

UNDERSTANDING, MODELLING AND PREDICTING TRANSPORT MOBILITY IN URBAN ENVIRONMENTS

Iain Cameron

BSc. (Environmental Science - First Class Honours), Murdoch University.

This thesis is presented for the degree of

Doctor of Philosophy at Murdoch University, Australia.

2004.

Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

.....

Iain Cameron

Abstract

In the last three decades the global population has been growing at an essentially constant rate, at around 1.5 per cent per year, to about 6.026 billion in 2000 when it was estimated that 47% of that population live in an urban environment. Further, a United Nations' projection indicates that 60% of the total global population may be living in an urban settlement by the year 2025. This increasing urbanisation brings with it increased employment, that delivers affluence, which then continues the cycle of migration and movement to these growing metropolitan areas in both developed and developing countries.

As cities increase in population and expand their urban area, there is a consequential expansion of urban transportation and accompanying service infrastructure. People travel daily, irrespective of their vast differences in culture, economic conditions and means of transportation. This daily mobility is sought for its own sake as well as to bridge the spatial distance that separates their homes from the work place, to accomplish their household's domestic needs and to undertake social journeys, such as visiting friends and taking holidays.

As the world's urban population undertakes its daily mobility by a variety of transportation modes, an individual's mobility behaviour and mode-choice is governed by a complex matrix of physical and human, social and management indicators, measures and/or drivers. A literature review describes the current understanding of this complex matrix and concludes by identifying and defining a set of fundamental underlying measures that drive private motorised, public transport and non-motorised (walking and bicycling) mobility at national, city and household levels.

As practical instruments, transportation models play an important role in providing decision-makers with analytical tools to help them understand their city's transportation and the different future scenarios it may face. While not necessarily producing foolproof information or predictions, models are still the best methods available to test the likely implications of alternative transportation policy decisions in a rapidly changing urban environment. Urban transport models are generally based on the notion that traffic can be modelled in aggregate measures through statistical data and predictive modelling techniques.

In this research, dimensional analysis is used to derive sketch-plan models for private motorised, public transport and non-motorised mobility for any urban environment based on four-decades of detailed land-use and travel pattern data from a large international sample of cities. These models are developed on the basis of a set of fundamental underlying measures

that are deemed to drive private motorised, public transport and non-motorised (walking and bicycling) mobility at the city level.

Importantly, the models also embody three key attributes. They are:

- easy to use, minimising user requirements and data inputs
- policy-sensitive, capable of assessing a sufficient range of policy options
- reliable and robust over time, so that the results can be consistently believed.

The capacity of the sketch-plan models to predict personal mobility in an urban environment is statistically validated against an independent land-use and travel pattern data set for 83 cities located on five continents. Despite their simplicity and maintaining a consistent functional form over a time-series of four-decades and across all geographic and cultural regions, the private motorised mobility model can consistently explain up to 92% of the variance in private motorised urban mobility. The results for the public transport mobility model are less reliable and consistent, in particular when developing cities are part of the model. Results for developed or wealthier cities are much better. Reasons for these results and their inadequacies are discussed. The non-motorised modes mobility model is the least successful part of the modelling work. This can be attributed to a combination of inadequate data and, very likely, the more micro-level determinants of usage of these modes.

The private motorised urban mobility sketch-plan model equation developed in this thesis is able to predict present and future trends of automobile use in individual cities to a high degree of statistical reliability. The model equation offers urban transport planners a focused direction on the fundamental measures that have the potential to control and deliver automobile restraint policies and strategies. A series of case studies shows that this model has wide applications in understanding past trends in private motorised mobility and in developing urban environmental strategy and policy through its ability to calculate and assess current and future motor vehicle emissions inventories in cities. The thesis makes suggestions for future work in this area of metropolitan level transport modelling, in particular, how to improve the public and non-motorised transport models so that total urban transport mobility can be better understood and modelled.

TABLE OF CONTENTS

Abstract	Page i
Table of Contents	iii
Appendix	vii
List of Figures	x
List of Tables	xiv
Abbreviations and Symbols	xxi
Acknowledgments	xxxv
Publications related to Thesis	xxxvi

Chapter One

Introduction: Transport mobility patterns and need for reliable macro-level models of urban transport mobility.

1.1	Background to the study.	1
1.2	Models of transport mobility.	5
1.3	Need for reliable models of urban transport mobility.	7
1.4	Research questions.	9
1.5	Structure and summary of the thesis.	10

Chapter Two

Review of underlying measures that drive private motorised mobility at a national, city and household level.

2.1	Introduction.	14
2.2	Population, urbanisation and automobiles: a global perspective.	15
2.3	Population, urbanisation and automobiles: a city perspective.	25
2.4	Population, urbanisation and automobiles: a household perspective.	31
2.5	What are the measures that drive private motorised mobility at the national, city and household level?	33
	2.5.1 Introduction.	33
	2.5.2 Per capita income: a measure that drives private motorised mobility.	34
	2.5.3 Urban form influences on private motorised mobility.	64
	2.5.4 Employment influences on private motorised mobility.	68
	2.5.5 Road and rail infrastructure and network influences on private motorised mobility.	71
	2.5.6 Automobile occupancy: an influence on private motorised mobility.	82
2.6	Private motorised mobility: a synthesis.	85
	2.6.1 Statistical analysis of the measures at national and city level.	86
	2.6.2 Household level statistical analysis of measures.	92
	2.6.3 Summary overview statement.	93
2.7	Chapter summary and conclusion.	93

Chapter Three

Review of underlying measures that drive public transport and non-motorised mobility at a national, city and household level.

3.1	Introduction.	96
3.2	Broad insights into public transport and non-motorised mobility at a national and city level.	98
3.2.1	National level public transport mobility.	98
3.2.2	City level public transport mobility.	98
3.2.3	Non-motorised mobility: walking.	99
3.2.4	Non-motorised mobility: bicycling.	99
3.3	What are the measures that drive public transport mobility at the national and city level?	100
3.3.1	Introduction.	100
3.3.2	Per capita income and automobiles.	101
3.3.3	Population and employment density.	112
3.3.4	Road network length and road network speed as measures that help to explain public transport mobility.	122
3.3.5	Parking provision and its relationship to public transport mobility.	130
3.4	What are the measures that drive non-motorised mobility at the city level?	134
3.4.1	Introduction.	134
3.4.2	Urban area, population and employment density and their influence on walking in cities.	135
3.4.3	Urban area, population and employment density measures and their relationship to levels of bicycle use in cities.	140
3.5	Human, social and management factors that influence public transport and non-motorised mobility.	142
3.5.1	Introduction.	142
3.6	Public transport and non-motorised urban mobility: a synthesis.	144
3.6.1	Statistical analysis of the measures.	146
3.7	Chapter summary and conclusion.	157

Chapter Four

Systems model of private motorised urban mobility.

4.1	Introduction.	161
4.2	The measures that drive private motorised urban mobility.	162
4.3	A non-dimensional private motorised urban mobility indicator.	164
4.4	Data sets for the controlling measures.	165
4.5	Model development: the underlying approach.	166
4.5.1	Transport models: brief overview.	167
4.5.2	Thesis model synopsis.	169
4.5.3	Dimensional analysis: a brief exposition.	171
4.5.4	Buckingham's Pi (II) Theorem.	173
4.6	Private motorised urban mobility model equations.	176
4.6.1	Model equations for automobiles-only for the decades 1960, 1970, and 1990.	177
4.6.2	Model equation for automobiles, motorcycles, and taxi mode for the 1990 data set.	179

4.6.3	Model equation for decades 1960 to 1990: a combined data set.	181
4.7	Model equation incorporating a vehicle saturation function.	183
4.8	Validation of Equation 4.11 using an independent data set.	186
4.8.1	Modelling private motorised urban mobility from an independent data set.	187
4.9	Discussion of model equation's predictions.	188
4.9.1	Over and under predicting cities.	188
4.9.2	Influence of cars, motorcycles and taxis in cities.	190
4.10	Chapter summary and conclusion.	191

Chapter Five

A sketch-plan model of public transport and non-motorised mobility.

5.1	Introduction.	193
5.2	A public transport mobility model.	194
5.2.1	The measures that drive public transport mobility.	194
5.3	A public transport mobility indicator.	196
5.4	Data sets used in development of the model equation.	197
5.5	Public transport mobility model development.	197
5.5.1	Dimensional analysis.	197
5.6	Public transport mobility equations.	198
5.6.1	Public transport mobility equations for decades 1960, 1970, 1980 and 1990.	200
5.7	Public transport mobility equation using combined data sets for 1960 to 1990.	202
5.8	Public transport mobility model validation of Equation 5.8.	204
5.8.1	Predicting public transport mobility in cities at varying GDP per capita levels.	205
5.9	A non-motorised mobility model.	209
5.9.1	Non-motorised mobility: a non-dimensional indicator.	210
5.9.2	Non-motorised mobility model: underlying approach.	211
5.9.3	Non-motorised mobility model equation.	212
5.10	Non-motorised mobility model validation of Equation 5.17.	214
5.11	Chapter summary and conclusion.	215

Chapter Six

Trends in vehicle kilometres of travel in world cities, 1960-1995: underlying drivers and policy responses.

6.1	Introduction.	218
6.2	Mathematical rearrangement of Equation 4.11.	218
6.3	City selection.	221
6.4	An examination of automobile restraint policies at the city level.	222
6.4.1	Background.	222
6.4.2	A case study of two Asian cities.	224
6.4.3	A case study of two European cities.	231
6.4.4	Case studies of American and Australian cities.	239
6.5	Automobile restraint policy implications.	244

Chapter Seven

Application of private motorised mobility model to prediction of automotive exhaust emissions.

7.1	Introduction.	247
7.2	Impact of automobile exhaust emissions on urban environments.	248
7.3	Automobile exhaust emission control strategy standards.	250
	7.3.1 Emissions regulations in developed countries.	250
	7.3.2 Emission regulation in a selection of developing countries – India and Thailand.	252
7.4	Automobile exhaust emissions ‘in-use’ automobile emissions values.	253
	7.4.1 Australian cities ‘in-use’ automobile exhaust emissions values.	253
	7.4.2 United States of America ‘in-use’ automobile exhaust emissions values.	255
	7.4.3 European cities ‘in-use’ automobile exhaust emissions values.	256
	7.4.4 Variation of ‘in-use’ automobile emission values (g/km) with road network speed (km/h) and fuel type.	256
7.5	Mass emissions inventory of primary automobile exhaust emissions.	259
	7.5.1 Mass emission inventory for automobile exhaust emissions in both developed and developing countries.	260
7.6	A case study of five Australian cities: first-stage inventory.	261
	7.6.1 Determination of ‘in-use’ automobile exhaust emission rates (g/km) an Australian case study.	262
	7.6.2 Determination of automobile ownership and use Australian case study cities 2000, 2010 and 2020.	264
	7.6.3 Determination of the first-stage mass inventory for automobile exhaust emission pollutants in Australian cities.	267
7.7	Predicting private motorised mobility: application to photochemical smog pollution.	274
	7.7.1 Ambient ozone: a case study of five Australian cities.	275
7.8	Chapter summary and conclusion.	276

Chapter Eight

Conclusion.

8.1	Overview.	278
8.2	Findings and conclusions on the fundamental measures underlying transport mobility.	279
	8.2.1 Private motorised mobility measures.	279
	8.2.2 Public transport mobility measures.	280
	8.2.3 Non-motorised transport mobility measures.	282
8.3	Findings and conclusions on the urban mobility model equations.	283
	8.3.1 Private motorised urban mobility model.	283
	8.3.2 Public transport mobility model.	284
	8.3.3 Non-motorised mobility model.	285
8.4	Applications of the private motorised urban mobility model.	286
	8.4.1 Changes in private motorised mobility in cities and their policy implications.	286
	8.4.2 Environmental policy implications of private motorised mobility in cities.	287
8.5	Suggested follow-up research.	288

8.5.1	Transport and land-use data.	288
8.5.2	Saturation of automobile ownership and use.	288
8.5.3	Private motorised mobility model.	289
8.5.4	Human, social and management measures.	289
8.6	Concluding comment.	289

Bibliography

References cited.	290
-------------------	-----

Appendix

Appendix 1 to 13	329
-------------------------	-----

Appendices for this thesis are contained in the attached CD-ROM. The following provides a detailed description of each Appendix. The thesis data is contained in *Microsoft Excel*® spreadsheets.

Appendix 1 - Model data

Appendix 1.1

This Appendix contains the primary data for 1960 – 1961 for 45 international cities taken from Kenworthy et al. (1999) and shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure. It also contains private motorised mobility and public transport model runs.

Appendix 1.2

This Appendix contains the primary data for 1970 – 1971 for 45 international cities taken from Kenworthy et al. (1999) and shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure. It also contains private motorised mobility and public transport model runs.

Appendix 1.3

This Appendix contains the primary data 1980 – 1981 for 45 international cities taken from Kenworthy et al. (1999) and shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure. It also contains private motorised mobility and public transport model runs.

Appendix 1.4

This Appendix contains the primary data for 1990 – 1991 for 45 international cities taken from Kenworthy et al. (1999) and shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure. It also contains private motorised mobility and public transport model runs.

Appendix 1.5

This Appendix contains the independent primary data for 1995 – 1996 for 36 international cities taken from Kenworthy and Laube (2001). This Appendix forms part one of the independent data set used to verify the model equations and shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure. These cities are similar to those in Appendices 1.1 to 1.4.

Appendix 1.6

This Appendix contains the independent primary data for 1995 – 1996 for 47 international cities taken from Kenworthy and Laube (2001). This Appendix forms part two of the independent data set used to verify the model equations and contains the new cities not used Appendices 1.1 to 1.4. It also shows the Buckingham (1914) dimensionless Pi group ratios developed by application of Stull's (1988) procedure.

Appendix 1.7

This Appendix contains the combined 1960/61 to 1990/91 primary data used to develop the private motorised urban mobility model equation, Equation 4.10 and Equation 4.11.

Appendix 1.8

This Appendix contains the combined 1960/61 to 1990/91 primary data set used to develop the public transport mobility model equation, Equation 5.8.

Appendix 1.9

This Appendix contains the independent data Kenworthy and Laube (2001) set used to validate the private motorised mobility model equation, Equation 4.11.

Appendix 1.10

This Appendix contains the independent data Kenworthy and Laube (2001) set used to validate the public transport model equation, Equation 5.8.

Appendix 1.11

This Appendix contains the independent data Kenworthy and Laube (2001) set used to establish and validate the non-motorised transport model equation Equation 5.17.

Appendix 1A – Sherrod model runs

This Appendix contains the Sherrod (1995) Nonlinear Regression Analysis Program (NLREG®) mobility model runs for Equation 4.8, Equation 4.9, Equation 4.10, Equation 4.11, Equation 5.8 and Equation 5.17. Print outs are shown in Appendix 14.1, 14.2 and 14.3. Sherrod's computer program is protected by a License Agreement. To run, a test version of Sherrod's software may be accessed from www.sandh.com/sherrod or email to: phil.sherrod@sandh.com.

Appendix 2 - United Nations – National population

This Appendix contains the estimated United Nations mid-year population values of 53 countries from 1947 to 1997.

Appendix 3 – United States of America data

This Appendix contains files from United States' Government Departments, Agencies and Authorities on the following topics: population, household structure, number of transport vehicles, automobile profiles, vehicle kilometres of travel, transport fuel price and Nationwide Personal Transportation Survey 1990. These data are for the period 1950 to 2003.

Appendix 4 – Chapter Two and Chapter Three data and 'r' correlation

This Appendix contains a number of spreadsheets formed from a wide range of referenced sources such as Kenworthy et al. (1999), Kenworthy and Laube (2001), Ingram and Lui (1997 and 1998), International Monetary Fund (2001), International Road Federation (1973 to 2002), United Nations (2000) and personal communications from professional personnel working for world cities. These data sets allow a statistical evaluation of the fundamental underlying

drivers / measures of transport mobility at the national, city and household level in Chapter 2 and Chapter 3.

Appendix 5 – Data and figures for Chapter Two

This Appendix contains data relevant to the Figures and Tables used in Chapter 2.

Appendix 6 and 6A - Data and figures for Chapter Three

This Appendix contains data relevant to the Figures and Tables used in Chapter 3.

Appendix 7 - Data and figures for Chapter Four

This Appendix contains data relevant to the Figures and Tables used in Chapter 4.

Appendix 8 - Data and figures for Chapter Five

This Appendix contains data relevant to the Figures and Tables used in Chapter 5.

Appendix 9 - Data and figures for Chapter Six

This Appendix contains all data and calculations relevant to the Figures and Tables used in Chapter 6 in particular data and calculations associated with Equation 6.5.

Appendix 10 - Data and figures for Chapter Seven

This Appendix shows all data and calculation procedures for automobile ownership and VKT projections and first-stage emission inventories for criteria air pollutants, photochemical smog precursors, as well as Figures that are used in Chapter 7.

Appendix 11 – IMF GDP per capita

This Appendix shows the International Monetary Fund’s values of GDP per capita (\$US) at current prices for 178 countries over the period 1970 to 2001.

Appendix 12 – World Road Statistics

This Appendix shows the International Road Federation’s statistics of the number of and kilometres of travel for automobiles, motorcycles and buses, and road infrastructure statistics in 46 countries between 1970 and 2003.

Appendix 13 – Thesis papers

This Appendix contains the published papers from this thesis.

Appendix 14 - Sherrod’s NLREG print out

Appendix 14.1 – Private motorised mobility Equation 4.11 330

The print out shows the ‘p’ parameters, proportion of variance explained, ‘t’ and ‘Prob t’ values for ‘p’ parameters for private motorised mobility Equation 4.11.

Appendix 14.2 – Public transport mobility Equation 5.8 331

The print out shows the ‘p’ parameters, proportion of variance explained, ‘t’ and ‘Prob t’ values for ‘p’ parameters for public transport mobility Equation 5.8.

Appendix 14.3 – Non-motorised mobility Equation 5.17 332

The print out shows the ‘p’ parameters, proportion of variance explained, ‘t’ and ‘Prob t’ values for ‘p’ parameters for non-motorised mobility Equation 5.17.

List of Figures

	Page	
Figure 1.1	Structure of the thesis.	11
Figure 2.1	Annual average automobiles per 1,000 person for selected World regions - 1970 to 1999.	17
Figure 2.2	Variation in automobiles per 1,000 persons in selected more developed countries – 1970 to 1999.	18
Figure 2.3	Change in composition of the United States 4-tyred passenger vehicle fleet 1970 to 2000.	19
Figure 2.4	Variation in automobiles per 1,000 persons in selected less developed countries – 1970 to 1999.	20
Figure 2.5	Annual average automobile VKT per capita for selected World regions - 1970 to 1999.	22
Figure 2.6	Annual average automobile VKT per capita for selected more developed countries - 1970 to 1999.	23
Figure 2.7	Annual average automobile VKT per capita for selected less developed countries - 1970 to 1999.	24
Figure 2.8	GDP per capita and automobiles per 1,000 for a selection of 36 more developed and less developed countries - 1970 and 1998.	36
Figure 2.9	GDP per capita and automobiles per 1,000 in a selection of 22 OECD member states for 1980 and 1990.	38
Figure 2.10	Annual average automobiles per 1,000 persons and automobile VKT per capita for a selection of 21 more developed and less developed countries – 1975 and 1995.	42
Figure 2.11	Annual average automobile VKT per capita for selected World regions – 1970 to 1995.	43
Figure 2.12	GDP per capita and automobile VKT per capita for a selection of 24 more and less countries – 1970 and 1995.	44
Figure 2.13	GDP per capita and automobile VKT per capita for a selection of 24 OECD member states – 1970 and 1995.	45
Figure 2.14	GDP per capita and automobiles per 1,000 for a selection of 31 more and less developed cities for 1990 and 1995.	51
Figure 2.15	GDP per capita and automobile VKT per capita for a selection of 31 more and less developed cities 1990 and 1995.	55
Figure 2.16	Variation in city metropolitan population density and annual average automobile per 1000 persons for a selection of more and less developed cities - 1980 and 1995.	66
Figure 2.17	Variation in city metropolitan population density and annual average automobile VKT per capita for a selection of more and less developed cities - 1980 and 1995.	66
Figure 2.18	Metropolitan urban jobs density and automobiles per 1,000 persons for a selection of more developed and less developed cities 1980 and 1995.	69
Figure 2.19	Metropolitan urban jobs density and automobile VKT per capita for a selection of more developed and less developed cities 1980 and 1995.	70
Figure 2.20	National road metres per capita and automobiles per 1,000 persons for a selection of more developed and less developed countries 1975 and 1995.	72
Figure 2.21	National road metres per capita and automobile VKT per capita for a selection of more developed and less developed countries 1975 and 1995.	73

Figure 2.22	Metropolitan road metres per capita and automobiles per 1,000 persons for a selection of more developed and less developed cities 1970 and 1995.	75
Figure 2.23	Metropolitan road metres per capita and automobile VKT per capita for a selection of more developed and less developed cities 1970 and 1995.	76
Figure 2.24	Metropolitan road m per capita and population density for a selection of cities 1995.	77
Figure 2.25	Metropolitan express road network length and automobiles per 1,000 persons for a selection of cities 1995.	78
Figure 2.26	Metropolitan express road network length and automobile VKT per capita for a selection of cities 1995.	78
Figure 2.27	Metropolitan urban rail network length (rail m/capita) and automobiles per 1,000 persons for a selection of more developed and less developed cities for 1990 and 1995.	80
Figure 2.28	Metropolitan urban rail network length (rail m/capita) and automobile VKT per capita for a selection of more developed and less developed cities for 1990 and 1995.	81
Figure 2.29	Relationship between average automobile occupancy and automobile VKT per capita for 21 developed cities 1960 to 1995.	83
Figure 2.30	Relationship between automobile occupancy and automobile VKT per capita for 21 developed cities 1960 to 1995.	84
Figure 2.31	The broad measures that influence private motorised mobility at the national, city and household level.	85
Figure 3.1	A comparison between automobile and bus VKT per capita for a selection of more and less developed countries from 1970 to 1995.	103
Figure 3.2	The influence of increasing GDP per capita on annual average bus VKT per capita for a selection of more and less developed countries for 1980 and 1995.	107
Figure 3.3	A comparison of automobile and public transport passenger kilometres per capita for a selection of more and less developed cities for 1970 and 1995.	109
Figure 3.4	Annual average automobile and public transport passenger kilometres per capita for selection of more and less developed cities between 1960 and 1995.	110
Figure 3.5	Metropolitan population density (p/sq km) and public transport passenger km per capita for a selection of both more and less developed world cities for 1970 and 1995.	117
Figure 3.6	A comparison of metropolitan employment density (p/sq km) and public transport passenger km per capita for a selection of both more and less developed cities for 1970 and 1995.	121
Figure 3.7	Total metropolitan road network length (rdm/capita) and public transport kilometres of service per capita for a selection of more and less developed cities for 1970 and 1995.	124
Figure 3.8	A comparison of total metropolitan road network length (rdm/capita) and public transport passenger kilometres per capita for a selection of more and less developed cities for 1970 and 1995.	126
Figure 3.9	The total road network speed and public transport passenger kilometres per capita for a selection of more and less developed cities for 1980 and 1995.	128
Figure 3.10	The relationship between total public transport network speed and public transport passenger kilometre per capita for a selection of more and less developed cities for 1980 and 1995.	129
Figure 3.11	The relationship between the ratio of public to road network speed and public transport passenger kilometre per capita for a selection of more and less developed cities for 1980 and 1995.	130

Figure 3.12	The relationship between CBD parking bays per 1,000 workers and public transport passenger km per capita for 1970 and 1995.	133
Figure 3.13	Metropolitan urbanised area and annual average walking trips per capita for 1995 in 83 cities.	137
Figure 3.14	Metropolitan population density and annual average walking trips per capita for 1995 in 83 cities.	138
Figure 3.15	Metropolitan urbanised employment density and walking trips capita for 1995 in 83 cities.	139
Figure 4.1	The measured private motorised mobility and that modelled using Equation 4.8 with the Kenworthy et al., (1999) 1990 data set.	178
Figure 4.2	The measured private motorised mobility and that modelled using Equation 4.9 with the Kenworthy et al., (1999) 1990 data set.	181
Figure 4.3	The measured private motorised mobility and that modelled using Equation 4.11 with the Kenworthy et al., (1999) combined 1960 to 1990 data set.	185
Figure 4.4	The measured private motorised mobility and that modelled using Equation 4.11 for automobiles+motorcycles+taxis for cities in the Kenworthy and Laube (2001) 1995 data set.	187
Figure 5.1	Measured public transport mobility and that modelled using Equation 5.8 with the Kenworthy et al., (1999) 1990 data set.	201
Figure 5.2	Measured public transport mobility and that modelled using Equation 5.8 for the Kenworthy et al., (1999) combined 1960 to 1990 data set.	203
Figure 5.3	Measured public transport mobility for an independent cities and that modelled using Equation 5.8 and Kenworthy and Laube (2001) data set.	204
Figure 5.4	Measured public transport mobility in the cities with a >\$US10K GDP per capita and that modelled using Equation 5.8 and the Kenworthy and Laube (2001) data set.	208
Figure 5.5	Measured public transport mobility in the cities with a <\$US10K GDP per capita and that modelled using Equation 5.8 and the Kenworthy and Laube (2001) data set.	208
Figure 5.6	Measured non-motorised mobility and that modelled using Equation 5.17 for the Kenworthy and Laube (2001) data set.	213
Figure 5.7	Measured non-motorised mobility and that modelled using Equation 5.17 for validating the Kenworthy and Laube (2001) data set cities.	214
Figure 6.1	Changes in the model equation's automobile saturation factor with automobiles per capita.	220
Figure 6.2	Changes in the factors using Equation 6.5 for Singapore 1960 to 1995.	227
Figure 6.3	Changes in the factors using Equation 6.5 for Hong Kong 1970 to 1995.	230
Figure 6.4	Changes in the factors using Equation 6.5 for Munich 1960 to 1995.	234
Figure 6.5	Changes in the factors using Equation 6.5 for Stockholm 1960 to 1995.	238
Figure 6.6	Changes in the factors using Equation 6.5 for New York 1960 to 1995.	240
Figure 6.7	Changes in the factors using Equation 6.5 for Phoenix 1960 to 1995.	242
Figure 6.8	Changes in the factors using Equation 6.5 for Perth 1960 to 1995.	243
Figure 7.1	Automobile exhaust emissions rate change with vehicle speed - gasoline-fuelled automobiles.	257
Figure 7.2	Automobile exhaust emissions rate change with vehicle speed - diesel-fuelled automobiles.	258
Figure 7.3	Australian case study cities automobiles per 1,000 persons – 1980 to 2020.	265
Figure 7.4	Australian case study cities automobiles VKT/capita – 1980 to 2020.	267
Figure 7.5	Scenario 1 first-stage inventory CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	268

Figure 7.6	Scenario 2 first-stage inventory CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	270
Figure 7.7	Scenario 3 first-stage inventory CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	271
Figure 7.8	Total tonnes of primary pollutants (CO+NOx+HC) for Perth in 2000, 2010 and 2020 for the three scenarios.	272
Figure 7.9	Total tonnes of primary pollutants (CO+NOx+HC) modelled for Scenario 3 in five Australian case study cities for 2000, 2010 and 2020.	273
Figure 7.10	Ozone chemical reaction.	275

List of Tables

	Page	
Table 1.1	Average key patterns of urban transport mobility in cities of the world by region, 1995.	4
Table 2.1	Estimated changes in the World's population and level of urbanisation for 1975, 2000 and 2025.	16
Table 2.2	Countries selected to represent the World regions of Europe, Asia-Pacific, South America and Africa.	17
Table 2.3	Comparison of automobiles per 1,000 persons in Thailand and Bangkok 1970 to 1999.	20
Table 2.4	GDP per capita (\$US, current prices) in Indonesia, Malaysia, Taiwan and Thailand for 1980 to 1998.	21
Table 2.5	Comparison of automobiles and motor cycles per 1,000 persons in Indonesia, Malaysia, Taiwan and Thailand 1980 to 1998.	21
Table 2.6	Influence of Australia's automobile VKT per capita in the Asia-Pacific region 1970 to 1999.	23
Table 2.7	Cities selected to characterise North American, European and Asia-Pacific regions 1970 and 1995.	26
Table 2.8	A selection of cities from Table 2.7 characterise into one of Thomson's (1977) five strategies.	26
Table 2.9	Metropolitan population, population density, automobiles per 1,000 persons and automobile VKT per capita for cities in Table 2.7 for 1970 and 1995.	29
Table 2.10	Households in selected cities of North America, Europe and Asia-Pacific regions 1970 and 1995.	32
Table 2.11	Litman's measures that drive and qualify automobile dependence at the city level.	48
Table 2.12	Comparison of automobiles per 1,000 in cities with similar GDP per capita (\$US) for 1990 and 1995.	51
Table 2.13	Comparison of GDP/capita and automobile VKT per capita in a selection of North American, European, Australian and Asian cities 1990 and 1995.	54
Table 2.14	Annual average income and number of vehicles (types) per household for the USA 1985 to 2000.	57
Table 2.15	Changes in household income and automobiles per household for London 1991 to 2000.	58
Table 2.16	Changes in income and number of automobiles per households for Copenhagen, Munich and Stockholm 1971 to 1995.	59
Table 2.17	Changes in real income and number of automobiles per household for Hong Kong, Singapore and Manila 1980 to 2000.	60
Table 2.18	Increasing household income and number of household trips for the Denver region 1997.	62
Table 2.19	Household income, automobiles per household and daily automobile trips per household in Edmonton 1994.	62
Table 2.20	Changes in annual average income, automobiles and VKT per household for Copenhagen, Munich and Stockholm 1981 to 1995.	62
Table 2.21	Regional variations in average metropolitan urban population density, automobiles per 1000 and VKT per capita for a selection of more and less developed cities 1980.	65
Table 2.22	Regional variations in average metropolitan urban population density, automobiles per 1000 and VKT per capita for a selection of more and less developed cities 1990.	65

Table 2.23	Regional variations in average metropolitan urban population density, automobiles per 1000 and VKT per capita for a selection of more and less developed cities 1995.	65
Table 2.24	Variation in automobile occupancy and automobile VKT per capita for a selection on more and less developed cities 1970 and 1995.	83
Table 2.25	Measures that drive private motorised mobility at a national, city and household level.	86
Table 2.26	Equations for the statistical relationships used in the analyses.	87
Table 2.27	Relationship between GDP per capita and automobiles per 1,000 persons at a national and city level.	87
Table 2.28	Relationship between GDP per capita and annual average passenger vehicle VKT per capita at a national and city level.	88
Table 2.29	Relationship between total metropolitan population density and automobile ownership and use at a city level.	89
Table 2.30	Relationship between employment density and automobiles per 1,000 persons and VKT per capita at a city level.	90
Table 2.31	Relationship between road infrastructure and automobiles per 1,000 persons at a city level.	90
Table 2.32	Relationship between road infrastructure as road metres per capita and automobile VKT per capita at a city level.	91
Table 2.33	Relationship between rail infrastructure and automobiles per 1,000 persons and VKT per capita at a city level.	91
Table 2.34	Relationship between public transport boardings per capita and automobiles per 1,000 persons and automobile VKT per capita at a city level.	92
Table 2.35	Relationship between public transport vehicle kilometres of service per capita and automobiles per 1,000 persons automobiles VKT per capita at a city level.	92
Table 2.36	Relationship between persons and automobiles per household in a selection of cities.	93
Table 2.37	Relationship between workers and automobile per household in a selection of cities.	93
Table 2.38	The fundamental drivers of private motorised mobility at national, city and household level.	95
Table 3.1	A comparison between automobile and bus VKT per capita in the USA, Europe and a selection of less developed countries from 1970 to 1998.	102
Table 3.2	A comparison of regional modal share for automobiles, buses and rail as % of total trips with annual average GDP per capita for 1960, 1970, 1980 and 1990 for a selected group of countries.	105
Table 3.3	The influence of increasing GDP per capita on automobile and bus VKT per capita for a selection of more and less developed countries from 1970 to 1995.	106
Table 3.4	Annual average GDP per capita of cities in Figure 3.4 for 1980, 1990 and 1995.	111
Table 3.5	Average values for urban population, urban area, and urban population and employment density in a selection of world cities from 1960 to 1995.	112
Table 3.6	Public transit market share as percent of all motorised transportation modes in a selection of European cities for 1998.	115
Table 3.7	Public transit market share as percent of all central core area motorised transportation modes in a selection of European cities for 1998.	115
Table 3.8	A comparison of population density and public transport passenger kms and vehicle kms of service per capita in New York and Los Angeles from 1960 to 1995.	115

Table 3.9	A comparison of population density and public transport passenger kms and vehicle kms of service per capita in Hong Kong and Tokyo from 1960 to 1995.	116
Table 3.10	A comparison of selected cities with similar metropolitan population density and different public transport passenger km per capita in 1970.	118
Table 3.11	A comparison of selected cities with similar metropolitan population density and different public transport passenger km per capita in 1995.	118
Table 3.12	Regional averages of CBD population density (p/sqkm) from 1960 to 1990.	119
Table 3.13	Regional averages in a city's outer area population density (p/sqkm) from 1960 to 1990.	119
Table 3.14	Selected total road network (rd m/capita) and annual average public transport vehicle kilometres of service per capita 1970 and 1995.	125
Table 3.15	Selected metropolitan road network length (rdm/capita) and public transport passenger km per capita for 1970 and 1995.	126
Table 3.16	Public transport modes for automobile and transit cities in 1970 and 1995.	127
Table 3.17	A regional comparison of cities - average supply of CBD parking bays per 1,000 CBD workers for 1980, 1990 and 1995 in various and regions.	132
Table 3.18	CBD parking bays per 1,000 CBD workers for 1980, 1990 and 1995 in a selection of world cities.	132
Table 3.19	A comparison between population density and annual average walking trips per capita in a selection of more and less developed cities for 1995.	138
Table 3.20	Physical and economic measures associated with public transport and non-motorised mobility at national, city and household level.	145
Table 3.21	Human social and management measures associated with public transport and non-motorised mobility at national and city level.	145
Table 3.22	Relationship between GDP per capita and public transport vehicle kilometres of service per capita at a national level and GDP per capita and public transport boardings, vehicles kilometres of service and passenger kilometres per at the city level.	147
Table 3.23	Relationship between automobile passenger km per capita and public transport boardings, vehicles kilometres of service and passenger kilometres per capita at the city level.	147
Table 3.24	Relationship between urban population density and public transport boardings, vehicles kilometres of service and passenger kilometres per capita for all cities and developed cities only in 1995.	148
Table 3.25	Relationship between total metropolitan employment density and public transport boardings, vehicle kilometres of service and passenger kilometres /capita for all cities and developed cities only in 1995.	150
Table 3.26	Relationship between total metropolitan road infrastructure and public transport boardings, vehicle kilometres of service and passenger kilometres /capita for all cities and developed cities only in 1995.	151
Table 3.27	Relationship between total metropolitan road infrastructure speed and public transport boardings, vehicle kilometres of service and passenger kilometres per capita for all cities and developed cities only in 1995.	152
Table 3.28	Relationship between overall public transport speed and annual average public transport boardings, vehicle kilometres of service and passenger kilometres per capita for all cities and developed cities only in 1995.	153
Table 3.29	Relationship between the ratio overall public transport speed to the Metropolitan road infrastructure speed and annual average public transport boardings, vehicle kilometres of service and passenger kilometres per capita for all cities and developed cities only in 1995.	154

Table 3.30	Relationship between CBD parking bays per 1,000 workers and public transport boardings, vehicle kilometres of service and passenger kilometres per capita.	155
Table 3.31	Best-fit relationships between total annual average non-motorised trips per capita and a series of measures for 1995.	156
Table 3.32	The fundamental underlying physical drivers of public transport and non-motorised mobility.	159
Table 3.33	The fundamental underlying human, social and management drivers of public transport and non-motorised mobility.	159
Table 4.1	Fundamental drivers of private motorised mobility and their corresponding controlling measures.	163
Table 4.2	Geographical distribution of cities in the 1960, 1970, 1980 and 1990 data sets.	165
Table 4.3	Cities included in each region and country for the 1960, 1970, 1980 and 1990 data sets.	166
Table 4.4	Dimensional form of the indicators and measures (controlling parameters) that drive private motorised mobility.	172
Table 4.5	Dimensionless ratios derived by Stull's (1988) procedure.	173
Table 4.6	Parameters of power function in Equation 4.8 and proportion of the variance explained using four data sets from 1960 to 1990.	177
Table 4.7	't' and 'prob t' statistics for 'p' parameters shown in Table 4.6.	178
Table 4.8	Statistical comparison between the measured private motorised mobility and that modelled by Equation 4.8.	179
Table 4.9	Parameters of power function in Equation 4.9 and proportion of the variance explained using data set for 1990.	180
Table 4.10	't' and 'prob t' statistics for 'p' parameters shown in Table 4.9.	180
Table 4.11	Statistical comparison between the measured private motorised mobility and that modelled by Equation 4.9.	181
Table 4.12	Parameters of power function in Equation 4.10 and 4.10a and the proportion of the variance explained using the combined 1960 to 1990 data set.	182
Table 4.13	't' and 'prob t' statistics for 'p' parameters shown in Table 4.12.	182
Table 4.14	Statistical comparison between measured and modelled private motorised mobility using Equation 4.10 and 4.10a.	182
Table 4.15	The 'p' parameters and proportion of the variance explained for Equation 4.11 using individual decade data sets for automobiles only.	184
Table 4.16	't' and 'prob t' statistics for 'p' parameters shown in Table 4.15.	184
Table 4.17	The 'p' parameters and proportion of variance explained using Equation 4.11 for the combined 1960 to 1990 data set with cars only and cars+motorcycles+taxis.	184
Table 4.18	't' and 'prob t' statistics for 'p' parameters shown in Table 4.17.	184
Table 4.19	Statistical comparison between measured and modelled private motorised mobility using Equation 4.11 for the combined 1960 to 1990 data set.	186
Table 4.20	Independent 1995 urban data set cities by geographical location.	186
Table 4.21	Statistical comparison between measured and modelled private motorised mobility using Equation 4.11.	187
Table 4.22	Variation for selected cities between measured and modelled values of private motorised mobility in the 1995 data set using Equation 4.11.	188
Table 4.23	Over-predicting cities in the 1995 data set.	189
Table 4.24	Under-predicting cities in the 1995 data set.	189
Table 4.25	Measured versus modelled private motorised mobility in the automobiles only and automobiles+motorcycles+taxis mode for Asian cities using Equation 4.11.	190
Table 4.26	Selected developed cities measured versus modelled private motorised urban mobility in the automobiles only and automobiles+motorcycles+taxis using Equation 4.11.	191

Table 5.1	The physical measures that drive public transport and non-motorised mobility and clarification of their terminology.	195
Table 5.2	The human, social and management measures that drive public transport and non-motorised mobility.	195
Table 5.3	Geographic distribution of cities in the 1960, 1970, 1980 and 1990 data.	197
Table 5.4	Dimensional form of the additional measures (controlling parameters) for public transport mobility determination.	198
Table 5.5	Dimensionless ratios derived by Stull's (1988) procedure applied to the additional public transport mobility measures.	198
Table 5.6	'p' parameters of the power function in for Equation 5.8 and proportion of variance explained using four data sets from 1960 to 1990.	200
Table 5.7	't' and 'Prob t' statistics for 'p' parameters shown in Table 5.6.	201
Table 5.8	Statistical comparison between the measured public transport mobility and that modelled by Equation 5.8 for 1980 and 1990 data sets.	201
Table 5.9	Public transport mobility model 'p' parameters for the 1960 to 1990 combined data sets.	202
Table 5.10	Statistical comparison between the measured public transport mobility and that modelled by Equation 5.8 for the combined data set 1960 to 1990.	202
Table 5.11	Statistical comparison between the measured public transport mobility and that modelled by Equation 5.8 in low and high income cities.	205
Table 5.12	Land-use, infrastructure and transportation factors of the cities identified in Figure 5.3.	206
Table 5.13	Independent 1995 data set cities with GDP per capita greater than \$US10,000 per annum.	207
Table 5.14	Independent 1995 data set cities with GDP per capita less than \$US10,000 per annum.	207
Table 5.15	'p' parameters of the power function in Equation 5.17 and proportion of variance explained for the 1995/96 data set.	213
Table 5.16	't' and 'Prob t' statistics for 'p' parameters shown in Table 5.15.	213
Table 5.17	Statistical comparison between the measured non-motorised mobility and that modelled by Equation 5.17 for the 1995/96 data set.	213
Table 5.18	Statistical comparison between the measured non-motorised mobility and that modelled by Equation 5.17 for the model validation cities, 1995/96.	215
Table 6.1	Key land-use and transport characteristics of the 7 case study cities in 1995.	222
Table 6.2	Transport and urban form characteristics for American and Australian cities contrasted with European and Asian cities (averages, 1995).	239
Table 7.1	Australian Design Rules automobile exhaust emission standards 1976 to 2005.	251
Table 7.2	European exhaust emission regulatory changes, 1970 to 2002.	251
Table 7.3	United States (Federal) and (Californian) exhaust emission changes 1970 to 2004.	252
Table 7.4	Automobile exhaust emission standards for gasoline fuelled vehicles in India and Thailand.	253
Table 7.5	Average values of 'in-use' automobile fleet exhaust emission values for Perth and Sydney 1981 to 1998.	254
Table 7.6	Australian cities percent of total automobile fleet in various ADR Groupings for 1997, 1999 and 2000.	255
Table 7.7	America's total automobile fleet 'in-use' exhaust emission factors 1990, 1995 and 2000 – with and without air conditioning operation.	255
Table 7.8	European automobile in-use' exhaust emission values – gasoline.	256
Table 7.9	European automobile in-use' exhaust emission values – LPG and diesel.	256
Table 7.10	Average, minimum and maximum 24-hour/7-day road network speed (km/h) for a selection of international cities from 1960 to 1995.	258

Table 7.11	Contribution of the transport sector to the total urban air pollution load.	259
Table 7.12	Modelled first-stage emission inventory of the primary automobile exhaust pollutants for a selection of Australian and American cities using average emission rates from the city's automobile fleet in tonnes per year.	260
Table 7.13	Modelled first-stage emission inventory of the primary automobile exhaust pollutants for a selection of European and Asian cities using average emission rates from the city's automobile fleet in tonnes per year.	261
Table 7.14	Modelled first-stage emission inventory of the primary automobile exhaust pollutants for a selection of Australian and American cities using average emission rates from the city's automobile fleet in tonnes per year.	261
Table 7.15	Australian automobiles by ADR groupings – actual values for 1997 to 2002 and predicted values for 2010 and 2020.	263
Table 7.16	Scenarios for 'in-use' exhaust emissions of the Australian national automobile fleet.	263
Table 7.17	Australian cities predicted weighted average exhaust emission rates for 2000, 2010 and 2020.	264
Table 7.18	Australian cities automobiles per 1,000 persons for 1980, 1990, 2000, 2010 and 2020.	265
Table 7.19	Australian cities automobile VKT for 1980, 1990, 2000, 2010 and 2020.	266
Table 7.20	Scenario 1 first-stage inventory of CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	268
Table 7.21	Scenario 2 first-stage inventory of CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	269
Table 7.22	Scenario 3 first-stage inventory of CO, NOx and HCs for Australian cities 2000, 2010 and 2020.	271
Table 7.23	Scenario 3 precursors for ambient ozone 2000, 2010 and 2020 (annual average tonnes of pollutant, NOx and HCs).	276

Abbreviations and symbols

The following abbreviations are used throughout the thesis.

000's	thousand
AAA	Australian Automobile Association
AATSE	Australian Academy of Technological Sciences and Engineering
ABS	Australian Bureau of Statistics
AD	Anderson Darling coefficient
ADB	Asian Development Bank
ADR	Australian Design Rules
AGO	Australian Greenhouse Office
ALF	Annual Vehicle License Fees
ALS	Area Licensing Scheme
AP	air pollutant
APTA	American Public Transit Association
ARF	Additional Registration Fee
Auto	automobile
av.	average
BTCE	Bureau of Transport and Communication Economics
BTRE	Bureau of Transport and Regional Services
CAN	Canada
CBD	central business district
CO	carbon monoxide
CO ₂	carbon dioxide
COE	Certificate of Entitlement
CRC	Chemical Rubber Company
CSE	Centre for Science and Environment
CST	Centre for Sustainable Transportation
CTRE	Centre for Transportation Research and Education
car	automobile
cars/1,000	automobiles per 1,000 persons
carVKT/capita	automobile vehicle kilometres of travel per capita
DET	Department of the Environment, Transport and Regions
DfTR	Department for Transport and Regional Services
DK	Danish Kroner (monetary)
DM	Deutsch Mark (monetary)
DoTUK	Department of Transport United Kingdom
ECMT	European Conference of Ministers of Transport
EEA	European Environment Agency
EMTA	European Metropolitan Transport Authorities
ERP	Electronic Road Pricing
ESTEEM	Estimation of Travel, Energy and Emissions Model
Europe	Western Europe
EU	European Union
e.g.	for example
Eqtn	Equation
et al.	and others
exp	exponential statistical function

FC	fuel consumption
FORS	Federal Office of Road Safety
FRT	First Registration Tax
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GNP	Gross National Product
g/km	grams per kilometre
HC	hydrocarbons
HK	Hong Kong
h/hold	household
ILUTM	Integrated Land-use Transport Models
IMF	International Monetary Fund
IRF	International Road Federation
JPL	Joules per litre
km	kilometre
km/h	kilometres per hour
LPG	liquid petroleum gas
LR	linear regression
LRT	Light Rail Transit
lin	linear statistical function
log	logarithmic statistical function
L/100km	litres per 100 kilometres
MRT	Mass Rapid Transit
MTH	Ministry of Transportation and Highways
mad	mean absolute difference
m-cycles	motor cycles
mcs	motor cycles
NA	not available
NAAQS	National Ambient Air Quality Standards
NEHF	National Environmental Health Forum
No.	number of
NO _x	oxides of nitrogen
NLREG	Sherrod's Non-linear Regression
NPTS	National Personal Transportation Survey
Nth	North
OECD	Organisation for Economic Co-operation and Development
pass veh	passenger vehicles, automobiles
Pb	lead
p/ha	persons per hectare
p/sq km	persons per square kilometre
PM	particulate matter
pow	power statistical function
Prob t	'Prob t' statistic
pub trans	public transport

RPS	Road Pricing Scheme
rdm	road metres
rmsd	square root of the mean of the square of the difference
S	sulphur
Sing	Singapore
SK	Swedish Kroner (monetary)
sq km	square kilometre
std.	standard
std. dev.	standard deviation
Stats	Statistics
TOPAZ	Technique for the Optimal Placement of Activities in Zones
TPM	transport planning models
TRB	Transportation Research Board
TTR	Transport and Travel Research
txs	taxis
UITP	International Union (Association) of Public Transport
UK	United Kingdom
UN	United Nations Organization
UNCHS	United Nations Centre for Human Settlements
UNEP	United Nations Environment Program
US, USA	United States of America
USOFR	United States Office of Federal Register
USBTS	United States Bureau of Transport Statistics
USCB	United States Census Bureau
USDC	United States Department of Commerce
USDL	United States Department of Labor
USEPA	United States Environmental Protection Agency
USDOT	United States Department of Transport
VKT	vehicle kilometres of travel
VQS	Vehicle Quota System
VTPI	Victoria Transport Policy Institute
WADoT	Western Australian Department of Transport
WBCSD	World Business Council for Sustainable Development
WHO	World Health Organisation

The following symbols are used throughout the thesis.

%	per cent
\$	dollar monetary
<	less than
>	greater than
£	pound monetary (UK)
<i>f</i>	function of
ρ	total urbanised population density
S	private passenger vehicle saturation factor
/	division
*	multiplication
Δ	represents the change in the individual measure
t	't' statistic
p	parameter of non-linear regression function
^	power function
'r'	linear regression coefficient

$\sqrt{\quad}$	square root
[L]	dimension of length
[M]	dimension of mass
[T]	dimension of time
[P]	dimension of people
[V]	dimension of vehicle
[\$]	dimension of economic (dollar)
β_p	Total population of the metropolitan area
β_e	Total number of jobs in the metropolitan area
λ_a	Total built-up (urbanised) area of the metropolitan area (sq km)
λ_{ro}	Total length of metropolitan road network (km)
λ_{ra}	Total length of metropolitan rail network (km)
α_c	Number of private passenger vehicles on register
α_k	Total annual VKT by passenger vehicles
α_o	Average passenger vehicle occupancy
δ_c	Number of motorcycles on register
δ_k	Total annual VKT by motorcycles
δ_o	Average motorcycles occupancy
η_c	Number of taxi on register
η_k	Average taxi occupancy
η_o	Average taxi occupancy
μ_b	Total annual public transport passenger boardings
μ_{sk}	Total annual public transport passenger seat kilometres
μ_{vk}	Total annual public transport vehicle kilometres of service
μ_l	Average public transport trip length (km)
σ_w	Total annual number of walking trips
σ_l	Average length of walking trip (km)
γ_c	Total annual number of cycling trips
γ_l	Average length of cycling trip (km)
$\psi_{\$}$	GDP per capita
ψ_r	Annual expenditure on road investment
ψ_p	Annual expenditure on public transport investment
α_{cps}	Total number of parking spaces per 1,000 CBD workers
λ_{rns}	Average road network speed
μ_{pts}	Overall average of the public transport modes speed
σ_{ws}	overall standardised average walking speed (km/h)
γ_{bs}	overall standardised average bicycling speed (km/h)

Π_1 to Π_{23}	Buckingham Pi groups
Π_{mob}	private motorised mobility indicator cars only
Π_{mob1}	private motorised mobility indicator cars+motorcycles+taxis
Π_{uf}	urban form
Π_{psk}	public transport vehicle kilometres of service
Π_{rds}	vehicle ownership saturation
$\Pi_{vehicle}$	vehicle ownership saturation
Π_{pub}	public transport mobility indicator
Π_{rdm}	city's road metres per capita
Π_{wa}	non-motorised mobility walking indicator
Π_{bi}	non-motorised mobility bicycling indicator
Π_{nmm}	non-motorised mobility indicator
Π_{speed}	ratio of road to public transport speed

Acknowledgments

This thesis would not be possible without the scholarship and painstaking research diligence of the academic staff of Murdoch University's Institute for Sustainability and Technology Policy (ISTP) and their post-graduate research students. A small group of ISTP researchers led by Professor Peter Newman and Associate Professor Jeff Kenworthy and their numerous post-graduate students have over the last two decades collected a robust and standardised database of land-use, transportation and travel pattern data from a large international sample of cities. This database was used extensively in my thesis.

I wish to acknowledge the invaluable support and encouragement of my thesis supervisors, Associate Professor Jeff Kenworthy and Professor Tom Lyons. Throughout the development of this thesis, Jeff has been inspirational and has created a strong environment of academic scholarship and professionalism. My many thanks to Tom for his clear thinking and logical approach to the difficult issues that arose during development of the personal mobility models. There are numerous University academics, professionals and researchers working for city departments, authorities and institutions throughout the world who have given their valuable time to reply to my e-mails. These personnel were most generous in providing valuable data, documents, reports and papers. To these people, collectively and individually, I extend my sincere thanks and appreciation.

Also thanks to Dr. Craig Townsend for his comments and to Dr. Julia Hobson and Ms Marie Arandiga for their input during the final preparation of this thesis. I wish to acknowledge the financial support given by Murdoch University's Research and Development Board for an Australian Postgraduate Award as well as a Strategic Top-up Award.

The thesis is dedicated to Jill, Catriona and Diana.

Publications related to this thesis

Cameron, I., Kenworthy, J. R. and Lyons, T. J., (2003). *Understanding and predicting private motorised urban mobility*. Transportation Research, Part D, Volume 8, Number 4, 267-283.

Cameron, I., Lyons, T. J. and Kenworthy, J. R., (2004). Trends in vehicle kilometres of travel in world cities, 1960 – 1990: underlying drivers and policy responses. Transport Policy, Volume 11, 287-298.

These papers are attached in Appendix 13.