	72	0	0	0	0	0	826	3529	3646	3894	83	11	0	0	756
Soshanguve	9	0	58	41	62	0	0	0	0	0	44	2435	15775	4013	141	146	0	0	1516
Klip- Kruisfontein	10	1	110	-201	90	0	0	0	0	0	105	4613	5433	5156	65	11	0	0	597
Garankuwa Industrial	11	1	90	-392	51	331	0	83	0	0	136	3791	11464	4937	1171	80	6158	0	1199
Garankuwa	12	2	88	-165	72	346	208	0	0	488	178	3704	4445	4148	483	383	0	0	996
Medunsa	13	0	6	-6	5	1	1	0	0	2	12	247	301	277	3	2	0	0	5650
Itsoseng	14	1	18	-137	4	0	0	0	0	0	57	750	7701	1520	88	71	0	0	603
Klip- Kruisfontein	15	0	19	-210	-2	0	0	0	0	0	21	790	5995	1390	91	38	0	0	329
Noord van Rosslyn	16	1	22	1076	130	349	158	0	0	268	71	923	8899	1812	670	208	0	0	1116
Rosslyn	17	0	0	5	1	0	0	6124	0	1	0	6	74	13	375	0	35178	0	141
Wes van Rosslyn	18	0	292	2687	560	88	66	0	0	185	0	918	2335	1151	105	79	0	0	210
Suid van Rosslyn	19	0	648	874	735	204	143	0	0	436	35	2280	4580	2738	369	232	0	0	856
Orchards	20	16	278	-4	277	36	24	0	0	57	1735	1475	95	1485	174	73	263	0	236
Clarina	21	0	27	-3	27	1	1	0	0	1	41	345	83	353	369	7	0	0	81
Klerksoord	22	0	1	1	1	0	0	2862	240	0	13	52	95	62	0	0	10204	487	20
Soshanguve	23	0	35	-234	12	0	0	0	0	0	33	1465	6429	2108	16	2	0	0	696
Nuwe Eersterus/Stinkwater	24	0	122	-511	71	0	100	0	0	0	0	5096	15406	6637	1117	369	0	0	1761
Temba/Dilopye	25	3	92	-473	45	386	127	0	0	329	332	3871	12783	5149	831	191	0	0	1675
Temba/Babelegi	26	1	138	-377	100	356	110	167	0	0	116	5779	11536	6933	2172	875	12375	0	1414
Refilwe Block G	27	0	1	581	59	76	17	0	0	125	1	54	948	149	76	17	0	0	142
Wonderboom Farms	28	1	6	-44	2	0	0	0	0	0	63	261	2919	553	52	26	0	0	252
South of Temba	29	0	34	-322	2	139	0	0	0	0	0	1441	10672	2508	280	85	0	0	761
Wonderboom Farms	30	0	1	27	4	1	1	0	0	7	14	52	225	74	1	1	0	0	19
Wonderboom Farms	31	0	1	31	4	1	1	0	0	8	6	24	120	36	1	1	0	0	21

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4.4 Summary

This chapter discusses the data provided and selection of the relevant data required for the transportation modelling process used in this study.

5 Development of the Strategic Transport Model for GFIP

This chapter describes the methodology followed in developing the strategic transport model using the SATURN modelling software. The calibration steps followed to check whether the strategic transport model assigned traffic flows realistically are included in this chapter. The calibration of the traffic assignment on the network played a crucial role in developing a distance-deterrence function. The development and calibration of the distance-deterrence function is addressed in Chapters 6 and 7.

The base year (2018) data used in the GFIP traffic model comprises of the following main elements:

- Road network data (road link lengths, number of lanes, operating and free flow speeds);
- Travel time survey data;
- Land use data;
- Trip generation rates related to land use; and
- Traffic counts.

5.1 Updating of the Existing Gauteng Freeway Improvement Project Strategic Transport Model

5.1.1 Warranting Reasons for the Update

The version of the GFIP transport model provided by SANRAL required extensive updating and calibrating. The road network of the existing strategic transport model was outdated in terms of the geometric layout of the road network. It also did not include the upgraded layouts of several interchanges on the GFIP road network. This affected the assignment of traffic volumes on the various links. This would result in inaccuracies and errors in the distribution of trips on the network. These factors would affect the accuracy of the outcomes of this study.

There are various reasons which make it necessary to update the existing strategic transport model. Some of these include:

- To ensure that traffic distribution is assigned realistically on the network;
- To ensure that the traffic assignment on the model presents an accurate representation of the traffic assignment on site;

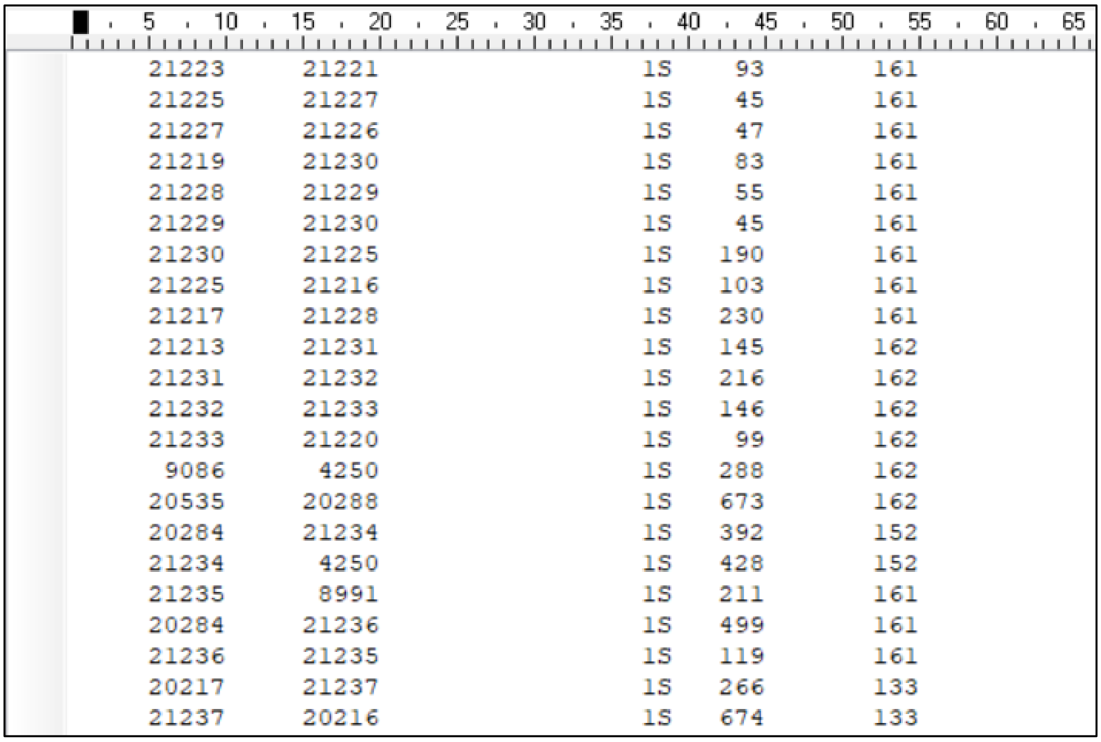
- To be able to extract, from the model, accurate information pertaining to trip distribution, travel times, traffic flows and congestion levels which could be used to evaluate the functionality of road sections included in the road network; in this instance, on the GFIP road network.
- To ensure that all future road planning including provincial and metropolitan roads planned for construction are included in the model;
- Ensuring that land use forecasts are reflected in the traffic model which can be used to evaluate traffic generation and distribution as a result of new developments in these areas;
- To enable funding agencies and road authorities to be able to accurately model traffic scenarios required for the determination of revenue streams; and
- To enable road agencies to assess and evaluate proposed upgrade projects for future implementation on the road network.

5.1.2 Methodology Applied for Model Updating Process

The existing strategic transport model was updated in the following manner:

- The land use data was reviewed and possibility of a more recent set of land use data was investigated;
- A thorough assessment of the road network layout in the existing model was completed. This involved inspecting and updating the orientation and configuration of each interchange, off-ramp and onramp which linked onto the main roads on the GFIP road network. The purpose of the inspection was to ensure that the orientation and configuration of these infrastructure elements corresponded to the latest infrastructure designs implemented on site. Two approaches were used to update the road network infrastructure: one method is to graphically edit the road network using the *P1X* module available in the SATURN software; the second method is to use hard coding (using a text reader called *Context* to store code cards as specified in the SATURN software manual). *Figure 5-1* contains an extract of the coding done in *Context* containing changes to reflect the updated network layout for a particular section of the GFIP network. *Figure 5-2* provides the graphical method of updating the network layout available on the SATURN software. *Figure 5-3* provides an example of a typical interchange after the updating of its layout and configuration. This image has been extracted from the SATURN software. The same approach was used to update the geometric layout of the remaining interchanges included in the GFIP network;
- After the orientation and layout of interchanges and ramps were updated, traffic was assigned to the GFIP strategic transport model. Thereafter, checks were completed to verify that the SATURN traffic modeling software was assigning traffic flows such that there was a correlation between modelled and observed traffic flows. Modelled flows are the flows

assigned on the network by the SATURN software and observed flows are the flows obtained through traffic counts on site. *Table 5-1* provides an extract from the database which contains the observed traffic flows for the base year, 2016. The calibration process of the observed and modelled traffic flows will be addressed in section 5.2 of this research project.



```
     21223     21221                  1S   93       161
     21225     21227                  1S   45       161
     21227     21226                  1S   47       161
     21219     21230                  1S   83       161
     21228     21229                  1S   55       161
     21229     21230                  1S   45       161
     21230     21225                  1S  190       161
     21225     21216                  1S  103       161
     21217     21228                  1S  230       161
     21213     21231                  1S  145       162
     21231     21232                  1S  216       162
     21232     21233                  1S  146       162
     21233     21220                  1S   99       162
      9086      4250                  1S  288       162
     20535     20288                  1S  673       162
     20284     21234                  1S  392       152
     21234      4250                  1S  428       152
     21235      8991                  1S  211       161
     20284     21236                  1S  499       161
     21236     21235                  1S  119       161
     20217     21237                  1S  266       133
     21237     20216                  1S  674       133
```

Figure 5-1: An Extract of the Hard Coding in Context used to Update the Layout of an Interchange

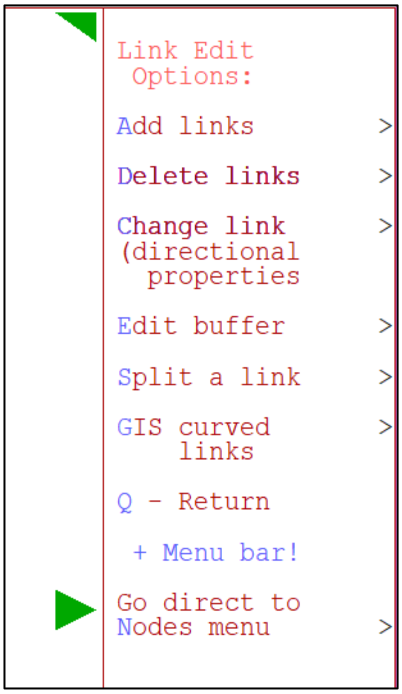


Figure 5-2: The Graphical Edit Option in the Saturn Software

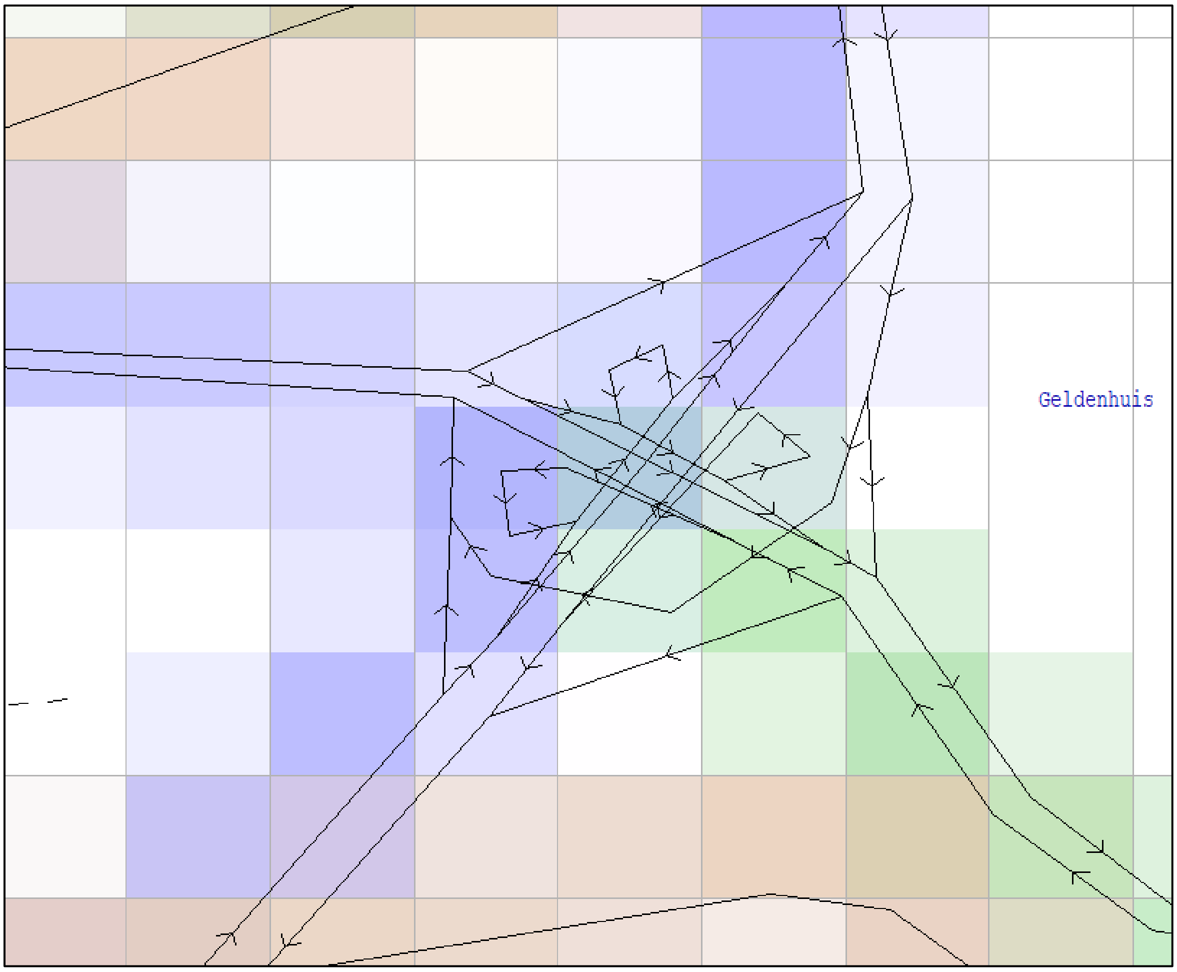


Figure 5-3: Updated Layout and Orientation of the Geldenhuis Interchange

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Table 5-1: An Extract from the Database containing Observed Traffic Flows for the Base Year (2018)

* A	B	C	FLOWS PER USER CLASS					Spd						
* Start Hour	7.00		1	2	3	TOTAL	*	4	CTO	LG				
2713	9873		1211	65	11	1288	*	0	13	1	Paul Kruger Ext	North	To R566 (K8)	4%
9873	2713		1096	60	17	1172	*	0	13	2	Paul Kruger Ext	South	To Wonderboompoort	5%
2443	11354		280	17	8	305	*	0	33	1	Doornrandjies	North	To Hartbeespoortdam	5%
11354	2443		381	9	2	392	*	0	33	2	Doornrandjies	South	To Diepsloot	5%
10376	10375		1061	50	10	1121	*	0	41	1	Poortview AH(BL)	East	To Ruimsig	6%
10375	10376		1065	103	24	1192	*	0	41	2	Poortview AH(BL)	West	To Tarlton	2%
6493	6490		247	28	8	283	*	0	45	1	Tarlton	East	To Krugersdorp	5%
6490	6493		192	22	7	222	*	0	45	2	Tarlton	West	To Magaliesburg	10%
9400	3118		1403	37	8	1448	*	0	57	1	Fourways Gardens	North	To Broadacres AH	18%
3118	9400		1223	39	5	1267	*	0	57	2	Fourways Gardens	South	To Fourways	6%
5309	3532		367	18	20	405	*	0	70	1	Westonaria North	North	To Randfontein	3%
3532	5309		538	25	19	582	*	0	70	2	Westonaria North	South	To Vereeniging	3%
11908	3620		300	14	19	333	*	0	72	1	Westonaria South(BL)	North	To Randfontein	5%
3620	11908		317	16	16	350	*	0	72	2	Westonaria South(BL)	South	To Vereeniging	5%
4915	11858		1428	37	55	1520	*	0	86	1	Kliprivier WIM	North	To Alberton	5%
11858	4915		802	61	51	914	*	0	86	2	Kliprivier WIM	South	To Vereeniging	5%
5482	9642		164	10	16	190	*	0	95	1	Spaarwater AH	North	To Dalpark	3%
9642	5482		197	11	4	212	*	0	95	2	Spaarwater AH	South	To Heidelberg	8%
4116	9203		320	23	3	346	*	0	108	1	Modderfontein Rd(CM)	East	To Birchleigh	6%
9203	4116		1333	22	9	1364	*	0	108	2	Modderfontein Rd(CM)	West	To Modderfontein	5%
3985	11523		804	8	5	818	*	0	110	1	Alan Manor	North	To Jhb CBD	7%
11523	3985		544	6	2	552	*	0	110	2	Alan Manor	South	To Kibler Park	2%
6445	11299		128	9	13	150	*	0	123	1	Magaliesburg (RH)	East	To Magaliesburg	1%
11299	6445		134	15	16	165	*	0	123	2	Magaliesburg (RH)	West	To Rustenburg	1%
5594	12080		135	16	10	161	*	100	127	1	Bronkorstspruit (RM)	East	To Bronkhorstspruit	7%
12080	5594		155	9	6	170	*	103	127	2	Bronkorstspruit (RM)	West	To Bapsfontein	12%
2372	11632		366	19	12	397	*	0	131	1	Pyramid (BH)	North	To Bela Bela	12%
11632	2372		483	19	16	518	*	0	131	2	Pyramid (BH)	South	To Paramid	6%

5.2 Data Analysis: Updating of the Base Year Model

This section of the research project focuses on discussing the updating process followed to ensure that there is a correlation between the modelled and observed traffic flows for the base year model.

The traffic count data for the base year (2018) was assigned to the GFIP strategic transport model.

The traffic count data received contains data of four (4) types:

- Freeway sections between interchanges;
- Interchange ramps;
- Between interchange on- and off-ramps on the freeway; and
- On the approach roads and across between the interchange terminals on the arterials.

Figure 5-4 below provides a graphical representation of assigned traffic flows on a typical interchange in the GFIP strategic transport model.

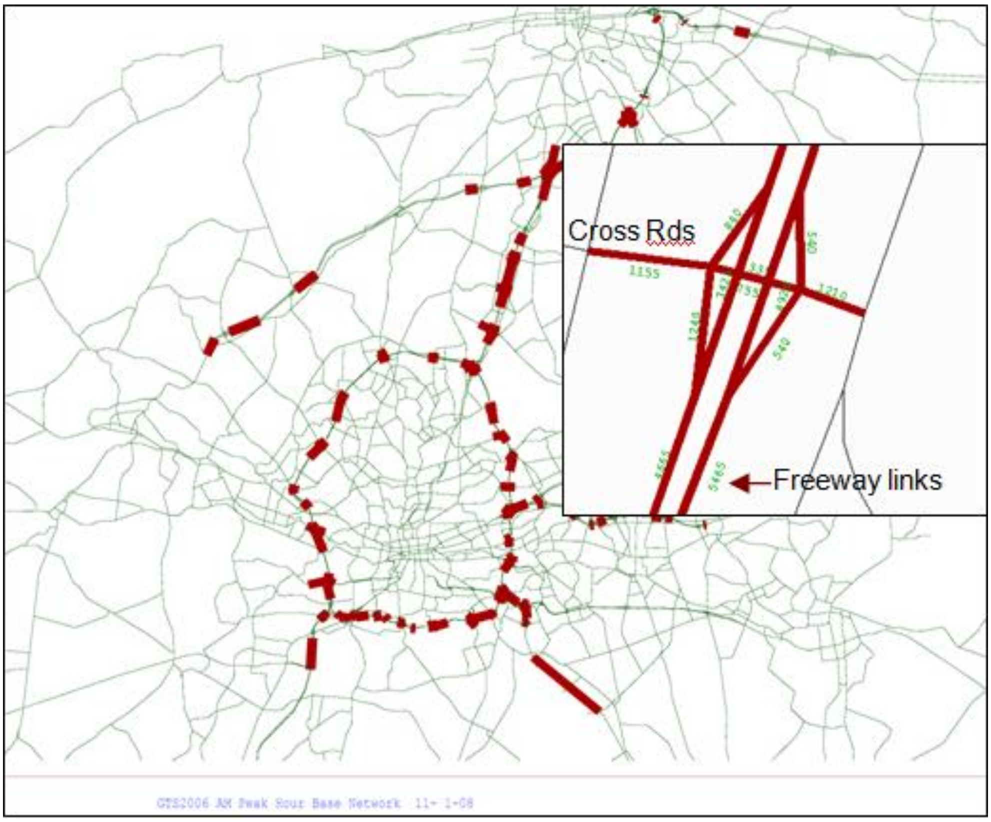

Figure 5-4: Graphical Representation of Assigned Traffic Flows on a Typical Interchange in the GFIP Strategic Transport Model

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5.2.1 Data Analysis: Updating of Traffic Counts

Traffic count journey times are the only true known inputs in the model that are not related to the road network. All other model inputs are estimated averages of countless factors, which include trip generation rates, land use values, perceived values of time, vehicle operating costs, etc. It is therefore necessary to update the model to known values using other input variables. Therefore, the updating of the model was done using the traffic counts and journey times on the road network. The acceptable calibration criteria are the target values of calibration statistics to which the model must conform. These criteria are discussed below.

5.2.1.1 Journey Time Calibration

The standard acceptable journey times calibration statistic is that the modelled journey time on a route is within 15% of the measured journey time on the route (on site) or within the standard deviation of the journey time surveys. Due to constraints of time and funding, the journey time surveys were only done once, when the initial version of the model was developed, and therefore the standard deviation could not be determined. An approach to overcome this limitation is that acceptable model journey times would be obtained through the strategic transport model for GFIP provided that they satisfy the following criteria:

- The journey times are within 15% of the observed journey times; or
- They are within 10 km/h of the measured journey speeds.

The second point listed as part of the criteria is applicable when journey speeds are low as a result of congested conditions. Therefore, this means that small differences in speeds can result in relatively high differences in journey times.

5.2.1.2 Traffic Count Calibration

5.2.1.2.1 Traffic Assignment Results for the Base Year Scenario (2018)

The results of the traffic assignment for the base year model, produced by the strategic transport model, were compared with the observed traffic flows. The results are illustrated in *Figure 5-5* below. The comparison reflects a poor correlation between the modelled traffic flows and the observed traffic flows. The comparison of both sets of traffic flows indicates a scatter trend in the values. There is deviation from the regression equation.

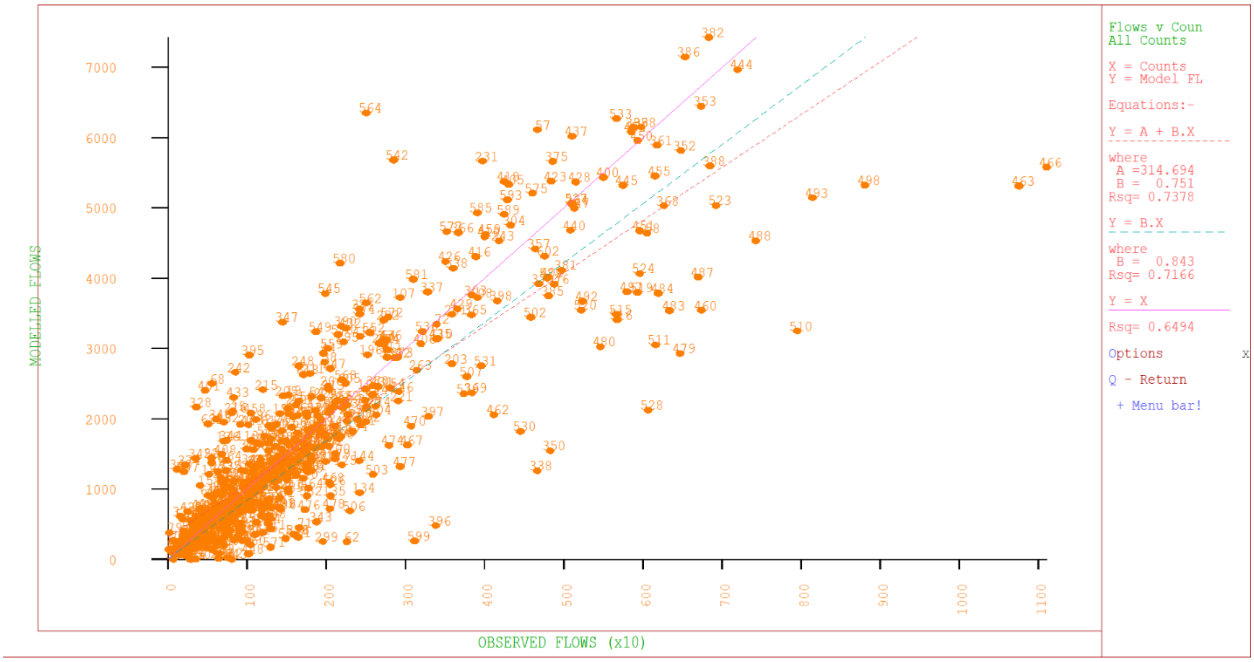
The regression equation is expressed below:

$$y = B.x \qquad \text{(Equation 5-1)}$$

Where:

- y is the modelled flow produced by the SATURN traffic modelling software
- x is the observed flow obtained from site

B is a constant in the equation



```
Flows v Coun
All Counts

X = Counts
Y = Model FL

Equations:-

Y = A + B.X
-----------------

where
 A =314.694
 B =  0.751
Rsq= 0.7378

Y = B.X
- - - - - - - - -

where
 B =  0.843
Rsq= 0.7166

Y = X

Rsq= 0.6494
```

Figure 5-5: Comparison of Modelled and Observed Traffic Flows after Initial Traffic Assignment on Base Year Model (Saturn Software Output)

The constant B provides an indication of whether the average traffic flows are overestimated or underestimated. The R^2 represents the goodness of fit of measure for linear regression models. The R^2 value is a statistical measure indicating how close the data points are to the fitted regression line. In essence the R^2 value reflects the degree of balance between the points to the fitted regression line.

An R^2 value which is close to the value 1 indicates that there is a good correlation between the data points.

The standard acceptable correlation between modelled traffic volumes and observed traffic volumes are measured in terms of the GEH statistic. The GEH statistic considers the correlation of low and high traffic volumes, i.e. within 15% of a low volume is generally acceptable but 15% of a high value may not be acceptable. The GEH statistic is used in traffic engineering, forecasting and modelling when comparing two sets of traffic volumes. In the context of this research project, the two sets of traffic volumes are the observed traffic flows and the modelled traffic flows.

The formula used for the GEH statistic is as follows:

GEH = $\sqrt{\frac{2(M-C)^2}{M+C}}$ **(**Equation 5-2) (NCHRP, 2016)

Where:

M is the hourly traffic volume as per the traffic model; and

C is the observed traffic volume as per site.

Applications of the GEH formula include the following instances:

- When a set of traffic volumes obtained from manual counts is compared with a set of traffic volumes obtained from the same location through automation;
- When traffic volumes for the current year are compared with traffic volumes from a previous year at the same location;
- When comparing traffic volumes obtained from travel demand models (for the base year condition) with observed traffic volumes from site; and
- When traffic volumes collected at different times are adjusted in order to achieve a consistent set of data which can be used as input data for travel demand models or in traffic simulations (NCHRP, 2016).

The criteria, for acceptance of traffic volumes, recommended by the *UK Department of Transport* include the following:

- For flows > 700 pcu/h the percentage of modelled traffic flow within + 15% of the observed traffic flow;
- For flows < 700 pcu/h the percentage of modelled traffic flows within + 100 of the observed traffic flow; and
- The percentage of counted (measured) links where the GEH statistic is less than or equal to 5.

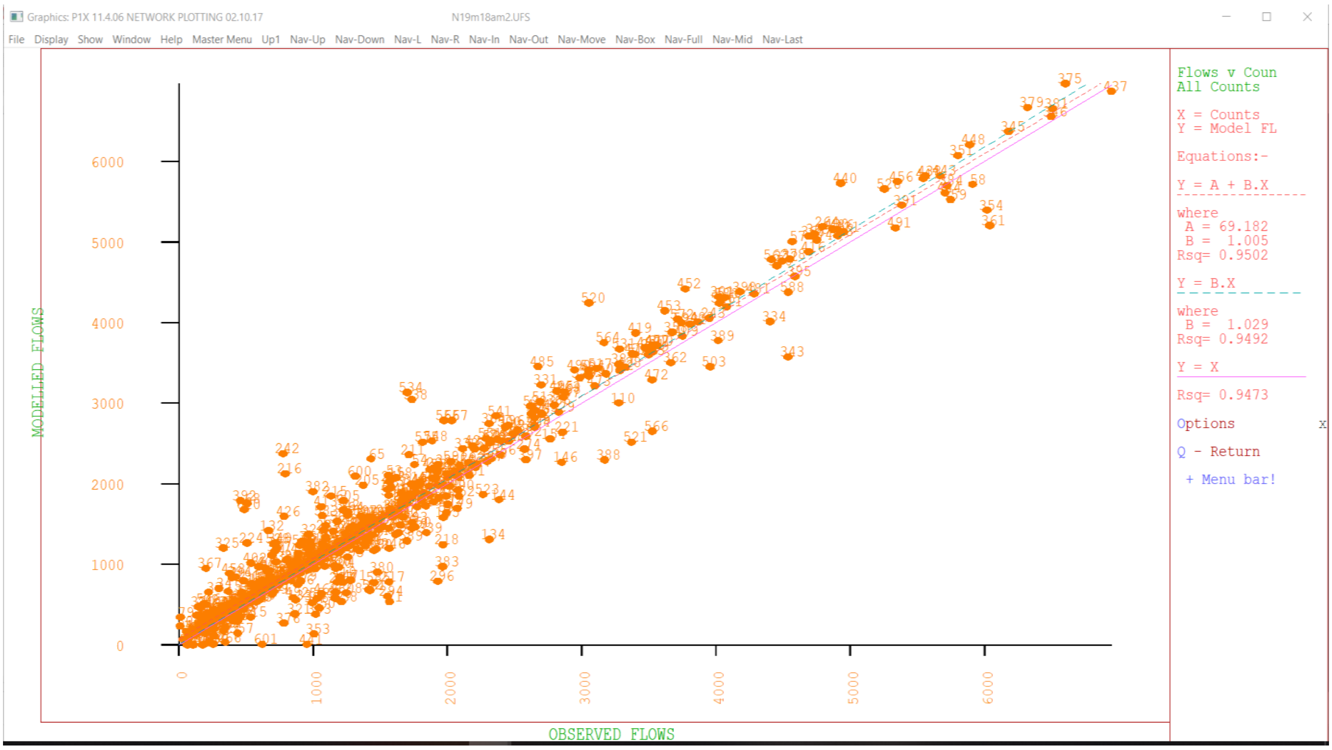
In the three cases listed above, the Department's recommendation is that 85% of the traffic counts should comply with the above criteria.

While the traffic counts were being audited it was found that there were significant differences between the actual (observed) traffic flows and the modelled traffic flows occurring at several links. The values for the GEH statistic ranged from 19.02 to 0.43. as mentioned earlier, the required value for the GEH statistic is 5. The table below provides an extract, from the results, of comparison of modelled and traffic flows after the first calibration run.

Table 5-2: GEH Statistics of the First Calibration Run of Modelled and Observed Traffic Flows (Saturn Software)

Count No.	A Node	B Node	Capacity	Modelled	Count	GEH
346	20002	20004	1900	1258	1014	7.23
476	8803	20153	7400	4225	3098	18.63
233	3922	3923	1600	479	576	4.24
124	12585	12584	4000	1782	1519	6.47
465	21145	21148	1900	711	552	6.34
191	3172	20028	1200	1111	1093	0.55
273	20342	4132	2400	1117	1083	1.02
252	21163	11576	2400	994	1008	0.43
220	3653	20436	2400	773	803	1.05
481	5558	20161	1900	1214	841	11.63
319	4124	9208	1300	811	587	8.49
250	4256	9085	2800	681	647	1.31
249	9085	4256	2800	1002	1051	1.52
101	5470	5857	1600	109	121	1.16
510	21255	9572	1900	0	107	14.63
614	20292	20294	5460	2146	1658	11.19
223	3414	21287	2400	1654	1600	1.33
245	11573	11572	4000	1138	1031	3.25
449	4147	20341	1900	953	971	0.57
153	8655	8656	2800	1944	1736	4.86
391	9382	21101	7400	1690	993	19.02
139	2647	9821	2400	1908	1809	2.3
175	3225	8859	2000	389	287	5.53
3	2715	9876	1200	639	700	2.34
592	20590	20592	7400	1736	1068	17.84
180	3192	20059	2400	1014	1035	0.66
170	3058	3103	2400	1173	964	6.4
1	3019	3044	2400	1493	1431	1.62
181	3194	3192	2800	1547	1361	4.88
320	4127	4123	1600	411	477	3.14
288	4218	4185	1600	560	452	4.8
477	3013	20153	1900	1401	891	15.06
323	4169	9033	2000	861	800	2.11
212	3245	21293	2400	2107	2058	1.07
305	20191	4163	2040	1798	1865	1.57
423	20632	21127	1900	1190	1169	0.6
341	20860	19997	4000	1201	1844	16.48
66	21057	20039	4000	334	236	5.81
265	4169	4047	1400	476	406	3.33
371	20042	21056	6000	3122	2797	5.97

Due to the high scatter in data points, the low B and R^2 values and the high GEH values, the traffic flows were calibrated again using approximately 4000 iterations. The purpose of further calibration of the traffic flows was to achieve a better correlation between the modelled and observe traffic flows. The results of the final calibration of the traffic flows are presented in Figure 5-6. The B and R^2 values for the comparison of the modelled and observed traffic flows were 1.029 and 0.9492 respectively. This indicates as good fit between the modelled and observed traffic flows. Therefore, there GFIP traffic model was not calibrated further.



```
Flows v Coun
All Counts

X = Counts
Y = Model FL

Equations:-

Y = A + B.X
-----------------
where
 A = 69.182
 B =  1.005
Rsq= 0.9502

Y = B.X
- - - - - - - - -
where
 B =  1.029
Rsq= 0.9492

Y = X

Rsq= 0.9473
```

Figure 5-6: Statistical Results at the Final Calibration

The values for the GEH statistic ranged from 19.02 to 0.43. as mentioned earlier, the required value for the GEH statistic is 5. The table below provides an extract, from the results, of comparison of modelled and traffic flows after the final calibration run. After the final calibration, the GEH values fanged from 0.55 to 0.01.

Table 5-3: GEH Statistics for the Final Calibration Run of Modelled and Observed Traffic Flows (Saturn Software)

Count No.	A Node	B Node	Capacity	Modelled	Count	GEH
346	20009	20011	7400	6498	6497	0.01
476	20164	20163	7400	3375	3377	0.03
233	3922	3923	1600	575	576	0.05
124	12585	12584	4000	1515	1519	0.09
465	3005	21020	1900	404	402	0.09
191	3172	20028	1200	1096	1093	0.1
273	20342	4132	2400	1079	1083	0.13
252	21163	11576	2400	1003	1008	0.15
220	3653	20436	2400	798	803	0.17
481	8935	20170	7400	4271	4283	0.18
319	4127	4123	1600	481	477	0.18
250	4256	9085	2800	641	647	0.23
249	9085	4256	2800	1043	1051	0.25
101	5470	5857	1600	124	121	0.25
510	21252	20569	1900	415	421	0.27
614	20114	20116	1900	169	172	0.27
223	3414	21287	2400	1611	1600	0.28
245	11573	11572	4000	1040	1031	0.28
449	20342	20339	1900	1179	1191	0.35
153	8655	8656	2800	1751	1736	0.36
391	20371	20370	7400	5410	5383	0.37
139	2647	9821	2400	1826	1809	0.39
175	3225	8859	2000	280	287	0.39
3	2715	9876	1200	711	700	0.4
592	20804	20517	1900	452	461	0.4
180	3192	20059	2400	1048	1035	0.41
170	3058	3103	2400	951	964	0.42
1	3019	3044	2400	1448	1431	0.44
181	3194	3192	2800	1345	1361	0.44
320	4123	4127	1600	624	613	0.45
288	4218	4185	1600	442	452	0.45
477	20160	20161	7400	3557	3530	0.46
323	9131	20209	4000	592	581	0.46
212	3245	21293	2400	2080	2058	0.48
305	9237	5615	2800	2059	2081	0.49
423	11244	20450	1900	376	386	0.5
341	20002	20004	1900	997	1014	0.53
66	21057	20039	4000	228	236	0.53
265	4169	4047	1400	395	406	0.54
371	3058	20047	1900	781	796	0.55

The comparison of the observed and modelled traffic flows as provided in Figure 5-6 indicates that the model represents a very good correlation of two sets of traffic volumes assigned on the GFIP road network. The GEH statistics are within the preferred range; i.e. the GEH values are between 0.01 and 5.

5.3 Conclusions and Recommendations

The above methodology followed to update the old GFIP strategic transport model produced a model that is fit for purpose for the objective of this research project. Justification has been provided by referring to the statistical parameters which indicate good correlation between modelled and observed traffic flows.

Therefore, when applying this to case study scenarios in order to test the of this research project, the author feels confident that:

- The model will provide reasonably reliable results pertaining to traffic flows on the freeway network; and
- The effect of the application of varying deterrence functions to the model will be reflected and tested with an acceptable level of accuracy required for the purpose of this research project. Therefore, the model is fit for purpose.

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6 Estimation of a Distance-Deterrence Function for the GFIP Network

Chapter 2 presents the background to the reasons which sparked the author's curiosity, intrigue and interest in the topic of this research project. This research project is aimed towards estimating a distance-deterrence function representing the trip distribution on the GFIP road network as accurately as possible. The land-use data and traffic volume data provided by the SANRAL have been used to update the strategic transport model (2006 version) for the GFIP road network as well as to calibrate a distance-deterrence function for trips on the network. Chapter 5 discusses the process and methods followed in updating the strategic model for year 2006. The Simulation and Assignment of Traffic in Urban Road Networks (SATURN) modelling software was used to develop the strategic transport model used in this research project. This chapter focuses on the process and methods used to develop a distance-deterrence function which replicates the trip distribution on the GFIP road network for the base year (2018) as closely as possible.

The distance-deterrence function developed was used in the gravity model to distribute the trips between origin and destination zones in the strategic transport model for the GFIP road network. This was completed for five scenarios each investigating the trip distribution based the reduction of the average trip length on the GFIP road network. The testing of the performance of the distance-deterrence function, in reducing the average trip length on the network, in these scenarios is presented and discussed in Chapter 7.

6.1 Extraction of Required Matrix from the Stacked Matrix

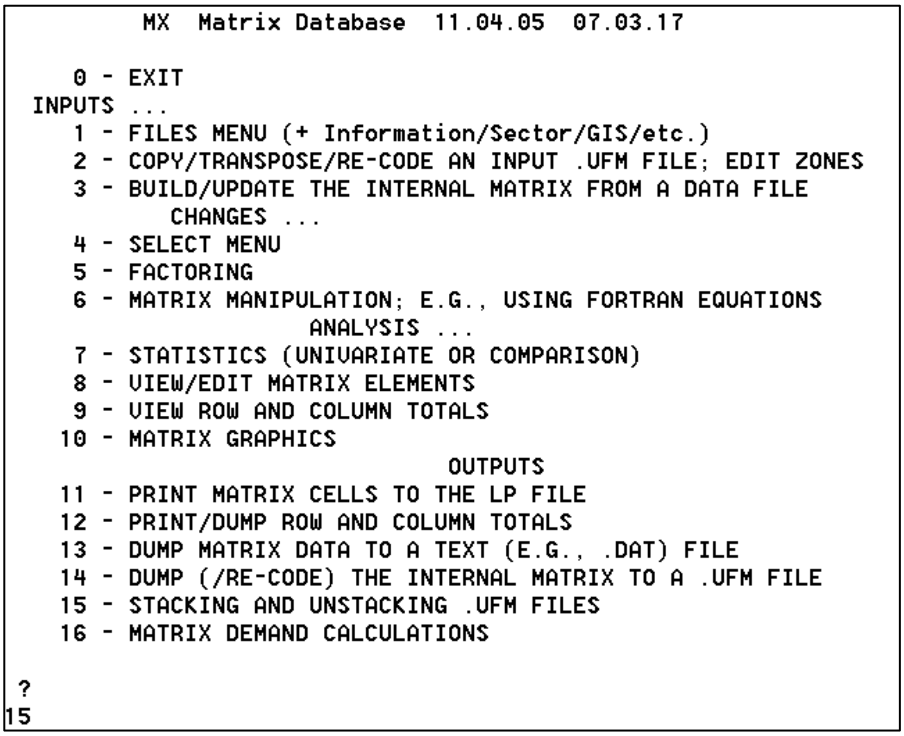
The origin-destination matrix for the base year included all vehicle classes (light and heavy vehicles). In summary, the origin-destination matrix was a stacked matrix. For the purpose of demonstrating the proof of concept of this research (that densification can be supported through the planning and implementation of road infrastructure which promotes shorter trip lengths) the average trip lengths for only light vehicles on the GFIP road network was considered. The reason for excluding the other vehicle classes, namely heavy vehicles, from the study is that heavy vehicles take longer to travel a section of road. This therefore skews the average trip length for a light vehicle on the GFIP road network to be longer than the actual average trip length on the network. The percentage of heavy vehicles on the road network is significantly lower than that of light vehicles. Therefore, excluding the heavy vehicle traffic from the study will not negatively affect the results for the average trip length on the network but rather assist in obtaining a more realistic value for the average trip length. The table below provides a sample, extracted from the traffic volume database used in the development of the strategic transport model for GFIP for the base year. This table illustrates the hourly traffic volumes of some of the roads with the highest traffic volumes on the network. This table illustrates the percentage of truck traffic included in the total traffic volume for a section of road.

Table 6-1: Sample of Traffic Volume Composition in Stacked Matrix for Base Year (2018)

Volume: Light Vehicles	Volume: Medium Trucks	Volume: Long Trucks	Total Volume	From	To	% Trucks
4404	165	96	4665	Lynnwood North Bound onramp	Johannesburg	5.6
3808	112	55	3974	OR Tambo International Airport Ormonde	Johannesburg CBD	4.2
4536	179	115	4830	Atterbury North Bound offramp	Off ramp to Atterbury Road	6.1
6497	151	88	6737	Rigel Avenue South Bound onramp	Johannesburg	3.5
6604	161	69	6835	Olifantsfontein Road South Bound offramp	Johannesburg	3.4
6507	232	109	6848	Allandale Road South Bound onramp	Johannesburg	4.9
4950	118	83	5152	N17 Soweto North Bound onramp	Onramp from N17 Soweto	3.9
4930	158	46	5135	M37 Edendale South Bound onramp	Bedfordview	3.9
5670	163	103	5936	Modderfontein North Bound onramp	Onramp from Modderfontein Road	4.5

The following methodology was used to unstack the base year origin-destination matrix into the individual vehicle classes:

- Run the MX module in SATURN for the stacked base year matrix;
- Select the option to unstack the matrix into separate levels, in this case the different vehicle classes; and
- Save the matrix as a UFM matrix file.



```
          MX  Matrix Database  11.04.05  07.03.17

     0 - EXIT
  INPUTS ...
     1 - FILES MENU (+ Information/Sector/GIS/etc.)
     2 - COPY/TRANSPOSE/RE-CODE AN INPUT .UFM FILE; EDIT ZONES
     3 - BUILD/UPDATE THE INTERNAL MATRIX FROM A DATA FILE
            CHANGES ...
     4 - SELECT MENU
     5 - FACTORING
     6 - MATRIX MANIPULATION; E.G., USING FORTRAN EQUATIONS
                      ANALYSIS ...
     7 - STATISTICS (UNIVARIATE OR COMPARISON)
     8 - VIEW/EDIT MATRIX ELEMENTS
     9 - VIEW ROW AND COLUMN TOTALS
    10 - MATRIX GRAPHICS
                                OUTPUTS
    11 - PRINT MATRIX CELLS TO THE LP FILE
    12 - PRINT/DUMP ROW AND COLUMN TOTALS
    13 - DUMP MATRIX DATA TO A TEXT (E.G., .DAT) FILE
    14 - DUMP (/RE-CODE) THE INTERNAL MATRIX TO A .UFM FILE
    15 - STACKING AND UNSTACKING .UFM FILES
    16 - MATRIX DEMAND CALCULATIONS

 ?
15
```

Figure 6-1: Option in SATURN's MX Module to Unstack Matrices

The table below provides a summary of the matrix totals for the unstacked origin-destination matrix obtained through the steps indicated above.

Table 6-2: Matrix Totals for Unstacked Matrix

Matrix	Grand Total	Inter-zonals	Intra-zonals
Unstacked matrix for light vehicles	659879	659879	0

Table 6-3 provides an extract of the unstacked OD trip matrix for the base year (2018). The full OD trip matrix includes trips between 1600 zones and therefore could not be included in this section.

Table 6-3: An Extract of Trips from the Unstacked OD Matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**
1	0	23.3	13.1	15.8	19	22.1	0
2	21.2	0	20.2	130.8	155.9	183.8	21.2
3	18.4	23.6	0	105	23.8	28.5	18.4
4	24.1	174.4	50.4	0	282.7	402.4	24.1
5	19	137.5	17.7	186.3	0	314.5	19
6	21.2	154.1	20.1	242.7	327.2	0	21.2
7	16.3	97.9	12.3	91	173.5	193.9	0

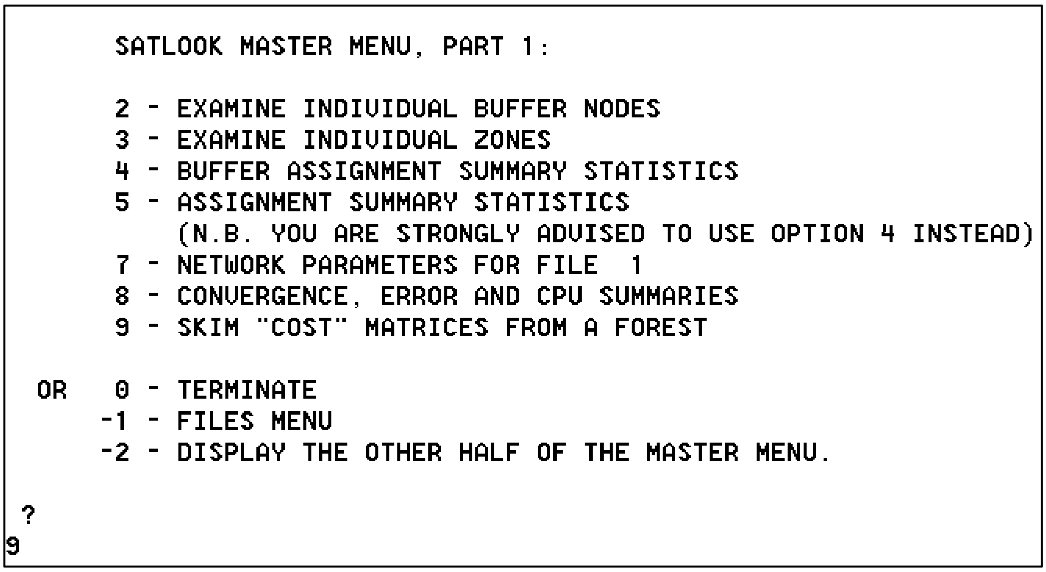
6.2 Generation of a Skimmed Matrix for Generalised Cost

According to Ortúzar and Willumsen (2011), generalised cost can be expressed in terms of distance, time or both distance and time. In order to highlight or emphasise the objective which this research is aiming to prove, the generalised cost was expressed in terms of distance. Ortúzar and Willumsen (2011) discuss a concept known as “tree building” which has two important uses in transportation planning and modelling; one being the use of trees to extract the cost of using a link in a network and the second use is producing information on the usage of specific links by specific OD pairs. Ortúzar and Willumsen (2011) further explains that the travel time experienced by drivers between two zones can be obtained through an exercise which runs through a sequence of links in a tree which connects them. At the end of this exercise the travel times for each link are summed. The term of this operation is known as “skimming” a tree. A skimmed matrix, based on distance, was developed to store the distances (in m) of each link in the GFIP road network. The intention of creating the skimmed matrix was to observe the trip assignment of vehicles as a result of the different distribution functions applied to the network. The calibration and development of synthesized distance-deterrence distribution functions will be discussed in the proceeding sections of this chapter.

The generation of the skimmed matrix was completed using the following methodology:

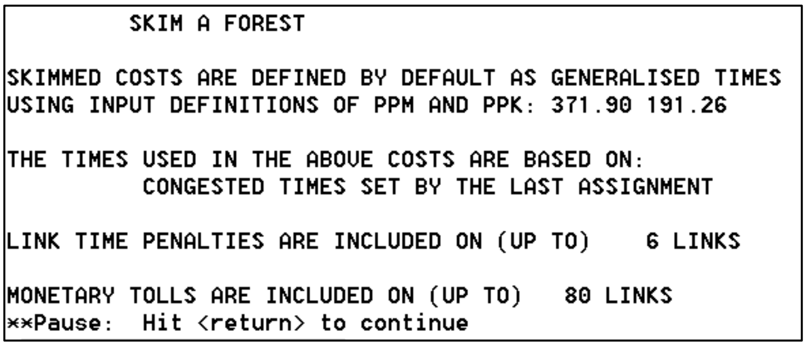
- The network (in a .DAT format) for the GFIP road network was skimmed using the SATLOOK module included in the SATURN software. The figures below illustrate the process followed to generate a skimmed matrix using the SATURN software.

Figure 6-2 presents the main option menu appearing in the SATLOOK module. Option 9 completes the function of skimming a cost matrix from a forest. As discussed in the paragraph above, a skimmed matrix is obtained through the skimming of a tree within the forest of links within the road network. Therefore, option 9 was used to skim the network matrix (forest) to form a matrix which can be used to represent the generalized cost, in terms of distance, of trips assigned on the GFIP road network. The default setting for representation of generalized cost in the SATURN software is in cost terms. However, this default setting can be changed to represent the generalized cost, using a skimmed matrix, in distance. This is illustrated in the options menu presented in Figure 6-2.



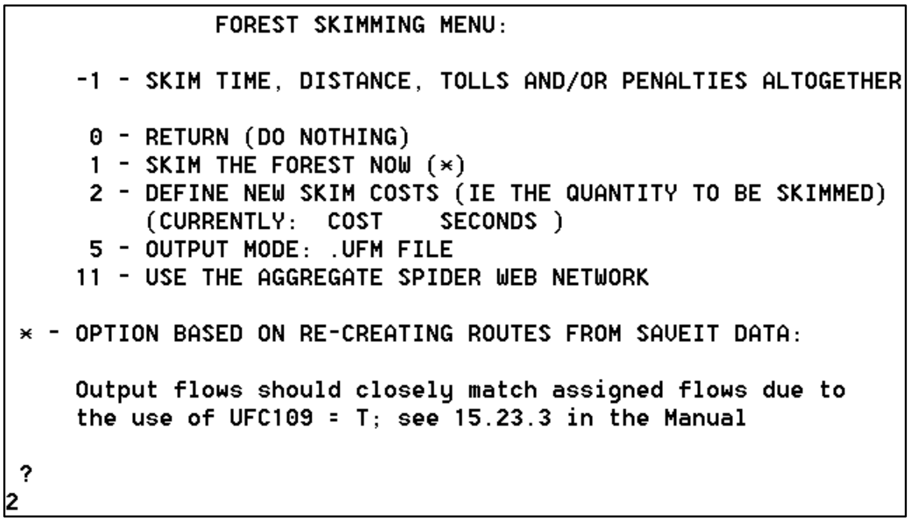
```
       SATLOOK MASTER MENU, PART 1:

       2 - EXAMINE INDIVIDUAL BUFFER NODES
       3 - EXAMINE INDIVIDUAL ZONES
       4 - BUFFER ASSIGNMENT SUMMARY STATISTICS
       5 - ASSIGNMENT SUMMARY STATISTICS
           (N.B. YOU ARE STRONGLY ADVISED TO USE OPTION 4 INSTEAD)
       7 - NETWORK PARAMETERS FOR FILE  1
       8 - CONVERGENCE, ERROR AND CPU SUMMARIES
       9 - SKIM "COST" MATRICES FROM A FOREST

  OR   0 - TERMINATE
      -1 - FILES MENU
      -2 - DISPLAY THE OTHER HALF OF THE MASTER MENU.

 ?
9
```

Figure 6-2: Step 1 in generating a skimmed matrix



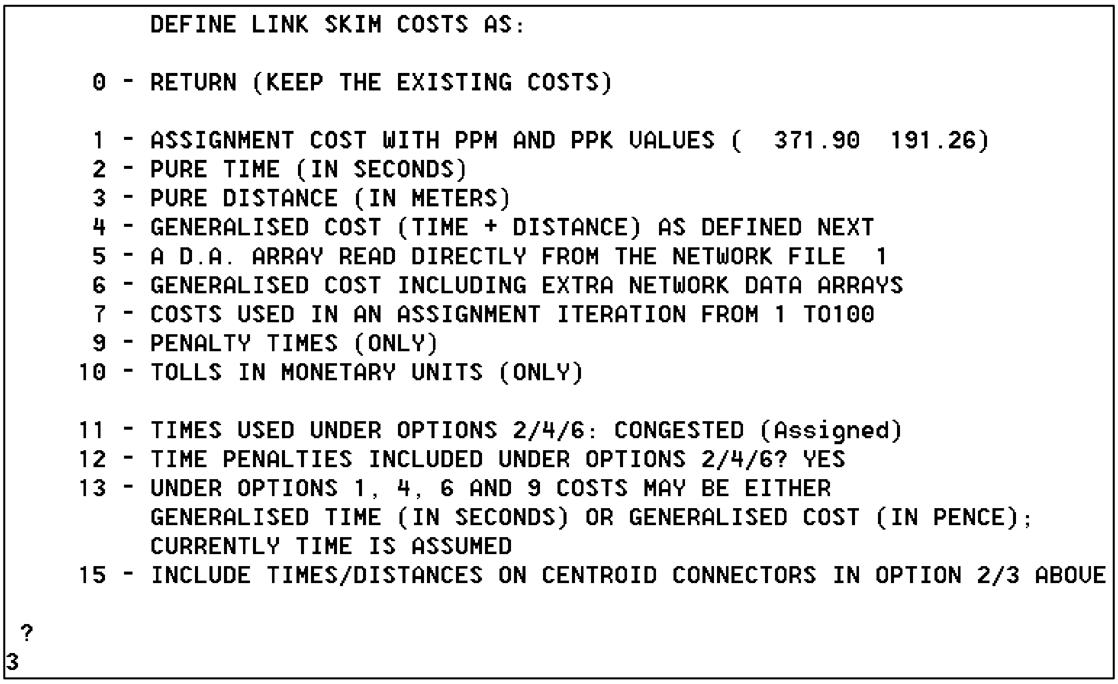
```
         SKIM A FOREST

SKIMMED COSTS ARE DEFINED BY DEFAULT AS GENERALISED TIMES
USING INPUT DEFINITIONS OF PPM AND PPK: 371.90 191.26

THE TIMES USED IN THE ABOVE COSTS ARE BASED ON:
          CONGESTED TIMES SET BY THE LAST ASSIGNMENT

LINK TIME PENALTIES ARE INCLUDED ON (UP TO)    6 LINKS

MONETARY TOLLS ARE INCLUDED ON (UP TO)   80 LINKS
**Pause:  Hit <return> to continue
```

Figure 6-3: Step 2 in generating a skimmed matrix



```
               FOREST SKIMMING MENU:

     -1 - SKIM TIME, DISTANCE, TOLLS AND/OR PENALTIES ALTOGETHER

      0 - RETURN (DO NOTHING)
      1 - SKIM THE FOREST NOW (*)
      2 - DEFINE NEW SKIM COSTS (IE THE QUANTITY TO BE SKIMMED)
          (CURRENTLY:  COST    SECONDS )
      5 - OUTPUT MODE: .UFM FILE
     11 - USE THE AGGREGATE SPIDER WEB NETWORK

 * - OPTION BASED ON RE-CREATING ROUTES FROM SAVEIT DATA:

     Output flows should closely match assigned flows due to
     the use of UFC109 = T; see 15.23.3 in the Manual

 ?
2
```

Figure 6-4: Step 3 in generating a skimmed matrix



```
          DEFINE LINK SKIM COSTS AS:

      0 - RETURN (KEEP THE EXISTING COSTS)

      1 - ASSIGNMENT COST WITH PPM AND PPK VALUES (  371.90  191.26)
      2 - PURE TIME (IN SECONDS)
      3 - PURE DISTANCE (IN METERS)
      4 - GENERALISED COST (TIME + DISTANCE) AS DEFINED NEXT
      5 - A D.A. ARRAY READ DIRECTLY FROM THE NETWORK FILE   1
      6 - GENERALISED COST INCLUDING EXTRA NETWORK DATA ARRAYS
      7 - COSTS USED IN AN ASSIGNMENT ITERATION FROM 1 TO100
      9 - PENALTY TIMES (ONLY)
     10 - TOLLS IN MONETARY UNITS (ONLY)

     11 - TIMES USED UNDER OPTIONS 2/4/6: CONGESTED (Assigned)
     12 - TIME PENALTIES INCLUDED UNDER OPTIONS 2/4/6? YES
     13 - UNDER OPTIONS 1, 4, 6 AND 9 COSTS MAY BE EITHER
          GENERALISED TIME (IN SECONDS) OR GENERALISED COST (IN PENCE);
          CURRENTLY TIME IS ASSUMED
     15 - INCLUDE TIMES/DISTANCES ON CENTROID CONNECTORS IN OPTION 2/3 ABOVE

 ?
3
```

Figure 6-5: Step 4 in generating a skimmed matrix

- After the skimmed matrix was generated, it was saved as a matrix file (.ufm) and stored in the project folder. The skimmed matrix was required for the development of synthesized matrices as part of the distance-deterrence function calibration.

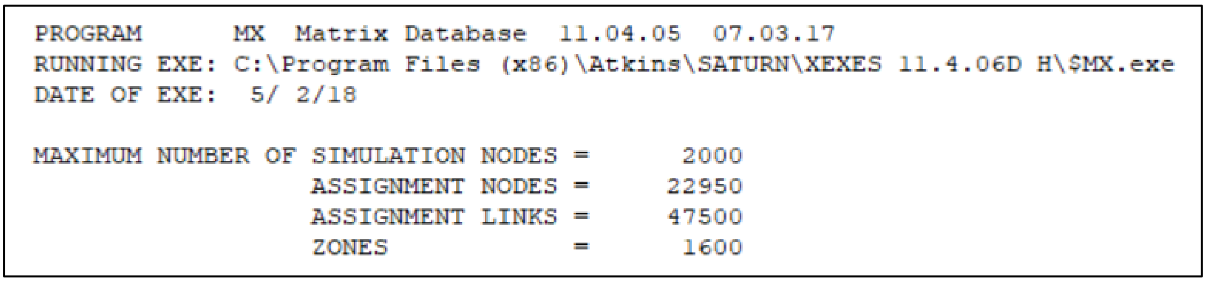
6.3 Development of a Synthesized Matrix

The purpose of developing a synthesized OD matrix is to assist in determining the behavior of trips being assigned on the road network relating to the different values used for the parameters in the distance-deterrence function forming part of the distribution function. Several synthesized matrices were developed for the different deterrence functions tested. By assigning each synthesized matrix to the road network, the distribution of trips was obtained. This provided a means of determining the average trip lengths travelled by vehicles on the road network. This exercise was completed for each synthesized matrix generated with the objective of determining the effect of changing the distance-deterrence function variables on the average trip length achieved on the road network. As discussed in section 3.4 of this research project, there are three forms of the deterrence function. In order to accurately determine the distance-deterrence function which best suited the distribution of trips on the road network for the base year, the author tested two out of the three forms of the function. The testing of these functions was completed through first determining the effect of the variables in the functions. For example, determining how the beta and n terms in the function changed the respective curve produced by the function. Once this effect was established, the parameters in the function were adjusted until its resultant curve matched that of the distance-deterrence curve for existing trips on the GFIP network as closely as possible.

With reference to equations 3-5 and 3-6 from section 3.4 of this report, equation 3-6 accounts for the intrazonal trips within the network and equation 3-5 ignores them. Intrazonal trips are defined as trips which do not travel from centroid to centroid. Excluding intra-zonal trips does not have a significant effect on model results. Nonetheless, all matrices used have been adjusted such that the intra-zonal trips have been ignored. The subsequent sections explain the methodology and process followed in using the OD trip matrix for the base year and the network file to determine the distance-deterrence function for the base and design years. It is to be understood that the distance-deterrence function for the base year was adjusted such that it was suitable to develop synthesized matrices which were later used to test the effect of the function on the average trip length on the network.

6.3.1 Estimation of the Average Trip Length on the GFIP Road Network

To determine the average trip length travelled by light vehicles on the GFIP road network, the total number of trips between zones for the OD matrix (2018) were extracted using the SATURN software and tabulated in an Excel spreadsheet. The figure below provides a summary of the parameters used to develop the network file for the GFIP road network. This figure provides an idea of the magnitude of the trips, nodes and zones which were involved in the development of the strategic transport model as well as an idea of the number of nodes and zones which trips were assigned.



```
PROGRAM       MX  Matrix Database  11.04.05  07.03.17
RUNNING EXE: C:\Program Files (x86)\Atkins\SATURN\XEXES 11.4.06D H\$MX.exe
DATE OF EXE:  5/ 2/18

MAXIMUM NUMBER OF SIMULATION NODES =      2000
                  ASSIGNMENT NODES =     22950
                  ASSIGNMENT LINKS =     47500
                  ZONES            =      1600
```

Figure 6-6: Modelling Parameters used in the Network File for the GFIP Road Network

Thereafter, the average distance travelled by those trips were also extracted using the SATURN software and tabulated in an Excel spreadsheet. The table presented on the next page illustrates the number of trips travelled within a certain distance (in metres) for the base year (2018).

Table 6-4: Trips Travelled within a Distance Range (m)

Range (m)		**Average Distance (m)**	**Base Year OD Matrix Trips**
0	2500	1.25	10951.04
2500	5000	3.75	64221.71
5000	7500	6.25	76668.78
7500	10000	8.75	77950.52
10000	12500	11.25	69810.66
12500	15000	13.75	60846.41
15000	17500	16.25	54486.89
17500	20000	18.75	39050.55
20000	22500	21.25	34090.52
22500	25000	23.75	27186
25000	27500	26.25	22282.76
27500	30000	28.75	18571.33
30000	32500	31.25	15721.24
32500	35000	33.75	12259.53
35000	37500	36.25	11377.44
37500	40000	38.75	8989.33
40000	42500	41.25	7648.85
42500	45000	43.75	6868.35
45000	47500	46.25	6055.16
47500	50000	48.75	5018.43
50000	52500	51.25	4437.95
			634493.45

The last two columns of data were used to calculate the weighted average of trips on the road network using the following formula:

SUMPRODUCT (values in the average distance column, values in the base year OD matrix trips column)

Once the value for weighted average trips was determined, the average trip length for typical trips on the network was determined using the following formula:

ROUND (Sum of base year OD Matrix trips/weighted average trips)

Once this calculation was completed, the average trip length for typical trips on the road network was 16 km.

Figure 6-7 illustrates the trip distribution curve for the base year (2018) which graphically represents the data presented in Table 6-4.

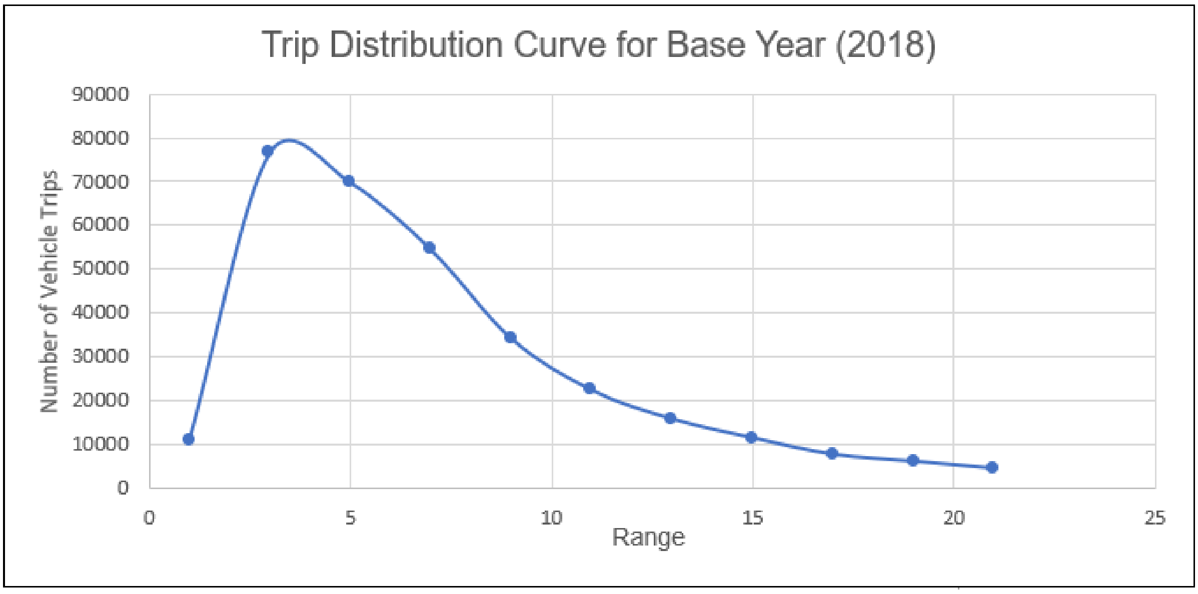


Figure 6-7: Trip Distribution Curve for Base Year (2018)

The profile for the trip distribution demonstrates a similarity to the graph developed from the combined deterrence function, $f\left(C_{ij}\right) = n * C_{ij}^{n} e^{-\beta C_{ij}}$. However, the right-hand portion of the graph resembles the exponential function form of the deterrence function, $f\left(C_{ij}\right) = n * e^{(-\beta C_{ij})}$. These equations have been discussed in section 3.4 of this research project.

Therefore, the curve fitting exercise used to determine the distance-deterrence function for the base year was completed for these two forms of the deterrence function.

6.3.2 Curve Matching and Determination of the Distance-Deterrence Function for the Base Year (2018)

The purpose of developing a curve which matches the trip distribution curve for trips on the GFIP road network is to determine the parameters of the deterrence function. The equation of the distribution curve relating to existing trips on the network is unknown, meaning that there is no way of knowing the exact equation of the existing deterrence function. Therefore, a

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method of estimating the parameters in the equation was developed. This method involves the following steps:

- Plotting the distribution curve for modelled trips using the data extracted from the SATURN software;
- Creating a column for synthesized trip distribution using the relevant equation form of the deterrence function (e.g. exponential or combined function);
- Creating a column for synthesized number of vehicle trips;
- Having an input cell for the beta and n variables which form the deterrence function.
- Estimation of the beta and n variables such that the synthesized curve matches the distribution curve for modelled trips as closely as possible.

Unfortunately, the author did not have access to specialized software pertaining to statistical analysis. The author completed all calculations and analysis using purely the SATURN software, Excel and first principles.

6.3.2.1 Curve Matching using the Combined Function Form

A trip matrix containing the trip distribution on the GFIP road network, refer to Table 6-4, was used to estimate the variables/parameters of a curve which closely match the trip distribution curve relating to the GFIP road network for the base year. The parameters in the combined function, $(f\left(C_{ij}\right) = n * C_{ij}^{n} e^{-\beta C_{ij}}),$ were estimated via a trial and error approach which incorporated the usage of the “goal seek” function in the “data” tab on Excel. The approach is demonstrated below:

- Two additional columns, synthesized distribution and synthesized trips, were added to *Table 6-4*;
- The column for synthesized distribution was coded using the exponential form of the deterrence-function;
- The column for synthesized trips was coded as follows: synthesized distribution * trip balancing factor * modelled trips total;
- Various values for n and beta were used to test the behaviour of the second curve (synthesized curve) in terms of how closely its profile matched that of the curve for the base year trips;
- Once values for n and beta were selected the “goal seek” function in Excel was used to seek a value for either n, beta or the matrix balancing factor which resulted in a zero difference between modelled and synthesized trips. The tables used to complete the curve matching exercise is provided in Appendix 6.1.

During the estimation process of n and beta terms in the exponential deterrence function it was observed that the n term changed the curve by increasing and decreasing the height of the curve and the beta term changed the curve by increasing or decreasing the grade of the curve. This is summarized in the table presented on the next page.

Table 6-5: Effect of changing the parameters in the Deterrence-Function on Curve Profile

Amendment of term in deterrence-function	**Result**
Increasing the beta term	Decreases width of the curve
Decreasing the beta term	Increases the width of the curve
Increasing the n term	Increase the height of the curve
Decreasing the n term	Decreases the height of the curve

After approximately 200 iterations, the parameters of the distance-deterrence function were estimated to be 1, 0.133 and 0. 0.0444 for n, beta and the matrix balancing factor respectively. Therefore, the distance-deterrence function representing trips on the GFIP network, in the exponential form, is expressed as:

$f\left(C_{ij}\right) = 0.0444 * C_{ij}^{1} e^{-0.133 C_{ij}}),$, where the Cij term is represents the generalised cost expressed in terms of distance.

Table 6-6 provides the modelled trips which represent the trips on the network as well as the synthesized trips. The calculation of the synthesized trips was explained at the beginning of this subsection. The purpose of the synthesized trips was to generate a synthesized distribution curve which closely matched the distribution curve for the modelled trips on the GFIP network.

Table 6-6: Modelled Trips and Synthesized Trips from Estimated Deterrence Function (Combined Function Form)

Range (m)		**Average Distance (km)**	**Modelled Trips**	**Synthesized Distribution**	**Synthesized Trips**
From	To				
0	2500	1.25	10951.04	1.058436223	29817.74578
2500	5000	3.75	64221.71	2.276646686	64136.57301
5000	7500	6.25	76668.78	2.720531646	76641.48223
7500	10000	8.75	77950.52	2.730807744	76930.97543
10000	12500	11.25	69810.66	2.517357296	70917.75419
12500	15000	13.75	60846.41	2.205993745	62146.17304
15000	17500	16.25	54486.89	1.869236132	52659.20286
17500	20000	18.75	39050.55	1.546398022	43564.36608
20000	22500	21.25	34090.52	1.256574235	35399.59259
22500	25000	23.75	27186	1.006936366	28366.91707
25000	27500	26.25	22282.76	0.797952261	22479.51944
27500	30000	28.75	18571.33	0.626606126	17652.44023
30000	32500	31.25	15721.24	0.488332907	13757.07497
32500	35000	33.75	12259.53	0.378136783	10652.68385
35000	37500	36.25	11377.44	0.291200646	8203.561676
37500	40000	38.75	8989.33	0.223185103	6287.461184
40000	42500	41.25	7648.85	0.170343914	4798.845128
42500	45000	43.75	6868.35	0.129535825	3649.21968
45000	47500	46.25	6055.16	0.098182196	2765.940642
47500	50000	48.75	5018.43	0.074200151	2090.330249
50000	52500	51.25	4437.95	0.055928505	1575.590378

Total	150 (km)	634493.45 (trips)		634493.45 (trips)
Difference between modelled and synthesized trips				0

Figure 6-8 demonstrates the result from the matching of the modelled trips with the synthesized trips used to estimate the parameters of the distance-deterrence function. This distribution curve was generated after numerous iterations of the distance-deterrence function and this was the closest match obtained.

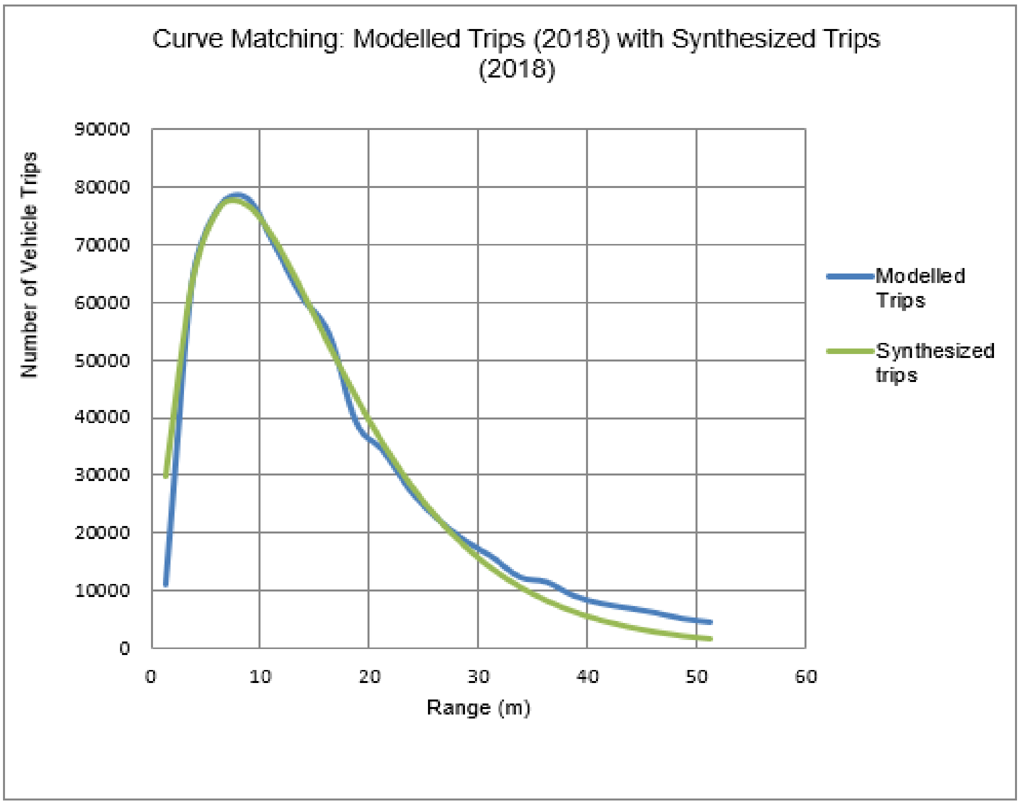

Figure 6-8: Curve Matching: Modelled Trips (2018) with Synthesized Trips (2018)

6.3.2.2 Trips per Distance for the Base Year (2018)

Once the suitable parameters for the distance-deterrence function were estimated, they were used to determine the average trip length travelled by a light vehicle on the GFIP network. The method used to calculate the average trip length, using Table 6-6, is as follows:

- The sumproduct of the average distance column and the modelled trips column was determined using Excel;
- The average trip length was then calculated by dividing the result from the sumproduct step by the total of the modelled trips. This result provides the average trip length for the modelled trips.

- The first step was modified and repeated as follows: The sumproduct of the average distance column and the synthesized trips column was determined using Excel;
- The average trip length was then calculated by dividing the result from the sumproduct step by the total of the synthesized trips. This result provides the average trip length for the synthesized trips.

Therefore, the average trip length calculated was 16 km for the modelled trips and 15 km for the synthesized trips.

6.3.2.3 Curve Matching using the Exponential Function Form

A trip matrix containing the trip distribution on the GFIP road network, refer to Table 6-4, was used to estimate the parameters of a second curve which closely matches the trip distribution curve relating to the GFIP road network for the base year. The parameters in the second combined function curve, $f\left(C_{ij}\right) = n * e^{(-\beta C_{ij})}$, were estimated via a trial and error approach which incorporated the usage of the “goal seek” function in the “data” tab on Excel. A balancing factor was also used to balance the total trips for modeled and synthesized trips. The approach is demonstrated below:

- Two additional columns, synthesized distribution and synthesized trips, were added to Table 6-4;
- The column for synthesized distribution was coded using the exponential form of the deterrence-function;
- The column for synthesized trips was coded as follows: synthesized distribution * trip balancing factor * modelled trips total;
- Various values for n and beta were used to test the behavior of the second curve in terms of how closely its profile matched that of the curve for the base year trips;
- Once values for n and beta were selected the “goal seek” function in Excel was used to seek a value for either n, beta or the matrix balancing factor which resulted in a zero difference between modelled and synthesized trips. The tables used to complete the curve matching exercise is provided in Appendix 6.2.

During the testing process of the n and beta terms in the exponential deterrence function it was observed that the n term changed the curve by increasing and decreasing the height of the curve and the beta term changed the curve by increasing or decreasing the grade of the curve. This is summarized in the table presented on the next page.

Table 6-7: Effect of terms in the Deterrence-Function on Curve Profile

Amendment of term in deterrence-function	**Result**
Increasing the beta term	Steepens grade of the curve
Decreasing the beta term	Lowers grade of the curve
Increasing the n term	Increase the height of the curve
Decreasing the n term	Decreases the height of the curve

After approximately 200 iterations, the parameters of the distance-deterrence function were estimated to be 1.592, 0.08 and 0.1793 for n, beta and the matrix balancing factor respectively. Therefore, the distance-deterrence function representing trips on the GFIP network, in the exponential form, is expressed as:

$f\left(C_{ij}\right) = 1.592 * e^{(-0.08C_{ij})}$, where the Cij term is represents the generalised cost expressed in terms of distance.

Table 6-8 provides the modelled trips which represent the trips on the network as well as the synthesized trips. The calculation of the synthesized trips was explained at the beginning of this subsection. The purpose of the synthesized trips was to generate a synthesized distribution curve which closely matched the distribution curve for the modelled trips on the GFIP network.

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Table 6-8: Modelled Trips and Synthesized Trips from Estimated Deterrence Function (Exponential Form)

Range (m)		**Average Distance (km)**	**Modelled Trips**	**Synthesized Distribution**	**Synthesized Trips**
From	To				
0	2500	1.25	10951.04	1.44095864	161102.62
2500	5000	3.75	64221.71	1.179757153	131899.6694
5000	7500	6.25	76668.78	0.965903462	107990.3157
7500	10000	8.75	77950.52	0.790814869	88414.99247
10000	12500	11.25	69810.66	0.647464453	72388.07337
12500	15000	13.75	60846.41	0.530099059	59266.34182
15000	17500	16.25	54486.89	0.434008402	48523.17667
17500	20000	18.75	39050.55	0.355336026	39727.41698
20000	22500	21.25	34090.52	0.290924532	32526.05802
22500	25000	23.75	27186	0.238188861	26630.08398
25000	27500	26.25	22282.76	0.195012546	21802.86871
27500	30000	28.75	18571.33	0.159662768	17850.67912
30000	32500	31.25	15721.24	0.130720819	14614.89996
32500	35000	33.75	12259.53	0.107025154	11965.66805
35000	37500	36.25	11377.44	0.087624785	9796.660413
37500	40000	38.75	8989.33	0.071741106	8020.827157
40000	42500	41.25	7648.85	0.05873665	6566.897859
42500	45000	43.75	6868.35	0.048089502	5376.521229
45000	47500	46.25	6055.16	0.039372354	4401.923275
47500	50000	48.75	5018.43	0.032235357	3603.989958
50000	52500	51.25	4437.95	0.026392078	2950.697412

Total	150 (km)	634493.45 (trips)		634493.45 (trips)
Difference between modelled and synthesized trips				0

Figure 6-9 demonstrates the result from the matching of the modelled trips with the synthesized trips used to estimate the parameters of the distance-deterrence function. This distribution curve was generated after numerous iterations of the distance-deterrence function and this was the closest match obtained.

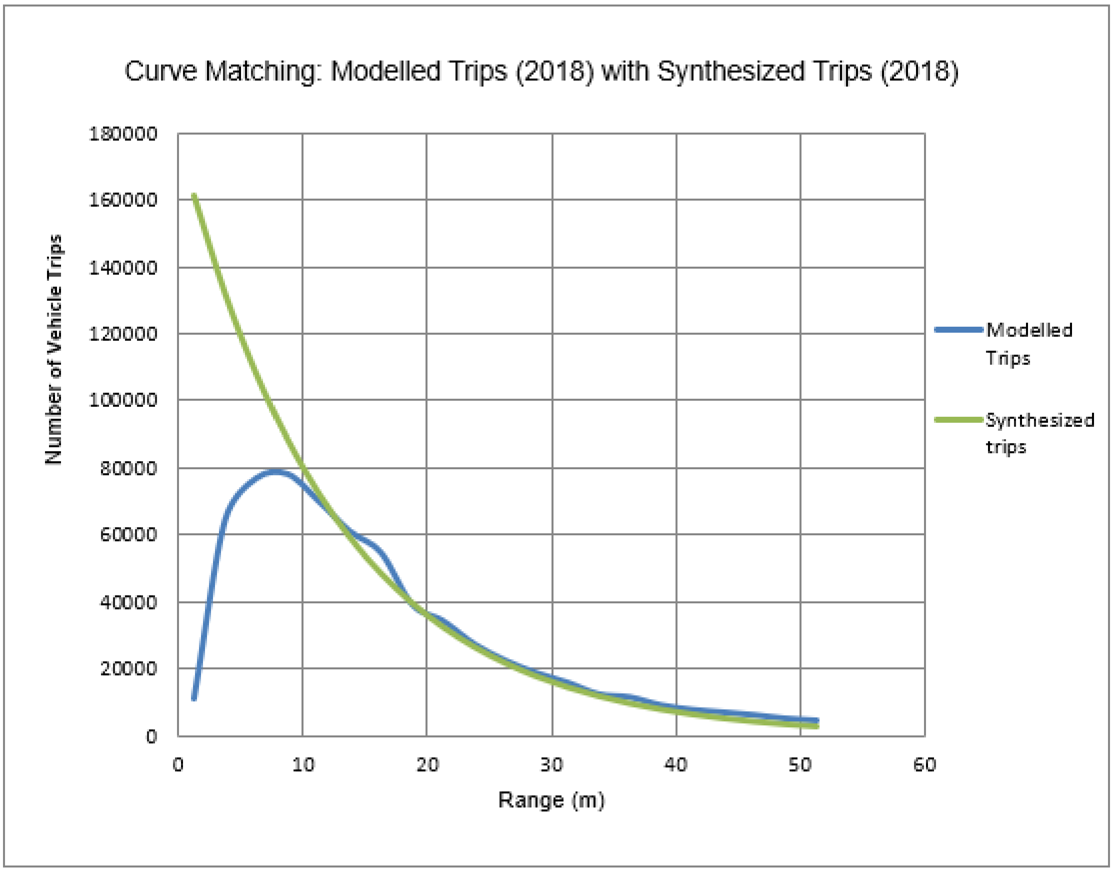

Figure 6-9: Curve Matching: Modelled Trips (2018) with Synthesized Trips (2018)

6.3.2.4 Trips per Distance for the Base Year (2018)

The process described in section 6.3.2.2 was applied and the average trip lengths for modelled and synthesized trips were 16km and 15km respectively.

Therefore, the average trip length calculated was 16km for the modelled trips and 15 km for the synthesized trips.

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6.4 Selection of the Appropriate Distance-Deterrence Function Form

After investigating the suitability of two of the three forms of the distance-deterrence function in respect to trips on the GFIP network, it was concluded that the distance-deterrence function in the exponential form was best suited for the rest of the research. This decision was based on the following:

- Since all matrices used in this study were adjusted such that all intra-zonal trips were removed, a fair comparison of the exponential and combined forms of the distance-deterrence functions could be made;
- The exponential form of the function provided a better curve fit compared with the combined form of the function and is suitable for the purpose of this academic paper.

6.5 Summary

A detailed analysis was undertaken using the trip data provided by the SANRAL and has been documented in Chapter 6. Two curve-fitting models were completed to determine the form of the distance-deterrence function best suited to represent the trip distribution and trip lengths on the GFIP network for the base year (2018). The results of the curve-fitting model process indicate that the exponential function best illustrates the trip distribution and trip lengths on the GFIP network and will be used in the Gravity Model to distribute trips for the test scenarios in chapters 8 and 9 of this study. The estimated distance-deterrence function is:

$$f\left(C_{ij}\right) = 1.592 * e^{(-0.08C_{ij})}$$

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7 Development of a Distance-Deterrence Function for Shorter Trips for the Design Year (2038)

In this chapter the process followed in the development of a distance-deterrence function which assigns shorter trip lengths are achieved is be discussed. In essence, drivers are being forced to take shorter trips.

Chapter 4 presents the trip data and land use data used in developing and updating the 2006 GFIP strategic transport model. Chapter 5 presents the methodology applied in updating the 2006 GFIP strategic transport model to reflect the trips for the base year (2018). Chapter 6 provides a step by step process followed to estimate suitable parameters for the distance-deterrence function representing the trip distribution on the GFIP network, for the base year. These parameters were used to estimate a suitable distance-deterrence function that can be applied to the GFIP network to distribute trips thereby replicating the actual trip distribution for the base year (2018). To be able to test the effect of varying the parameters in the distance-deterrence function on the average trip length on the network, several synthesized trip matrices were developed. A synthesized trip matrix was developed and assigned to the GFIP road network for each beta value tested. There was a total of twenty synthesized matrices developed to test the effect of twenty different beta values on the average trip length travelled by light vehicles on the GFIP network.

The method of creating the synthesized matrices, as well as the average trips lengths resulting from the different betas, will be discussed.

7.1 Development of Synthesized Matrices

Before the synthesized matrices could be developed, the base year OD matrix was forecasted to represent the trips for the design year (2038). This was done by growing/forecasting the OD trip matrix by 3%. A growth of 3% was selected because it correlated with the growth in trips on the GFIP network in a financial study for toll operations. This growth was derived from the author’s current career experience.

The MX Module in the SATURN Software was used to develop the synthesized matrices as through the following steps:

- The distance matrix (skimmed matrix) and the OD trip matrix for the design year (2038) were entered into the MX Module and furnessed using the doubly constrained furness method;

- The resultant matrix from the furnessing step provided an indication of the probability of trips based on generalized cost (in terms of distance). The furnessed matrix was saved as a synthesized OD matrix for the design year (2038).

This matrix now forms the base OD matrix for the design year (2038). This matrix will be used to generate the different synthesized OD matrices for the different beta values. The characteristics of this matrix is as follows:

- No intra-zonal trips;
- Trips were balanced using the doubly constrained furness method;
- The distance-deterrence function is still that of the function for the original distribution function. The only difference between the original OD matrix and the synthesized matrix is that the synthesized matrix has been balanced using the skimmed matrix (the distance matrix).

For the purpose of simplicity, the following references will be used in the rest of the report:

- **m38amUC1.ufm** = is the OD trip matrix for the design year 2038. This OD trip matrix was developed by growing/forecasting the OD trip matrix for the base year (2018) by 3%.
- **skimdistUC1.ufm** = is the matrix is the distance matrix and contains the distances of available routes for trips on the GFIP network. This matrix stays the same for the design year since no change to the GFIP network was considered. Further expansion of the GFIP network was not considered due to information not being available.
- **synm38am.ufm** = is the OD trip matrix for the design year (2038) after it has been balanced using the doubly constrained furness method.

Thereafter, fortran equations were applied to the synm38am.ufm matrix for each beta value tested. Each resultant synthesized matrix was saved.

The fortran equations applied to the m38amUC1.ufm matrix for each beta value were based on the form of $f\left(C_{ij}\right) = n * e^{(-\beta C_{ij})}$. The fortran equations are summarized in the table below:

Table 7-1: Fortran Equation per Beta Value

Beta Value	Fortran Equation Applied to m38amUC1.ufm
0.0550	Exp(-0.055*X2/1000)
0.0612	Exp(-0.0612*X2/1000)
0.0650	Exp(-0.0650*X2/1000)
0.0700	Exp(-0.0700*X2/1000)
0.0750	Exp(-0.0750*X2/1000)
0.0800	Exp(-0.0800*X2/1000)
0.0850	Exp(-0.0850*X2/1000)
0.0900	Exp(-0.0900*X2/1000)
0.0950	Exp(-0.0950*X2/1000)
0.1000	Exp(-0.1000*X2/1000)
0.1100	Exp(-0.1100*X2/1000)
0.1200	Exp(-0.1200*X2/1000)
0.1300	Exp(-0.1300*X2/1000)
0.1400	Exp(-0.1400*X2/1000)
0.1500	Exp(-0.1500*X2/1000)
0.1700	Exp(-0.1700*X2/1000)
0.1850	Exp(-0.1850*X2/1000)
0.2000	Exp(-0.2000*X2/1000)
0.2200	Exp(-0.2200*X2/1000)
0.2400	Exp(-0.2400*X2/1000)

The m38amUC1.ufm, skimdistUC1.ufm and each synthesized matrix were entered into the MX module to determine the correlation between the two OD matrices. The distribution curves below illustrate the correlation of the two OD trip matrices for each beta value tested. The following legend is to be applied when reading the distribution curves:

- The red bar graph represents the distribution curve for the m38amUC1.ufm matrix;

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- The green bar graph represents the distribution curve for the synthesized OD trip matrix which will has the general form of the synm38am.ufm matrix except that the beta value will be different in each distance-deterrence function used to create the synthesized matrix.

The correlation tables which represent these distribution curves have been included in Appendix 7.

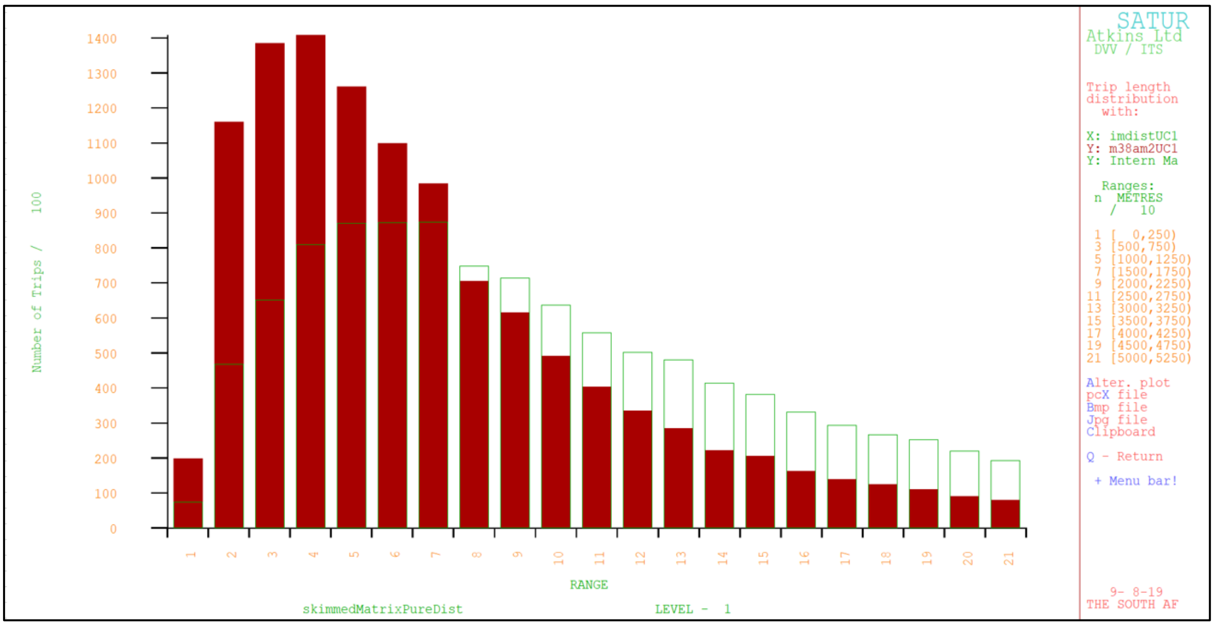

Figure 7-1: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.055)

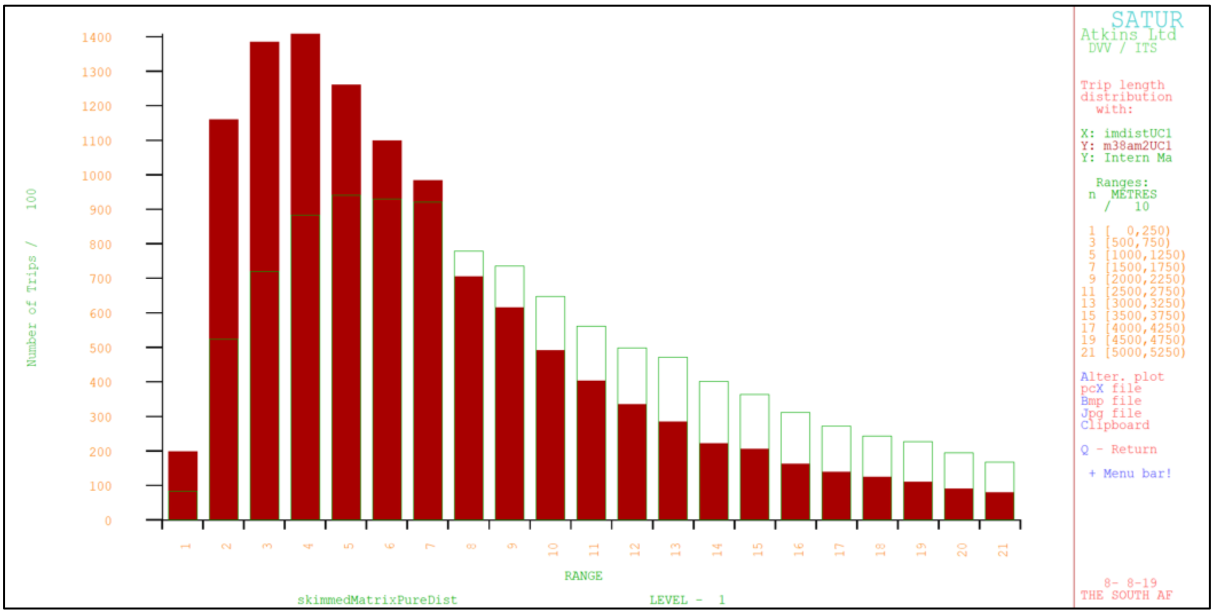

Figure 7-2: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0612)

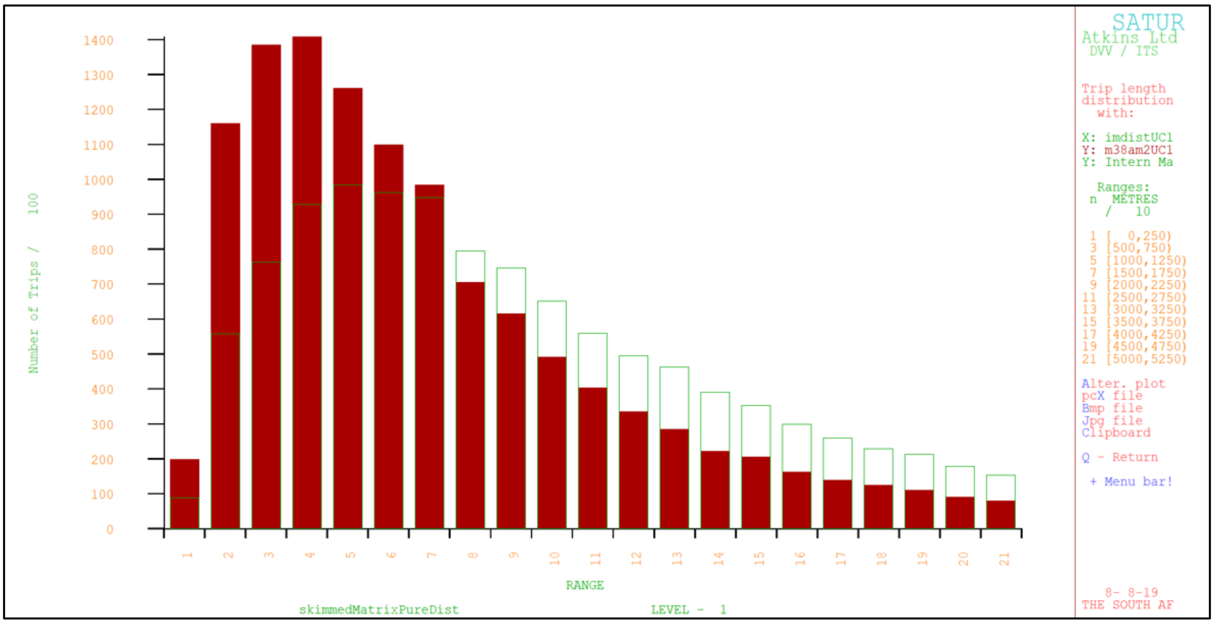

Figure 7-3: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0650)

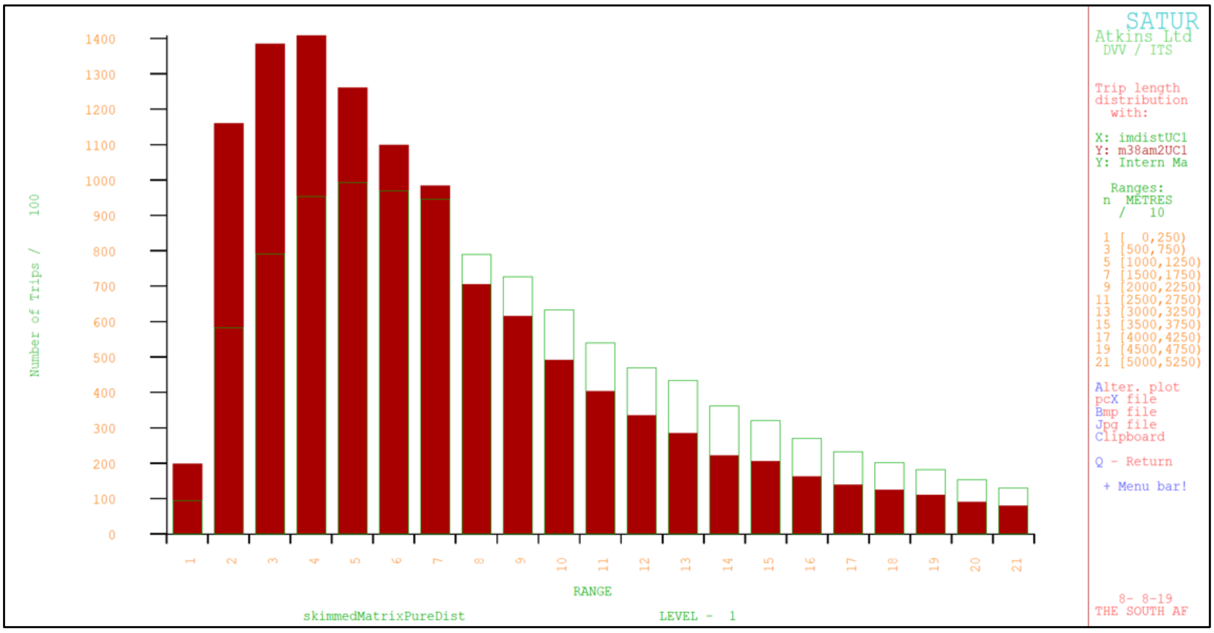

Figure 7-4: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0700)

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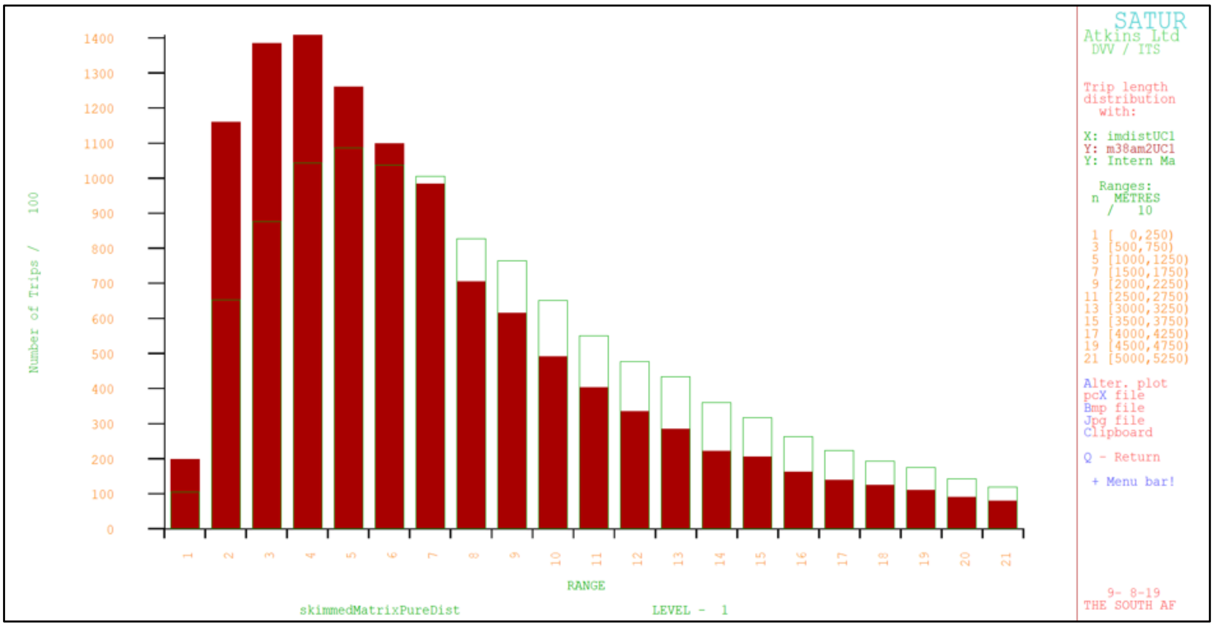

Figure 7-5: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0750)

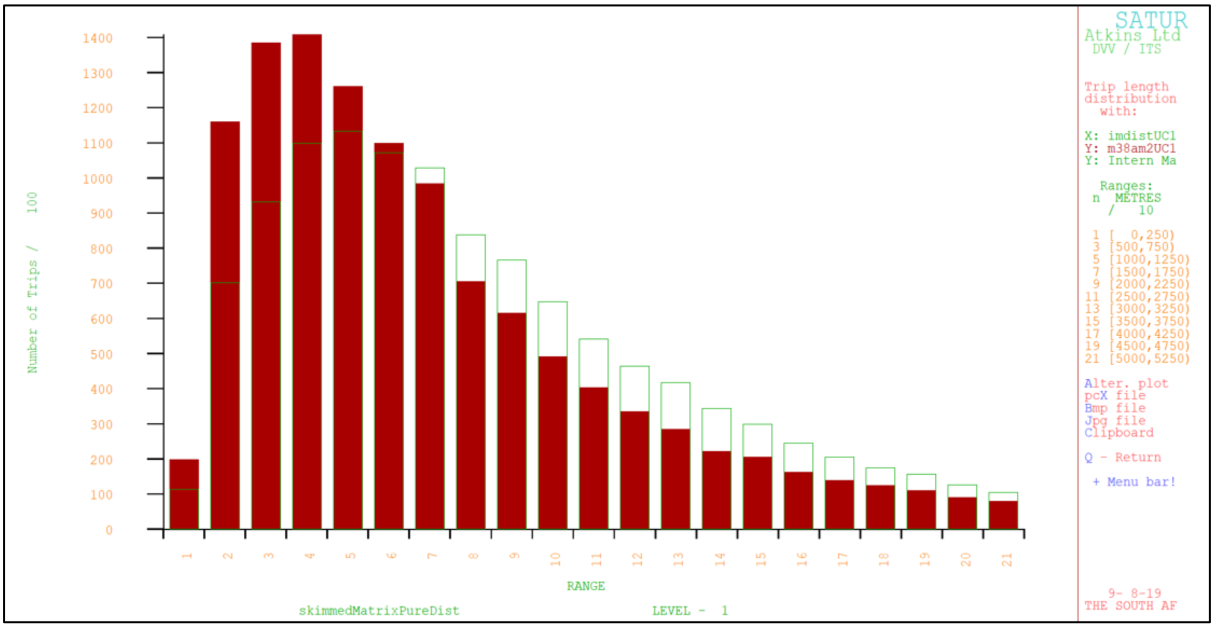

Figure 7-6: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0800)

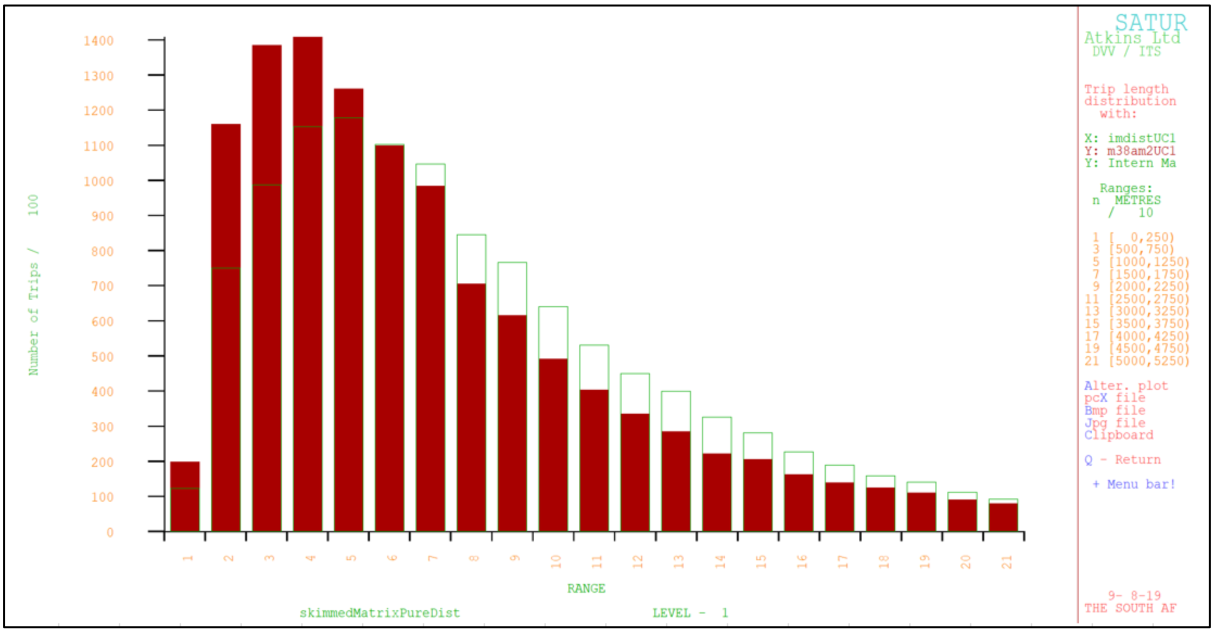

Figure 7-7: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0850)

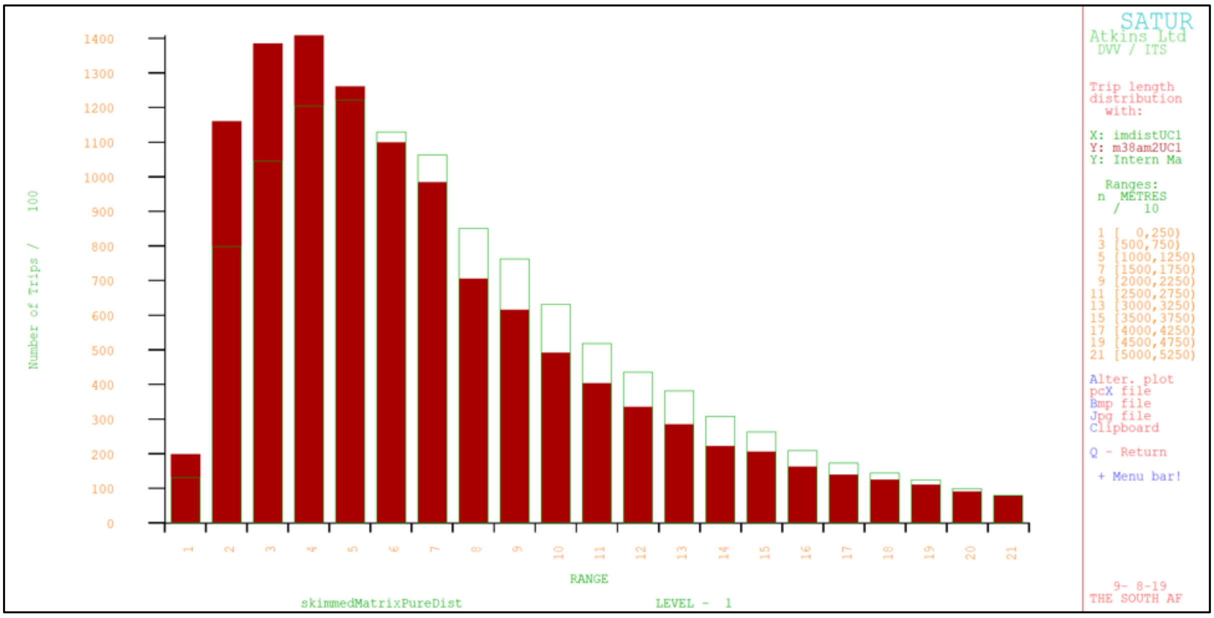

Figure 7-8: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0900)

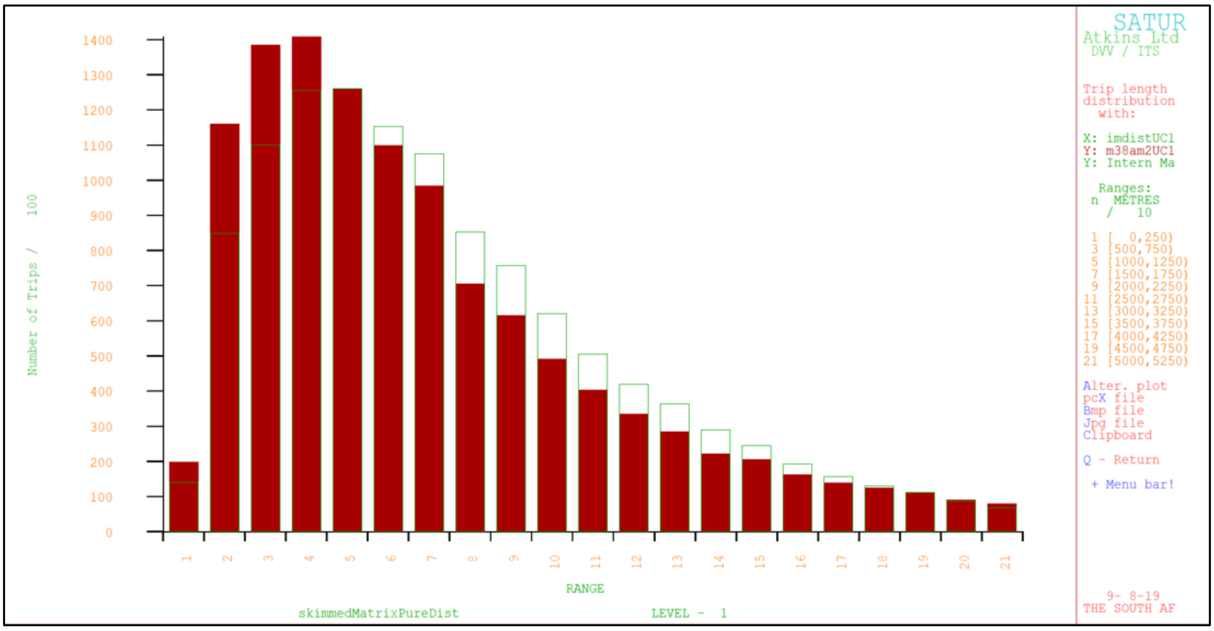

Figure 7-9: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0950)

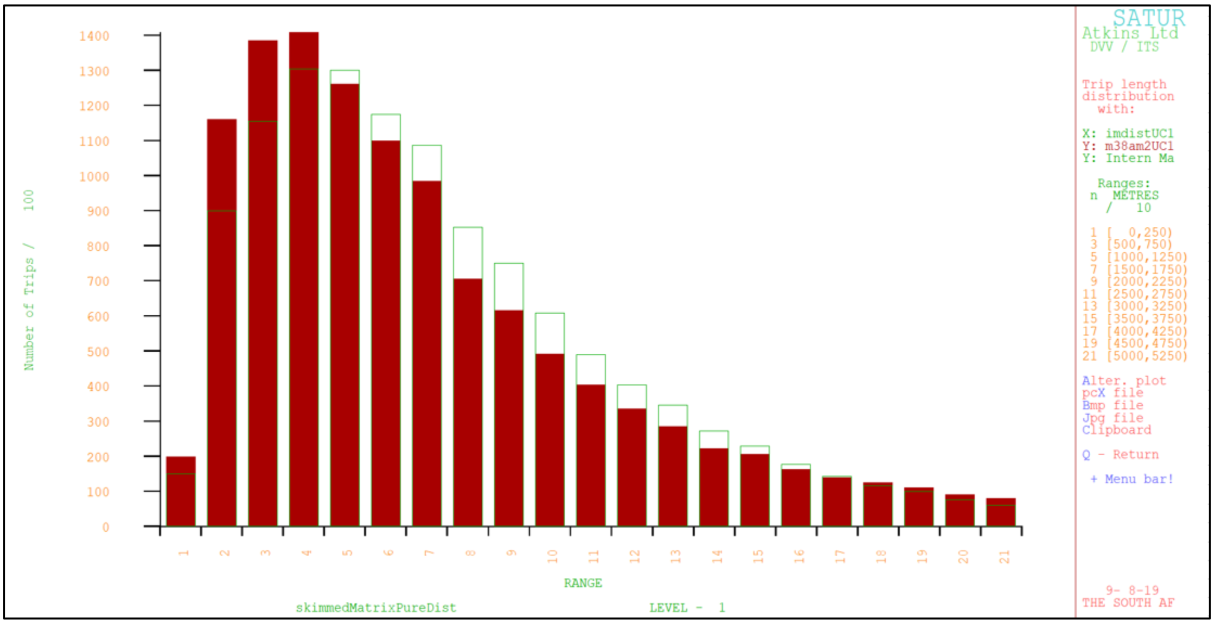

Figure 7-10: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1000)

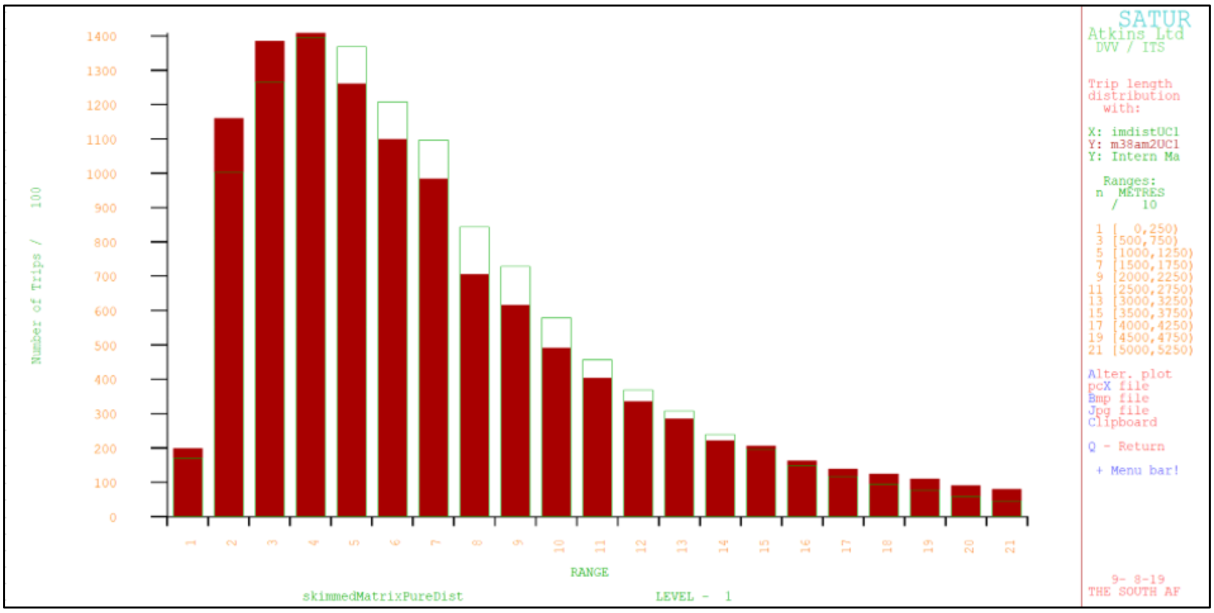

Figure 7-11: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1100)

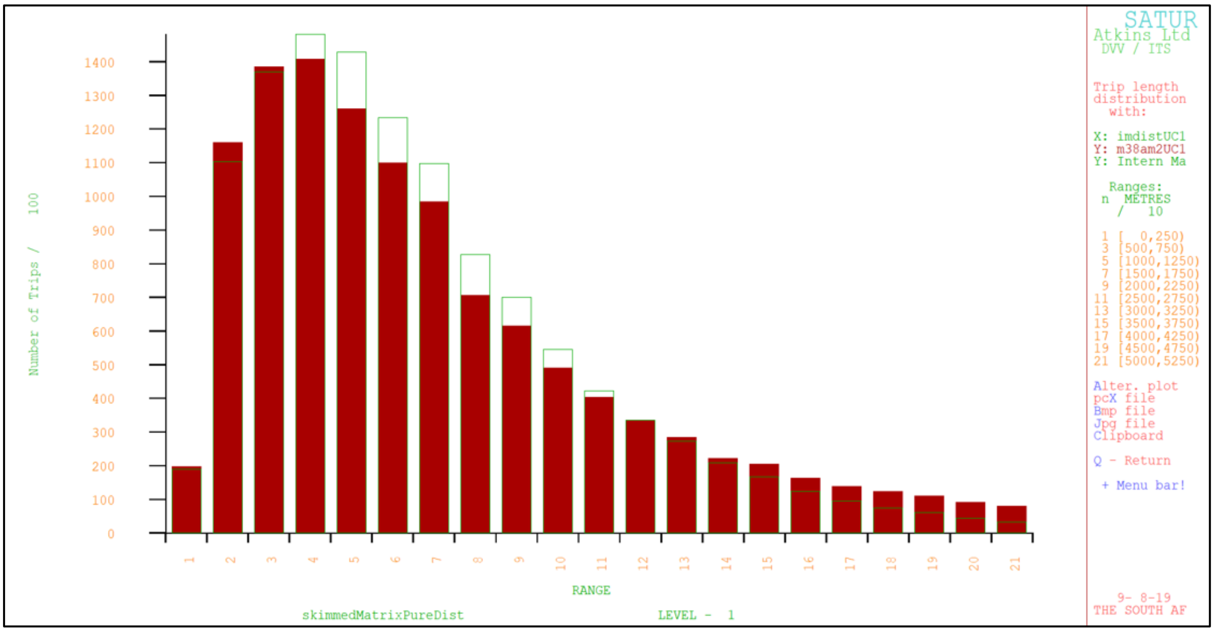

Figure 7-12: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1200)

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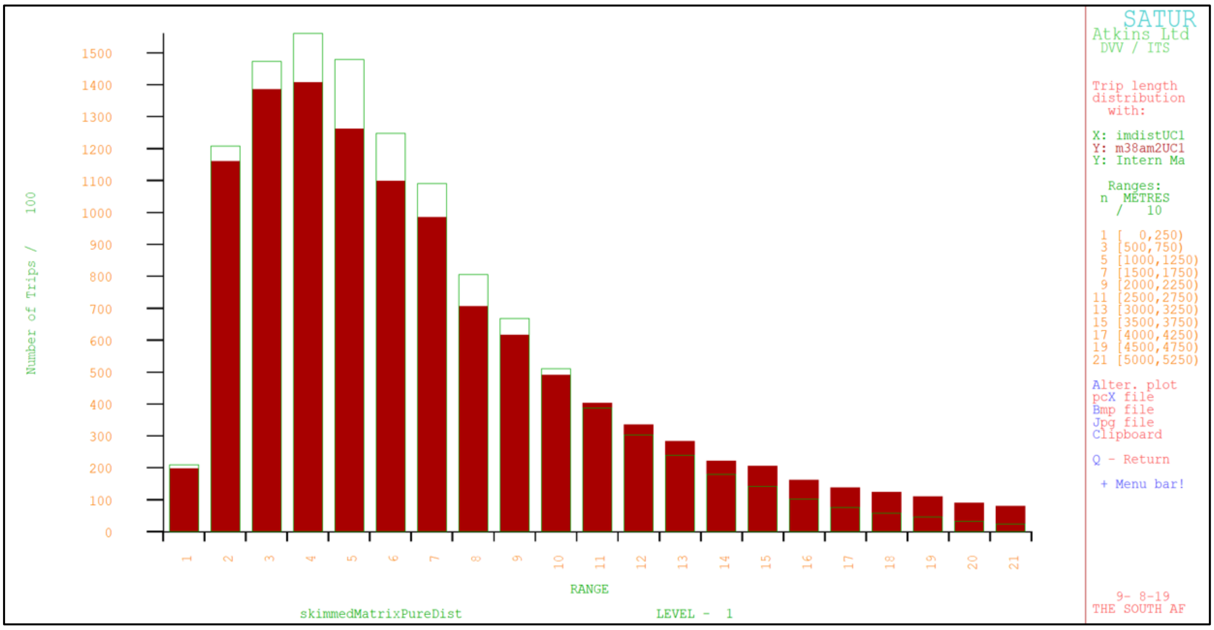

Figure 7-13: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1300)

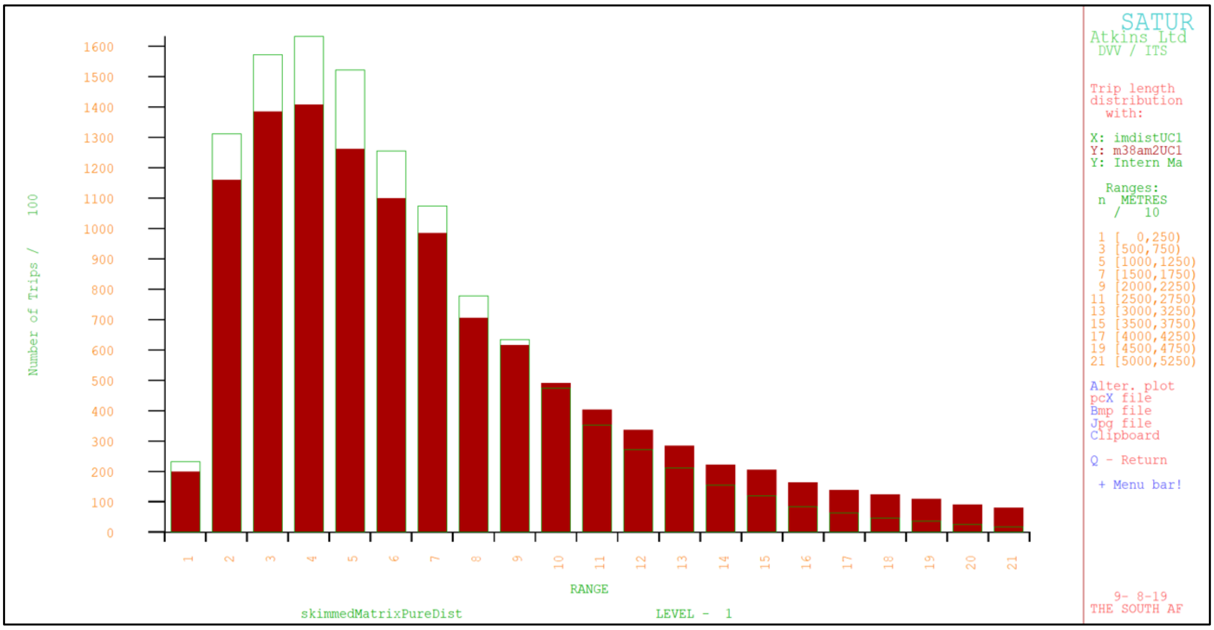

Figure 7-14: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1400)

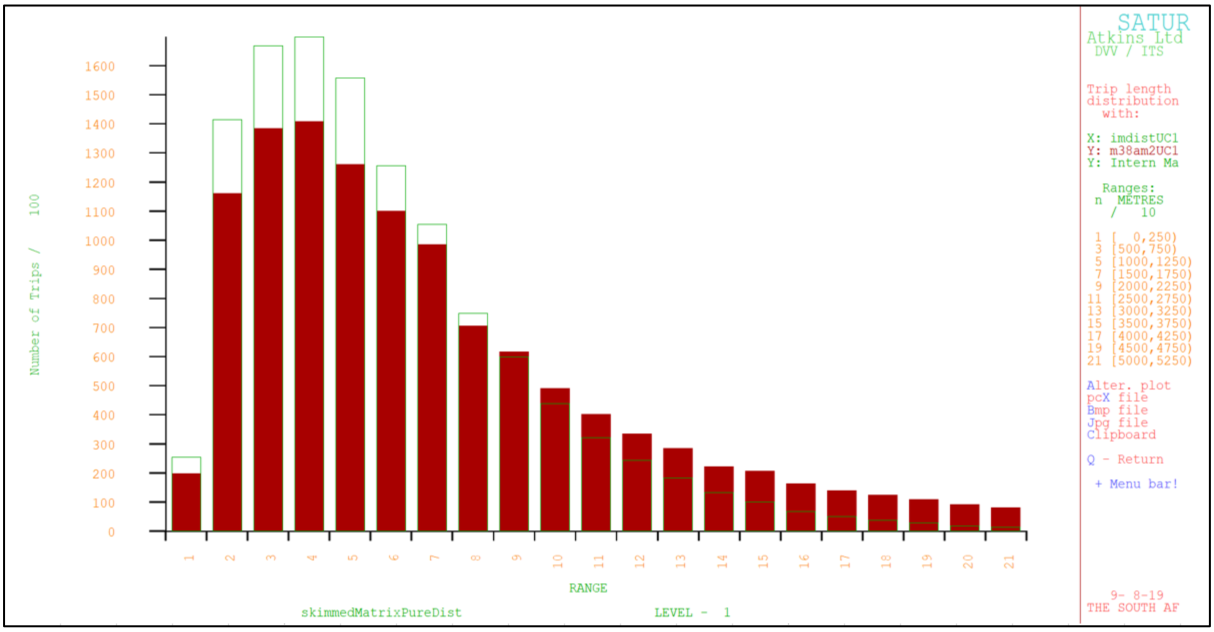

Figure 7-15: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1500)

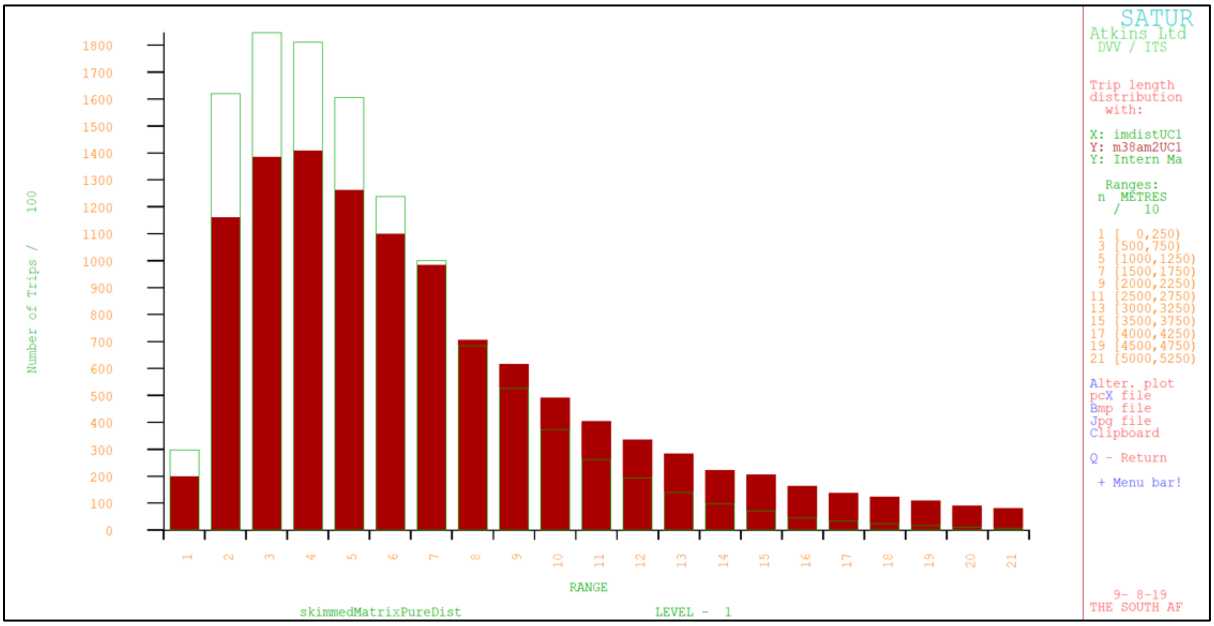

Figure 7-16: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1700)

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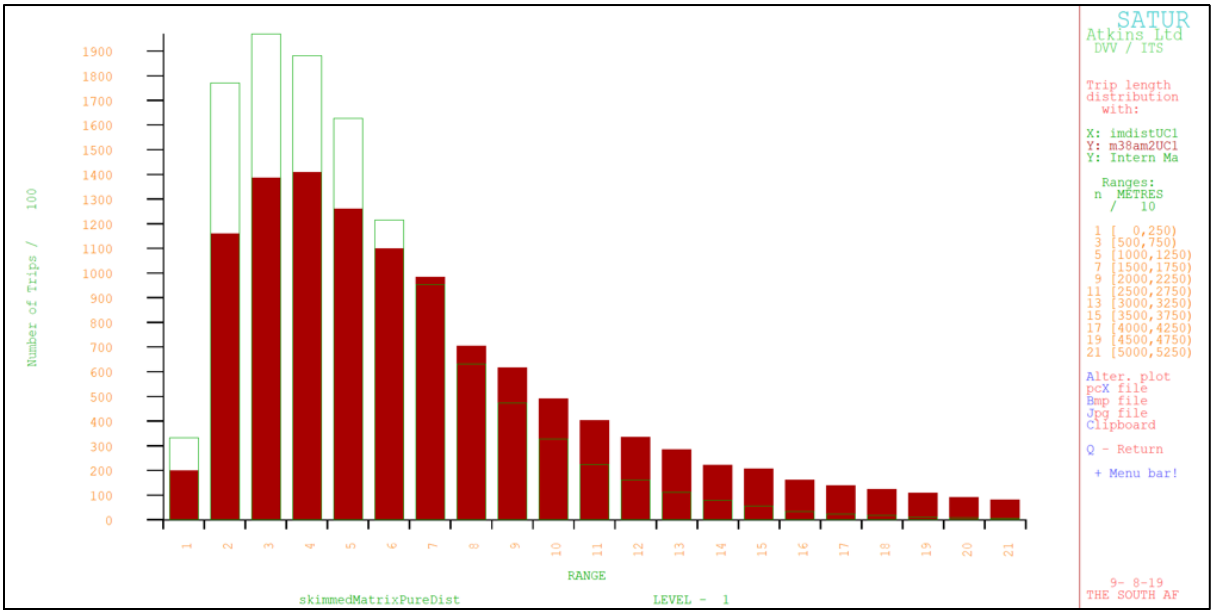

Figure 7-17: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1850)

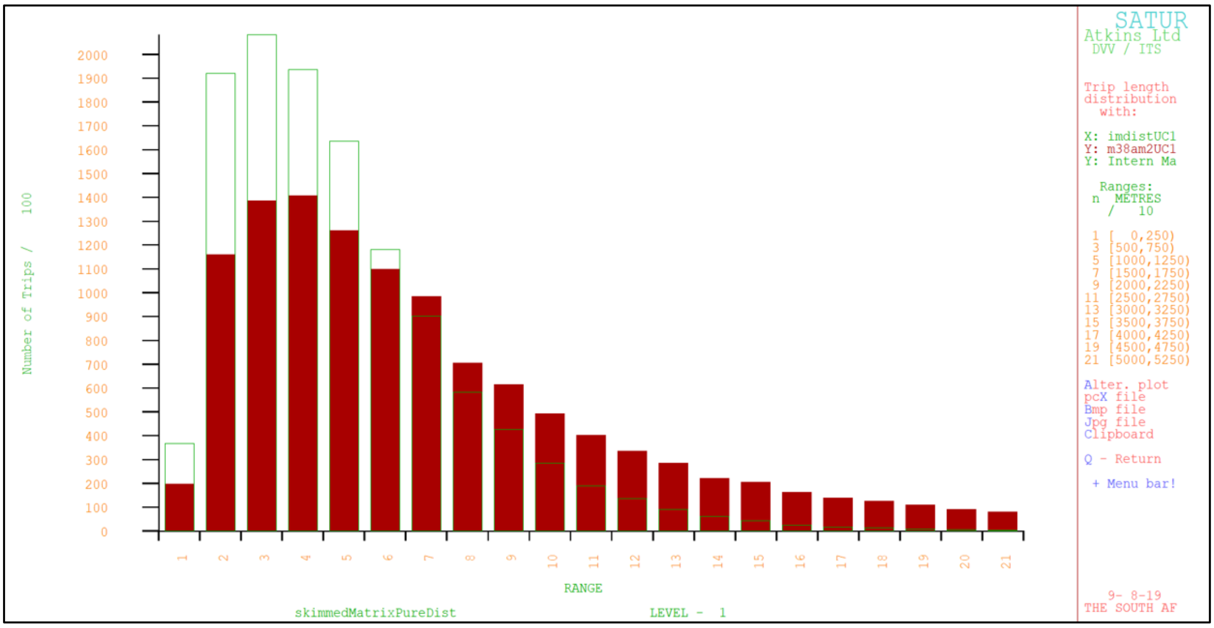

Figure 7-18: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2000)

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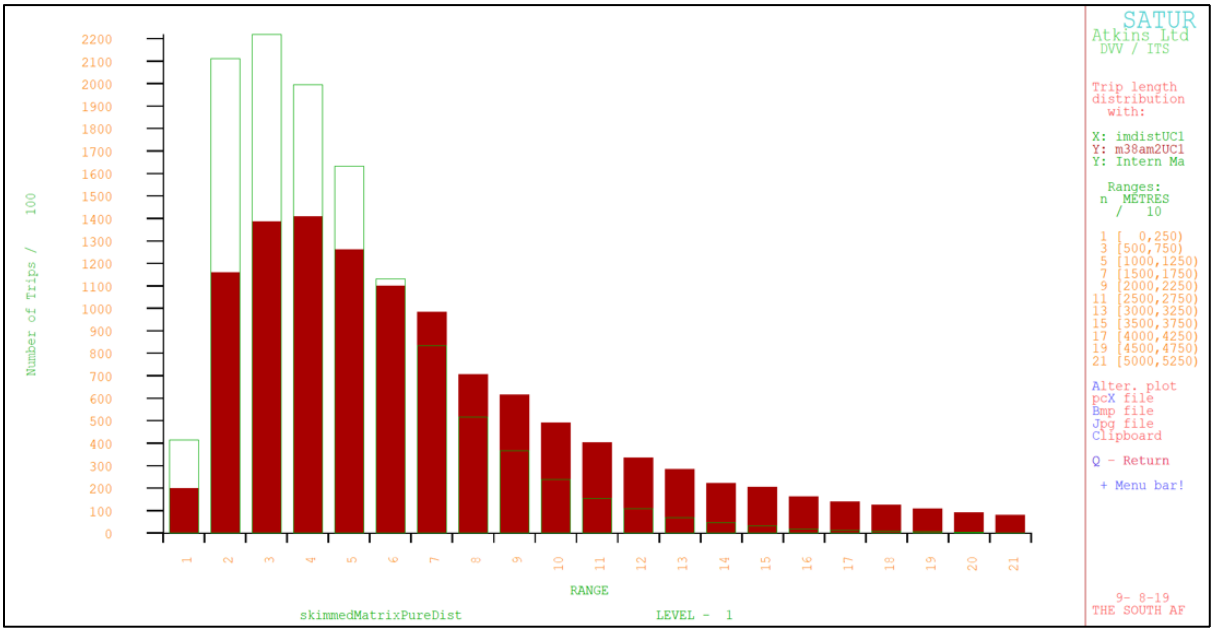

Figure 7-19: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2200)

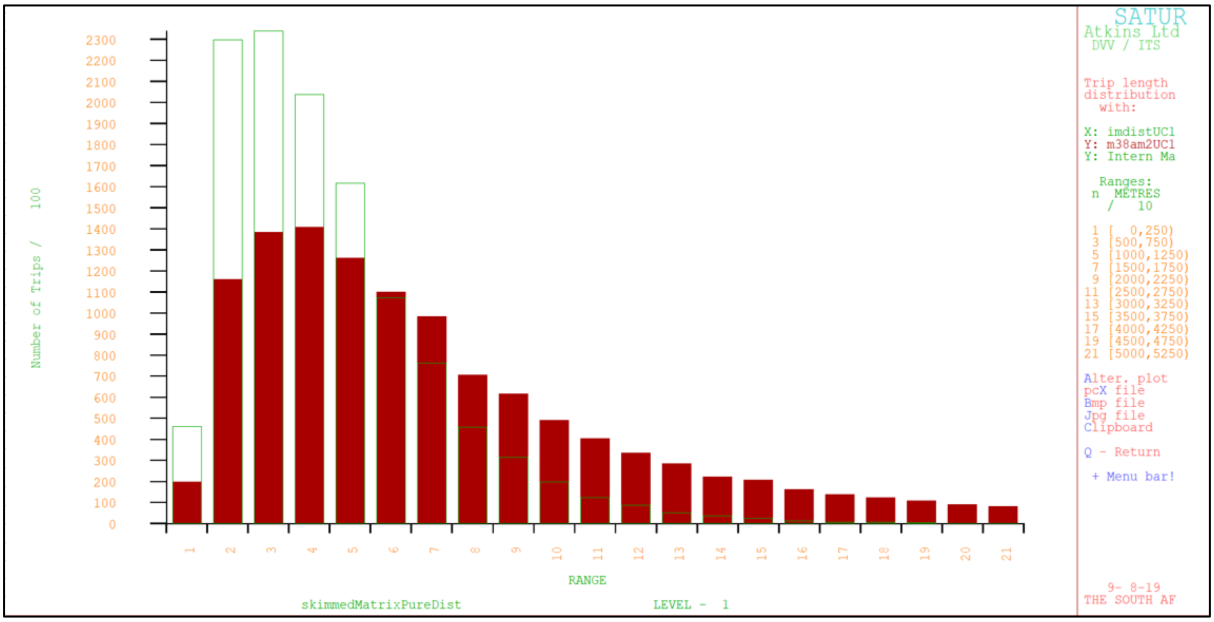

Figure 7-20: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2400)

7.2 Testing the Effect of Different Beta Values on the Average Trip length on the GFIP Network for the Design Year (2038)

Once each synthesized OD trip matrix was generated, the average trip length for each trip matrix was calculated. The R-squared value indicating the correlation of trips between each synthesized trip matrix and the trip matrix for the design year (2038) was recorded. The purpose of the R-squared value is to estimate the value of beta suitable for the exponential equation used in the trip distribution for the design year (2038). Table 7-3 indicates the R-Squared values for the respective beta values. Once the testing of the twenty beta values was completed, it was concluded that the suitable beta, using the exponential function, that accurately represents the trip distribution for the design year is 0.14. The average trip length corresponding to the different values of beta is summarized in Table 7-2

The distribution curves plotted, as part of the process of determining the change in average trip lengths, were generated using the data included in the table below. Note that the data represented relates to a trip distribution function which tests the effect of a beta value of 0.055 on the average trip length. The data tables for the other beta values tested is provided in Appendix 7.

Table 7-2: Table for Trip Comparison Synthesized Matrix (Beta = 0.055) with the Trip Matrix for the Design Year

		Matrix 1 Trips	**Matrix 2 Trips**
	Range (km)	**Design Matrix: m38amUC1.ufm**	**Synthesized Matrix**
Beta = 0.055	0-2.5	19777.58	7355.1
	2.5-5.0	115984.38	46737.8
	5.0-7.5	138463.7	65008.6
	7.5-1.0	140778.88	80850
	1.0-1.25	126078.25	87057.2
	1.25-1.5	109888.49	87258.2
	1.5-1.75	98403.21	87388
	1.75-2.0	70525.51	74738.8
	2.0-2.25	61567.38	71399.6
	2.25-2.5	49097.96	63625.5

	2.5-2.75	40242.53	55747.9
	2.75-3.0	33539.89	50153.4
	3.0-3.25	28392.57	48089.6
	3.25-3.5	22140.71	41449.6
	3.5-3.75	20547.68	38148.4
	3.75-4.0	16234.75	33164.1
	4.0-4.25	13813.85	29386.3
	4.25-4.5	12404.24	26601.3
	4.5-4.75	10935.59	25169.2
	4.75-5.0	9063.27	21879.9
	5.0-5.25	8014.97	19189.8

The trip data for the design year OD matrix and the synthesized matrix, using 0.055 for beta, was plotted against each other to determine the effect on the average trip length by changing beta from 0.14 to 0.0550. This process was repeated for each beta value tested. The distribution curves have been provided in the next few pages.

Note that the blue curve represents the trip distribution for the design year OD matrix and the orange curve represents the trip distribution for the synthesized matrix.

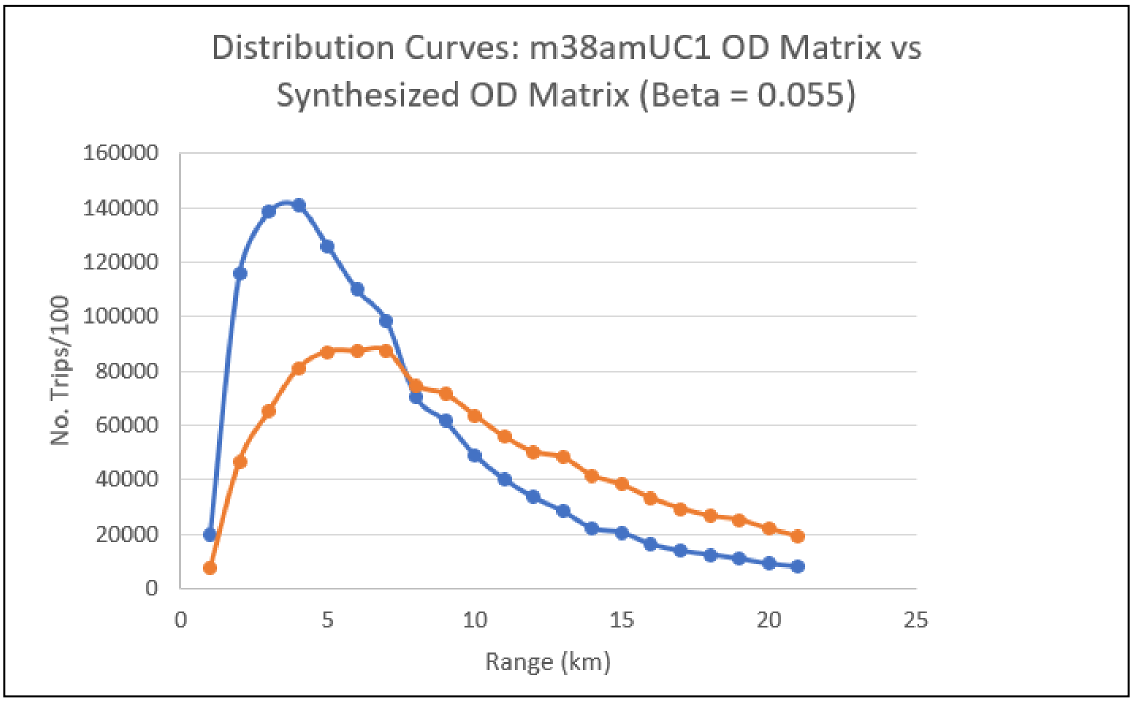

Figure 7-21: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0550)

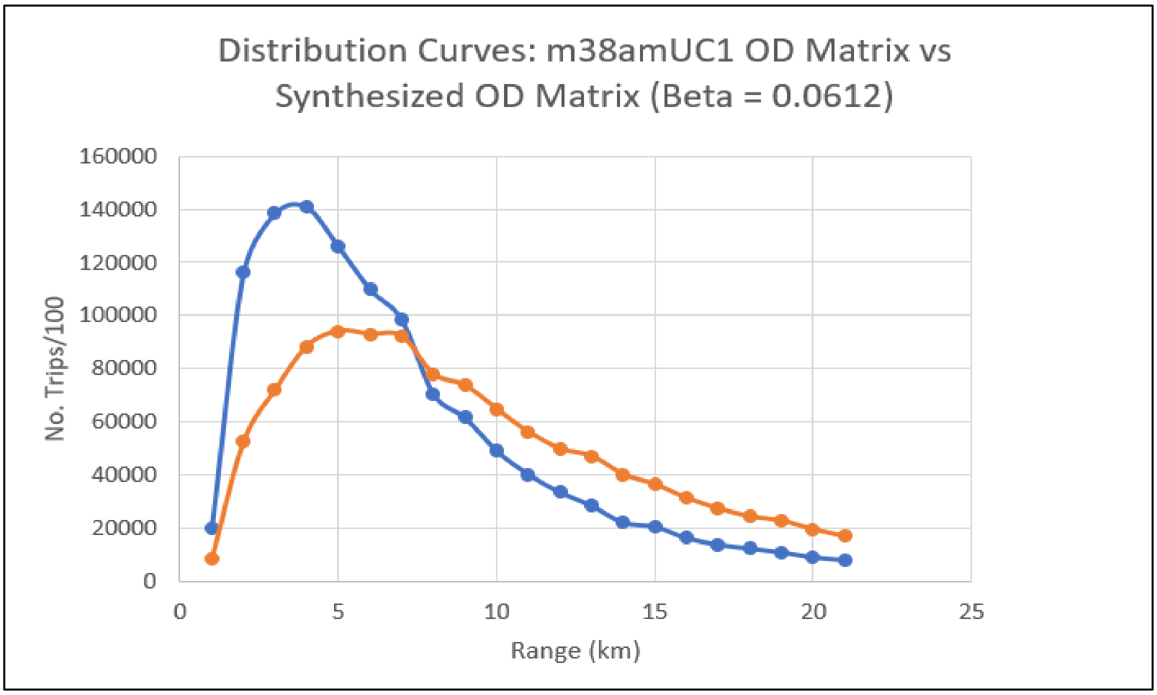

Figure 7-22: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0612)

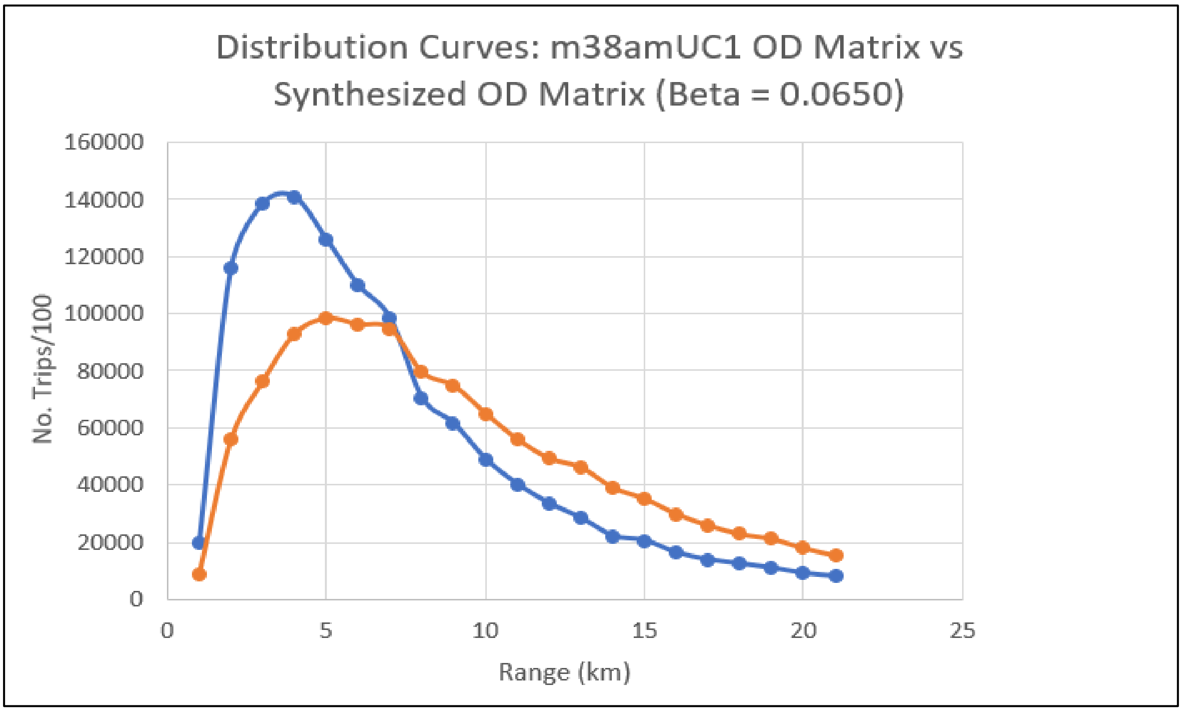

Figure 7-23: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0650)

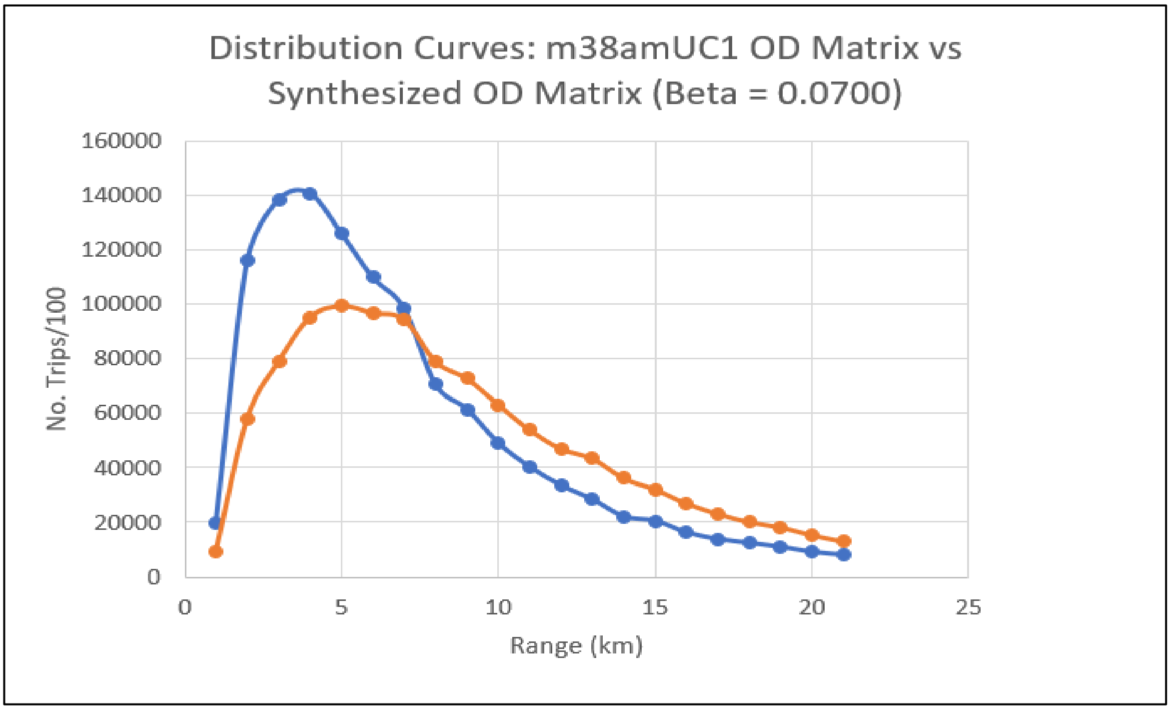

Figure 7-24: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.070)

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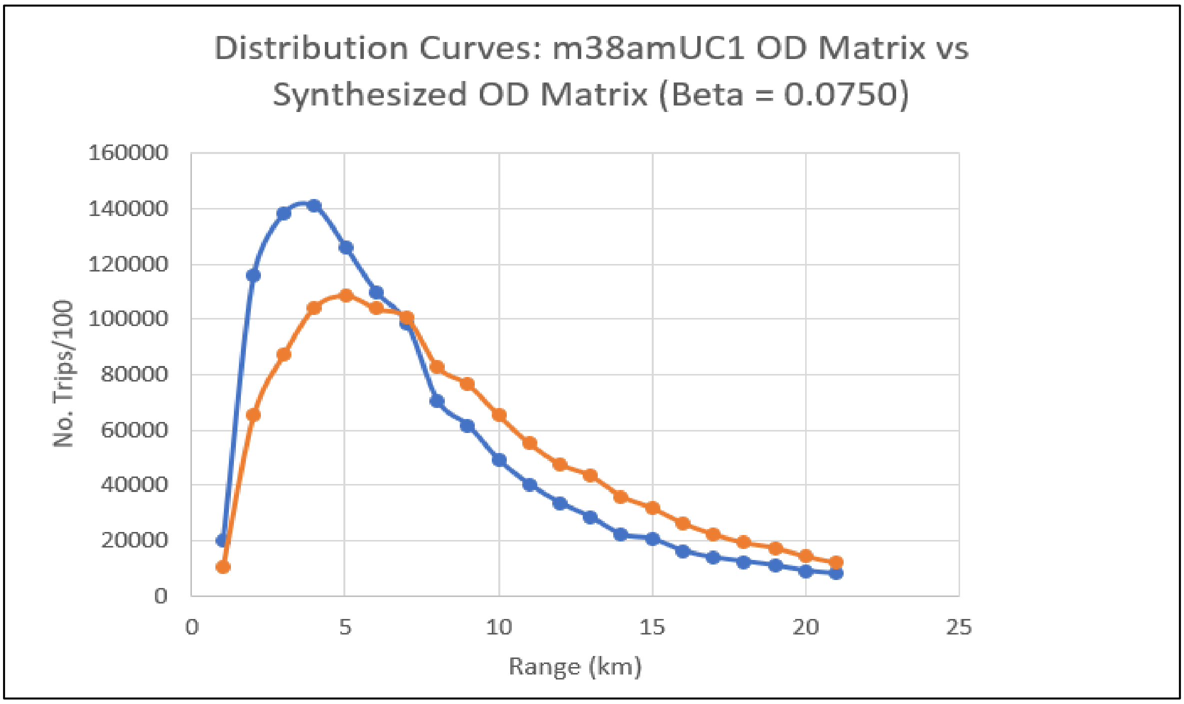

Figure 7-25: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0750)

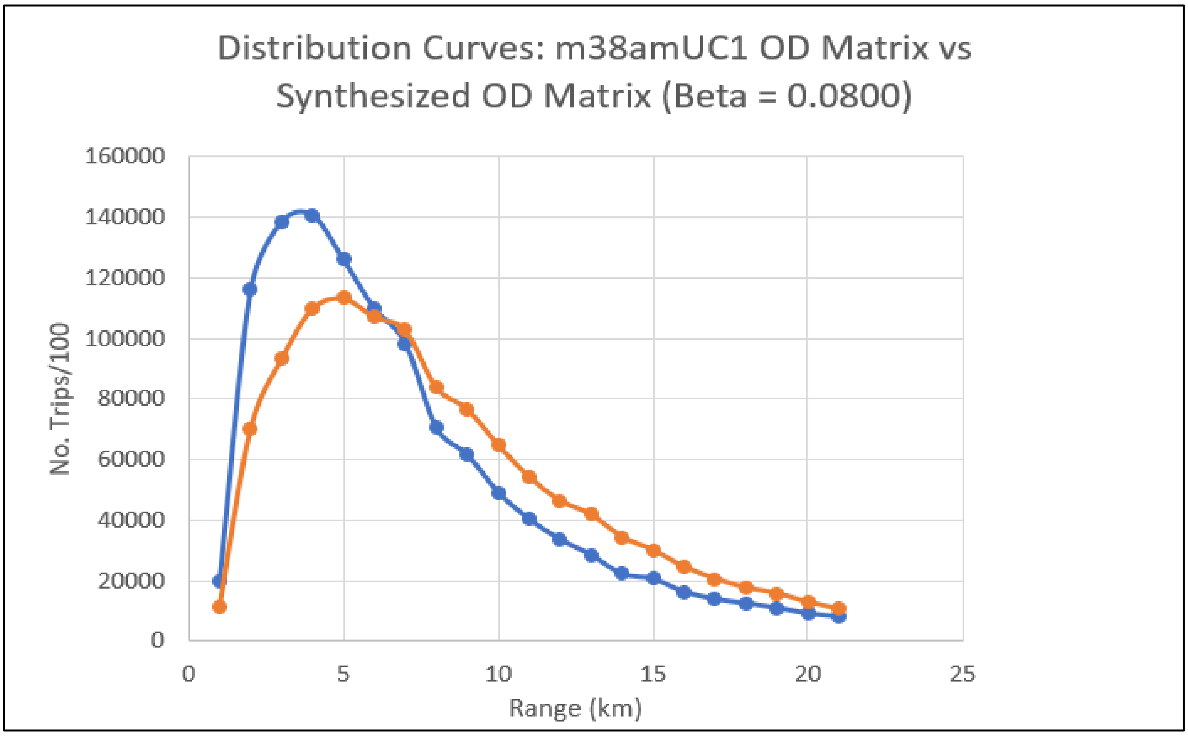

Figure 7-26: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0800)

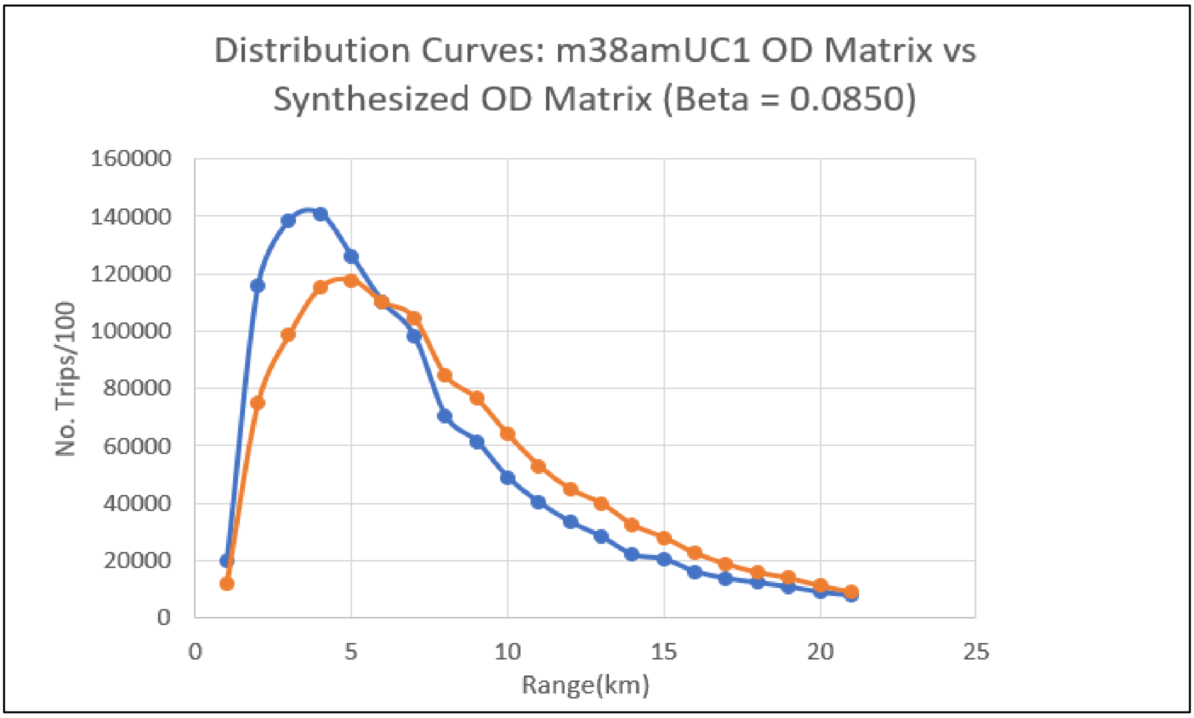

Figure 7-27: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0850)

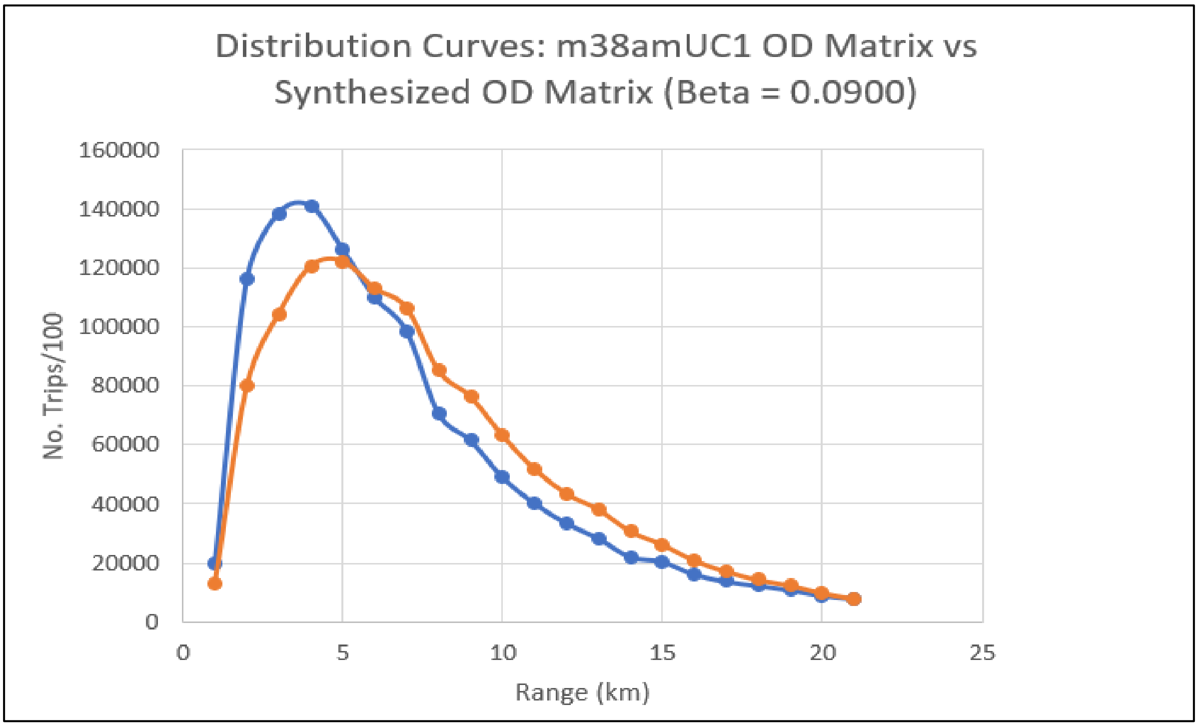

Figure 7-28: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0900)

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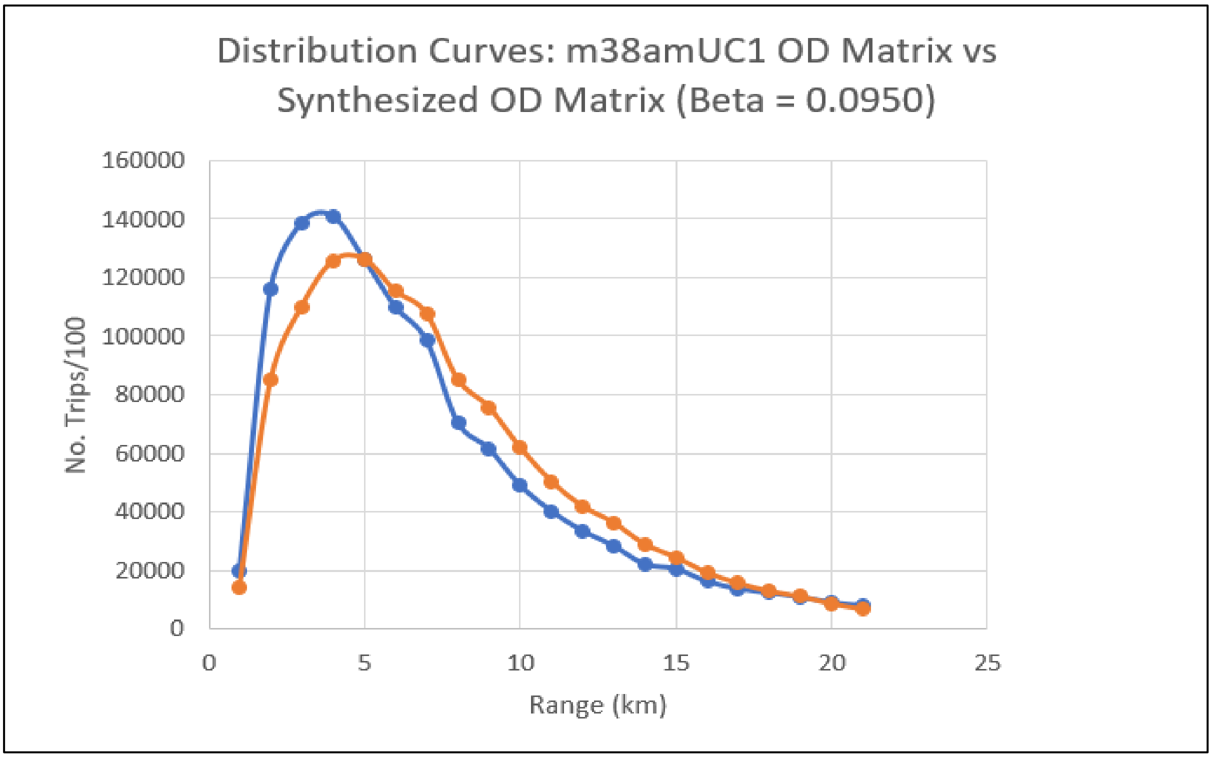

Figure 7-29: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.0950)

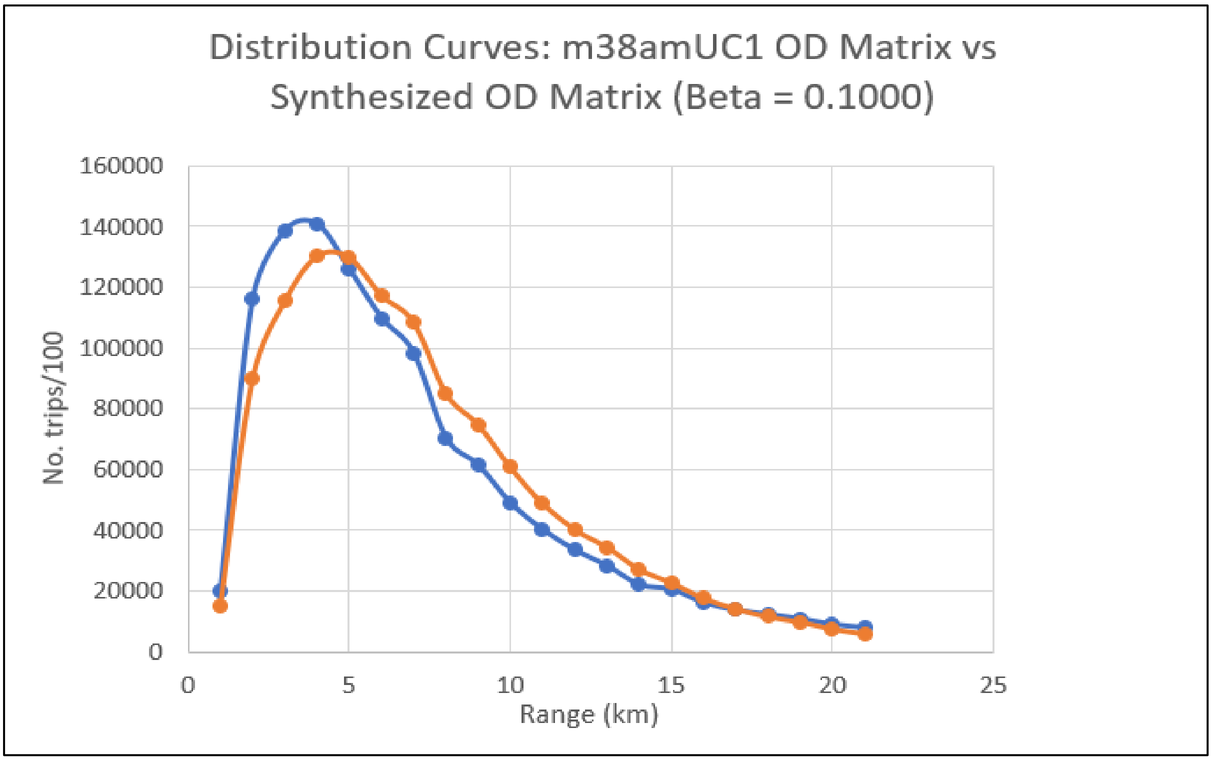

Figure 7-30: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1000)

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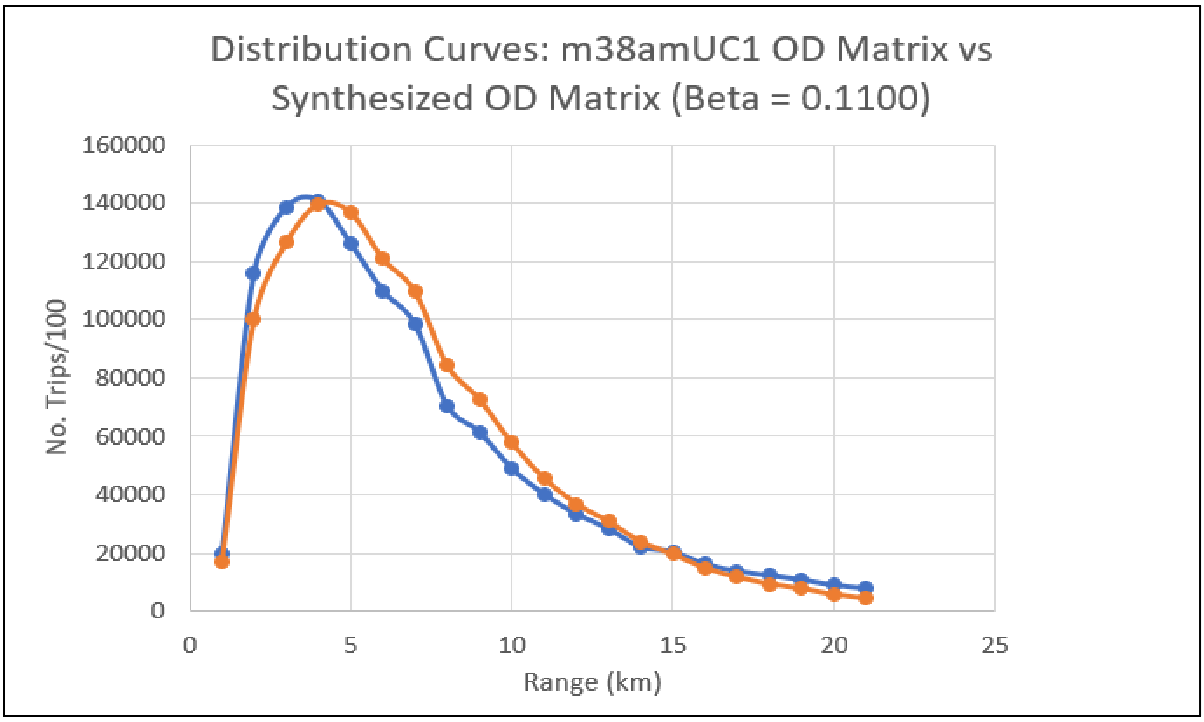

Figure 7-31: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1100)

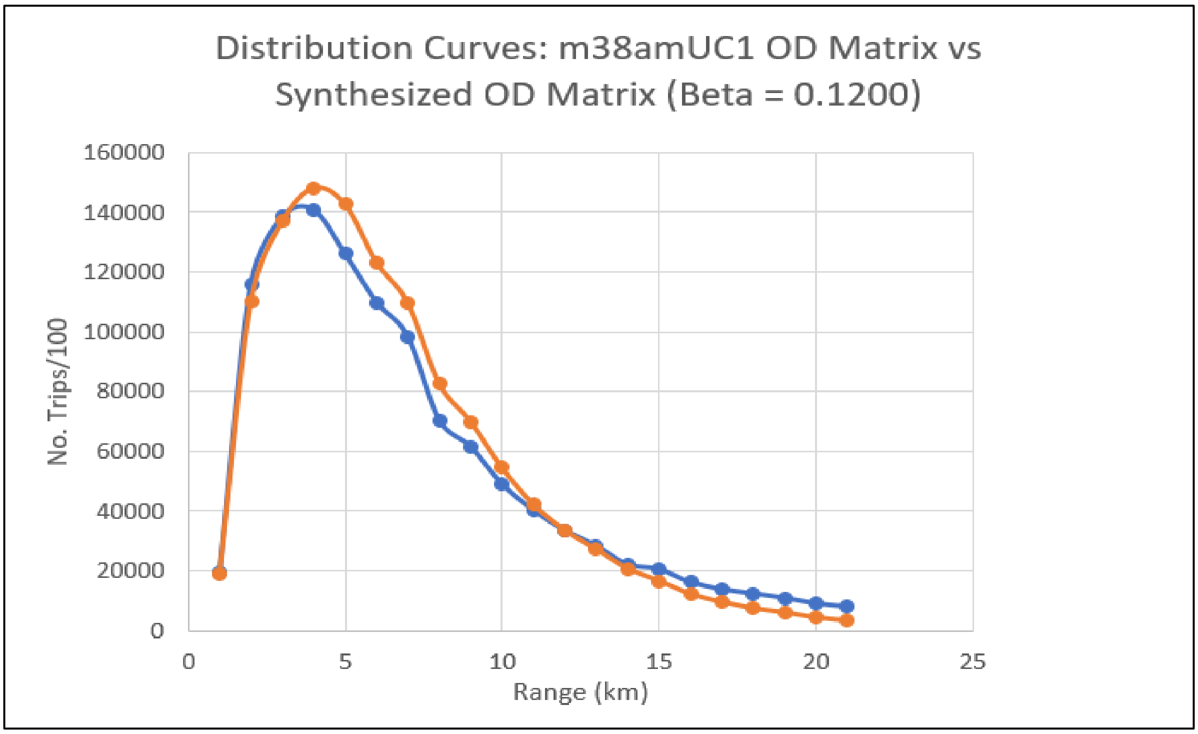

Figure 7-32: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1200)

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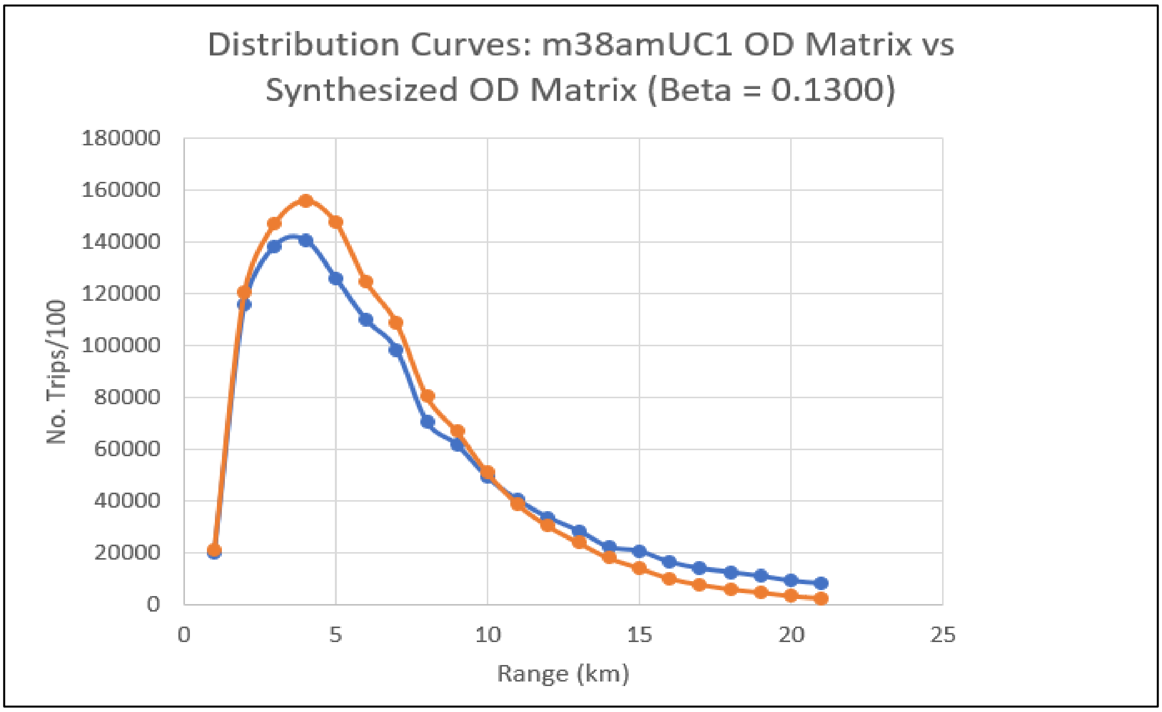

Figure 7-33: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1300)

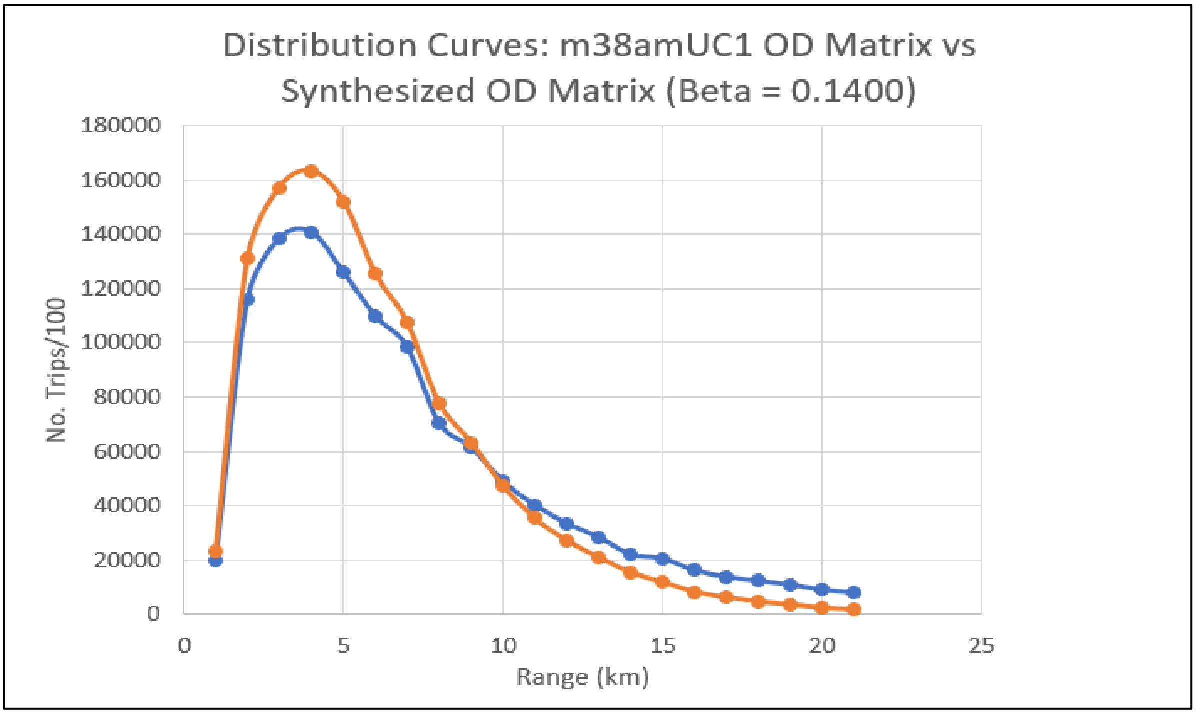

Figure 7-34: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1400)

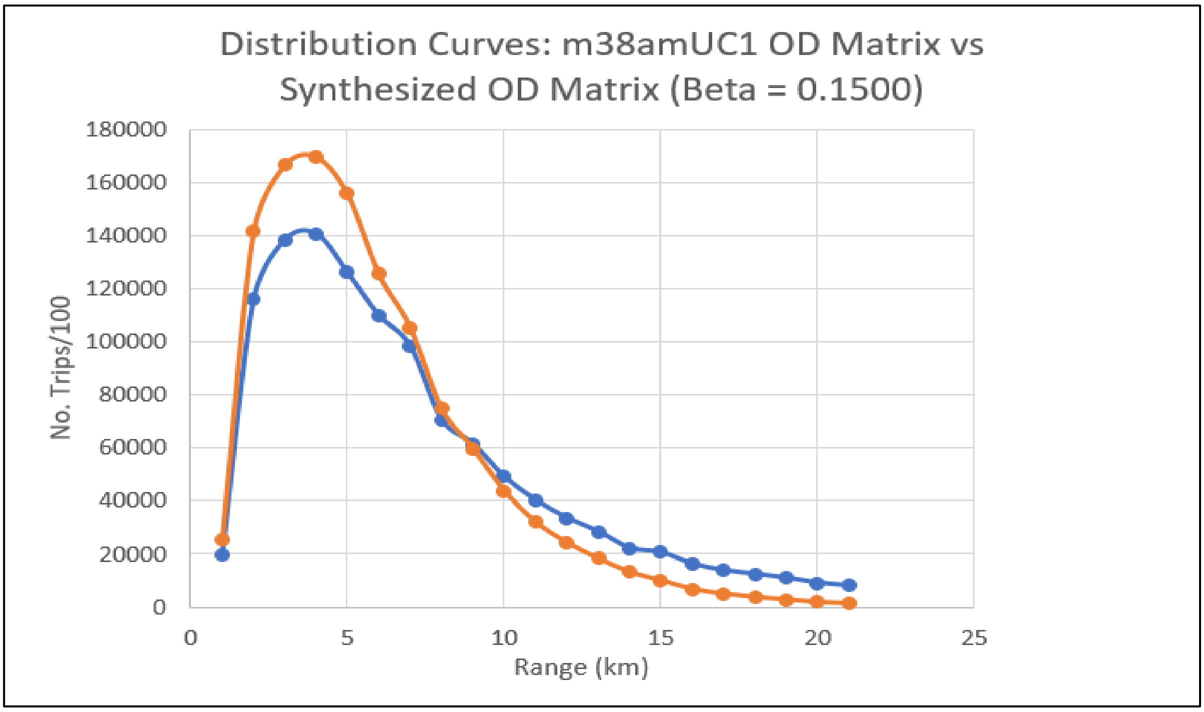

Figure 7-35: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1500)

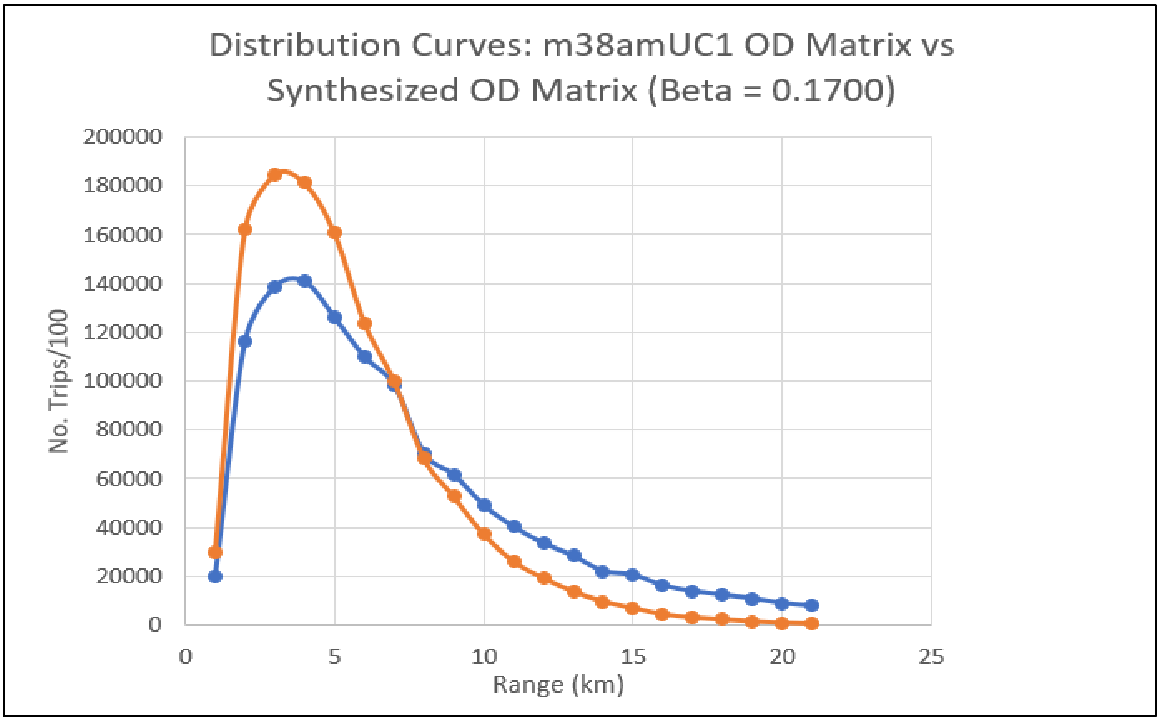

Figure 7-36: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1700)

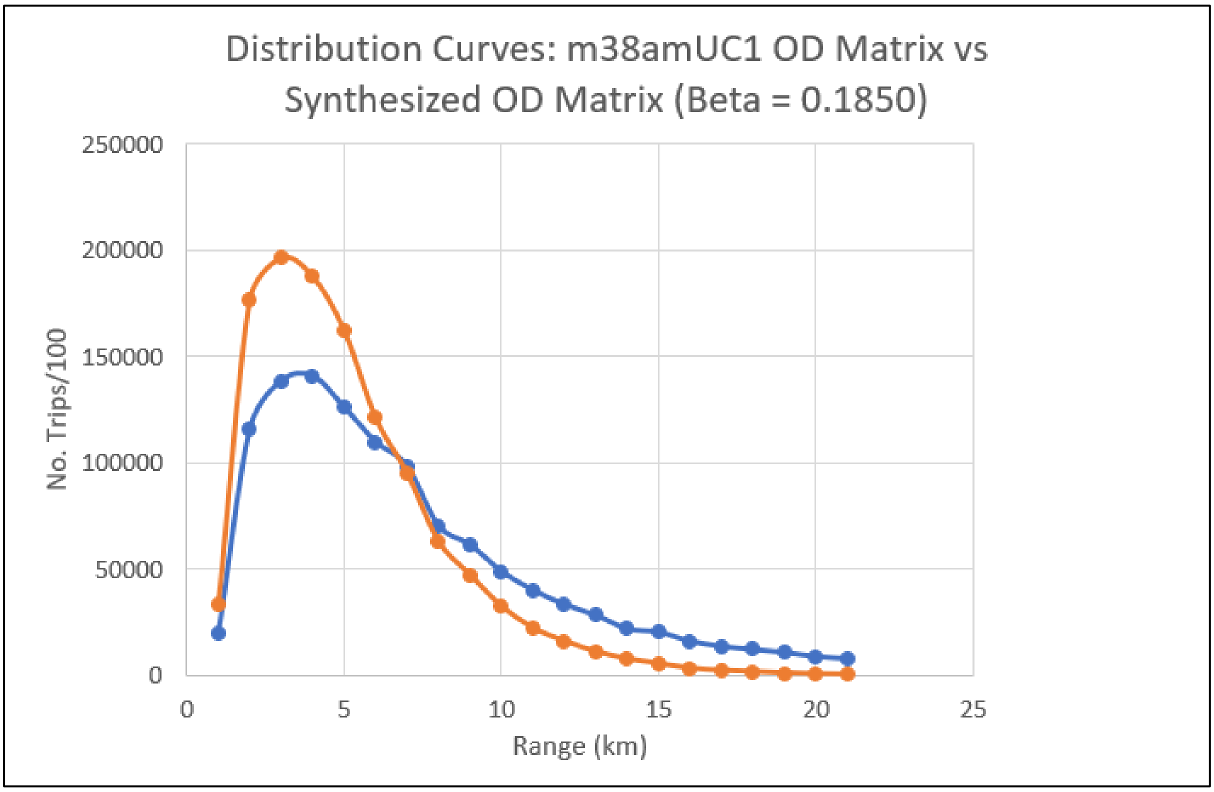

Figure 7-37: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.1850)

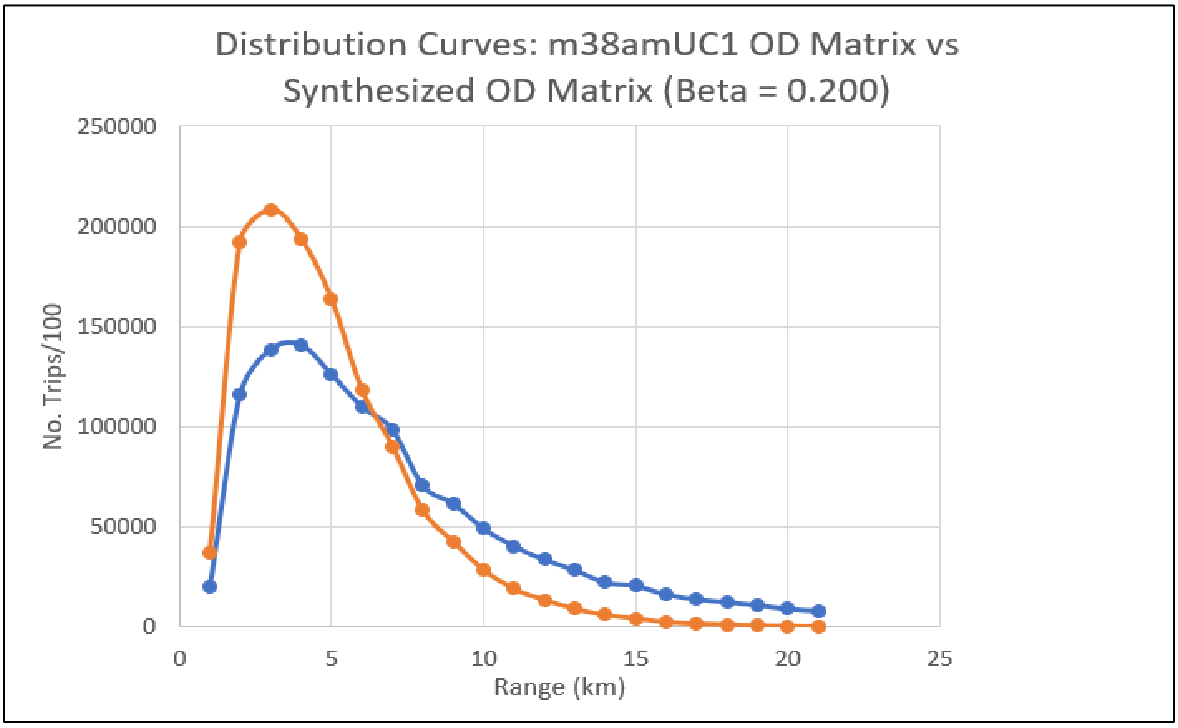

Figure 7-38: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2000)

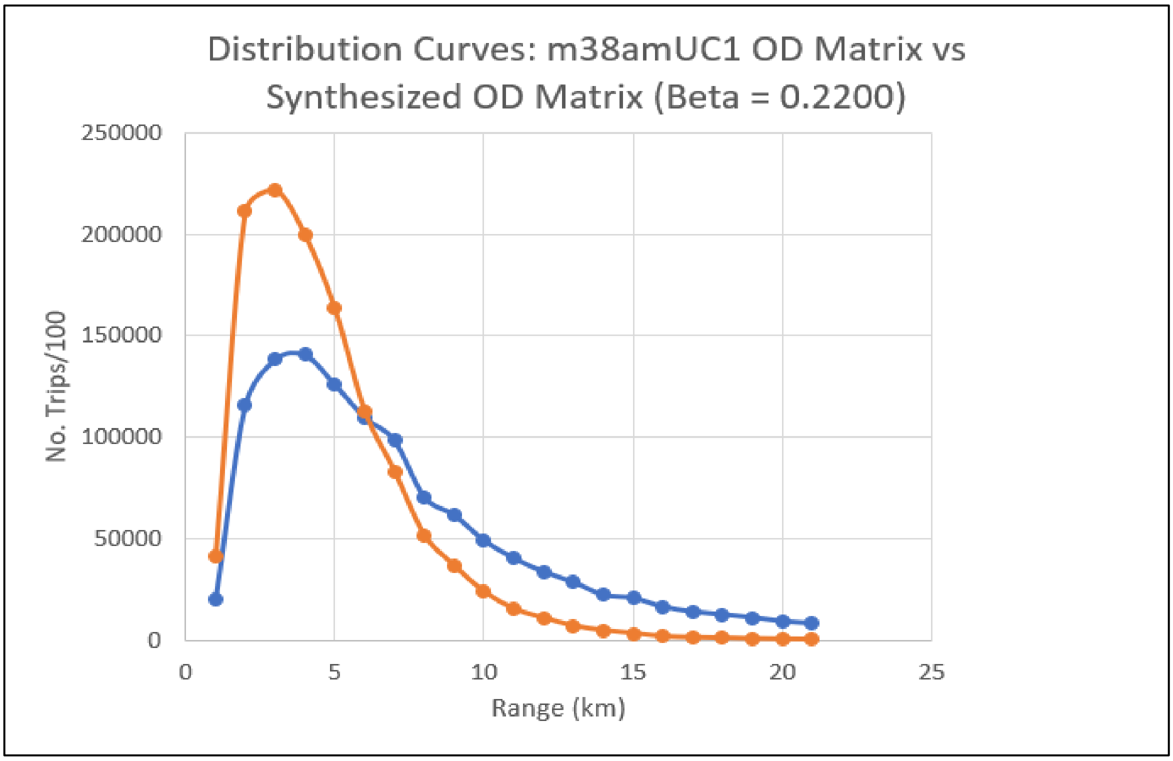

Figure 7-39: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2200)

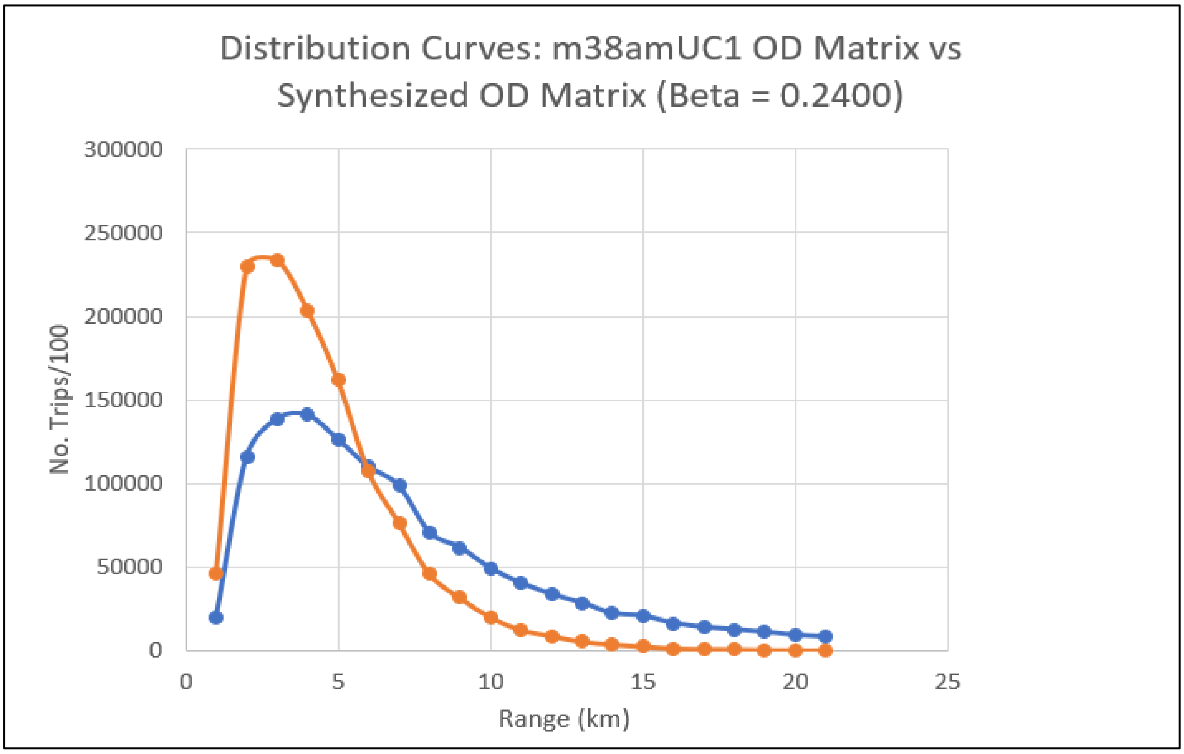

Figure 7-40: Comparison of Distribution Curves for Design Year Trip Matrix and Synthesized Trip Matrix (beta = 0.2400)

Table 7-3 provides the results obtained through testing the effect of the beta value used on the exponential function on the average trip length on the GFIP network.

Table 7-3: Trips Lengths and R-Squared Values for each Beta Value Tested

Beta	Trip Length (km)	R-Squared Value
0.0550	23	0.657
0.0612	22	0.726
0.0650	21	0.762
0.0700	21	0.802
0.0750	20	0.838
0.0800	20	0.869
0.0850	19	0.894
0.0900	18	0.917
0.0950	18	0.935
0.1000	18	0.951
0.1100	17	0.974
0.1200	16	0.989
0.1300	15	0.996
0.1400	14	0.997
0.1500	14	0.993
0.1700	13	0.974
0.1850	12	0.953
0.2000	12	0.929
0.2200	11	0.893
0.2400	10	0.856

7.3 Summary

Through an extensive testing process to determine the effect of selected beta values on the average trip lengths travelled by light vehicles on the GFIP network, it was concluded that the average trip travelled by light vehicles decreases as the value of beta increases. This in theory means that drivers favour shorter trips. But how can this information be used to improve the way in which the planning and implementation of road infrastructure is done in the future? How

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can we use this to prevent further sprawl in cities? To demonstrate the link between shorter trips and improved road infrastructure planning, the synthesized OD trip matrices, developed through the testing of different beta values, must be assigned to the GFIP road network. The purpose of this is to observe the behavior of drivers, through their trip distribution, on the GFIP network. This analysis will be discussed in Chapter 8.

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8 Case Study: Testing the Performance of the Distance-deterrence Functions

This chapter focuses on demonstrating a method of identifying road infrastructure which require upgrades/improvements to promote shorter trips and in turn support densification. Essentially the aim of this chapter is to use the appropriate synthesized trip matrices, discussed in Chapters 6 and 7, to highlight the resulting consequences of not changing the current approach to road infrastructure planning. The Gravity model was used to distribute the trips for the selected synthesized matrices.

This chapter will also assist in forming an introduction to the idea of promoting shorter trips through improved road infrastructure planning which incorporates the idea of shorter average trip lengths as discussed in Chapters 6 and 7. This idea will be tested using road infrastructure improvement project scenarios in Chapter 9.

In essence, this chapter identifies road infrastructure improvement (in terms of capacity) requirements identified by forcing drivers to take shorter trips through the simulation of distance-deterrence functions representing shorter trip lengths on the road network. This is simulated through the assignment of the distance-deterrence functions (for shorter trip lengths) on the road network.

This is demonstrated by using the GFIP network as a case study.

8.1 Selected Scenarios for Testing

There were six key scenarios that were modelled, using the SATURN software, to test the performance of the selected synthesized trip matrices. The scenarios are summarized below:

- The trip distribution and congestion levels for the base year (2018);
- The predicted trip distribution and congestion levels for the design year (2038) if the current approach to planning road infrastructure does not change;
- The predicted trip distribution and congestion levels for the design year (2038) by reducing the average trip length by 10%;
- The predicted trip distribution and congestion levels for the design year (2038) by reducing the average trip length by 20%;
- The predicted trip distribution and congestion levels for the design year (2038) by reducing the average trip length by 30%; and
- The predicted trip distribution and congestion levels for the design year (2038) by reducing the average trip length by 40%.

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The table below provides the beta values and corresponding average trip lengths that form part of each scenario to be tested.

Table 8-1: Test Cases for Average Trip Lengths per Beta Value: For the Design Year, 2038

Test Case	**Average Trip Length (km)**	**Beta Value**
Scenario 1: Do-Nothing Scenario	16	0.08
Scenario 2: Decrease Average Trip Length by 10%	14.4	0.140
Scenario 3: Decrease Average Trip Length by 20%	12.8	0.170
Scenario 4: Decrease Average Trip Length by 10%	11.2	0.22
Scenario 5: Decrease Average Trip Length by 40%	9.6	0.24

Figure 8-1 provides a map of the road network including in the Gauteng Freeway Improvement Project.

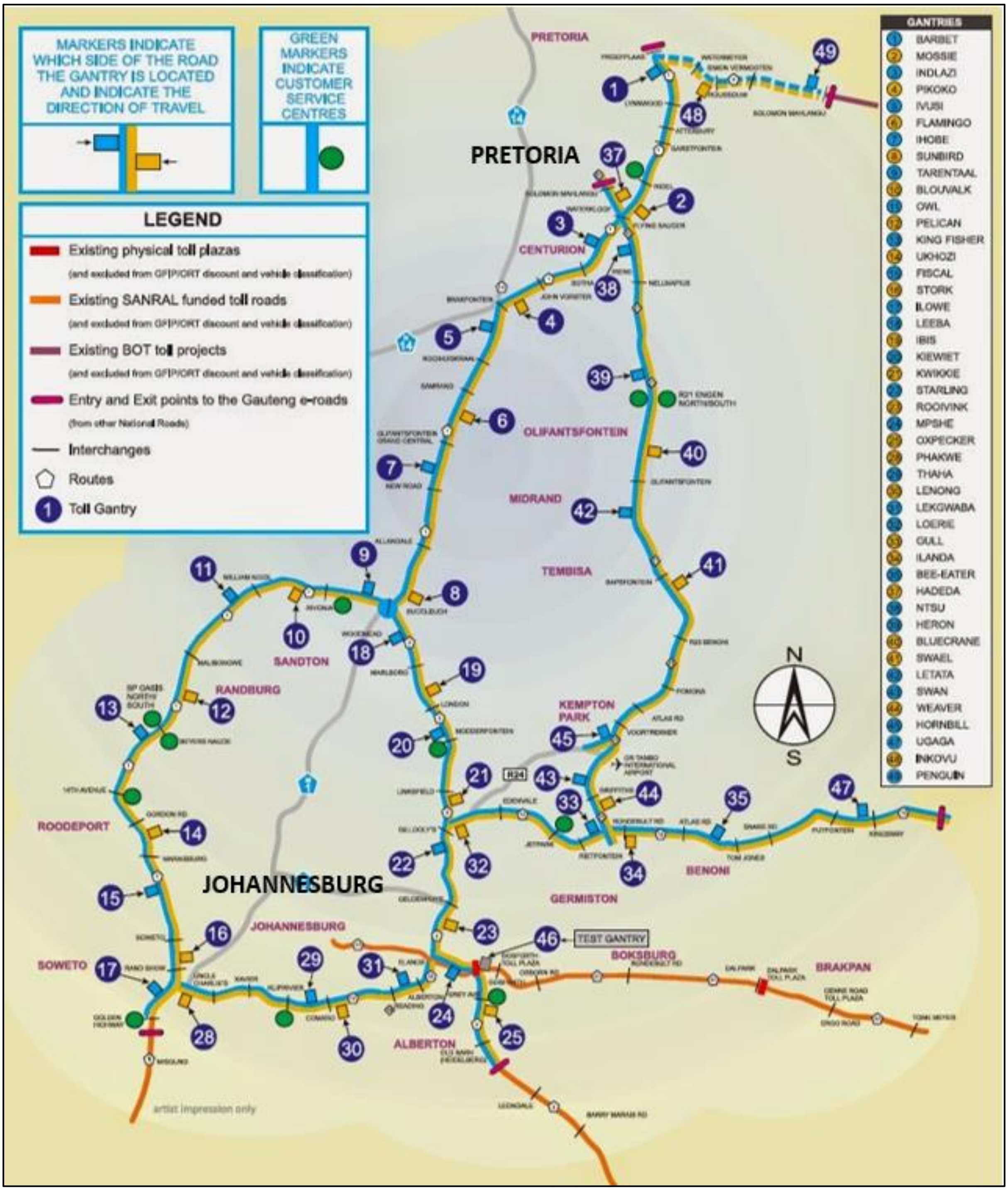

Figure 8-1: GFIP Road Network (Source: SANRAL Toll Strategy, 2019)

The next section of this report provides graphical results of the assignments of the different distance-deterrence functions on the GFIP road network. Explanations for each assignment will be provided under the relevant sub-section.

Congestion levels (volume/capacity) on the road network are indicated by the following legend:

- Band 1: 50%: light green
- Band 2: 60%: green

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- Band 3: 70%: Magenta
- Band 4: 80%: orange
- Band 5: 95% and higher: red

8.2 Existing Congestion Levels on the GFIP Road Network. Scenario for the Base Year Origin-Destination Matrix

Before the synthesized trip matrices for each scenario could be assigned to the GFIP road network, the trip matrix for the base year (2018) needed to be assigned to the GFIP network. This is to determine the following:

- The current congestion levels on the GFIP network;
- Road infrastructure which require capacity improvements;
- An understanding of congestion levels on road sections further away from the Pretoria and Johannesburg CBDs; and
- An understanding of current congestion levels on existing road infrastructure close to the Pretoria and Johannesburg CBDs.

The figure below illustrates the current congestion levels on the GFIP network obtained from the assignment of the base year trip matrix. The following observations can be made:

- There is congestion on sections of road, on the second order roads, close to both CBDs which indicate that there is a high volume of traffic moving in and around the CBDs. This could most likely be work trips.
- There is indication of high congestion levels on the second order roads linking to the freeways. This indicates that people are travelling from areas which are further away from both CBDs. This is an indication of an imbalance in jobs and housing.
- There is little congestion present on the freeways (mobility routes).
- The majority of the congestion is indicated on the second order roads. This results in longer average trip lengths, longer delays in trips and higher costs in terms of generalised cost values (cost of travel per km + value of time spent per driver).

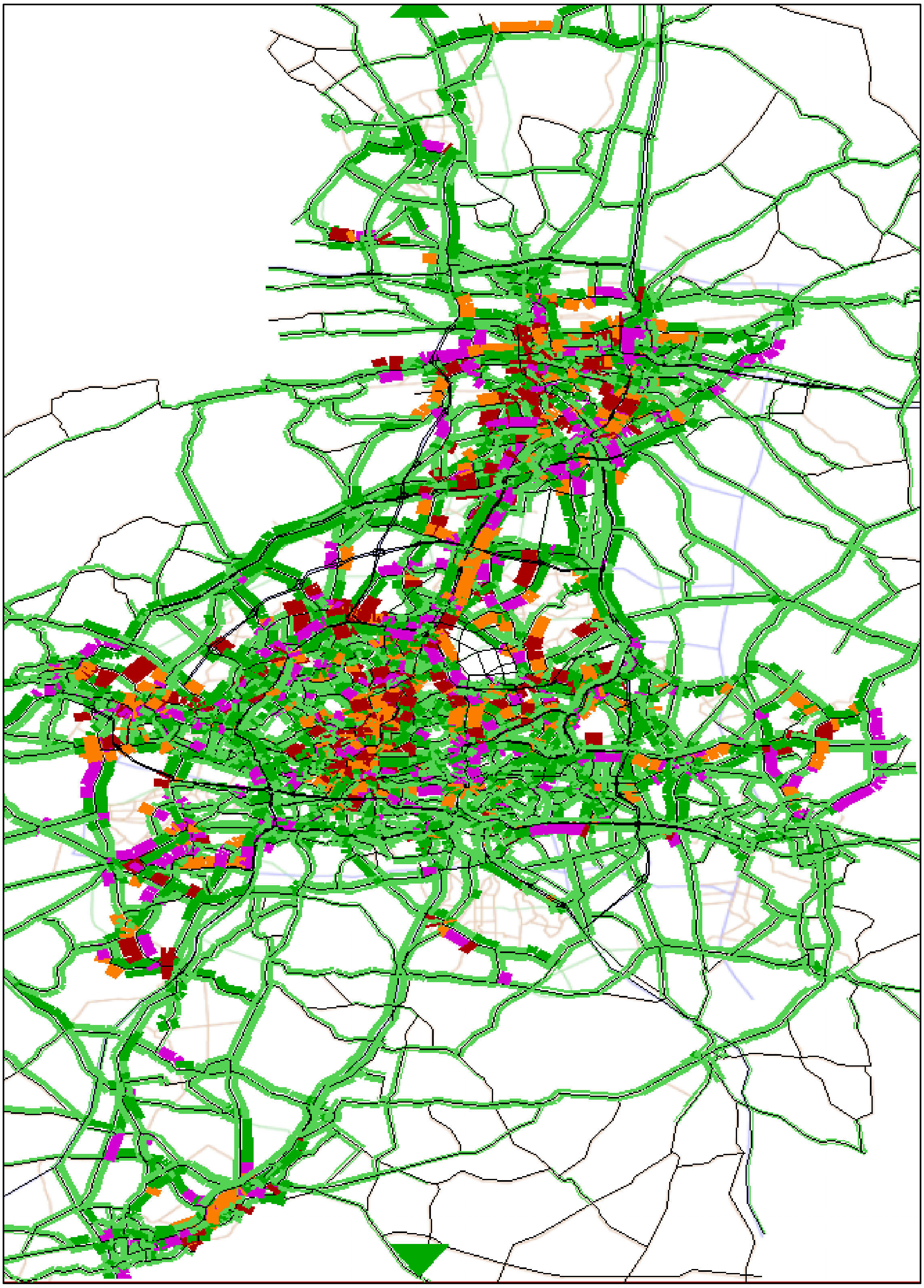

Figure 8-2: Trip Distribution and Congestion Levels for Base Year (2018) OD Trip Distribution

8.3 The Do-Nothing Scenario using the Design Year (2038) Origin-Destination Matrix

After understanding the graphical results of the trip assignment for the base year sceanrio, further trip assignments could be generated for each synthesized trip matrix to test and determine the effect of the synthesized matrices on the following aspects:

- Congestion levels on the GFIP network;
- Road infrastructure which require capacity improvements;
- An understanding of the change in congestion levels on road sections further away from the Pretoria and Johannesburg CBDs per synthesized matrix.

The figure below illustrates the congestion levels on the GFIP network obtained from the assignment of the design year trip matrix accounting for a 3% growth in trips over a twenty year period. The following observations can be made:

- There is congestion on both the freeways and second order roads close to both CBDs which indicate that there is a high volume of traffic moving in and around the CBDs as well as high volumes of traffic moving towards the freeways from areas further away from the CBDs. This could most likely be work trips.
- The red bands highlight the road infrastructure that will require capacity improvements/upgrades by the year 2038 given that the current trips grow by 3%. This will result in billions of Rands being spent on road infrastructure to support longer trips due to sprawl. This is a consequence of poor transportation planning in terms of jobs-housing balance, poor implementation of a viable, affordable and efficient public transport system and an ongoing neglect to improve the capacity of the second order road network. This indicates that people are still travelling from areas which are further away from both CBDs.
- This results in longer average trip lengths, longer delays in trips and higher costs in terms of generalised cost values (cost of travel per km + value of time spent per driver).

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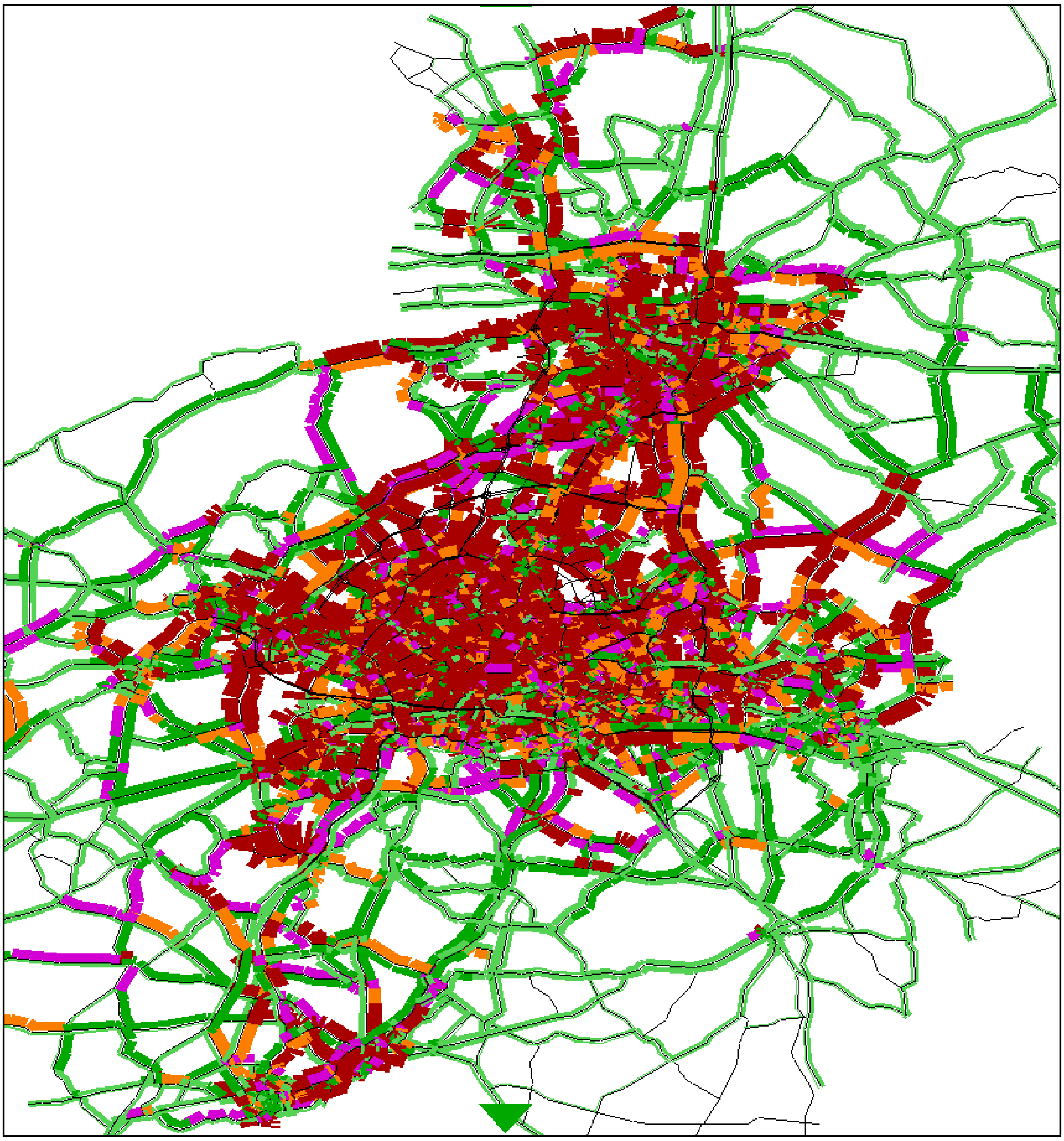

Figure 8-3: Trip Distribution and Congestion Levels for Design Year (2038): Normal Trip Lengths (No reduction in trip lengths)

8.4 Reduced Average Trip Length by 10% in the Design Year (2038)

After understanding the graphical results of the trip assignment for the base year sceanrio, and the trip assignment for the design year, as well as the resultant consequences of not changing the way in which we plan and implement road infrastructure, further trip assignments could be generated for each synthesized trip matrix to test and determine the effect of the synthesized matrices on the following aspects:

Congestion levels on the GFIP network;

Road infrastructure which require capacity improvements;

An understanding of the change in congestion levels on road sections further away from the Pretoria and Johannesburg CBDs per synthesized matrix.

The figure below illustrates the congestion levels on the GFIP network obtained from the assignment of the design year trip matrix accounting for a 3% growth in trips over a twenty year period. The difference in this scenario is that the synthesized trip matrix assigns trips on the network such that the average trip length is 10% shorter than that for the base year. This means that the synthesized trip matrix will assign trips such that the average trip length on the network is 14.4km as opposed to the 16 km for the base year scenario.

The following observations can be made:

- There is a reduction in congestion levels on both the freeways and second order roads close to both CBDs. This is observed through the reduction in red bands when comparing to the graphical results from the trip assignment for the Do nothing scenario for the design year. This indicates that people are now moving closer towards both the Pretoria and Johannesburg CBDs. This could most likely be for work trips purpsoses and to some extent leisure purposes.
- The red bands highlight the road infrastructure that will require capacity improvements/upgrades by the year 2038 given that the current trips grow by 3% and with a reduced average trip length on the network. This will result in a smaller budget being required for road infrastructure upgrades to support travel demands compared with the Do -Nothing scenario.
- This results in reduced average trip lengths, reduced delays in trips and higher savings in terms of generalized cost values (cost of travel per km + value of time spent per driver) as opposed to that of the Do-Nothing scenario for the design year.

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- This scenario is an improvement on the Do-Nothing scenario and is definitely a step in the right direction in terms of changing the way we approach transportation planning. However, a 10% reduction in the average trip length travelled on the network is not sufficient to support densification or create an environment which is conducive to the implmentation of a viable, affordable and efficient public transport system. Therefore, it is necessary to test further trip length reduction scenarios.

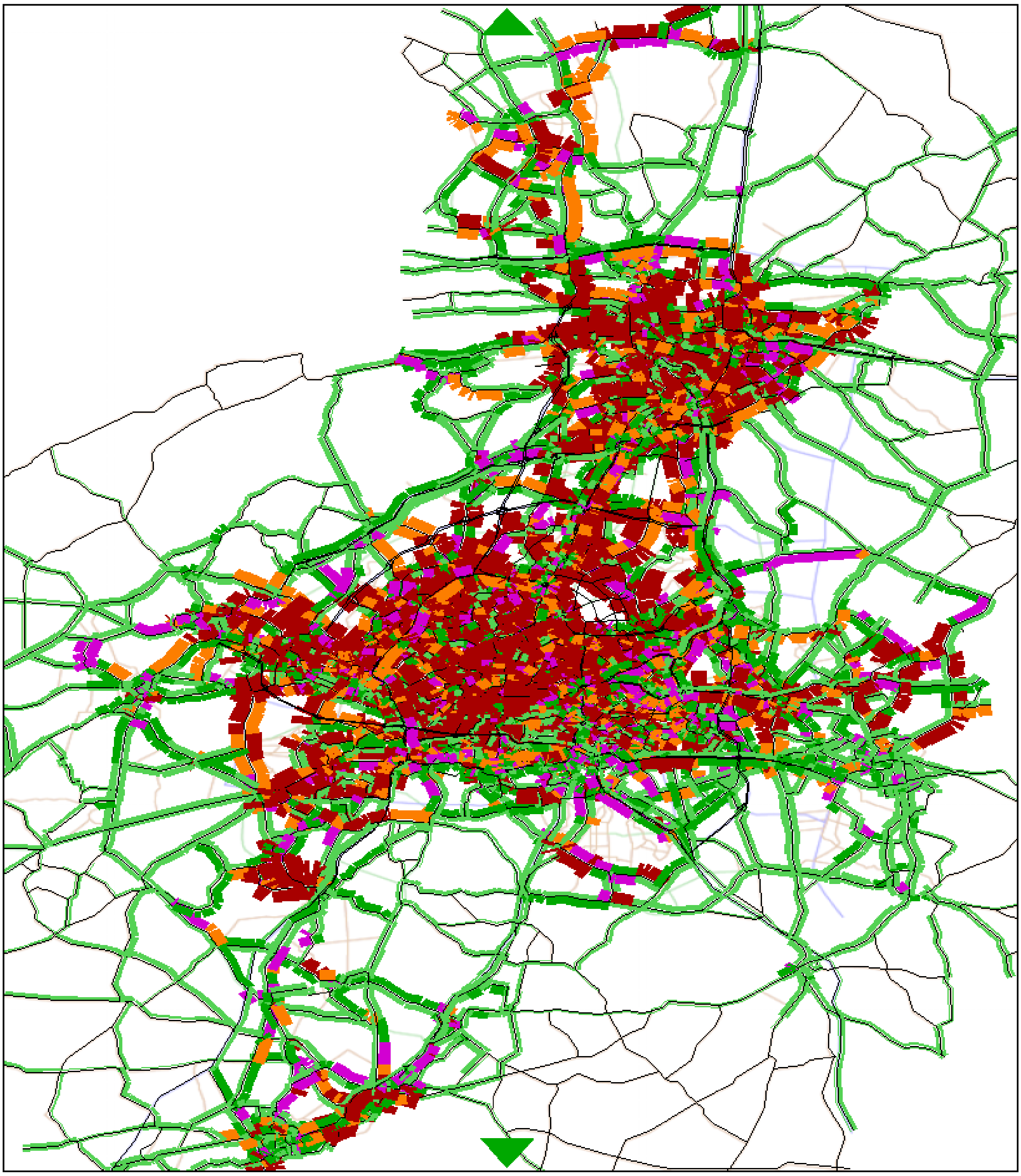

Figure 8-4: Trip Distribution and Congestion Levels for Design Year (2038): 10% Reduction in Trip Lengths

8.5 Reduced Average Trip Length by 20% in the Design Year (2038)

The process followed for the above scenarios was repeated using the synthesized trip matrix which assigns trips onto the network such that the average trip length is 20% shorter than that for the base year. This means that the synthesized trip matrix will assign trips such that the average trip length on the network is 12.8 km as opposed to the 16 km for the base year scenario.

The figure below illustrates the congestion levels on the GFIP network obtained from the trip assignment.

The following observations can be made:

- There is a reduction in congestion levels on both the freeways and second order roads close to both CBDs. This is observed through the reduction in red bands when comparing to the graphical results from the trip assignments for the Do nothing scenario and the 10% reduction in the average trip length for the design year. This indicates that people are now moving closer towards both the Pretoria and Johannesburg CBDs. This could most likely be for work trips purpsoses and to some extent leisure purposes.
- The red bands highlight the road infrastructure that will require capacity improvements/upgrades by the year 2038 given that the average trip length on the network is reduced by 20%. This will result in a smaller budget being required for road infrastructure upgrades to support travel demands compared with the Do -Nothing and the 10% reduction in the average trip length scenarios.
- This results in reduced average trip lengths, reduced delays in trips and higher savings in terms of generalized cost values (cost of travel per km + value of time spent per driver) as opposed to that of the previous scenarios.
- This scenario is an improvement on the previous two scenarios and is definitely a step in the right direction in terms of changing the way we approach transportation planning. However, a 20% reduction in the average trip length travelled on the network is not sufficient to support densification or create an environment which is conducive to the

implmentation of a viable, affordable and efficient public transport system. Therefore, it is necessary to test further trip length reduction scenarios.

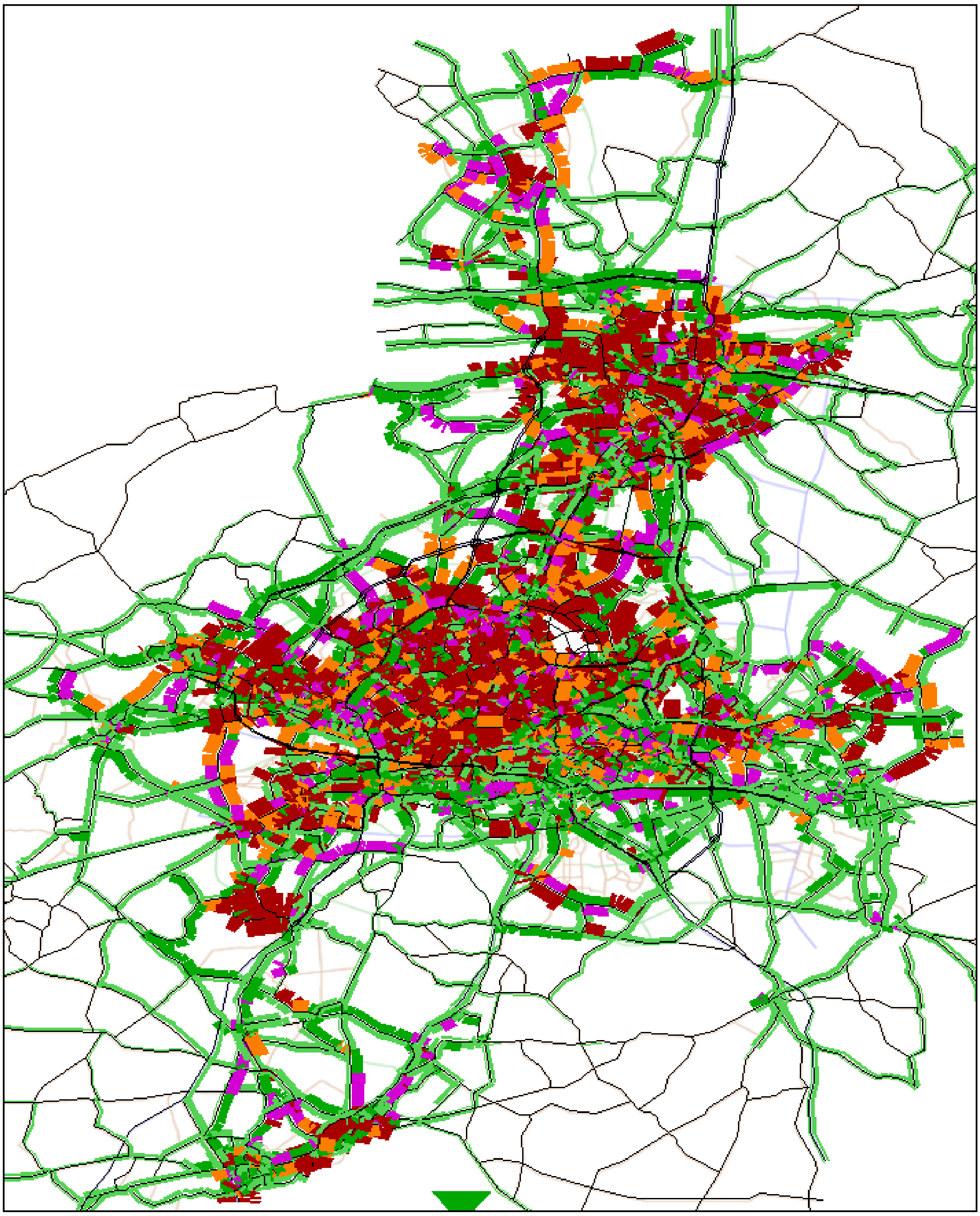

Figure 8-5: Trip Distribution and Congestion Levels for Design Year (2038): 20% Reduction in Trip Lengths

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8.6 Reduced Average Trip Length by 30% in the Design Year (2038)

The process followed for the above scenarios was repeated using the synthesized trip matrix which assigns trips onto the network such that the average trip length is 30% shorter than that for the base year. This means that the synthesized trip matrix will assign trips such that the average trip length on the network is 11.2 km as opposed to the 16 km for the base year scenario.

The figure below illustrates the congestion levels on the GFIP network obtained from the trip assignment.

The following observations can be made:

- There is a reduction in congestion levels on both the freeways and second order roads close to both CBDs. This is observed through the reduction in red bands when comparing to the graphical results from the trip assignments for the previous scenarios. This indicates that people are now moving closer towards both the Pretoria and Johannesburg CBDs. This could most likely be for work trips purpsoses and to some extent leisure purposes.
- The red bands highlight the road infrastructure that will require capacity improvements/upgrades by the year 2038 given that the average trip length on the network is reduced by 30%. This will result in a smaller budget being required for road infrastructure upgrades to support travel demands compared with the previous scenarios.
- This results in reduced average trip lengths, reduced delays in trips and higher savings in terms of generalized cost values (cost of travel per km + value of time spent per driver) as opposed to that of the previous scenarios.
- This scenario is an improvement on the previous scenarios and is definitely a step in the right direction in terms of changing the way we approach transportation planning. A 30% reduction in the average trip length travelled on the network may be sufficient to support densification or create an environment which is conducive to the implmentation of a viable, affordable and efficient public transport system.

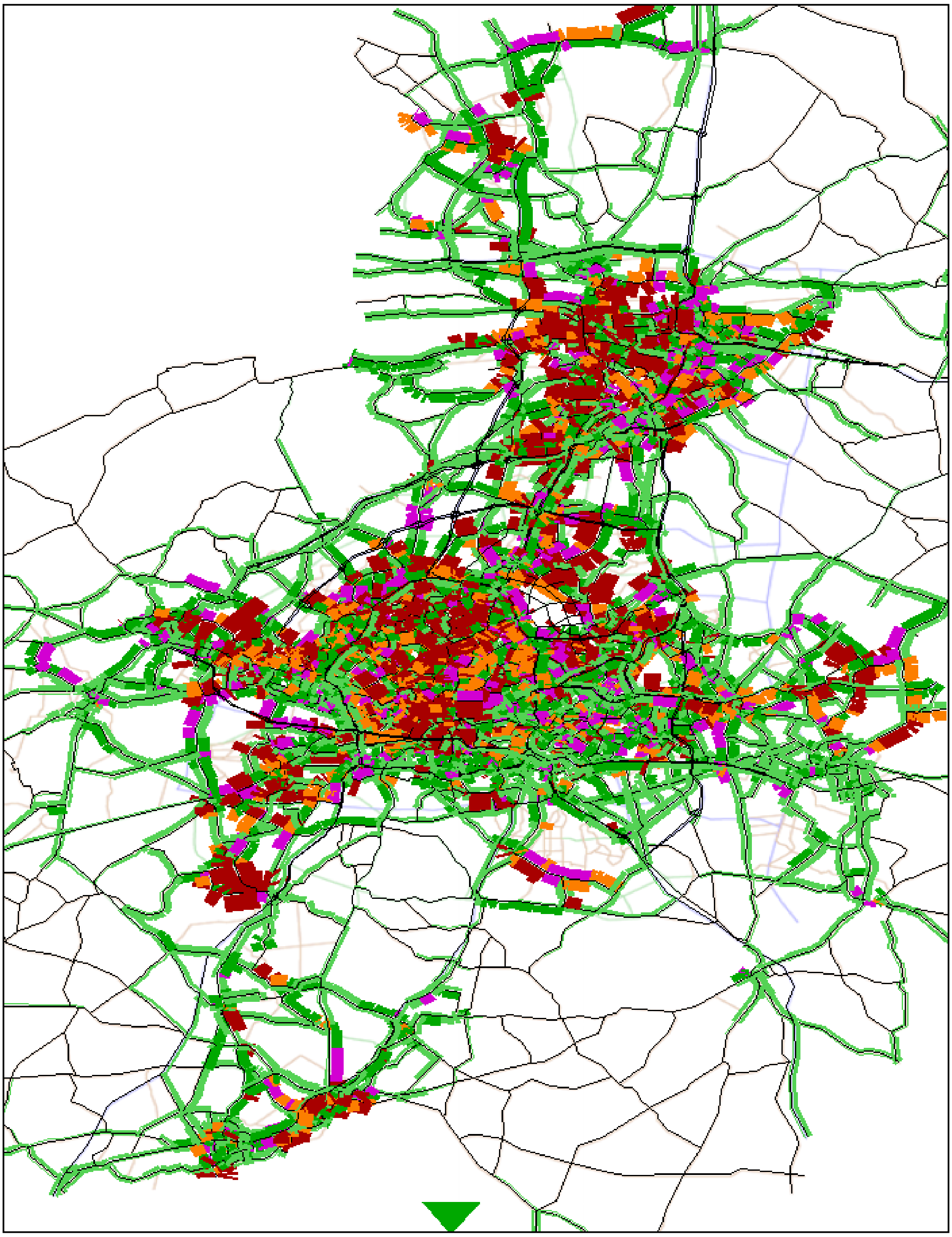

Figure 8-6: Trip Distribution and Congestion Levels for Design Year (2038): 30% Reduction in Trip Lengths

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8.7 Reduced Average Trip Length by 40% in the Design Year (2038)

The process followed for the above scenarios was repeated using the synthesized trip matrix which assigns trips onto the network such that the average trip length is 40% shorter than that for the base year. This means that the synthesized trip matrix will assign trips such that the average trip length on the network is 9.6 km as opposed to the 16 km for the base year scenario. This is the *'Utopia'* of scenarios and will most likely be very expensive to construct. But for the purposes of presenting a complete suite of solutions and scenarios, this scenario has been included in the study.

The figure below illustrates the congestion levels on the GFIP network obtained from the trip assignment.

The following observations can be made:

- Almost all of the red bands (high congestion levels) present in the previous scenarios have disappeared. This means that people have now moved closer to the CBDs and majority of trips (work and leisure)are confined to the CBDs and surrounding areas.
- The red bands highlight the road infrastructure that will require capacity improvements/upgrades by the year 2038 given that the average trip length on the network is reduced by 40%. The graphical representation of the trip assignment proves that only the second order road network require capacity improvements/upgrades and the freeways can maintain the road infrastructure design of the base year (2018). This will mean that the budget for road infrastructure should be spent on improving the capacity of the second order road networks.
- This results in reduced average trip lengths, reduced delays in trips and higher savings in terms of generalized cost values (cost of travel per km + value of time spent per driver) as opposed to that of the previous scenarios.
- A 40% reduction in the average trip length travelled on the network may be sufficient to support densification or create an environment which is conducive to the implmentation of a viable, affordable and efficient public transport system.This scenario is the *'Utopia'* and ideal scenario representing the approach that should be adopted in future transportation planning.

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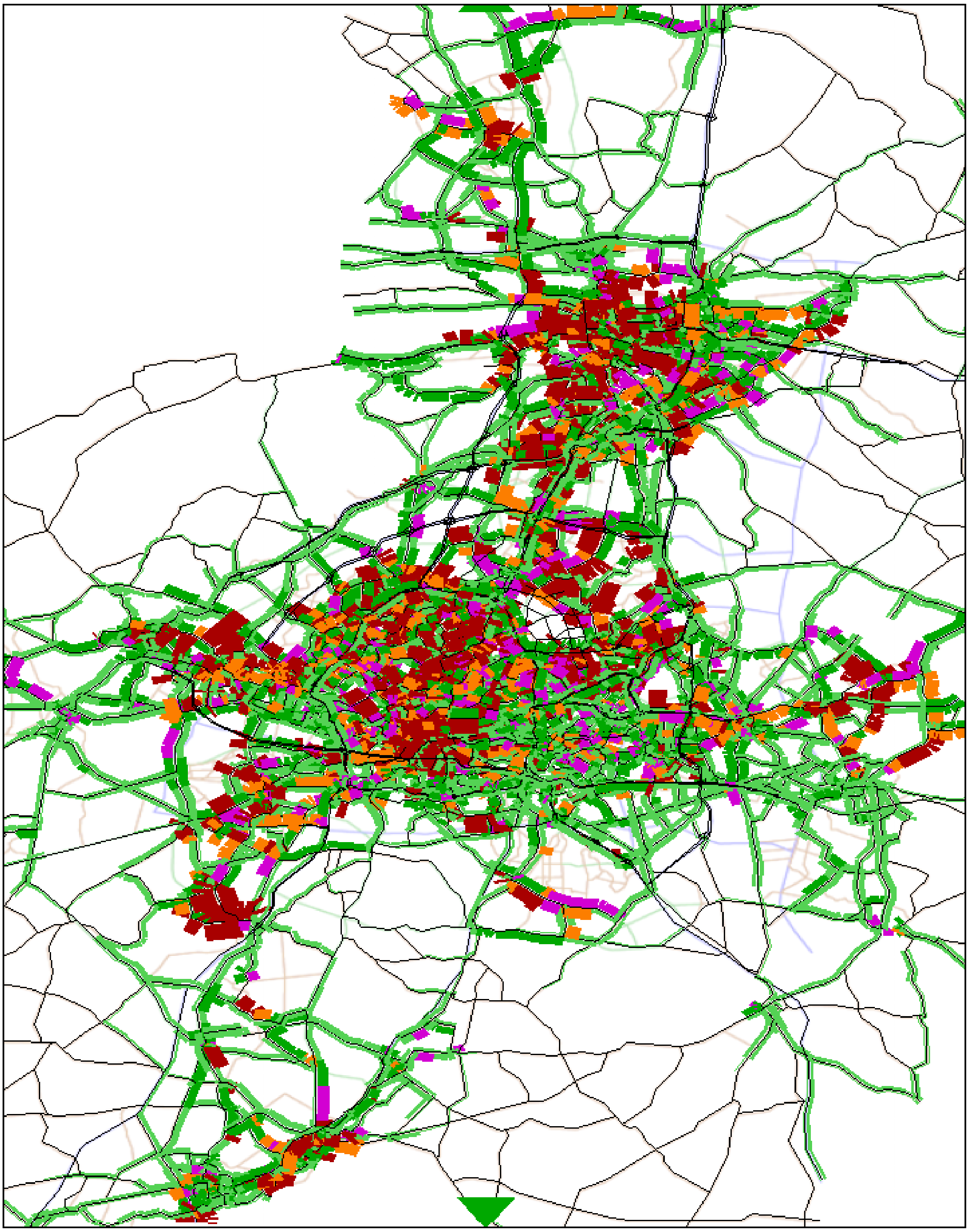

Figure 8-7: Trip Distribution and Congestion Levels for Design Year (2038): 40% Reduction in Trip Lengths

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8.8 Summary

The results of the trip assignments for the various scenarios, through the simulation of shorter average trip lengths on the GFIP network, have shown that:

- Shorter average trip lengths can be encouraged and supported by upgrading the capacity of the second order road networks;
- Upgrading the capacity of the second order road networks promotes shorter trip lengths as well as provide an environment which supports densification. This was concluded by observing trip distribution and driver behaviour on the network resulting from the assignment of each synthesized trip matrix.
- Based on the results from the trip assignment simulations, it is obvious that planning and implementation of road infrastructure should be done by first analysing current driver behaviour and trip distributions. Thereafter, identify places of employment and residential areas. Analyse different trip distribution scenarios for synthesized average trip lengths to identify the effects of shorter trip lengths on trip distribution and driver behaviour. Then use the results from the simulations to identify road infrastructure requiring capacity improvements based on aiming towards creating a more densified environment. The environment which supports the operation of a viable, affordable and efficient public transport system must be included in this approach towards achieving a more compact city layout.

9 Testing the Effect of Different Road Infrastructure Improvement Projects on Total Time and Distance Travelled Savings

Chapter 8 focused on testing the effect of the different synthesized matrices, developed from the respective distance-deterrence functions, on congestion levels on the GFIP road network. Chapter 8 also demonstrated a method of using the different synthesized trip matrices developed to identify road infrastructure which required capacity improvements. This was completed for four scenarios each identifying the capacity improvement requirements to achieve shorter trip lengths for the following cases:

- A 10% reduction in the average trip length on the GFIP network;
- A 20% reduction in the average trip length on the GFIP network;
- A 30% reduction in the average trip length on the GFIP network; and
- A 40% reduction in the average trip length on the GFIP network.

This chapter builds on the idea proposed in Chapter 8 by determining the change in the total travel time (hours) and the total distance travelled (km) by the total number of vehicles on the GFIP network for each of the scenarios. The scenarios that will be tested are explained below:

- The Do-Nothing scenario for the base year (2018). This scenario involves assigning the base year trip OD matrix to the base year network;
- Assigning shorter trips to the network for the base year (2018). This scenario involves assigning the synthesized matrix for a reduction in trip lengths by 10% to the base year network;
- Improving the capacity of the freeway road infrastructure by 10% for the base year (2018). This scenario involves firstly improving the capacity of the freeways on the network by 10%. This is achieved by increasing the capacity of the respective freeway links included in the network. Thereafter, the base year OD matrix is assigned to the improved network;
- Assigning shorter trips to the network with capacity improvements to the freeway for the base year (2018). This scenario involves assigning the synthesized distance-deterrence function for a reduction in trip lengths by 10% to the network with capacity improvements to the freeway;
- Improving the capacity of the second order road infrastructure by 10% for the base year (2018). This scenario involves firstly improving the capacity of the second order roads on the network by 10%. This is achieved by increasing the capacity of the respective second

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order road links included in the network. Thereafter, the base year OD matrix is assigned to the improved network;

- Assigning shorter trips to the network with capacity improvements to the second order roads for the base year (2018). This scenario involves assigning the synthesized distance-deterrence function for a reduction in trip lengths by 10% to the network with capacity improvements to the second order roads;
- The Do-Nothing scenario for the design year (2038). This scenario involves assigning the base year trip OD matrix to the design year network;
- Assigning shorter trips to the network for the design year (2038) this scenario involves assigning the synthesized matrix for a reduction in trip lengths by 10% to the design year network;
- Improving the capacity of the freeway road infrastructure by 10% for the design year (2038). This scenario involves firstly improving the capacity of the freeways on the network by 10%. This is achieved by increasing the capacity of the respective freeway links included in the network. Thereafter, the design year OD matrix is assigned to the improved network;
- Assigning shorter trips to the network with capacity improvements to the freeway for the design year (2038). This scenario involves assigning the synthesized distance-deterrence function for a reduction in trip lengths by 10% to the network with capacity improvements to the freeway;
- Improving the capacity of the second order road infrastructure by 10% for the design year (2038). This scenario involves firstly improving the capacity of the second order roads on the network by 10%. This is achieved by increasing the capacity of the respective second order road links included in the network. Thereafter, the design year OD matrix is assigned to the improved network;
- Assigning shorter trips to the network with capacity improvements to the second order roads for the design year (2038). This scenario involves assigning the synthesized distance-deterrence function for a reduction in trip lengths by 10% to the network with capacity improvements to the second order roads.

Appendix 9 provides a summary of the road capacity before and after the capacity improvement.

Note: The networks used for the base and design years were the same. The author acknowledges that the design year network would be different in a reality due to developmental growth in land use as well as the inclusion of additional road infrastructure as per a region’s integrated development plan (IDP). Due to the time, resource and data constraints associated with a postgraduate research project, the networks for the base and design years were assumed to be the same. Different networks accounting for changes on land use can be included in further research.

9.1 Discussion of Total Travel Times and Total Distance Travelled for All Light Vehicles

The tables below provide the results obtained through the testing of each of the 12 road infrastructure improvement alternatives. The accompanying discussions are applicable to both the base and design years since a similar trend has been indicated

The results presented in the table below represent the total travel time for all light vehicles on the GFIP network during a typical peak hour. The typical peak hour used for this study was from 7am to 8am. The total travel time is presented for each improvement alternative tested for both the base and design years.

Table 9-1: Total Travel Time for all light Vehicles (hours) on the GFIP Network

Road Infrastructure Improvement Alternative Proposed	Total Travel Time for all Light Vehicles (hours)	
	2018	2038
The Do-Nothing Scenario	284 756	2 433 667
Assignment of OD matrix for shorter trips on the unchanged Network	217 500	1 546 394
Assignment of unchanged OD matrix to improved network: Improved capacity on freeways	276 036	2 269 367
Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways	214 435	1 474 355
Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads	268 164	2 150 574
Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads	206 504	1 378 218

The results for the total travel time for all light vehicles for each improvement alternative tested was then compared with that of the Do-Nothing alternative. The purpose of this is to determine which improvement alternative had the biggest saving in terms of total travel time on the network. The results of the comparison of total travel times for each improvement alternative against the Do-Nothing alternative are summarized in the table below.

Table 9-2: Comparison of Improvement Alternatives with the Do-Nothing Alternative

Road Infrastructure Improvement Alternative Proposed	**Difference in Total Travel Time (hours) of Improved Alternative against the Do-Nothing Alternative**	
	2018	**2038**
Assignment of OD matrix for shorter trips on the unchanged Network	67 255	887 273
Assignment of unchanged OD matrix to improved network: Improved capacity on freeways	8 720	164 300
Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways	70 321	959 312
Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads	16 592	283 093
Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads	78 252	1 055 449

The results indicate that the road infrastructure improvement where the capacity of the second order roads is improved by 10% and drivers make shorter trips (i.e. the environment is such that shorter trips are encouraged) has the biggest saving in terms of total travel time for all light vehicles on the GFIP network. This is applicable for both the base and design years.

The second highest saving in terms of total travel time for all light vehicles on the network was for the alternative where the capacity of the freeways is increased by 10% and drivers make shorter trips. Even though this alternative produces the second highest total travel time saving, it is not recommended. The reason for this is that increasing the capacity of the freeways may address the issue of congestion and mobility for longer trips, but it does not contribute to reducing and controlling sprawl, supporting densification and working towards changing the approach of transportation planning in the future. Increasing the capacity of freeways encourages longer trip lengths and also encourages people living far away from city centres which in turn results in an increase in urban sprawl. This alternative does not contribute towards supporting densification, the compact city concept, the future city concept or towards

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creating an environment which is conducive for the implementation and operation of a public transport system.

The third highest saving in terms of total travel time for all light vehicles on the network was for the alternative where drivers make shorter trips. To fully understand the effect of shorter trips on the total travel time, the result for this alternative must be compared with that of the previous alternative discussed. That is, by increasing the capacity on freeways by 10% as well as drivers making shorter trips a travel time saving of 68 135 hours was achieved. By drivers simply making shorter trips (10% shorter than the current average trip length on the GFIP network), a total travel time saving of 67 255 hours was obtained. There is a difference of 880 hours between the two alternatives. However, an upgrade to the capacity of the freeways, and creating a more densified environment, will cost more than simply encouraging drivers to make shorter trips by living closer to places of work. This can be achieved through creating a more densified environment and implementation of policies focused on increasing the gross-population densities of cities. In the long term, creating an environment which promotes shorter trips should cost less than continuously expanding the freeways which is accompanied by high maintenance costs. The economic benefits will be presented and discussed in the next chapter.

The fourth highest saving in terms of total travel time for all light vehicles on the network was for the alternative whereby the capacity of the second order road network was increased by 10%. This is realistic since currently majority, if not all, of the second order roads are operating at capacity. This is one of the prime reasons for congestion on in Pretoria. This also justifies the need for capacity improvements required on the second order roads in Gauteng. This will assist with reducing the delays and congestion linking from the second order roads onto the freeways in the GFIP network.

The alternative with the lowest saving in total travel time is that of increasing the capacity of the freeways by 10%. This makes sense and is a true reflection of what is happening currently on the GFIP network. The GFIP network is almost operating at capacity and having second order roads which are in dire need of capacity improvements only makes things worse in terms of delays and increased travel times. In short, congested second order roads are linking onto an almost congested freeway. There is nowhere for traffic to move.

The results presented in the table below represent the total travel distance for all light vehicles on the GFIP network during a typical peak hour. The total travel distance is presented for each improvement alternative tested for both the base and design years.

Table 9-3: Total Travel Distance for all Light Vehicles (km) on the GFIP Network

Road Infrastructure Improvement Alternative Proposed	**Total Travel Distance for all Light Vehicles (km)**	
	2018	**2038**
The Do-Nothing Scenario	11 886 087	22 740 782
Assignment of OD matrix for shorter trips on the unchanged Network	9 394 101	18 092 844
Assignment of unchanged OD matrix to improved network: Improved capacity on freeways	11 899 731	22 766 064
Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways	9 408 231	18 157 850
Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads	11 841 648	22 647 036
Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads	9 368 043	17 963 454

The results for the total travel distance for all light vehicles for each improvement alternative tested were then compared with that of the Do-Nothing alternative. The purpose of this was to determine which improvement alternative would have the biggest saving in terms of total travel distance on the network. The results of the comparison of total travel distances for each improvement alternative against the Do-Nothing alternative are summarized in the following table.

Table 9-4: Comparison of Improvement Alternatives with the Do-Nothing Alternative

Road Infrastructure Improvement Alternative Proposed	**Difference in Total Travel Time (hours) of Improved Alternative against the Do-Nothing Alternative**	
	2018	**2038**
Assignment of OD matrix for shorter trips on the unchanged Network	2 491 986	4 647 938
Assignment of unchanged OD matrix to improved network: Improved capacity on freeways	-13 644	-25 282
Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways	2 477 856	4 582 932
Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads	44 439	93 746
Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads	2 518 044	4 777 328

The results indicate that the road infrastructure improvement where the capacity of the second order roads is improved by 10% and drivers make shorter trips (i.e. the environment is such that shorter trips are encouraged) has the biggest saving in terms of total travel distance for all light vehicles on the GFIP network. This is realistic as it is envisaged that by improving the capacity of the second order roads as well as encouraging people to live closer to their places of work, they would not need to travel far distances. This is applicable for both the base and design years.

The second highest saving in terms of total travel distance was for the alternative whereby drivers make shorter trips. This is realistic and makes sense because if people live closer to their places of work, then they would travel less.

The third highest saving in terms of total travel distance for all light vehicles on the network was for the alternative whereby the capacity of the freeways is increased by 10% and drivers make shorter trips.

The fourth highest saving in terms of total travel time for all light vehicles on the network was for the alternative whereby the capacity of the second order road network was increased by

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10%. This reflects the current driver behavior of commuters. These results can be understood as drivers tending to travel on the improved second order roads as opposed to their initial longer routes used previously to avoid congested links. Initially drivers would travel longer distances to achieve a shorter travel time. With the capacity improvement on the second order roads, drivers would be able to use shorter routes and still have the benefit of a shorter travel time and also a shorter trip length.

The alternative with the lowest saving in terms of total travel distance is the alternative where the capacity of the freeways is increased by 10%. If fact, the results obtain reflect a negative saving which means that the total travel distance for all light vehicles has increased as compared with that for the Do-Nothing alternative. This can be explained as more drivers using the freeways and travelling longer distances. This does not necessarily mean that they are spending time in congestion and experiencing delayed trips. It could mean that more drivers choose to use the freeways and travel longer distances since their overall travel time saving could be shorter than using other routes. The discussion relating to the total travel time for vehicles on the network for this alternative, showed that there was a total travel time saving achieved. Therefore, it can be understood that despite drivers travelling longer distances as a result of this improvement alternative, they are saving in terms of total travel time.

The results presented in the Table 9-5 represent the average speeds for all light vehicles on the GFIP network during a typical peak hour. The average speed is presented for each improvement alternative tested for both the base and design years.

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Table 9-5: Average Travel Speed (km/hr) for all Light Vehicles on the GFIP Network

Road Infrastructure Improvement Alternative Proposed	Average Speed for all Light Vehicles (km/hr)	
	2018	2038
The Do-Nothing Scenario	42	9
Assignment of OD matrix for shorter trips on the unchanged Network	43	12
Assignment of unchanged OD matrix to improved network: Improved capacity on freeways	43	10
Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways	44	12
Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads	44	11
Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads	46	13

The results indicate that the highest average speed for all light vehicles during a typical peak hour can be achieved by drivers making shorter trips as well as by improving the capacity of the second order roads. This is realistic because if the second order roads are improved in terms of capacity, they support a densified environment and people are able to make shorter trips to places of work and leisure.

The improvement alternative which results in the lowest average speed is the capacity improvement to the freeways. This makes sense because the freeways are already operating close to capacity. A capacity improvement of 10% will make little difference to the travel speeds.

9.2 Summary

Different road infrastructure improvement alternatives were tested using the SATURN software and the results have indicated that the different alternatives affect total travel time and total travel distances of all light vehicles differently. The table below provides a summary of the ranking of the alternatives in terms of biggest benefit for all light vehicles under the respective category (total travel time (hours), total travel distance (km) and average speed (km/hr)).

Table 9-6: Summary of Benefits Per Category: Highest to Lowest

Total Travel Time (Hours)	Total Travel Distance (km)	Average Speed (km/hr)
• Shorter Trips • Improved capacity on second order roads	• Shorter Trips • Improved capacity on second order roads	• Shorter Trips • Improved capacity on second order roads
• Shorter Trips • Improved capacity on freeways	• Shorter Trips • Unchanged Network	• Shorter trips • Improved capacity on freeways
• Shorter trips • Unchanged Network	• Shorter trips • Improved capacity on freeways	• Unchanged Trip lengths • Improved capacity on second order roads
• Unchanged Trip Lengths • Improved capacity on second order roads	• Unchanged Trip Lengths • Improved capacity on second order roads	• Shorter trips • Unchanged Network
• Unchanged Trip Lengths • Improved capacity on freeways	• Unchanged Trip Lengths • Improved capacity on freeways	• Unchanged Trip Lengths • Improved capacity on freeways

The results in the summary table above indicate that the road infrastructure improvement whereby the capacity of the second order roads is improved by 10% and drivers make shorter trips (i.e. the environment is such that shorter trips are encouraged) has the biggest saving in terms of total travel distance for all light vehicles on the GFIP network. This provides the key to the method in which road infrastructure improvement project should be budgeted for and implemented. This alternative uses a combination of supporting densification through encouraging shorter trip lengths. Shorter trip lengths are encouraged through the planning and implementation of road infrastructure; in this case capacity improvements to the second order roads. The combination of densification and shorter trips also support the concept of the compact city, the future city and the implementation and operation of a viable, affordable and efficient public transport system.

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10 Economic Evaluation: Investigating the Different Economic Benefits of the Different Road Infrastructure Improvement Alternatives

Chapter 8 demonstrated a method of using the different synthesized trip matrices developed to identify road infrastructure which required capacity improvements. Chapter 9 focused on determining the change in the total travel time (hours) and the total distance travelled (km) by the total number of vehicles on the GFIP network for different scenarios.

This chapter focuses on determining the economic benefit, in terms of generalized cost, of each road infrastructure alternative tested in chapter 9. Since the focus of this research project is not heavily aimed at economics but rather on using basic economic principles to justify the objectives of this research, the process used in determining the economic benefits of each alternative was simplified.

The economic benefits derived were based solely on total travel time savings and total travel distance savings from each road improvement alternative proposed.

10.1 Background

The results in Chapter 9 indicate that the alternative with shorter trips and capacity improvements to the second order roads has the highest benefit in terms of total travel time (hours) and total distance travelled (km) by all light vehicles. However, an economic analysis is required to determine the most common economic indicators for each improvement alternative tested. The most common economic indicators that will be used for the purpose of this study are as follow:

- Net Present Value (NPV): is defined as the difference between the present worth of economic benefits and capital expenditure over an analysis period (Investopedia, 2019). NPV is used to determine mutually exclusive projects as well as to determine and compare the profitability of different alternatives of a single project. In cases where the benefits derived exceed the capital costs of a project, the NPV is a good indicator of the extent of the excess benefit resulting from the implementation of the project alternative under analysis. The following formula can be used in the NPV calculation:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \qquad \text{(Equation 10-1)}$$

where: R_t = The net difference in cash inflows and cash outflows during the period t

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i = the discount rate

t = the number of periods in the analysis

- The Economic Internal Rate of Return (IRR): The Economic Internal Rate of Return is used to estimate the profitability of a project/project alternative. The IRR indicates the most advantageous project/project alternative compared with the do-nothing project alternative.

The costs and benefits were discounted each year as per basic economic practice. The net present value (NPV) and economic internal rate of return relating to each alternative was calculated. A detailed discussion of the approach and methodology used to complete the economic evaluation for each project alternative is provided in this chapter.

10.2 Justification of Assumptions Used

The assumptions used in the economic evaluation are listed and briefly justified in the subsections below.

10.2.1 Economic Evaluation Analysis Period

The analysis period of 20 years was used as this represents a typical analysis period for a project of similar magnitude and scope.

10.2.2 Rand Value of Costs, Benefits and Inflation

All costs and benefits were calculated using 2019 Rand value. Inflation was ignored for simplicity of the economic evaluation.

10.2.3 Calculation of the Economic Rand Value

The calculation used to convert the financial costs into economic costs is as follows:

Economic Rand value = Financial Rand value * 0.85. The factor of 0.85 was obtained through the “Transport Economics” course notes from the University of Stellenbosch. This value was also crossed referenced with factors used in industry.

10.2.4 Annual Maintenance Cost for Road Infrastructure

The annual maintenance cost was assumed to be 5% of the total initial capital cost spent up till the analysis year.

10.2.5 Rehabilitation Period and Cost

The rehabilitation of the project alternatives investigated was assumed to take place from year 10 to year 14. This was in line with other SANRAL projects of a similar magnitude. The rehabilitation costs of each project alternative were assumed to be 40% of the initial capital costs reserved for the analysis year.

10.2.6 Capital Cost for Project Alternatives

The capital cost used for all road infrastructure improvement alternatives was assumed to be R20 billion. This value was purely based on a suitable guess given the scope of the project network.

10.2.7 Vehicle Operating Cost (VOC) and Value of Time (VOT) Cost

The vehicle Operating Cost per vehicle km was based on the AA rate per kilometer of R3.61/km (CRS, 2019). The economic value of time is purely based on the average income, per capita, of South African citizens. Hayes and Venter (2016) wrote a paper titled *“Trip Utility and the Value of Travel Time Savings (VTTS) for Commuter Trips: Critique and Recent Advances”.* In this paper, the authors provide the different value of travel time savings in Rand/hr for different road-based projects in South Africa. These were provided in Table 1 of the same paper. The project which closely resembled the nature of the case study used in this research project had an estimated VOT between R104 and R125. Therefore, a VOT of R110/hr was assumed based on the average salary in South Africa.

10.2.8 Discount Rate

A discount rate of 8% was used in all calculations. This value has been commonly used in industry and was therefore deemed suitable for the purpose of this simple economic evaluation.

10.2.9 Traffic Growth

The existing traffic for the base year was forecasted at 3% from year 1 to year 9. Thereafter, the traffic volumes were forecasted at 2% from year 10 to year 20. The purpose of varying the traffic growth percentages was to incorporate realistic increases in traffic volumes given the nature and location of the project. Historic traffic data recorded for road sections of the network have indicated a similar trend in traffic growth. Therefore, the chosen traffic growths were deemed as suitable for the purpose of this study.

10.2.10 Number of Peaks

Each typical day was assumed to have two peak periods which experience the benefits derived from each project alternative. The first peak in which the benefits can be experienced is the morning peak (7 am to 8 am) period and the second being the afternoon peak (4 pm to 5 pm) period.

10.2.11 Number of Weekdays in a Year

The number of weekdays in a year which experience the benefit of the improvement alternative was estimated to be 250. This was determined by subtracting all school holidays, public holidays and total off peak hours (converted to days) from the total number of days in a year (365). The reason for excluding these days is that the benefit of shorter trip lengths and travel times will be most effective during very busy hours when the network is most likely to be congested had the improvement measures not been implemented. School holidays, public holidays and off peak hours mean that the trips will now be distributed differently due to there being many more destination zones as opposed to a common one, such as work based (employment) zones. This means that the routes that are usually congested would be less congested and the benefit of the improvement alternative would not be experienced as intended. This could affect the results indicating the viability of the project alternative and this could in turn skew the results.

10.2.12 Hours per Weekday

The hours per a single weekday which experience the benefit of the improvement alternative was assumed to be 6. Three hours dedicated to the morning peak period and three hours dedicated to the afternoon peak period.

10.3 Method and Approach Used in Determining the Economic Indicators: NPV and IRR

The method and approach followed in determining the economic indicators is described as follows:

- The benefits in terms of total travel time (hours) and total distance travelled savings by all light vehicles on the network was determined as discussed in Chapter 9. This was completed for all improvement alternatives proposed. The results are summarized in *Table 10-1*
- The results from the above step were used to calculate the annual benefits from the base year to the design year. Thereafter, the benefits were incrementally increased from the base year to the design year annually. This was to determine the benefits achieved for each year. The results are provided in Table 10-2.
- Thereafter, the annual benefits were used in the calculations to determine the economic indicators, NPV and the IRR for each improvement alternative proposed.

Table 10-1: Summary of Benefits at Base and Design Years

The Do-Nothing Alternative					
	Time Cost (2019 Rand/Million Value)	**Distance Cost (2019 Rand/Million Value)**	**Total Cost (2019 Rand/Million Value)**	**Benefit (2019 Rand/Million Value)**	**Percentage Growth over 20 Year Period**
2018	39937.0	54708.7	94645.7	0.0	
2038	341321.7	104670.1	445991.9	0.0	
Shorter Trips & Existing Network					
2018	39937.0	54708.7	94645.7	0.0	
2038	216881.7	83276.8	300158.6	145833.3	
Normal Trips & Improved Capacity on Freeways					
2018	38714.0	54771.5	93485.5	1160.2	
2038	318278.7	104786.5	423065.2	22926.6	16.09%
Normal Trips & Improved Capacity on Second Order Roads					
2018	37610.0	54504.1	92114.2	2531.5	
2038	301618.0	104238.6	405856.6	40135.2	14.82%
Shorter Trips & Improved Capacity on Freeways					
2018	38714.0	54771.5	93485.5	1160.2	
2038	206778.3	83576.0	290354.3	155637.5	27.76%
Shorter Trips & Improved Capacity on Freeways					
2018	37610.0	54504.1	92114.2	2531.5	
2038	193295.0	82681.3	275976.3	170015.5	23.41%

Table 10-2: Total Annual Benefits Derived in Rand/Million

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Short Trips & Existing Network	0	470	636	860	1163	1572	2127	2876	3891
Normal Trips & Improved Freeways	1160	1347	1564	1815	2107	2446	2840	3297	3827
Normal Trips & Improved Second Order Roads	2532	2907	3337	3832	4400	5052	5800	6659	7646
Short Trips & Improved Freeways	1160	1482	1894	2419	3091	3948	5044	6444	8233
Short Trips & Improved Second Order Roads	2532	3124	3856	4758	5872	7247	8944	11037	13622
Period Continued…	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Short Trips & Existing Network	5262	7117	9626	13020	17610	23819	32217	43575	58937
Normal Trips & Improved Freeways	4443	5158	5987	6950	8069	9367	10874	12624	14654
Normal Trips & Improved Second Order Roads	8779	10080	11573	13288	15257	17518	20114	23094	26516

Short Trips & Improved Freeways	10518	13438	17167	21932	28019	35796	45732	58424	74641
Short Trips & Improved Second Order Roads	16810	20746	25603	31597	38994	48124	59390	73294	90454
Period Continued…	**2036**	**2037**	**2038**						
Short Trips & Existing Network	79716	107821	145833						
Normal Trips & Improved Freeways	17012	19749	22927						
Normal Trips & Improved Second Order Roads	30445	34956	40135						
Short Trips & Improved Freeways	95358	121824	155638						
Short Trips & Improved Second Order Roads	111629	137763	170016						

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10.4 Economic Evaluation: Summary of Results

The costs and benefits of the road infrastructure improvement alternatives were transferred into the economic evaluation spreadsheet in which the economic indicators are determined. The results from the economic evaluation for each of the five scenarios are presented in Tables 10-4 to 10-8.

The overall summary of the economic analysis of the proposed improvement alternatives indicate that the project is well founded. In all scenarios the proposed alternatives have high net present values. In all scenarios the economic internal rate of return exceeded the NPV discount rate of 8%. The IRR for each scenario is provided in the table below.

Table 10-3: Summary of the Economic Internal Rate of Return (IRR) per Improvement

Road Infrastructure Improvement Alternative	Economic Internal Rate of Return (IRR)
Shorter Trips & Existing Network	20%
Normal Trips & Improved Freeway	11%
Normal Trips & Improved Second Order Roads	24%
Shorter Trips & Improved Freeways	28%
Shorter Trips & Improved Second Order Roads	39%

The road infrastructure improvement alternative in which the capacity of the second order roads is improved as well as shorter trips being encouraged, has the highest IRR. This is in line with the vision and hypothesis of this research project. This alternative derives the highest economic benefit from the allocated R20 billion project budget.

It is also envisaged, based on the literature review study and traffic simulations completed, that this alternative will assist in promoting shorter trips and support densification. It is also envisaged that this combination, shorter trip lengths and a densified environment, will contribute towards providing an environment conducive to the implementation and operation of a viable, affordable and efficient public transport system.

It is therefore recommended that this project alternative be prioritized based on the results from the economic evaluation of all project alternatives proposed.

Table 10-4: Economic Evaluation for Alternative: Shorter Trips & Existing Network

ECONOMIC EVALUATION OF PROPOSED SHORTER TRIPS ON EXISTING ROAD NETWORK (IN 2019 RAND)

Year	Initial capital costs	Annual Routine Road Maintenance Costs	Routine Road Maintenance Costs	Total Cost	Benefits		Total Benefits	Net Benefit	Discounted Costs	Discounted Benefits	Net present value
					Modelled Benefit	Realised Benefit		Benefit - Cost	8%	8%	8%
0	17,000.00	5%	40%		R 0.00	R 0.00	R 0.00		R 0.00		R 0.00
1	R 3,400.00	R -	R -	R 3,400.00	R 469.79	R 0.00	R 0.00	(R 3,400.00)	R 3,148.15	R 0.00	(R 3,148.15)
2	R 3,400.00	R 173.45	R -	R 3,573.45	R 635.42	R 127.08	R 127.08	(R 3,446.37)	R 3,063.66	R 108.95	(R 2,954.70)
3	R 3,400.00	R 350.51	R -	R 3,750.51	R 859.44	R 343.78	R 343.78	(R 3,406.73)	R 2,977.28	R 272.90	(R 2,704.37)
4	R 3,400.00	R 531.34	R -	R 3,931.34	R 1,162.44	R 697.47	R 697.47	(R 3,233.87)	R 2,889.65	R 512.66	(R 2,376.99)
5	R 3,400.00	R 716.10	R -	R 4,116.10	R 1,572.27	R 1,257.82	R 1,257.82	(R 2,858.29)	R 2,801.35	R 856.05	(R 1,945.30)
6		R 904.98	R -	R 904.98	R 2,126.58	R 2,126.58	R 2,126.58	R 1,221.60	R 570.29	R 1,340.11	R 769.82
7		R 915.13	R -	R 915.13	R 2,876.33	R 2,876.33	R 2,876.33	R 1,961.19	R 533.97	R 1,678.31	R 1,144.34
8		R 925.58	R -	R 925.58	R 3,890.39	R 3,890.39	R 3,890.39	R 2,964.81	R 500.06	R 2,101.86	R 1,601.79
9		R 936.35	R -	R 936.35	R 5,261.97	R 5,261.97	R 5,261.97	R 4,325.62	R 468.41	R 2,632.30	R 2,163.89
10		R 943.75	R 1,360.00	R 2,303.75	R 7,117.11	R 7,117.11	R 7,117.11	R 4,813.37	R 1,067.08	R 3,296.60	R 2,229.52
11		R 951.29	R 1,360.00	R 2,311.29	R 9,626.29	R 9,626.29	R 9,626.29	R 7,315.01	R 991.27	R 4,128.55	R 3,137.28
12		R 958.98	R 1,360.00	R 2,318.98	R 13,020.10	R 13,020.10	R 13,020.10	R 10,701.12	R 920.90	R 5,170.46	R 4,249.56
13		R 966.83	R 1,360.00	R 2,326.83	R 17,610.42	R 17,610.42	R 17,610.42	R 15,283.59	R 855.57	R 6,475.31	R 5,619.75
14		R 974.83	R 1,360.00	R 2,334.83	R 23,819.08	R 23,819.08	R 23,819.08	R 21,484.25	R 794.92	R 8,109.47	R 7,314.55
15		R 982.99	R -	R 982.99	R 32,216.64	R 32,216.64	R 32,216.64	R 31,233.65	R 309.88	R 10,156.03	R 9,846.15
16		R 991.32	R -	R 991.32	R 43,574.81	R 43,574.81	R 43,574.81	R 42,583.49	R 289.36	R 12,719.07	R 12,429.72
17		R 999.81	R -	R 999.81	R 58,937.38	R 58,937.38	R 58,937.38	R 57,937.56	R 270.22	R 15,928.94	R 15,658.72
18		R 1,008.48	R -	R 1,008.48	R 79,716.11	R 79,716.11	R 79,716.11	R 78,707.63	R 252.37	R 19,948.88	R 19,696.51
19		R 1,017.31	R -	R 1,017.31	R 107,820.50	R 107,820.50	R 107,820.50	R 106,803.19	R 235.72	R 24,983.31	R 24,747.59
20		R 1,026.32	R -	R 1,026.32	R 145,833.28	R 145,833.28	R 145,833.28	R 144,806.95	R 220.20	R 31,288.27	R 31,068.07
TOTAL:		R 16,275.40	R 6,800.40	R 40,075.35	R 558,146.37	R 555,873.15	R 555,873.15	R 515,797.79	R 23,160.38	R 151,708.11	R 128,547.81

IRR

Nett present value of Project = R 128547.81 in Discounted Rands at a 8.0 % per annum discount rate

19.87%

Table 10-5: Economic Evaluation for Alternative: Normal Trips & Improved Capacity on Freeways

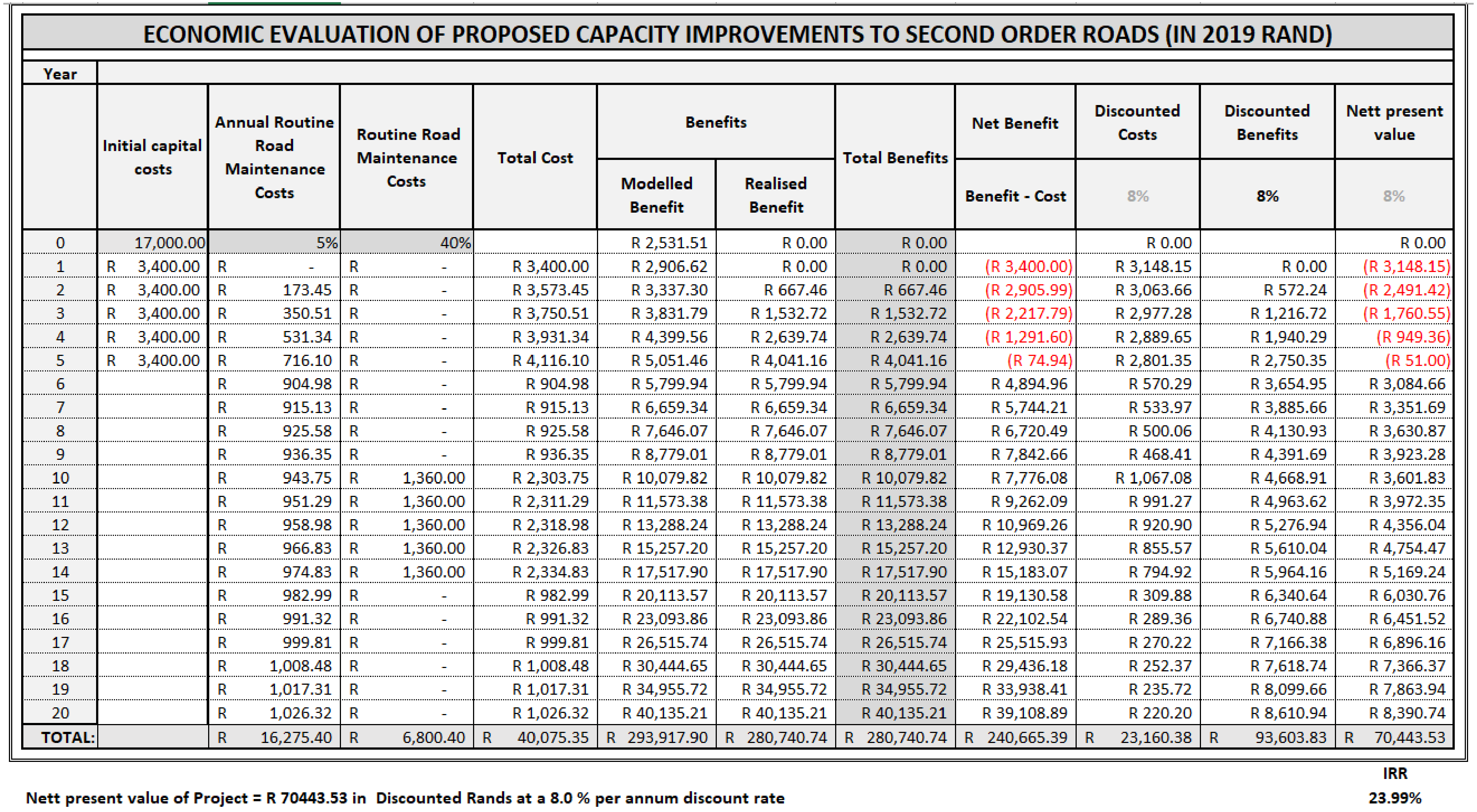
ECONOMIC EVALUATION OF PROPOSED CAPACITY IMPROVEMENTS TO FREEWAYS (IN 2019 RAND)

Year	Initial capital costs	Annual Routine Road Maintenance Costs	Routine Road Maintenance Costs	Total Cost	Benefits		Total Benefits	Net Benefit	Discounted Costs	Discounted Benefits	Net present value
					Modelled Benefit	Realised Benefit		Benefit - Cost	8%	8%	8%
0	17,000.00	5%	40%		R 1,160.15	R 0.00	R 0.00		R 0.00		R 0.00
1	R 3,400.00	R -	R -	R 3,400.00	R 1,346.81	R 0.00	R 0.00	(R 3,400.00)	R 3,148.15	R 0.00	(R 3,148.15)
2	R 3,400.00	R 173.45	R -	R 3,573.45	R 1,563.50	R 312.70	R 312.70	(R 3,260.75)	R 3,063.66	R 268.09	(R 2,795.57)
3	R 3,400.00	R 350.51	R -	R 3,750.51	R 1,815.05	R 726.02	R 726.02	(R 3,024.49)	R 2,977.28	R 576.34	(R 2,400.94)
4	R 3,400.00	R 531.34	R -	R 3,931.34	R 2,107.08	R 1,264.25	R 1,264.25	(R 2,667.09)	R 2,889.65	R 929.26	(R 1,960.39)
5	R 3,400.00	R 716.10	R -	R 4,116.10	R 2,446.08	R 1,956.87	R 1,956.87	(R 2,159.24)	R 2,801.35	R 1,331.81	(R 1,469.54)
6		R 904.98	R -	R 904.98	R 2,839.64	R 2,839.64	R 2,839.64	R 1,934.65	R 570.29	R 1,789.45	R 1,219.16
7		R 915.13	R -	R 915.13	R 3,296.51	R 3,296.51	R 3,296.51	R 2,381.37	R 533.97	R 1,923.48	R 1,389.51
8		R 925.58	R -	R 925.58	R 3,826.88	R 3,826.88	R 3,826.88	R 2,901.30	R 500.06	R 2,067.55	R 1,567.48
9		R 936.35	R -	R 936.35	R 4,442.59	R 4,442.59	R 4,442.59	R 3,506.24	R 468.41	R 2,222.40	R 1,753.99
10		R 943.75	R 1,360.00	R 2,303.75	R 5,157.36	R 5,157.36	R 5,157.36	R 2,853.62	R 1,067.08	R 2,388.86	R 1,321.78
11		R 951.29	R 1,360.00	R 2,311.29	R 5,987.13	R 5,987.13	R 5,987.13	R 3,675.85	R 991.27	R 2,567.78	R 1,576.51
12		R 958.98	R 1,360.00	R 2,318.98	R 6,950.41	R 6,950.41	R 6,950.41	R 4,631.43	R 920.90	R 2,760.10	R 1,839.20
13		R 966.83	R 1,360.00	R 2,326.83	R 8,068.66	R 8,068.66	R 8,068.66	R 5,741.83	R 855.57	R 2,966.83	R 2,111.26
14		R 974.83	R 1,360.00	R 2,334.83	R 9,366.83	R 9,366.83	R 9,366.83	R 7,032.00	R 794.92	R 3,189.04	R 2,394.12
15		R 982.99	R -	R 982.99	R 10,873.87	R 10,873.87	R 10,873.87	R 9,890.87	R 309.88	R 3,427.90	R 3,118.02
16		R 991.32	R -	R 991.32	R 12,623.37	R 12,623.37	R 12,623.37	R 11,632.05	R 289.36	R 3,684.64	R 3,395.28
17		R 999.81	R -	R 999.81	R 14,654.35	R 14,654.35	R 14,654.35	R 13,654.54	R 270.22	R 3,960.62	R 3,690.40
18		R 1,008.48	R -	R 1,008.48	R 17,012.10	R 17,012.10	R 17,012.10	R 16,003.62	R 252.37	R 4,257.26	R 4,004.89
19		R 1,017.31	R -	R 1,017.31	R 19,749.18	R 19,749.18	R 19,749.18	R 18,731.87	R 235.72	R 4,576.12	R 4,340.40
20		R 1,026.32	R -	R 1,026.32	R 22,926.64	R 22,926.64	R 22,926.64	R 21,900.31	R 220.20	R 4,918.87	R 4,698.67
TOTAL:		R 16,275.40	R 6,800.40	R 40,075.35	R 158,214.18	R 152,035.34	R 152,035.34	R 111,959.99	R 23,160.38	R 49,806.47	R 26,646.17

IRR

Nett present value of Project = R 26646.17 in Discounted Rands at a 8.0 % per annum discount rate **10.96%**

Table 10-6: Economic Evaluation for Alternative: Normal Trips & Improved Capacity on Second Order Roads



ECONOMIC EVALUATION OF PROPOSED CAPACITY IMPROVEMENTS TO SECOND ORDER ROADS (IN 2019 RAND)

Year	Initial capital costs	Annual Routine Road Maintenance Costs	Routine Road Maintenance Costs	Total Cost	Benefits		Total Benefits	Net Benefit	Discounted Costs	Discounted Benefits	Nett present value
					Modelled Benefit	Realised Benefit		Benefit - Cost	8%	8%	8%
0	17,000.00	5%	40%		R 2,531.51	R 0.00	R 0.00		R 0.00		R 0.00
1	R 3,400.00	R -	R -	R 3,400.00	R 2,906.62	R 0.00	R 0.00	(R 3,400.00)	R 3,148.15	R 0.00	(R 3,148.15)
2	R 3,400.00	R 173.45	R -	R 3,573.45	R 3,337.30	R 667.46	R 667.46	(R 2,905.99)	R 3,063.66	R 572.24	(R 2,491.42)
3	R 3,400.00	R 350.51	R -	R 3,750.51	R 3,831.79	R 1,532.72	R 1,532.72	(R 2,217.79)	R 2,977.28	R 1,216.72	(R 1,760.55)
4	R 3,400.00	R 531.34	R -	R 3,931.34	R 4,399.56	R 2,639.74	R 2,639.74	(R 1,291.60)	R 2,889.65	R 1,940.29	(R 949.36)
5	R 3,400.00	R 716.10	R -	R 4,116.10	R 5,051.46	R 4,041.16	R 4,041.16	(R 74.94)	R 2,801.35	R 2,750.35	(R 51.00)
6		R 904.98	R -	R 904.98	R 5,799.94	R 5,799.94	R 5,799.94	R 4,894.96	R 570.29	R 3,654.95	R 3,084.66
7		R 915.13	R -	R 915.13	R 6,659.34	R 6,659.34	R 6,659.34	R 5,744.21	R 533.97	R 3,885.66	R 3,351.69
8		R 925.58	R -	R 925.58	R 7,646.07	R 7,646.07	R 7,646.07	R 6,720.49	R 500.06	R 4,130.93	R 3,630.87
9		R 936.35	R -	R 936.35	R 8,779.01	R 8,779.01	R 8,779.01	R 7,842.66	R 468.41	R 4,391.69	R 3,923.28
10		R 943.75	R 1,360.00	R 2,303.75	R 10,079.82	R 10,079.82	R 10,079.82	R 7,776.08	R 1,067.08	R 4,668.91	R 3,601.83
11		R 951.29	R 1,360.00	R 2,311.29	R 11,573.38	R 11,573.38	R 11,573.38	R 9,262.09	R 991.27	R 4,963.62	R 3,972.35
12		R 958.98	R 1,360.00	R 2,318.98	R 13,288.24	R 13,288.24	R 13,288.24	R 10,969.26	R 920.90	R 5,276.94	R 4,356.04
13		R 966.83	R 1,360.00	R 2,326.83	R 15,257.20	R 15,257.20	R 15,257.20	R 12,930.37	R 855.57	R 5,610.04	R 4,754.47
14		R 974.83	R 1,360.00	R 2,334.83	R 17,517.90	R 17,517.90	R 17,517.90	R 15,183.07	R 794.92	R 5,964.16	R 5,169.24
15		R 982.99	R -	R 982.99	R 20,113.57	R 20,113.57	R 20,113.57	R 19,130.58	R 309.88	R 6,340.64	R 6,030.76
16		R 991.32	R -	R 991.32	R 23,093.86	R 23,093.86	R 23,093.86	R 22,102.54	R 289.36	R 6,740.88	R 6,451.52
17		R 999.81	R -	R 999.81	R 26,515.74	R 26,515.74	R 26,515.74	R 25,515.93	R 270.22	R 7,166.38	R 6,896.16
18		R 1,008.48	R -	R 1,008.48	R 30,444.65	R 30,444.65	R 30,444.65	R 29,436.18	R 252.37	R 7,618.74	R 7,366.37
19		R 1,017.31	R -	R 1,017.31	R 34,955.72	R 34,955.72	R 34,955.72	R 33,938.41	R 235.72	R 8,099.66	R 7,863.94
20		R 1,026.32	R -	R 1,026.32	R 40,135.21	R 40,135.21	R 40,135.21	R 39,108.89	R 220.20	R 8,610.94	R 8,390.74
TOTAL:		R 16,275.40	R 6,800.40	R 40,075.35	R 293,917.90	R 280,740.74	R 280,740.74	R 240,665.39	R 23,160.38	R 93,603.83	R 70,443.53

IRR

Nett present value of Project = R 70443.53 in Discounted Rands at a 8.0 % per annum discount rate **23.99%**

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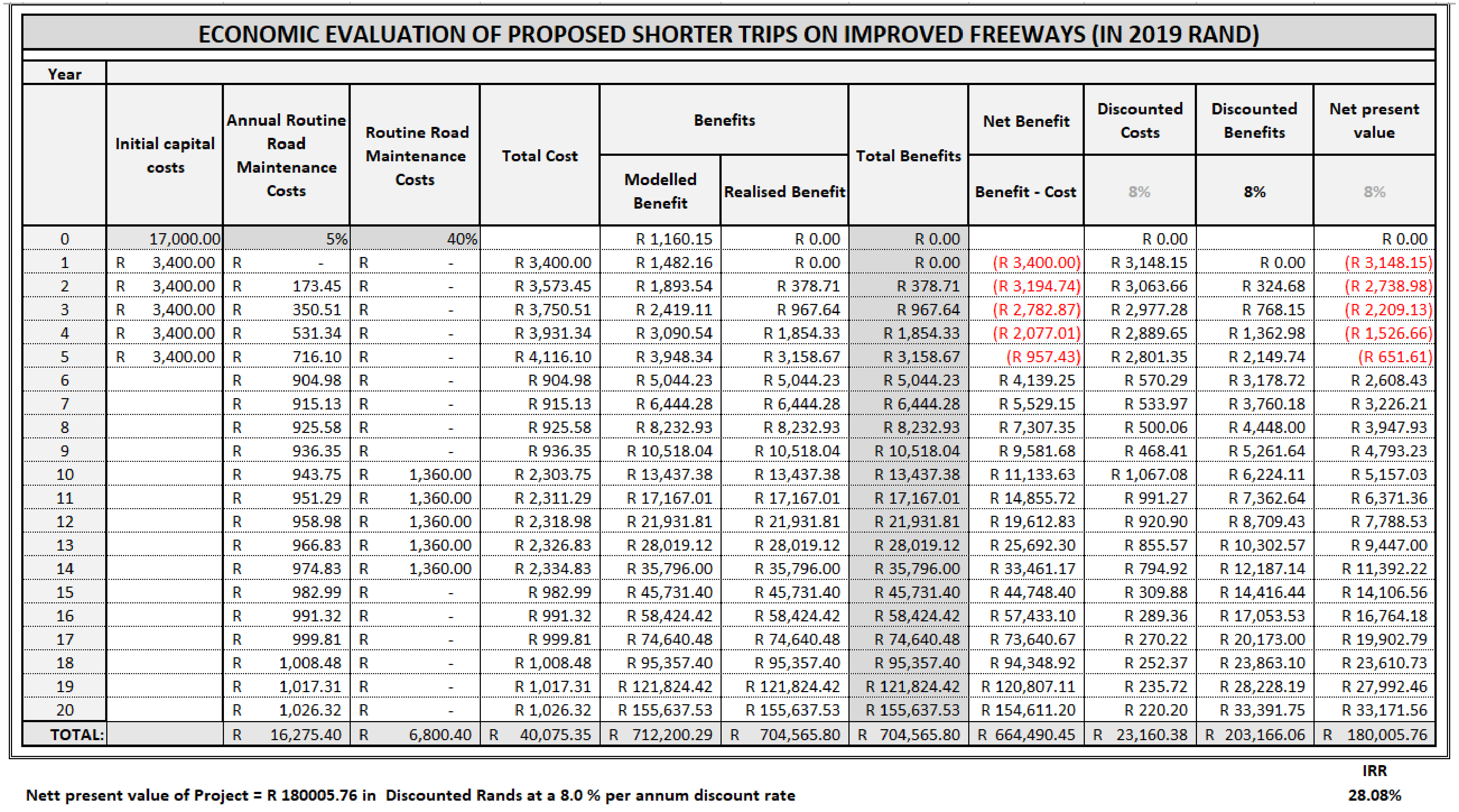
Table 10-7: Economic Evaluation for Alternative: Shorter Trips & Improved Capacity on Freeways



ECONOMIC EVALUATION OF PROPOSED SHORTER TRIPS ON IMPROVED FREEWAYS (IN 2019 RAND)

Year	Initial capital costs	Annual Routine Road Maintenance Costs	Routine Road Maintenance Costs	Total Cost	Benefits		Total Benefits	Net Benefit	Discounted Costs	Discounted Benefits	Net present value
					Modelled Benefit	Realised Benefit		Benefit - Cost	8%	8%	8%
0	17,000.00	5%	40%		R 1,160.15	R 0.00	R 0.00		R 0.00		R 0.00
1	R 3,400.00	R -	R -	R 3,400.00	R 1,482.16	R 0.00	R 0.00	(R 3,400.00)	R 3,148.15	R 0.00	(R 3,148.15)
2	R 3,400.00	R 173.45	R -	R 3,573.45	R 1,893.54	R 378.71	R 378.71	(R 3,194.74)	R 3,063.66	R 324.68	(R 2,738.98)
3	R 3,400.00	R 350.51	R -	R 3,750.51	R 2,419.11	R 967.64	R 967.64	(R 2,782.87)	R 2,977.28	R 768.15	(R 2,209.13)
4	R 3,400.00	R 531.34	R -	R 3,931.34	R 3,090.54	R 1,854.33	R 1,854.33	(R 2,077.01)	R 2,889.65	R 1,362.98	(R 1,526.66)
5	R 3,400.00	R 716.10	R -	R 4,116.10	R 3,948.34	R 3,158.67	R 3,158.67	(R 957.43)	R 2,801.35	R 2,149.74	(R 651.61)
6		R 904.98	R -	R 904.98	R 5,044.23	R 5,044.23	R 5,044.23	R 4,139.25	R 570.29	R 3,178.72	R 2,608.43
7		R 915.13	R -	R 915.13	R 6,444.28	R 6,444.28	R 6,444.28	R 5,529.15	R 533.97	R 3,760.18	R 3,226.21
8		R 925.58	R -	R 925.58	R 8,232.93	R 8,232.93	R 8,232.93	R 7,307.35	R 500.06	R 4,448.00	R 3,947.93
9		R 936.35	R -	R 936.35	R 10,518.04	R 10,518.04	R 10,518.04	R 9,581.68	R 468.41	R 5,261.64	R 4,793.23
10		R 943.75	R 1,360.00	R 2,303.75	R 13,437.38	R 13,437.38	R 13,437.38	R 11,133.63	R 1,067.08	R 6,224.11	R 5,157.03
11		R 951.29	R 1,360.00	R 2,311.29	R 17,167.01	R 17,167.01	R 17,167.01	R 14,855.72	R 991.27	R 7,362.64	R 6,371.36
12		R 958.98	R 1,360.00	R 2,318.98	R 21,931.81	R 21,931.81	R 21,931.81	R 19,612.83	R 920.90	R 8,709.43	R 7,788.53
13		R 966.83	R 1,360.00	R 2,326.83	R 28,019.12	R 28,019.12	R 28,019.12	R 25,692.30	R 855.57	R 10,302.57	R 9,447.00
14		R 974.83	R 1,360.00	R 2,334.83	R 35,796.00	R 35,796.00	R 35,796.00	R 33,461.17	R 794.92	R 12,187.14	R 11,392.22
15		R 982.99	R -	R 982.99	R 45,731.40	R 45,731.40	R 45,731.40	R 44,748.40	R 309.88	R 14,416.44	R 14,106.56
16		R 991.32	R -	R 991.32	R 58,424.42	R 58,424.42	R 58,424.42	R 57,433.10	R 289.36	R 17,053.53	R 16,764.18
17		R 999.81	R -	R 999.81	R 74,640.48	R 74,640.48	R 74,640.48	R 73,640.67	R 270.22	R 20,173.00	R 19,902.79
18		R 1,008.48	R -	R 1,008.48	R 95,357.40	R 95,357.40	R 95,357.40	R 94,348.92	R 252.37	R 23,863.10	R 23,610.73
19		R 1,017.31	R -	R 1,017.31	R 121,824.42	R 121,824.42	R 121,824.42	R 120,807.11	R 235.72	R 28,228.19	R 27,992.46
20		R 1,026.32	R -	R 1,026.32	R 155,637.53	R 155,637.53	R 155,637.53	R 154,611.20	R 220.20	R 33,391.75	R 33,171.56
TOTAL:		R 16,275.40	R 6,800.40	R 40,075.35	R 712,200.29	R 704,565.80	R 704,565.80	R 664,490.45	R 23,160.38	R 203,166.06	R 180,005.76

Nett present value of Project = R 180005.76 in Discounted Rands at a 8.0 % per annum discount rate

IRR
28.08%

Table 10-8: Economic Evaluation for Alternative: Shorter Trips & Improved Capacity on Second Order Roads

ECONOMIC EVALUATION OF PROPOSED SHORTER TRIPS ON IMPROVED SECOND ORDER ROADS (IN 2019 RAND)

Year	Initial capital costs	Annual Routine Road Maintenance Costs	Routine Road Maintenance Costs	Total Cost	Benefits		Total Benefits	Net Benefit	Discounted Costs	Discounted Benefits	Nett present value
					Modelled Benefit	Realised Benefit		Benefit - Cost	8%	8%	8%
0	17,000.00	5%	40%		R 2,531.51	R 0.00	R 0.00		R 0.00		R 0.00
1	R 3,400.00	R -	R -	R 3,400.00	R 3,124.18	R 0.00	R 0.00	(R 3,400.00)	R 3,148.15	R 0.00	(R 3,148.15)
2	R 3,400.00	R 173.45	R -	R 3,573.45	R 3,855.59	R 771.12	R 771.12	(R 2,802.33)	R 3,063.66	R 661.11	(R 2,402.55)
3	R 3,400.00	R 350.51	R -	R 3,750.51	R 4,758.24	R 1,903.30	R 1,903.30	(R 1,847.21)	R 2,977.28	R 1,510.90	(R 1,466.38)
4	R 3,400.00	R 531.34	R -	R 3,931.34	R 5,872.21	R 3,523.33	R 3,523.33	(R 408.01)	R 2,889.65	R 2,589.75	(R 299.90)
5	R 3,400.00	R 716.10	R -	R 4,116.10	R 7,246.98	R 5,797.59	R 5,797.59	R 1,681.49	R 2,801.35	R 3,945.74	R 1,144.39
6		R 904.98	R -	R 904.98	R 8,943.61	R 8,943.61	R 8,943.61	R 8,038.63	R 570.29	R 5,635.99	R 5,065.70
7		R 915.13	R -	R 915.13	R 11,037.44	R 11,037.44	R 11,037.44	R 10,122.30	R 533.97	R 6,440.24	R 5,906.27
8		R 925.58	R -	R 925.58	R 13,621.46	R 13,621.46	R 13,621.46	R 12,695.87	R 500.06	R 7,359.25	R 6,859.19
9		R 936.35	R -	R 936.35	R 16,810.44	R 16,810.44	R 16,810.44	R 15,874.08	R 468.41	R 8,409.40	R 7,940.99
10		R 943.75	R 1,360.00	R 2,303.75	R 20,746.00	R 20,746.00	R 20,746.00	R 18,442.26	R 1,067.08	R 9,609.41	R 8,542.33
11		R 951.29	R 1,360.00	R 2,311.29	R 25,602.94	R 25,602.94	R 25,602.94	R 23,291.65	R 991.27	R 10,980.66	R 9,989.39
12		R 958.98	R 1,360.00	R 2,318.98	R 31,596.96	R 31,596.96	R 31,596.96	R 29,277.98	R 920.90	R 12,547.59	R 11,626.69
13		R 966.83	R 1,360.00	R 2,326.83	R 38,994.26	R 38,994.26	R 38,994.26	R 36,667.43	R 855.57	R 14,338.11	R 13,482.54
14		R 974.83	R 1,360.00	R 2,334.83	R 48,123.38	R 48,123.38	R 48,123.38	R 45,788.55	R 794.92	R 16,384.13	R 15,589.22
15		R 982.99	R -	R 982.99	R 59,389.75	R 59,389.75	R 59,389.75	R 58,406.76	R 309.88	R 18,722.13	R 18,412.25
16		R 991.32	R -	R 991.32	R 73,293.75	R 73,293.75	R 73,293.75	R 72,302.43	R 289.36	R 21,393.75	R 21,104.39
17		R 999.81	R -	R 999.81	R 90,452.87	R 90,452.87	R 90,452.87	R 89,453.05	R 270.22	R 24,446.60	R 24,176.38
18		R 1,008.48	R -	R 1,008.48	R 111,629.18	R 111,629.18	R 111,629.18	R 110,620.71	R 252.37	R 27,935.10	R 27,682.73
19		R 1,017.31	R -	R 1,017.31	R 137,763.18	R 137,763.18	R 137,763.18	R 136,745.87	R 235.72	R 31,921.39	R 31,685.67
20		R 1,026.32	R -	R 1,026.32	R 170,015.53	R 170,015.53	R 170,015.53	R 168,989.20	R 220.20	R 36,476.53	R 36,256.33
TOTAL:		R 16,275.40	R 6,800.40	R 40,075.35	R 885,409.45	R 870,016.06	R 870,016.06	R 829,940.70	R 23,160.38	R 261,307.85	R 238,147.55

	IRR
Nett present value of Project = R 238147.55 in Discounted Rands at a 8.0 % per annum discount rate	**38.76%**

11 Conclusions and Recommendations for Further Research

11.1 Conclusions

The aim of this research project was to develop a proof of concept to investigate the supporting of densification through the planning and implementation of road infrastructure in the South African context.

A comprehensive literature review exploring the elements required in the development of the proof of concept for this study was completed. Only after understanding these elements, their dependency on each other, their interaction with each other and their lack of presence in the South African transportation planning context could the building blocks of the proof of concept be developed. The literature review focused on the following elements:

- Urban Sprawl;
- Types of City Layouts:
    - The Concept of Urban Spatial Structure and Associated Commuting Patterns
    - Urban Spatial Planning in South Africa (Gauteng)/Past Travel Patterns in Gauteng
    - The Concept of a Compact City
    - Jobs-Housing Balance
- Requirements for Public Transport Implementation:
    - Relationship between Density and Trip Length
    - Population Density Requirements
    - Infrastructure Requirements
- The Future City:
    - Features of The Future City
    - Barcelona Superblocks
    - Jewel City in the Johannesburg CBD

An extensive literature review focusing on suitable methods which could enable the achievement of the objective of the study was completed on the following aspects:

- Integrated Transportation and Land Use Models
- The Four Step Modelling Process (expanded to include the Gravity Model)
- Deterrence Functions
- The Furness Method of Balancing Factors

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- Trip Length Calibration
- Origin-Destination (OD) Trip Matrix Estimation

These methods, in combination with the SATURN software, were used to estimate the parameters in the distance-deterrence function for existing trips on the Gauteng Freeway Improvement Project (GFIP) network. There are three common forms of the deterrence functions namely the Exponential function, Combined function and the Gamma function. To estimate suitable parameters for a distance-deterrence function to represent existing trips on the GFIP network, the Combined function and the Exponential functions were used in a curve-fitting exercise. After numerous iterations estimating the parameters in the deterrence function for existing trips on the network, it was found that the Exponential function was best suited in representing existing trips on the GFIP network. The following distance-deterrence function was estimated through the curve-fitting exercise:

$$f\left(C_{ij}\right) = 1.592 * e^{(-0.08C_{ij})}$$

The purpose of the curve-fitting exercise was also to investigate the effect of beta on the average trip lengths on the GFIP network. After the curve-fitting exercise was completed, it was found that as the beta value increased, the average length of trips on the network decreased.

The Gravity Model is commonly used in industry to synthetically distribute trips on a network. Therefore, the Gravity Model was used in this study to develop a set of synthesized distance-deterrence functions to reflect different measures of reduction in the average trip lengths. The synthesized distance-deterrence functions were used to develop the relevant synthesized OD trip matrices. Thereafter, the performance of the synthesized distance-deterrence OD matrices was tested on the network to determine the trip distribution, congestion levels and average trip lengths. This was completed for the base and design years (2018 and 2038 respectively). These were used to identify the sections of road infrastructure which would most likely require capacity improvements in the design years, in twenty years' time.

Different road infrastructure improvement alternatives were proposed. The GFIP network was adjusted to reflect the different improvement alternatives. The different synthesized OD trip matrices were assigned to the different network alternatives to determine the total travel time (hours) and total travel distance (km) for all light vehicles on the network. The scenarios tested, for the base and design years, are summarized below:

- The Do-Nothing Scenario
- Assignment of OD matrix for shorter trips on the unchanged Network

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- Assignment of unchanged OD matrix to improved network: Improved capacity on freeways
- Assignment of OD matrix for shorter trips on improved network: Improved capacity on freeways
- Assignment of unchanged OD matrix to improved network: Improved capacity on second order roads
- Assignment of OD matrix for shorter trips on improved network: Improved capacity on second order roads

The results indicated that the highest total travel time saving (hours) and total distance travelled saving (km) can be achieved by drivers making shorter trips on the network and by improving the capacity of the second order roads. It is to be noted that shorter trips are encouraged and can be achieved through the capacity improvement of the second order roads.

The total travel time and total distance travelled savings (reflecting the benefits) were used in the respective calculations to determine the economic indicators, Net Present Value and the economic Internal Rate of Return for each alternative proposed.

The results from the simple economic analysis indicated that the alternative whereby drivers make shorter trips on the network and by improving the capacity of the second order roads yields the highest economic internal rate of return. It is also envisaged, based on the literature review study and traffic simulations completed, that this alternative will assist in promoting shorter trips and support densification. It is also envisaged that this combination - shorter trip lengths and a densified environment - will contribute towards providing an environment conducive to the implementation and operation of a viable, affordable and efficient public transport system.

It is therefore concluded that the proof of concept applied in supporting densification through the planning and implementation of road infrastructure in the South African context works. It is evident that the current approach used in road infrastructure planning and implementation needs to be improved and adapted to meet the needs of the new era of professionals. We need to move towards “The Compact City” and “The Future City”. Continuous expansion of freeways is not always the most economical solution and the spending of road infrastructure budgets should be based on a holistic benefit (societal and mobility) and not primarily on congestion alleviation. The existing public transport system in South Africa is not yet synchronised with the spatial planning in the country. Before we can hope to have a public transport, system which is viable, affordable and efficient, we need to improve the existing spatial planning in South Africa and adopt a fresh and innovative approach for future spatial planning. We can control sprawl and driver behaviour by simply controlling the environment concerned. It’s time for something new.

11.2 Recommendations for Further Research

The topic researched as part of this study forms one part of an extensive and complicated element in transportation planning and modelling. For the purpose of achieving the requirements of a postgraduate Masters’ degree project within the time constraints the study needed to be constrained to a limited set of objectives.

To continue research in this field of study, future researchers are encouraged to expand the study to include the following aspects:

- Model trip distributions according to variable distribution functions;
- Model trip distributions according to variable demand models; and
- Model different public transport modes and route choice on the network per scenario tested.

Due to the limited data, time and resources available, the methodology applied in this research project was developed by the author. It is recommended that the methodology discussed and applied in this research project be expanded and applied such that the above-mentioned aspects are included. This will require dedicated, high powered computers, the latest accurate land use and traffic data and public transport data.

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References

Akinbami, J.F.K. and Fadara, S.O. (1997). *Strategies for sustainable urban and transport development in Nigeria.* Obafemi Awolowo University, Department of Urban and Regional Planning,. Nigeria: Centre for Energy Research and Development.

Amny (2019). *Mta bus action plan.* Available from https://www.amny.com/transit/mta-bus-action-plan-1.18210453 [Accessed 20 September 2019].

Aropet, R (2017). Southern African solutions to public transport challenges. 36th Southern African Transport Conference (SATC 2017) ISBN Number: 978-1-920017-73-6.

Atterbury (2019). *Jewel City.* Available from https://www.atterbury.co.za/portfolio-items/jewel-city/ [Accessed 19 September 2019].

Bertaud, A 2003, The Spatial Organization of Cities: Deliberate Outcome or Unforeseen Consequence?, World Development Report 2003: Dynamic Development in a Sustainable World, World Bank.

Bester, C. (2017). *Transport Economics.* Lecture Notes, Economic Evaluation, University of Stellenbosch.

Britannica (2019). *Urban Sprawl.* Available from https://www.britannica.com/topic/urban-sprawl [Accessed 09 September 2019].

BusinessTech (2019). *A look at Jewel City-A massive redevelopment project in the middle of Joburg's CBD.* Available from https://businesstech.co.za/news/property/272725/a-look-at-jewel-city-a-massive-redevelopment-project-in-the-middle-of-joburgs-cbd/ [Accessed 20 September 2019].

BusinessTech (2019). *The best and worst areas in Pretoria for property growth.* Available from https://businesstech.co.za/news/property/237591/the-best-and-worst-areas-in-pretoria-for-property-growth/ [Accessed 14 September 2019].

CDOT (2012), *Effect of Connectivity on Fire Station Service Area & Capital Facilities Planning: Looking at Connectivity from an Emergency Response Perspective,* Charlotte Department of Transportation; presentation at www.charlotteobserver.com/static/images/pdf/CNUPresentation.pdf.

Cervero, R 1989, 'Jobs-Housing Balancing and Regional Mobility', Journal of the American Planning Association, vol. 55, no. 2, pp. 136-150.

Stellenbosch University https://scholar.sun.ac.za

CityMayors (2019). *Largest Cities Densities.* Available from http://www.citymayors.com/statistics/largest-cities-density-125.html [Accessed 20 March 2019].

CNT (2010), *Penny Wise, Pound Fuelish: New Measures of Housing + Transportation Affordability,* Center for Neighbourhood Technology (www.cnt.org); at www.cnt.org/repository/pwpf.pdf.

CNU (2019). *Great ideas new urbanism.* Available from https://www.cnu.org/publicsquare/2017/10/31/25-great-ideas-new-urbanism [Accessed 19 September 2019].

Cooke, S. and Behrens, R. (2014). A Comparative Empirical Analysis of the Relationship Between Public Transport and Land Use Characteristics. Paper presented at *33rd Annual Southern African Transport Conference.* Pretoria, South Africa, 7-10 July 2014. Cape Town: Department of Civil Engineering at the University of Cape Town.

Cooke, S. and Behrens, R. (2016). Correlation od cause? The Limitations of population density as an indicator for public transport viability in the context of a rapidly growing developing city. Paper presented at *World Conference on Transport Research*. Shanghai, 10-15 July 2016. Cape Town: Department of Civil Engineering at the University of Cape Town, pp 3006-3016.

CRS (2019). *South Africa’s 2019-2020 CRS Tax Pocket Guide.* Available from https://www.crs.co.za/2019/02/22/news-flash-22-february-2019-south-africa-2019-2020-crs-tax-pocket-guide/ [Accessed 22 September 2019].

C40 Knowledge hub (2019). *How to make public transport an attractive option in your city.* Available from https://www.c40knowledgehub.org/s/article/How-to-make-public-transport-an-attractive-option-in-your-city?language=en_US [Accessed 20 September 2019].

Doblas, J. and Benitez, F.g., (2004), An Approach to estimating and updating origin-destination matrices based upon traffic counts preserving the prior structure of a survey matrix, Transportation Engineering, University of Sevilla.

Engineering News (2019). *Divercity’s Jewel City Project brings six Joburg CBD blocks back to life with strategic urban rejuvenation.* Available from https://www.engineeringnews.co.za/article/divercitys-jewel-city-project-brings-six-joburg-cbd-blocks-to-life-with-strategic-urban-rejuvenation-2019-03-27 [Accessed 20 September 2019].

Stellenbosch University https://scholar.sun.ac.za

Ewing, R, Deanna, M & Li, S-C 1996, ‘Land Use Impacts on Trip Generation Rates’ , Transportation Research Record, vol. 1518, pp.1-6.

Frank, LD & Pivo, G 1994, An Analysis of Relationships Between Urban Form (Density, Mix, and Jobs: Housing Balance) and Travel Behaviour (Mode Choice, Trip Generation, Trip Length, and Travel Time), Washington State Transportation Center (TRAC), University of Washington, Seattle.

Gautrain (2019). *Commuter Station Information.* Available from https://www.gautrain.co.za/commuter/stationinfo [Accessed 14 March 2019].

Giuliano, G & Small, KA 1993, ‘Is the Journey to Work Explained by Urban Structure?’, Urban Studies, vol.30, no. 9, pp. 1485-1500.

Govender, K (2018). *Transportation Planning Assignment.* Unpublished assignment. University of Stellenbosch.

Hayes, G. and Venter, C. (2016). Trip Utility and the Value of Travel Time Savings (VTTS) for Commuter Trips: Critique and Recent Advances. 35th Southern African Transport Conference (SATC 2016) ISBN Number: 978-1-920017-64-4.

Holz-Rau, C., Sceiner J. and Sicks, K. (2013), ‘Travel Distances in daily travel and long-distance travel: what role is played by urban form?’, Environment and Planning, vol. 46, pp. 488-507.

IBI (2008), *Implications of Alternative Growth Patterns on Infrastructure Costs,* Plan-It Calgary, City of Calgary (www.calgary.ca); at www.calgary.ca/docgallery/BU/planning/pdf/plam_it/plan_it_calgary_cost_study_analysis_april_third.pdf.

Investopedia (2019). *Economic Indicators.* Available from https://www.investopedia.com/terms/n/npv.asp [Accessed 25 September 2019].

Joburg (2019). *About the City of Joburg.* Available from https://www.joburg.org.za/about_/Pages/About%20the%20City/About%20Joburg/Population-and-People.aspx [Accessed 21 March 2019].

Jonathan Ford (2009), *Smart Growth & Conventional Suburban Development: Which Costs More?* USEPA (www.epa.gov/smartgrowth/sg_business.htm); at http://bit.ly/1EN0Fud.

Jones, P. (2011). Developing sustainable transport for the next generation: The need for a multi-sector approach. *Centre for Transport Studies,* 35 (2012): 41-47. Available from http://dx.doi.org/10.1016/j.iatssr.2011.11.001 [Accessed 1 April 2019].

Levinson, DM 1998, ‘Accessibility and the Journey to Work’, Journey of Transport Geography, vol. 6, no. 1, pp. 11-21

Lin, D., Allan, A. and Cui, J. (2013). Does Polycentric Urban Spatial Development Lead to Less Commuting: A Perspective of Jobs-housing Balance. Paper presented at *49th ISOCARP Congress*. Australia, 1-4 October 2013. Australia: Universities of South Australia and Griffith University, pp 1-10.

Lu, Y., Sun, G., Sarkar, C., Gou, Z. and Xiao, Y. (2018). Commuting Mode Choice in a High-Density City: Do Land-Use Density and Diversity Matter in Hong Kong? *International Journal of Environmental Research and Public Health,* 15 (920), 1-13.

Madbookings (2019). *Map of Johannesburg and Pretoris CBDs.* Available from www.madbookings.com [Accessed on 20 March 2019].

McKinsey & Company (2018). *Elements of success: Urban transportation systems of 24 global cities.* [no publication details given]

Milanocard (2019). *How to use the Milanocard for the Public Transport Service in Milan.* Available from https://www.milanocard.it/ [Accessed 20 September 2019].

Minitab (2019). *Regression Analysis – how do I interpret R squared and assess the goodness of fit.* Available from https://blog.minitab.com/blog/adventures-in-statistics-2/regression-analysis-how-do-i-interpret-r-squared-and-assess-the-goodness-of-fit [Accessed 20 May 2019].

Moscovery (2019). *Public Transport.* Available from https://www.moscovery.com/public-transport/ [Accessed 20 September 2019].

National Cooperative Highway Research Program (NCHRP) (2018) *Integrated Transportation and Land Use Models.* Washington DC.

National Geographic (2019). *Sustainable future city designed for people and nature.* Available from https://www.nationalgeographic.com/magazine/2019/04/see-sustainable-future-city-designed-for-people-and-nature/ [Accessed 20 September 2019].

Nora Libertun de Duren and Roberto Guerrero Compean (2015), “Growing resources for growing cities: Density and the cost of municipal public services in Latin America, “*Urban*

Studies, (DOI: 2015004209801560157 9); abstract at http://usj.sagepub.com/content/early/2015/09/15/0042098015601579.abstract.

Ortúzar, J., & Willumsen, L. (2011). *Modelling Transport, Fourth Edition.* Wiley.

Private Property (2019). *Top inner-city Johannesburg suburbs for buyers.* Available from https://www.privateproperty.co.za/advice/news/articles/top-inner-city-johannesburg-suburbs-for-buyers/6931 [Accessed 14 September 2019].

Price of Travel (2019). *Public Transportation Prices in 80 Cities Around the World.* Available from https://www.priceoftravel.com/595/public-transportation-prices-in-80-worldwide-cities/ [Accessed 20 March 2019].

Property24 (2019). *Houghton Estate Property Trends.* Available from https://www.property24.com/johannesburg/houghton-estate/property-trends/5926 [Accessed 14 September 2019].

Rasouli, A. (2018). *Calibrating the Distance-Deterrence Function for the Perth Metropolitan Area.* PhD thesis, Curtin University, Department of Civil Engineering.

Reavaya (2019). *Consumer Information on Fares.* Available from http://www.reavaya.org.za/rea-vaya-integrated-map [Accessed 14 March 2019].

ReserachGate (2014). *Past and Present Travel Patterns in the Gauteng Region.* Available from https://www.researchgate.net/publication/264991722_Past_and_present_travel_patterns_in_the_Gauteng_City_Region [Accessed 14 September 2019].

Robert W. Burchell and Sahan Mukkherji (2003), “Conventional Development Versus Managed Growth: The Costs of Sprawl,” *American Journal of Public Health,* Vol. 93, No. 9 (www.aiph.org), Sept., pp. 1534-1540; at www.ncbi.nlm.nih.gov/pmc/articles/PMC1448006.

Robinson, R. (2017). *Validating Traffic Models Using Large-Scale Automatic Number Plate Recognition (ANPR) Data.* Masters thesis, University of Pretoria, Department of Civil Engineering.

Sa Affordable Housing (2019). *Jewel City bringd six Joburg CBD blocks back to life.* Available from http://saaffordablehousing.co.za/jewel-city-brings-six-joburg-cbd-blocks-to-life/ [Accessed 20 September 2019].

Safer spaces (2019). *The state of public transport in South Africa.* Available from https://www.saferspaces.org.za/understand/entry/the-state-of-public-transport-in-south-africa [Accessed 20 September 2019].

SANRAL Toll Strategy publication (2019)

SGA (2014), *Measuring Sprawl,* Smart Growth America (www.smartgrowthamerica.org); at www.smartgrowthamerica.org/documents/measuring-sprawl-2014.pdf.

Shrewsbury, John Stephen. 2012. *Calibration of Trip Distribution by Generalised Linear Models. NZ Transport Agency Research Report 473.* Wellington, New Zealand: NZ Transport Agency.

http://www.nzta.govt.nz/resources/research/reports/473/docs/473.pdf.

Sieg, S M. and Landre, M. (1991). The Measurement of Residential Sprawl in The Johannesburg Metropolitan Area. S.l, p 3-9.

Smart cities dive (2019). *21 Features of a future sustainable city.* Available from https://www.smartcitiesdive.com/ex/sustainablecitiescollective/21-features-future-sustainable-city/285946/ [Accessed 20 September 2019].

StatisticsTimes (2019). *Population Densities of Countries.* Available from http://statisticstimes.com/demographics/countries-by-population-density.php [Accessed 20 March 2019].

The Conversation (2019). *Barcelona Superblocks could improve mental health.* Available from https://theconversation.com/superblocks-barcelonas-car-free-zones-could-extend-lives-and-boost-mental-health-123295 [Accessed 19 September 2019].

ThoughtCo (2019). *New Urbanism Planning Design Movement.* Available from https://www.thoughtco.com/new-urbanism-urban-planning-design-movement-1435790 [Accessed 19 September 2019].

Transport Modeller (2019). *Distribution Overview.* Available from http://www.transportmodeller.com/distributionoverview.html [Accessed 12 April 2019].

Tripsavvy (2019). *Chicago trains subways and buses.* Available from https://www.tripsavvy.com/chicago-trains-subways-and-buses-1492804 [Accessed 20 September 2019].

UNHABITAT (2014), *Planning and Design for Sustainable Urban Mobility: Global Report on Human Settlements 2013,* Chapter 5, January 2014 revision

Urban Hub (2019). *Cities.* Available from http://www.urban-hub.com/cities/ [Accessed 19 September 2019].

Varma, GR. (2017). A Study on New Urbanism and Compact City and their Influence on Urban Mobility. Paper presented at *2nd IEEE International Conference on Intelligent Transportation Engineering.* Singapore, 1-3 September 2017. United States of America: Transportation Systems and Design, Art Center College of Design, pp 250-253.

Venter, C. (2018). *Transportation Planning.* Lecture notes, The Four Step Process, University of Stellenbosch.

Victoria Transport Policy Institute (2019). *Evaluating Transportation Land Use Impacts.* Available from https://scholar.google.co.za/scholar?q=evaluating+transportation+land+use+impacts+site:http://www.vtpi.org&hl=en&as_sdt=0&as_vis=1&oi=scholart [Accessed 22 March 2019].

Weforum (2019). *The Most Crowded Cities in The World.* Available from https://www.weforum.org/agenda/2017/05/these-are-the-world-s-most-crowded-cities/ [Accessed 20 March 2019].

World Atlas (2019). *The Top 10 best public transit systems in the world.* Available from https://www.worldatlas.com/articles/the-top-10-best-public-transit-systems-in-the-world.html [Accessed 20 September 2019].

World Population Review (2019). *South Africa's Population.* Available from http://worldpopulationreview.com/countries/south-africa-population/ [Accessed 20 March 2019].

World Population Review (2019). *Johannesburg population.* Available from http://worldpopulationreview.com/world-cities/johannesburg-population/ [Accessed 21 March 2019].

Yusuf, MP. and Allopi, D. (2010). The Impact of Urban Sprawl on the Inhabitants of the eThekwini Municipality and the Provision of Infrastructure. Paper presented at *29th Annual Southern African Transport Conference.* Pretoria, South Africa, 16-19 August 2010. Durban: Durban University of Technology, pp 415-424.

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12 APPENDICES

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13 APPENDICES: CHAPTER 4

Appendix 4.1: An Extract of the Traffic Data obtained from the grantries and CTO stations and provided by SANRAL

1	2	3		4	5		6					7	8	9	10	11
* Station	LG	A NODE-B NODE	*	* A NODE	B NODE	UC					Spd					
			*	* Start Hour	7.00	1	2	3		*	4	CTO	LG			
13	1	2713-9873		2713	9873	1211	65	11	1288	*	0	13	1	Paul Kruger Ext	North	To R566 (K8)
13	2	9873-2713		9873	2713	1096	60	17	1172	*	0	13	2	Paul Kruger Ext	South	To Wonderboompoort
33	1	2443-11354		2443	11354	280	17	8	305	*	0	33	1	Doornrandjies	North	To Hartbeespoortdam
33	2	11354-2443		11354	2443	381	9	2	392	*	0	33	2	Doornrandjies	South	To Diepsloot
41	1	10376-10375		10376	10375	1061	50	10	1121	*	0	41	1	Poortview AH(BL)	East	To Ruimsig
41	2	10375-10376		10375	10376	1065	103	24	1192	*	0	41	2	Poortview AH(BL)	West	To Tarlton
45	1	6493-6490		6493	6490	247	28	8	283	*	0	45	1	Tarlton	East	To Krugersdorp
45	2	6490-6493		6490	6493	192	22	7	222	*	0	45	2	Tarlton	West	To Magaliesburg
57	1	9400-3118		9400	3118	1403	37	8	1448	*	0	57	1	Fourways Gardens	North	To Broadacres AH
57	2	3118-9400		3118	9400	1223	39	5	1267	*	0	57	2	Fourways Gardens	South	To Fourways
70	1	5309-3532		5309	3532	367	18	20	405	*	0	70	1	Westonaria North	North	To Randfontein
70	2	3532-5309		3532	5309	538	25	19	582	*	0	70	2	Westonaria North	South	To Vereeniging
72	1	11908-3620		11908	3620	300	14	19	333	*	0	72	1	Westonaria South(BL)	North	To Randfontein
72	2	3620-11908		3620	11908	317	16	16	350	*	0	72	2	Westonaria South(BL)	South	To Vereeniging
86	1	4915-11858		4915	11858	1428	37	55	1520	*	0	86	1	Kliprivier WIM	North	To Alberton
86	2	11858-4915		11858	4915	802	61	51	914	*	0	86	2	Kliprivier WIM	South	To Vereeniging
95	1	5482-9642		5482	9642	164	10	16	190	*	0	95	1	Spaarwater AH	North	To Dalpark
95	2	9642-5482		9642	5482	197	11	4	212	*	0	95	2	Spaarwater AH	South	To Heidelberg
108	1	4116-9203		4116	9203	320	23	3	346	*	0	108	1	Modderfontein Rd(CM)	East	To Birchleigh
108	2	9203-4116		9203	4116	1333	22	9	1364	*	0	108	2	Modderfontein Rd(CM)	West	To Modderfontein
110	1	3985-11523		3985	11523	804	8	5	818	*	0	110	1	Alan Manor	North	To Jhb CBD
110	2	11523-3985		11523	3985	544	6	2	552	*	0	110	2	Alan Manor	South	To Kibler Park
123	1	6445-11299		6445	11299	128	9	13	150	*	0	123	1	Magaliesburg (RH)	East	To Magaliesburg
123	2	11299-6445		11299	6445	134	15	16	165	*	0	123	2	Magaliesburg (RH)	West	To Rustenburg
127	1	5594-12080		5594	12080	135	16	10	161	*	100	127	1	Bronkorstspruit (RM)	East	To Bronkhorstspruit
127	2	12080-5594		12080	5594	155	9	6	170	*	103	127	2	Bronkorstspruit (RM)	West	To Bapsfontein
131	1	2372-11632		2372	11632	366	19	12	397	*	0	131	1	Pyramid (BH)	North	To Bela Bela
131	2	11632-2372		11632	2372	483	19	16	518	*	0	131	2	Pyramid (BH)	South	To Paramid
133	1	5668-10618		5668	10618	222	19	13	254	*	2	133	1	R25 Bapsfontein	North	To Bronkhorstspruit
133	2	10618-5668		10618	5668	299	15	11	325	*	2	133	2	R25 Bapsfontein	South	To Bapsfontein
139	1	11795-11792		11795	11792	222	19	13	254	*	2	139	1	Moloto (BH)	North	To Moloto
139	2	11792-11795		11792	11795	299	15	11	325	*	2	139	2	Moloto (BH)	South	To Pretoria
140	1	2314-2510		2314	2510	1150	29	14	1193	*	0	140	1	Mabopane (CH)	North	To Soshanguve
140	2	2510-2314		2510	2314	1929	39	13	1980	*	0	140	2	Mabopane (CH)	South	To Akasia
141	1	2418-9915		2418	9915	147	11	5	163	*	0	141	1	Wes Moot (BM)	East	To Pretoria
141	2	9915-2418		9915	2418	135	13	5	153	*	0	141	2	Wes Moot (BM)	West	To Brits
151	1	3645-3644		3645	3644	235	12	17	264	*	0	151	1	Glenharvie HSWIM	East	To Johannesburg
151	2	3644-3645		3644	3645	279	21	22	321	*	0	151	2	Glenharvie HSWIM	West	To Potchefstroom

Appendix 4.2: An Extract of the Land Use trip ends data provided by SANRAL

TOLL STUDY:		2015									2010								
Car Ownership Growth	High	0.25%		Medium	1.50%														
Years	5																		
AREA		2015 RESIDENTIAL				2015 BASE YEAR EMPLOYMENT					2010 Residential				2010 BASE YEAR EMPLOYMENT				
Description	Model Zone	Households			+ 10% Low	FORMAL WORKERS					Households			+ 10% Low	RS				
		High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving	High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving
	Gen Rate	**1.519**			**0.539**	**0.200**	**0.600**	**0.200**	**0.600**	**0.200**									
2005 Data		**666217**	**1009825**	**1854567**	**1195282**	**543384**	**924951**	**680447**	**59275**	**416750**									
Annual Growth		**1.96%**	**1.97%**	**0.77%**	**1.79%**	**3.51%**	**3.97%**	**3.24%**	**3.44%**	**1.87%**									
		1.34%				**3.35%**													
TOTALS		**733939**	**1113554**	**1926905**	**1306245**	**645577**	**1123941**	**798091**	**70199**	**457181**	**666217**	**1009825**	**1854567**	**1195282**	**543384**	**924951**	**680447**	**59275**	**416750**
Winterveld	1	52	735	3989	1134	242	50	0	0	603	52	718	4137	1132	242	50	0	0	603
Winterveld	2	470	4002	11772	5179	1026	63	20	0	1663	466	3907	12210	5128	1026	63	20	0	1663
Soshanguve	3	134	2744	8299	3574	93	13	0	0	803	132	2679	8608	3540	82	7	0	0	772
Soshanguve	4	214	7941	11553	9096	81	21	0	0	1447	212	7752	11982	8950	81	21	0	0	1447
Soshanguve	5	1797	11265	8256	12091	718	99	77	0	1414	1780	10997	8529	11850	718	35	77	0	1414
Mabopane	6	1167	7852	10150	8867	3444	405	850	0	1455	1156	7665	10229	8688	3076	405	770	0	1455
Mabopane Prison	7	303	4551	9620	5513	408	162	0	0	993	300	4443	9978	5441	298	52	0	0	701
Soshanguve	8	827	3540	3630	3903	83	11	0	0	756	819	3456	3753	3831	83	11	0	0	756
Soshanguve	9	44	2443	15780	4021	141	146	0	0	1516	44	2385	15739	3959	141	146	0	0	1516
Klip- Kruisfontein	10	105	4628	5406	5168	65	11	0	0	597	104	4517	5607	5078	65	11	0	0	597
Garankuwa Industrial	11	136	3803	11413	4944	1214	80	6168	0	1199	134	3712	11805	4893	884	80	6085	0	1199
Garankuwa	12	178	3715	4423	4158	529	410	0	0	1060	176	3627	4588	4086	183	202	0	0	572
Medunsa	13	12	248	300	278	3	3	0	0	5650	12	242	306	272	2	2	0	0	5648
Itsoseng	14	57	752	7683	1521	88	71	0	0	603	57	734	7821	1517	88	71	0	0	603
Klip- Kruisfontein	15	21	793	5968	1390	91	38	0	0	329	21	774	6178	1392	91	38	0	0	329
Noord van Rosslyn	16	71	925	9040	1829	715	229	0	0	1151	70	903	7963	1700	366	70	0	0	883
Rosslyn	17	0	6	75	13	375	0	35980	0	141	0	6	70	13	374	0	29856	0	140
Wes van Rosslyn	18	0	956	2687	1225	117	88	0	0	234	0	664	0	664	29	22	0	0	49
Suid van Rosslyn	19	35	2365	4695	2834	396	251	0	0	913	35	1717	3820	2099	192	108	0	0	477
Orchards	20	1737	1511	95	1521	179	76	263	0	243	1721	1234	98	1243	143	52	263	0	186
Clarina	21	41	349	83	357	369	7	0	0	81	40	322	86	330	368	6	0	0	79
Klerksoord	22	13	53	95	62	0	0	10579	519	20	13	51	94	61	0	0	7717	278	20
Soshanguve	23	33	1470	6399	2110	16	2	0	0	696	33	1435	6632	2098	16	2	0	0	696
Nuwe Eersterus/Stinkwater	24	0	5112	15339	6646	1117	382	0	0	1761	0	4990	15850	6575	1117	282	0	0	1761
Temba/Dilopye	25	332	3883	12721	5155	882	208	0	0	1718	329	3791	13194	5110	496	80	0	0	1389
Temba/Babelegi	26	116	5797	11486	6946	2218	889	12397	0	1414	115	5659	11864	6846	1862	780	12230	0	1414
Refilwe Block G	27	1	55	1024	157	86	19	0	0	159	1	53	443	98	10	2	0	0	34
Wonderboom Farms	28	63	262	2913	553	52	26	0	0	252	62	256	2958	552	52	26	0	0	252
South of Temba	29	0	1445	10630	2508	298	85	0	0	761	0	1411	10952	2506	159	85	0	0	761
Wonderboom Farms	30	14	52	229	75	1	1	0	0	20	14	51	202	71	0	0	0	0	13
Wonderboom Farms	31	6	25	124	37	1	1	0	0	22	6	24	93	33	0	0	0	0	14

alanr:
Input % Low to be included

alanr:
Input % Low to be included

TOLL STUDY:		Difference									2015								
Car Ownership Growth	High											Factor	86.9%						
Years	5																		
AREA		2010-2005 RESIDENTIAL				2010-2005 BASE YEAR EMPLOYMENT					2011 RESIDENTIAL				2011 BASE YEAR EMPLOYMENT				
Description	Model Zone	Households			+ 10% Low	RKERS					Households			+ 10% Low	FORMAL WORKERS				
		High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving	High	Medium	Low	Medium Generators	Retail	Office	Industrial	Commercial	Local Serving
	Gen Rate																		
2005 Data		**666217**	**1009825**	**1854567**	**1195282**	**543384**	**924951**	**680447**	**59275**	**416750**	**666217**	**1009825**	**1854567**	**1195282**	**543384**	**924951**	**680447**	**59275**	**416750**
Annual Growth		**10.17%**	**10.27%**	**3.90%**	**9.28%**	**18.81%**	**21.51%**	**17.29%**	**18.43%**	**9.70%**	**8.83%**	**8.93%**	**3.39%**	**8.07%**	**16.34%**	**18.70%**	**15.02%**	**16.01%**	**8.43%**
		6.91%				**17.91%**					**0.98%**				**2.44%**				
TOTALS		**67722**	**103729**	**72338**	**110963**	**102193**	**198991**	**117645**	**10924**	**40431**	**725067**	**1099966**	**1917429**	**1291709**	**632190**	**1097874**	**782680**	**68768**	**451884**
Winterveld	1	0	18	-148	3	0	0	0	0	0	52	733	4008	1134	242	50	0	0	603
Winterveld	2	4	95	-438	51	0	0	0	0	0	469	3989	11829	5172	1026	63	20	0	1663
Soshanguve	3	1	65	-309	34	11	6	0	0	31	133	2736	8340	3570	91	13	0	0	799
Soshanguve	4	2	189	-430	146	0	0	0	0	0	214	7916	11609	9077	81	21	0	0	1447
Soshanguve	5	17	268	-273	241	0	64	0	0	0	1795	11230	8292	12059	718	90	77	0	1414
Mabopane	6	11	187	-79	179	368	0	80	0	0	1166	7827	10160	8843	3395	405	840	0	1455
Mabopane Prison	7	3	108	-358	73	111	110	0	0	292	303	4537	9667	5504	394	147	0	0	954
Soshanguve	8	8	84	-123	72	0	0	0	0	0	826	3529	3646	3894	83	11	0	0	756
Soshanguve	9	0	58	41	62	0	0	0	0	0	44	2435	15775	4013	141	146	0	0	1516
Klip- Kruisfontein	10	1	110	-201	90	0	0	0	0	0	105	4613	5433	5156	65	11	0	0	597
Garankuwa Industrial	11	1	90	-392	51	331	0	83	0	0	136	3791	11464	4937	1171	80	6158	0	1199
Garankuwa	12	2	88	-165	72	346	208	0	0	488	178	3704	4445	4148	483	383	0	0	996
Medunsa	13	0	6	-6	5	1	1	0	0	2	12	247	301	277	3	2	0	0	5650
Itsoseng	14	1	18	-137	4	0	0	0	0	0	57	750	7701	1520	88	71	0	0	603
Klip- Kruisfontein	15	0	19	-210	-2	0	0	0	0	0	21	790	5995	1390	91	38	0	0	329
Noord van Rosslyn	16	1	22	1076	130	349	158	0	0	268	71	923	8899	1812	670	208	0	0	1116
Rosslyn	17	0	0	5	1	0	0	6124	0	1	0	6	74	13	375	0	35178	0	141
Wes van Rosslyn	18	0	292	2687	560	88	66	0	0	185	0	918	2335	1151	105	79	0	0	210
Suid van Rosslyn	19	0	648	874	735	204	143	0	0	436	35	2280	4580	2738	369	232	0	0	856
Orchards	20	16	278	-4	277	36	24	0	0	57	1735	1475	95	1485	174	73	263	0	236
Clarina	21	0	27	-3	27	1	1	0	0	1	41	345	83	353	369	7	0	0	81
Klerksoord	22	0	1	1	1	0	0	2862	240	0	13	52	95	62	0	0	10204	487	20
Soshanguve	23	0	35	-234	12	0	0	0	0	0	33	1465	6429	2108	16	2	0	0	696
Nuwe Eersterus/Stinkwater	24	0	122	-511	71	0	100	0	0	0	0	5096	15406	6637	1117	369	0	0	1761
Temba/Dilopye	25	3	92	-473	45	386	127	0	0	329	332	3871	12783	5149	831	191	0	0	1675
Temba/Babelegi	26	1	138	-377	100	356	110	167	0	0	116	5779	11536	6933	2172	875	12375	0	1414
Refilwe Block G	27	0	1	581	59	76	17	0	0	125	1	54	948	149	76	17	0	0	142
Wonderboom Farms	28	1	6	-44	2	0	0	0	0	0	63	261	2919	553	52	26	0	0	252
South of Temba	29	0	34	-322	2	139	0	0	0	0	0	1441	10672	2508	280	85	0	0	761
Wonderboom Farms	30	0	1	27	4	1	1	0	0	7	14	52	225	74	1	1	0	0	19
Wonderboom Farms	31	0	1	31	4	1	1	0	0	8	6	24	120	36	1	1	0	0	21

alanr:
Input % Low to be included

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14 APPENDICES: CHAPTER 5

Appendix 5.1: Extract from the Database containing Observed Traffic Flows for the Base Year (2018)

* A	B	C	FLOWS PER USER CLASS					Spd						
* Start Hour	7.00		1	2	3	TOTAL	*	4	CTO	LG				
2713	9873		1211	65	11	1288	*	0	13	1	Paul Kruger Ext	North	To R566 (K8)	4%
9873	2713		1096	60	17	1172	*	0	13	2	Paul Kruger Ext	South	To Wonderboompoort	5%
2443	11354		280	17	8	305	*	0	33	1	Doornrandjies	North	To Hartbeespoortdam	5%
11354	2443		381	9	2	392	*	0	33	2	Doornrandjies	South	To Diepsloot	5%
10376	10375		1061	50	10	1121	*	0	41	1	Poortview AH(BL)	East	To Ruimsig	6%
10375	10376		1065	103	24	1192	*	0	41	2	Poortview AH(BL)	West	To Tarlton	2%
6493	6490		247	28	8	283	*	0	45	1	Tarlton	East	To Krugersdorp	5%
6490	6493		192	22	7	222	*	0	45	2	Tarlton	West	To Magaliesburg	10%
9400	3118		1403	37	8	1448	*	0	57	1	Fourways Gardens	North	To Broadacres AH	18%
3118	9400		1223	39	5	1267	*	0	57	2	Fourways Gardens	South	To Fourways	6%
5309	3532		367	18	20	405	*	0	70	1	Westonaria North	North	To Randfontein	3%
3532	5309		538	25	19	582	*	0	70	2	Westonaria North	South	To Vereeniging	3%
11908	3620		300	14	19	333	*	0	72	1	Westonaria South(BL)	North	To Randfontein	5%
3620	11908		317	16	16	350	*	0	72	2	Westonaria South(BL)	South	To Vereeniging	5%
4915	11858		1428	37	55	1520	*	0	86	1	Kliprivier WIM	North	To Alberton	5%
11858	4915		802	61	51	914	*	0	86	2	Kliprivier WIM	South	To Vereeniging	5%
5482	9642		164	10	16	190	*	0	95	1	Spaarwater AH	North	To Dalpark	3%
9642	5482		197	11	4	212	*	0	95	2	Spaarwater AH	South	To Heidelberg	8%
4116	9203		320	23	3	346	*	0	108	1	Modderfontein Rd(CM)	East	To Birchleigh	6%
9203	4116		1333	22	9	1364	*	0	108	2	Modderfontein Rd(CM)	West	To Modderfontein	5%
3985	11523		804	8	5	818	*	0	110	1	Alan Manor	North	To Jhb CBD	7%
11523	3985		544	6	2	552	*	0	110	2	Alan Manor	South	To Kibler Park	2%
6445	11299		128	9	13	150	*	0	123	1	Magaliesburg (RH)	East	To Magaliesburg	1%
11299	6445		134	15	16	165	*	0	123	2	Magaliesburg (RH)	West	To Rustenburg	1%
5594	12080		135	16	10	161	*	100	127	1	Bronkorstspruit (RM)	East	To Bronkhorstspruit	7%
12080	5594		155	9	6	170	*	103	127	2	Bronkorstspruit (RM)	West	To Bapsfontein	12%
2372	11632		366	19	12	397	*	0	131	1	Pyramid (BH)	North	To Bela Bela	12%
11632	2372		483	19	16	518	*	0	131	2	Pyramid (BH)	South	To Paramid	6%

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Appendix 5.2: An Extract of the First Set of GEH Values

Count No.	A Node	B Node	Capacity	Modelled	Count	GEH
346	20002	20004	1900	1258	1014	7.23
476	8803	20153	7400	4225	3098	18.63
233	3922	3923	1600	479	576	4.24
124	12585	12584	4000	1782	1519	6.47
465	21145	21148	1900	711	552	6.34
191	3172	20028	1200	1111	1093	0.55
273	20342	4132	2400	1117	1083	1.02
252	21163	11576	2400	994	1008	0.43
220	3653	20436	2400	773	803	1.05
481	5558	20161	1900	1214	841	11.63
319	4124	9208	1300	811	587	8.49
250	4256	9085	2800	681	647	1.31
249	9085	4256	2800	1002	1051	1.52
101	5470	5857	1600	109	121	1.16
510	21255	9572	1900	0	107	14.63
614	20292	20294	5460	2146	1658	11.19
223	3414	21287	2400	1654	1600	1.33
245	11573	11572	4000	1138	1031	3.25
449	4147	20341	1900	953	971	0.57
153	8655	8656	2800	1944	1736	4.86
391	9382	21101	7400	1690	993	19.02
139	2647	9821	2400	1908	1809	2.3
175	3225	8859	2000	389	287	5.53
3	2715	9876	1200	639	700	2.34
592	20590	20592	7400	1736	1068	17.84
180	3192	20059	2400	1014	1035	0.66
170	3058	3103	2400	1173	964	6.4
1	3019	3044	2400	1493	1431	1.62
181	3194	3192	2800	1547	1361	4.88
320	4127	4123	1600	411	477	3.14
288	4218	4185	1600	560	452	4.8
477	3013	20153	1900	1401	891	15.06
323	4169	9033	2000	861	800	2.11
212	3245	21293	2400	2107	2058	1.07
305	20191	4163	2040	1798	1865	1.57
423	20632	21127	1900	1190	1169	0.6
341	20860	19997	4000	1201	1844	16.48
66	21057	20039	4000	334	236	5.81
265	4169	4047	1400	476	406	3.33
371	20042	21056	6000	3122	2797	5.97

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Appendix 5.3: An Extract of the Final Set of GEH Values

Count No.	A Node	B Node	Capacity	Modelled	Count	GEH
346	20009	20011	7400	6498	6497	0.01
476	20164	20163	7400	3375	3377	0.03
233	3922	3923	1600	575	576	0.05
124	12585	12584	4000	1515	1519	0.09
465	3005	21020	1900	404	402	0.09
191	3172	20028	1200	1096	1093	0.1
273	20342	4132	2400	1079	1083	0.13
252	21163	11576	2400	1003	1008	0.15
220	3653	20436	2400	798	803	0.17
481	8935	20170	7400	4271	4283	0.18
319	4127	4123	1600	481	477	0.18
250	4256	9085	2800	641	647	0.23
249	9085	4256	2800	1043	1051	0.25
101	5470	5857	1600	124	121	0.25
510	21252	20569	1900	415	421	0.27
614	20114	20116	1900	169	172	0.27
223	3414	21287	2400	1611	1600	0.28
245	11573	11572	4000	1040	1031	0.28
449	20342	20339	1900	1179	1191	0.35
153	8655	8656	2800	1751	1736	0.36
391	20371	20370	7400	5410	5383	0.37
139	2647	9821	2400	1826	1809	0.39
175	3225	8859	2000	280	287	0.39
3	2715	9876	1200	711	700	0.4
592	20804	20517	1900	452	461	0.4
180	3192	20059	2400	1048	1035	0.41
170	3058	3103	2400	951	964	0.42
1	3019	3044	2400	1448	1431	0.44
181	3194	3192	2800	1345	1361	0.44
320	4123	4127	1600	624	613	0.45
288	4218	4185	1600	442	452	0.45
477	20160	20161	7400	3557	3530	0.46
323	9131	20209	4000	592	581	0.46
212	3245	21293	2400	2080	2058	0.48
305	9237	5615	2800	2059	2081	0.49
423	11244	20450	1900	376	386	0.5
341	20002	20004	1900	997	1014	0.53
66	21057	20039	4000	228	236	0.53
265	4169	4047	1400	395	406	0.54
371	3058	20047	1900	781	796	0.55

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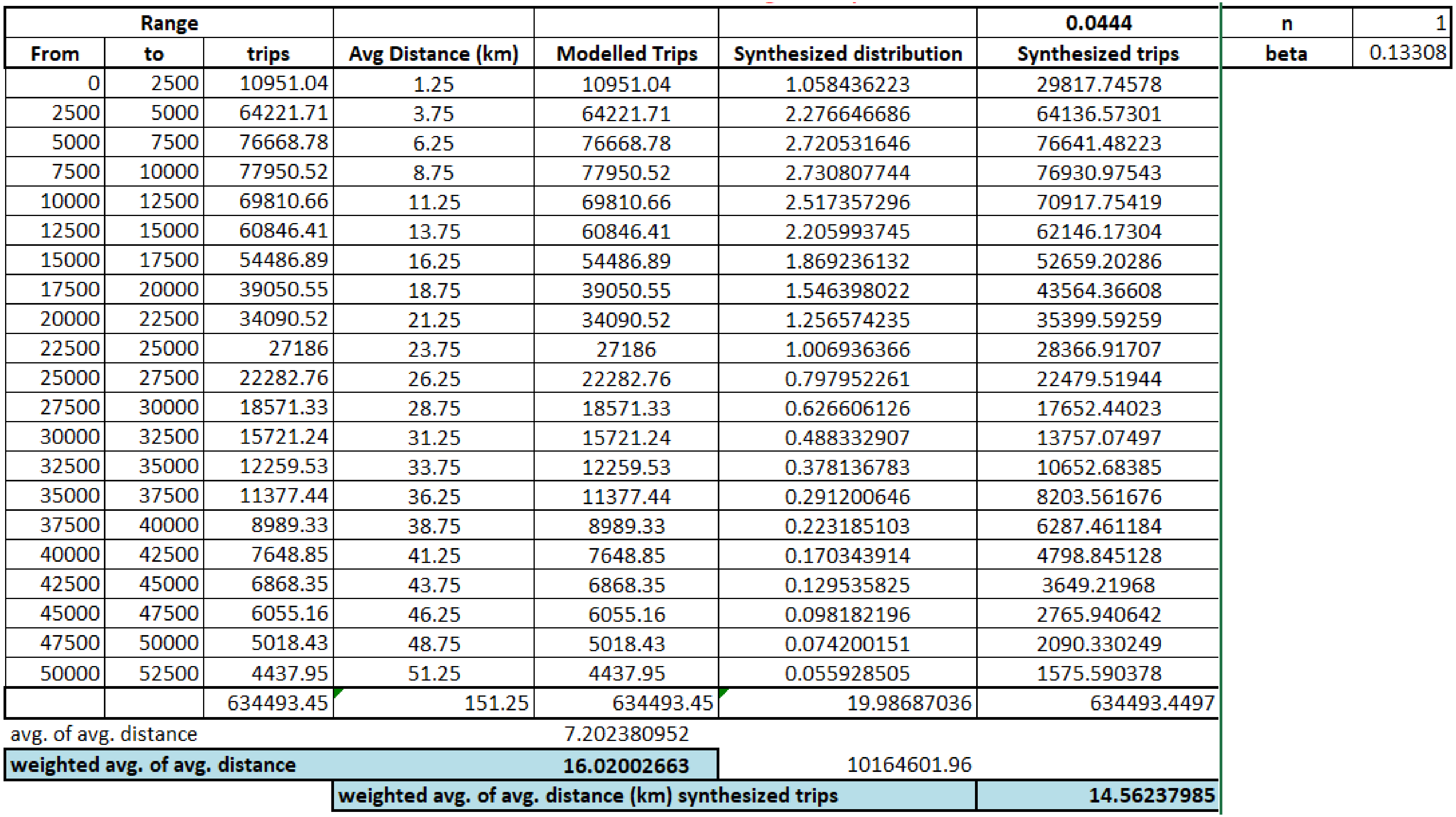
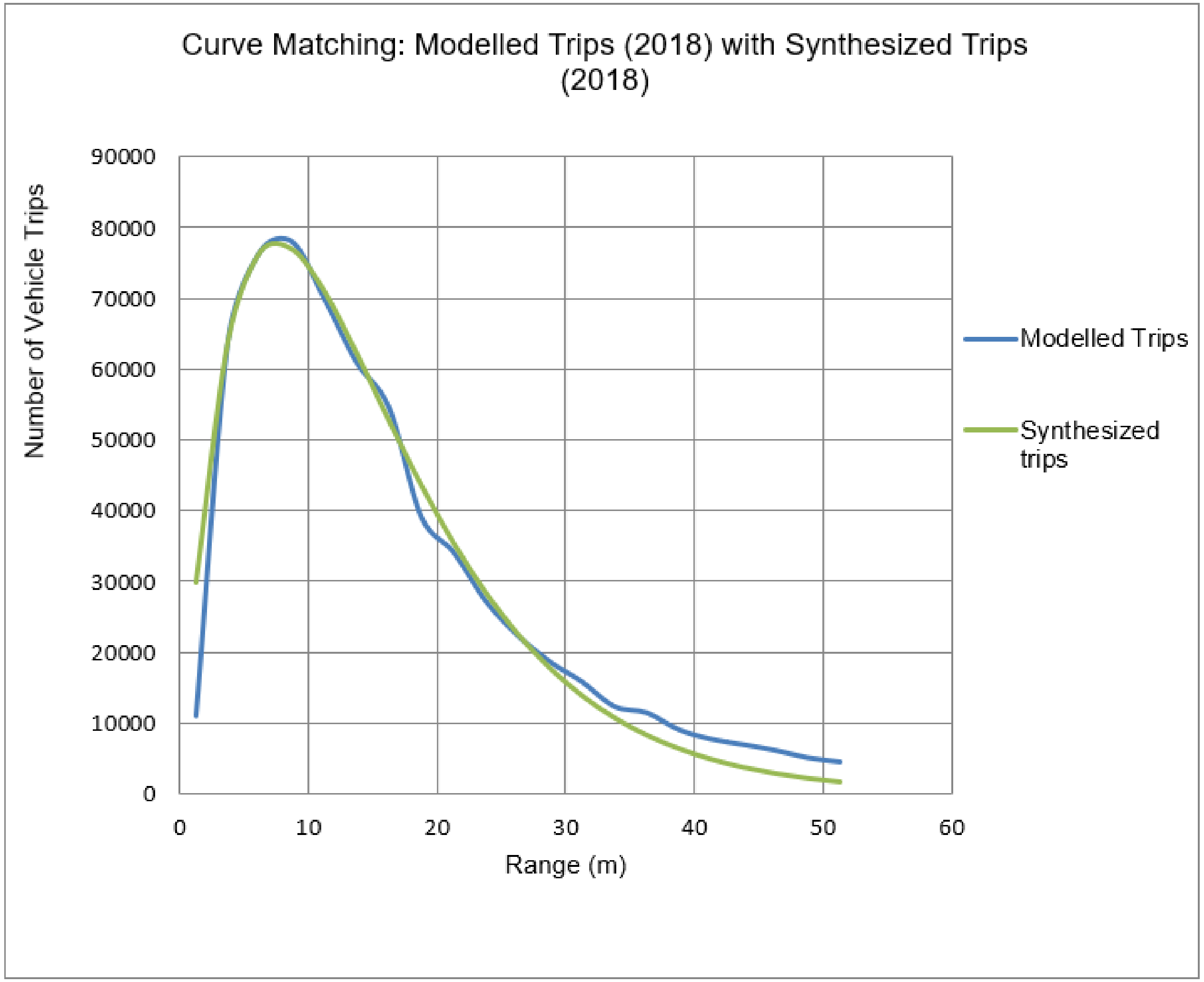
15 APPENDICES: CHAPTER 6

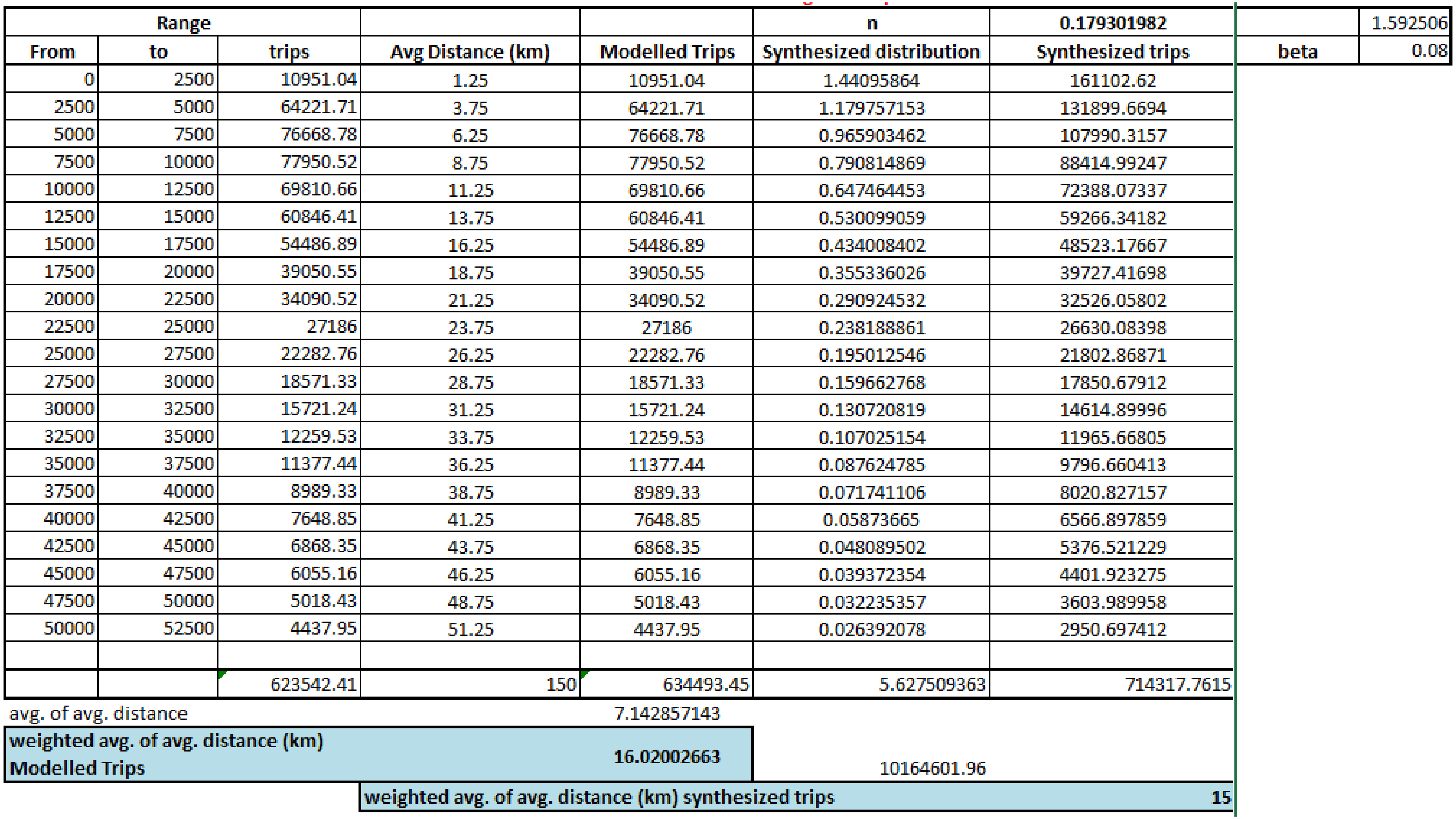
Appendix 6.1: Estimation of Distance-Deterrence Function for Existing Trips on Network for base year-Using Curve-Fitting Approach and The Combined Function



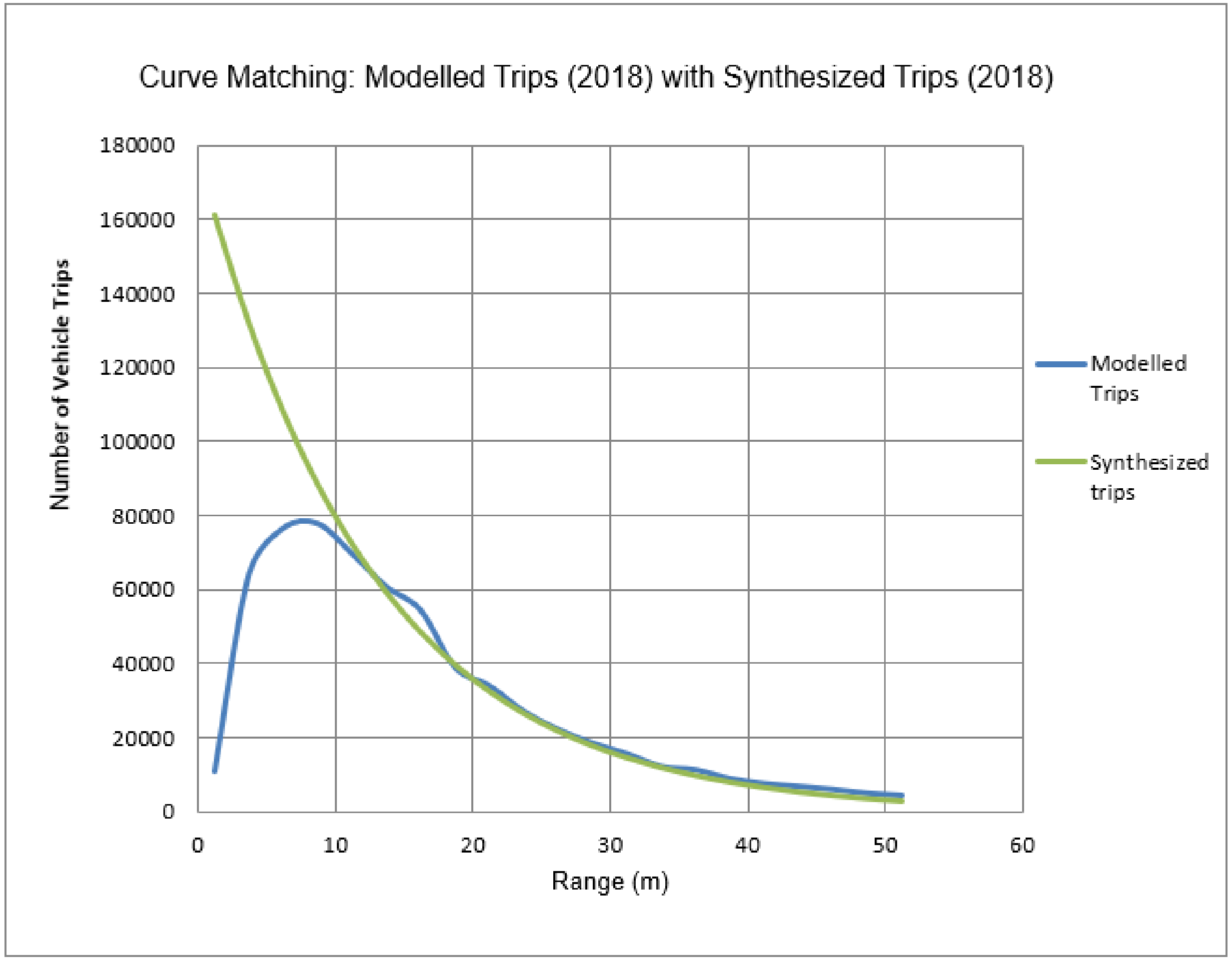
Range						0.0444	n	1
From	**to**	**trips**	**Avg Distance (km)**	**Modelled Trips**	**Synthesized distribution**	**Synthesized trips**	**beta**	0.13308
0	2500	10951.04	1.25	10951.04	1.058436223	29817.74578		
2500	5000	64221.71	3.75	64221.71	2.276646686	64136.57301		
5000	7500	76668.78	6.25	76668.78	2.720531646	76641.48223		
7500	10000	77950.52	8.75	77950.52	2.730807744	76930.97543		
10000	12500	69810.66	11.25	69810.66	2.517357296	70917.75419		
12500	15000	60846.41	13.75	60846.41	2.205993745	62146.17304		
15000	17500	54486.89	16.25	54486.89	1.869236132	52659.20286		
17500	20000	39050.55	18.75	39050.55	1.546398022	43564.36608		
20000	22500	34090.52	21.25	34090.52	1.256574235	35399.59259		
22500	25000	27186	23.75	27186	1.006936366	28366.91707		
25000	27500	22282.76	26.25	22282.76	0.797952261	22479.51944		
27500	30000	18571.33	28.75	18571.33	0.626606126	17652.44023		
30000	32500	15721.24	31.25	15721.24	0.488332907	13757.07497		
32500	35000	12259.53	33.75	12259.53	0.378136783	10652.68385		
35000	37500	11377.44	36.25	11377.44	0.291200646	8203.561676		
37500	40000	8989.33	38.75	8989.33	0.223185103	6287.461184		
40000	42500	7648.85	41.25	7648.85	0.170343914	4798.845128		
42500	45000	6868.35	43.75	6868.35	0.129535825	3649.21968		
45000	47500	6055.16	46.25	6055.16	0.098182196	2765.940642		
47500	50000	5018.43	48.75	5018.43	0.074200151	2090.330249		
50000	52500	4437.95	51.25	4437.95	0.055928505	1575.590378		
		634493.45	151.25	634493.45	19.98687036	634493.4497		
avg. of avg. distance				7.202380952				
weighted avg. of avg. distance				**16.02002663**	10164601.96			
			weighted avg. of avg. distance (km) synthesized trips			**14.56237985**		


Curve Matching: Modelled Trips (2018) with Synthesized Trips (2018)
Number of Vehicle Trips
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
10
20
30
40
50
60
Range (m)
Modelled Trips
Synthesized trips

Appendix 6.2: Estimation of Distance-Deterrence Function for Existing Trips on Network for base year-Using Curve-Fitting Approach and The Exponential Function



Range					n	0.179301982		1.592506
From	to	trips	Avg Distance (km)	Modelled Trips	Synthesized distribution	Synthesized trips	beta	0.08
0	2500	10951.04	1.25	10951.04	1.44095864	161102.62		
2500	5000	64221.71	3.75	64221.71	1.179757153	131899.6694		
5000	7500	76668.78	6.25	76668.78	0.965903462	107990.3157		
7500	10000	77950.52	8.75	77950.52	0.790814869	88414.99247		
10000	12500	69810.66	11.25	69810.66	0.647464453	72388.07337		
12500	15000	60846.41	13.75	60846.41	0.530099059	59266.34182		
15000	17500	54486.89	16.25	54486.89	0.434008402	48523.17667		
17500	20000	39050.55	18.75	39050.55	0.355336026	39727.41698		
20000	22500	34090.52	21.25	34090.52	0.290924532	32526.05802		
22500	25000	27186	23.75	27186	0.238188861	26630.08398		
25000	27500	22282.76	26.25	22282.76	0.195012546	21802.86871		
27500	30000	18571.33	28.75	18571.33	0.159662768	17850.67912		
30000	32500	15721.24	31.25	15721.24	0.130720819	14614.89996		
32500	35000	12259.53	33.75	12259.53	0.107025154	11965.66805		
35000	37500	11377.44	36.25	11377.44	0.087624785	9796.660413		
37500	40000	8989.33	38.75	8989.33	0.071741106	8020.827157		
40000	42500	7648.85	41.25	7648.85	0.05873665	6566.897859		
42500	45000	6868.35	43.75	6868.35	0.048089502	5376.521229		
45000	47500	6055.16	46.25	6055.16	0.039372354	4401.923275		
47500	50000	5018.43	48.75	5018.43	0.032235357	3603.989958		
50000	52500	4437.95	51.25	4437.95	0.026392078	2950.697412		
		623542.41	150	634493.45	5.627509363	714317.7615		
avg. of avg. distance				7.142857143				
weighted avg. of avg. distance (km) **Modelled Trips**				**16.02002663**	10164601.96			
			weighted avg. of avg. distance (km) synthesized trips			**15**		


Curve Matching: Modelled Trips (2018) with Synthesized Trips (2018)
Number of Vehicle Trips
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
10
20
30
40
50
60
Range (m)
Modelled Trips
Synthesized trips

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16 APPENDICES: CHAPTER 7

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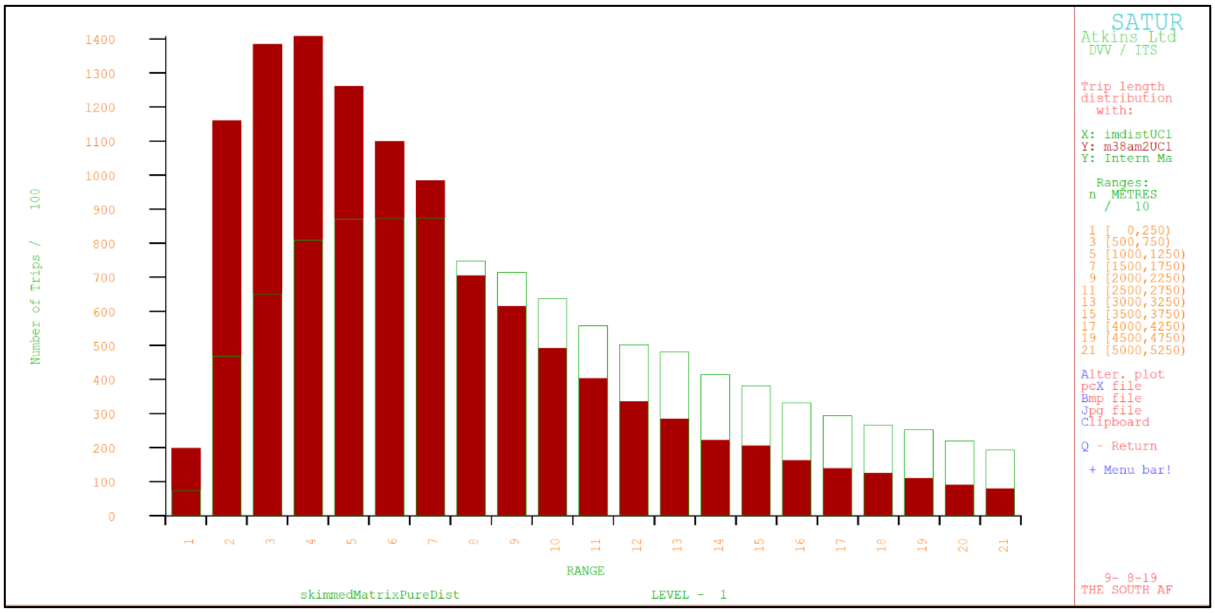
Appendix 7.1: Synthesized OD Trip Matrix using Beta = 0.055

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	7355.1	1.25	7355.1
2500	5000	115984.38	46737.8	3.75	46737.8
5000	7500	138463.7	65008.6	6.25	65008.6
7500	10000	140778.88	80850	8.75	80850
10000	12500	126078.25	87057.2	11.25	87057.2
12500	15000	109888.49	87258.2	13.75	87258.2
15000	17500	98403.21	87388	16.25	87388
17500	20000	70525.51	74738.8	18.75	74738.8
20000	22500	61567.38	71399.6	21.25	71399.6
22500	25000	49097.96	63625.5	23.75	63625.5
25000	27500	40242.53	55747.9	26.25	55747.9
27500	30000	33539.89	50153.4	28.75	50153.4
30000	32500	28392.57	48089.6	31.25	48089.6
32500	35000	22140.71	41449.6	33.75	41449.6
35000	37500	20547.68	38148.4	36.25	38148.4
37500	40000	16234.75	33164.1	38.75	33164.1
40000	42500	13813.85	29386.3	41.25	29386.3
42500	45000	12404.24	26601.3	43.75	26601.3
45000	47500	10935.59	25169.2	46.25	25169.2
47500	50000	9063.27	21879.9	48.75	21879.9
50000	52500	8014.97	19189.8	51.25	19189.8
		1145895.39			1060398.3

Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	23392344.88	**avg.trip length**	23	km



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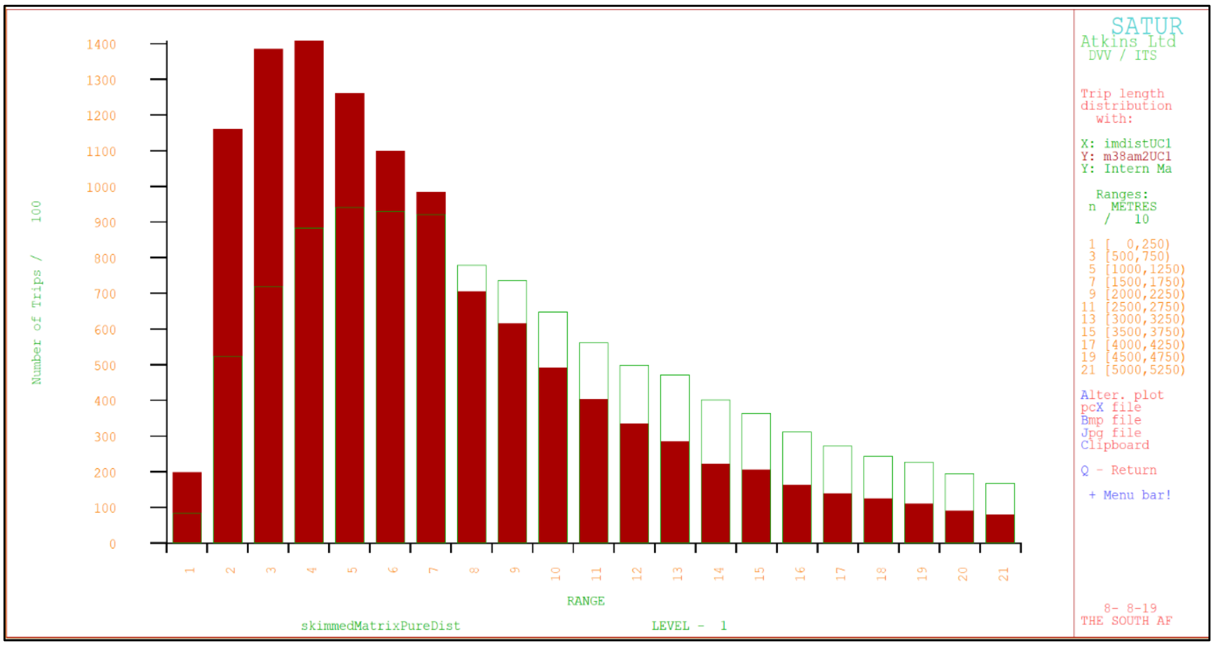
Appendix 7.2: Synthesized OD Trip Matrix using Beta = 0.0612

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	8292.2	1.25	8292.2
2500	5000	115984.38	52330.4	3.75	52330.4
5000	7500	138463.7	71946.1	6.25	71946.1
7500	10000	140778.88	88353.5	8.75	88353.5
10000	12500	126078.25	94120.9	11.25	94120.9
12500	15000	109888.49	92944.9	13.75	92944.9
15000	17500	98403.21	92123.1	16.25	92123.1
17500	20000	70525.51	77874.4	18.75	77874.4
20000	22500	61567.38	73625.6	21.25	73625.6
22500	25000	49097.96	64717.3	23.75	64717.3
25000	27500	40242.53	56065.9	26.25	56065.9
27500	30000	33539.89	49820.4	28.75	49820.4
30000	32500	28392.57	47032.5	31.25	47032.5
32500	35000	22140.71	40063.7	33.75	40063.7
35000	37500	20547.68	36398.3	36.25	36398.3
37500	40000	16234.75	31162.5	38.75	31162.5
40000	42500	13813.85	27238.9	41.25	27238.9
42500	45000	12404.24	24297.7	43.75	24297.7
45000	47500	10935.59	22671.7	46.25	22671.7
47500	50000	9063.27	19373.2	48.75	19373.2
50000	52500	8014.97	16756	51.25	16756
		1145895.39			1087209.2

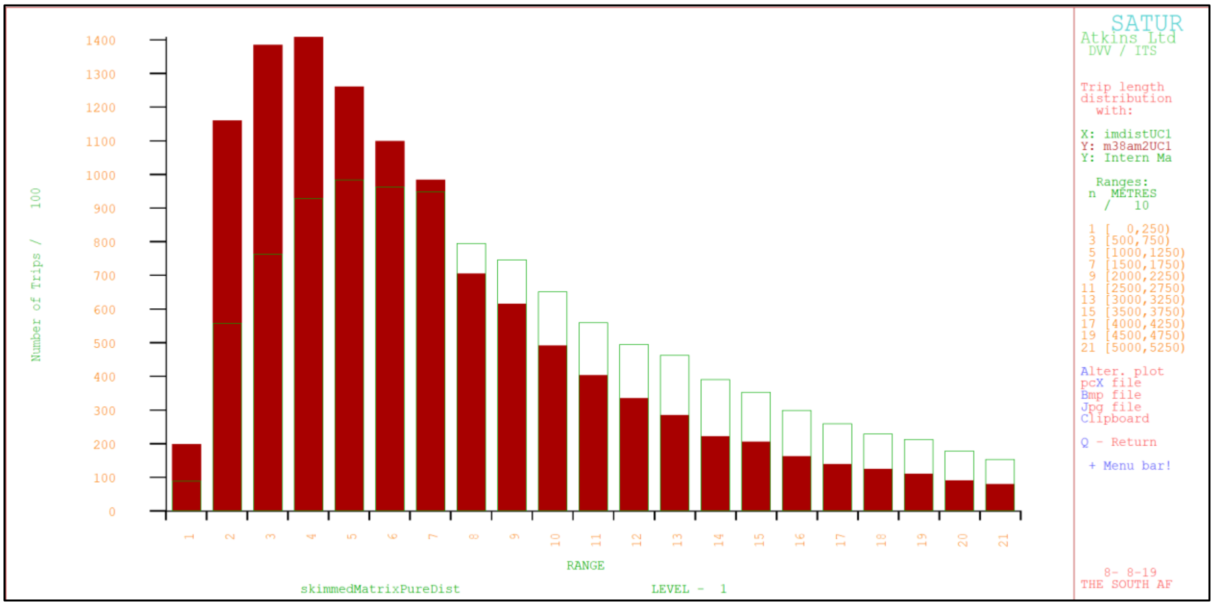
Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	23116289	**avg.trip length**	22	km



Appendix 7.3: Synthesized OD Trip Matrix using Beta = 0.0650

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	8885.4	1.25	8885.4
2500	5000	115984.38	55829.1	3.75	55829.1
5000	7500	138463.7	76221.5	6.25	76221.5
7500	10000	140778.88	92859.1	8.75	92859.1
10000	12500	126078.25	98274.8	11.25	98274.8
12500	15000	109888.49	96183.5	13.75	96183.5
15000	17500	98403.21	94720.4	16.25	94720.4
17500	20000	70525.51	79497.4	18.75	79497.4
20000	22500	61567.38	74669.6	21.25	74669.6
22500	25000	49097.96	65100.2	23.75	65100.2
25000	27500	40242.53	56006	26.25	56006
27500	30000	33539.89	49390.8	28.75	49390.8
30000	32500	28392.57	46184.5	31.25	46184.5
32500	35000	22140.71	39053.3	33.75	39053.3
35000	37500	20547.68	35200	36.25	35200
37500	40000	16234.75	29852.2	38.75	29852.2
40000	42500	13813.85	25877.3	41.25	25877.3
42500	45000	12404.24	22876.3	43.75	22876.3
45000	47500	10935.59	21160.6	46.25	21160.6
47500	50000	9063.27	17890	48.75	17890
50000	52500	8014.97	15342.1	51.25	15342.1
		1145895.39			1101074.1

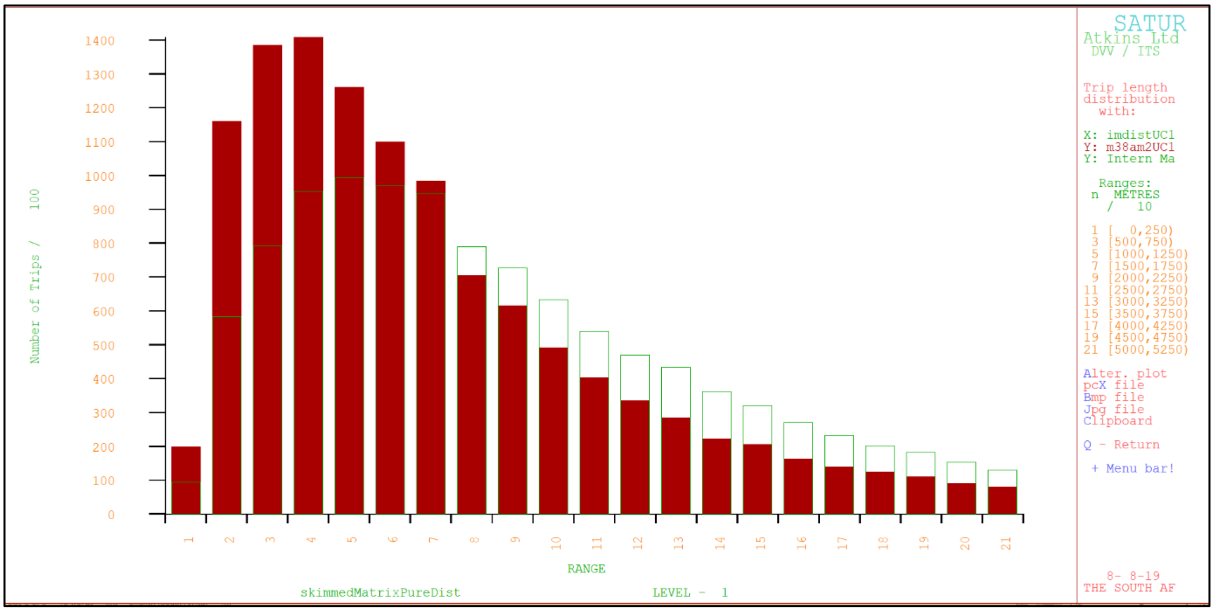
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	22889728.38	avg.trip length	21	km



Appendix 7.4: Synthesized OD Trip Matrix using Beta = 0.0700

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	9392.9	1.25	9392.9
2500	5000	115984.38	58208.6	3.75	58208.6
5000	7500	138463.7	79078	6.25	79078
7500	10000	140778.88	95319.8	8.75	95319.8
10000	12500	126078.25	99315.8	11.25	99315.8
12500	15000	109888.49	96890.8	13.75	96890.8
15000	17500	98403.21	94522.7	16.25	94522.7
17500	20000	70525.51	78998.3	18.75	78998.3
20000	22500	61567.38	72700.2	21.25	72700.2
22500	25000	49097.96	63231.9	23.75	63231.9
25000	27500	40242.53	53869.4	26.25	53869.4
27500	30000	33539.89	46983.9	28.75	46983.9
30000	32500	28392.57	43352.9	31.25	43352.9
32500	35000	22140.71	36128.6	33.75	36128.6
35000	37500	20547.68	32107.7	36.25	32107.7
37500	40000	16234.75	26965	38.75	26965
40000	42500	13813.85	23166.8	41.25	23166.8
42500	45000	12404.24	20141.3	43.75	20141.3
45000	47500	10935.59	18224.4	46.25	18224.4
47500	50000	9063.27	15317.3	48.75	15317.3
50000	52500	8014.97	13014.5	51.25	13014.5
		1145895.39			1076930.8

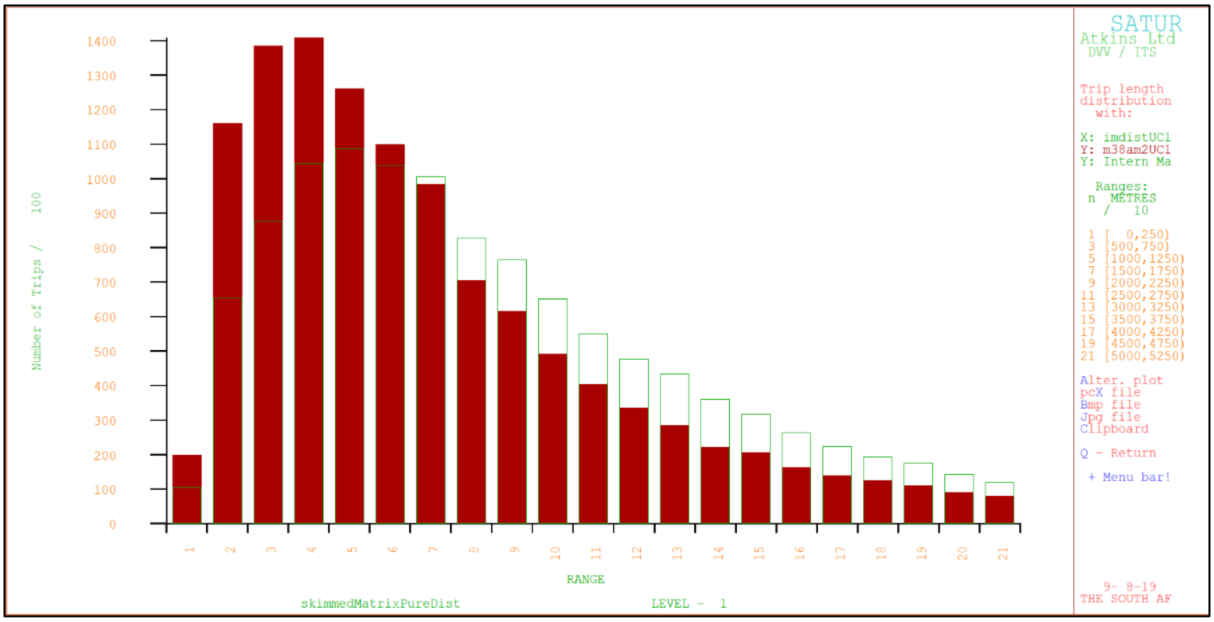
Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	21712886.75	**avg.trip length**	21	km



Appendix 7.5: Synthesized OD Trip Matrix using Beta = 0.0750

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	10512.7	1.25	10512.7
2500	5000	115984.38	65260	3.75	65260
5000	7500	138463.7	87508.3	6.25	87508.3
7500	10000	140778.88	104331.4	8.75	104331.4
10000	12500	126078.25	108539	11.25	108539
12500	15000	109888.49	103805.8	13.75	103805.8
15000	17500	98403.21	100469.8	16.25	100469.8
17500	20000	70525.51	82732.1	18.75	82732.1
20000	22500	61567.38	76333.2	21.25	76333.2
22500	25000	49097.96	65167	23.75	65167
25000	27500	40242.53	55037	26.25	55037
27500	30000	33539.89	47577.2	28.75	47577.2
30000	32500	28392.57	43385.1	31.25	43385.1
32500	35000	22140.71	35974	33.75	35974
35000	37500	20547.68	31750.9	36.25	31750.9
37500	40000	16234.75	26257.2	38.75	26257.2
40000	42500	13813.85	22272.9	41.25	22272.9
42500	45000	12404.24	19231.1	43.75	19231.1
45000	47500	10935.59	17377.6	46.25	17377.6
47500	50000	9063.27	14280.8	48.75	14280.8
50000	52500	8014.97	11975.9	51.25	11975.9
		1145895.39			1129779

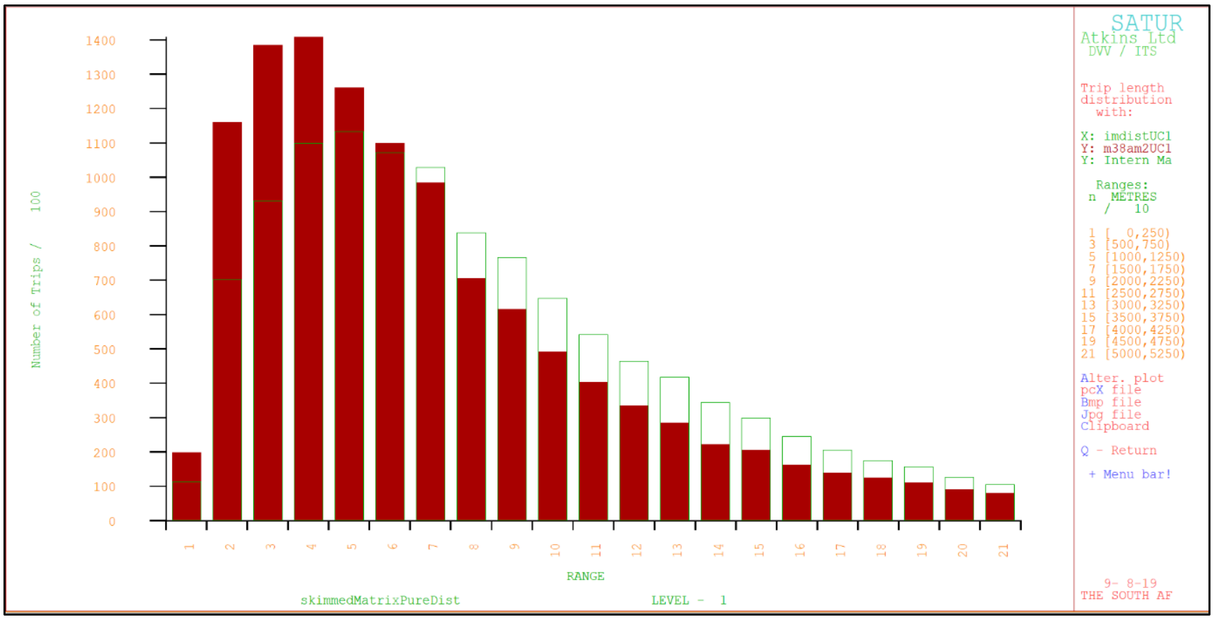
Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	22144438.75	**avg.trip length**	20	km



Appendix 7.6: Synthesized OD Trip Matrix using Beta = 0.0800

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	11361.6	1.25	11361.6
2500	5000	115984.38	70083.1	3.75	70083.1
5000	7500	138463.7	93150	6.25	93150
7500	10000	140778.88	109845.4	8.75	109845.4
10000	12500	126078.25	113300.4	11.25	113300.4
12500	15000	109888.49	107133.6	13.75	107133.6
15000	17500	98403.21	102772.5	16.25	102772.5
17500	20000	70525.51	83819.1	18.75	83819.1
20000	22500	61567.38	76625.6	21.25	76625.6
22500	25000	49097.96	64745.5	23.75	64745.5
25000	27500	40242.53	54174.7	26.25	54174.7
27500	30000	33539.89	46366.7	28.75	46366.7
30000	32500	28392.57	41754	31.25	41754
32500	35000	22140.71	34280.7	33.75	34280.7
35000	37500	20547.68	29939	36.25	29939
37500	40000	16234.75	24445.7	38.75	24445.7
40000	42500	13813.85	20516.3	41.25	20516.3
42500	45000	12404.24	17507.8	43.75	17507.8
45000	47500	10935.59	15635.2	46.25	15635.2
47500	50000	9063.27	12665.3	48.75	12665.3
50000	52500	8014.97	10504.6	51.25	10504.6
		1145895.39			1140626.8

Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	21716385.75	avg.trip length	20	km



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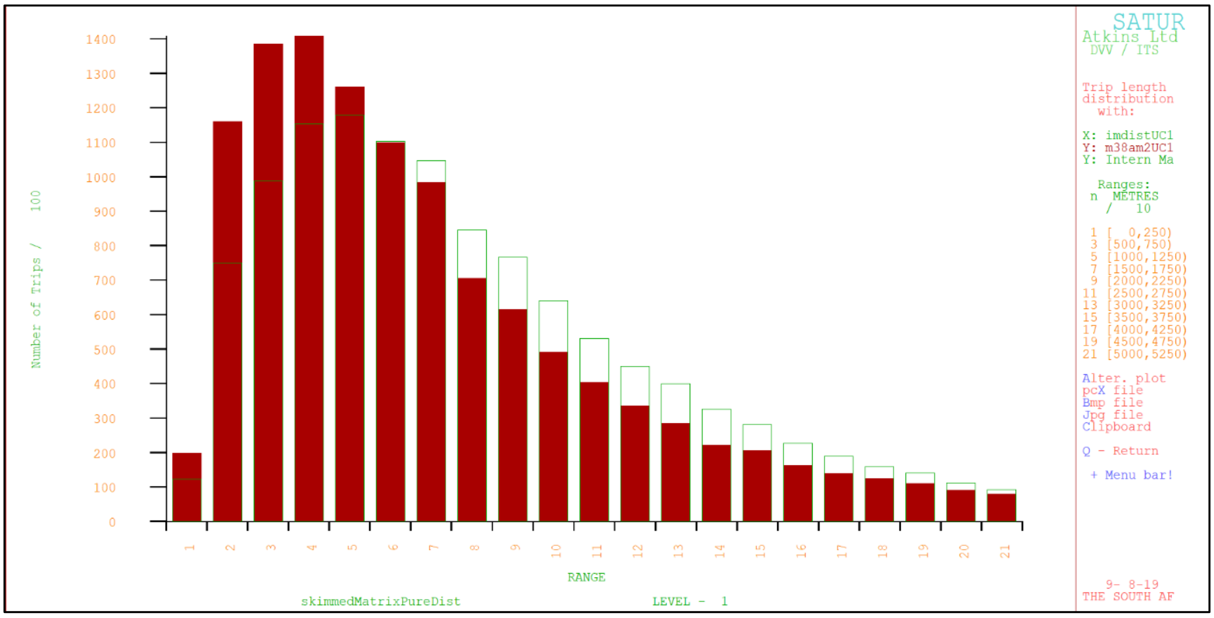
Appendix 7.7: Synthesized OD Trip Matrix using Beta = 0.0850

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	12233.3	1.25	12233.3
2500	5000	115984.38	74969	3.75	74969
5000	7500	138463.7	98777	6.25	98777
7500	10000	140778.88	115204.4	8.75	115204.4
10000	12500	126078.25	117817	11.25	117817
12500	15000	109888.49	110148.9	13.75	110148.9
15000	17500	98403.21	104715.7	16.25	104715.7
17500	20000	70525.51	84581.4	18.75	84581.4
20000	22500	61567.38	76599.8	21.25	76599.8
22500	25000	49097.96	64063.4	23.75	64063.4
25000	27500	40242.53	53103.7	26.25	53103.7
27500	30000	33539.89	45002.4	28.75	45002.4
30000	32500	28392.57	40018.3	31.25	40018.3
32500	35000	22140.71	32532.8	33.75	32532.8
35000	37500	20547.68	28113.3	36.25	28113.3
37500	40000	16234.75	22664	38.75	22664
40000	42500	13813.85	18821.9	41.25	18821.9
42500	45000	12404.24	15875.8	43.75	15875.8
45000	47500	10935.59	14010.7	46.25	14010.7
47500	50000	9063.27	11187	48.75	11187
50000	52500	8014.97	9175.7	51.25	9175.7
		1145895.39			1149615.5

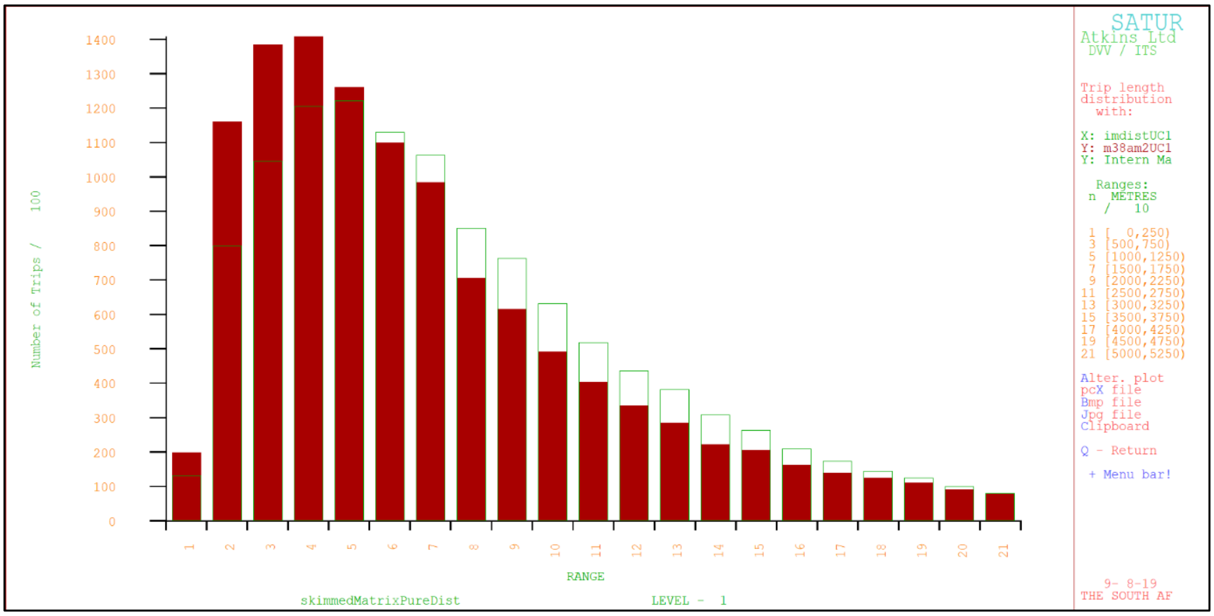
Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	21266859.13	**avg.trip length**	19	km



Appendix 7.8: Synthesized OD Trip Matrix using Beta = 0.0900

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	13127.3	1.25	13127.3
2500	5000	115984.38	79911.1	3.75	79911.1
5000	7500	138463.7	104378.9	6.25	104378.9
7500	10000	140778.88	120405	8.75	120405
10000	12500	126078.25	122089	11.25	122089
12500	15000	109888.49	112858.6	13.75	112858.6
15000	17500	98403.21	106314.1	16.25	106314.1
17500	20000	70525.51	85040.2	18.75	85040.2
20000	22500	61567.38	76285.6	21.25	76285.6
22500	25000	49097.96	63152.6	23.75	63152.6
25000	27500	40242.53	51857.2	26.25	51857.2
27500	30000	33539.89	43516.7	28.75	43516.7
30000	32500	28392.57	38212.3	31.25	38212.3
32500	35000	22140.71	30759.8	33.75	30759.8
35000	37500	20547.68	26301.6	36.25	26301.6
37500	40000	16234.75	20932.9	38.75	20932.9
40000	42500	13813.85	17205.1	41.25	17205.1
42500	45000	12404.24	14345.1	43.75	14345.1
45000	47500	10935.59	12511.2	46.25	12511.2
47500	50000	9063.27	9845.9	48.75	9845.9
50000	52500	8014.97	7986.8	51.25	7986.8
		1145895.39			1157037

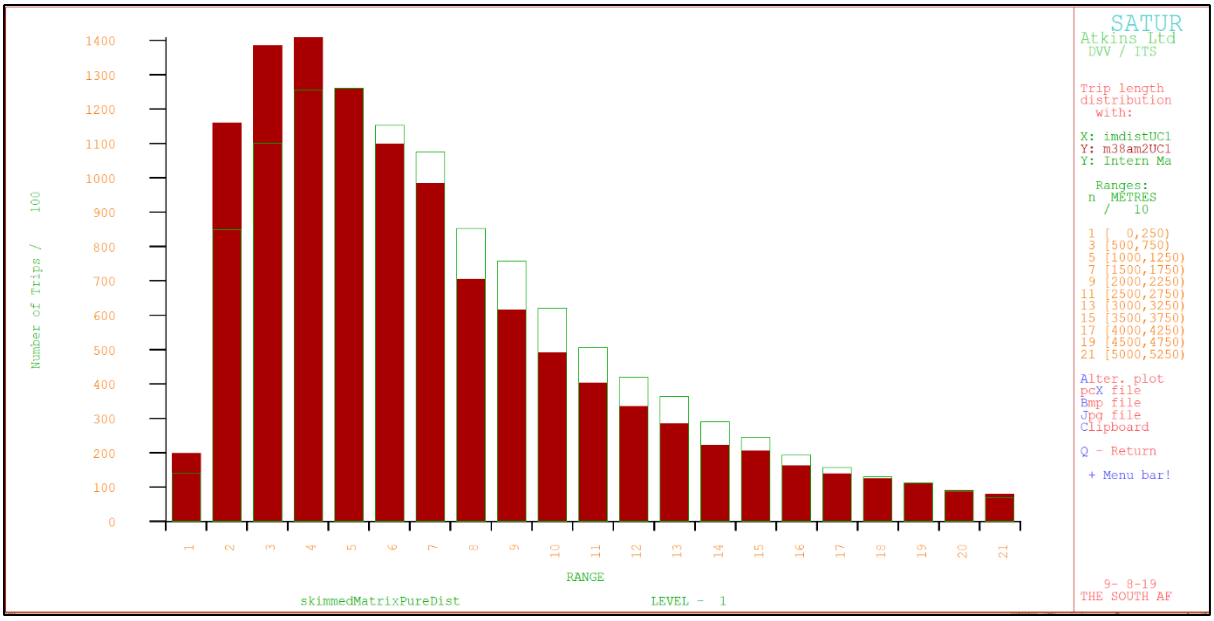
Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	20804825.5	**avg.trip length**	18	km



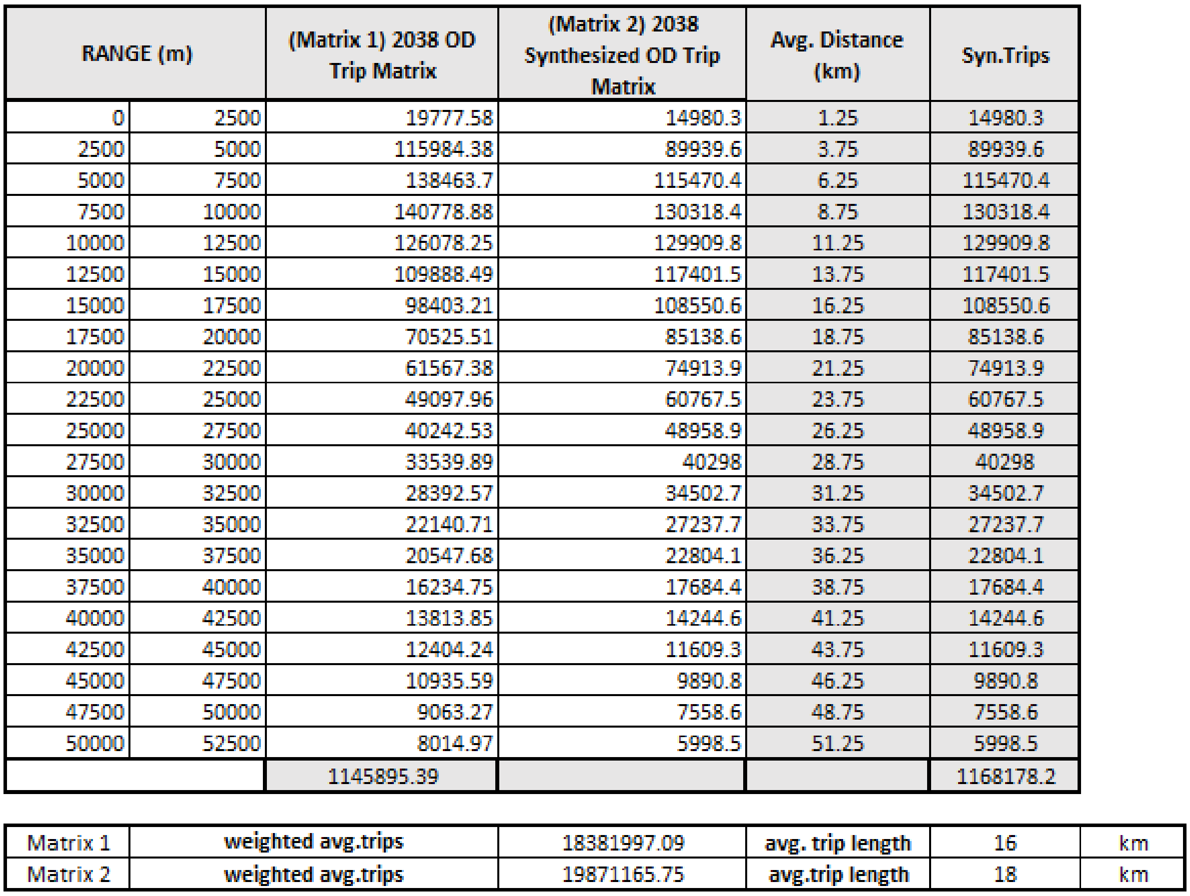
Appendix 7.9: Synthesized OD Trip Matrix using Beta = 0.0950

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	14043.2	1.25	14043.2
2500	5000	115984.38	84903.3	3.75	84903.3
5000	7500	138463.7	109946.5	6.25	109946.5
7500	10000	140778.88	125444	8.75	125444
10000	12500	126078.25	126118.8	11.25	126118.8
12500	15000	109888.49	115272.8	13.75	115272.8
15000	17500	98403.21	107586.2	16.25	107586.2
17500	20000	70525.51	85218.1	18.75	85218.1
20000	22500	61567.38	75713.6	21.25	75713.6
22500	25000	49097.96	62043.9	23.75	62043.9
25000	27500	40242.53	50466	26.25	50466
27500	30000	33539.89	41939.4	28.75	41939.4
30000	32500	28392.57	36365	31.25	36365
32500	35000	22140.71	28987.8	33.75	28987.8
35000	37500	20547.68	24525.9	36.25	24525.9
37500	40000	16234.75	19269.1	38.75	19269.1
40000	42500	13813.85	15677	41.25	15677
42500	45000	12404.24	12922.1	43.75	12922.1
45000	47500	10935.59	11138.5	46.25	11138.5
47500	50000	9063.27	8638.4	48.75	8638.4
50000	52500	8014.97	6930.7	51.25	6930.7
		1145895.39			1163150.3

Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	20337621.63	**avg.trip length**	18	km

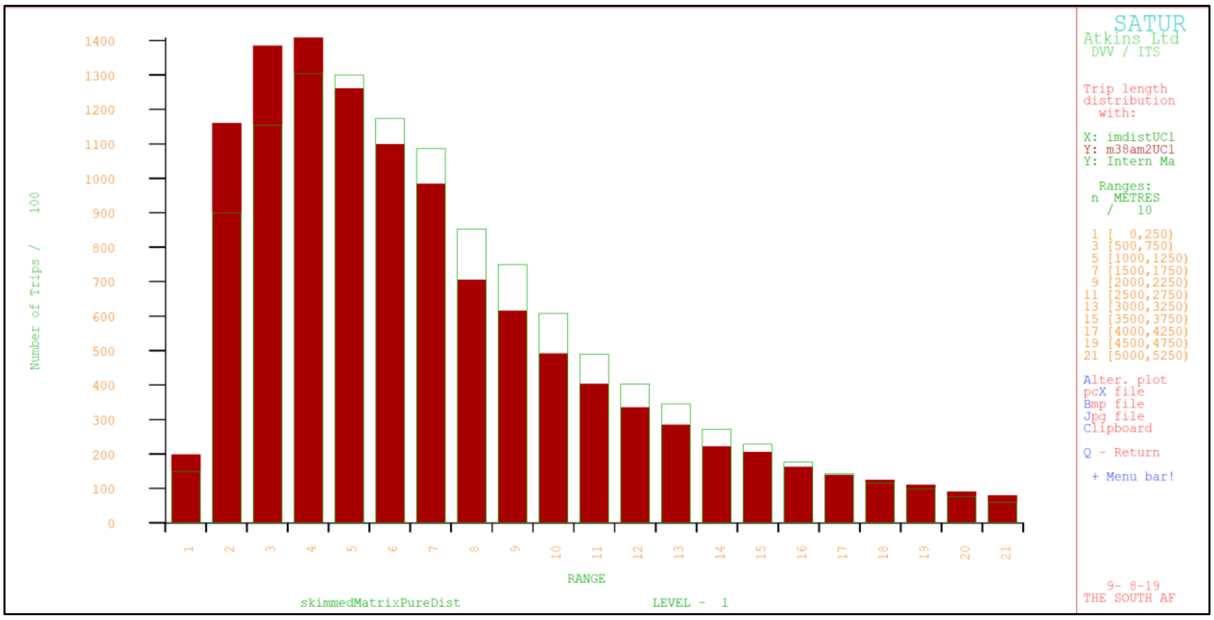


Appendix 7.10: Synthesized OD Trip Matrix using Beta = 0.1000



RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	14980.3	1.25	14980.3
2500	5000	115984.38	89939.6	3.75	89939.6
5000	7500	138463.7	115470.4	6.25	115470.4
7500	10000	140778.88	130318.4	8.75	130318.4
10000	12500	126078.25	129909.8	11.25	129909.8
12500	15000	109888.49	117401.5	13.75	117401.5
15000	17500	98403.21	108550.6	16.25	108550.6
17500	20000	70525.51	85138.6	18.75	85138.6
20000	22500	61567.38	74913.9	21.25	74913.9
22500	25000	49097.96	60767.5	23.75	60767.5
25000	27500	40242.53	48958.9	26.25	48958.9
27500	30000	33539.89	40298	28.75	40298
30000	32500	28392.57	34502.7	31.25	34502.7
32500	35000	22140.71	27237.7	33.75	27237.7
35000	37500	20547.68	22804.1	36.25	22804.1
37500	40000	16234.75	17684.4	38.75	17684.4
40000	42500	13813.85	14244.6	41.25	14244.6
42500	45000	12404.24	11609.3	43.75	11609.3
45000	47500	10935.59	9890.8	46.25	9890.8
47500	50000	9063.27	7558.6	48.75	7558.6
50000	52500	8014.97	5998.5	51.25	5998.5
		1145895.39			1168178.2

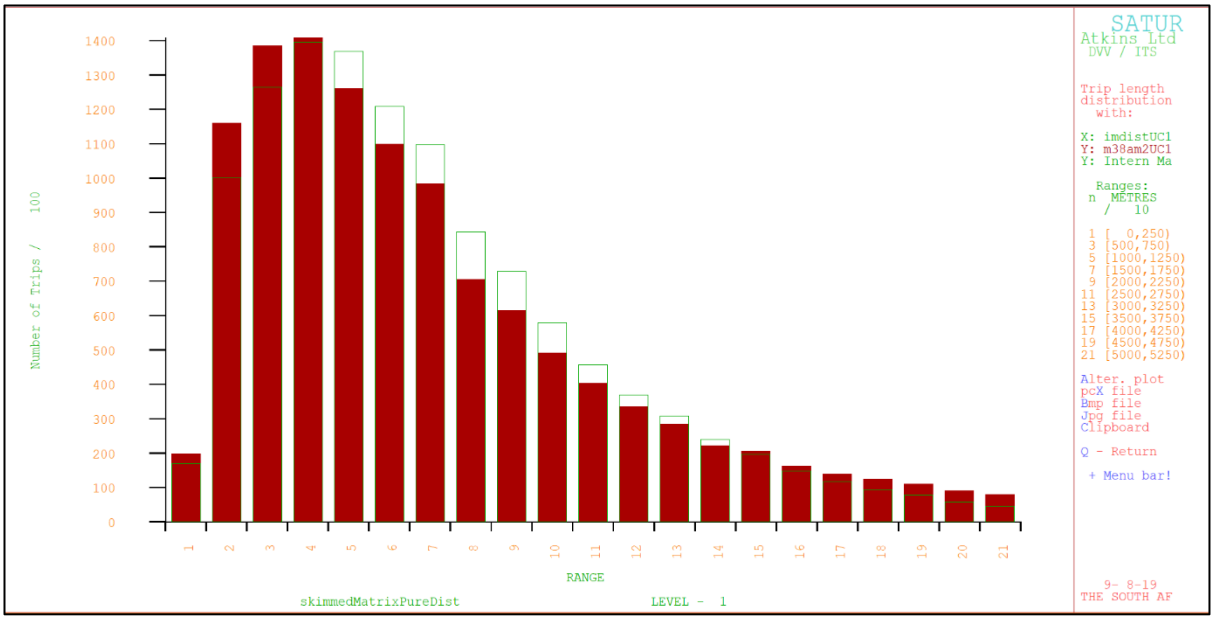
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	19871165.75	avg.trip length	18	km



Appendix 7.11: Synthesized OD Trip Matrix using Beta = 0.1100

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	16914.8	1.25	16914.8
2500	5000	115984.38	100119	3.75	100119
5000	7500	138463.7	126355.4	6.25	126355.4
7500	10000	140778.88	139567.8	8.75	139567.8
10000	12500	126078.25	136790.4	11.25	136790.4
12500	15000	109888.49	120848.6	13.75	120848.6
15000	17500	98403.21	109634	16.25	109634
17500	20000	70525.51	84299	18.75	84299
20000	22500	61567.38	72743.3	21.25	72743.3
22500	25000	49097.96	57821.3	23.75	57821.3
25000	27500	40242.53	45698.4	26.25	45698.4
27500	30000	33539.89	36916.1	28.75	36916.1
30000	32500	28392.57	30816.9	31.25	30816.9
32500	35000	22140.71	23869.1	33.75	23869.1
35000	37500	20547.68	19571.8	36.25	19571.8
37500	40000	16234.75	14781.9	38.75	14781.9
40000	42500	13813.85	11678.6	41.25	11678.6
42500	45000	12404.24	9310.6	43.75	9310.6
45000	47500	10935.59	7750.5	46.25	7750.5
47500	50000	9063.27	5749.2	48.75	5749.2
50000	52500	8014.97	4464.6	51.25	4464.6
		1145895.39			1175701.3

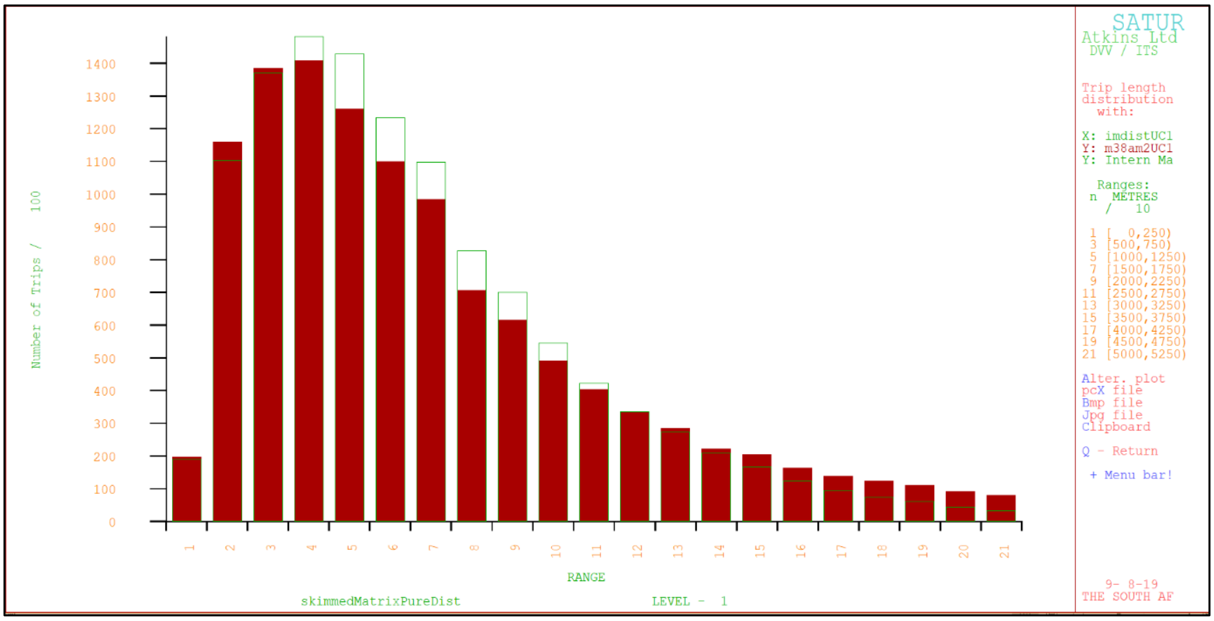
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	18957732.63	avg.trip length	17	km



Appendix 7.12: Synthesized OD Trip Matrix using Beta = 0.1200

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	18924	1.25	18924
2500	5000	115984.38	110402.8	3.75	110402.8
5000	7500	138463.7	136971.7	6.25	136971.7
7500	10000	140778.88	148143.7	8.75	148143.7
10000	12500	126078.25	142764.8	11.25	142764.8
12500	15000	109888.49	123293.2	13.75	123293.2
15000	17500	98403.21	109718.9	16.25	109718.9
17500	20000	70525.51	82696.2	18.75	82696.2
20000	22500	61567.38	69982.8	21.25	69982.8
22500	25000	49097.96	54513.2	23.75	54513.2
25000	27500	40242.53	42257.6	26.25	42257.6
27500	30000	33539.89	33528.5	28.75	33528.5
30000	32500	28392.57	27288.2	31.25	27288.2
32500	35000	22140.71	20751.1	33.75	20751.1
35000	37500	20547.68	16671	36.25	16671
37500	40000	16234.75	12254.8	38.75	12254.8
40000	42500	13813.85	9505.6	41.25	9505.6
42500	45000	12404.24	7421.3	43.75	7421.3
45000	47500	10935.59	6036	46.25	6036
47500	50000	9063.27	4344.4	48.75	4344.4
50000	52500	8014.97	3301.1	51.25	3301.1
		1145895.39			1180770.9

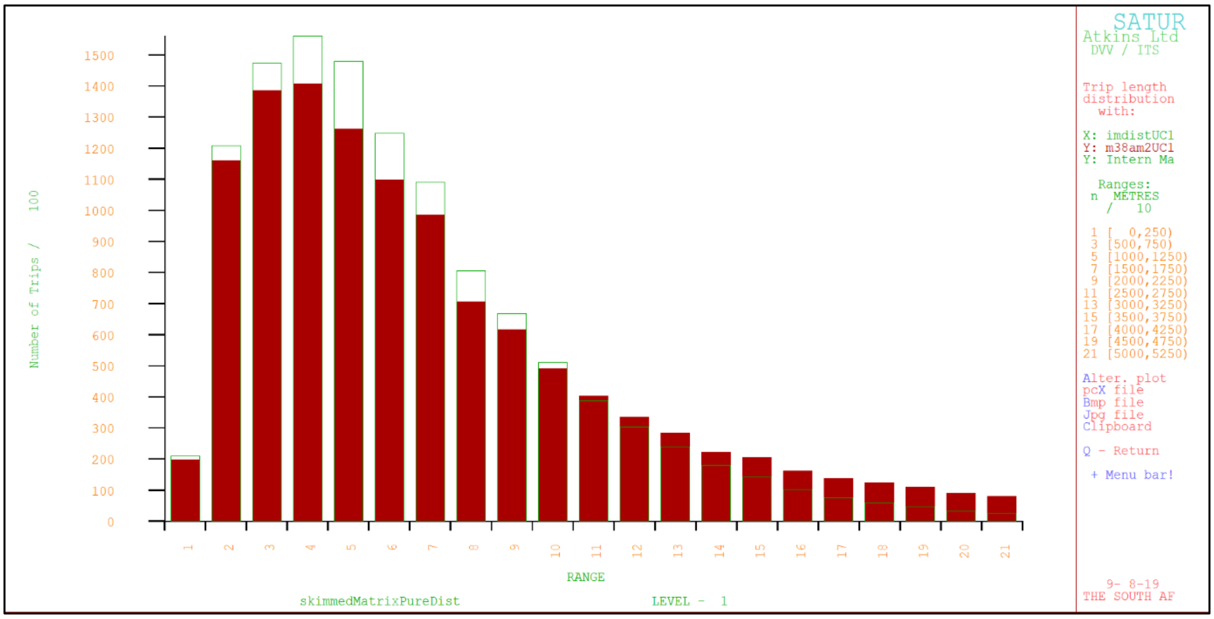
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	18089123.63	avg.trip length	16	km



Appendix 7.13: Synthesized OD Trip Matrix using Beta = 0.1300

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	21000.3	1.25	21000.3
2500	5000	115984.38	120746.2	3.75	120746.2
5000	7500	138463.7	147269.7	6.25	147269.7
7500	10000	140778.88	156044.6	8.75	156044.6
10000	12500	126078.25	147871.2	11.25	147871.2
12500	15000	109888.49	124833.2	13.75	124833.2
15000	17500	98403.21	108955.4	16.25	108955.4
17500	20000	70525.51	80493.3	18.75	80493.3
20000	22500	61567.38	66811.3	21.25	66811.3
22500	25000	49097.96	51008	23.75	51008
25000	27500	40242.53	38778.9	26.25	38778.9
27500	30000	33539.89	30247	28.75	30247
30000	32500	28392.57	24001.3	31.25	24001.3
32500	35000	22140.71	17933.9	33.75	17933.9
35000	37500	20547.68	14124.3	36.25	14124.3
37500	40000	16234.75	10097.1	38.75	10097.1
40000	42500	13813.85	7696.9	41.25	7696.9
42500	45000	12404.24	5894.1	43.75	5894.1
45000	47500	10935.59	4681.6	46.25	4681.6
47500	50000	9063.27	3268.5	48.75	3268.5
50000	52500	8014.97	2429.3	51.25	2429.3
		1145895.39			1184186.1

Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	17277691.38	avg.trip length	15	km



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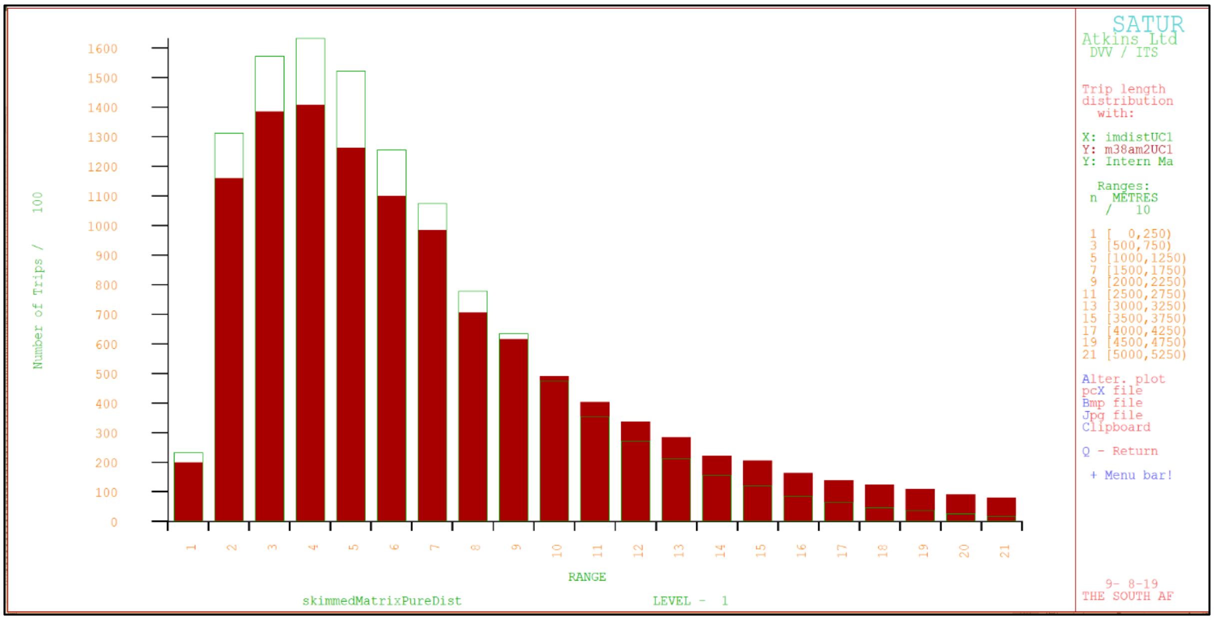
Appendix 7.14: Synthesized OD Trip Matrix using Beta = 0.1400

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	23135.9	1.25	23135.9
2500	5000	115984.38	131108.5	3.75	131108.5
5000	7500	138463.7	157208.8	6.25	157208.8
7500	10000	140778.88	163276.4	8.75	163276.4
10000	12500	126078.25	152155.5	11.25	152155.5
12500	15000	109888.49	125567.5	13.75	125567.5
15000	17500	98403.21	107485.1	16.25	107485.1
17500	20000	70525.51	77834.1	18.75	77834.1
20000	22500	61567.38	63379.3	21.25	63379.3
22500	25000	49097.96	47436.1	23.75	47436.1
25000	27500	40242.53	35368	26.25	35368
27500	30000	33539.89	27145.8	28.75	27145.8
30000	32500	28392.57	21003	31.25	21003
32500	35000	22140.71	15434.7	33.75	15434.7
35000	37500	20547.68	11925.8	36.25	11925.8
37500	40000	16234.75	8282	38.75	8282
40000	42500	13813.85	6210.9	41.25	6210.9
42500	45000	12404.24	4675.1	43.75	4675.1
45000	47500	10935.59	3622.2	46.25	3622.2
47500	50000	9063.27	2452.6	48.75	2452.6
50000	52500	8014.97	1781.8	51.25	1781.8
		1145895.39			1186489.1

Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	16528040.38	avg.trip length	14	km



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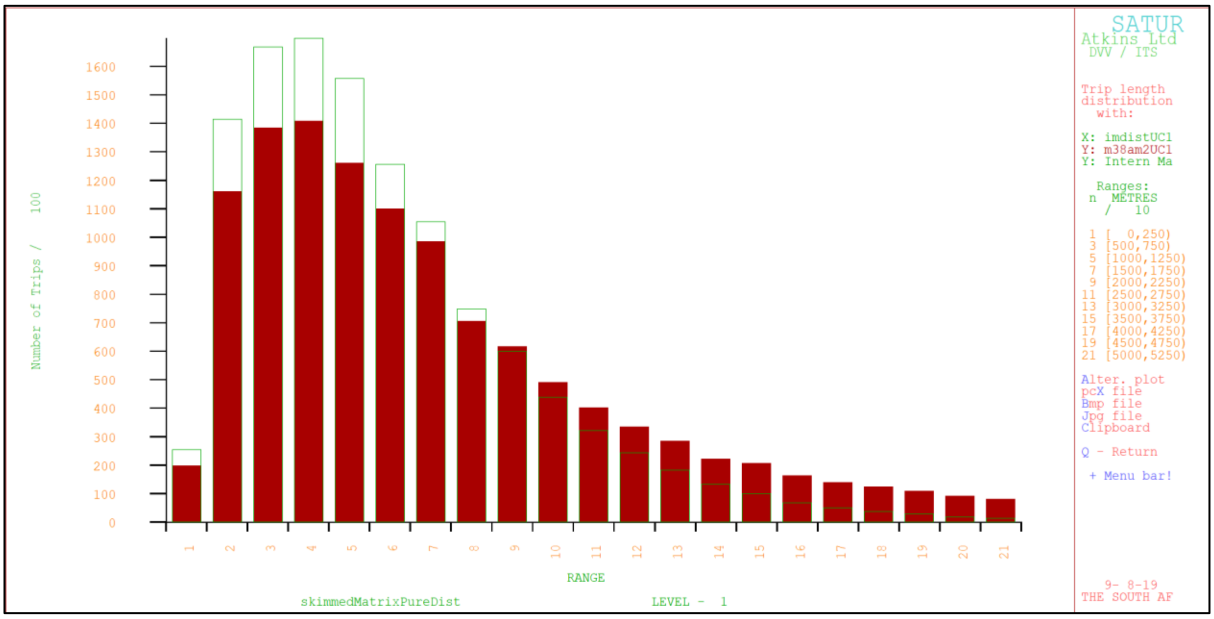
Appendix 7.15: Synthesized OD Trip Matrix using Beta = 0.1500

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	25322.6	1.25	25322.6
2500	5000	115984.38	141453.7	3.75	141453.7
5000	7500	138463.7	166759.7	6.25	166759.7
7500	10000	140778.88	169853.5	8.75	169853.5
10000	12500	126078.25	155667.6	11.25	155667.6
12500	15000	109888.49	125592.8	13.75	125592.8
15000	17500	98403.21	105439	16.25	105439
17500	20000	70525.51	74846.8	18.75	74846.8
20000	22500	61567.38	59808.8	21.25	59808.8
22500	25000	49097.96	43896.1	23.75	43896.1
25000	27500	40242.53	32099.4	26.25	32099.4
27500	30000	33539.89	24269.5	28.75	24269.5
30000	32500	28392.57	18311.1	31.25	18311.1
32500	35000	22140.71	13248.7	33.75	13248.7
35000	37500	20547.68	10051.8	36.25	10051.8
37500	40000	16234.75	6772.2	38.75	6772.2
40000	42500	13813.85	5002	41.25	5002
42500	45000	12404.24	3711	43.75	3711
45000	47500	10935.59	2799.2	46.25	2799.2
47500	50000	9063.27	1838.3	48.75	1838.3
50000	52500	8014.97	1304	51.25	1304
		1145895.39			1188047.8

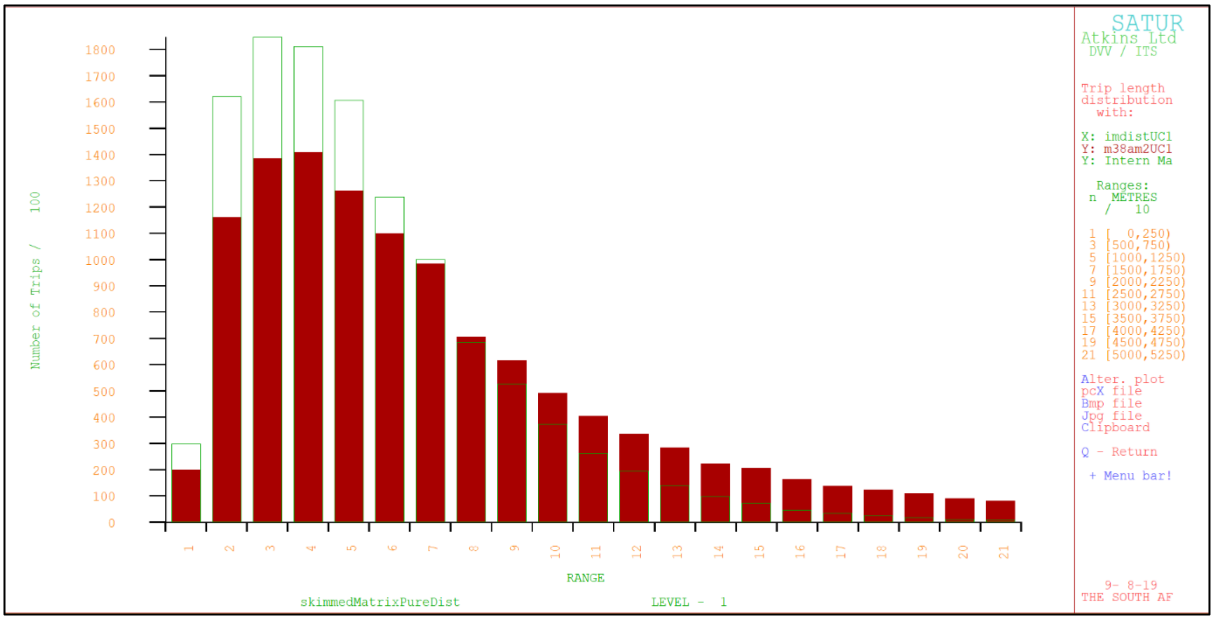
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	15840085.25	avg.trip length	14	km



Appendix 7.16: Synthesized OD Trip Matrix using Beta = 0.1700

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	29818.4	1.25	29818.4
2500	5000	115984.38	161968	3.75	161968
5000	7500	138463.7	184622.8	6.25	184622.8
7500	10000	140778.88	181120.2	8.75	181120.2
10000	12500	126078.25	160596.9	11.25	160596.9
12500	15000	109888.49	123887.7	13.75	123887.7
15000	17500	98403.21	100074.8	16.25	100074.8
17500	20000	70525.51	68298.4	18.75	68298.4
20000	22500	61567.38	52616.6	21.25	52616.6
22500	25000	49097.96	37179.2	23.75	37179.2
25000	27500	40242.53	26162.4	26.25	26162.4
27500	30000	33539.89	19262	28.75	19262
30000	32500	28392.57	13826.9	31.25	13826.9
32500	35000	22140.71	9734.5	33.75	9734.5
35000	37500	20547.68	7142.7	36.25	7142.7
37500	40000	16234.75	4506.4	38.75	4506.4
40000	42500	13813.85	3240.7	41.25	3240.7
42500	45000	12404.24	2360.5	43.75	2360.5
45000	47500	10935.59	1672	46.25	1672
47500	50000	9063.27	1033.9	48.75	1033.9
50000	52500	8014.97	696.2	51.25	696.2
		1145895.39			1189821.2

Matrix 1	**weighted avg.trips**	18381997.09	**avg. trip length**	16	km
Matrix 2	**weighted avg.trips**	14636522.5	**avg.trip length**	13	km



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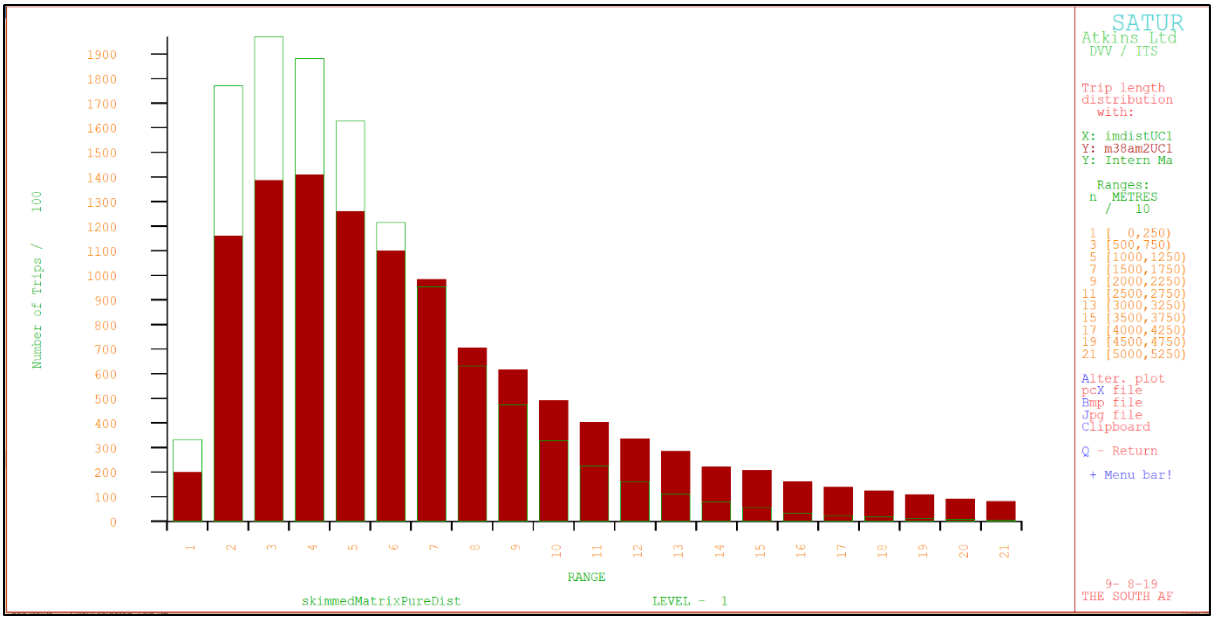
Appendix 7.17: Synthesized OD Trip Matrix using Beta = 0.1850

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	33268.3	1.25	33268.3
2500	5000	115984.38	177099.6	3.75	177099.6
5000	7500	138463.7	196902.5	6.25	196902.5
7500	10000	140778.88	188018.8	8.75	188018.8
10000	12500	126078.25	162685.8	11.25	162685.8
12500	15000	109888.49	121403.8	13.75	121403.8
15000	17500	98403.21	95316.8	16.25	95316.8
17500	20000	70525.51	63200.3	18.75	63200.3
20000	22500	61567.38	47424.8	21.25	47424.8
22500	25000	49097.96	32612.7	23.75	32612.7
25000	27500	40242.53	22309.3	26.25	22309.3
27500	30000	33539.89	16154.8	28.75	16154.8
30000	32500	28392.57	11177.4	31.25	11177.4
32500	35000	22140.71	7740.4	33.75	7740.4
35000	37500	20547.68	5555	36.25	5555
37500	40000	16234.75	3317.8	38.75	3317.8
40000	42500	13813.85	2347.4	41.25	2347.4
42500	45000	12404.24	1706.5	43.75	1706.5
45000	47500	10935.59	1139.8	46.25	1139.8
47500	50000	9063.27	674.8	48.75	674.8
50000	52500	8014.97	434.9	51.25	434.9
		1145895.39			1190491.5

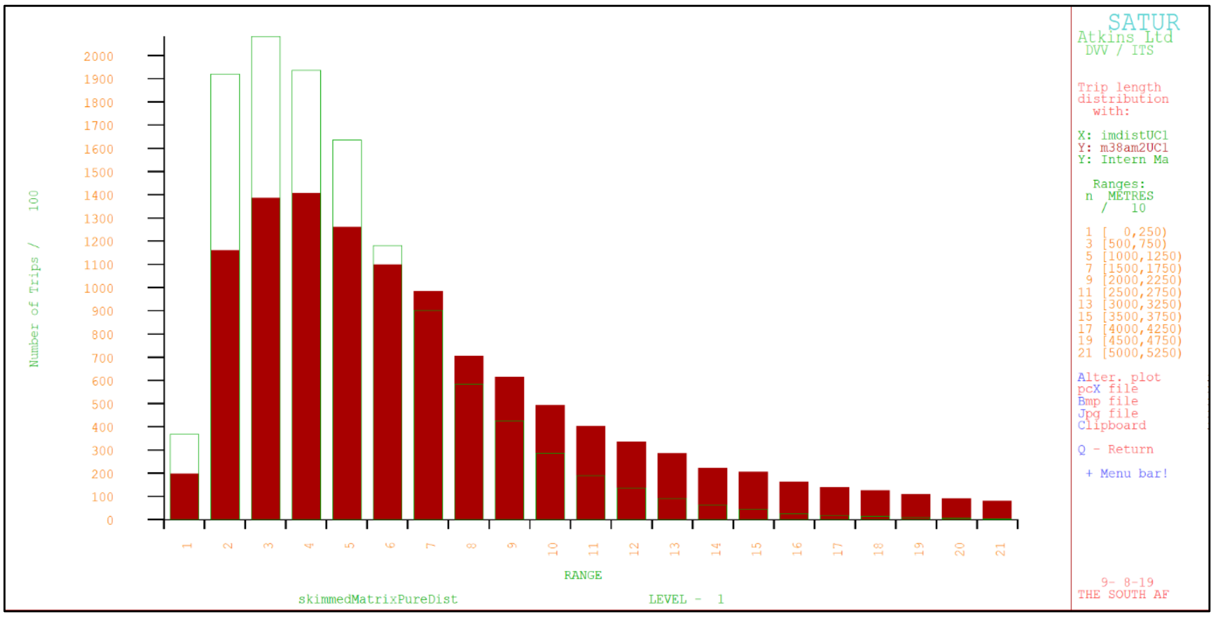
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	13867189.63	avg.trip length	12	km



Appendix 7.18: Synthesized OD Trip Matrix using Beta = 0.2000

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	36760.1	1.25	36760.1
2500	5000	115984.38	191937.1	3.75	191937.1
5000	7500	138463.7	208224	6.25	208224
7500	10000	140778.88	193697.2	8.75	193697.2
10000	12500	126078.25	163610.1	11.25	163610.1
12500	15000	109888.49	118166	13.75	118166
15000	17500	98403.21	90216.6	16.25	90216.6
17500	20000	70525.51	58157.8	18.75	58157.8
20000	22500	61567.38	42553.1	21.25	42553.1
22500	25000	49097.96	28515.6	23.75	28515.6
25000	27500	40242.53	18975.4	26.25	18975.4
27500	30000	33539.89	13557.6	28.75	13557.6
30000	32500	28392.57	9045.9	31.25	9045.9
32500	35000	22140.71	6187.8	33.75	6187.8
35000	37500	20547.68	4354.6	36.25	4354.6
37500	40000	16234.75	2447.7	38.75	2447.7
40000	42500	13813.85	1710.3	41.25	1710.3
42500	45000	12404.24	1256.7	43.75	1256.7
45000	47500	10935.59	781.4	46.25	781.4
47500	50000	9063.27	444	48.75	444
50000	52500	8014.97	272.2	51.25	272.2
		1145895.39			1190871.2

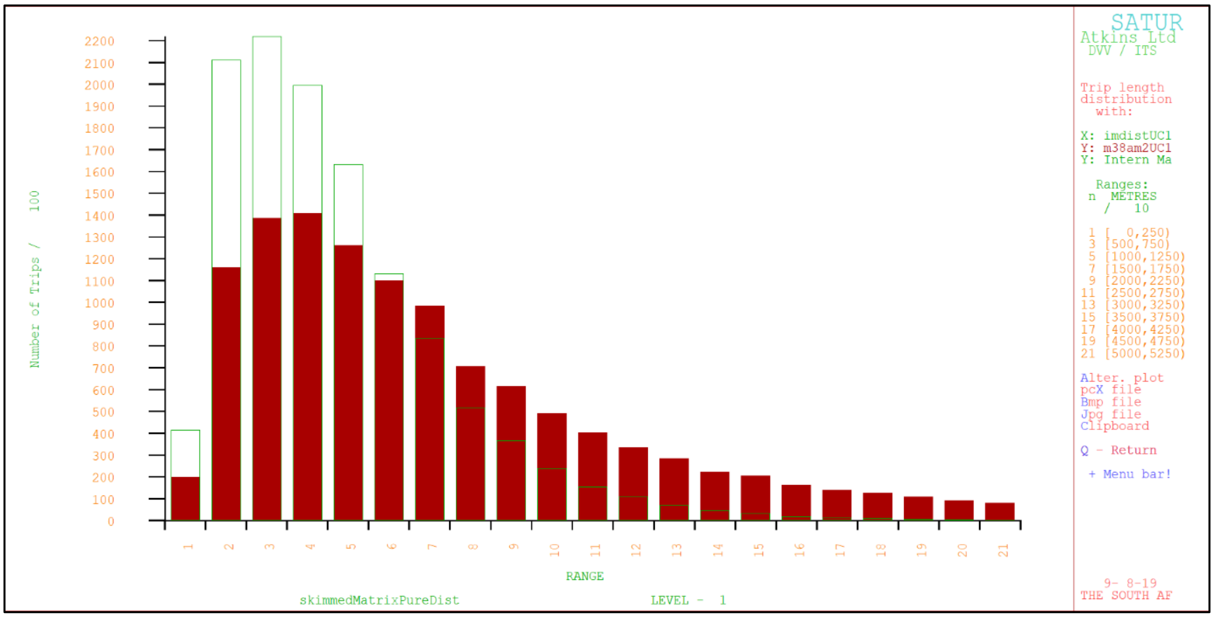
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	13194714.25	avg.trip length	12	km



Appendix 7.19: Synthesized OD Trip Matrix using Beta = 0.2200

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	41447.9	1.25	41447.9
2500	5000	115984.38	211175.5	3.75	211175.5
5000	7500	138463.7	221865.6	6.25	221865.6
7500	10000	140778.88	199553.5	8.75	199553.5
10000	12500	126078.25	163344.8	11.25	163344.8
12500	15000	109888.49	113035	13.75	113035
15000	17500	98403.21	83215.6	16.25	83215.6
17500	20000	70525.51	51735.2	18.75	51735.2
20000	22500	61567.38	36666.3	21.25	36666.3
22500	25000	49097.96	23792	23.75	23792
25000	27500	40242.53	15278.9	26.25	15278.9
27500	30000	33539.89	10782.6	28.75	10782.6
30000	32500	28392.57	6859.7	31.25	6859.7
32500	35000	22140.71	4652.8	33.75	4652.8
35000	37500	20547.68	3202.5	36.25	3202.5
37500	40000	16234.75	1642.1	38.75	1642.1
40000	42500	13813.85	1136.5	41.25	1136.5
42500	45000	12404.24	866.9	43.75	866.9
45000	47500	10935.59	478.6	46.25	478.6
47500	50000	9063.27	258.8	48.75	258.8
50000	52500	8014.97	146.7	51.25	146.7
		1145895.39			1191137.5

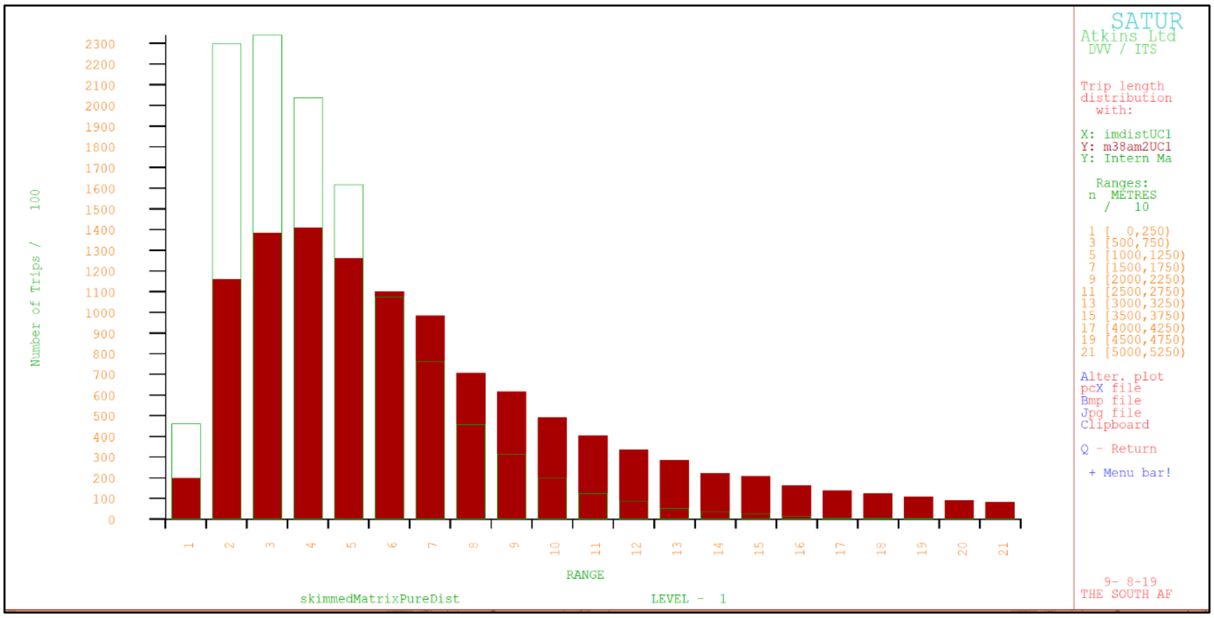
Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	12424106.88	avg.trip length	11	km



Appendix 7.20: Synthesized OD Trip Matrix using Beta = 0.2400

RANGE (m)		(Matrix 1) 2038 OD Trip Matrix	(Matrix 2) 2038 Synthesized OD Trip Matrix	Avg. Distance (km)	Syn.Trips
0	2500	19777.58	46137.5	1.25	46137.5
2500	5000	115984.38	229712.6	3.75	229712.6
5000	7500	138463.7	233921.3	6.25	233921.3
7500	10000	140778.88	203680.8	8.75	203680.8
10000	12500	126078.25	161724.9	11.25	161724.9
12500	15000	109888.49	107339.4	13.75	107339.4
15000	17500	98403.21	76282.8	16.25	76282.8
17500	20000	70525.51	45813.9	18.75	45813.9
20000	22500	61567.38	31520.3	21.25	31520.3
22500	25000	49097.96	19859.5	23.75	19859.5
25000	27500	40242.53	12329.3	26.25	12329.3
27500	30000	33539.89	8655	28.75	8655
30000	32500	28392.57	5254.9	31.25	5254.9
32500	35000	22140.71	3572.4	33.75	3572.4
35000	37500	20547.68	2414.7	36.25	2414.7
37500	40000	16234.75	1113.2	38.75	1113.2
40000	42500	13813.85	770.1	41.25	770.1
42500	45000	12404.24	628.1	43.75	628.1
45000	47500	10935.59	299.2	46.25	299.2
47500	50000	9063.27	155.4	48.75	155.4
50000	52500	8014.97	79.8	51.25	79.8
		1145895.39			1191265.1

Matrix 1	weighted avg.trips	18381997.09	avg. trip length	16	km
Matrix 2	weighted avg.trips	11771385.13	avg.trip length	10	km



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17 APPENDICES: CHAPTER 9

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Appendix 9.1: Improved Network: Improved Capacity on Freeways

Capacity Before Improvement	Capacity After Improvement (10% Increase in Capacity)
3640	4004
5460	6006
2100	2310
4000	4400
6000	6600
7400	8140
8200	9020
9500	10450
4000	4400
5900	6490
7600	8360
3640	4004
5460	6006
1800	1980
4000	4400
5900	6490
1900	2090
2500	2750
6000	6600
6600	7260

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Appendix 9.2: Improved Network: Improved Capacity on Second Order Roads

Capacity Before Improvement	Capacity After Improvement (10% Increase in Capacity)
1600	1760
2400	2640
1200	1320
2400	2640
1600	1760
1000	1100
1600	1760
2400	2640
1300	1430
2400	2640
1200	1320
1600	1760
1550	1705
3100	3410
4800	5280
1400	1540
2800	3080
4000	4400
5200	5720
6400	7040

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1200	1320
2400	2640
3600	3960
4800	5280