UNDERSTANDING, MODELLING AND PREDICTING TRANSPORT MOBILITY IN URBAN ENVIRONMENTS

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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.

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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.

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Appendix

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.

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

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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

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.

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.

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.

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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)
f	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

√	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

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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.

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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.