

An energy efficient mass transportation model for Gauteng

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ABSTRACT

Public transportation in South Africa is characterized by little or no consideration for energy efficiency and use of cleaner fuels. In the case of transport planning in South African cities, no assessment of the economic or environment impact of limited or highly priced electricity or conventional liquid fuels has been included in the decision-making process. Recent examples of the Gautrain and the Bus Rapid Transit programmes (both in Gauteng) reinforce this weakness in current planning methodologies.

This study has focused on the need to introduce energy efficiency and greenhouse gas consideration in mass transport decision-making in Gauteng. The intention of the study was to produce a strategic modeling tool that would be a high-level product for politicians to use. At the same time, the tool should feature more advanced capabilities such as optimisation algorithms to satisfy specific objective functions, such as time, cost, energy or global warming potential. In this way, sensitivity studies based on different orderings of these objective functions could be undertaken using this model.

The model's performance was tested using two different scenarios. In the *least time scenario*, which is practically the base case, the order of optimisation was time first, then cost, then energy and then global warming. The constraint on objective functions was relaxed by 10% after each optimization to get to the final result, which is then understood to be the least global warming impact for a particular plan that was initially optimized for time. In the *least global warming scenario*, the order of optimisation was changed, with first global warming, then energy, then time and then cost optimised. The resultant plan is the lowest cost plan that could be developed if global warming was the most important consideration.

The results obtained for both scenarios are discussed and compared to each other where practical. Where possible model verification and validation have been undertaken and where it has not been possible, the approach to be taken in a follow up study will serve to provide such validation. The model has been shown to be an effective high-level strategic decision-making tool. It is a tool that should be used by politicians and transport planners alike to ensure energy efficiency and greenhouse gas reduction are factored into future transport options considered.

Keywords: energy efficiency, transport planning, strategic decision-making support tool, global warming potential, Gauteng, optimisation

CONTENTS

1. Introduction	13
1.1 Background	13
1.1.1 The South African context.....	13
1.1.2 Current and future energy outlook.....	14
1.1.3 Environmental considerations	18
1.1.4 The Gauteng context.....	23
1.2 Objectives of study	25
1.3 Methodology.....	26
1.3.1 Needs analysis	26
1.3.2 Decision tool or model building	26
1.3.3 Scope and Limitations	27
1.3.4 Model testing and verification	30
1.3.5 Scenario building for validation purposes.....	30
1.4 Conclusion.....	30
2 Supply chain model development	33
2.1 Background	33
2.2 Selection of supply chain model	33
2.2.1 Literature review of transport models considered	33
2.2.2 Summary of review of models	45
2.3 Requirements of supply chain model	45
2.3.1 Definitions	45
2.4 Input data for the model.....	53
2.4.1 Background to mobility	53
2.4.2 The Pathways Structuring Mobility	54
2.4.3 Road Infrastructure	55
2.4.4 Bus Rapid Transit Infrastructure	58
2.4.5 Rail Infrastructure	60
2.4.6 Light Rail Infrastructure.....	60
2.5 The Modes Enabling Mobility	63
2.5.1 Cars.....	65

2.5.2	Minibus Taxis.....	71
2.5.3	Metrobus.....	72
2.5.4	Bus Rapid Transit.....	72
2.5.5	Old Rail - Business Express	73
2.5.6	Gautrain.....	76
2.6	Refining model parameters	76
2.6.1	Spread Sheet Variables	76
2.7	Conclusion.....	79
3	Testing the supply chain model	82
3.1	Background	82
3.2	Verification process	82
3.2.1	Initial optimisation process – each objective function independently:.....	82
3.2.2	Optimisation for multiple objectives in order of priority and relaxing each by 5%, 10%, 20% and 50%:.....	83
3.2.3	Discussion of results of verification process	84
3.3	Conclusion.....	85
4	Results	87
4.1	Background	87
4.1.1	The Least Time Scenario.....	87
4.1.2	Least GWP Scenario	87
4.2	Scenario Least Time results	88
4.2.1	Discussion of Least Time Scenario Result	88
4.2.2	Movement between Bubbles.....	90
4.3	Scenario Least Emissions results.....	91
4.3.1	Discussion of Least Emissions Result	91
4.3.2	Movement between Bubbles.....	93
4.4	Comparative Cost implications	94
4.5	Summary of results	94
4.5.1	Validation of the model chosen	95
4.6	Conclusion.....	97
5	Closure.....	99
5.1	Conclusion.....	99
5.1.1	Model’s role in future climate change mitigation.....	99
5.1.2	Verification of the Model’s performance.....	99

5.2	Recommendations for further work	100
5.2.1	Data availability	100
5.2.2	Commuter behaviour prediction.....	101
5.2.3	Improvements and maintenance of the model	101
6	References	103
	APPENDIX 1: Workflow Documentation.....	111
1.	Add Constraint - Cost	111
2.	Add Constraint - Energy	111
3.	Add Constraint - GWP	112
4.	Add Constraint - Time	112
5.	Add Version, Objectives - Cost.....	112
6.	Add Version, Objectives - Energy.....	113
7.	Add Version, Objectives - GWP	113
8.	Add Version, Objectives - Time	114
9.	Clear Objectives and Constraints.....	114
10.	Create Bubble Tables	115
11.	Create Buckets - Cost	115
12.	Create Buckets - Energy	115
13.	Create Buckets - GWP	115
14.	Create Dims.....	116
15.	Create Facts - Cost	118
16.	Create Facts - Energy	119
17.	Create Facts - GWP	119
18.	Create Facts - Time	119
19.	Create Versions - Cost.....	119
20.	Create Versions - Energy.....	119
21.	Create Versions - GWP.....	120
22.	Create Versions - Time	120
23.	Display Bubble Paramaters	120
24.	Formulate LP - Cost	120
25.	Formulate LP - Energy	121
26.	Formulate LP - GWP	121
27.	Formulate LP - Time	121
28.	Objective Relaxation	121

29.	Create Buckets - Time	122
30.	Scenario Paramater.....	122
31.	Shrink Database - Cost	122
32.	Shrink Database - Energy	122
33.	Shrink Database - GWP	122
34.	Shrink Database - Time	123
35.	Solved - Cost.....	123
36.	Solved - Energy.....	123
37.	Solved - GWP.....	123
38.	Solved - Time.....	124
39.	Update GIS_Links	124
40.	Update LP - Cost.....	124
41.	Update LP - Energy.....	125
42.	Update LP - GWP.....	125
43.	Update LP - Time.....	125
Procedure Documentation		126
1	Populations	126
2	Initial Populations	126
3	Destinations	127
4	Destinations Reached	128
5	Trips	128
6	Trip Capacities.....	129
7	Build Mode and Node	130
8	Budget.....	131
9	Commuter Change Overs.....	131
10	Objectives	132
7	APPENDIX 2: RAW DATA USED IN LIMITED VERIFICATION OF MODEL PERFORMANCE	133

LIST OF TABLES

Table 1: Mitigation measures (wedges) considered in the LTMS Study (ERC, 2008)	22
Table 2: Summary of Models Surveyed	42
Table 3: Assumed data for various transport options (infrastructure costs and constructed space) ..	62
Table 4: assumed data for various transport options (prices and average life cycle data)	64
Table 5: assumed data for cars	71
Table 6: assumed data for min-bus taxis	72
Table 7: assumed data for metrobus	72
Table 8: ASSUMED DATA FOR BUS RAPID TRANSIT	72
Table 9: assumed data for prasa options	75
Table 10: assumed data for gautrain	76
Table 11: verification results (scenario 1)	83
Table 12: verification results (scenario 2)	84
Table 13: verification results (scenario 3)	84
Table 14: verification results (scenario 4)	84
Table 15: verification results (summary)	84
Table 16: Summary of Results obtained for the different scenarios	94

LIST OF FIGURES

Figure 1: Modes of Transport used in SA in 2001(Statistics SA, 2004)	14
Figure 2: History of annual oil discoveries and production in the UK (Zittel, 2001)	16
Figure 3: Analysis of production of Forties Field and production forecast (Source: Campbell and Laherrère, 1998)	16
Figure 4: Crude oil prices since 1861 (BP Statistical Review, 2010)	17
Figure 5: Oil consumption and production in SA (EIA, 2009).....	18
Figure 6: World emissions per sector in 2008 (IEA, 2010)	19
Figure 7: CO ₂ emissions from transport in 2007 and 2008 (IEA, 2010)	19
Figure 8: Top 10 Emitters of CO ₂ in 2008 (IEA, 2010)	20
Figure 9: Different scenarios considered in the LTMS study (ERC, 2008).....	21
Figure 10: List of pathways for commuter use in SA	54
Figure 11: Operational and Capital Expenditure for Toll roads (SANRAL, 2009)	56
Figure 12: Operational and Capital Expenditure for Non-Toll Roads (SANRAL, 2009)	57
Figure 13: Bus Rapid transit example from bogota, colombia.....	58
Figure 14: Phase 1 of Johannesburg's Rea Vaya Bus Rapid Transit Project (Rea vaya, 2008)	59
Figure 15: Proposed Gautrain rapid rail Routes for Gauteng (van der merwe 2004)	61
Figure 16: Travel Behaviour of people from different income groups (CSS OctoberHouseholdsurvey, DOT SUMS database, sarcc, 1995).....	63
Figure 17: vehicle Emissions for Europe (Belmans and vergels, 2004).....	68
Figure 18: Energy-related co ₂ emissions in europe (belmans and vergels, 2004)	69
Figure 19: Passenger Rail Transport in Southern Africa	74
Figure 20: Breakdown of mode of transport by objective (least time)	89
Figure 21: least time scenario - movement between bubbles	90
Figure 22: breakdown of transport mode by objective (least emission).....	92
Figure 23: least emissions scenario - movement between bubbles.....	93

List of Abbreviations and Terms

Bubble	Area of demarcation used in this study, distinct from TAZ
C	Carbon
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
CSIR	Council for Industrial and Scientific Research
DEAT	Department of Environmental Affairs and Tourism
DME	Department of Minerals and Energy
EPA	Environmental Protection Agency (US)
ERC	Energy Research Centre
GHG	Greenhouse Gas/Gases
GHGI	Greenhouse gas inventory
GJ	Gigajoule; unit of energy; 1 GJ = 1 x 10 ⁹ Joule
GWh	Gigawatt hour
GWP	Global Warming Potential
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle
HFC	Hydro-fluorocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kT	Kilo Tons (based on metric tons, i.e. 1000 kg)
LCV	Light Commercial Vehicle
LNG	Liquid Natural Gas
LP	Leaded Petrol
LPG	Liquefied Petroleum Gas
LTMS	Long Term Mitigation Scenarios
MJ	Mega Joule; unit of energy; 1 MJ = 1 x10 ⁶ J
MW	Megawatt
MWh	Megawatt hours
na	Not applicable
NG	Natural gas
NO _x	Oxides of nitrogen
PM	Particulate matter
PM ₁₀	Particulate matter below 10 µm diameter
ppm	Parts per million
RON	Research Octane Number
RSA	Republic of South Africa
SANEDI	South African National Energy Development Institute
SI	Spark ignition
SO ₂	Sulphur dioxide
SO _x	Oxides of sulphur
Tactix	Supply chain model adapted for use in this study
TAZ	Transport Analysis Zone
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

UNEP	United Nations Environmental Programme
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Units, factors and abbreviations

Multiplication factors, abbreviations, prefixes and symbols

Multiplication factor	Abbreviation	Prefix	Symbol
1 000 000 000 000 000	10^{15}	peta	P
1 000 000 000 000	10^{12}	tera	T
1 000 000 000	10^9	giga	G
1 000 000	10^6	mega	M
1 000	10^3	kilo	k
100	10^2	hecto	h
0,1	10^{-1}	deci	d
0,01	10^{-2}	centi	c
0,001	10^{-3}	milli	m

Units and abbreviations

Abbreviation	Units
°C	Degrees Celsius
yr	Year (annum)
cal	Calorie
g	Gram
h	Hour
ha	Hectare
J	Joule
m ³	Cubic meter
t	Metric tons (1000 kg)
W	Watt

Chapter 1

INTRODUCTION

Summary

This chapter introduces the study and its stated objectives. The rationale for the development of the model used in this study is elaborated on. The need for a strategic high-level decision making tool is highlighted. The international, national and provincial context is provided as a basis for highlighting the urgent energy and climate constraints facing the transport sector.

The methodology adopted for this study is detailed. It illustrates the scope of work and the manner in which the proposed model is to be expanded on, if a suitable alternative is not located. The chapter serves not only as background to the proposed study but also focuses on the broader developments in the energy sector that will influence decision-making in the transport sector in the future.

1. INTRODUCTION

South Africa has experienced periods of sustained economic growth in the period following its first democratic elections in 1994. The country has, however, also experienced a concomitant increase in demand for natural and processed resources. Critical to the supply chain of beneficiation of minerals, processing of fresh produce and general labour practice is the requirement for effective and efficient transportation. While adequate rail and road infrastructure exists for the movement of commodities, it is passenger commuting that has been neglected the most. Of concern is the high number of passenger vehicles on South African roads and the consequent impact on energy use and the environment.

South Africa has committed itself to a voluntary greenhouse gas emission reduction target of 34% of CO₂ equivalent by 2020 and 42% by 2025 (State President Zuma in his address to COP15 in Copenhagen in 2010). In order to realise this goal, South Africa will have to implement both supply and demand side options to curb anthropogenic-sourced greenhouse gas emissions. The transport sector is a significant contributor to the national emissions inventory of South Africa and is the sector least addressed in the current legislative and policy framework of government.

What is needed is an overall perspective on the quantity of energy utilised in passenger commuting, as well as the related environmental impact. If high-level decision makers in government are exposed to decision support tools that simplify the input requirements as well as the subsequent outputs, then they will be more likely to engage in scenario and sensitivity study activities prior to making decisions regarding the nature of future mass transit schemes introduced in the country.

1.1 Background

1.1.1 *The South African context*

According to the Department of Environmental Affairs and Tourism's State of the Environment report of 2008, there were over 7 million vehicles on South Africa's roads in 2001. This figure has been revised to about 9.8 million in October 2010 by the National Traffic Information System (eNaTIS). Minister of Transport, Mr Sibu Ndebele indicated at the International Transport Investors Conference in June 2011 that the number of registered vehicles in Gauteng alone is growing by 10% per annum. The concern remains the lack of a scrapping age for vehicles in South Africa. The same reference cites the average age of vehicles on SA roads today being 10 years for cars, 13 years for mini-buses and between 11-12 years for buses and trucks. The increasing number of older and badly maintained vehicles on the road will have a significant impact on long-term fuel use and emissions.

Transport planning in South Africa is heavily influenced by current urbanisation trends. As a result, most efforts aimed at connecting people from point of residence to point of work have resulted in significant congestion on our highways. All focus in terms of transport planning has therefore been on spatial planning techniques with little or no consideration for energy consumption and associated emissions. A good example is the Rea Vaya Bus Rapid Transit (BRT) system deployed in Johannesburg. The success of the system internationally was measured on the basis of the number of commuters using the system. The net energy savings, if any, realised by introducing BRT in

countries such as Colombia and Nigeria did not feature in the feasibility study that proposed the introduction of the Rea Vaya System in Johannesburg.

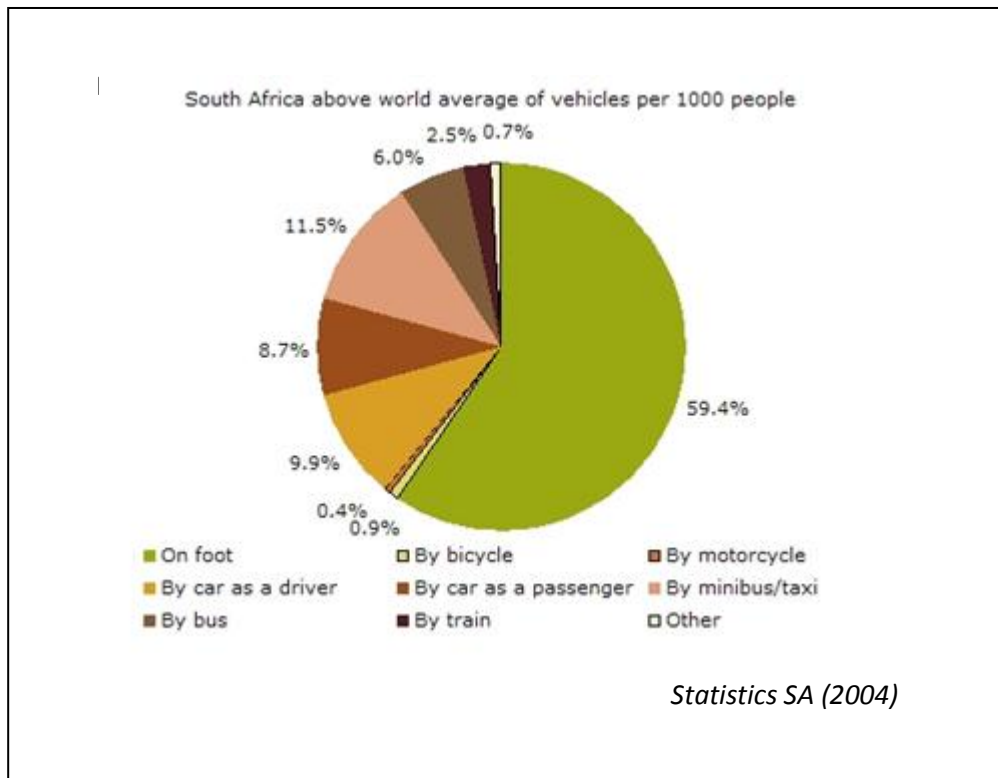


Figure 1: Modes of Transport used in SA in 2001(Statistics SA, 2004)

Statistics SA (2004) has categorised the various forms of transportation in South Africa, based on 2001 census data. Figure 1 details the various forms of transport used by South Africans. It is worth noting the large contribution from passenger vehicles in the country. This includes mini-bus taxis and private passenger vehicles. South Africa has a high dependency on imported crude oil for the supply of petrol and diesel for predominantly road transportation of freight and commuters.

Of concern is the high number of pedestrians in the country, totalling almost 60% of the country's commuters according to a . It is natural to assume that these pedestrians would switch to minibus/taxis, if their economic situation improved sufficiently. Thus, economic growth that translates into socio-economic upliftment will have the unintended consequence of placing an even greater burden on the environment through increased fossil fuel emissions. In addition, the switch to minibus/taxis will result in increased demand for liquid fuels. The outlook for energy supply from crude oil is a much debated topic. Current output from North Sea oil platforms suggests that the much publicised Peak Oil scenario may in fact be accurate. The next section deals with the outlook for crude oil availability.

1.1.2 Current and future energy outlook

Divergent views exist with regard to the supply of crude oil that will be available in the future. One perspective that has steadily gained support relates to the so-called Peak Oil scenario. Under this scenario it is hypothesized that peak production of oil is imminent. Campbell and Laherrère (1998) proffered that oil flow from any large region drops off once half the resource is gone. This is in accordance with the model proposed by M. King Hubbert in 1956. According to Hubbert, the extraction of a finite resource follows a bell-shaped curve, peaking when roughly half of the resource is depleted.

Using this technique, Hubbert was able to accurately predict that oil production would peak in the lower 48 states of the USA in 1969. In fact, production peaked in 1970 (Hubbert M.K. 1956). Other regions have also followed this pattern, including the former Soviet Union and oil-producing regions outside the Middle East. The Middle East countries have been more difficult to model, since the Arab states have a tendency to rein in production following the oil price shocks of 1973 and 1978. Using a variation of the Hubbert model, Campbell and Laherrère predicted that oil production in Norway and the UK would peak by the turn of the Millennium.

Just how accurate he was is seen in a paper by Höök & Aleklett (2008), in which it is reported that oil production in Norway peaked in 2001. In the case of Norway, production from giant oil fields is diminishing by 13% per annum, with smaller fields experiencing significantly larger rates of decrease, up to 40% per annum in some cases. The authors project that Norway will experience a dramatic decline in oil exports by 2030. In the case of the UK, Zitte (2001) reports that peak production in the UK occurred in 1999, also following Hubbert's prediction. The profile of oil production does not however follow a classical bell-shaped curve, with a skewed bell-shaped curve ending in an almost linear decline in production in later years.

Figure 2 illustrates the production of oil in the UK, measured against new discoveries. It is important to note that most oil production post 1980 relies on discoveries made in the 1970s. Figure 3 indicates the profile of production over time from Forties Field, the largest of the oil fields in the UK. As Zittel further indicates, the UK provides about half of Europe's oil supply and it is of concern that all oil fields are demonstrating a decrease in oil production, as high as 60% in some cases (Ferrier, RW; Bamberg, JH (1982)).

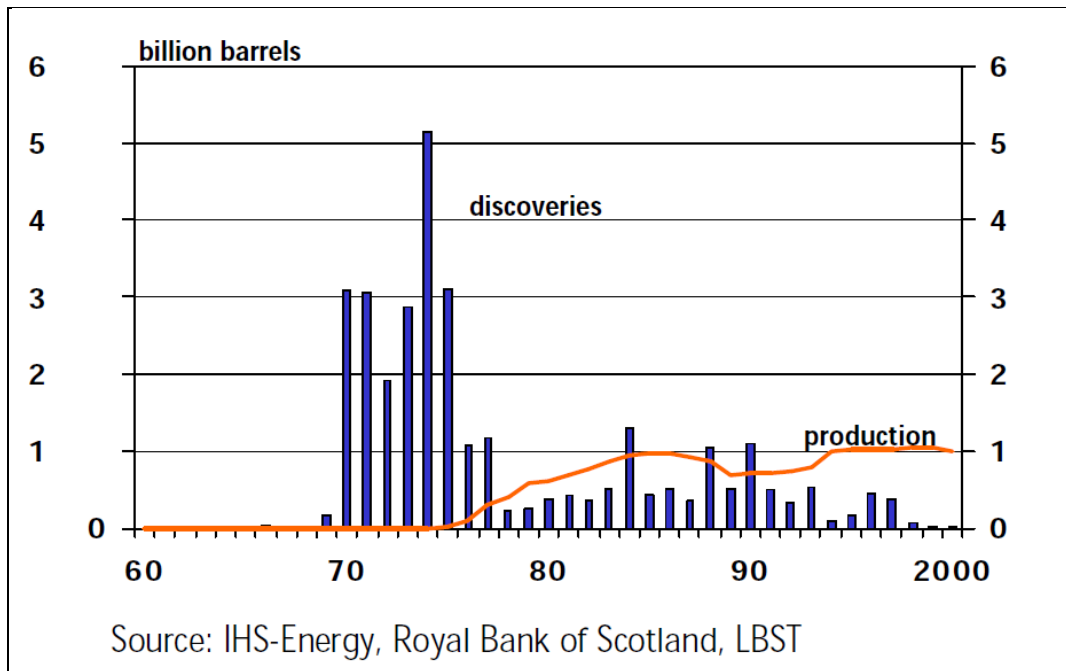


Figure 2: History of annual oil discoveries and production in the UK (Zittel, 2001)

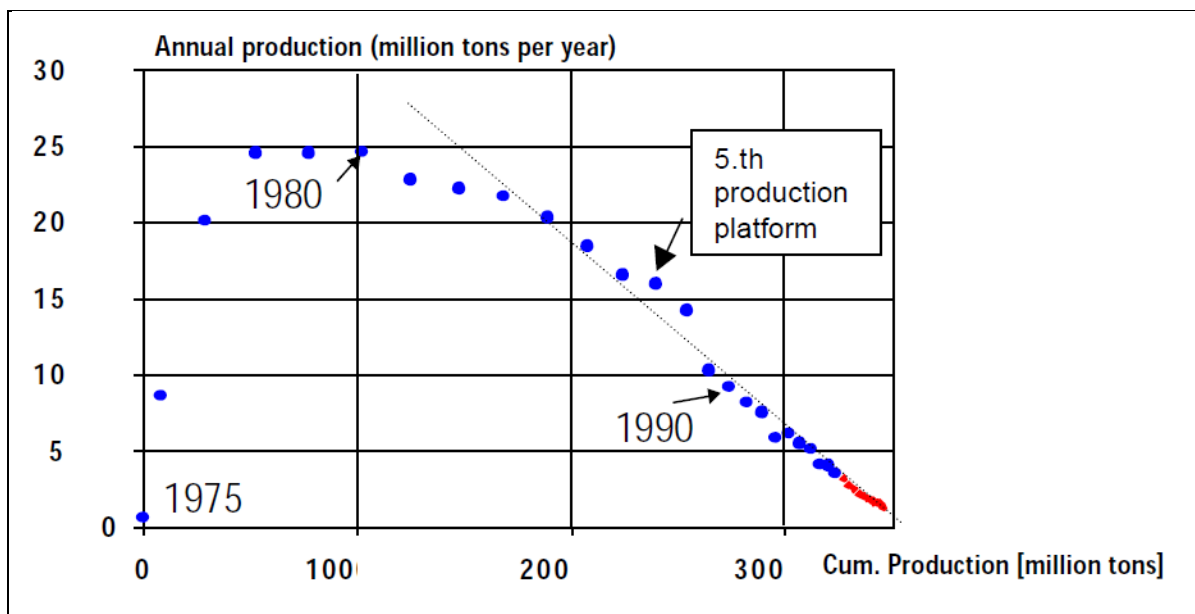


Figure 3: Analysis of production of Forties Field and production forecast (Source: Campbell and Laherrère, 1998)

South Africa has been relatively sheltered from the severe impacts of the oil price spikes in 1973 and 1978. South Africa anticipated shortages in supply due to international boycotts and sanctions in the early 1970s. As a consequence of this concern, South Africa had the foresight to pioneer the large scale commercial production of synthetic liquid fuels from coal. Later, South Africa would also pioneer high and low temperature conversion of natural gas to synthetic liquid fuels. Figure 4 illustrates the price of crude oil since the 1860s. With its pioneering of the synfuels industry development, South Africa been able to provide a buffer against some of the impact of the oil price shocks of the 1970s and in 2008.

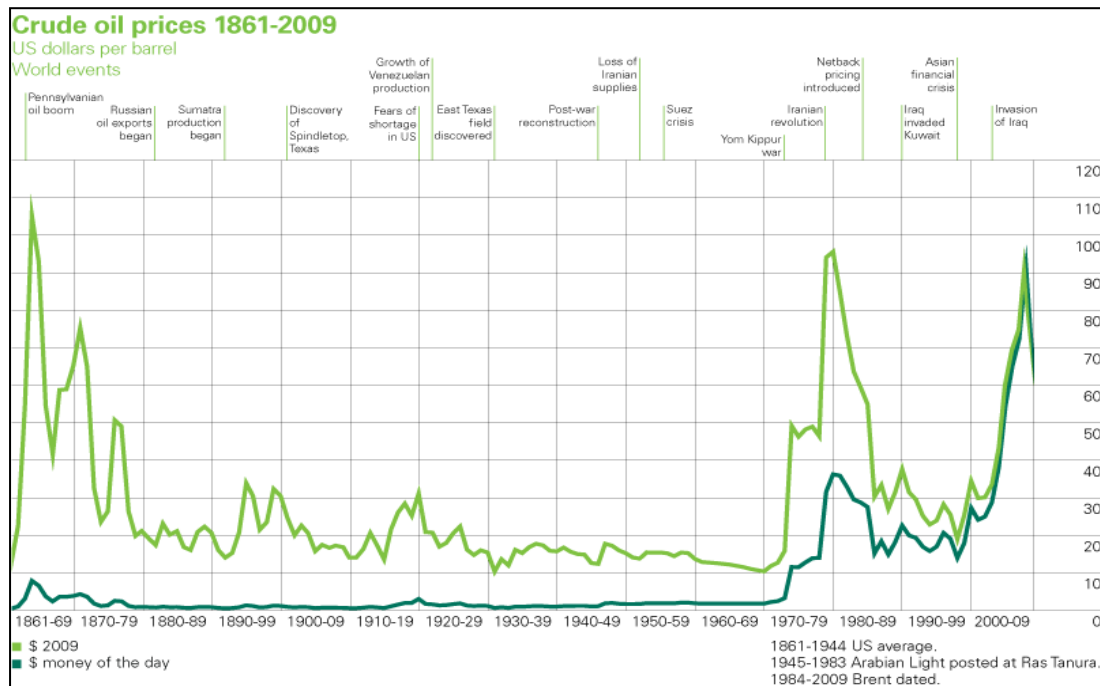


Figure 4: Crude oil prices since 1861 (BP Statistical Review, 2010)

The *Oil and Gas Journal (O&GJ)* indicates that South Africa had proven oil reserves of 15 million barrels as of January 2010. The proven reserves are located offshore of southern South Africa in the Bredasdorp basin and also off the west coast of the country near the border with Namibia. Some exploration work is in progress further offshore on both the western coastline of South Africa as well as in the Indian Ocean. There have been no major discoveries in the past 5 years (SAPIA 2001). The O&GJ also specifies that in 2008, South Africa produced 195,000 barrels of oil per day (bbl/d) of oil, of which about 160,000 bbl/d was synthetic liquids processed from coal and natural gas.

The Department of Energy in its Energy Statistics publication of 2007 indicates that South Africa meets 37% of its liquid fuel oil requirement from the synthetic fuels industry (Department of Energy's Digest of Energy Statistics, 2007). Figure 5 indicates the trend in increasing oil consumption, with a widening gap between consumption and production. This is of concern, given the trend in oil prices. Prices have increased rapidly since 2001, as is evident in Figure 4, and it is only the global recession of 2009 and 2010 that is limiting further rapid increases.

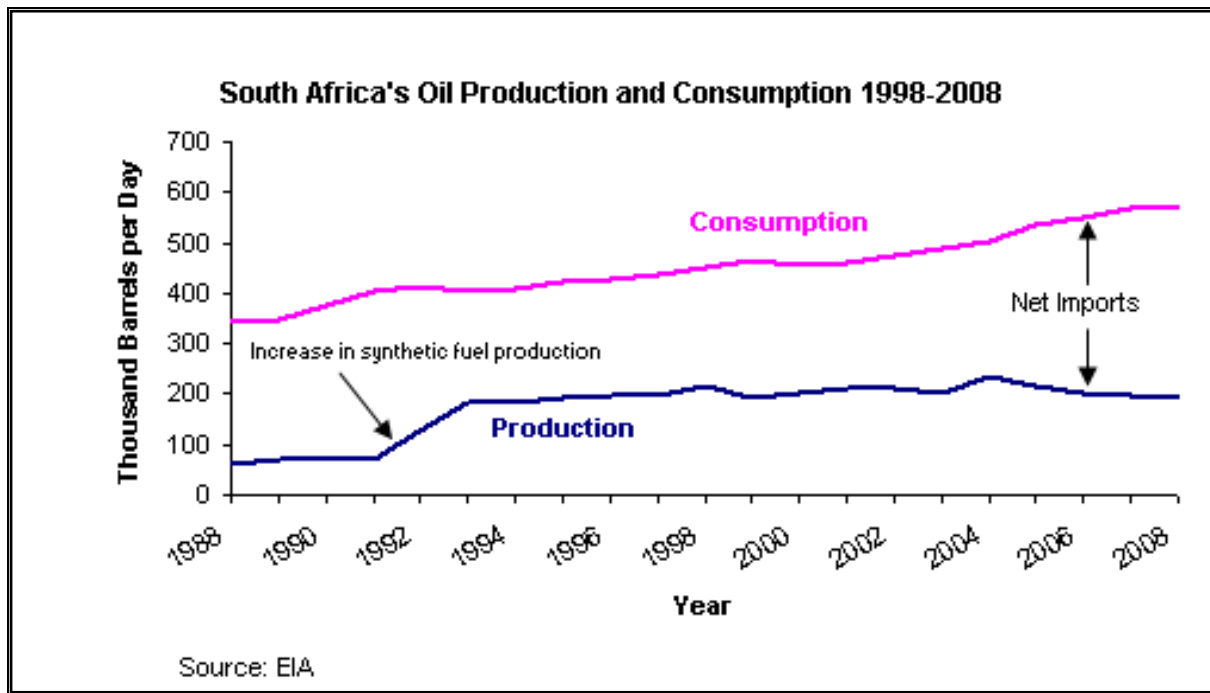


Figure 5: Oil consumption and production in SA (EIA, 2009)

It is further estimated that South African oil consumption is approximately 575,000 bbl/d, of which roughly 380,000 bbl/d is imported (67 percent of consumption). The Global Trade Atlas indicates that the majority of South African oil imports are from Saudi Arabia and Iran, followed by Nigeria and Angola. Figure 5 highlights the growing gap between demand for crude oil and production capacity. Despite significant increases to synthetic fuel production in 1991, almost 67% of consumption as stated above is still imported.

There is inelasticity of demand for liquid fuels, i.e. consumers are unable or unwilling to switch fuels or modes of transport when prices increase significantly. It is important that additional reserves of oil be located to offset the anticipated higher cost of imported crude oil. There is however the problem of environmental impact, which will be covered in the next section.

1.1.3 Environmental considerations

1.1.3.1 Global emissions

The IEA estimates that the transport sector is responsible for 22% of global emissions (IEA Statistics, 2008). Together with the electricity and heat generation sector this comprises almost two-thirds of all anthropogenic-related emissions. Figure 6 illustrates the various sub-categories that comprised global emissions in 2008.

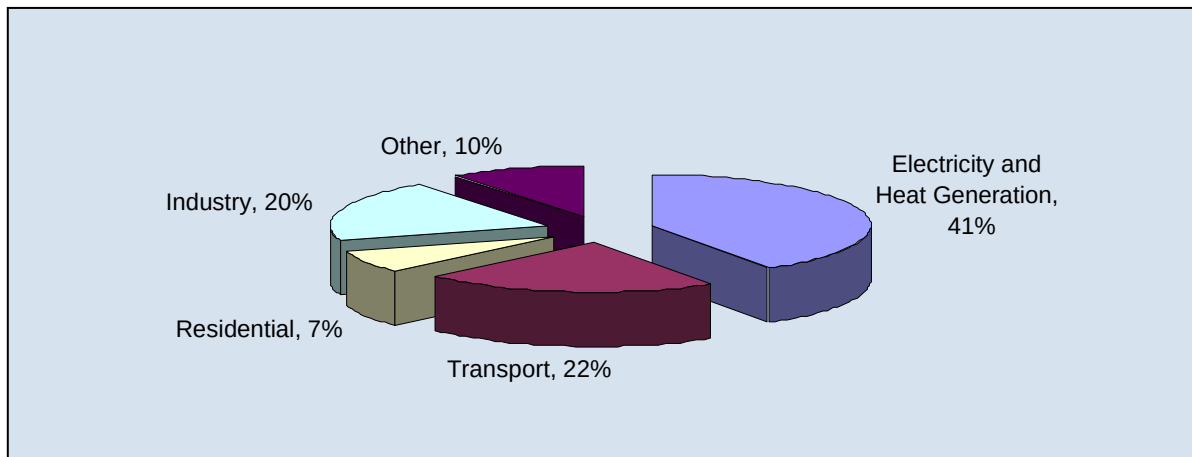


Figure 6: World emissions per sector in 2008 (IEA, 2010)

Figure 7 illustrates the global CO₂ emissions from transport for the years 2007 and 2008. Road transportation provides for the bulk of the emissions, comprising almost 5000 Mt CO₂ per annum, of a total of about 6600 Mt CO₂. While year on year variation is limited, there are indications that major growth in the transport sector is expected, particularly in developing countries.

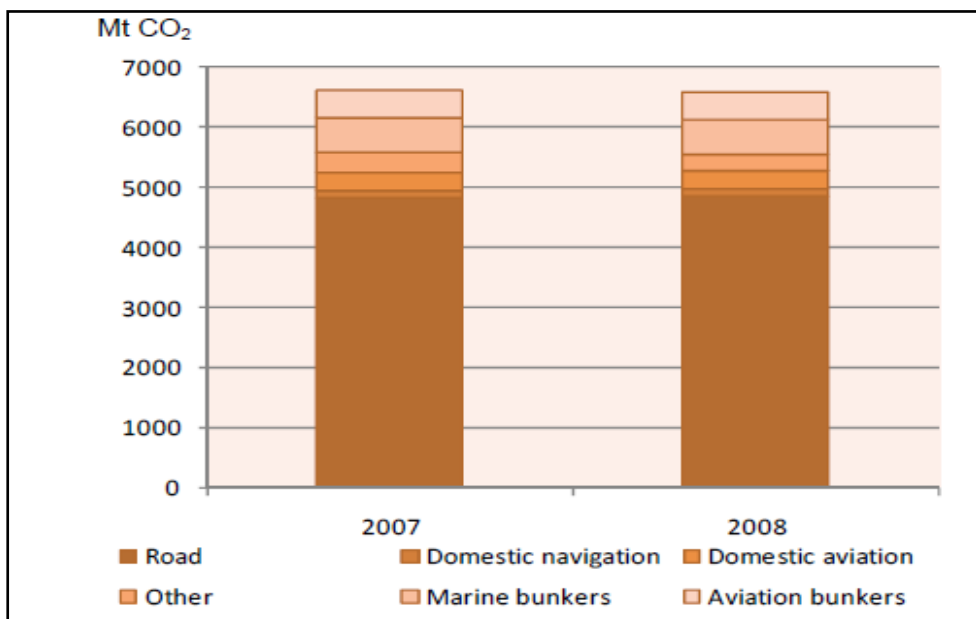


Figure 7: CO₂ emissions from transport in 2007 and 2008 (IEA, 2010)

The IEA further predicts that emissions from the transport sector are likely to increase by 45% by 2030 (World Energy Outlook, 2009). Factors that are expected to contribute to this growth include rapid urbanisation in developing countries, increased movement of goods due to high economic growth in major emerging economies and population growth. While the IEA points out that transport efficiency policies are being introduced in major CO₂ emitting countries such as the USA, other countries in the top 10 list of emitters are lagging behind in this regard. Figure 8 lists the top 10 emitters of CO₂. Increased manufacturing of vehicles, particularly from China, is resulting in

cheaper, less efficient vehicles being sold globally. This fact, among others, will result in passenger vehicles remaining at the top of the list of sources of CO₂ emissions in the transport sector.

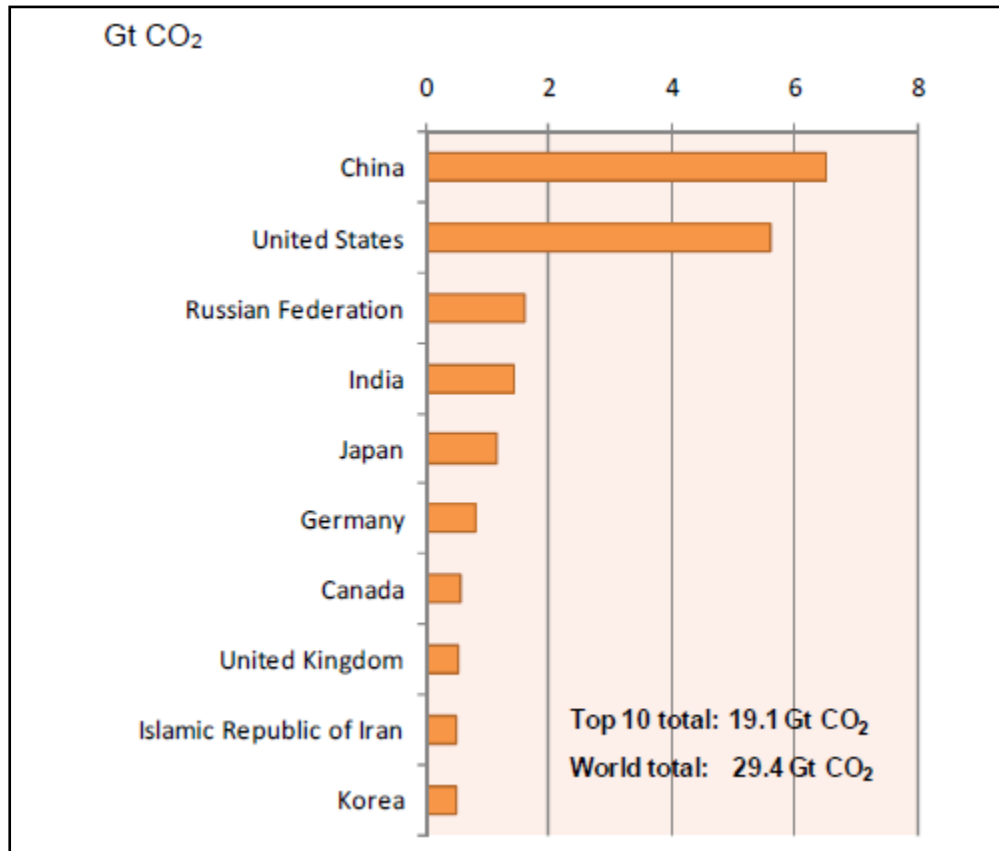


Figure 8: Top 10 Emitters of CO₂ in 2008 (IEA, 2010)

An important fact to consider is that these ten countries account for almost two-thirds of global emissions. It is therefore important that initiatives aimed at reducing transport emissions originate in these countries. Countries such as South Africa, where passenger rail infrastructure is limited, need to study best practice in mass transit in these top 10 emitting countries to avoid making the same mistakes. Given the prevalence worldwide to make transport planning decisions without due consideration to energy use and environmental impact, it is possible for South Africa to become a pioneer in energy efficient mass transportation.

1.1.3.2 Long Term Mitigation Scenario for South Africa

The South African cabinet approved in July 2008 the development and consideration of the so-called Long Term Mitigation Scenarios Study (LTMS). Various scenarios were considered in the study to determine what South Africa's greenhouse gas emission reduction strategy should be. Key to this strategy was the premise that in order to reduce emissions below the desired 400 Mt CO₂-equivalent level by 2050 (National Climate Change Response Strategy Green Paper, 2010), the country would have to introduce significant measures to curb emissions. These measures were categorised under so-called stabilisation wedges, each wedge contributing about 1 Gt of CO₂-equivalent emission reduction. The cost implications of such wedges were rated according to whether there was a positive mitigation cost, i.e., a net cost to the economy of introducing such measures or a negative mitigation cost, i.e., a net gain for the economy resulting from the introduction of the measure.

The scenarios that were developed included reference or base case, considering a business as usual approach. This scenario is termed the “Growth Without Constraints” scenario. Under this scenario, emissions resulting from positive economic growth are unchecked. Emissions rise above the 1600 Mt level by 2050, which would be disastrous for both South Africa and the globe. Various other scenarios were then modelled, taking into account different programmes or measures that could be introduced. The scenario that addresses the goal of keeping the global mean temperature increase to below 2°C by 2050 is termed the “Required by Science” scenario. Under this scenario, emissions are brought under the 400 Mt CO₂ level by 2050, which is under current levels of emissions. This scenario requires the adoption of aggressive measures to bring emissions below the required limit. In keeping with South Africa’s goal of pursuing the sustainable development of the economy, a “Peak, Plateau and Decline” philosophy is to be adopted. In this philosophy, emissions are allowed to increase till about 2020, plateau until about 2035 and then decrease by 2050. Figure 9 illustrates the various scenarios.

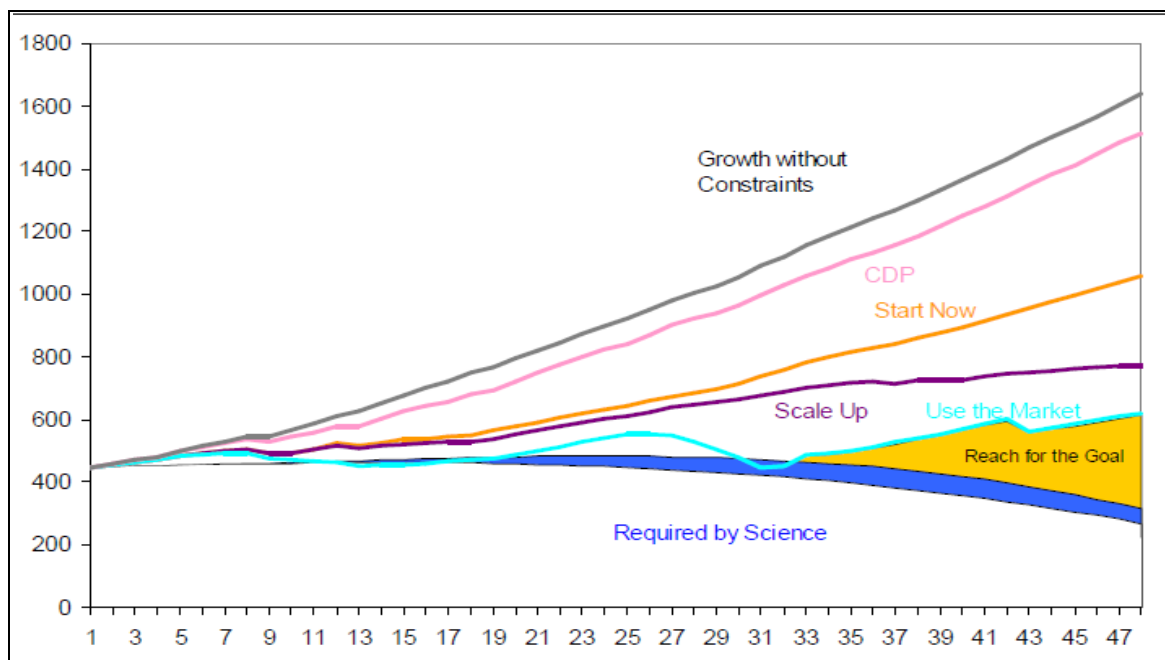


Figure 9: Different scenarios considered in the LTMS study (ERC, 2008)

The Energy Research Centre (ERC) at the University of Cape Town, which undertook the LTMS study on behalf of Cabinet, has considered the mitigation measures from the transport sector. In essence, modal shifts represent a major infrastructure option – from private to public transport modes for passengers, and from road to rail for freight. Analysis of passenger modal shift indicated that this was a more attractive option than freight. This is a negative cost mitigation option (saving of about R1,300 per ton CO₂-eq) with reductions of 469 Mt CO₂-eq. The analysis of modal shifts includes elements such as infrastructure costs, but not returns on investment.

Biofuels are considered separately as another stabilisation wedge. This is due to the limited emission reduction potential envisaged as a result of the limitations imposed on feedstock availability. The potential for energy efficiency in the transport sector is significant and should ideally be considered as the most attractive option. The introduction of vehicle efficiency results in a net saving, amounting to R269/t CO₂-eq (2008 South African Rands). It is also a negative cost mitigation option. Electric vehicles are expected to play a larger role in terms of passenger commuting but the full benefit of this option will only be realised if the supply of electricity to charge these vehicle’s batteries is sourced from renewable or nuclear energy sources. There is, however, a benefit even at this stage where coal still dominates the supply of electricity in the country. Table 1 indicates all the

options considered as well as the cost implications from the perspective of either cost or saving (R/ton CO₂-eq, % of GDP).

Table 1: Mitigation measures (wedges) considered in the LTMS Study (ERC, 2008)

<i>Mitigation action</i>	<i>Mitigation cost (R / t CO₂-eq)</i>	<i>GHG emission reduction, Mt CO₂-eq, 2003-2050</i>	<i>Rank costs - lowest cost is no.1</i>	<i>Rank emission reductions - highest reduction is no.1</i>	<i>Mitigation costs as share of GDP</i>	<i>Increase on GWC energy system costs</i>
	<i>Average of incremental costs of mitigation action vs base case, at 10% discount rate</i>	<i>Positive numbers are reductions of emissions by sources or removals of emissions by sinks</i>	<i>Rank cost</i>	<i>Rank ER</i>	<i>%, negative numbers mean lower costs</i>	<i>%, negative numbers mean lower costs</i>
<i>Combined energy cases</i>						
Start Now	-R 13	11,079			-0.5%	-2.2%
Scale Up	R 39	13,761			0.8%	3.6%
Use the Market	R 10	17,434			0.1%	0.6%
Current Development Plans	-R 510	3,412			-2.4%	-11.4%
<i>Individual Wedges</i>						
Limit on less efficient vehicles	-4,404	18	1	36	-0.2%	-0.7%
Passenger modal shift	-1,131	469	2	16	-1.1%	-4.9%
Improved vehicle efficiency	-269	758	3	14	-0.4%	-1.9%
SWH subsidy	-208	307	4	25	-0.1%	-0.4%
Commercial efficiency	-203	381	5	22	-0.1%	-0.6%
Residential efficiency	-198	430	6	21	-0.1%	-0.5%
Renewables with learning	-143	2,757	7	10	-0.4%	-2.1%
Industrial efficiency	-34	4,572	8	5	-0.3%	-1.2%
Agriculture: manure management	-19	47	9	34	n/a	n/a
Land use: fire control and savannah thickening	-15	455	10	17	0.0%	n/a
Cleaner coal	-4.8	167	11	28	0.0%	0.0%
Aluminium	0.2	29	12	35	0.0%	n/a
Renewables with learning, extended	3	3,990	13	6	0.0%	0.1%
Synfuels methane reduction	8	146	14	30	0.0%	n/a

(Continues overleaf)

Table 1 (contd.) MITIGATION MEASURES (WEDGES) CONSIDERED IN THE LTMS STUDY (ERC, 2008)

<i>Mitigation action</i>	<i>Mitigation cost (R / t CO₂-eq)</i>	<i>GHG emission reduction, Mt CO₂-eq, 2003-2050</i>	<i>Rank costs - lowest cost is no. 1</i>	<i>Rank emission reductions - highest reduction is no. 1</i>	<i>Mitigation costs as share of GDP</i>	<i>Increase on GWC energy system costs</i>
	<i>Average of incremental costs of mitigation action vs base case, at 10% discount rate</i>	<i>Positive numbers are reductions of emissions by sources or removals of emissions by sinks</i>	<i>Rank cost</i>	<i>Rank ER</i>	<i>%, negative numbers mean lower costs</i>	<i>%, negative numbers mean lower costs</i>
<i>Combined energy cases</i>						
Start Now	-R 13	11,079			-0.5%	-2.2%
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Use the Market	R 10	17,434			0.1%	0.6%
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Cleaner coal	-4.8	167	11	28	0.0%	0.0%
Aluminium	0.2	29	12	35	0.0%	n/a
Renewables with learning, extended	3	3,990	13	6	0.0%	0.1%
Synfuels methane reduction	8	146	14	30	0.0%	n/a

1.1.4 The Gauteng context

A primary challenge facing urban transport in South Africa is one of a lack of affordable basic access for a large proportion of the population). Thirteen percent or 2.8 million potential urban transport customers are stranded (Gauteng Department of Public Transport, Roads and Works' technical report 2001). They walk or cycle long distances for their primary trip purpose. In effect, they lack financial and/or physical access to the public transport system. The "stranded" are predicted to grow by 28% to 3.6 million by the year 2020 if nothing is done to address their needs. Forty-five percent of the "stranded" are unemployed and 42% are scholars. Even though government spent R2.8 billion in 1997 on bus and rail commuter subsidies, only 40% of "stranded" customers say they have access to a bus, and only 20% say they have access to a train, whilst 78% say they can access the unsubsidized and more expensive minibus taxi mode. The public transport system is essentially failing its customers. For most indicators including access time, journey time, safety, security and fares, customer goals are not being met for large numbers of passengers. (Patel, etd., 2001)

According to the Integrated Transportation Plan (2004), Gauteng covers 1.4% of the total surface area of South Africa, but is home to 9.1 million people or 17% of the country's population of a little more than 46 million people. The total road network in Gauteng spans 34 100 km. Every working day, 1 471 100 passenger trips are carried out by taxi, 430 100 by bus and 1 406 400 by rail (Integrated Transport Plan, 2004). Congestion has become a major problem in metropolitan areas, causing massive delays in certain areas and costs in general to the economy.

For optimisation, control and maintenance of transport systems, information is needed on a regular basis. Decision-making at all levels, aimed at improving the transport system, depends on the content and quality of the information and the frequency at which it is updated. In line with government policy, these improvements should contribute to creating a better life for the entire population. The process of obtaining such information is called transportation surveying". There are currently various transportation-related functions that cannot be optimally managed because of a lack of integrated transportation information. The link between improved transportation conditions and a "better life for all" is also not clear (Integrated Transportation Plan 2003/2008, 2004).

Goyns (2008) estimates annual vehicular emissions from passenger vehicles in Johannesburg at 4.1 Mt of CO₂. This is of interest to this study, as CO₂ is one of the major greenhouse gases and South Africa will be expected to reduce its greenhouse gas emissions in line with any multinational treaty agreed to by the parties to the United Nations Framework Convention on Climate Change (UNFCCC).

Various studies have been undertaken over the past twenty years to predict or model emission levels in the country. A more recent study was undertaken by the CSIR on behalf of SANERI. (Mapako, Oliver et al, 2009). The study focused on remote sensing of emissions at predefined areas of known traffic congestion in Cape Town and Johannesburg. Information gleaned in this manner can be used to define "exclusion zones" or pollution hotspots. Planners and policy makers can introduce measures to limit access to these "exclusion zones" by fossil fuelled vehicles.

A joint implementation strategy was developed by the Departments of Environment and Minerals & Energy in 2003 (Departments of Environmental Affairs and of Minerals and Energy, Government Gazette 3324 of 2003). This strategy served to indicate the manner in which exhaust emissions from road-going vehicles in SA would be controlled. Various measures, included compliance with Euro II and Euro III limits for emissions were proposed.

1.2 Objectives of study

With a myriad of transport options to choose from, transport planners in cities in South Africa still prefer the least cost option. What is needed, however, is due consideration of the energy consumption of the mode being considered, as well as the related environmental impact. It is necessary to consider a least cost approach to planning, but in addition to the cost of moving a passenger per km, it is vital that energy constraints are factored into the lifecycle costs.

In an ideal planning environment, a full assessment of the costs associated with the production, utilisation and disposal of a transport mode should be considered. This is the so-called “well-to-wheel” cost. While there are some studies that purport to identify these full lifecycle costs, there is no standard figure that can be used in planning models. It is therefore proposed in this study that the cost of transport options be limited to known parameters, such as cost of establishing the infrastructure supporting the option, the capital cost of the option and the running costs, i.e, operations and maintenance costs for the option once in use.

Government agencies are occasionally approached by the private sector with proposals for new mass transit options, such as mono-rail and subway systems. While these options may appear feasible at first glance, there are bound to be energy and environmental impacts that may impair or negate the perceived benefit of a seemingly cost effective option. A planning tool is therefore required to assist high-level decision makers in making so-called “go” or “no-go” preliminary decisions. In order for decision makers to utilise such a planning tool, it should characteristically be simple to use, quick to run and be easily customised. This includes being able to add new transport modes to the system with minimal effort. This study aims to produce such a planning tool.

In addition, South Africa is committing itself to long-term and far-reaching emission reduction targets. These targets will rely on mitigation measures being introduced in various sectors comprising energy demand. The measures introduced in the transport sector will range from low or no cost options, such as transport energy efficiency, to higher cost options such as road to rail modal shifts. The Long Term Mitigation Scenarios study, published in July 2008, identifies the major mitigation measures that are required to ensure that South Africa remains below the 400 Mt CO₂ emission level per annum. The abatement or mitigation cost for the transport sector is based on assumption and has never been truly quantified. A planning or decision tool, such as the one developed in this study, will assist in further defining the true cost of abatement in the transport sector. In order to arrive at this cost, it is necessary to model a base case scenario, in which a conventional lowest cost approach is taken to optimisation of a predefined system, and a low carbon scenario, in which the emissions for the same system are constrained. The cost of then moving people in an emission-constrained system can be determined.

Lastly, Gauteng has the biggest passenger commuting requirement in the country and also provides for the most emissions in terms of CO₂, SO_x, NO_x, CO and particulates. In order to develop more energy efficient and environmentally benign mass transit schemes it is necessary to understand the demand profile of commuters in the province. A planning tool that allows for a high-level assessment of commuting requirements in Gauteng will assist in assessing alternative, more efficient mass transit options. This planning tool should make use of all available census, household and lifestyle surveys to estimate the likely movement of people in and around Gauteng.

In summary, the objectives of this study can be defined as follows:

1. To develop a robust planning framework for Cities' Planners and Transport Authorities to allow them to incorporate elements of energy conservation and negative environmental impact mitigation into decision-making
2. To demonstrate the practical benefits of alternative propulsion systems for use in the various modes of transportation used in commuting and freight handling
3. To optimise the use of various modes of transport in order to develop an efficient, integrated mass transit scheme for cities, to allow for seamless transition between modes and high-levels of interoperability in the system
4. To maintain a knowledge management system within SANERI that will allow local and international clients the opportunity to obtain a licensed product to assist in their own transport planning processes

The Hypothesis Statement for this study can be stated as follows:

It is **possible** to find "**the optimised solution**" in terms of passengers delivered for the mode-energy choice combination under set constraints such as selected route, energy and environmental impacts for best performance (passenger.km/h) or least cost.

1.3 Methodology

1.3.1 Needs analysis

The need for an optimised mass transportation system in any city is self evident. What is required to be understood is the effectiveness of various forms of transport in meeting the current and predicted future demand for transportation. A literature review of the current models available for planning purposes will be undertaken. This will demonstrate that alternative options have been considered in this study. It is vital that any planning tool chosen should be easy to populate with new data and easy to operate as well as understand. If no suitable alternative is identified then a local product will have to be developed. This model should be readily available, easy to populate and interpret the outputs. Such a model needs to produce optimised solutions that can be used by high-level decision makers. A scan of the local market will assist in identifying if such a product exists already. If not, a suitable model should be customised where possible.

1.3.2 Decision tool or model building

Once identified, the model will need to be customised for the purposes of this study. This will require the development of suitable algorithms that will form the basis of the model's operation.

Since linear programming is the most commonly used approach, the development of the model will involve the appropriate algorithm, objective functions and workflow process.

Data are essential for the building of the model. Various data sources have been used to obtain as much data as is available at present. Most of these are sources from census data as well as transport surveys.

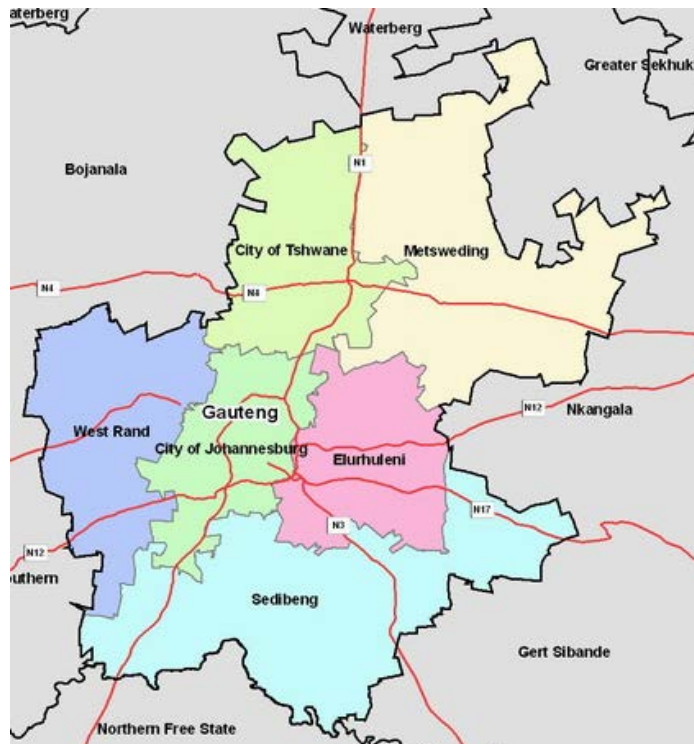
It is vital that accurate data are obtained to form a coherent baseline that can be used as a reference when considering various sensitivity studies in the future. The assumptions regarding transport options, demarcation zones and related factors will need to be justified once selected.

1.3.3 Scope and Limitations

Once proven to be accurate and with available data, the decision tool can be used unlimited by size of area or population and with more variables. The first objective is the development of a strategic decision tool (or “model”). Therefore, the variable data used will serve the purpose of model development and evaluation as a priority, before spending time and effort with data refining, accumulation and verification. However, every effort was made within these parameters to have an evaluation of the model and an optimised integrated mass transit solution that reflects reality.

1.3.3.1 Area

The area and population under consideration for the purpose of model building and evaluation has been limited to the area of Gauteng. The data used, comes from “The First South African National Household Travel Survey 2003” published in 2005. This survey findings show 12 432 000 households in South Africa, 2 921 000 which are in Gauteng, consisting of 9 million people out of a total of 46 million people. The sample size for Gauteng was 9 507 households. These were spread over 3 metros, 3 districts, 9 municipalities and 58 transport analysis zones (South African National Household Travel Survey 2003, 2005). This sample is believed to be big enough to provide useful information and small enough for speedy calculation.



Part of the procedures of the South African National Household Travel Survey (SANHTS) was to divide each municipality into a number of transport analysis zones (TAZ). This was done to measure

movements between different parts of a metropolitan or district municipality. The minimum number of households per analysis zone was 100 households.

A *geographic information system (GIS)* form was designed to do automated linking of zones based on the various modes available. The demarcation/border lines of the TAZ's were however problematic as dual carriage ways would often not link the same TAZ's. e.g. North Traffic would be between zones A and B, and south traffic between C and D instead of B and A. In most instances the border lines of the zones were based on the centre lines between the dual carriage way. In other words this meant that in the morning peak, people would travel through one TAZ and during the evening peak through another TAZ, using the same route. This did not make sense. It was necessary to adapt the TAZ's to areas now termed "bubbles" that made more sense in terms of their borders. In this process some TAZ's were grouped together.

Then again some TAZ's were exceptionally big, irregularly shaped, and did not form geometric shapes with equal cross sections. When a highway did cross such a zone, the zone is linked from its centroid to the next zone's centroid causing skewed distances for the modes. This made it possible for another mode to be selected by the model leading to a less optimised solution. To counter this problem, all highways were created manually with their own virtual bubbles, at intersections, linked to each other to form a highway that is roughly based on existing interchanges and on and off ramps. The relevant bubbles were then linked to the virtual bubbles with access routes that resulted in a more accurate distance allocation. The downside was that a large amount of virtual bubbles were created that tends to slow down model execution. In an ideal situation, the bubble centroids should be close to major nodes (interchanges, stations, mobility hubs) etc.

High density TAZ's, in terms of transportation, could be smaller bubbles and lower density TAZ's calls for larger bubbles. In the cases where adjacent TAZ's differed too much in size (<50%) linking of the bubble centroids resulted in skewed distances.

Route information (distances, modes, links, etc.) are derived from geospatial information. This is then overlaid by input data such as tabled in this dissertation.

1.3.3.2 Commuters

One of the objectives of the NHTS was to use the source and destination data generated by the survey to calculate the flow of commuters between TAZ's, deriving commuter patterns, populations and types (private or public) commuters are generated at their TAZ sources (bubble) and are designated by their destination and the type of commuter (private or public) flow of commuters happens along a pathway (route or link between two bubble centroids) using a vehicle (mode) resulting in a trip.

The type of commuter is defined by the NHTS (National Household Transport Survey 2003, 2005). Commuters having their own transport are defined as private with the assumption that they own a car. The type of commuter (private or public) determines the mode and vehicle types that could be used e.g., Taxi (Vehicle) on Highway (Mode) for Public Commuter, or Car (Vehicle) on Regional Road (Mode) for Private Commuter.

It was ruled that:

- Commuters can change over from private to public in the morning traffic but not back to private.
- In the afternoon commuters can change over from public to private but not back to private again on the same day. An example of this would be the Gautrain, where a commuter would take a bus to the train station and then reach their destination station where they would change to their private vehicle. The assumption here is that once in their private vehicle they will continue directly to their home destination without changing back to a bus, taxi or train. A shift to a public form of transport thereafter will also unduly complicate the modelling process, undermining the basic premise of a simplistic yet strategic modelling process.
- Further, all commuters must reach their destinations.

The changeovers should balance for the same bubble between morning and afternoon traffic.

1.3.3.3 Pathways or Infrastructure

The links between bubbles are limited by the existing infrastructure. Only in the case of the Gautrain were future infrastructure considered.

However, once an understanding of the commuter flows have been developed the model can also be used to test new non existing pathways, for instance, a new bus service, overhead ultra light rail system or even a “GridCar Train”.

1.3.3.4 Modes and Energy

The modes and energy combinations have been chosen to reflect a reasonable range of options in order to illustrate the functioning of the model. These were to some extent limited by the incomplete information and statistics. Mode-energy combinations can of course be expanded to include future options still to be introduced into the system.

1.3.3.5 Objective Functions

The main objective function was to optimise for the best mode-energy combinations to use for moving people from home to work in terms of maximising performance expressed as people kilometres/hour, while minimising energy consumption and CO₂ emissions. Toxic emissions were used as a constraint.

Other objective functions can also be calculated. One could also find the optimal solution in terms of minimising cost, travel time, energy consumption, emissions, or even budget.

These objectives could not be related to each other to allow for simultaneous optimisation as they compete in some cases for preferential sequencing, but optimisation can be done in a sequential step process whereby each objective is optimized, and then used as a constraint for the next

objective. This can be done by reducing the constraining effect with a factor to allow for degradation in overall performance to improve on another objective the calculated solution of the model represents the final steady state, and not the interim transient states to get to final.

Not part of the original scope, but as suspected, it would be possible from the outcomes of the model to indicate the economic gain a country may generate in terms of foreign exchange savings and pollution and greenhouse gas prevention. For a developing country this may provide an opportunity for green investments and carbon exchange deals. Should further work be done with the model, this could be further explored.

1.3.4 Model testing and verification

Once populated with the available data, the model could be subjected to the process of verification of its performance. Verification involved running the model with increasing relaxation of constraints, to determine if results obtained were realistic. The results obtained should reflect the appropriate increase or decrease in the prioritised objective function, based on the degree of relaxation of constraints.

1.3.5 Scenario building for validation purposes

In order to determine if the model is indeed suitable for proposed uses, it is necessary to define scenarios that can be compared to expected outcomes. In the case of this model, it is necessary to consider the value that this model offers in terms of decision support. The most relevant and topical scenario to consider is the low carbon future, in which emissions are reduced. The transport sector as a major emitter of greenhouse gases is a natural target. Gauteng, due to its high density of vehicles on the road, and proportion of vehicles to commuters, is also a preferred test case.

Two scenarios will be used to show the value of the model. In the first scenario, also deemed the reference or base case, the focus is on limiting the duration of the trips conducted by commuters. In the second scenario, the focus shifts to limiting the global warming potential of the modes of the transport available to commuters. The result of this optimisation process should yield (based on the prioritisation of objective functions) a cost figure for reducing greenhouse gas emissions. In a follow-up study, this figure can be used, if compared to real life data, to roughly calculate the abatement cost of emissions from the transport options. An abatement figure, so derived, could be used to assist in formulating a position on a carbon tax. This carbon tax, if imposed on fossil fuelled modes of transport, will provide the necessary funding source for mitigation measures.

The follow-up study should therefore ensure that this abatement figure is derived correctly and can be tested by other models where applicable. The model also has the added benefit of allowing for different alternatively powered transport options to be included, understanding what opportunity may exist for this technology option.

1.4 Conclusion

South Africa has limited access to a domestic supply of liquid fuels, with just over 30% of liquid fuels being sourced from the synfuels industry in South Africa. On- and offshore reserves of crude oil are practically non-existent. Therefore it is necessary to conserve as much fuel as possible. Market

signals indicate major increases in crude oil prices are imminent. Coupled to a probable Peak Oil Scenario, the future availability of cost effective crude oil supplies appears constrained and most likely to peter out by 2030. It is vital therefore that South Africa be proactive in its approach to transport planning and adopt measures that place it on a more sustainable trajectory.

With a proposed CO₂-equivalent emission reduction target of 34% reduction by 2020 and 42% by 2025, it is vital that the true costs of mitigating the impact of greenhouse gas emissions are understood. This section has defined both the international and domestic energy landscape and what pressures are facing the transport sector. With climate change mitigation as topical as it is, it makes sense for decision makers to be considering (at a high-level) the means by which public transport can be made greener. The means to make that decision is through a strategic decision-making tool or model. Many transport models are in existence today and it is firstly necessary to ascertain if those identified are suited to this application. If not, a new model has to be developed that meets all the requirements of this study, as detailed in the Objectives section.

Chapter 2

SUPPLY CHAIN MODEL DEVELOPMENT

Summary

This chapter focuses on the literature review conducted on similar transport planning models identified. These models were assessed for their suitability in undertaking the activities specified in the Objectives section of Chapter 1. Once assessed, the author proceeded to highlight the shortcomings of these models in being used as a high-level decision-making tool.

The search for a suitable high-level decision-making support tool in SA did not yield any results and therefore the author proposed the development of a new, customised solution for the SA market. The product development phase is detailed, in terms of the algorithms, definitions and workflow. The data and assumptions that were used to populate the model are also included.

2 SUPPLY CHAIN MODEL DEVELOPMENT

2.1 Background

This chapter provides an introduction to transport planning and optimisation models and explains their relevance in presenting complex problems in a simple form. The role of models in policy formation and decision making are discussed. Decision support systems (DSS) used by decision makers to formulate policies are presented and categorised.

In order to test whether a new model should be developed for the purpose of meeting the objectives specified for this study, it is necessary to assess the models that are readily available in the market. There may well be modelling tools that exist that could perform the same functions as those required in this study. On the other hand, these models may prove too costly to purchase and/or maintain. The models may also prove complex to operate for the purpose of a high-level decision-making exercise.

The decision of whether to proceed with the development of a new, supply chain-based model is then largely influenced by the complexity and maintenance costs of existing modelling options. The development of the new model is detailed, with the relevant definitions and workflow processes. It is worth noting at this stage that supply chain models are not new, but the application of optimising for energy efficiency and emission reduction in transport planning is novel.

2.2 Selection of supply chain model

2.2.1 Literature review of transport models considered

2.2.1.1 Definition

Models are simplified or idealized descriptions, or conceptions of a particular system, situation, or process, often in mathematical terms, that are promulgated as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.; a conceptual or mental representation of something [considered too complex to understand] (adapted from Oxford English Dictionary, 2011). In practical terms, a model is similar to but simpler than and easier to understand than the system it represents. Models assist policy makers to understand and predict the effect of changes in a situation or impact of a particular decision. A model should however be an idea of the real system and include most of its prominent characteristics. Also, it should not be so complex that it is impossible to understand and test (Anu Maria, 1997).

2.2.1.2 Application of Models

Generally, models used for a simulation study are mathematical models developed with the help of simulation software. Mathematical models are usually classified as (Anu Maria, 1997).

- a) Deterministic (input and output variables are fixed values) or
- b) Stochastic (at least one of the input or output variables is probabilistic);
- c) Static (time is not taken into account) or
- d) Dynamic (time-varying interactions among variables are taken into account).

Typically, simulation models are stochastic and dynamic (Anu Maria, 1997). Simulations are tools that help to measure, test, standardize or evaluate the performance of an existing or proposed system. Simulation helps to answer questions like: What is the best design for a new transport system? What are the associated resource requirements? How will a transport network perform when the traffic load increases? (Anu Maria, 1997)

A linear program is a mathematical formulation of a problem. One can define a set of decision variables which describe the decisions we wish to make. Then we formulate or define an objective function using these variables. We also define a set of constraints which restrict the decision options open to us. Depending on the decision we wish to make, the task of solving a linear program is to find the feasible solution to the problem that optimizes our objective function. If it is a maximization problem, this will be the solution with the largest objective value. If it is a minimization problem, then we'll select the solution with the smallest objective value. This solution is called the optimal solution. In linear programming the commonly understood definition is that variables must be continuous and the objective function and constraints must be linear expressions.

Linear programming is therefore a mathematical problem solving technique that:

- makes various assumptions about a set of data,
- works within well defined constraints and
- produces a solution by modelling these assumptions and constraints

Practical optimisation is the art and science of allocating scarce resources to reach the best possible effect. Optimisation techniques are commonly used pertaining to questions of industrial planning, resource allocation, scheduling and decision-making, to name but a few examples.

Real life problems typically contain a lot of details and complexities, some relevant and some not. From this complexity the essential elements are extracted to create a model. An algorithm is then constructed in order to solve the mathematical problem. Due to the complexity and large number of calculations, computers are typically used in the process of solving the algorithm. An important part of successful applied optimisation is still in determining what is and what is not important during the process of selection and to understand the solution constraints.

A linear program is one of the most widely used techniques for constraint optimisation (Dantzig and Muthapa, 1997). The first step is to accurately define the real world problem. Analysing this problem then leads to the building of the algorithm or model that will be used to solve the problem. During analysis, the essential elements of the problem are defined. Once the algorithm has been

constructed numerical methods are used to create a program that can be solved using a computer. By computing the algorithm one then can verify if the algorithm is being solved in the way it was intended to. Once this has been done one can be assured that the algorithm can be used to solve the problem. This however is not the end of the process. The next step involves validation and sensitivity analysis. The results of the computer calculation are now compared with observations in the real world. Should the results not be appropriate or not make sense, the model needs to be modified and the process repeats.

2.2.1.3 *Models and Policy Formulation*

Models play a critical role in policy formulation and decision making in transport planning, land use, energy and the environment, (Goyns, 2008). Policy makers use decision support systems as tools to determine the impact of transport and energy services on the environment, the society and associated effect on the economy. These models take into consideration macro-economic indicators to derive demand for fossil fuel and the emission resulting there from. Decision Support Systems are complex computer programs that are used in forecasting, simulating and optimising the impact of policy options for different situations with further ability to take into consideration certain externalities.

A brief synopsis of the salient information describing the relevant models identified is provided below.

2.2.1.3.1 TRAN

TRAN is the United States of America's National Energy Modelling System (NEMS), (DOE/EIA, 2004). NEMS is a suite of models used by the US Energy Information Agency (EIA) to estimate the demand, supply, conversion and economic impacts of energy use within the different sectors of the US economy. The purpose of TRAN is to forecast energy demand, vehicle fleet structure and emissions from transport. Inputs into TRAN include fuel prices, new vehicle sales by region, economic data (such as GDP and income distribution), demographic data (such as population and age distribution) and defence spending.

2.2.1.3.2 STEEDS

Scenario-based framework to modelling Transport technology deployment: Energy–Environment Decision Support (STEEDS) (Brand *et al.*, 2002) is software based decision support system. Its purpose is to allow decision makers to evaluate transport energy and environment policy options without needing to integrate a variety of different models. This is accomplished by integrating several models into one system.

The input phase of the modelling process allows users to develop various scenarios based on parameters external to transport systems. This can include population growth, economic development and international fuel prices. Policy options are also developed at the input stage such as investment in public transport, local fuel prices and land use policies. The modelling phase of the system uses information from scenarios and policy options combined with information about vehicle fleets, transports system and lifecycle analysis to calculate transport demand and related fuel consumption and emissions.

2.2.1.3.3 TREMOVE

TREMOVE was developed by Transport and Mobility Leuven for the European Commission to simulate transport and environment policies and consider their impacts on transport demand, modal shares, fleet structure, emissions reduction technologies and emissions from transport (De Ceuste *et al.* 2006). The original version of the TREMOVE model was developed as a technical motivation for the European Auto-Oil II programme. The model consists of three main modules estimating travel demand, vehicle fleet size and structure and a fuel consumption and emissions. Two additional modules calculate life cycle emissions and changes in welfare due to the policy scenarios. TREMOVE consists of several sub-models, each developed within programmes supported by the European Commission. An understanding of the operation of the sub-models can be overwhelming and the advantage of a single integrated system such as STEEDS is emphasised, (De Ceuste *et al.* 2006)

2.2.1.3.4 NEMESIS

The NEMESIS model (new econometric model for environment and sustainable development implementation strategies) is an econometric macro/sectoral model built by a European research consortium, (Brécard *et al.*, 2006). It can be used for several purposes including: assessment of structural policies, mainly environmental and R&D policies; studies of short, medium and long-term consequences of a wide spectrum of economic policies; macro and sector-based “forecasts” for short and medium terms (up to 8 years) and for building baseline scenarios (for up to 30 years). Three principal characteristics of the model distinguish it from others used for similar analysis:

- a) An energy-environment module which transforms activity indicators from the macro model at a sectoral level into energy relevant indexes with price effects and pollutants emissions (CO₂, SO₂, NOX, HFC, PFC and CF₆).
- b) Five types of conversion matrices for interlinking: final consumption, investment goods, intermediate consumption, energy-environment and technological transfers. These are necessary because goods/services produced by firms are often used in “bundles” in final demand.
- c) The supply-side block which incorporates some properties of new theories of growth.

2.2.1.3.5 E3MG

E3MG is an econometric simulation model of the global energy–environment–economy system, estimated on annual data (1971–2002) and projecting annually to 2030 and every 10 years to 2100 (Dagoumas & Barker., 2010). It is a non-equilibrium model with an open structure such that labour, foreign exchange and public financial markets are not necessarily closed. It is very disaggregated, with 20 world regions (including the 13 nation states with the highest CO₂ emissions in 2000), 12 energy carriers, 19 energy users, 28 energy technologies, 14 atmospheric emissions and 42 industrial sectors, with comparable detail for the rest of the economy.

The model represents a novel long-term economic modelling approach in the treatment of technological change, since it is based on cross- section and time-series data analysis of the global system (1970– 2002) using formal econometric techniques, and thus provides a different perspective on stabilization costs. The methodology of the model can be described as post-Keynesian, following

that of the European model E3ME developed by Cambridge Econometrics (E3ME), except that at the global level various markets are closed, e.g., total exports equal total imports at a sectoral level allowing for imbalances in the data.

E3MG is designed to address the issues of energy security and climate stabilization both in the medium and long terms, with particular emphasis on dynamics, uncertainty and the design and use of economic instruments, such as emission allowance trading schemes. The model is able to address the question of the costs of stabilizing atmospheric concentrations of greenhouse gases by projecting emissions up to 2100. At this stage, the model is not yet finalized and continues or represents work in progress. The model will be extended to include multi-gas abatement and Foreign Direct Investment and applied in a model comparison exercise.

2.2.1.3.6 e3.at

The core of the macro-econometric model system e3.at consists of an economy model, including input–output tables, labour market data, and the system of national accounting and balancing items (Stocker et al., 2011). Additional modules are an energy model, a material model, a transportation model, a regional housing inventory model and a model for international trade. “e3.at” has a soft link to the world model GINFORS (Global Inter Industry Forecasting System (Meyer et al., 2007; Lutz et.al. 2010), in order to illustrate the effects of international trade on the Austrian economy. e3.at was recently extended by a regional housing inventory model (Bohunovsky et. al., 2010), showing the energy consumption of private households on a regional level. Depending on the improvement of accommodation (including heating systems), the energy consumption and CO₂ emissions are influenced by changing energy sources and/or energy-efficient heating systems. The e3.at model also comprises a transportation module for private households. This enables the analysis of mobility and allows valuable insights about the effects of transport on total energy consumption and CO₂ emissions. Großmann and Wolter (2010).

2.2.1.3.7 AIM/CGE Model

The AIM/CGE model is a recursive dynamic CGE (computable general equilibrium) model on a global scale (Matsumoto & Masui, 2011). The model consists of 21 industrial sectors and 24 world regions. These definitions are based on the GTAP6 database, which is also used for the economic data. In addition, the Energy Balances section is used for the energy data, the EDGAR 3.2 Fast Track 2000 is used for the emission data, and the FAOSTAT module is used for the land-use data for the base year data. The basic mechanism of this model is similar to the GTAP model and the GTAP-E model. However, the AIM/CGE structure differs from the rest. Some significant differences can be summarized as follows:

- a) dynamic structure is considered; not only CO₂ emissions but also other GHG, aerosol, and chemical emissions are incorporated;
- b) Power generation by various resources such as fossil fuels, nuclear, water, and other renewables (e.g., geothermal, solar, wind, and biomass), and also that with CCS (carbon capture and storage) technology are considered. Concerning the dynamics in the model, the acceleration principle is applied to determine the investment and autonomous energy efficiency improvement is adopted for the technological change.

2.2.1.3.8 MARKAL

MARKAL (MARKet ALlocation) is a bottom-up, dynamic linear optimization model (Kypreos, 1996). First developed in the 1970s, the model has undergone continuing refinement and extension, coordinated by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. Central to MARKAL is the so-called reference energy system (RES), which represents a user-specified network of energy technologies.

The RES can cover the entire energy system and range from fuel extraction to processing, transmission and distribution, storage, and demand for energy services at the end-use level. The model then optimizes over the time horizon of the analysis, generating that mix of fuels and technologies out of the associated database that minimizes discounted cumulative costs. The key output of MARKAL for our purposes is the technology dynamics, i.e., the specific technologies (specified in the database) that would be used at every time step to satisfy the projected demand while meeting a constraint, such as CO₂ emissions target (e.g., Kypreos, 1996).

2.2.1.3.9 GTAP-E

GTAP-E is a Computable General Equilibrium (CGE) models. CGE models are used in economic analysis to simulate the impacts of prospective policies taking into account inter-sectoral and international interactions. The CGE model "GTAP-E" model, outlined in Burniaux and Truong (2002) modifies the production structure of the standard GTAP model in order to more closely mimic the ability of firms to substitute among alternative fuels as well as between labour, capital and energy. It also incorporates CO₂ emissions from the combustion of fossil fuels as well as a mechanism to trade these emissions internationally. McDougall and Golub 2007 subsequently streamlined and improved this particular model.

Uses of GTAP-E have ranged from biofuels (Banse et al., 2008; Hertel et al., 2010; Taheripour et al., 2010) to climate-change-induced changes in tourism demand (Berrittella et al., 2005), to the costs of climate mitigation policies (Nijkamp et al., 2005; Kemfert et al., 2006). Also, the framework has been used to examine water scarcity (Berrittella et al., 2006) and the economic impacts of a rise in sea levels (Bosello et al., 2007). Additionally, Gan and Smith (2006) utilized the GTAP-E model to investigate the cost competitiveness of woody biomass for electricity production in the U.S. under alternative CO₂ emission targets.

2.2.1.3.10 LEAP

LEAP is an energy-planning system developed at the Stockholm Environment Institute (SEI), Boston. The central concept of LEAP is an end-use driven scenario analysis, (Kumar & Srinivasachary., 1997). In this approach, the computer system is used to analyze the current energy scene and to simulate alternative energy futures along with environmental emissions under a range of user-defined assumptions. LEAP emphasizes the detailed evaluation of specific energy problems within the context of integrated energy and environmental planning for each 'what-if' scenario or combinations of scenarios. This in turn can help clarify which policies, investments and actions are needed to guide energy demands and supply in that direction.

Within the LEAP framework, the problem considered is disaggregated into four so-called 'activity' levels, both in the energy part and in the associated environmental database. These levels are sector (activity 1); sub-sector (activity 2); end-use (activity 3) and device (activity 4), respectively. Finally, an energy intensity and emission factors for each pollutant are associated with each device at the fourth level. Under each activity level, five reference years can be chosen for which the energy demand and environmental emissions are evaluated.

2.2.1.3.11 Integrated Transportation and Land Use Package (ITLUP)

The ITLUP framework has been developed and applied by Professor Stephen Putman at the University of Pennsylvania, Philadelphia, USA, over 25 years. It includes a number of sub-models, the best known of which are DRAM (Disaggregate Residential Allocation Model) and EMPAL (Employment Allocation Model). It uses a Lowry-derivative form (Lowry, 1964) to allocate households (usually by four income categories, though further categorizations are possible), employment (usually by four types, though more detailed Standard Industrial Classification (SIC) groupings are possible) and travel patterns (public and private modes). Exogenous study area forecasts of employment, population and trips, activity rates and household types are inputs. Detailed documentation of the model is provided by Putman (1983, 1991, 1994), with useful summary descriptions also available (Webster *et al.*, 1988; Wegener, 1994; Southworth, 1995; Putman, 1996).

Notable features of ITLUP are as follows:

- a) ITLUP (more specifically, DRAM and EMPAL) is the most widely used spatial allocation framework in the USA today. A recent count indicates over a dozen active US applications (Putman, 1997); although over 40 calibrations have been performed across the USA and elsewhere.
- b) It contains a multinomial logic modal split sub-model, as well as a trip assignment sub-model that can support various network assignment algorithms. Trip generation and distribution are developed within DRAM, simultaneously with household location. However, DRAM and EMPAL often are used separately and have been linked in actual applications with other commercial travel demand forecasting models (including EMME/2, TRANPLAN and UTPS). Thus, considerable detailing of travel demand and travel costs can be provided through exogenous links.
- c) Compared with other frameworks, it has relatively parsimonious data requirements. Southworth (1995) notes that an important advantage of DRAM/EMPAL is its basis in generally available data (i.e., related to population, households and employment). However, it is also noted that this reflects a weakness of the approach; namely, that the framework does not account for land market clearing processes (or, it follows, other market clearing processes).
- d) A recent development is METROPILUS, which is aimed at improving linkages with geographic information system (GIS) databases and in revising the framework towards greater system modularity. It operates within an Arc View shell, which supports linkages with an Arc View GIS database, and is Windows compatible (Putman, 1997)

2.2.1.3.12 MEPLAN

The MEPLAN framework is contained in proprietary software developed by Marcial Echenique and Partners Ltd in the UK, a private consulting firm. It draws on 25 years of experience in practical integrated urban modelling, with work on the software package itself beginning in 1985. It has been applied to over 25 regions throughout the world, including Sacramento, California and the Cross-Cascades Corridor in the US. Detailed documentation can be found in various sources (Echenique *et al.*, 1969, 1990; Echenique and Williams, 1980; Echenique, 1985; Hunt and Echenique, 1993; Hunt and Simmonds, 1993; Hunt, 1994).

MEPLAN is an aggregate model: space is divided into zones, quantities of households and economic activities (called 'factors' or 'sectors') are allocated to these zones, and flows of interactions among these factors in different zones give rise to flows of transport demand. The heart of the framework is a spatially disaggregated input–output matrix, or social accounting matrix, extended to include variable technical coefficients, labour sectors and space sectors. All economic activities, including households, are treated as producing and consuming activities, with consumption patterns expressed using technical coefficients. Spatial disaggregation is accomplished by having the further production arising to satisfy consumption allocated among the spatial zones according to discrete choice models reacting to the prices for such production. The resulting interactions among zones give rise to the demand for travel.

Temporal change is simulated by considering sequential points in time. Space (both land and floor space) is 'non-transportable' and must be consumed in the zone where it is produced. The supply of space in each zone is fixed at a given point in time. The technical coefficients for the consumption of space are elastic with respect to price, and prices for space that ensure demand equates with supply in each zone are established endogenously as part of an equilibrium solution established for each point in time considered. Prices for the outputs of other sectors are established endogenously running back along the chains of production–consumption.

Travel demands arising for a given point in time are allocated to a multimodal network using logit functions representing mode and route choice, taking account of congestion. Transport dis-utilities feed back into the next time period, representing lags in response to transport conditions. Exogenous demand, which is analogous to the 'Lowry' (1964) basic sector, provides the initial impetus for economic activity. Changes in study-wide exogenous demand and in the quantity of space in each zone from one time period to the next fuel economic change, with these changes allocated among zones.

2.2.1.3.13 Modelo de Uso de Suelo de Santiago (MUSSA)

MUSSA is an operational model of urban land and floor space markets developed by Professor Francisco Martínez for Santiago, Chile. It is 'fully connected' with a thorough four-stage model (known as ESTRAUS); together, the combined models are referred to as 5-LUT, and provide equilibrated forecasts of land use and travel demand for Santiago. The model has been used to examine various transportation and/or land-use policies, usually involving transit as a central component of the policy. Documentation of the model is provided by Martínez (1992a, b, 1996, 1997, 2000) and Martínez and Donoso (1995). Notable features of MUSSA include the following:

- a) Consistently based throughout on an extremely rigorous and compelling application of microeconomic theory.
- b) Equilibrium model of building stock supply and demand. Demand for building stock (whether by households or firms) is based on their willingness to pay (WP). Buyers attempt to maximize their surplus (WP less price actually paid), while sellers attempt to maximize the price paid. Building stock is supplied by developers so as to maximize profits, given the apparent demand. Building stock prices are endogenously determined within the equilibration process.
- c) Solves for a static equilibrium in the forecast year by adjusting the amount of building stock supplied, a supply response, and consumers' expectation levels (expected utility to be obtained from their housing), a demand response, until demand and supply balance. The model end state is path independent and does not require solution for intermediate year results, although such intermediate results can also be generated.

Uses traffic analysis zones as its spatial unit of analysis, thereby providing a relatively fine level of spatial disaggregation. In addition, extensions to more micro-levels of spatial analysis are being investigated (Martínez, 1997).

Table 2 provides the summary of the various models considered. The table includes a short description of the option considered, the related accessibility and ease of use. From the analysis undertaken, it is evident that there are numerous models in existence, which largely share common approaches to problem solving. In most cases, the models may be available free of charge, but do require significant training of operating staff to utilise them. In addition, suppliers of models charge a fee to maintain or update the model. The user is then exposed to significant additional costs. In addition, the models are largely complex in nature, perhaps too detailed and complex for the purpose of being a high-level decision-making tool.

A domestic model, derived from a supply chain model, has been evaluated to determine if it is suitable for customisation. If so, a robust, proven solution can be adapted to meet the needs of this study. The next section goes into detail regarding the nature of this model and how the necessary algorithm has been compiled.

Table 2 details the analysis of the models surveyed. The table highlights the major principles of operation, the levels of complexity as well as the bases for accessing the models. Where the information is not clearly available, the author has indicated this with the appropriate text in the relevant box.

TABLE 2: SUMMARY OF MODELS SURVEYED

Model	Operation	Function	Complexity	Accessibility
TRAN	Energy Demand, Transport, Emission	The purpose of TRAN is to forecast energy demand, vehicle fleet structure and emissions from transport. Inputs into TRAN include fuel prices, new vehicle sales by region, economic data (such as GDP and income distribution), demographic data (such as population and age distribution) and defence spending.	High	Web access but installation and input of data and scenarios require technical assistance.
STEEDS	Transport, Energy, Environment.	Its purpose is to allow decision makers to evaluate transport energy and environment policy options without needing to integrate a variety of different models. This is accomplished by integrating several models into one system.	Medium	STEEDS requires understanding of several models since the strength of this model lies in its integration of other models into one. Readily available but does require expert assistance.
TREMOVE	Transport, Environmental Policies	To simulate transport and environment policies and consider their impacts on transport demand, modal shares, fleet structure, emissions reduction technologies and emissions from transport.	High	TREMOVE was developed by Transport and Mobility Leuven for the European Commission to simulate transport and environment policies and consider their impacts on transport demand, modal shares, fleet structure, emissions reduction technologies and emissions from transport. The model software is freely downloadable at www.tremove.org .
NEMESIS	Policy, Environment, R&D	It can be used for several purposes including: assessment of structural policies, mainly environmental and R&D policies; studies of short, medium and long-term consequences of a wide spectrum of economic policies; macro and sector-based “forecasts.	Medium	The model is readily available but considers far too many factors to be used for high-level decision-making purposes.
E3MG	Macro-Economics, International Trade, Energy.	E3MG is an econometric simulation model of the global energy–environment–economy system, estimated on annual data 1971–2002 and projecting annually to 2030 and every 10 years to 2100.	Medium	The E3MG model was developed by the Cambridge Centre for Climate Change Mitigation Research, Department of Land Economy, University of Cambridge. Information about the model and its applications is available at the Cambridge econometrics website.

(Continues overleaf)

Table 2 (Contd.):

Model	Operation	Function	Complexity	Accessibility
e3.at	Macro-Economics, International Trade, Energy.	Macro-econometric model system e3.at consists of an economy model, including input–output tables, labour market data, and the system of national accounting and balancing items. Additional modules are an energy model, a material model, a transportation model, a regional housing inventory model and a model for international trade.	Low	The model is suitable for high-level decision-making but is data intensive and requires technical assistance to install and maintain.
AIM/CGE	Energy, Climate Change, CO₂ Emission, Fossil Fuel	It's used for simulating global energy and climate change environment including CO ₂ emissions and GHG, aerosol, and chemical emissions. It also incorporate Power generation by various resources such as fossil fuels, nuclear, water, and other renewables (e.g. geothermal, solar, wind, and biomass), and also that with CCS (carbon capture and storage) technology are considered.	High	High-level of complexity coupled with data intensity limits the efficacy of AIM/CGE. The model can be accessed online.
MARKAL	Energy Planning, Environmental and Climate Change, CO₂ Emission, Fossil Fuel	It covers the entire energy system and range from fuel extraction to processing, transmission and distribution, storage, and demand for energy services at the end-use level. The model optimizes over the time horizon of the analysis, generating that mix of fuels and technologies out of the associated database that minimizes discounted cumulative costs.	Medium	MARKAL was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). The model can be accessed from the IEA website ¹ .
GTAP-E	Carbon Emission, Fossil Fuel, Energy, Economy and Trade Linkages	GTAP-E is used in economic analysis to simulate the impacts of prospective policies taking into account inter-sectoral and international interactions. It also incorporates CO ₂ emissions from the combustion of fossil fuels as well as a mechanism to trade these emissions internationally.	Medium	GTAP-E is the environmental version of Global Trade Analysis project (GTAP) developed by the Purdue University, The model can be accessed online from the Purdue University website ² .

Table 2 (Contd.)

¹ The Energy Technology Systems Analysis Program (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy,economy,environment and engineering (4E) analytical capability The MARKAL Model is accessible from the IEA website at <http://www.iea-etsap.org/web/index.asp>

² GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. GTAP's goal is to improve the quality of quantitative analysis of global economic issues within an economy-wide framework. Since its inception in 1993, GTAP has rapidly become a common "language" for many of those conducting global economic analyses. The environmental version of GTAP, GTAP-E, can be downloaded from https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=923

Model	Operation	Function	Complexity	Accessibility
LEAP	Energy, emissions, alternative energy	Long –range Energy Alternatives Planning System (LEAP) is a tool for Sustainable Energy Analysis used to analyze the current energy scene and to simulate alternative energy futures along with environmental emissions under a range of user-defined assumptions.	Low	LEAP is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. LEAP can be accessed from the Community for Energy, Environment and Development (Command) website ³ .
ITLUP	Transport	It is used to simulate transport trends by households, employment (usually by four types and travel patterns. It also forecasts employment, population and trips and activity rates.	High	The ITLUP framework has been developed and applied by Professor Stephen Putman at the University of Pennsylvania, Philadelphia, USA. The model is not easily accessible.
MEPLAN	Integrated Land Use	It is used to model economic activities and particularly treats households as producing and consuming activities.	High	Highly complex model that does not specifically relate to the objectives of this study, although there are elements that the model considers that are relevant.
MUSSA	Transport, Land Use	The model has been used to examine various transportation and/or land-use policies, usually involving transit as a central component of the policy.	Medium	MUSSA was developed by the Transport and Land Use Modelling Laboratory of the University of Chile. The software is available for download at www.mussa.cl .

³ LEAP is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyze emissions of local and regional air pollutants, making it well-suited to studies of the climate co-benefits of local air pollution reduction. LEAP can be accessed from the Command website at <http://www.energycommunity.org/default.asp?action=47>

2.2.2 Summary of review of models

While most of the planning tools considered are considered effective for their intended use, they are in fact considered too complex for the purpose identified in this study. Most of the models are readily accessible and links, where possible, have been provided to these models. Most are available for download but will require some form of assistance and training for installation and maintenance. For a high-level strategic decision support tool, it is vital that the model be easy to update and use. These models are designed with transport planners, town planners, energy planners and researchers in mind. There is an obvious need to identify a modelling tool that is readily accessible, low in complexity and yet flexible enough to provide the necessary high-level answers that government authorities need.

The author therefore proposes that a new, supply chain-based model be developed or an existing one customised for the objective specified in this report. A product available in the market, called Tactix, has been identified as a suitable option. This is an example of a linear optimisation model. The next section details the reason for this choice, as well as the customisation thereof for the objectives specified.

2.3 Requirements of supply chain model

The model that has been chosen for this purpose has been selected on the basis of its simplicity of use. Notwithstanding this, there are key definitions of model parameters that need listing. As has been stated before, the model is an example of a linear programming optimisation supply chain model. Four objectives were considered in the optimisation process, namely time, cost, energy and Global Warming Potential (GWP). These and other parameters are detailed in the following sub-section.

2.3.1 Definitions

2.3.1.1 Linear Programming (LP) Formulation

The LP formulation is the heart of the entire model. It expresses the relationships between the variables (decision points) and the constraints that govern the model. Variables are the quantitative decisions that are made to satisfy the objective of the model and are defined on a very detail level (multiple dimensions), such as the number of commuters travelling from location 1 to location 2 in a taxi on the highway, during morning peak. The constraints however could be either on a detailed or on a more aggregated level, depending on the dimensions that are used to express the constraint.

2.3.1.2 Dimensions

Dimension defines the grain of the model, with more dimensions added to a variable or constraint resulting in more detailed decision making ability. There are a number of dimensions in the model, and will be discussed in detail below. These dimensions can be mixed and matched in

the model building section in groups that make logical sense, and for which data are available on the same level that is defined in the dimensions.

2.3.1.2.1 Bubble

Bubbles act as the location dimension, and refer to a geographical area. Depending on the size of the bubble, a micro (Sandton) or macro (Johannesburg) model could be derived, but the smaller the bubbles, the more bubbles are required for a higher level model that results in more complex models with exponential increases in solving times. The aim is to define bubble sizes that would provide an amount of detail suitable for comparative sensitivity studies, without taking days to solve. For smaller bubbles the level of data requirements also improves significantly.

2.3.1.2.2 Commuter

A commuter is defined in terms of his destination and whether he is private or public transport inclined. Commuters originate in one bubble (from location) and would like to travel to its destination bubble (to location). The commuter can travel from one bubble to the next bubble until it reaches its destination.

2.3.1.2.3 Mode

Modes are infrastructure related links between nodes (bubbles) and defines the type of access method, e.g., highways, rail links, Gautrain, regional roads, BRT, access roads, etc.

2.3.1.2.4 Vehicle

Vehicles define the type of vehicle that can be used for trips between bubbles. A vehicle is defined as either private or public transport and can only use certain modes, e.g., cars are not allowed to travel on rails.

2.3.1.2.5 Objective

The model has various objectives that are optimized. From a modelling perspective, objectives are added as a dimension to improve the storage of data and definition of constraints based on the objective.

2.3.1.2.6 Bucket

A Bucket is a time period, and is primarily built for a single period such as the morning traffic peak that stretches over 3 hours. Multiple buckets could be defined, but significantly increases the size of the model and the time it takes to solve.

2.3.1.2.7 Version

Multiple versions can be defined to store previous model results for comparison and scenario purposes. Additionally with the multi-objective nature of the model, each objective is solved as a different version.

2.3.1.3 Variables

The variables address the decisions that are made within the model. These variables are aligned with the strategic intent of the model objective, and illustrate the behaviour of the model. The values that the variables can take on are dependent on the constraints of the model.

2.3.1.3.1 Populations

Defines the number of commuters there are in a specific bubble at a specific point in time.

Dimensions

- Bubble
- Bucket
- Commuter
- Version

2.3.1.3.2 Trips

A trip is classified as the movement of commuters between two bubbles using a specific vehicle and mode combination in a given bucket. A commuter would then travel from one bubble to the next using a single trip. In order for a commuter to reach its destination, multiple trips would then be required to move the commuter between adjacent bubbles.

Dimensions

- Bucket
- Commuter
- FromBubble
- Mode
- ToBubble
- Vehicle
- Version

2.3.1.3.3 Destination Reached

This variable registers the number of commuters that has travelled between bubbles and reached its destination.

Dimensions

- Bubble
- Bucket
- Commuter
- Version

2.3.1.3.4 Commuter Change Overs

A commuter can decide whether he wants to change his transport preference from private to public at a specific point. Commuters can change from private to public, but not from public back to private for morning peaks, and change from public to private during afternoon peaks.

Dimensions

- Bubble
- Bucket
- CommuterFrom
- CommuterTo
- Version

2.3.1.3.5 Mode and Node Builder

A new mode can be constructed between two bubbles such as building a highway between two bubbles.

Dimensions

- Bucket
- FromBubble
- Mode
- ToBubble
- Version

2.3.1.4 Objective

The objective drives the overall direction that the variables interact with the constraints. For different objectives, different behaviour would be observed.

Minimize Travel Time					
-	$\sum_{j \in J} A_j X_j$	-	$\sum_{j \in J} E_j X_j$	-	$\sum_{j \in J} T_j X_j - \sum_{j \in J} A_j X_j$
Cost		Energy		Travel Time	GWP
					M A X
					0
Version					

The model is built to be a multi objective model. Unfortunately the various objectives are not expressed in the same unit of measure, and cannot be solved simultaneously. To solve this problem, the model is solved for a specific objective. To compensate for the various objectives,

which are not related to each other, a multiple solution approach is implemented, whereby the model is first solved for any given objective. Once solved, the result of the objective is added as a constraint with a relaxed value e.g., Minimize travel time resulted in 2000 man hours, but is added as constraint with a relaxation of 10%. Now the next objective could be solved for with the travel time constraint not exceeding 2200 man hours.

The following objectives are added:

2.3.1.4.1 Travel Time

Travel Time would result in vehicle, mode and trip selections that would minimize the overall travel time in the model by selecting vehicle and trip combinations that would result in the shortest possible time to move from origin to destination.

2.3.1.4.2 Cost

Cost would result in commuters selecting the least possible cost to move between origin and destination, ignoring the travel time objective.

2.3.1.4.3 Energy

Energy would oblige commuters to select vehicle and trip combinations that would have the least impact on energy consumption.

2.3.1.4.4 Global Warming Potential (GWP)

Results in behaviour that would minimize the Global Warming Index of the model.

Whenever an objective is not selected, it would not appear as a term in the objective function, with at most one term within the objective function.

Terms

- Cost
- Energy
- GWP
- Travel Time

Dimensions

- Version

2.3.1.5 Constraints

The constraint has a direct impact on how the variables will react. Typically a constraint would be the maximum number of commuters that can travel between two bubbles on a given mode.

2.3.1.5.1 Balance Population

This is the most important constraint in the model and defines the interaction of the commuters at a bubble for a given period. Essentially the commuter movement at the bubble needs to balance the inflow and outflow of commuters so that commuters do not vanish or appear inexplicably. All commuters flowing into the bubble are positive terms, and those flowing out are negative, with the overall effect equal to zero.

Balance Population									
$-\sum x$	$+\sum x$	$-x$	$-x$	$+x$	$-\sum x$	$+\sum x$		=	0
Type Change From	Type Change To	Destination Reached	Population End	Population Start	Bubble Despatched	Bubble Received			- B Initial Population
Commuter, Bubble, Bucket, Version									

Terms

- Bubble Despatched – Commuters flowing out of bubble
- Bubble Received – Commuters flowing into bubble
- Destination Reached – Commuters reaching their final destination
- Population End – The number of commuters remaining in the bubble at the end of the bucket
- Population Start – The number of commuters in the bubble at the start of the bucket
- Type Change From – The number of commuter changing from private to public, or vice versa at the bubble
- Type Change To – The number of commuters changing from public to private, or vice versa at the bubble
- Initial Population – The initial commuter population in the beginning of the model

Dimensions

- Bubble
- Bucket
- Commuter
- Version

2.3.1.5.2 Max Destination

Once a commuter has reached its final destination they can be counted, and should be equal to the number of commuters that has the bubble as their final destination.

Max Destination	
$+ \sum X$ Destination Reached Qty	$= 0 + B$ Destination Required Qty
Bubble, Bucket, Version	

Terms

- Destination Reached Qty – Commuters reaching their destination
- Destination Required Qty – Total number of commuters that should reach their destination

Dimensions

- Bubble
- Bucket
- Version

2.3.1.5.3 Max Trip Constraint

For every trip variable there is an impact on various constraint types, such as maximum commuters between two bubbles, maximum emissions, etc.

Max Trip Constraints	
$+ \sum \sum X$ Commuters	$\leq 0 + B$ Max Commuters
FromBubble, ToBubble, Mode, ConstraintType, Bucket, Version	☐ Relax

Terms

- Commuters – The impact of the trips on the constraint
- Max Commuters – The maximum constraint value defined

Dimensions

- Bucket
- ConstraintType
- FromBubble
- Mode
- ToBubble
- Version

2.3.1.5.4 Max Build Mode and Node

New modes can be added to the model dynamically, and once build the commuters can make use of that mode between two bubbles.

Max Build Mode and Node	
$- \sum A X + \sum \sum X$ Build Commuters	≤ 0
FromBubble, ToBubble, Mode, Bucket, Version	☐ Relax

Terms

- Build – The maximum commuters that can use the mode if built
- Commuters – The number of commuters using the mode.

Dimensions

- Bucket
- FromBubble
- Mode
- ToBubble
- Version

2.3.1.5.5 Max Budget

In order to build new modes dynamically between two bubbles, the cost of the build should be taken into account, with sum of all building activity being less than the available budget.

Max Budget	
$+ \sum \sum \sum A X$ BuildModeAndNode	$\leq 0 + B$ Budget
Version	☐ Relax

Terms

- BuildModeAndNode – The total cost impact of all building activity
- Budget – The maximum budget allowance for building

Dimensions

- Version

2.3.1.5.6 Max Objective

These are the multi-object constraints that are added. These constraints only appear once each has been solved as a constraint and an objective value has been determined, e.g., Total Travel

Time was 2000 man hours, now it could be used as travel time constraint with a maximum of 2200 man hours. If the term has not been solved as an objective, the term will return a zero value.

Max Objective	
$+ \sum \text{Cost} + \sum \text{Energy} + \sum \text{TravelTime} + \sum \text{GWP}$	$\leq 0 + B$ Max Objective Value
Version, Objective	☐ Relax

Terms

- Cost – Total cost impact
- Energy – Total energy impact
- GWP – Total global warming impact
- TravelTime – Total travel time impact
- Max Objective Value – The respective relaxed objective value dependent on the objective.

Dimensions

- Objective
- Version

2.4 Input data for the model

2.4.1 Background to mobility

In a world of ever increasing scarcity of resources (time, energy and space) it is important to understand the need for mobility. Mobility objectives need to be met effectively using resources efficiently while minimizing negative impacts in order to sustain economic development.

Everyday millions of South Africans need to travel from home to places of work, places of education, places of service and places of social activities in order to take part in economic life, development and recreation.

The current public transportation system in South Africa is inadequate and in desperate need of transformation and development. We have approximately 3,9 million public transport commuters. Of these, 2.5 million are commuting using taxis. This accounts for over 63% of public transport work trips. Bus services account for another 22% of public transport commuters and the balance of home-work-home commuter travel by train. About 325 000 commuters use taxis as a feeder mode to other public transport services. 30% of households in southern Africa spend more than 10% of their income on public transport (South African Infrastructure Report, 2009).

As the economy grows more people will need to commute and the need will continue to grow. More people purchasing more vehicles will consume more energy and create more pollution. In time to come, our commuting behaviour and choices will need to change. Commuters will somehow have to use much less energy and space for individual mobility or have to be motivated to make use of public transport where possible and start to embrace ways of becoming more sustainable in terms of mobility.

2.4.2 The Pathways Structuring Mobility

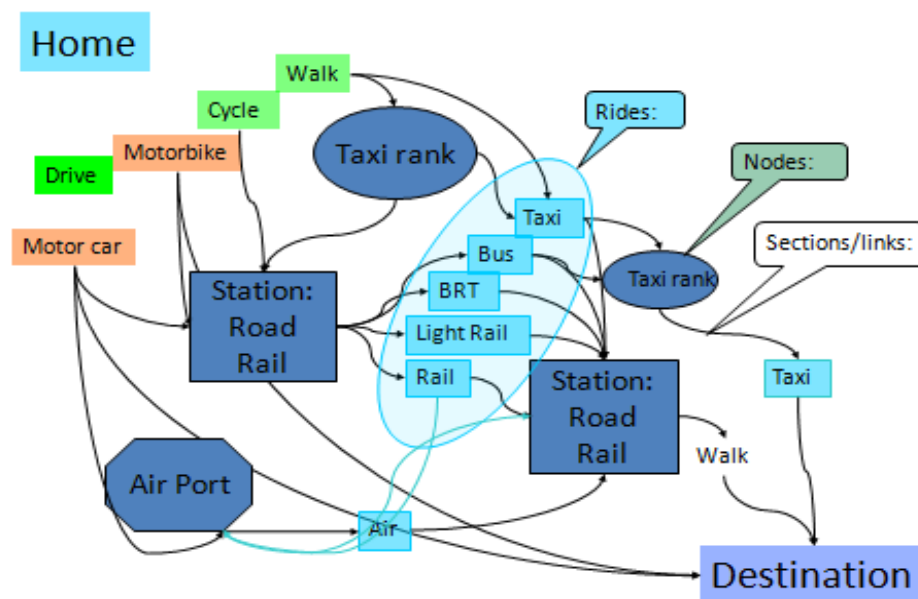


FIGURE 10: LIST OF PATHWAYS FOR COMMUTER USE IN SA

South Africa has a reasonably modern and well-developed transport infrastructure (when compared to the rest of Africa) which has been deteriorating over the last 10 years mainly due to a lack of investment and skills shortage in the country. The system is, however, extensive and in relatively good condition. The air and rail networks are the largest on the continent and the country's sea ports provide any natural stopover for shipping to and from Europe, the Americas, Asia, Australasia and both coasts of Africa. Public transport infrastructure is by popular consensus not, however, up to international standard. The NHTS of 2003 showed that 74% of train users, 55% of train users and 54% of bus users were dissatisfied with overcrowding of the relevant transport options. The study also showed that 74% of bus users, 64% of taxi users and 53% of train users were dissatisfied with facilities at stations, ranks and stops (NHTS, 2003).

The FIFA 2010 World Cup has provided an incentive and a 9 billion rand investment into improving infrastructure in the nine host cities in order to cope with the expected massive influx of visitors. This means major upgrades to the country's airports and improvements to the general

transport system, including the taxi recapitalisation program, consolidation of passenger rail and a transformation of the bus industry” (Swiss Business Hub South Africa, 2009).

South Africa will do well to preserve existing transport assets and make better use of these to ensure international competitiveness in the long term. This will enhance continued development of the nation’s resources, promote population development and improve mobility and safety standards for all our citizens. In order to do this, a better understanding of true infrastructure costs and the performance of present transport modes and routes needs to be obtained and understood. Only with this information in hand can a government influence the behaviour of commuters in the best interest of the country.

A positive and interactive rail and road transport policy can play an important part for future development in South Africa. Railways and roads are essential for providing efficient overland freight and passenger transport (Railroad Association of South Africa 2009).

2.4.3 Road Infrastructure

“South Africa has the longest road network (about 754 000 kilometres) of any country in Africa. Its national road network currently covers about 9 600 km. These roads include 1 600 km of dual carriage freeway, 440 km of single carriage freeway and 6 300 km of single carriage main road with unlimited access. 27 mainline toll plazas service approximately 1 900 km of toll roads.” (South Africa Online: Transport. *Public Transport Strategy (2007 – 2020)*).

In terms of the classification of roads, **National Roads** are roads providing mobility of national importance. These roads are usually roads between major cities and smaller cities and towns, with vehicles travelling long distances at higher speeds with minimum interference to the free flow of traffic. National roads are primarily provided for economic reasons and to improve and support economic growth. **Provincial Roads** are roads providing access and ability in a regional context. These roads link cities and towns not situated on the National Roads. **Urban Roads** provide mobility and access in urban areas, while **Rural Roads** provide mobility and access to remote communities and areas.

Roads identified as strategic and economically important are the responsibility of the South African National Roads Agency Limited (SANRAL). According to their annual report (SANRAL, 2009) the SANRAL currently manages 16 170 km of roads in South Africa. It is SANRAL’s intention to grow this to an already identified 20 000 km by 2010. This task was previously the responsibility of provincial road authorities.

This initiative will be financed through:

1. funding from the national fiscus,
2. funding from the collection of tolls, which enables development and maintenance of roads on a ‘user-pay’ principle, and

3. Contracting concessionaires for certain sections of road which are tolled to pay for the development over a fixed period of time. The asset will then revert to SANRAL free of charge in a specified condition.

Road performance is related to the condition that it is maintained in. Bad road conditions do not only have costs for those responsible for roads maintenance, but also for the users of the road. Roads deteriorate over time primarily due to traffic and environmental damages. Timing of maintenance is crucial and if this is not performed when needed, can lead to much higher costs to rectify the situation.

Figure 11 shows the operational expenditure and capital expenditure for toll roads.

Toll Roads - Operational Expenditure			
Description	Number of Project	Length (km)	Amount R'000
Toll operations and routine maintenance	37	1832	R 456,929
Periodic maintenance	3	153	R 108,212
Special maintenance	1	1	R 1,753
TOTAL	41	1986	R 566,894
Note: The Operational Expenditure excludes any accruals made at year-end and also includes expenditure related to contracts awarded in previous financial years, but incurred during 2008/2009.			
Toll Roads - Capital Expenditure			
Description	Number of Project	Length (km)	Amount R'000
Strengthening	3	81	R 281,012
Improvements	30	484	R 4 863,241
New facilities	18	126	R 851,938
TOTAL	51	691	R 5,996,191
Note: The Capital Expenditure excludes any accruals made at year-end and also includes expenditure related by contracts awarded in previous years, but incurred during 2008/2009.			

FIGURE 11: OPERATIONAL AND CAPITAL EXPENDITURE FOR TOLL ROADS (SANRAL, 2009)

Ideal regular maintenance is that done before any visible sign of distress on the road is apparent to the road user. Typical cost at this stage is about R 0.1 million/per km (2000 Rand).

Maintenance delayed by 3 years, when the road has been allowed to deteriorate and shows visible signs of distress to the road user, has typical costs to the order of R 0.6 million/per km (2000 Rand) for the same road. This means a cost increase of about six times. It also means that for every bit of poorer road maintained at this level, 6 km of good road could have been maintained with the same budget.

Maintenance delayed by 5 years, when the road has been allowed to deteriorate and starts affecting the user, has typical costs in the order of R 1.8million per km (2000 Rand) for the same road. Again this means a cost increase of 18 times or 18 km of road that could have been maintained by the same budget.

Figure 12 shows the operational expenditure and capital expenditure for non-toll roads:

Non-Toll Roads - Operational Expenditure			
Description	Number of Project	Length (km)	Amount R'000
Routine maintenance	57	13050	R 776,618
Periodic maintenance	21	988	R 443,998
Special maintenance	8	175	R 142,741
TOTAL	86	14213	R 1,363,357

Note: The Operational Expenditure excludes any accruals made at year-end and also includes expenditure related to contracts awarded in previous financial years, but incurred during 2008/2009.

Non-Toll Roads - Capital Expenditure			
Description	Number of Project	Length (km)	Amount R'000
Strengthening	17	618	R 1,262,327
Improvements	13	177	R 582,911
New facilities	5	71	R 557,650
TOTAL	35	866	R 2,402,888

Note: The Capital Expenditure excludes any accruals made at year-end and also includes expenditure related to contracts awarded in previous years, but incurred during 2008/2009.

FIGURE 12: OPERATIONAL AND CAPITAL EXPENDITURE FOR NON-TOLL ROADS (SANRAL, 2009)

The economic costs of bad roads due to delayed or no maintenance are primarily born by road users. For each rand not spent on timely maintenance, the vehicle user incurs a rise of R 2.00 to R 3.00 in terms of vehicle operating costs. This means that perceived savings in road maintenance actually leads to increased costs to the population of road users. It is often the case that taxes collected from the road users for the purpose of road maintenance are used for other purposes and not for maintaining of the roads.

For the development of the model use was made of the following figures (SANRAL, 2009)

Road infrastructure capital cost: R 1 800 000/km/lane with a 25 year life

Road infrastructure operational cost: R 100 000/km/lane/yr

Gauteng Road network area: 18 810 km² (Dept of Public Works, SANRAL, SABITA)

The total length of the road network in the Gauteng province is 34 000 km. Of these about 4 830 km are provincial roads (Department of Transport, 2009).

2.4.4 Bus Rapid Transit Infrastructure

Buses typically travel on the same road infrastructure that other vehicles use. In some cases, at peak hours, buses have dedicated lanes and enjoy right of way. This enables BRT to move great numbers of people efficiently; reaching the objective that Bus Rapid Transit (BRT) has been designed and developed for. Contrasting to conventional bus systems, with pure BRT systems however, buses have their own road infrastructure and stations. This can be seen in the figure below. The BRT stations are in the middle between two bus lanes, transporting people in opposite directions and these again are between two conventional roads:

The intention is to provide a better service to commuters in terms of reliability and speed. It is hoped that in this way that bus services would be made much more attractive to the public. BRT has been shown to decrease travel times and increase passenger volumes at low cost.



FIGURE 13. BUS RAPID TRANSIT EXAMPLE FROM BOGOTA, COLOMBIA (INTERNET STOCK PHOTO, 2009)

BRT in many respects are similar to light rail transit. The main difference is that BRT makes use of rubber on road. “BRT is an integrated system of facilities, services, and amenities that collectively improves the speed, reliability, and identity of bus transit” (Transit Cooperative Research Program, 2003).

It is envisaged that the City of Johannesburg’s Rea Vaya Bus Rapid Transit (BRT) system will in future form the backbone of the city’s public transport system. It is expected to be similar to Bus Rapid Transit (BRT) systems operating successfully in other developing countries such as South America, e.g., the Transmilenio in Bogotá, Columbia. The Rea Vaya service will have articulated buses providing a high capacity service on the BRT trunk routes. The service will operate along

dedicated median bus lanes and stations will be located in the centre of the busways. (Shown in the picture above).

Basic stations will feature ticketing facilities, pedestrian crosswalks or overpasses for commuters to reach the station platforms, weather cover, real-time information display and CCTV security. Larger stations will offer park-and-ride facilities, drop-off zones, bike parking, information kiosks, metered-taxi ranks, and bathroom facilities. Where applicable, stations will provide integration with the Gautrain rapid-rail system. The BRT trunk routes will be served by feeder services

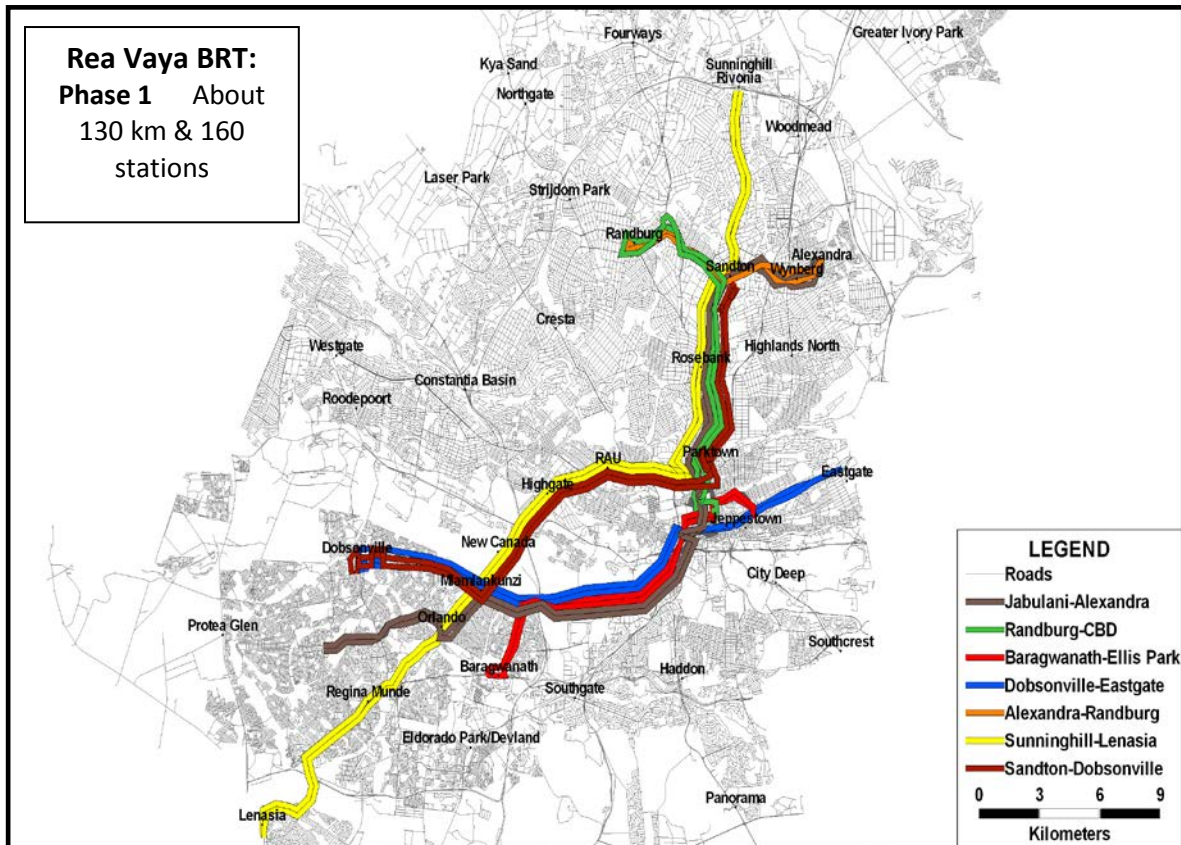


FIGURE 14: PHASE 1 OF JOHANNESBURG'S REA VAYA BUS RAPID TRANSIT PROJECT (REA VAYA, 2008)

operating on the surrounding road network, but will not be segregated from other road users.

Currently only two BRT routes were implemented in 2010; namely a north-south corridor connecting Soweto with Sunninghill via Sandton and an east-west corridor from Alexandra to Randburg. The timeframe for the implementation of the BRT route on the K101 is unknown at this stage and there are no firm plans in place for the extension of the Sandton to Sunninghill route northwards to Midrand (BRT Operations Plan - July 2007).

For the development of the model use was made of the following figures:

BRT busway capital cost: R 20 000 000/km, with a life of 25 years

BRT busway operational cost: R 200 000/km/year

2.4.5 Rail Infrastructure

South Africa's rail network of 20 000 km is the 10th longest in the world and represents about 80% of Africa's total rail network. However, only half of the track is being fully utilised. 35% of the total track carries no or very low activity. Due to the narrow gauge (1,067 mm) there are some limitations on heavy freight transport. In 2008 government promised to invest R 19.5 billion over the next four years in order to upgrade ports and rail infrastructure, 50% of this going towards freight rail. (South Africa Online: Transport. *Public Transport Strategy (2007 – 2020)*).

The cost of road maintenance and construction is higher than the cost of construction and maintaining new heavy railway tracks. Railroad tracks are also more reliable and better suited for the moving of freight.

For the development of the model use was made of the following figures:

Old railway and stations capital cost: R 150 000 000/km with a life of 35 years

Old railway and stations operational cost: R 2 500/km/year

2.4.6 Light Rail Infrastructure

The Gautrain Development, a new public transport service under construction and similar to "Light Rail" will be used here for comparison in the model to conventional rail and other mass transit options. The Gautrain infrastructure will be an 80km of rail track, connecting Johannesburg, Pretoria and OR Tambo International airport. That rail lines will be constructed on standard gauge (1,435 mm) in order to allow for high-speed trains. The first phase of the construction between the O.R Tambo airport, Marlboro (Wynberg) and Sandton was completed in time for the 2010 FIFA World Cup. The second phase, linking Rosebank, Sandton, Midrand and Hatfield (Pretoria) was completed by mid 2011.

The Gautrain rail network will have two major corridors: South-North and West-East.

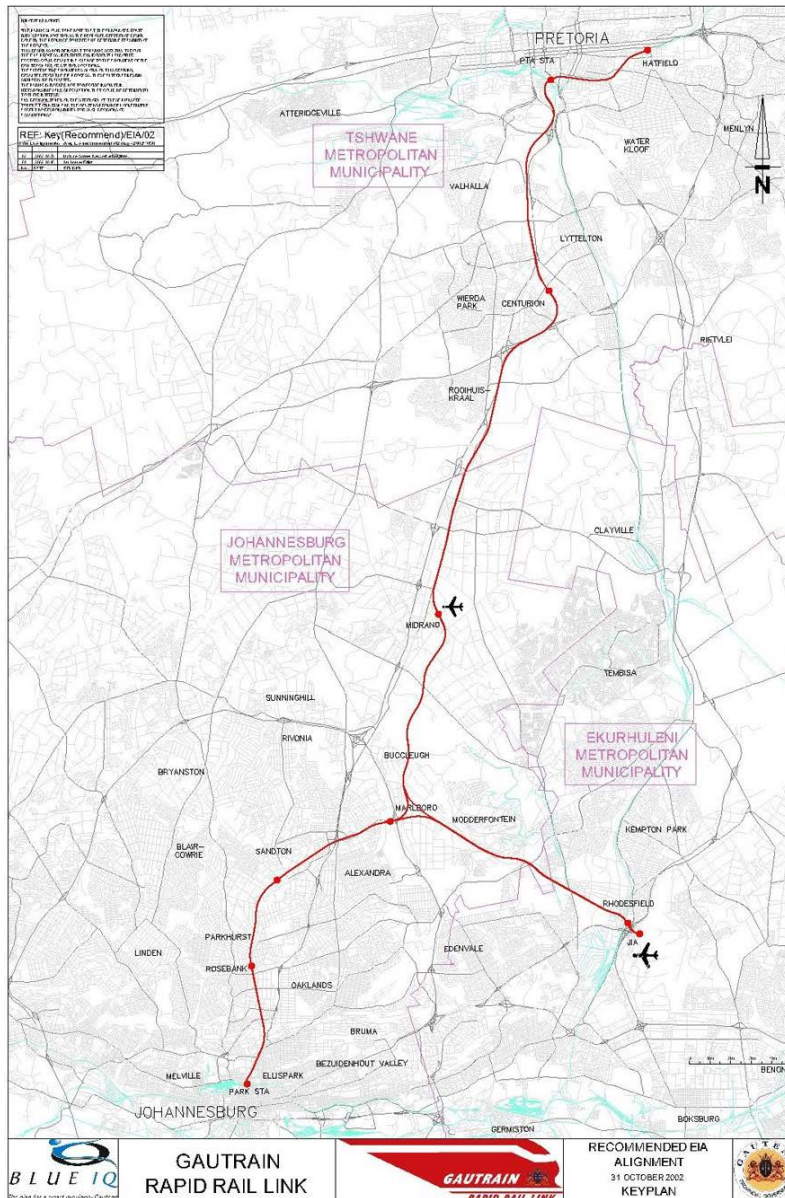


FIGURE 15: PROPOSED GAUTRAIN RAPID RAIL ROUTES FOR GAUTENG (VAN DER MERWE 2004)

North-South:

Johannesburg to Tshwane

The South-North route starts in the Park Station precinct in central Johannesburg and proceeds north underground for six kilometres beneath the Parktown ridge and Oxford Road to Rosebank Station. From there the single rail track tunnel continues underground for a further five kilometres beneath Dunkeld, Hyde Park, Inanda Ext 1 and Rivonia Road to a station within the Sandton business district. After Sandton Station the route remains underground beneath Sandown, Strathavon, the M1 and Marlboro Drive before appearing onto the surface at Marlboro portal, approximately four kilometres from Sandton.

From Marlboro Station, adjacent to the Marlboro Drive/N3 interchange, the route heads further north, running to the east of Buccleuch until it reaches Midrand Station next to Grand Central Airport. After Midrand Station, the route largely tracks the Old Pretoria-Johannesburg Road (past

Glen Austin and Randjesfontein) and the N1 before it stops at the Centurion Station in Centurion's central business district, just north of Centurion Lake. Thereafter the route runs to the west of the Ben Schoeman highway from the Jean Avenue interchange down the Snake Valley and east of Salvokop into Pretoria.

Pretoria Station is the next stop, 11 kilometres from Centurion, and is situated adjacent to the existing Pretoria Station. Here the Gautrain links to other rail services. The line will then runs east for six kilometres, largely using the existing South Africa Rail Commuter Corporation rail corridor, to Hatfield Station.

The West-East: Sandton to OR Tambo International Airport

The West-East route will take passengers from Sandton Station, via Marlboro, to Rhodesfield Station in Kempton Park. From there it will connect to a station built within the airport terminal complex at OR Tambo International Airport. The route from Sandton to Marlboro is the same as for the South-North route. After Marlboro Station, the West-East route crosses the northern boundary of the Linbro Park landfill, past the Linbro Park Agricultural Holdings and across the Modderfontein property before connecting to the existing rail corridor, serving the Kelvin Power Station and the Spartan/Isando industrial area, into Rhodesfield. The last link between Rhodesfield and OR Tambo International Airport will negotiate the R21/R24 road interchange.

For the development of the model use was made of the following figures:

New railway and stations capital cost: R 200 000 000/km, with a life of 35 years

New railway and stations operational cost: R 3 125/km/year

In summary then, for the development of the model use was made of the following figures:

TABLE 3: ASSUMED DATA FOR VARIOUS TRANSPORT OPTIONS (INFRASTRUCTURE COSTS AND CONSTRUCTED SPACE)

Mobility Pathways	Infrastructure Costs					Constructed Space		
	Capex	Life	Capex/yr	Maint/yr	Total/yr	Length lane.km	Useful Area (m ²)	Taken Area (m ²)
	R'000/km	Yr	R'000/km	R'000/km	R'000/km			
Car and Taxi Road	R 1 800	25	R 72	R 100	R 172	3 759	37 590 000	112 770 000
Bus Road + Stops	5% of road				R 8.6	376	3 759 000	11 277 000
BRT Road + Stations	R 20 000	25	R 800	R 200	R 1 000	188	1 879 500	5 638 500
BRT Road+Stations +Catenary	R 22 000	25	R 880	R 220	R 1 100	188	1 880 000	5 640 000
Old Rail + Stations	R 15 000	35	R 429	R 2.5	R 431	800	8 000 000	24 000 000
New Rail + Stations	R 200 000	35	R 5 714	R 3.1	R 5 717	120	1 200 000	3 600 000

2.5 The Modes Enabling Mobility

Why do people use whatever they use for travel? Is it always a free choice? How many people really do have a choice?

Travel is not a simple story to sort out or explain. Start with the trips people make from home to work, and then home again. Each commute reflects choices of where to live, where to work, when to work, when to go home, how to get from home to work, and what side-trips to make in either direction. Each decision depends on the opportunities available, with those in turn explained by the characteristics, resources, and values of workers, their families, their employers, other travellers, and of course the built environment of sidewalks, streets, bus routes, and rail lines connecting home to work.

People, who can afford to travel by car, do not make use of public transport. Figure 15 shows that as income increases so does the use of cars. Mainly those who have no choice walk or use taxis. Around the lower to middle income there is some competition between taxis, buses and trains.

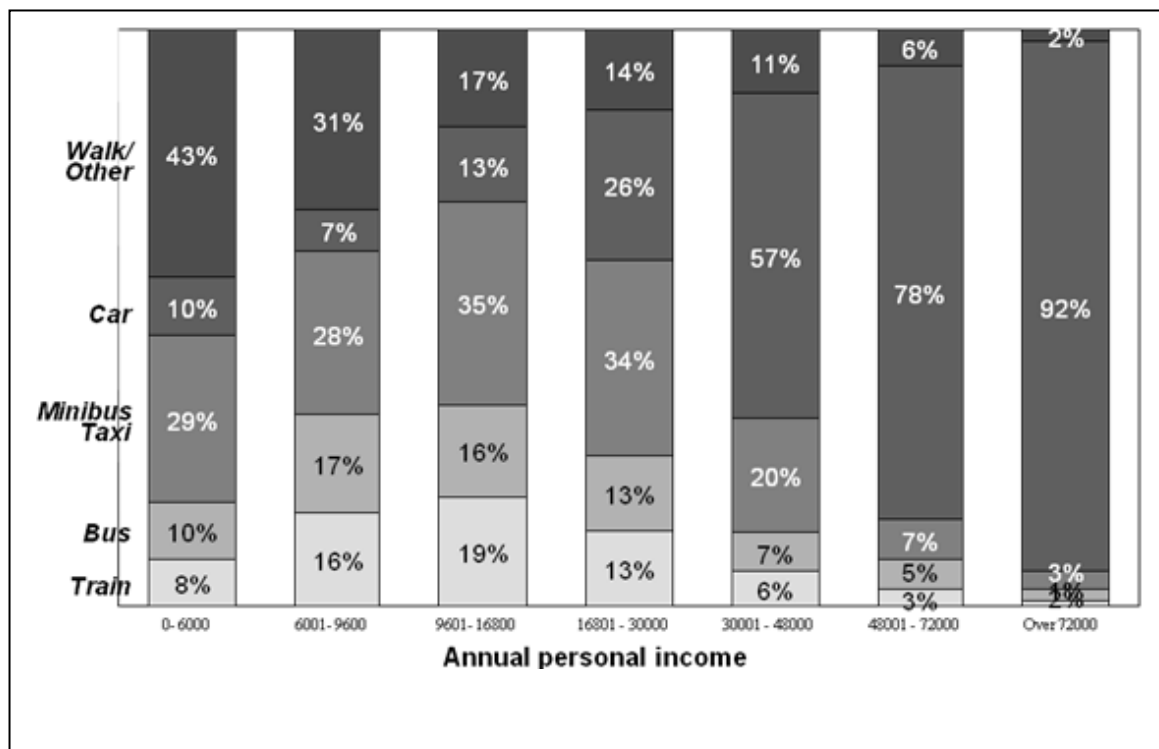


FIGURE 16: TRAVEL BEHAVIOUR OF PEOPLE FROM DIFFERENT INCOME GROUPS (CSS OCTOBERHOUSEHOLDSURVEY, DOT SUMS DATABASE, SARCC, 1995)

The perception of the general public can also be a driving force in terms of the choice of a specific transport mode or type. The magnitude of contribution of different vehicle types to environmental problems depends very much on how it is expressed, for example buses are seen to be very 'dirty' as a whole, but an analysis done in the UK on London transport buses showed buses to be much cleaner per passenger.kilometer than cars for most pollutants (The Centre for Independent Transport Research in London, 1996).

In the draft report of the First National Communication on Climate Change to the UNFCCC by South Africa (2000), the rate of growth in the motor vehicle population has exceeded the human population growth rate since 1970. Of this growth, the minibus taxi population showed the greatest increase.

Table 4 presents a collection of choices for mobility that people have today. It is by no means conclusive and it is expected that in the near future many more options will become available that people could use in order to travel from point A to point B. The choice made should be influenced by the constraints the world is about to face in terms of space, energy and allowed emissions while using the transport option of choice.

With the focus on the priority of developing the model, the options have been limited to what is available currently or in the near term future and the author did not attempt to exhaust all possible alternatives. Once the model has been developed and is functioning properly one can then add more variables and constraints.

For the development of the model use was made of the following figures as reflected in Table 4:

TABLE 4: ASSUMED DATA FOR VARIOUS TRANSPORT OPTIONS (PRICES AND AVERAGE LIFE CYCLE DATA)

Mode		Price	M & R	Speed	Life	Use	Life use	Unit cost	Units	Pax	Work
Energy		R'000	R'000	Ave km/h	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km/h
Car	Petrol	150	49,5	60	10	18 000	180 000	1.1083	3 000 000	1	60
	Diesel	165	41,3	60	12		216 000	0.9549		1	60
	Electric	260	13	60	25		450 000	0.6067		1	60
Taxi	Petrol	300	150	60	3	240 000	720 000	0.0391	200 000	16	960
	Diesel	350	140	60	4		960 000	0.0204		25	1500
Bus	Metro	2 000	1 400	40	16	42 000	672 000	0.0973	532	52	2080
BRT	Diesel	2 600	780	30	8	60 000	480 000	0.0880	330	80	2400
	Hybrid	3 700	740	30	12		720 000	0.0771		80	2400
	Trolley	3 000	300	30	16		960 000	0.0430		80	2400
Old Rail	PRASA	25 000	1 250	80	30	100 000	3 000 000	0.0284	150	308	24640
New Rail	GauTrain	30 000	1 500	80	30	100 000	3 000 000	0.0467	24	225	17976

The above table of alternatives provided some simplification, but also provides enough variety in order to develop an understanding of the functioning and proper evaluation of the mode in the next section these transport options are discussed and highlight their comparative advantages and disadvantages. The text will also provide some clarity towards their selection for use with the decision tool.

2.5.1 Cars

Cars as we know them today come in many shapes and sizes. For the purpose of developing the model we have selected three types of cars: a petrol car, a diesel car and a battery electric car. We have numerous years of practical experience and recorded operational data for an electric car in the city commuting between home and work. For this reason similar sized petrol and diesel cars were chosen to make the comparison as even and fair as we could, using real operational data and not simulated or calculated values. A more general choice of vehicle could have been an average for the total vehicle population. However, this would not have given us an indication of the performance of a typical city car, compared to public transportation options. Obviously a bigger car would have had a disadvantage.

2.5.1.1 Conventional Petrol and Diesel Cars

The petrol or spark ignition engine is based on the "Otto cycle" in which the fuel-air mixture is ignited by a spark plug. Therefore "spark ignition engine". With the petrol engine the fuel and air are premixed before compression takes place. This was done in older engines through the use of carburettors. Modern engines use electronically controlled fuel injection to much more accurately inject the correct mixture of fuel and air required by the operating conditions.

The biggest difference between petrol and diesel engines is that the diesel engine uses compression ignition (CI) to ignite and burn the fuel, which is injected into a highly compressed air combustion chamber. This causes the fuel to burn without any spark needed. An engine running on diesel compresses the air inside the cylinder to high pressures and temperatures. Typical ratios of compression range from 14:1 to 25:1 (Howstuffworks, 2011)).

Rudolf Diesel originally designed the diesel engine to use coal dust as a fuel. He also experimented with various oils, including some vegetable oils, such as peanut oil, which was used to power the engines which he exhibited at the 1900 Paris Exposition and the 1911 World's Fair in Paris (inventors.about.com, 2011).

Typically, petrol engines are better suited for racing and high-speed driving, while diesel engines are better suited for operating under partial throttle conditions (doing work). This is one of the reasons why some of the fastest cars in the world run on petrol and most trucks run on diesel. It also explains the fact that petrol engines operate at higher revolutions per minute than diesel engines. Driving conditions in cities have become such that it actually favours diesel vehicles.

Diesel engines are much more efficient than petrol engines when at low power and at engine idle. This is because diesel engines, unlike petrol engines, do not have a butterfly valve (throttle) in the inlet system, which closes at idle. This creates reduction of the incoming air, leading to reduced efficiency of petrol engines at idle. This is important to note due to traffic congestion typical of commuting from home to work in the city (*Office of Transportation and Air Quality*. United States Environmental Protection Agency, 2005).

Diesel engines also offer better fuel efficiency compared to petrol engines in general. This is mainly due to the higher energy content per volume of the diesel fuel. The calorific value of diesel is 44 800 kJ/kg, versus 43 000 kJ/kg for petrol, making diesel slightly more efficient than petrol (The

Engineeringtoolbox, 2011). The intrinsic efficiency of the diesel engine due to the high compression ratio of combustion adds to this. Then diesel engines typically also have a higher and flatter torque curve, which further reduces fuel consumption if used properly in the driving cycle. It has also been found that a diesel engine can typically last longer than a petrol engine (Clerk, 1897 – reviewed 2011).

In terms of emissions, diesel engines consume around 20% to 30% less fuel than petrol engines, which results in significantly lower carbon dioxide emissions. Diesel engines produce virtually no carbon monoxide. Hydrocarbon emissions contained in petrol engine emissions are however considerably more than that in diesel engine emissions (Hollembek, 2004). Although the largest part of most combustion gases is relatively harmless like nitrogen (N_2), water vapour (H_2O) (except with pure-carbon fuels), and carbon dioxide (CO_2) a relatively small part of it is undesirable noxious or toxic substances, such as carbon monoxide (CO), hydrocarbons (benzene), nitrogen oxides (NO_x), partly unburned fuel, and particulate matter. For this reason modern exhaust systems are equipped with catalytic converters – converting harmful gases to less harmful gases.

Diesel combustion produces more particulate matter (PM). PM refers to solid particles suspended in open air, such as soot generated by combustion of the fuel. These may cause respiratory problems and even lung cancer, because of their tendency to deposit themselves in the lungs. For this reason modern diesel vehicles are equipped with particulate filters. (Mateen and Brook, 2011).

2.5.1.2 Electric Cars

It is becoming clearer that in time to come all modes of transportation will be electric where possible. Conventional petroleum fuels and their substitutes will be used in areas where it is not possible to use electric propulsion, mainly due to the range limitations of energy storage systems currently available for electric cars. This is due to the smaller amount of energy that can be stored on board the vehicle (personal transport) or the lack of infrastructure supplying electricity (public mass transit).

An electric motor uses much less energy (three times or more) than internal combustion engines to produce the same amount of kilometres (same amount of work (Auto.howstuffworks.com, 2005). Furthermore no emissions or noise are produced at point of use. At point of production of the electricity, it is also much easier to control emissions than it is to control emissions at the exhausts of millions of vehicles. Transportation of electricity to point of use is also much easier with electricity than with petroleum fuels.

The fact that electric vehicles can make use of regenerative braking is also a major advantage. This makes it possible for a vehicle to recuperate on average 15% and up to 25% (if driving carefully) of the energy used in the driving cycle ([*Transactions of the American Institute of Electrical Engineers, Volume 36*: 2010](#)). When the driver wants to brake (slow down the vehicle), the motor operates as an alternator. The potential energy of the moving vehicle (kinetic energy) is converted into electrical energy and the speed of the vehicle is reduced. This recovered energy can then be used to assist

acceleration again, thus further reducing the energy consumption and related emissions of mobility (Belman and Vergels, 2004).

Depending on the energy source used to produce electricity, the amount of CO₂ and other pollution produced is therefore reduced because of the low energy consumption of the electric vehicle. Displacing internal combustion engine vehicles with electric vehicles where possible would lead to reduction in energy consumption and of course then also reduction in harmful emissions and global warming gases. This always results in lower costs to the user and the country.

It is also becoming evident that personal vehicles of the future will be much smaller than the vehicles we use today. In congested cities conventional vehicles will become a major problem. It just does not make sense to use a big vehicle to transport one person. Unnecessary energy is consumed, emissions produced and space occupied – all with cost implications. Ultimately the user will have to pay for the damage.

Furthermore, logistical challenges make it difficult for people living in different places to share one vehicle. It makes much more sense to use public transport. However, individual, independent travel will always be needed. This is where a small electric vehicle, transporting one or two people also serving as an integrated feeder into a public transport system, would find a niche market. These vehicles in a city centre would require much less of the parking space and half of the travelling space of vehicles today.

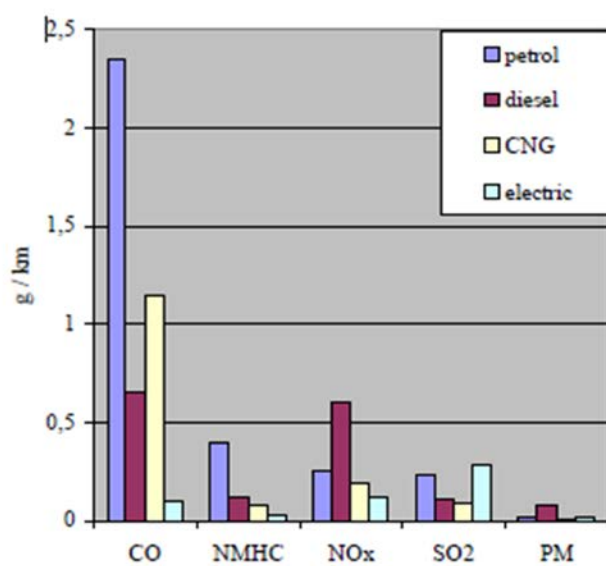


Figure 5.11: Vehicle emissions in Europe, 2002 [2]

Abbreviations:

CO	carbon monoxide
NMHC	non-methane hydrocarbon
NO _x	nitrogen oxides
SO ₂	sulphur dioxide
PM	particulate matter
CNG	compressed natural gas

FIGURE 17: VEHICLE EMISSIONS FOR EUROPE (BELMANS AND VERGELS, 2004)

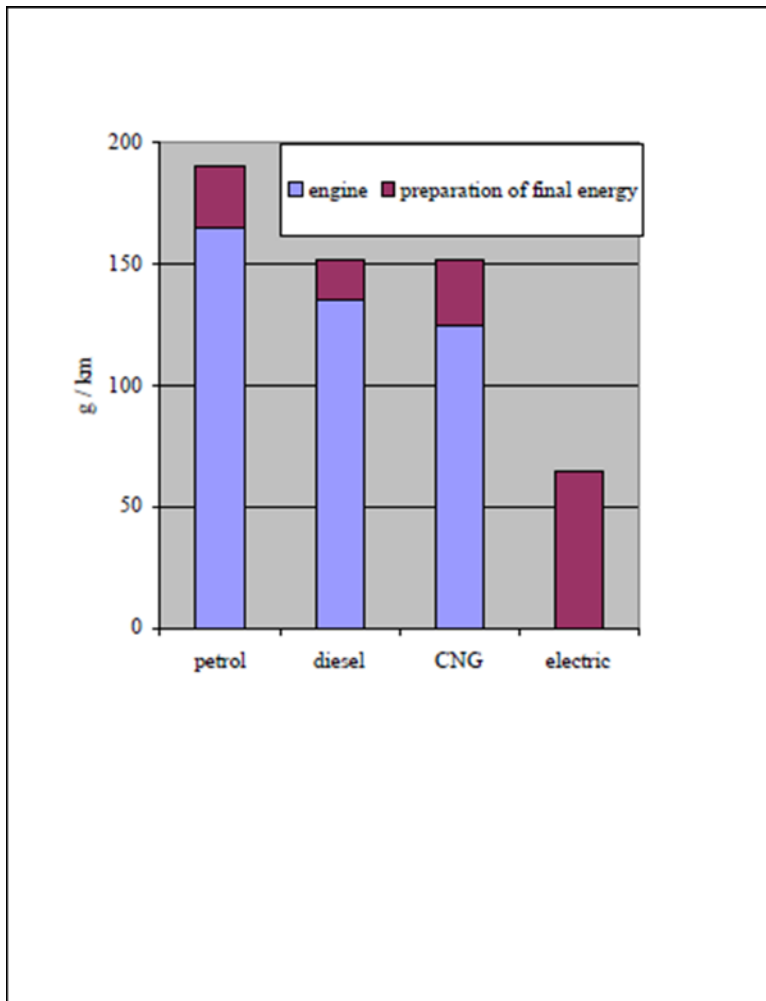


FIGURE 18: ENERGY-RELATED CO₂ EMISSIONS IN EUROPE (BELMANS AND VERGELS, 2004)

Electric vehicles developed today come in three different types:

1. pure battery-driven electric vehicles,
2. hybrid vehicles and
3. fuel cell vehicles.

The electric vehicle (EV) of today has developed into a reliable and marketable product. Latest developments with electric traction technology make the electric vehicle suitable for virtually any application. Various recognised vehicle manufacturers have indicated that they will introduce hybrid or full electric vehicles with them the next couple of years. In South Africa, a private company called Optimal Energy is busy with the development of their electric car called the Joule (Carmag.co.za 2010).

The major drawback of electric vehicles is the cost of the new low volume technology required to produce them to be competitive with the conventional car. Another perceived negative has always

centred on the amount of energy one can store on board the vehicle. The energy stored in the fuel tank of an internal combustion engine vehicle, is much more than could be stored in heavy batteries on board an electric vehicle (typically 10 times more in the case of lead acid batteries). Today the favoured energy storage battery seems to be based on lithium ion technology with energy densities up to four times more than lead acid batteries ([What's the best battery?](#)*Batteryuniversity.com*).

New battery types such as the Zebra battery (a high-temperature sodium-nickel-chloride battery) from Mes-Dea, metal-hydride batteries from Panasonic, SAFT and Varta, and lithium-based batteries from the great number of manufacturers will become available in the short-term future. Due to their high energy content they will offer much more acceptable vehicle ranges as well as life cycles. (What's the best battery? *Batteryuniversity.com*).

Hybrid vehicles will be an interim step to condition and prepare car users for the eventual use of full electric vehicles. Longer distance travel between cities should preferably be done with public transport on rail. However, hybrid vehicles will make it possible for users to cover long distances. The Toyota Prius is a good example of this, although this is not a typical pure hybrid vehicle. The electric motor and battery in the Prius are only used to improve the energy and unwanted emissions performance of the petrol car. The battery is not charged via the electricity grid, but by using the petrol engine and regenerative braking. If the option was available to charge the battery via the electricity grid the energy efficiency of the vehicle would be further improved and it could be termed pure "hybrid" (Russ, C., [Toyota Prius \(2001\)](#))

The hybrid option is favoured for heavy vehicles such as city buses. This makes it possible for these vehicles to travel on batteries when in congested or polluted city areas and on the internal combustion engine when in open areas where pollution or noise is not a problem.

Belmans and Vergels in 2004, reported on research they conducted in 2002 in Europe, where they compared the emissions for petrol, diesel compressed natural gas (CNG) and electricity.

Figure 17 above) shows emission values as the total sum of operation-related emissions and emissions associated with final energy supply for Europe in the year 2000, for conventional cars (petrol, diesel and CNG) and electric cars. Figure 18 above shows the CO₂ emissions from the engine and those associated with final energy supply, for European cities.

It is clear that the introduction of electric cars would lead to a significant decrease of pollutants in the atmosphere. Only in the case of sulphur dioxide emissions was it found that the emissions for the electric choice were higher. This is due to the primary energy used for electricity generation. No sulphur dioxide is produced where the electric car is driving. This however, will be decreased as the production of electricity from coal would be phased out and cleaner sources such as gas and renewable energies will be used in future. It is of importance to note that emissions from electric vehicles are located **outside the cities** and it is easier to control emissions of one electricity plant than to control thousands of vehicles exhaust pipes.

It is possible to power internal combustion engine vehicles with hydrogen. Internal combustion engines can use hydrogen directly as a fuel or it can be converted to electricity via a fuel cell to power the electric motor of an electric vehicle (Soler, Macanás, Muñoz, and Casado. Journal of Power 2007)

Refuelling infrastructure however, would be costly and complex. Transporting, storing and delivery of hydrogen is difficult and dangerous and could be very expensive. (Keith, and Farrell, 2003)

Therefore it is not believed that practical hydrogen cars are close enough in terms of time to consider their inclusion in the model at this stage.

For the development of the model use was made of the figures as shown in Table 5.

TABLE 5: ASSUMED DATA FOR CARS

Mode Energy		Price	M & R	Speed	Life	Use	Life use	Unit cost	Units	Pax	Work
		R'000	R'000	Ave km/h	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km/h
Car	Petrol	150	49.5	60	10	18 000	180 000	1.1083	3 000 000	1	60
	Diesel	165	41.25	60	12		216 000	0.9549		1	60
	Electric	260	13	60	25		450 000	0.6067		1	60

2.5.2 Minibus Taxis

Due to South Africa's legacy of segregation of population groups and urban demographics not developing in the most efficient way, we face unique and complex passenger transport issues. One of the biggest issues is one of population density close to places of work. Unfortunately people that work in the city are staying far away from the city. Typically our suburbs are sparsely populated and people have depended on private road transport in the past, making the support for public transport not adequate to pay for the investment required for its implementation.

For this reason the taxi transit industry has grown in an almost uncontrolled way. Fulfilling a desperate need and without the support of any subsidies, taxi operators have become a kind of their own. This is not a phenomenon only to South Africa. However, with the increase in private car use, this has lead to excessive route congestion and air pollution.

Minibus taxis are responsible for 65% of the 2.5 billion annual passenger trips in urban areas, as well as a high percentage of rural and inter-city transport. A "Taxi Recapitalisation Programme" intends to replace the current ageing minibus taxi fleet with new, safer, purpose-built 18-seater and 35-seater vehicles, which will be locally assembled.

The same background information that was mentioned in the previous paragraphs about petrol and diesel cars is also valid for petrol and diesel minibuses. However, in choosing a vehicle, in this case the petrol minibus taxi is a 16 seat vehicle, while the diesel minibus taxi is a 25-seat vehicle. This is not only closest to the real situation, but it was also done in support of the taxi recapitalisation program. It was thought that it would be interesting to compare these two with each other as well as with other public passport options.

For the development of the model use was made of the figures in Table 6s.

TABLE 6: ASSUMED DATA FOR MIN-BUS TAXIS

Mode Energy		Price	M & R	Speed	Life	Use	Life use	Unit cost	Units	Pax	Work
		R'000	R'000	Ave km/h	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km/ h
Taxi	Petrol	300	150	60	3	240 000	720 000	0.0391	200 000	16	960
	Diesel	350	140	60	4		960 000	0.0204		25	1500

2.5.3 Metrobus

Due to their operating cycle being low speed start-stop driving, buses are typically diesel powered. For the development of the model use was made of the figures shown in Table 7.

TABLE 7: ASSUMED DATA FOR METROBUS

Mode Energy		Price	M & R	Speed	Life	Use	Life use	Unit cost	Units	Pax	Work
		R'000	R'000	Ave km/h	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km /h
Bus	Metro	2 000	1 400	40	16	42 000	672 000	0.0973	532	52	2080

2.5.4 Bus Rapid Transit

Trunk Buses are articulated buses with a capacity of up to 112 passengers. These buses will only travel on the designated median lane trunk routes. They will only have doors on the right side of the bus with high-level boarding, as they will only be picking passengers up from the Rea Vaya Stations on the trunk routes.

Complementary buses which will be able to pick up passengers at Rea Vaya stations on the trunk routes and will also be able to operate on the kerbside, will have a capacity of 75 passengers. These buses will have doors on the left side in order to pick up passengers from bus stops along the kerbside but will also have high-level boarding doors on the right side for picking up passengers from Rea Vaya stations.

For the development of the model use was made of the figures: shown in Table 8.

Table 8: ASSUMED DATA FOR BUS RAPID TRANSIT

Mode Energy		Price	M & R	Speed	Life	Use	Life use	Unit cost	Units	Pax	Work
		R'000	R'000	km/h	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km/

											h
BRT	Diesel	2 600	780	30	8	60 000	480 000	0.0880	330	80	2400
	Hybrid	3 700	740	30	12		720 000	0.0771		80	2400
	Trolley	3 000	300	30	16		960 000	0.0430		80	2400

2.5.5 Old Rail - Business Express

For the purpose of this report, “Rail Mass Transit” is defined as conventional heavy rail trains operating the longer distances at reasonably high speeds and is powered by electricity. The practical example of this mode of transit for use in the strategic decision model is an average of the Business Express Rail systems operated today by Passenger Rail Agency of South Africa (PRASA).

Poor service delivery in the past caused rail to become increasingly discredited as an effective transport mode. This not only applies to passengers, but even more so to freight rail. More consumer friendly road services have led to road congestion, increased costs and pollution. It seems however, with the advent of the soccer World Cup in South Africa this situation is about to change.

2.5.5.1 The Passenger Rail Agency of South Africa (PRASA)

The Passenger Rail Agency of South Africa, (PRASA) combines and merges the operations, personnel and assets of

1. the South African Rail Commuter Corporation,
2. Metrorail,
3. Intersite Property Management Services,
4. Shosholoza Meyl and
5. the long distance bus company, Autopax (Translux and City-to-City).

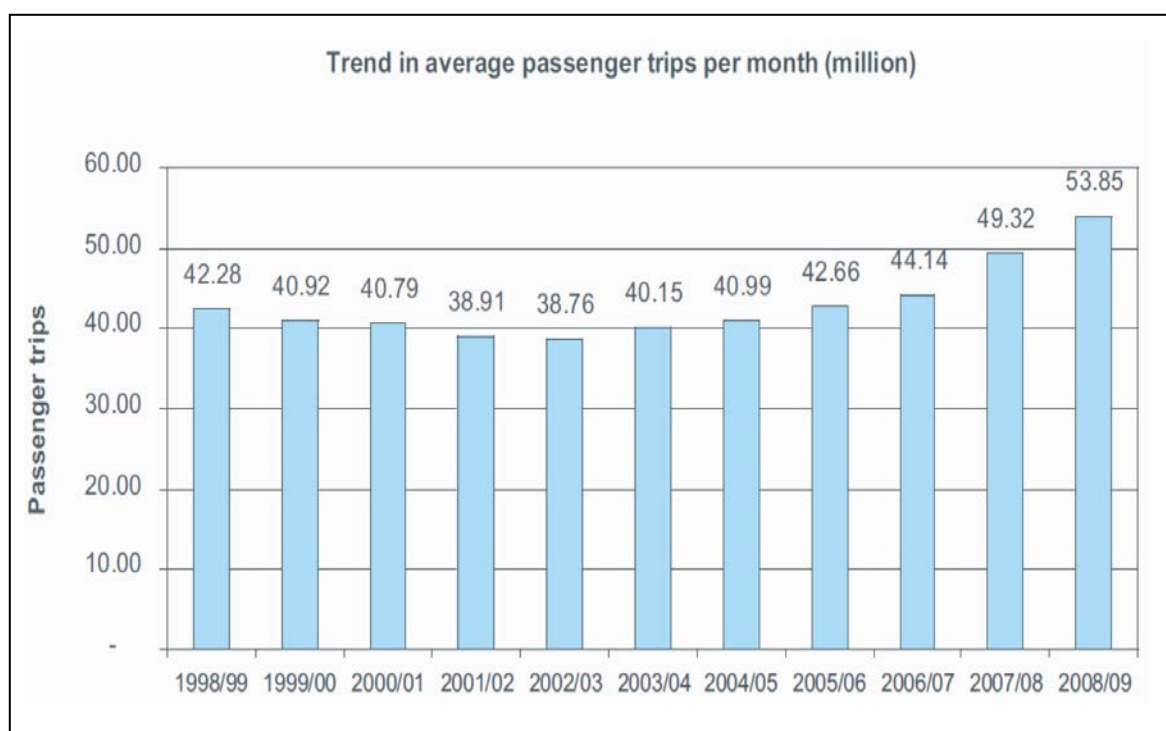


FIGURE 19: PASSENGER RAIL TRANSPORT IN SOUTHERN AFRICA

The National Rail Plan, approved by Cabinet in December 2006, identified the funding and investment requirements for passenger rail over the next 10 years. PRASA sees its role to transform public transport in southern Africa and sees rail services forming the backbone of the network. The objective is to integrate inter-modal facilities and services into public transport solutions that optimise the performance of the whole transport system. Key drivers for this restructuring and transformation were the historical underperformance of rail passenger services, underinvestment in the sector and the urgent need for efficient public transport during the 2010 FIFA World Cup. Figure 19 illustrates the growth in average passenger trips per month over the period 1998/9 to 2008/9. The steady growth in passenger trips since 2003/4 is placing the rail service under further stress.

PRASA has been tasked:

1. to ensure that rail commuter services are provided,
2. to provide long haul passenger rail and road based transport services, and
3. to develop and manage rail and related transport infrastructure.

“This is supported by the focused management of a property portfolio that is being developed to enhance passengers' travelling experience. This is being achieved through the transformation of key station properties into transit orientated development precincts that can generate sustainable income streams” (PRASA's Annual Report 2008-09).

2.5.5.2 Metrorail

Metrorail is responsible for transporting over 2.2 million passengers annually in Gauteng, Cape Town, Durban and Eastern Cape the PRASA owns 317 stations of the 468 stations Metrorail operates (with the remainder belonging to Transnet Freight Rail) and provides commuter rail services on 3180 kilometres of track of which it owns 2228 kilometres (Transnet Freight Rail the rest) (www.prasa.com/rail)

The rolling stock fleet of 406 train sets comprises 4638 coaches, of which the vast majority were built between 1958 and 1985. Fewer than 3 percent of the fleet are coaches that were bought in the mid-eighties with relatively newer technology. (www.prasa.com/rail). Diesel locomotives are leased to assist with yard operations and provide the traction supply for the Eastern Cape services.

Established as a fully fledged business unit of Transnet in 1996, Metrorail has focused on the delivery of commuter rail services in six major metropolitan areas, while assuming responsibility for the maintenance of the operational asset base. However, the separation of asset management (SARCC)

from operations (Metrorail) proved to be a major contributing factor in the failure of these entities to provide an adequate passenger service.

2.5.5.3 Express Rail

This concept is an effort to bring about a change in the public's perception of rail through demonstrating comfort and convenience, a choice of rail services, restoring dignity to rail travel and responding to customer willingness to pay for a superior service.

The express trains are distinctly branded. The cabins are air-conditioned. The seats are comfortable and the curtains and carpets are luxurious. Onboard services include cabin and security crew, a complimentary daily newspaper and refreshments. Operating are:

1. Since 2007: The SOWETO BUSINESS EXPRESS operating between Soweto to Johannesburg, seating a maximum of 360 passengers and stopping at Naledi, Dube and Johannesburg Park stations with a travel time of 90 minutes (Metrorail website).
2. Since 2007: The KHAYELITSHA EXPRESS operating between Khayelitsha to Cape Town, seating a maximum of 300 passengers and stopping at Khayelitsha, Heideveld, Mutual and Cape Town stations with a travel time of 40 minutes (Metrorail website).
3. Since 2008: The TSHWANE BUSINESS EXPRESS operating between Rick Torre and Johannesburg, seating a maximum of 520 passengers and stopping at Pretoria, Centurion, Kempton Park and Johannesburg Park stations with a travel time on 90 minutes (Metrorail website).

For the development of the model use was made of the figures shown in Table 9.

TABLE 9: ASSUMED DATA FOR PRASA OPTIONS

Mode	Price	M & R	Speed km/h	Life	Use	Life use	Unit cost	Units	Pax	Work
Energy	R'000	R'000	Ave	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.km/h
PRASA	25 000	1 250	80	30	100 000	3 000 000	0.0284	150	308	24640

2.5.5.4 Shosholoza Meyl

Shosholoza Meyl, the main-line division of PRASA - provides long distance inter-city rail services. Servicing 21 scheduled routes, it carries over 3.9 million passengers per year, any of whom are migrant workers travelling between the rural areas and the Metropolitan centres of South Africa, as well as migrant workers from neighbouring countries Shosholoza stops at 95 stations and owns 1223 rail coaches, of which some 1086 are used for passenger transport (PRASA website).

2.5.5.5 Autopax

Autopax is PRASA's bus subsidiary, a road based passenger transport business operating the following established brands: Translux and City-to-City. Autopax Bus runs on a commercial basis, transporting 2.6 million passengers per year on 50 000 bus trips, travelling a distance of 42,2 million kilometres.

Note: PRASA's assets are managed by a separate company, Intersite, taking responsibility for property management and portfolio development. (PRASA website).

2.5.6 Gautrain

The Gautrain can be seen as a light rail mass transit system. This mode of transportation provides fast and flexible transport of passengers in urban areas and is powered by electricity. The intention with light rail systems is to improve energy efficient mass transit and to relieve traffic congestion and pollution.

The Gautrain system will have 96 railcars operated in 24 train sets (each consisting of four cars) designed to travel at a top speed of 160 km/h. real operating speeds will be set for every single minute of track in order to maintain safety requirements.

Ten of these cars are specially customised for use on the airport link, and contain additional features such as extra luggage space and wider seats. The other 86 rail cars are designed for commuter services. Depending on need a train set can include up to 8 cars.

Each four-car commuter train set can comfortably carry up to 321 seated passengers.

The Sandton-OR Tambo International Airport rail service will take airline passengers between the two points in less than 15 minutes, whereas the trip between Johannesburg and Tshwane will be less than 40 minutes (Van der Merwe, 2004).

For the development of the model use was made of the figures as shown in Table 10.

TABLE 10: ASSUMED DATA FOR GAUTRAIN

Mode Energy	Price	M & R	Speed km/h	Life	Use	Life use	Unit cost	Units	Pax	Work
	R'000	R'000	Ave	yr	km/yr	Life km	R/Pax.km	Number	Ave	Pax.k m/h
<i>GauTrain</i>	30 000	1 500	80	30	100 000	3 000 000	0.0467	24	225	17976

2.6 Refining model parameters

2.6.1 Spread Sheet Variables

The values for the variables used in the model are either based on experience, fact, empirical findings or have been derived from information in the references listed below.

In cases where the values for the variables were not public knowledge, references for the value used are given. This was based on personal communication with experienced people in the related field or on published figures from literature.

In some cases the information we looked for was sensitive for competition reasons and we were forced to make informed calculations or estimates. This was typical for operational information.

2.6.1.1 Purchase Price Values for Modes (Vehicles)

The costs of the various types of vehicles have been derived with guidance from the lists of vehicle prices in the November 2009 issue of CAR magazine and from the AA tables on fixed vehicle costs.

- of a small petrol city car – average purchase price: R 150 000
- of a small diesel city car – average purchase price: R 165 000
- of a small electric city car – estimated purchase price: R 260 000
- of a petrol taxi – average purchase price: R 300 000
- of a diesel taxi – average purchase price: R 350 000
- of a Metro bus – Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – (Knote, Seiler and Snyman, 2008)
- of a hybrid BRT bus – (Knote, Seiler and Snyman, 2008)
- of a trolley BRT bus – (Knote, Seiler and Snyman, 2008)
- of a conventional train – (Van der Merwe, 2004)
- of a Gautrain – (Van der Merwe, 2004)

2.6.1.2 Values for maintenance and refurbishment (Vehicles)

The running costs of the various types of vehicles have been derived with guidance from the AA tables assuming annual total kilometres as indicated in the table. (AA vehicle running costs. 2009)

- of a small petrol city car – estimated at 33% of the price
- of a small diesel city car – estimated at 25% of the price
- of a small electric city car – estimated at 5% of the price
- of a petrol taxi – estimated at 50% of the price
- of a diesel taxi – estimated at 40% of the price
- of a Metro bus – Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – (Knote, Seiler and Snyman, 2008)
- of a hybrid BRT bus – (Knote, Seiler and Snyman, 2008)
- of a trolley BRT bus – (Knote, Seiler and Snyman, 2008)
- of a conventional train – (personal communication with PRASA official)
- of a Gautrain – (Van der Merwe, 2004)

2.6.1.3 Values for maximum and average speeds

Maximum is at the speed limit and average is the expected average speed. (This can be varied for sensitivity analysis or to adjust for congestion). Below is a list of assumed average speeds:

- of a small petrol city car – 60km/h
- of a small diesel city car – 60km/h
- of a small electric city car – 60km/h
- of a petrol taxi – 60km/h
- of a diesel taxi – 60km/h
- of a Metro bus - Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – 30km/h
- of a hybrid BRT bus – 30km/h
- of a trolley BRT bus – 30km/h
- of a conventional train – 80km/h
- of a Gautrain – 80km/h

2.6.1.4 Values for life of the mode (vehicle)

- of a small petrol city car – this is a calculated figure based on assumed useful life and annual km.
- of a small diesel city car – this is a calculated figure based on assumed useful life and annual km.
- of a small electric city car – this is a calculated figure based on assumed useful life and annual km.
- of a petrol taxi – this is a calculated figure based on assumed useful life and annual km
- of a diesel taxi – this is a calculated figure based on assumed useful life and annual km
- of a Metro bus – Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – (Knote, Seiler and Snyman, 2008)
- of a hybrid BRT bus – (Knote, Seiler and Snyman, 2008)
- of a trolley BRT bus – (Knote, Seiler and Snyman, 2008)
- of a conventional train – (personal communication with PRASA official)
- of a Gautrain – (personal communication with Gautrain management)

2.6.1.5 Values for annual kilometre distance travelled

- of a small petrol city car – estimate (AA says 20 000 to 25 000).
- of a small diesel city car – estimate (AA says 20 000 to 25 000).
- of a small electric city car – estimate (AA says 20 000 to 25 000).
- of a petrol taxi – Various reports speculate on this, so a “calculated average” was taken
- of a diesel taxi – Various reports speculate on this, so a “calculated average” was taken
- of a Metro bus – Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – (Knote, Seiler and Snyman, 2008)
- of a hybrid BRT bus – (Knote, Seiler and Snyman, 2008)
- of a trolley BRT bus – (Knote, Seiler and Snyman, 2008)
- of a conventional train – (personal communication with PRASA officials)
- of a Gautrain – (personal communication with Gautrain management)

2.6.1.6 Fuel consumption values

- of a small petrol city car – VW study, Car magazine
- of a small diesel city car – VW study, Car magazine
- of a small electric city car – Eskom measurements

- of a petrol taxi – Car magazine, various editions
- of a diesel taxi – Assumed
- of a Metro bus – Personal communication, Dave Gregory, Metrobus
- of a diesel BRT bus – (Knote, Seiler and Snyman, 2008)
- of a hybrid BRT bus – (Knote, Seiler and Snyman, 2008)
- of a trolley BRT bus – (Knote, Seiler and Snyman, 2008)
- of a conventional train – (Strickland, 2007)
- of a Gautrain – (Strickland, 2007), , Draft EIA for rapid rail link between Jhb, PTA and Jhb International Airport, 2003)

2.6.1.7 Energy prices

Real energy prices on the day (at the time the spread sheet was compiled, November 2009) were used.

2.6.1.8 Values for mobility pathway costs

- Road – (Mitchell, Mobility Jan/Mar 09)
- BRT – Chapter 6 Tshwane Report
- Old Rail – Chapter 6 Tshwane Report
- Gautrain rail – Chapter 6 Tshwane Report

2.7 Conclusion

In this chapter, the author has detailed the various options that realistically make up the public transport space. Of interest is that new options can be readily added, provided reasonable specific data is available. In this way, sensitivity studies focusing on new transport options can be readily undertaken. The input tables for the model demonstrate that the model is not data intensive. It will be shown in the next chapter, however, that the model is more than capable of producing meaningful results.

The spreadsheet variables that have been selected have been largely based on available data and personal communication with key stakeholders in local, provincial and national government. As and when new relevant data is published, the model will be updated accordingly.

The next chapter of this dissertation focuses on the testing of the model, now that the available data has been inserted into it. The verification process, through relaxing constraints imposed on the prioritised objective functions, is also addressed.

Chapter 3

TESTING THE SUPPLY CHAIN MODEL

Summary

Once the requisite model has been built it is necessary to test or verify its performance. The process of verification can be simply stated as answering the question; “Have I built the system RIGHT?” as opposed to validation of the approach taken, which involves answering the question “Have I built the RIGHT system?”

This chapter deals with the verification of the model’s performance. This model is new and is an optimisation model, comparing its outputs to real world empirical results, or compare outputs to another transport planning model which has different demarcation areas. The approach that has been taken is to conduct a series of runs of the model, in which constraints are progressively relaxed. The output from the runs should reflect the change in optimisation induced by the relaxation in constraints.

3 TESTING THE SUPPLY CHAIN MODEL

3.1 Background

When addressing the verification of the performance of a solution such as a model, one has to ask the question “Have I built the system right?” In the case of a model that approximates a real world situation, it is relatively easy to empirically compare the output of the model with the expected or observed result in real life. The degree to which the model approximates the real or expected parameter indicates the effectiveness of the model. In the development of an optimisation model, where the model output will differ from the real or expected result, a common approach is to compare the model’s output to that of a similar model.

In this model however, the data selected (in terms of assumptions) as well as the choice of bubbles (or demarcation zones) is novel. This therefore does not allow for easy comparison with any other existing models. The best approach that can be taken then is to alter the constraints imposed on the objective functions prioritised and to study the resultant output. If the resultant output is expected in terms of trend, then there is a reasonable chance that the model is operating to its expected levels.

3.2 Verification process

The model can be described as a multi objective network optimisation solution. It can look at and solve for more than one objective. The model is used to optimise for specific scenarios and arrives at related solutions according to the workflow process developed as described in Appendix 1.

To verify and evaluate the functioning of the model it was decided to run four scenarios (one for each objective). This process and the results obtained are detailed below.

3.2.1 Initial optimisation process – each objective function independently:

Optimising for each objective we find:

- Minimum TIME for the commute is 736 395 hours for a typical day
- Minimum COST is R 2 876 749, for a typical day
- Minimum ENERGY it is 6 420 252 MJ/day and
- Minimum GWP is 662 979 411 gram emissions and particulates per day

The results indicate that for a typical day, the minimum time it takes for commuters (in the specified bubbles) to reach their work places and return home is 736 395 hours. By relaxing the TIME constraint the cost of transportation is allowed some flexibility, thereby introducing a new minimum cost for commuters travelling to work and back on a typical week day. This amount is R2 876 749. By further relaxing the COST constraint, further flexibility in energy source is allowed, providing for new minimum energy consumption and similarly for Global Warming Potential. The optimisation process therefore results in a solution that has initially aimed to minimise the time of commuting, which is the primary concern of commuters, followed by minimising cost, energy and GWP. The final solution

is therefore the minimum emissions and particulates that could be released into the atmosphere if we started with the premise that we wished to firstly commute in the shortest period of time to work and back and only limited flexibility in time, cost and energy was allowed.

However, the objective is to solve for multiple objectives. This serves to enhance understanding of the various mass transit systems and their inter relationships.

To verify and evaluate the functioning of the model with multiple objectives, a number of scenarios were run (this time sixteen – to investigate the outcomes of optimising our objectives in order of priority and changing the “importance” of each in the order of priority):

3.2.2 Optimisation for multiple objectives in order of priority and relaxing each by 5%, 10%, 20% and 50%:

The model was used to solve for minimum TIME as first priority, then COST, ENERGY and GWP.

In **Scenario 1** it is shown that minimum total TIME for the commute is 736 395 hours (this is the same as solving for time independently of the other objectives).

TABLE 11: VERIFICATION RESULTS (SCENARIO 1)

Scenario 1 (5%)	Summarised values of:						Average Speed
	Time (h)	Cost (R.cc)	Energy (MJ)	GWP (g)	Distance (km)	Pax Speed (Pax.km/h)	
Time	736 395	6 948 698	11 108 115	1 061 447 411	50 786 833	336 995 228	69.0
Cost	771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	773 215	2 766 210	5 008 778	655 945 911	56 262 240	381 369 035	72.8
GWP	773 215	2 766 210	5 259 217	667 915 413	56 081 764	369 122 238	72.5

TIME was “relaxed” by 5% (i.e. TIME was allowed to increase up to 5%) in order to allow for solving for minimum of (another objective such as) COST, we find minimum COST of the commute to be R2 634 486. We now observe that TIME for minimum COST (with TIME not more than 5% of its minimum of 736 395 hours) is now 771 774 hours. That means for a TIME not more than 5% of its minimum and for COST at its minimum at R 2 634 486, the commute takes 771 774 hours in total (at an average speed of 70,5km/h for an average commuter or a delivery of 366 304 773 Pax.km/h).

Now, in order to optimise for ENERGY, TIME was kept at 5% and COST was relaxed with 5% too. The model was run again and now we observe TIME has changed to 810 034 hours, COST to R2 897 934 and we find minimum ENERGY consumed during the commute to be 4 691 339 MJ. In order to take GWP also into account ENERGY is also relax by 5% and the model run to optimise for minimum GWP. Now we observe the same values for TIME and COST (not relaxed further than 5%), a new value for ENERGY at 5,26 TJ and minimum GWP to be 667 915 413 gram or 668 ton for the commute.

In Scenario 2 the relaxed percentage is 10% and we use the same procedure:

TABLE 12: VERIFICATION RESULTS (SCENARIO 2)

Scenario 2 (10%)	Summarised values of:						Average Speed
	Time (h)	Cost (R.cc)	Energy (MJ)	GWP (g)	Distance (km)	Pax Speed (Pax.km/h)	
Time	736 395	6 426 721	10 360 389	1 040 366 608	50 786 833	336 995 228	69.0
Cost	771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	810 034	2 897 934	4 691 339	672 840 873	59 672 359	412 379 556	73.7
GWP	810 034	2 897 934	5 160 473	693 685 686	59 108 982	390 816 655	73.0

In Scenario 3 the relaxed percentage is 20% and we use the same procedure:

TABLE 13: VERIFICATION RESULTS (SCENARIO 3)

Scenario 3 (20%)	Summarised values of:						Average Speed
	Time (h)	Cost (R.cc)	Energy (MJ)	GWP (g)	Distance (km)	Pax Speed (Pax.km/h)	
Time	736 395	7 334 492	11 559 698	1 098 404 263	50 786 833	336 995 228	69.0
Cost	771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	859 473	3 161 383	4 525 442	701 178 317	62 737 575	448 613 146	73.0
GWP	835 685	3 161 383	5 430 530	716 728 970	60 485 191	409 167 361	72.4

In Scenario 4 the relaxed percentage is 50% and we use the same procedure:

TABLE 14: VERIFICATION RESULTS (SCENARIO 4)

Scenario 4 (50%)	Summarised values of:						Average Speed
	Time (h)	Cost (R.cc)	Energy (MJ)	GWP (g)	Distance (km)	Pax Speed (Pax.km/h)	
Time	736 395	6 847 488	10 807 153	1 082 147 157	50 786 833	336 995 228	69.0
Cost	771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	864 582	3 951 728	4 378 944	693 969 685	63 346 689	465 868 976	73.3
GWP	864 393	3 687 986	6 568 416	783 654 863	60 733 352	412 033 050	70.3

In summary the observations are:

TABLE 15: VERIFICATION RESULTS (SUMMARY)

	Time (h)	Cost (R.cc)	Energy (MJ)	GWP (g)	Distance (km)	Performance (Pax.km/h)
Scenario 1	773 215	2 766 210	5 259 217	667 915 413	56 081 764	369 122 238
Scenario 2	810 034	2 897 934	5 160 473	693 685 686	59 108 982	390 816 655
Scenario 3	835 685	3 161 383	5 430 530	716 728 970	60 485 191	409 167 361
Scenario 4	864 393	3 687 986	6 568 416	783 654 863	60 733 352	412 033 050

3.2.3 Discussion of results of verification process

From the results above it is observed that as TIME is relaxed (becoming less important) COST decreases at first, but then starts to increase again as it too is relaxed (also becomes less important). This however, does not result in a better overall outcome (ENERGY and GWP also rise in Scenarios 3 and 4) It can then be concluded that we should choose between Scenario 1 and Scenario 2 in the example used depending on the set priorities.

Two columns of metrics have been included in the above tables to show that various related measurements can be calculated that may further inform the optimisation runs of the model. In this case Distance and Performance were selected for display.

For ease of explanation and understanding, some areas of the tables were shaded and should not be regarded as these are not optimised results. The numbers do indicate the model's choice, but not under any constraint. It just indicates that there are many ways (choices) for commuters to get to work from home, but they may not be optimal.

In the computer generated values shown in Appendix 2, it is possible to find the mode/energy combinations selected by the model during the optimisation process according to the rules set by the operator of the model, this verifies that the model is functional and can be used to find an integrated optimised solution for mass transit and that the solution scenario can be described in real terms.

However, some uncertainty in terms of the assumptions that were made and the accuracy of statistical data exists. Therefore an in-depth analysis of the detailed data would at this stage not be practical even though the model is functional. The veracity of the input data and assumptions needs to be tested before the results of this model can be fully trusted. The intention at this stage of the study is to demonstrate the optimisation process to determine a consistent and repeatable method of arriving at the optimised solution. More accurate data, gleaned from the public as discussed in Chapter 5 of the dissertation will lead to results that are usable in decision-making. For now, it is considered more important to demonstrate the logical pathway that the model follows and test whether the algorithms used produced a result which is plausible. A proper uncertainty analysis is not required at this stage, since the results are not meant to be defensible, just the process of arriving at the result.

3.3 Conclusion

The verification process undertaken has demonstrated that the model is effective in undertaking the functions required. The veracity of the data selected as well as assumptions made need to be tested further however. The author has not gone into a detailed discussion of the meaning of the results obtained, other than to highlight, in the tables given, that the model does produce predictable results.

A follow up study needs to be undertaken to further refine the data set and assumptions made. This is proposed in the Recommendations section of the final chapter of this dissertation.

Chapter 4

RESULTS

Summary

In an effort to validate the approach taken in developing the model, two scenarios were developed that could be used to gauge if the model would be suitable for high-level decision-making in an energy and emission-constrained environment. The two scenarios relate to; firstly, a base case (Least time scenario), where the approach is the same in chapter 3 with respect to optimisation and the order of prioritisation of objectives. The second scenario (Least emission scenario) puts the emphasis on the cost of reducing emissions. This will be useful when calculating the additional cost associated with reducing emissions in the country.

The results from the two runs are described in this chapter and the significance of the findings discussed. The author also addresses the issue of validation and makes the case for the model's suitability to meet the objectives specified in chapter 1.

4 RESULTS

4.1 Background

Two runs of the model were completed as a means of validating the methodology adopted. In both runs, the input data is exactly the same. The only difference is the order in which the model optimises, based on the order of the objective functions chosen.

4.1.1 *The Least Time Scenario*

Under this scenario the primary objective function is *time*, i.e. the total time it takes to move commuters from their point of origin to their destination. The model uses the bubbles developed and described in Chapter 2 as the basis for the calculation. The order of optimisation is as follows:

Min Time → Cost → Energy → GWP

The constraint imposed on subsequent objective functions was relaxed by 10% each time. In other words, once an optimised solution for total time was reached, the model relaxes the constraint on time by 10%, to allow for further optimisation to take place, this time based on cost. This is then repeated for the energy and GWP objective functions. In so doing, the model ultimately produces an optimised solution for GWP, having initially constrained time. The output of this plan therefore represents the least time it takes to move between bubbles at peak times with GWP an outcome of this plan.

4.1.2 *Least GWP Scenario*

In this scenario, GWP becomes the primary objective function and then energy, time and then cost are optimised for. This is reflected as follows:

Min GWP → Energy → Time → Cost

In this way, the model will produce a result that indicates what the optimal mix of transport options should be, to move commuters between bubbles in Gauteng. As an outcome of this plan, the model will then identify the cost associated with such an option. This cost then represents the abatement cost of reducing greenhouse gas and particulate emissions by a certain level. This then becomes a powerful planning tool. In following this methodology, planners and decision makers can start to budget for a series of future emission reduction

measures. The run described represents an extreme example of what can be achieved if GWP is the primary objective.

The results from the two runs are intended to be independent of each other, as each represents a separate optimised solution. The absence of reliable data presents a challenge when considering the baseline for current energy consumption and GWP impacts in Gauteng. The author has commissioned a study at the CSIR in 2008 to investigate the present emissions associated with passenger commuting on Gauteng roads. The results of this study will be used as input to a subsequent study by the author. This is mentioned later in the Conclusions and Recommendations section of the Closure chapter of this dissertation.

4.2 Scenario Least Time results

4.2.1 Discussion of Least Time Scenario Result

4.2.1.1 Dominance of rail transportation

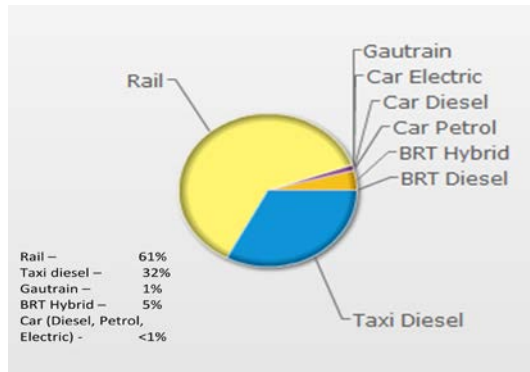
The model produced results that indicated an expected breakdown of modes of transport for passengers commuting in Gauteng on a typical day. The figure 18 highlights the modes of transport, for the different objective functions, as the constraints were relaxed. It is worth noting that the rail option is the most favoured, followed by diesel taxis. The diesel BRT option is also favoured. As the cost and energy constraints are progressively relaxed, the diesel taxi option becomes more attractive. In terms of people speed, however, the rail option remains the favoured form of transport irrespective of objective function. The diesel taxi is the more energy efficient of the options considered. The BRT diesel option will become more attractive over time, as routes are expanded, and the associated infrastructure cost decreases.

4.2.1.2 Exclusion of private passenger vehicles from optimal solution

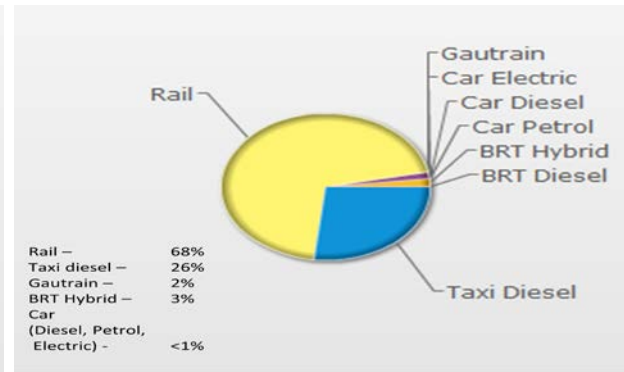
The optimisation process has resulted in practically no private passenger vehicles being selected. Electric vehicles are the exception, even though they constitute only a tiny fraction of the output in terms of contribution to moving commuters. The reason for the exclusion of private passenger vehicles is attributed to the low occupancy of the vehicles, high energy cost (R/km) and the low speed attributed to these vehicles during peak times.

4.2.1.3 Role of Gautrain

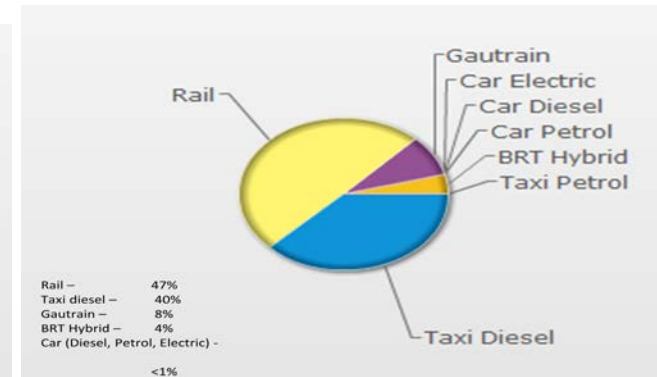
The Gautrain does not feature prominently in the optimised solution, due to its limited area of operation and perceived high cost of construction and operation. An electric option such as Gautrain will gain prominence in the future, as the accessibility to the service is improved and the price of the tickets stabilise at competitive levels.



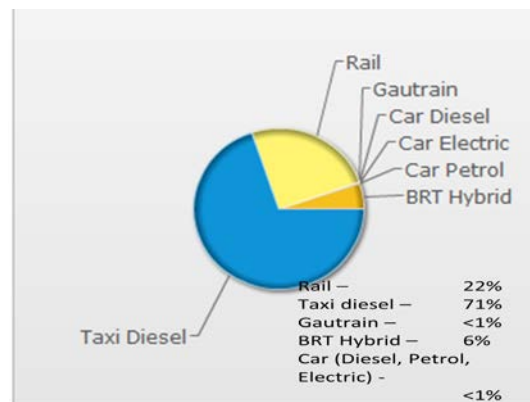
(a) Breakdown by time



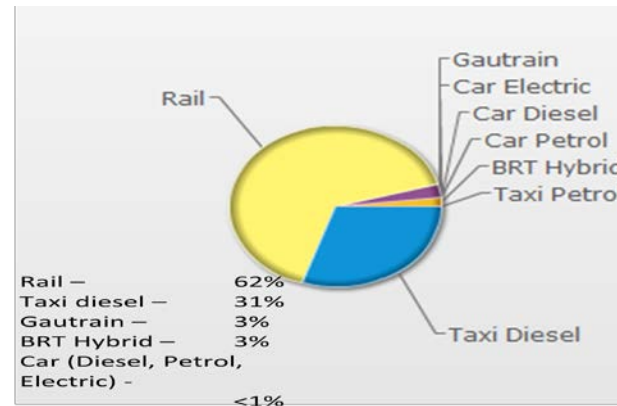
(b) Breakdown by distance



(c) Breakdown by cost



(d) Breakdown by energy



(e) Breakdown by people speed

FIGURE 20: BREAKDOWN OF MODE OF TRANSPORT BY OBJECTIVE (LEAST TIME)

4.2.2 Movement between Bubbles

Figure 19 below indicates the movement of commuters between the various so-called bubbles. The thickness of the arrow indicates the density of commuters using that particular route and the direction of the arrow indicates the direction of movement between the bubbles.

Bubbles are identified by a unique number. The number of people resident in that bubble is also estimated. The types of access to the bubble, i.e., road or rail, are also defined. The type of road, i.e., national, regional or local, is also specified for each route. For the purposes of the scenario, it is worth noting that the various forms of transport are intended to move people to places of work, such as Johannesburg Central, Randburg or Sandton. As the scenario constraints are relaxed and different objective functions are considered, the model will then produce a new map. The map will now feature arrows of different direction, different thickness and potentially following new routes.

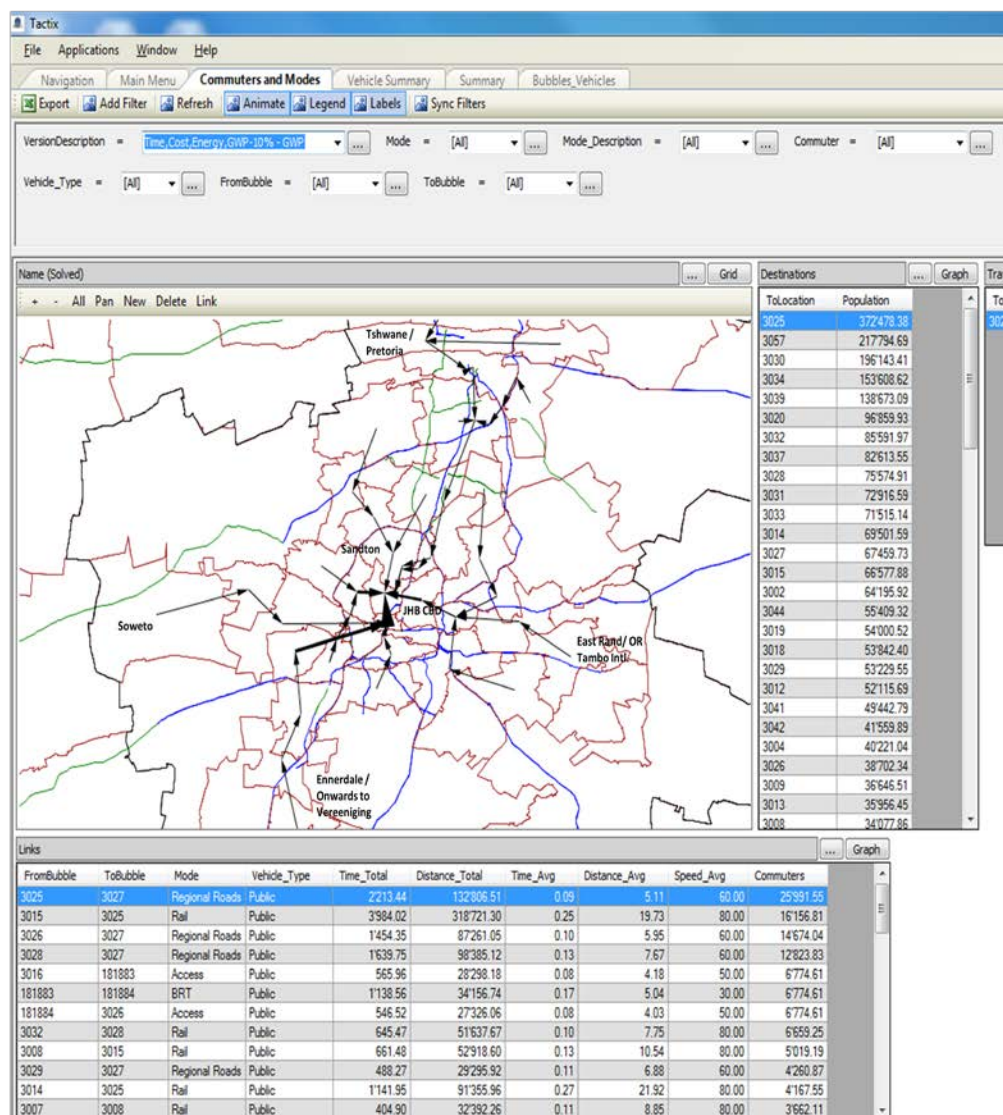


FIGURE 21: LEAST TIME SCENARIO - MOVEMENT BETWEEN BUBBLES

4.3 Scenario Least Emissions results

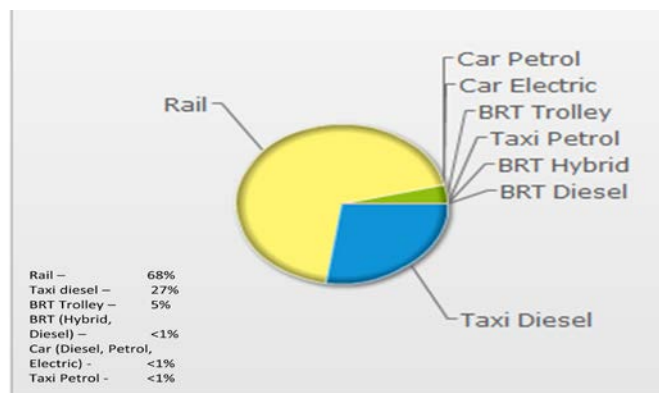
4.3.1 Discussion of Least Emissions Result

4.3.1.1 Role of Rail

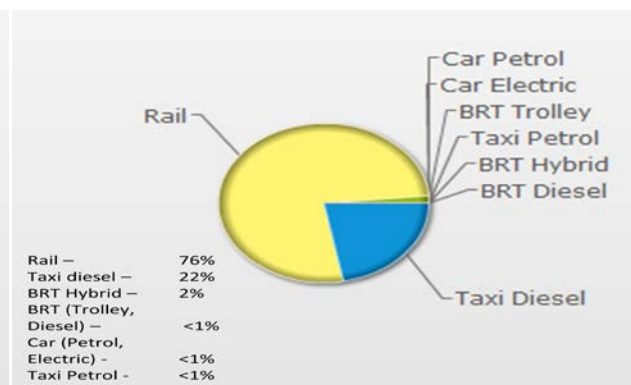
In this scenario, the focus remains heavily on rail transportation. Figure 20 details the breakdown of transport options chosen by the model for this scenario. With the focus now on reducing greenhouse gas emissions, the model has still selected rail and diesel taxis as the preferred modes of transport. Rail is still the favoured option from a GWP, cost and time perspective. This is due to low price of commuting, no emissions (at point of use) and density of commuters able to use the rail system. Diesel taxis are preferred as well due to the improved fuel efficiency versus petrol vehicles and the number of commuters making use of taxis on a daily basis.

4.3.1.2 Introduction of Diesel Options

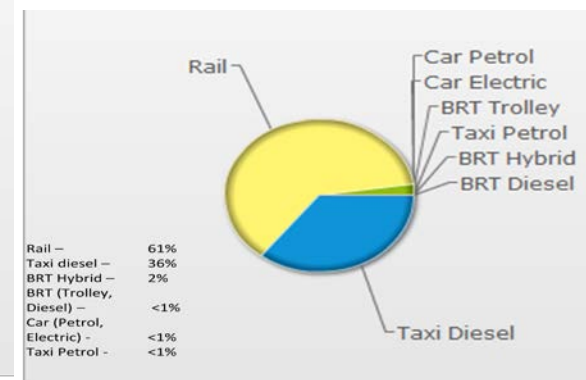
Of interest is the increased contribution from a BRT diesel option. With the diesel option being more fuel efficient than a petrol equivalent metro bus, it is reasonable to expect that the mass transit option fuelled by diesel is preferred in an emission and energy constrained scenario. Where cost becomes less of an issue, the BRT option becomes more attractive. As in the case of the Least Time Scenario, the diesel taxi option becomes the preferred option when energy constraints are relaxed. Cost constraints have also been relaxed in the process, further promoting the use of the diesel options. Once again, the private passenger vehicles are not favoured, due to the reasons stated in the previous section.



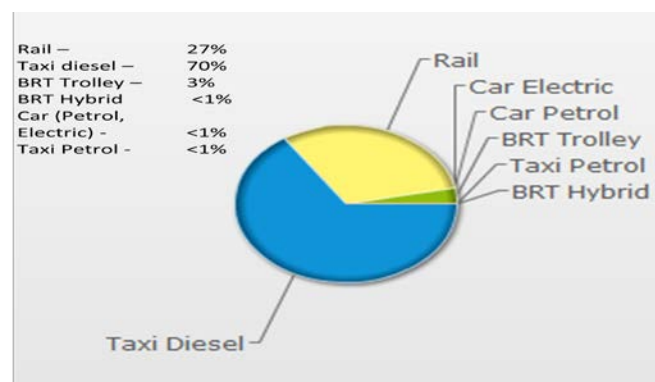
(a) Breakdown by time



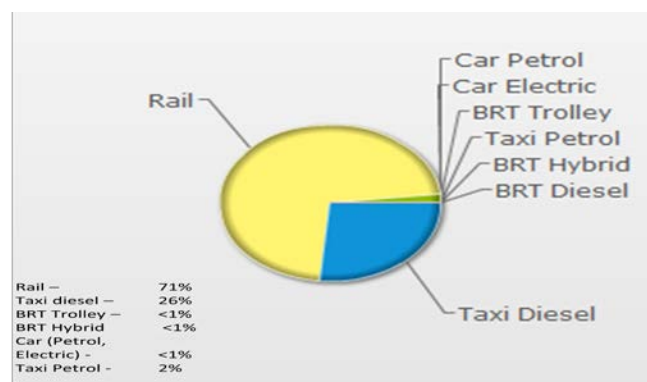
(b) Breakdown by distance



(c) Breakdown by cost



(d) Breakdown by energy



(e) Breakdown by people speed

FIGURE 22: BREAKDOWN OF TRANSPORT MODE BY OBJECTIVE (LEAST EMISSION)

4.3.2 Movement between Bubbles

As per the discussion above, the model produces a map that details the movement between the various bubbles. For comparative purposes, the user can visually determine the changes in output as well, by comparing the routes, direction and thickness of the arrows. For the purposes of illustration, the author has included reference to the same bubbles and compared the output for the two scenarios. The reader will be able to determine the changes in routing and commuter density by a visual inspection of the two maps.

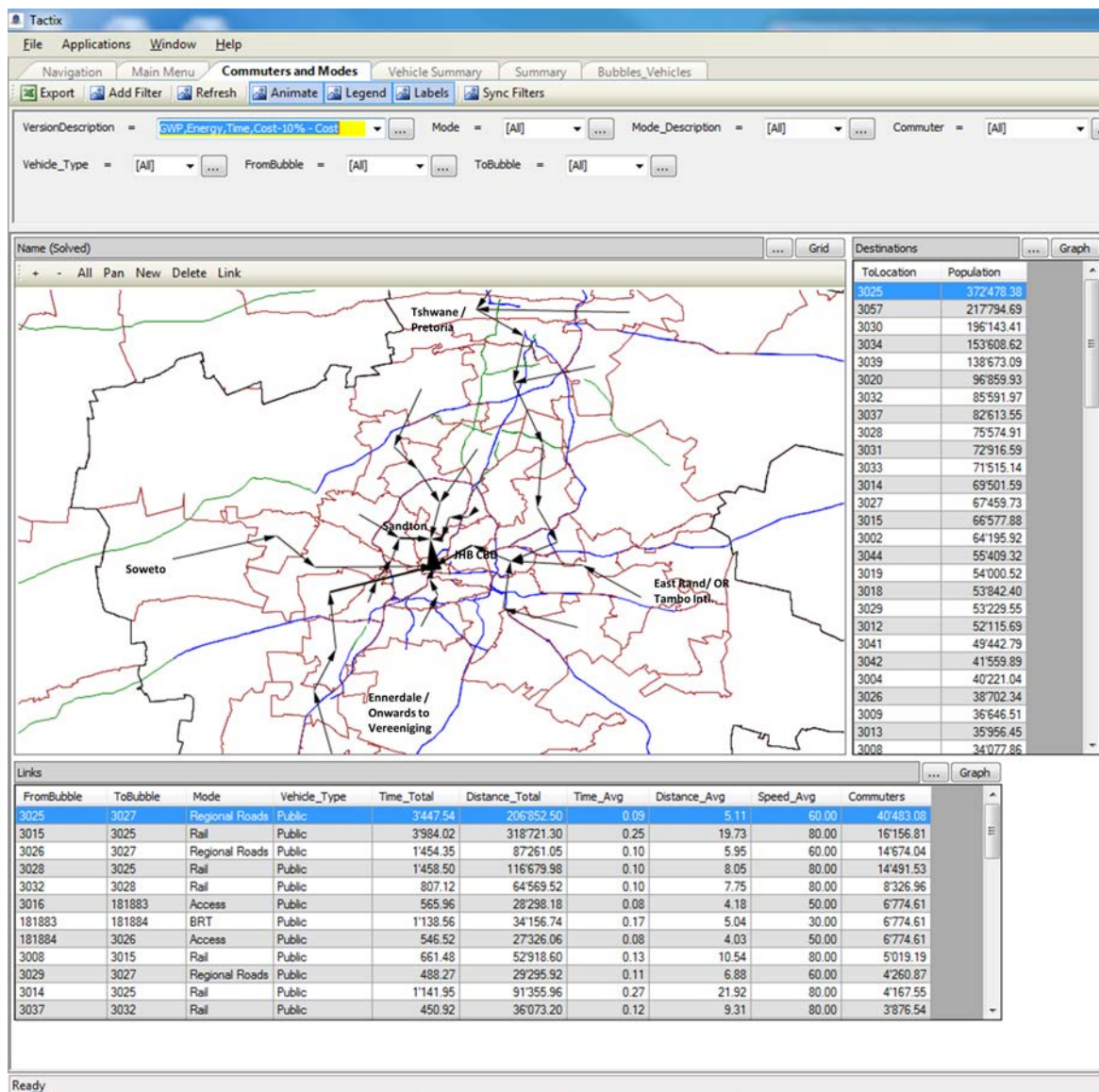


FIGURE 23: LEAST EMISSIONS SCENARIO - MOVEMENT BETWEEN BUBBLES

4.4 Comparative Cost implications

Table 16 depicts the summarised data for the output of the two model runs undertaken for the two scenarios. The top four rows relate to the least emissions scenario while the next four rows relate to the least time scenario. As can be seen from the greyed blocks, the cost of the plan is marginally higher for the least emissions scenario versus the least time scenario. Since the two outputs are based on optimisation results, it is not easy to compare outcomes of one scenario to that of the other. Both have to be compared to real life data where the true cost of mitigation can be established. The higher cost for the least emissions scenario does however further reinforce the veracity of the model.

TABLE 16: SUMMARY OF RESULTS OBTAINED FOR THE DIFFERENT SCENARIOS

Row Labels	Sum of Time (h)	Sum of Distance (km)	Sum of Energy (MJ)	Sum of Cost (R)	Sum of GWP
GWP,Energy,Time,Cost-10% - Cost	820 262	59 014 820	4 808 618	2 694 810	686 435 998
GWP,Energy,Time,Cost-10% - Energy	864 945	63 363 416	4 371 471	4 259 848	691 181 867
GWP,Energy,Time,Cost-10% - GWP	796 688	55 202 986	5 131 162	4 073 991	628 347 153
GWP,Energy,Time,Cost-10% - Time	771 923	56 346 077	4 808 618	3 794 143	638 453 419
Time,Cost,Energy,GWP-10% - Cost	771 774	54 376 676	5 309 694	2 634 486	664 697 278
Time,Cost,Energy,GWP-10% - Energy	810 034	59 672 359	4 691 339	2 897 934	672 840 873
Time,Cost,Energy,GWP-10% - GWP	780 255	55 157 979	5 160 473	2 897 934	643 964 521
Time,Cost,Energy,GWP-10% - Time	736 395	50 786 833	11 169 260	7 098 953	1 104 668 683
Grand Total	6 352 276	453 921 146	45 450 636	30 352 099	5 730 589 791

4.5 Summary of results

Two scenarios were developed to showcase the ability of the model to optimise for different priorities. The model produced results and these were discussed in this chapter. Since this is a new model, a lot more work is required to gain a sense of confidence in the actual numbers produced. At this stage, the numbers are treated as indicative, rather than actual. With time, these figures will become more reliable, once accurate and reliable data is obtained from the relevant sources. The Conclusions chapter makes reference to the further work that is still required to get the model to the point where it can be used with a greater sense of confidence.

A certain question that will arise from the two scenarios chosen is why there are so few passenger vehicles selected as part of the optimised solution? A further question would be whether this would be plausible in reality? The answer to the first question is based purely on the assumed costs for passenger vehicles, where the fuel and capital cost per vehicle for mostly single occupancy travel is higher than other specified options. Average speed is also a factor and with the low average speed

associated with passenger vehicles, particularly during peak hours, the model will seek the minimum time to reach the destination. The model will therefore only consider petrol and diesel passenger vehicles as a last resort. The second question is answered as follows. Since this is an optimisation model and not a simulation model, it is to be expected that the model will produce results that are best case end states and not necessarily realistic. The model becomes more realistic as sensitivity studies are undertaken, as proposed in the next chapter. By introducing new options, a new optimised plan is produced, with a realistic cost to the economy of introducing such an option. Boundary conditions can be set in the model which will introduce a minimum number of passenger vehicles into the plan. This will naturally limit the optimisation process but produce more realistic results. For sensitivity studies, it will be necessary to introduce boundary conditions, to allow the model limited freedom in choosing between options.

4.5.1 *Validation of the model chosen*

A common definition of validation involves proving that a proposed approach is best suited to solving a stated problem. In other words, the question “Have I built the RIGHT system?” needs to be addressed. In the case of verification, the author has attempted to answer the question “Have I built the system RIGHT?” This question is addressed in Chapter 3 of this dissertation. As regards validation of the approach taken in this study, the following section details the rationale supporting this approach.

In the process of validating the approach taken in this study, it was necessary at the outset to identify a set of key answers that needed to be answered in the affirmative. It will be at the discretion of the examiners whether the author has a) identified an appropriate set of questions and b) whether the author has satisfactorily answered these questions.

The questions that the author has identified for this study include the following:

1. Is there a need for a high-level decision making-tool for mass transit planning using energy and environmental criteria?
2. If yes, does such a model exist elsewhere, either in SA or internationally?
3. If the models identified in the literature review are similar in nature to the proposed model, then is there still a case to be made for the development of this model?
4. Are there energy and environmental constraints that need to be factored into decision making regarding the adoption of various mass transit options?
5. Does the model developed allow for optimisation of transport options using energy and environmental criteria?
6. Are the transport options considered appropriate for this type of study?
7. Is there sufficient credible data to base the model’s operation on?
8. Are the assumptions used in the establishment of the data set for the model valid, given the amount of credible data that is available?
9. Are the scenarios selected for this study appropriate, given the current context under which transport planning is managed and the need to consider future constraints imposed on the emission of greenhouse gases from the transport sector?

10. Can such a model be used to effectively pre-screen technology options under consideration and compare their impact (energy and environmental) to other existing or proposed technologies?
11. Is the model developed easy to use and easy to maintain?
12. Are there sufficient grounds to consider a follow-up study using a more robust data set?
13. If a more robust data set does not exist at present, should it be developed as a follow up to this study?
14. Are their grounds to consider additional add-on modules (e.g. emission inventories) to add to the proposed model's applicability?

The author believes that he has demonstrated, through the development, limited verification and use of the model that the approach taken is valid. The questions above have been answered in the affirmative throughout this dissertation. While additional work is required, as proposed in Chapter 5, the model is performing to expectation and the model's design will allow it to be used for the intended purpose.

South Africa has indicated, through President Zuma's address at the Copenhagen UNFCCC Conference of the Parties meeting in 2009 that South Africa would be willing to consider emission reductions in the coming years. This translated into a proposed target of 34% reduction of emissions (2000 baseline) by 2020 and 42% reduction by 2025. Such an ambitious target relies on a substantial reduction in emissions from all consumers and producers of energy. In the case of transport, it is through modal shifts, cleaner fuels and energy efficiency that South Africa intends abating the growth in emissions from this sector.

Till now, the models used in South Africa for the determination of these emission levels and so-called "*stabilisation wedges*" relate to stochastic models or spreadsheet-based models using assumptions in a wide range of areas. It is not possible to find a single optimisation tool in SA that can claim to have a comprehensive and reliable transport demand data set. The model developed in this study acknowledges the limitation in data availability but produces an optimised solution based on few decision variables. The linear programming approach used is tried and tested for transport applications, but the supply chain modelling approach is new. This has ensured that adequate optimisation occurs at each decision point, in this case, at each node.

In this study, the model developed provides the practical, high-level answers that are required to be made by decision makers. With minimal changes to the order of objective functions and the degree of relaxation of constraints imposed, the model provides meaningful results.

As indicated in Chapter 3 of this dissertation, other models identified are either costly, maintenance or data intensive or require specialist operation. This often entails the dedicated service of specialists with years of planning and modelling expertise. Given the data intensity of most models analysed, it is logical that the time required for a model run to be completed is lengthy. The benefit of this model is that a typical run is completed in under an hour and results obtained are easy to display graphically and to interpret.

The model is easily customisable, as detailed in the dissertation. This will allow the user to undertake sensitivity studies where appropriate and update the base data set as appropriate. The user is also able to utilise the tool with minimal outside assistance. It is the intention of the author, however, for

SANERI to play a significant role in updating and maintaining this tool. It will then be housed in SANERI where decision makers may choose to make use of SANERI's services. They will also have the option of obtaining the product directly from SANERI and using it for their own purposes.

4.6 Conclusion

The model produces results for two selected scenarios that are consistent with expected outcomes. The expected outcomes are based on the validation questions posed in the preceding section of this chapter. Essentially, the expected outcome relates to the development of a practical, easy to use and interpret model that can assist in high-level decision making. The data that is available at present, while generally considered incomplete is adequate enough to draw conclusions on the optimal transport mix for a city. Consistent results have been obtained for verification purposes and such a model is suitable for conducting high level sensitivity studies with. The implication therefore is that the model will have a role to play in assisting decision makers to study various transport options. In so doing, they will be able to conduct sensitivity studies with different transport options, demarcation zones, assumptions and costs. This model will require further refining to ensure that it is maintained at a high-level of reliability.

Chapter 5

CLOSURE

Summary

The development of the new high-level decision-making tool for planning mass transportation in Gauteng has been concluded with numerous recommendations for further work. The author has identified the need for data as a critical challenge for the use of the model. A novel way of obtaining the necessary data is proposed as a follow up study which the author intends undertaking.

There are key challenges that need to be overcome still, apart from data availability. The issue of consumer behaviour, competing infrastructure requirements and maintaining such a model need to be resolved. The author has demonstrated though that a strategic decision-making tool is possible and it can be useful in supporting energy and climate conscious decision making by our political leadership.

5 CLOSURE

This study has achieved its objective of developing a strategic decision-making support tool. The hypothesis postulated in Section 1.6 of this dissertation outlining the possibility of setting up such a tool has been proven to be possible. While further work is required to ensure that this study can be effectively used in mitigation of climate change impacts it is clear that this tool is suitable for this purpose.

5.1 Conclusion

5.1.1 Model's role in future climate change mitigation

Two scenarios were developed for demonstration of the optimisation process followed by the model. The scenarios produced rational results that are detailed in this dissertation. The results point to a definitive cost implication for a modal shift away from greenhouse gas emitting modes of transport. This cost will have to be verified in a follow up study as discussed below but the preliminary estimate serves as an indicative figure. This figure reflects the approximate cost of a modal shift and can be used for planning purposes as part of a national climate change response strategy. Government is already set to produce a White Paper on a Climate Change Response Strategy for South Africa and it is likely that such a model will feature in the implementation planning of mitigation measures in the transport sector.

5.1.2 Verification of the Model's performance

Data remains a constraint in the use and verification of the model's performance. There are currently no other models in use (that the author was able to identify) that use the same principle of zone demarcation and data assumptions. It is therefore not that easy to verify the performance of the model by comparing it to other established models. What has been achieved is an empirical affirmation of the model's optimisation process.

The data obtained from the four scenarios selected for verification purposes yielded consistent results in terms of duration, cost, energy and GWP. This indicated that the model was able to produce predictable results when constraints were systematically relaxed over the four scenarios. Naturally, a follow-up study should consider the means by which real data from the transport environment could be used to produce results that are intuitively more accurate. Since the model does not try to simulate a real world situation, it is not as simple an exercise to compare the outcomes with anything in place yet. The author is of the opinion that sufficient consideration of the verification process has been reflected in this study, even though the inherent difficulties in verification have proved challenging.

5.2 Recommendations for further work

5.2.1 Data availability

A limiting factor in this study has been the availability of reliable data. Most data sets have been sourced from national census type sources, together with municipal data. As a consequence, there have been numerous instances where data sets are inconsistent and where municipal boundaries do not coincide with TAZs. This has an impact on the demarcation of zones or bubbles in the model. In addition, the last national census was held in 2001, with most data being somewhat out dated, albeit still usable.

The proposed solution, to be addressed in the subsequent follow up study, involves a two-pronged approach to data collection. In the first instance, the cellular networks will be approached for assistance in providing a “snapshot” of commuter behaviour in Gauteng. The suggested approach involves taking a “snapshot” of subscribers on their network at 12:00 am and then again at 12:00 pm, for an entire typical week. The demarcation zones, defined as bubbles in this study, will be used to assist the networks in mapping commuters’ movement during a typical day. This will then yield an accurate picture of people’s movement between bubbles. Since the data will be aggregated and anonymous, the privacy of subscribers will not be compromised in any way. The data obtained in this way from the participating networks will form the basis of the base case scenario in the proposed follow up study.

A second data collection method involves a conventional survey to be undertaken by university students. These students will be dispatched to common communal meeting points, such as shopping malls, markets, community halls, etc. The survey will be undertaken in communities such as Soweto, Alexandra, Diepkloof, Thembisa and Mamelodi. The survey will focus on the mode of transportation used daily, as well as the associated daily cost and duration of the trip. The survey will be used to refine the assumptions used in this study. The interoperability of different modes of transport can be assessed as well, leading to more realistic constraints being placed on movement between different transport modes.

Stats SA, together with the National Department of Transport, SANRAL, Gauteng Provincial Department of Transport and the CSIR will further be approached for more up to date data sets regarding traffic flows and impact of toll roads. The introduction of the new toll roads in Gauteng, together with the increased usage of the Gautrain service, will further serve to affect the use of passenger vehicles on our roads. The BRT system is now in its second phase of development and data available from the first phase will be incorporated into the follow up study. This will allow for more accurate modelling as accurate average speeds, running costs and commuter uptake can be inputted into the data set.

Emissions data is a further problem area. Goyns (2008) has developed a model for predicting emissions from different vehicle types on our roads. The CSIR has, in a further study, obtained real time data for specific emissions measured on selected major roads in Gauteng. This data, while still being compiled, will be extremely valuable in not only refining the model’s assumptions with respect to emissions, but also assisting in developing an emission cap or limit per bubble. This emission limit,

if adopted by the relevant environmental and transport authority in Gauteng province, will allow for a limitation in access to the most polluted areas by conventional fossil-fuelled vehicles.

5.2.2 *Commuter behaviour prediction*

A new area of research being studied that relates to commuter behaviour is termed *Agent Based Modelling*. In this approach, complex stochastic and artificial intelligence based modelling is used to predict consumer behaviour. This approach is novel, in that conventional modelling relies on prescribed movements and common choices for transport options. Destinations are also usually pre-set, without consideration of factors affecting people's choices of destination or mode of transport.

Agent Based Modelling will assist in creating a more realistic impression of transport demand. The associated impact that changes to transport options in terms of mode and cost will have on commuters can also be assessed.

5.2.3 *Improvements and maintenance of the model*

The model developed will be housed within SANERI, the South African National Energy Research Institute. In order to keep the model relevant, in terms of updated options and costs, the institute will provide a service to local authorities, national government and prospective developers. This service, albeit offered on a cost recovery basis, will be a highly cost effective option for the user. As the latest public transport options introduced, e.g., BRT and Gautrain, provide meaningful data from their first years of operation, it will be possible to keep the model up to date. Sensitivity studies, such as new light rail systems should be studied to determine their feasibility, versus options such as subway systems. It is possible, using this tool, to determine a preliminary assessment of the relative value of these options.

Chapter 6

REFERENCES

Summary

A listing of the main references used in this study is provided. In cases where a hyperlink to an internet site is provided, it should be noted that this source was cross-referenced first and the internet link is only provided to verify the authenticity of the source.

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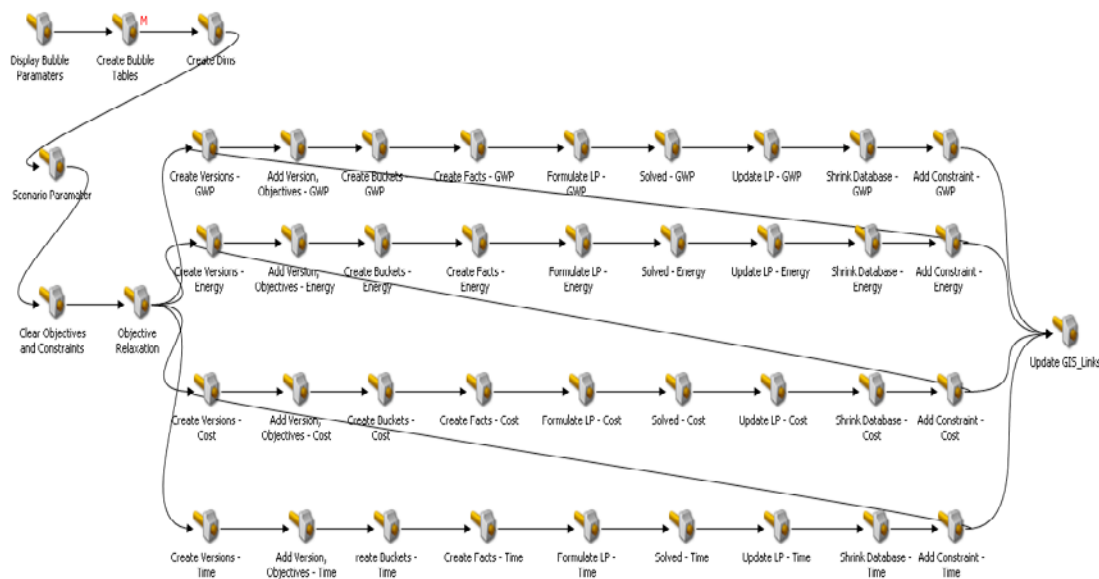
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APPENDIX 1: WORKFLOW DOCUMENTATION

This annex details the workflow protocol followed by the model in its optimisation process. Below the workflow representation is the detailed summary of the programming per stage of optimisation. This is useful for cross referencing to other models, where users may wish to compare the algorithm and programme code to that available elsewhere.



1. Add Constraint - Cost

Properties

Type : Execute__SQL
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Add Constraint

Update Bubbles Objectives

Set

IsConstraint = 1,
 MaxObjectiveValue = -1 * //Solved - Cost.LPObjective// * (1 + //Objective
 Relaxation.Relax Objective//)

Where

Objective = 'Cost'

2. Add Constraint - Energy

Properties

Type : Execute__SQL

Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Add Constraint

Update Bubbles_Objectives

Set

IsConstraint = 1,
 MaxObjectiveValue = -1 * //Solved - Energy.LPObjective// * (1 + //Objective
 Relaxation.Relax Objective//)

Where

Objective = 'Energy'

3. Add Constraint - GWP

Properties

Type : Execute__SQL
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Add Constraint

Update Bubbles_Objectives

Set

IsConstraint = 1,
 MaxObjectiveValue = -1 * //Solved - GWP.LPObjective// * (1 + //Objective
 Relaxation.Relax Objective//)

Where

Objective = 'GWP'

4. Add Constraint - Time

Properties

Type : Execute__SQL
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Add Constraint

Update Bubbles_Objectives

Set

IsConstraint = 1,
 MaxObjectiveValue = -1 * //Solved - Time.LPObjective// * (1 + //Objective
 Relaxation.Relax Objective//)

Where

Objective = 'Travel Time'

5. Add Version, Objectives - Cost

Properties

Type : Execute__SQL
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Update Current Version No

```

Update CM_Globals
Set
    ParamaterValue = '//Create Versions - Cost.VersionNo//'
Where
    [Category] = 'Current'
And    [ParamaterName] = 'VersionNo'
Add Objective
Update Bubbles_Objectives
Set
    IsObjective = 0

Update Bubbles_Objectives
Set
    IsObjective = 1

Where
    Objective = 'Cost'

```

6. Add Version, Objectives - Energy

```

Properties
Type                : Execute__SQL
Execution Days      : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window    : 00:00 to 00:00
Automated           : True
Backtrack           : True
Tool                :
Update Current Version No
Update CM_Globals
Set
    ParamaterValue = '//Create Versions - Energy.VersionNo//'
Where
    [Category] = 'Current'
And    [ParamaterName] = 'VersionNo'
Add Objective
Update Bubbles_Objectives

Set
    IsObjective = 0
Update Bubbles_Objectives
Set
    IsObjective = 1
Where
    Objective = 'Energy'

```

7. Add Version, Objectives - GWP

```

Properties
Type                : Execute__SQL
Execution Days      : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window    : 00:00 to 00:00
Automated           : True
Backtrack           : True
Tool                :
Update Current Version No
Update CM_Globals
Set
    ParamaterValue = '//Create Versions - GWP.VersionNo//'
Where

```

```

[Category] = 'Current'
And [ParamaterName] = 'VersionNo'

```

Add Objective

```
Update Bubbles_Objectives
```

```
Set
```

```
IsObjective = 0
```

```
Update Bubbles_Objectives
```

```
Set
```

```
IsObjective = 1
```

```
Where
```

```
Objective = 'GWP'
```

8. Add Version, Objectives - Time

Properties

```

Type : Execute__SQL
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

```

Update Current Version No

```
Update CM_Globals
```

```
Set
```

```
ParamaterValue = '//Create Versions - Time.VersionNo//'
```

```
Where
```

```
[Category] = 'Current'
```

```
And [ParamaterName] = 'VersionNo'
```

Add Objective

```
Update Bubbles_Objectives
```

```
Set
```

```
IsObjective = 0
```

```
Update Bubbles_Objectives
```

```
Set
```

```
IsObjective = 1
```

```
Where
```

```
Objective = 'Travel Time'
```

9. Clear Objectives and Constraints

Properties

```

Type : Execute__SQL
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

```

Clear Objectives

```
Update Bubbles_Objectives
```

```
Set
```

```
IsObjective = 0
```

Clear Constraints

```
Update Bubbles_Objectives
```

```
Set
```

```

IsConstraint = 0,
MaxObjectiveValue = 0,
MinObjectiveValue = 0

```

10. Create Bubble Tables

Properties

Type : Execute__Procedures
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : False
Backtrack : True
Tool :

Parameters

Categories - ProcedureCategory (Required) : Populate Bubbles

11. Create Buckets - Cost

Properties

Type : SP__Create_Buckets
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :

Parameters

VersionNo - Number (Required) : //Globals.Current.VersionNo//
FromDate - Text (Required) : 20080101
Periods - Number (Required) : 1
BucketType - Text (Required) : day
Duration - Number (Required) : 1

12. Create Buckets - Energy

Properties

Type : SP__Create_Buckets
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :

Parameters

VersionNo - Number (Required) : //Globals.Current.VersionNo//
FromDate - Text (Required) : 20080101
Periods - Number (Required) : 1
BucketType - Text (Required) : day
Duration - Number (Required) : 1

13. Create Buckets - GWP

Properties

Type : SP__Create_Buckets
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :

Parameters

VersionNo - Number (Required) : //Globals.Current.VersionNo//
FromDate - Text (Required) : 20080101
Periods - Number (Required) : 1
BucketType - Text (Required) : day
Duration - Number (Required) : 1

14. Create Dims

Properties

Type : Execute__SQL
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Modes

Insert Into SP_Dim_Modes

```
(
    [Mode]
)
Select Distinct
    [Bubbles_Modes].[Mode]
From
    [Bubbles_Modes]
Where
    [Bubbles_Modes].[Mode] not in (Select Mode From SP_Dim_Modes)
```

Bubbles

Insert Into SP_Dim_Bubbles

```
(
    [Bubble],
    [Bubble_PartID]
)
Select Distinct
    [Bubbles_Locations].[Location],
    [Bubbles_Locations].[Part_ID]
From
    [Bubbles_Locations]
Where
    [Bubbles_Locations].[Location] not in (Select Bubble From SP_Dim_Bubbles)
```

From and To Bubbles

Insert Into SP_Dim_FromBubbles(

```
    FromBubble_ID,
    FromBubble,
    FromBubble_Desc,
    FromBubble_PartID
```

```
)
Select
    Bubble_ID,
    Bubble,
    Bubble_Desc,
    Bubble_PartID
```

From SP_Dim_Bubbles

Where Bubble not in (Select Distinct FromBubble From SP_Dim_FromBubbles);

Insert Into SP_Dim_ToBubbles(

```
    ToBubble_ID,
    ToBubble,
    ToBubble_Desc,
    ToBubble_PartID
```

```
)
Select
    Bubble_ID,
    Bubble,
    Bubble_Desc,
    Bubble_PartID
```

```

From SP_Dim_Bubbles
Where Bubble not in (Select Distinct ToBubble From SP_Dim_ToBubbles);
Commuters
Insert Into SP_Dim_Commuters
(
    [Commuter],
    [ToLocation],
    Commuter_Type
)
Select Distinct
    [Bubbles_Destinations].[Destination] + '_' + Mode.Mode_Type,
    [Bubbles_Destinations].[Destination],
    Mode.Mode_Type
From
    [Bubbles_Destinations],
    (Select 'Private' as Mode_Type Union Select 'Public') as Mode
Where
    [Bubbles_Destinations].[Destination] + '_' + Mode.Mode_Type not in (Select
        Commuter From SP_Dim_Commuters)
From and To Commuters
Insert Into SP_Dim_CommutersFrom
(
    [CommuterFrom_ID],
    [CommuterFrom],
    [CommuterFrom_ToLocation],
    [CommuterFrom_Type]
)
Select
    [Commuter_ID],
    [Commuter],
    [ToLocation],
    [Commuter_Type]
From
    SP_Dim_Commuters
Where
    Commuter not in (Select CommuterFrom From SP_Dim_CommutersFrom)
Insert Into SP_Dim_CommutersTo
(
    [CommuterTo_ID],
    [CommuterTo],
    [CommuterTo_ToLocation],
    [CommuterTo_Type]
)
Select
    [Commuter_ID],
    [Commuter],
    [ToLocation],
    [Commuter_Type]
From
    SP_Dim_Commuters
Where
    Commuter not in (Select CommuterTo From SP_Dim_CommutersTo)
Constraint Types
Insert Into SP_Dim_ConstraintTypes
(
    [ConstraintType]
)

```

```

Select Distinct
    [Bubbles_LinkConstraints].[ConstraintType]
From
    [Bubbles_LinkConstraints]
Where
    [Bubbles_LinkConstraints].[ConstraintType] not in (Select ConstraintType From
    SP_Dim_ConstraintTypes)

```

Vehicles

```

Insert Into SP_Dim_Vehicles

```

```

(
    [Vehicle],
    [Vehicle_Type]
)

```

```

Select Distinct
    [Bubbles_Vehicles].[Vehicle],
    [Bubbles_Vehicles].[Vehicle_Type]
From
    [Bubbles_Vehicles]
Where
    [Bubbles_Vehicles].[Vehicle] not in (Select Vehicle From SP_Dim_Vehicles)

```

Objectives

```

Insert Into SP_Dim_Objectives

```

```

(
    [Objective]
)

```

```

Select
    'Travel Time'
Where 'Travel Time' not in (Select [Objective] From SP_Dim_Objectives)

```

```

Insert Into SP_Dim_Objectives

```

```

(
    [Objective]
)

```

```

Select
    'Cost'
Where 'Cost' not in (Select [Objective] From SP_Dim_Objectives)

```

```

Insert Into SP_Dim_Objectives

```

```

(
    [Objective]
)

```

```

Select
    'Energy'
Where 'Energy' not in (Select [Objective] From SP_Dim_Objectives)

```

```

Insert Into SP_Dim_Objectives

```

```

(
    [Objective]
)

```

```

Select
    'GWP'
Where 'GWP' not in (Select [Objective] From SP_Dim_Objectives)

```

15. Create Facts - Cost

Properties

Type	: Execute__Procedures
Execution Days	: Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window	: 00:00 to 00:00
Automated	: True
Backtrack	: True

Tool :
Paramaters
Categories - ProcedureCategory (Required) : Populate Facts

16. Create Facts - Energy

Properties
Type : Execute__Procedures
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :
Paramaters
Categories - ProcedureCategory (Required) : Populate Facts

17. Create Facts - GWP

Properties
Type : Execute__Procedures
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :
Paramaters
Categories - ProcedureCategory (Required) : Populate Facts

18. Create Facts - Time

Properties
Type : Execute__Procedures
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :
Paramaters
Categories - ProcedureCategory (Required) : Populate Facts

19. Create Versions - Cost

Properties
Type : SP__Version_Create
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :
Paramaters
Description - Text (Required) : //Scenario Paramater.Scenario// - Cost
VersionNo - Number (Required) :

20. Create Versions - Energy

Properties
Type : SP__Version_Create
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True

Backtrack : False
Tool :
Paramaters
Description - Text (Required) : //Scenario Paramater.Scenario// - Energy
VersionNo - Number (Required) :

21. Create Versions - GWP

Properties
Type : SP__Version_Create
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :
Paramaters
Description - Text (Required) : //Scenario Paramater.Scenario// - GWP
VersionNo - Number (Required) :

22. Create Versions - Time

Properties
Type : SP__Version_Create
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :
Paramaters
Description - Text (Required) : //Scenario Paramater.Scenario// - Time
VersionNo - Number (Required) :

23. Display Bubble Paramaters

Properties
Type : Data__Display_Table
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :
Paramaters
Tables - Table (Required) : Bubbles_Objectives|Bubbles_Vehicles

24. Formulate LP - Cost

Properties
Type : SP__Formulate_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :
Paramaters
LPName - Text (Required) : Minimize Travel Time
PlanningVersion - Text (Required) : //Create Versions - Cost.VersionNo//
SolvingGroupMultiple - Number (Required) : 2000
PlanningGroupDimension - DimTable (Required) : SP_Dim_Items
RelaxConstraints - Text :
IgnoreConstraints - Text : Max Budget

25. Formulate LP - Energy

Properties

Type : SP__Formulate_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Parameters

LPName - Text (Required) : Minimize Travel Time
PlanningVersion - Text (Required) : //Create Versions - Energy.VersionNo//
SolvingGroupMultiple - Number (Required) : 2000
PlanningGroupDimension - DimTable (Required) : SP_Dim_Items
RelaxConstraints - Text :
IgnoreConstraints - Text : Max Budget

26. Formulate LP - GWP

Properties

Type : SP__Formulate_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Parameters

LPName - Text (Required) : Minimize Travel Time
PlanningVersion - Text (Required) : //Create Versions - GWP.VersionNo//
SolvingGroupMultiple - Number (Required) : 2000
PlanningGroupDimension - DimTable (Required) : SP_Dim_Items
RelaxConstraints - Text :
IgnoreConstraints - Text : Max Budget

27. Formulate LP - Time

Properties

Type : SP__Formulate_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Parameters

LPName - Text (Required) : Minimize Travel Time
PlanningVersion - Text (Required) : //Create Versions - Time.VersionNo//
SolvingGroupMultiple - Number (Required) : 2000
PlanningGroupDimension - DimTable (Required) : SP_Dim_Items
RelaxConstraints - Text :
IgnoreConstraints - Text : Max Budget

28. Objective Relaxation

Properties

Type : Paramater
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True

Tool :
Paramaters
Relax Objective - Number (Required) :

29. Create Buckets - Time

Properties

Type : SP__Create_Buckets
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : False
Tool :

Paramaters

VersionNo - Number (Required) : //Globals.Current.VersionNo//
FromDate - Text (Required) : 20080101
Periods - Number (Required) : 1
BucketType - Text (Required) : day
Duration - Number (Required) : 1

30. Scenario Paramater

Properties

Type : Paramater
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Paramaters

Scenario - Text (Required) :

31. Shrink Database - Cost

Properties

Type : Database__Shrink
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

32. Shrink Database - Energy

Properties

Type : Database__Shrink
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

33. Shrink Database - GWP

Properties

Type : Database__Shrink
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

34. Shrink Database - Time

Properties

Type : Database__Shrink
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

35. Solved - Cost

Properties

Type : SP__Solve_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Parameters

Presolve - Bool (Required) : True
MIPs - Bool (Required) : False
Max Time - Number (Required) : 300
Relative Stop - Number (Required) : 0.99
MIP Absolute Cut Off - Number (Required) : 0.90
SolveStatus - Text (Required) :
Solved - Bool (Required) :
LPObjective - Number (Required) :
MIPObjective - Number (Required) :
MIPSolutions - Number (Required) :
BestBound - Number (Required) :
MPSFileSize - Number (Required) :

36. Solved - Energy

Properties

Type : SP__Solve_LP
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Execution Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

Parameters

Presolve - Bool (Required) : True
MIPs - Bool (Required) : False
Max Time - Number (Required) : 300
Relative Stop - Number (Required) : 0.99
MIP Absolute Cut Off - Number (Required) : 0.90
SolveStatus - Text (Required) :
Solved - Bool (Required) :
LPObjective - Number (Required) :
MIPObjective - Number (Required) :
MIPSolutions - Number (Required) :
BestBound - Number (Required) :
MPSFileSize - Number (Required) :

37. Solved - GWP

Properties

Type : SP__Solve_LP
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Parameters

Presolve - Bool (Required) : True
 MIPs - Bool (Required) : False
 Max Time - Number (Required) : 300
 Relative Stop - Number (Required) : 0.99
 MIP Absolute Cut Off - Number (Required) : 0.90
 SolveStatus - Text (Required) :
 Solved - Bool (Required) :
 LPObjective - Number (Required) :
 MIPObjective - Number (Required) :
 MIPSolutions - Number (Required) :
 BestBound - Number (Required) :
 MPSFileSize - Number (Required) :

38. Solved - Time

Properties

Type : SP__Solve_LP
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Parameters

Presolve - Bool (Required) : True
 MIPs - Bool (Required) : False
 Max Time - Number (Required) : 300
 Relative Stop - Number (Required) : 0.99
 MIP Absolute Cut Off - Number (Required) : 0.90
 SolveStatus - Text (Required) :
 Solved - Bool (Required) :
 LPObjective - Number (Required) :
 MIPObjective - Number (Required) :
 MIPSolutions - Number (Required) :
 BestBound - Number (Required) :
 MPSFileSize - Number (Required) :

39. Update GIS_Links

Properties

Type : Execute__Procedures
 Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
 Execution Window : 00:00 to 00:00
 Automated : True
 Backtrack : True
 Tool :

Parameters

Categories - ProcedureCategory (Required) : Update

40. Update LP - Cost

Properties

Type : SP__Update_LP_Solution

Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

41. Update LP - Energy

Properties

Type : SP__Update_LP_Solution
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

42. Update LP - GWP

Properties

Type : SP__Update_LP_Solution
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

43. Update LP - Time

Properties

Type : SP__Update_LP_Solution
Execution Days : Mon,Tue,Wed,Thu,Fri,Sat,Sun
Exectuion Window : 00:00 to 00:00
Automated : True
Backtrack : True
Tool :

PROCEDURE DOCUMENTATION

1 Populations

Delete From SP_Fact_Populations Where Version_ID = //Globals.Current.VersionNo//

Insert Into SP_Fact_Populations

```
(
    [Version_ID],
    [Bubble_ID],
    [Commuter_ID],
    [Bucket_ID]
)
Select Distinct
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_Commuters.Commuter_ID,
    SP_Dim_Buckets.Bucket_ID
From
    SP_Dim_Versions,
    SP_Dim_Bubbles,
    SP_Dim_Commuters,
    SP_Dim_Buckets,
    Bubbles_Destinations,
    (Select Location, Cast(Substring(ReferencePoint,1,charindex(',',ReferencePoint)-1) as Float)
as X, Cast(Substring(ReferencePoint,charindex(',',ReferencePoint)+1,10) as Float) as Y From
Bubbles_Locations) as FromLocation,
    (Select Location, Cast(Substring(ReferencePoint,1,charindex(',',ReferencePoint)-1) as Float)
as X, Cast(Substring(ReferencePoint,charindex(',',ReferencePoint)+1,10) as Float) as Y From
Bubbles_Locations) as ToLocation,
    (Select Location, Cast(Substring(ReferencePoint,1,charindex(',',ReferencePoint)-1) as Float)
as X, Cast(Substring(ReferencePoint,charindex(',',ReferencePoint)+1,10) as Float) as Y From
Bubbles_Locations) as Bubble
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo
and    Bubble.Location = SP_Dim_Bubbles.Bubble
and    Bubbles_Destinations.Destination = SP_Dim_Commuters.ToLocation
and    SP_Dim_Commuters.Commuter_Type in ('Private','Public')
and    FromLocation.Location = Bubbles_Destinations.Location
and    ToLocation.Location = Bubbles_Destinations.Destination
and    Sqrt(Square(FromLocation.X - Bubble.X) + Square(FromLocation.Y - Bubble.Y)) +
Sqrt(Square(ToLocation.X - Bubble.X) + Square(ToLocation.Y - Bubble.Y)) <= 2 *
Sqrt(Square(FromLocation.X - ToLocation.X) + Square(FromLocation.Y - ToLocation.Y))
```

2 Initial Populations

Delete From SP_Fact_InitialPopulations Where Version_ID = //Globals.Current.VersionNo//

Insert Into SP_Fact_InitialPopulations

```
(
    [Version_ID],
    [Bubble_ID],
    [Commuter_ID],
    [Bucket_ID],
    [Initial_Qty]
)
```

```

Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_Commuters.Commuter_ID,
    SP_Dim_Buckets.Bucket_ID,
    Bubbles_Destinations.Splits * Bubbles_Locations.Population * Power((1 +
Bubbles_Locations.Growth), Cast(SP_Dim_Buckets.BucketNo as Float) - 1)
From
    SP_Dim_Versions,
    SP_Dim_Bubbles,
    SP_Dim_Commuters,
    SP_Dim_Buckets,
    Bubbles_Destinations,
    Bubbles_Locations
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    Bubbles_Destinations.Location = SP_Dim_Bubbles.Bubble
and    Bubbles_Locations.Location = Bubbles_Destinations.Location

and    Bubbles_Destinations.Destination = SP_Dim_Commuters.ToLocation
and    Bubbles_Destinations.CommuterType = SP_Dim_Commuters.Commuter_Type
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo

```

3 Destinations

Delete From SP_Fact_Destinations Where Version_ID = //Globals.Current.VersionNo//

Insert Into SP_Fact_Destinations

```

(
    [Version_ID],
    [Bubble_ID],
    [Bucket_ID],
    [Destination_Qty]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_Buckets.Bucket_ID,
    Sum(Bubbles_Destinations.Splits * Bubbles_Locations.Population * Power((1 +
Bubbles_Locations.Growth), Cast(SP_Dim_Buckets.BucketNo as Float) - 1))
From
    SP_Dim_Versions,
    SP_Dim_Bubbles,
    SP_Dim_Buckets,
    Bubbles_Destinations,
    Bubbles_Locations
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo

and    Bubbles_Destinations.Destination = SP_Dim_Bubbles.Bubble
and    Bubbles_Locations.Location = Bubbles_Destinations.Location
Group By
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_Buckets.Bucket_ID

```

4 Destinations Reached

Delete From SP_Fact_DestinationReached Where Version_ID = //Globals.Current.VersionNo//
Insert Into SP_Fact_DestinationReached

```
(
    [Version_ID],
    [Bubble_ID],
    [Commuter_ID],
    [Bucket_ID]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_Commuters.Commuter_ID,
    SP_Dim_Buckets.Bucket_ID
From
    SP_Dim_Versions,
    SP_Dim_Bubbles,
    SP_Dim_Commuters,
    SP_Dim_Buckets
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo
and    SP_Dim_Bubbles.Bubble = SP_Dim_Commuters.ToLocation
and    SP_Dim_Commuters.Commuter_Type in ('Private','Public')
```

5 Trips

Delete From SP_Fact_Trips Where Version_ID = //Globals.Current.VersionNo//
Insert Into SP_Fact_Trips

```
(
    [Version_ID],
    [FromBubble_ID],
    [ToBubble_ID],
    [Mode_ID],
    [Vehicle_ID],
    [Commuter_ID],
    [Bucket_ID],
    [Travel_Time],
    [Travel_Distance],
    [Travel_Cost],
    [Travel_Energy],
    [Travel_GWP]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_FromBubbles.FromBubble_ID,
    SP_Dim_ToBubbles.ToBubble_ID,
    SP_Dim_Modes.Mode_ID,
    SP_Dim_Vehicles.Vehicle_ID,
    SP_Dim_Commuters.Commuter_ID,
    SP_Dim_Buckets.Bucket_ID,
    Case
        When Bubbles_Modes.Speed < Bubbles_Vehicles.Speed Then
            Bubbles_Links.Distance / Bubbles_Modes.Speed
        Else
            Bubbles_Links.Distance / Bubbles_Vehicles.Speed
    End as Travel_Time,
```

```

        Bubbles_Links.Distance as Travel_Distance,
        Bubbles_Vehicles.MobilityCost * Bubbles_Links.Distance as Travel_Cost,
        Bubbles_Vehicles.Energy / Bubbles_Vehicles.Capacity * Bubbles_Links.Distance as
Travel_Energy,
        Bubbles_Vehicles.GWP / Bubbles_Vehicles.Capacity * Bubbles_Links.Distance as Travel_GWP
From
    SP_Dim_Versions,
    SP_Dim_FromBubbles,
    SP_Dim_ToBubbles,
    SP_Dim_Modes,
    SP_Dim_Vehicles,
    SP_Dim_Commuters,
    SP_Dim_Buckets,
    SP_Fact_Populations as FromPopulation,
    SP_Fact_Populations as ToPopulation,
    Bubbles_Links,
    Bubbles_Modes,
    Bubbles_Vehicles
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo
and    FromPopulation.Version_ID = SP_Dim_Versions.Version_ID
and    FromPopulation.Bubble_ID = SP_Dim_FromBubbles.FromBubble_ID
and    FromPopulation.Commuter_ID = SP_Dim_Commuters.Commuter_ID
and    FromPopulation.Bucket_ID = SP_Dim_Buckets.Bucket_ID
and    ToPopulation.Version_ID = SP_Dim_Versions.Version_ID
and    ToPopulation.Bubble_ID = SP_Dim_ToBubbles.ToBubble_ID
and    ToPopulation.Commuter_ID = SP_Dim_Commuters.Commuter_ID
and    ToPopulation.Bucket_ID = SP_Dim_Buckets.Bucket_ID
and    Bubbles_Links.FromLocation = SP_Dim_FromBubbles.FromBubble
and    Bubbles_Links.ToLocation = SP_Dim_ToBubbles.ToBubble
and    Bubbles_Links.Mode = SP_Dim_Modes.Mode
and    Bubbles_Links.Mode = Bubbles_Modes.Mode
and    Bubbles_Vehicles.Vehicle = SP_Dim_Vehicles.Vehicle
and    Bubbles_Modes.Active = 1
and    Bubbles_Vehicles.Active = 1
and    Bubbles_Vehicles.Vehicle_Type = SP_Dim_Commuters.Commuter_Type
and    Bubbles_Vehicles.Modes like '%' + Bubbles_Modes.Mode + '%'

```

6 Trip Capacities

Delete From SP_Fact_TripCapacities Where Version_ID = //Globals.Current.VersionNo//

Insert Into SP_Fact_TripCapacities

```

(
    [Version_ID],
    [FromBubble_ID],
    [ToBubble_ID],
    [Mode_ID],
    [ConstraintType_ID],
    [Bucket_ID],
    [MaxValue]
)
Select Distinct
    SP_Dim_Versions.Version_ID,
    SP_Dim_FromBubbles.FromBubble_ID,
    SP_Dim_ToBubbles.ToBubble_ID,
    SP_Dim_Modes.Mode_ID,

```

```

        SP_Dim_ConstraintTypes.ConstraintType_ID,
        SP_Dim_Buckets.Bucket_ID,
        Bubbles_LinkConstraints.ConstraintValue
From
    SP_Dim_Versions,
    SP_Dim_FromBubbles,
    SP_Dim_ToBubbles,
    SP_Dim_Modes,
    SP_Dim_ConstraintTypes,
    SP_Dim_Buckets,
    Bubbles_LinkConstraints,
    Bubbles_Modes
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    Bubbles_LinkConstraints.FromLocation = SP_Dim_FromBubbles.FromBubble
and    Bubbles_LinkConstraints.ToLocation = SP_Dim_ToBubbles.ToBubble
and    Bubbles_LinkConstraints.Mode = SP_Dim_Modes.Mode
and    Bubbles_LinkConstraints.ConstraintType = SP_Dim_ConstraintTypes.ConstraintType
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo
and    Bubbles_LinkConstraints.Mode = Bubbles_Modes.Mode

```

7 Build Mode and Node

Delete From SP_Fact_ModeAndNodeBuilder Where Version_ID = //Globals.Current.VersionNo//
Insert Into SP_Fact_ModeAndNodeBuilder

```

(
    [Version_ID],
    [FromBubble_ID],
    [ToBubble_ID],
    [Mode_ID],
    [Bucket_ID],
    [BuildCost],
    [BigM]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_FromBubbles.FromBubble_ID,
    SP_Dim_ToBubbles.ToBubble_ID,
    SP_Dim_Modes.Mode_ID,
    SP_Dim_Buckets.Bucket_ID,
    [Bubbles_Links].[Distance] * [Bubbles_Modes].[BuildCost] as BuildCost,
    1000000000
From
    SP_Dim_Versions,
    SP_Dim_FromBubbles,
    SP_Dim_ToBubbles,
    SP_Dim_Modes,
    SP_Dim_Buckets,
    Bubbles_Links,
    Bubbles_Modes
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//

and    SP_Dim_Versions.VersionNo = SP_Dim_Buckets.BucketVersion
and    [Bubbles_Links].[FromLocation] = SP_Dim_FromBubbles.FromBubble
and    [Bubbles_Links].[ToLocation] = SP_Dim_ToBubbles.ToBubble
and    [Bubbles_Links].[Mode] = SP_Dim_Modes.Mode

```

```

and    [Bubbles_Modes].[Mode] = SP_Dim_Modes.Mode
and    [Bubbles_Links].[Active] = 0

```

8 Budget

```

Delete From SP_Fact_Budget Where Version_ID = //Globals.Current.VersionNo//
Insert Into SP_Fact_Budget
(
    [Version_ID],
    [BudgetCost]
)
Select
    SP_Dim_Versions.Version_ID,
    400000000
From
    SP_Dim_Versions
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//

```

9 Commuter Change Overs

```

Delete From SP_Fact_CommuterChangeOvers Where Version_ID = //Globals.Current.VersionNo//
Insert Into SP_Fact_CommuterChangeOvers
(
    [Version_ID],
    [Bubble_ID],
    [CommuterFrom_ID],
    [CommuterTo_ID],
    [Bucket_ID]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_Bubbles.Bubble_ID,
    SP_Dim_CommutersFrom.CommuterFrom_ID,
    SP_Dim_CommutersTo.CommuterTo_ID,
    SP_Dim_Buckets.Bucket_ID
From
    SP_Dim_Versions,
    SP_Dim_Buckets,
    SP_Dim_Bubbles,
    SP_Dim_CommutersFrom,
    SP_Dim_CommutersTo,
    SP_Fact_Populations as FromPopulation,
    SP_Fact_Populations as ToPopulation
Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and    SP_Dim_Buckets.BucketVersion = SP_Dim_Versions.VersionNo
and    FromPopulation.Version_ID = SP_Dim_Versions.Version_ID
and    FromPopulation.Bubble_ID = SP_Dim_Bubbles.Bubble_ID
and    FromPopulation.Commuter_ID = SP_Dim_CommutersFrom.CommuterFrom_ID
and    FromPopulation.Bucket_ID = SP_Dim_Buckets.Bucket_ID
and    ToPopulation.Version_ID = SP_Dim_Versions.Version_ID
and    ToPopulation.Bubble_ID = SP_Dim_Bubbles.Bubble_ID
and    ToPopulation.Commuter_ID = SP_Dim_CommutersTo.CommuterTo_ID
and    ToPopulation.Bucket_ID = SP_Dim_Buckets.Bucket_ID
and    SP_Dim_CommutersFrom.CommuterFrom_ToLocation =
    SP_Dim_CommutersTo.CommuterTo_ToLocation

```

```

and      SP_Dim_CommutersFrom.CommuterFrom_Type
SP_Dim_CommutersTo.CommuterTo_Type
and      SP_Dim_CommutersTo.CommuterTo_Type = 'Public'

```

<>

10 Objectives

```
Delete From SP_Fact_TravelObjectives Where Version_ID = //Globals.Current.VersionNo//
```

```
Insert Into SP_Fact_TravelObjectives
```

```

(
    [Version_ID],
    [Objective_ID],
    [ObjectiveName],
    [IsObjective],
    [IsConstraint],
    [MinObjective],
    [MaxObjective]
)
Select
    SP_Dim_Versions.Version_ID,
    SP_Dim_Objectives.Objective_ID,
    SP_Dim_Objectives.Objective,
    Bubbles_Objectives.IsObjective,
    Bubbles_Objectives.IsConstraint,
    Bubbles_Objectives.MinObjectiveValue,
    Bubbles_Objectives.MaxObjectiveValue

```

```

From
    SP_Dim_Versions,
    SP_Dim_Objectives,
    Bubbles_Objectives

```

```

Where
    SP_Dim_Versions.VersionNo = //Globals.Current.VersionNo//
and
    Bubbles_Objectives.Objective = SP_Dim_Objectives.Objective

```

7 APPENDIX 2: RAW DATA USED IN LIMITED VERIFICATION OF MODEL PERFORMANCE

Computer generated data tables showing scenario details (Raw data referenced in Chapter 3):

Scenario	05 Perc	Summarised values of:						Average
Objective	Vehicle	Time (h)	Cost (R)	Energy (MJ)	GWP (g)	Distance (km)	Pax_Speed (Pax.km/h)	Speed (km/h)
Cost	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	27 825	55 846	140 031	25 940 225	834 762	6 077 011	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	-	-	-	-	-	-	
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	467 180	1 390 328	1 237 724	356 148 905	37 374 400	243 724 083	80.0
	Taxi Diesel	276 768	1 188 312	3 931 939	282 608 149	16 167 514	116 503 679	58.4
Cost Total	Taxi Petrol	-	-	-	-	-	-	
		771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
Energy Total	BRT Trolley	3 869	7 766	19 472	3 607 113	116 078	843 175	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	5 775	145 386	10 718	3 083 993	461 983	7 151 921	80.0
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	509 549	1 516 417	1 349 973	388 448 061	40 763 885	262 381 744	80.0
	Taxi Diesel	254 022	1 096 642	3 628 616	260 806 744	14 920 294	110 992 195	58.7
	Taxi Petrol	-	-	-	-	-	-	
		773 215	2 766 210	5 008 778	655 945 911	56 262 240	381 369 035	72.8
GWP	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
GWP Total	BRT Trolley	1 735	3 482	8 732	1 617 577	52 054	309 730	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	2 521	63 476	4 679	1 346 476	201 702	1 838 444	80.0
	Metro Bus Diesel	720	7 299	15 214	1 092 735	40 821	891 791	56.7
	Rail	500 703	1 490 091	1 326 537	381 704 544	40 056 218	253 575 908	80.0
	Taxi Diesel	251 828	1 089 938	3 606 433	259 212 381	14 829 084	100 637 048	58.9
	Taxi Petrol	15 708	111 924	297 622	22 941 700	901 885	11 869 317	57.4
		773 215	2 766 210	5 259 217	667 915 413	56 081 764	369 122 238	72.5
Time	BRT Diesel	577	2 675	4 191	324 613	17 301	102 945	30.0
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	-	-	-	-	-	-	
	Car Diesel	15 701	1 268 866	1 746 572	125 418 756	929 028	4 525 383	59.2 58.7
	Car Electric	6 494	257 199	205 973	59 121 769	381 431	2 494 172	
	Car Petrol	14 358	1 421 465	1 840 056	141 213 591	855 840	5 043 618	59.6
	Gautrain	18 754	472 139	34 807	10 015 217	1 500 282	13 664 331	80.0
	Metro Bus Diesel	112 734	1 185 283	2 470 615	177 455 957	6 629 102	50 330 469	58.8
	Rail	334 051	994 137	885 019	254 659 862	26 724 101	168 577 746	80.0

	Taxi Diesel	120 134	522 065	1 727 433	124 159 240	7 102 931	47 169 654	59.1
	Taxi Petrol	113 592	824 870	2 193 450	169 078 407	6 646 817	45 086 910	58.5
Time Total		736 395	6 948 698	11 108 115	1 061 447 411	50 786 833	336 995 228	69.0
05 Perc Total		3 054 598	15 115 604	26 685 805	3 050 006 013	217 507 513	1 453 791 274	71.2
10 Perc Cost								
	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	27 825	55 846	140 031	25 940 225	834 762	6 077 011	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	-	-	-	-	-	-	
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	467 180	1 390 328	1 237 724	356 148 905	37 374 400	243 724 083	80.0
	Taxi Diesel	276 768	1 188 312	3 931 939	282 608 149	16 167 514	116 503 679	58.4
	Taxi Petrol	-	-	-	-	-	-	
Cost Total		771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy								
	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	6 677	13 400	33 600	6 224 197	200 296	1 475 739	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	9 298	234 076	17 256	4 965 325	743 807	11 878 164	80.0
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	573 715	1 707 376	1 519 972	437 364 626	45 897 208	291 920 666	80.0
	Taxi Diesel	220 345	943 082	3 120 511	224 286 724	12 831 048	107 104 988	58.2
	Taxi Petrol	-	-	-	-	-	-	
Energy Total		810 034	2 897 934	4 691 339	672 840 873	59 672 359	412 379 556	73.7
GWP								
	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	145	521	1 137	53 770	4 354	73 675	30.0
	BRT Trolley	6 469	12 983	32 553	6 030 362	194 058	1 525 128	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	3 904	98 298	7 247	2 085 138	312 354	3 932 765	80.0
	Metro Bus Diesel	1 828	18 411	38 376	2 756 417	102 970	2 608 932	56.3
	Rail	551 152	1 640 228	1 460 195	420 163 925	44 092 160	267 854 544	80.0
	Taxi Diesel	222 295	958 594	3 171 837	227 975 756	13 042 091	91 955 692	58.7
	Taxi Petrol	24 242	168 900	449 128	34 620 319	1 360 995	22 865 920	56.1
GWP Total		810 034	2 897 934	5 160 473	693 685 686	59 108 982	390 816 655	73.0
Time								
	BRT Diesel	466	2 163	3 389	262 459	13 989	83 234	30.0
	BRT Hybrid	110	397	865	40 911	3 313	19 711	30.0
	BRT Trolley	-	-	-	-	-	-	
	Car Diesel	11 064	889 929	1 224 972	87 963 431	651 581	3 561 190	58.9
	Car Electric	11 442	454 480	363 962	104 470 500	674 003	3 607 085	58.9
	Car Petrol	9 640	948 653	1 228 011	94 242 733	571 168	3 660 526	59.2
	Gautrain	18 754	472 139	34 807	10 015 217	1 500 282	13 664 331	80.0
	Metro Bus Diesel	123 294	1 294 276	2 697 801	193 773 907	7 238 680	45 535 011	58.7
	Rail	334 051	994 137	885 019	254 659 862	26 724 101	168 577 746	80.0
	Taxi Diesel	98 644	426 471	1 411 127	101 424 777	5 802 333	39 071 589	58.8
	Taxi Petrol	128 929	944 076	2 510 436	193 512 810	7 607 383	59 214 805	59.0
Time Total		736 395	6 426 721	10 360 389	1 040 366 608	50 786 833	336 995 228	69.0
10 Perc Total		3 128 238	14 857 075	25 521 896	3 071 590 445	223 944 850	1 506 496 212	71.6
20 Perc Cost								
	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	27 825	55 846	140 031	25 940 225	834 762	6 077 011	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	-	-	-	-	-	-	

	Metro Bus	-	-	-	-	-	-	
	Diesel	-	-	-	-	-	-	
	Rail	467 180	1 390 328	1 237 724	356 148 905	37 374 400	243 724 083	80.0
	Taxi Diesel	276 768	1 188 312	3 931 939	282 608 149	16 167 514	116 503 679	58.4
	Taxi Petrol	-	-	-	-	-	-	
Cost Total		771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	28 858	57 919	145 229	26 903 145	865 749	5 208 327	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	17 864	449 739	33 155	9 540 062	1 429 104	21 166 601	80.0
	Metro Bus	-	-	-	-	-	-	
	Diesel	-	-	-	-	-	-	
	Rail	615 983	1 833 166	1 631 955	469 587 143	49 278 651	312 458 084	80.0
	Taxi Diesel	196 768	820 559	2 715 102	195 147 967	11 164 071	109 780 134	56.7
	Taxi Petrol	-	-	-	-	-	-	
Energy Total		859 473	3 161 383	4 525 442	701 178 317	62 737 575	448 613 146	73.0
GWP	BRT Diesel	1 028	4 769	7 473	578 802	30 849	322 628	30.0
	BRT Hybrid	2 738	9 833	21 460	1 014 491	82 145	488 777	30.0

	BRT Trolley	1 658	3 328	8 345	1 545 917	49 748	431 334	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	160	5 396	4 321	1 240 320	8 002	139 433	50.0
	Car Petrol	-	-	-	-	-	-	
	Gautrain	9 111	229 387	16 911	4 865 867	728 908	6 276 766	80.0
	Metro Bus Diesel	7 683	74 484	155 255	11 151 445	416 577	6 897 221	54.2
	Rail	555 999	1 654 652	1 473 035	423 858 677	44 479 888	262 276 170	80.0
	Taxi Diesel	220 802	934 555	3 092 296	222 258 741	12 715 031	93 636 060	57.6
	Taxi Petrol	36 505	244 979	651 434	50 214 710	1 974 043	38 698 970	54.1
GWP Total		835 685	3 161 383	5 430 530	716 728 970	60 485 191	409 167 361	72.4
Time	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	577	1 157	2 902	537 633	17 301	102 945	30.0
	Car Diesel	19 410	1 548 663	2 131 707	153 074 722	1 133 887	6 730 137	58.4
	Car Electric	7 067	284 067	227 490	65 297 956	421 277	2 672 934	59.6
	Car Petrol	15 280	1 504 988	1 948 175	149 511 119	906 128	5 019 750	59.3
	Gautrain	18 754	472 139	34 807	10 015 217	1 500 282	13 664 331	80.0
	Metro Bus Diesel	120 643	1 263 651	2 633 965	189 188 827	7 067 399	48 905 548	58.6
	Rail	334 051	994 137	885 019	254 659 862	26 724 101	168 577 746	80.0
	Taxi Diesel	117 675	507 893	1 680 539	120 788 774	6 910 113	47 438 003	58.7
	Taxi Petrol	102 938	757 797	2 015 094	155 330 153	6 106 345	43 883 834	59.3
Time Total		736 395	7 334 492	11 559 698	1 098 404 263	50 786 833	336 995 228	69.0
20 Perc Total		3 203 327	16 291 743	26 825 365	3 181 008 827	228 386 275	1 561 080 509	71.3
50 Perc Cost	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	27 825	55 846	140 031	25 940 225	834 762	6 077 011	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	-	-	-	-	-	-	
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	467 180	1 390 328	1 237 724	356 148 905	37 374 400	243 724 083	80.0
	Taxi Diesel	276 768	1 188 312	3 931 939	282 608 149	16 167 514	116 503 679	58.4
	Taxi Petrol	-	-	-	-	-	-	
Cost Total		771 774	2 634 486	5 309 694	664 697 278	54 376 676	366 304 773	70.5
Energy	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	29 594	59 396	148 933	27 589 315	887 830	5 383 033	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	-	-	-	-	-	-	
	Car Petrol	-	-	-	-	-	-	
	Gautrain	53 515	1 347 293	99 324	28 579 372	4 281 198	46 681 834	80.0
	Metro Bus Diesel	-	-	-	-	-	-	
	Rail	596 081	1 773 936	1 579 227	454 414 823	47 686 462	297 951 035	80.0
	Taxi Diesel	185 391	771 103	2 551 460	183 386 174	10 491 200	115 853 075	56.6
	Taxi Petrol	-	-	-	-	-	-	
Energy Total		864 582	3 951 728	4 378 944	693 969 685	63 346 689	465 868 976	73.3
GWP	BRT Diesel	1 362	6 316	9 897	766 570	40 857	227 713	30.0
	BRT Hybrid	2 785	10 000	21 825	1 031 718	83 540	602 827	30.0
	BRT Trolley	21 607	43 365	108 736	20 142 842	648 201	2 849 757	30.0
	Car Diesel	-	-	-	-	-	-	
	Car Electric	78	2 769	2 217	636 437	4 106	92 189	52.5
	Car Petrol	-	-	-	-	-	-	
	Gautrain	14 963	376 713	27 772	7 991 011	1 197 056	9 506 769	80.0
	Metro Bus Diesel	36 811	382 236	796 736	57 226 823	2 137 784	31 125 754	58.1
	Rail	502 959	1 496 805	1 332 514	383 424 437	40 236 704	226 156 914	80.0
	Taxi Diesel	226 554	963 938	3 189 522	229 246 869	13 114 809	90 001 108	57.9
	Taxi Petrol	57 274	405 844	1 079 198	83 188 157	3 270 296	51 470 019	57.1
GWP Total		864 393	3 687 986	6 568 416	783 654 863	60 733 352	412 033 050	70.3
Time	BRT Diesel	-	-	-	-	-	-	
	BRT Hybrid	-	-	-	-	-	-	
	BRT Trolley	577	1 157	2 902	537 633	17 301	102 945	30.0

	Car Diesel	11 925	968 710	1 333 412	95 750 349	709 262	4 524 300	59.5
	Car Electric	12 759	509 720	408 199	117 168 232	755 924	3 569 239	59.2
	Car Petrol	12 716	1 249 179	1 617 036	124 098 081	752 110	4 260 993	59.1
	Gautrain	18 754	472 139	34 807	10 015 217	1 500 282	13 664 331	80.0
	Metro Bus							
	Diesel	135 173	1 415 989	2 951 501	211 996 334	7 919 403	52 592 365	58.6
	Rail	334 051	994 137	885 019	254 659 862	26 724 101	168 577 746	80.0
	Taxi Diesel	101 370	440 755	1 458 390	104 821 778	5 996 669	41 838 503	59.2
	Taxi Petrol	109 071	795 702	2 115 888	163 099 671	6 411 781	47 864 806	58.8
Time Total		736 395	6 847 488	10 807 153	1 082 147 157	50 786 833	336 995 228	69.0
50 Perc Total		3 237 143	17 121 687	27 064 207	3 224 468 983	229 243 550	1 581 202 028	70.8
Grand Total		12 623 307	63 386 109	106 097 274	12 527 074 269	899 082 188	6 102 570 022	