

***AN EXAMINATION OF CONGESTION IN ROAD TRAFFIC
EMISSION MODELS AND THEIR APPLICATION TO URBAN
ROAD NETWORKS***

**Robin Smit
M.Sc.**

School of Environmental Planning

Faculty of Environmental Sciences

Griffith University

Submitted in fulfilment of the requirements of the degree of Doctor of Philosophy

March 2006

ABSTRACT

The level of air pollution in urban areas, which is largely affected by road traffic, is an issue of high political relevance. Congestion is most prevalent in urban areas and a common and increasingly present phenomenon worldwide.

The first four chapters of this study have investigated how and to what extent models, which are used to predict emissions on road links in urban road networks, include the effects of congestion on emissions. In order to make this assessment, traffic engineering literature and empirical studies have been examined and used as a basis to review (current) emission models that exist or have been used around the world. Congestion causes changes in driving patterns of individual vehicles in a traffic stream, and these changes are subsequently reflected in changes in congestion indicators and changes in emission levels.

This consideration and a literature review has led to a proposed “congestion typology” of emission models, which reflects the different ways in which and the extent to which congestion has been incorporated in these models. The typology clarifies that six of in total ten families of emission models that were investigated in this thesis *explicitly* consider congestion in the modelling process (i.e. model variables are related to congestion), although this is done in different ways.

For the remaining four families of emission models it was not possible to determine the extent to which congestion has been incorporated on the basis of literature review alone. Two families fell beyond the scope of this work since they cannot be used to predict emission on road links. For the other two families it became clear in the course of the thesis that the extent can be determined through analysis of driving pattern data (and other information with respect to e.g. data collection) that were used in the model development.

A new methodology is presented in this thesis to perform this analysis and to assess the mean level of congestion in driving patterns (driving cycles). The analysis has been carried out for one important family of emission models, the so-called travel speed models (“average speed models”), which are used extensively in urban network modelling. For four current models (COPERT III, MOBILE 6, QGEPA 2002, EMFAC 2000), it is concluded that these models *implicitly* (i.e. congestion is inherently

considered) take varying levels of congestion into account, but that this conclusion is subject to a number of limitations.

It became clear in the course of this study that prediction of (the effects of) congestion in both traffic models and emission models is generally restricted to certain modelling dimensions. As a consequence, the effects of congestion are only partially predicted in current air emission modelling.

Chapter 5 has attempted to address the question whether congestion is actually an important issue in urban network emission modelling or not. It also addressed the question if different types of emission models actually predict different results. On the basis of a number of selection criteria, two types of models were compared, i.e. one explicit model (TEE-KCF 2002) and two implicit models (COPERT III, QGEPA 2002).

The research objectives have been addressed by applying these emission models to a case-study urban network in Australia (Brisbane) for which various model input attributes were collected from different sources (both modelled and field data). The findings are limited by the fact that they follow from one urban network with particular characteristics (fleet composition, signal settings, speed limits) and application of only a few particular emission models. The results therefore *indicate* that:

1. Changes in traffic activity (i.e. distribution of vehicle kilometres travelled on network links) over the day appear to have the largest effect on predicted traffic emissions.
2. Congestion is an important issue in the modelling of CO and HC emissions. This appears not to be the case for NO_x emissions, where basic traffic composition is generally a more important factor. For the most congested parts in the urban network that have been investigated, congestion can more than double predicted emissions of CO and HC.
3. Different types of emission models can produce substantially different results when absolute (arithmetic) differences are considered, but can produce similar results when relative differences (ratio or percent difference) are considered.

TABLE OF CONTENTS

1	INTRODUCTION	1
1.1	Air Pollution From Urban Road Traffic	1
1.2	Congestion and Air Pollution	12
1.3	The Rationale and Research Objectives of This Study	15
1.3.1	The Rationale for this Research Project	15
1.3.2	The Research Approach	15
2	THE NATURE OF CONGESTION	19
2.1	Introduction to Congestion	20
2.2	Congestion from a Traffic Engineering Perspective	22
2.2.1	Basic Traffic Stream Model	25
2.2.2	Shock Wave Theory	30
2.2.3	Traffic Performance Models	37
2.2.4	Congestion Functions	46
2.2.5	Speed Fluctuation	57
2.2.6	Level of Service (LOS)	64
2.2.7	Network Congestion Indicators	66
2.2.8	Other Congestion Indicators	68
2.3	Congestion Indicators in Air Emission Modelling	70
2.4	Quantification of Congestion in this Study	73
2.5	Traffic Models & Traffic Field Data	79
2.5.1	Strategic Planning Models (SPMs)	79
2.5.2	Dense Network Models (DNMs)	82
2.5.3	Traffic Performance Models (TPMs)	83
2.5.4	Microscopic Simulation Models (MSMs)	84
2.5.5	Other Traffic Models	86
2.5.6	Traffic Field Data	87
2.6	Discussion & Conclusion	90

3	CURRENT VEHICULAR EMISSION MODELS FOR ROAD TRAFFIC	95
3.1	Introduction to Vehicle Emissions and Congestion	96
3.2	Review of Emission Models	104
3.2.1	Introduction to the Empirical Base of Emission Models	104
3.2.2	A Review of Emission Models	110
3.2.2.1	Instantaneous and Aggregate Modal Emission Models	111
3.2.2.2	Speed and Speed Fluctuation Emission Models	118
3.2.2.3	Queuing Emission Model (Matzoros Emission Model)	121
3.2.2.4	Reconstructed Speed-Time Profile Emission Model (TEE Model)	122
3.2.2.5	(Average) Travel Speed Emission Models	127
3.2.2.6	Qualitative and Quantitative Traffic Situation Models	139
3.2.2.7	Area-Wide or National Emission Models	142
3.2.2.8	Fuel Based Emission Models	143
3.2.3	Discussion and Conclusions	143
3.3	Classification of Emission Models With Respect To Congestion	150
3.4	Conclusions	157
4	CONGESTION IN CURRENT TRAVEL SPEED EMISSION MODELS	159
4.1	Driving Cycle Construction and Congestion	160
4.2	Qualitative Analysis of Congestion in Travel Speed Models	165
4.2.1	Known Levels of Congestion in Driving Cycles	166
4.2.2	Congestion in COPERT, QGEPA and EMFAC	175
4.2.3	Conclusions of the Qualitative Analysis	187
4.3	Quantitative Analysis of Congestion in Travel Speed Models	188
4.3.1	Methodology	188
4.3.2	MOBILE 6	197
4.3.3	EMFAC 2000	203
4.3.4	COPERT III	208
4.3.5	QGEPA 2002	219
4.4	Discussion & Conclusion	226

5	PRACTICAL NETWORK APPLICATION OF EMISSION MODELS	231
5.1	Network Preparation and Emission Model Application	234
5.1.1	Test Network Characteristics and Level of Congestion	237
5.1.2	Preparation of a Detailed Traffic Composition	247
5.1.3	Computation of Link and Network Emissions (Model Application)	257
5.2	The Importance of Congestion in Urban Network Modelling	259
5.3	Disparities in Predictions between Implicit and Explicit Models	270
5.4	Analysis of Composite Emission Factors	277
5.5	Best Model Choice	286
5.5.1	Aspects that Affect Model Choice	286
5.5.2	Best Model Choice for Chapter 5	295
5.6	Conclusions	299
6	SUMMARY OF CONCLUSIONS	303
	REFERENCES	317
	APPENDIX A – STRATEGIC PLANNING MODELLING	357
	APPENDIX B – CONGESTION IN DRIVING CYCLES	359

LIST OF FIGURES

FIGURE 1 – RELATIVE CONTRIBUTION OF ROAD TRAFFIC TO ANTHROPOGENIC EMISSIONS IN SOUTH-EAST QUEENSLAND (2000)	3
FIGURE 2 – RELATIONSHIPS BETWEEN AIR POLLUTION AND ITS EFFECTS	3
FIGURE 3 – FUNDAMENTAL MACROSCOPIC RELATIONSHIPS OF UNINTERRUPTED TRAFFIC FLOW	25
FIGURE 4 – SHOCK WAVES AT AN UNSATURATED SIGNALISED INTERSECTION	31
FIGURE 5 – SHOCK WAVES IN SATURATED CONDITIONS	35
FIGURE 6 – CONGESTION RELATIONSHIPS (DELAY & NUMBER OF STOPS) ON URBAN ROADS USING TRAFFIC PERFORMANCE MODELS	43
FIGURE 7 – CONGESTION RELATIONSHIPS (QUEUE LENGTH & DENSITY) ON URBAN ROADS USING TRAFFIC PERFORMANCE MODELS	45
FIGURE 8 – RELATIONSHIP BETWEEN CONGESTION AND SIGNAL SETTINGS	46
FIGURE 9 – EFFECT OF CONGESTION ON TRAVEL SPEED	52
FIGURE 10 – MEAN TRAVEL SPEED AS AN INDICATOR OF CONGESTION	54
FIGURE 11 – ACCELERATION NOISE VERSUS VOLUME-TO-CAPACITY RATIO BY ROAD TYPE FOR UNINTERRUPTED CONDITIONS	59
FIGURE 12 – RELATIONSHIP BETWEEN SPEED FLUCTUATION AND DENSITY ON A US FREEWAY (DATA DERIVED FROM BARTH, JOHNSTON & TADI, 1996)	62
FIGURE 13 – INFLUENTIAL FACTORS INCLUDED IN EMISSION MODELLING AT THE DIFFERENT SCALES OF INDIVIDUAL VEHICLE, ROAD LINK AND ROAD NETWORK	99
FIGURE 14 – VARIATION OF ENGINE-OUT EXHAUST EMISSION CONCENTRATIONS WITH A/F RATIO (SOURCE: HEYWOOD, 1988, P. 571)	101
FIGURE 15 – STANDARD DRIVING CYCLES (US FTP75 CITY AND EU NEDC)	106
FIGURE 16 – FUNDAMENTAL TEE MODEL RELATIONSHIP FOR UNINTERRUPTED CONDITIONS	123
FIGURE 17 – RECONSTRUCTED TEE CYCLES	124

FIGURE 18 – MOBILE 6 SPEED CORRECTION FACTORS FOR LIGHT-DUTY CATALYST PETROL VEHICLES	132
FIGURE 19 – EMFAC 2000 CYCLE CORRECTION FACTORS FOR LIGHT-DUTY PETROL VEHICLES	135
FIGURE 20 – TYPE I, II & III EMISSION MODELS	151
FIGURE 21 – MOBILE 6 FREEWAY DRIVING CYCLES	167
FIGURE 22 – CARB FREEWAY DRIVING CYCLES	168
FIGURE 23 – TNO MOTORWAY DRIVING CYCLES	170
FIGURE 24 – MOBILE 6 ARTERIAL DRIVING CYCLES	171
FIGURE 25 – CARB ARTERIAL DRIVING CYCLES	173
FIGURE 26 – COPERT DRIVING CYCLES (TRAVEL SPEEDS 130-56 KM/H)	178
FIGURE 27 – QGEPA DIESEL VEHICLE DRIVING CYCLES (TRAVEL SPEEDS 7-75 KM/H)	182
FIGURE 28 – EMFAC DRIVING CYCLES (UCC 65 – UCC 35)	184
FIGURE 29 – VALIDATION OF ESTIMATION METHOD FOR FREE-FLOW SPEEDS DEVELOPED IN THIS SECTION	196
FIGURE 30 – COMPARISON OF TWO DIFFERENT METHODS TO COMPUTE INSTANTANEOUS ACCELERATION (MOBILE 6 CYCLES)	202
FIGURE 31 – MODAL ACTIVITY DISTRIBUTION AND SPEED FLUCTUATION IN EMFAC 2000 CYCLES	207
FIGURE 32 – EXAMPLE OF AN UNCONGESTED PART IN THE UCC 65 CYCLE	208
FIGURE 33 – TRAVEL TIME BASED CONGESTION INDICATOR VALUES FOR COPERT DRIVING CYCLES	216
FIGURE 34 – SPEED FLUCTUATION BASED CONGESTION INDICATOR VALUES FOR COPERT DRIVING CYCLES	216
FIGURE 35 – ACCELERATION DISTRIBUTIONS FOR TWO COPERT DRIVING CYCLES	218
FIGURE 36 – TRAVEL TIME BASED CONGESTION INDICATOR VALUES FOR QGEPA DIESEL DRIVING CYCLES	224
FIGURE 37 – SPEED FLUCTUATION CONGESTION INDICATOR VALUES FOR QGEPA DIESEL DRIVING CYCLES	225
FIGURE 38 – BRISBANE TEST NETWORK	238

FIGURE 39 – VALIDATION OF TRAVEL DEMAND MODEL	240
FIGURE 40 – LINK VOLUME-TO-CAPACITY RATIOS IN THE TEST NETWORK	240
FIGURE 41 – INTERNATIONAL COMPARISON OF URBAN NETWORK CONGESTION	245
FIGURE 42 – DISTRIBUTION OF TOTAL TRAVEL BY VEHICLE TYPE AND MODEL YEAR IN THE YEAR 2000	252
FIGURE 43 – RELATIONSHIP BETWEEN TRAVEL SPEED (CONGESTION) AND COMPOSITE EMISSION FACTORS FOR THREE MODELS	258
FIGURE 44 – TOTAL NETWORK CO EMISSION PREDICTIONS BY THREE MODELS	261
FIGURE 45 – TOTAL NETWORK HC EMISSION PREDICTIONS BY TWO IMPLICIT MODELS	262
FIGURE 46 – TOTAL NETWORK NO _x EMISSION PREDICTIONS BY TWO IMPLICIT MODELS	262
FIGURE 47 – SENSITIVITY OF NETWORK EMISSIONS TOWARDS CONGESTION	268
FIGURE 48 – SENSITIVITY OF NETWORK EMISSIONS TOWARDS CONGESTION	268
FIGURE 49 – DISPARITY BETWEEN NORMALISED NETWORK CO EMISSIONS OF TEE-KCF 2002 AND COPERT III	272
FIGURE 50 – DISPARITY BETWEEN NORMALISED NETWORK CO EMISSIONS OF TEE-KCF 2002 AND QGEPA 2002	272
FIGURE 51 – DISPARITY BETWEEN NORMALISED NETWORK CO EMISSIONS OF COPERT III AND QGEPA 2002	274
FIGURE 52 – COMPOSITE CO EMISSION FACTORS OF THE IMPLICIT MODELS	278
FIGURE 53 – COMPOSITE CO EMISSION FACTORS OF THE EXPLICIT MODEL	278
FIGURE 54 – COMPOSITE HC EMISSION FACTORS OF THE IMPLICIT MODELS	279
FIGURE 55 – COMPOSITE NO _x EMISSION FACTORS OF THE IMPLICIT MODELS	279

FIGURE 56 – DIFFERENCE IN COMPOSITE CO EMISSION FACTORS BETWEEN MODELS	284
---	-----

LIST OF TABLES

TABLE 1 – AN OVERVIEW OF AIR EMISSION MODELLING STUDIES, THE AIR EMISSION MODELS THAT WERE USED,	6
TABLE 2 – REPORTED EFFECT OF CONGESTION ON AIR POLLUTION	13
TABLE 3 – OVERVIEW OF CONGESTION FUNCTIONS	49
TABLE 4 – REPRESENTATIVE PARAMETER VALUES FOR THREE BASIC ROAD TYPES	53
TABLE 5 – EFFECT OF CONGESTION ON MODAL ACTIVITY DISTRIBUTION IN TRAFFIC STREAMS	63
TABLE 6 – TRAFFIC VARIABLES WITH VALUES FOR LOS E CONDITIONS (LEVEL TERRAIN)	65
TABLE 7 – TRAFFIC VARIABLES WITH VALUES FOR LOS F CONDITIONS (LEVEL TERRAIN)	65
TABLE 8 – OVERVIEW OF CONGESTION INDICATORS, LEVEL OF ANALYSIS AND USE IN EMISSION MODELS	71
TABLE 9 – OVERVIEW OF CONGESTION INDICATORS TO BE USED IN CHAPTERS 4 & 5	77
TABLE 10 – EMISSION MODEL CLASSIFICATION WITH RESPECT TO THE USE OF DRIVING PATTERN DATA	156
TABLE 11 – THE INFLUENCE OF CONTROLLED INTERSECTIONS IN ARTERIAL CYCLES	172
TABLE 12 – DRIVING CYCLES USED FOR EACH COPERT VEHICLE CLASS	176
TABLE 13 – PERCENT DISTANCE DRIVEN BY ROAD TYPE FOR EMFAC 2000 CYCLES	186
TABLE 14 – PERCENT DIFFERENCE IN CYCLE STATISTICS DUE TO DIFFERENT ACCELERATION COMPUTATION METHODS	191
TABLE 15 – CONGESTION INDICATOR VALUES (TRAVEL TIME BASED) FOR MOBILE 6 DRIVING CYCLES	198

TABLE 16 – CONGESTION INDICATOR VALUES (SPEED FLUCTUATION BASED) FOR MOBILE 6 DRIVING CYCLES	199
TABLE 17 – CONGESTION INDICATOR VALUES (TRAVEL TIME BASED) FOR EMFAC 2000 DRIVING CYCLES	204
TABLE 18 – CONGESTION INDICATOR VALUES (SPEED FLUCTUATION BASED) FOR EMFAC 2000 DRIVING CYCLES	205
TABLE 19 – CONGESTION INDICATOR VALUES (TRAVEL TIME BASED) FOR COPERT III DRIVING CYCLES	209
TABLE 20 – CONGESTION INDICATOR VALUES (SPEED FLUCTUATION BASED) FOR COPERT III DRIVING CYCLES	212
TABLE 21 – CONGESTION INDICATOR VALUES (TRAVEL TIME BASED) FOR QGEPA DIESEL DRIVING CYCLES	220
TABLE 22 – CONGESTION INDICATOR VALUES (SPEED FLUCTUATION BASED) FOR QGEPA DIESEL DRIVING CYCLES	222
TABLE 23 – SUMMARY OF THE APPROPRIATENESS OF EMISSION MODELS FOR APPLICATION IN CHAPTER 5	230
TABLE 24 – LEVELS OF NETWORK CONGESTION AND OTHER FEATURES OF THE TEST NETWORK BY CITY REGION, ROAD TYPE AND TIME OF DAY	242
TABLE 25 – MAJOR VEHICLE CLASSES FOR THIS STUDY (LDVS)	249
TABLE 26 – DIFFERENCES BETWEEN ABS DATA AND PREDICTIONS BASED ON TRAVEL DISTRIBUTIONS	253
TABLE 27 – PERCENT OF TOTAL VKT BY MAJOR VEHICLE CLASS FOR THE BASE YEAR 2000	254
TABLE 28 – CORRESPONDING AUSTRALIAN AND EUROPEAN VEHICLE CATEGORIES USED IN THIS STUDY	256
TABLE 29 – SECTION OF EMISSION MODELLING INPUT AND OUTPUT DATABASE	259
TABLE 30 – SENSITIVITY OF TOTAL EMISSION PREDICTIONS TO RANGE VARIATION OF RELEVANT INPUT VARIABLES	265
TABLE 31 – DISPARITIES BETWEEN NORMALISED NETWORK CO EMISSIONS (G/VKT) OF THE EXPLICIT AND IMPLICIT MODELS BY GEOGRAPHIC LOCATION, ROAD TYPE AND TIME OF DAY	271

TABLE 32 – INTERFACE BETWEEN TYPES OF EMISSION MODELS, TRAFFIC MODELS AND TRAFFIC FIELD DATA	289
TABLE 33 – TEE-KCF MODEL VALIDATION TEST RESULTS (SOURCE: EC, 1995)	295

NOTATIONS AND DEFINITIONS

a	mean acceleration (m/s^2)
a_t	instantaneous acceleration (m/s^2)
$a_{t+\Delta t,i}$	instantaneous acceleration of the i^{th} vehicle at time $t+\Delta t$ (m/s^2)
AADT	average annual daily traffic volume (veh/h)
AADT/C	AADT-to-capacity ratio (-)
c	signal cycle time (s)
C	capacity of a road (link) or an intersection approach (veh/h, veh/h.lane)
Cl_i	link congestion index (-)
Cl_n	network congestion index (-)
COV_{vt}	coefficient of variation of instantaneous speeds (-)
CR	congested roads (km)
CSI	congestion severity indicator (veh.h/ 10^6 veh.km)
CT	congested travel (veh.km)
$x_{t,i}$	location on the road of following vehicle (m)
$x_{t,i-1}$	location on the road of leading vehicle (m)
\bar{d}	average delay per vehicle (s/veh, s/veh.cycle)
\bar{d}_{un}	average uniform delay (s/veh)
\bar{d}_{of}	average overflow delay (s/veh)
\bar{d}_c	average cruise delay (s/veh)
\bar{d}_{int}	average intersection delay (s/veh)
\bar{d}^*	average delay rate (s/km)
d_{ratio}	delay ratio (-)
D	total delay (veh.h, veh.s/cycle)
DC	degree of congestion (-)
DRI	delay rate index (-)
DVKT	average delay per VKT (min/VKT)

e_t	amount of pollutants emitted per unit time (g/s)
e_x	(composite) amount of pollutants emitted per unit distance (g/km)
ϕ	volume-to-capacity ratio (-)
g^*	effective green time (s)
g	effective green time ratio (-)
Γ	displayed green time (sec)
I	intergreen time (sec)
J_A	Akçelik delay parameter (-)
J_D	Davidson delay parameter (-)
ϕ	intersection density (signals/km)
k	average traffic density (veh/km, veh/km.lane, pce/km, pce/km.lane)
k_j	traffic jam density (veh/km, veh/km.lane, pce/km, pce/km.lane)
k_n	mean network traffic density (veh/km.lane)
ℓ_i	number of lanes on link i (-)
L	length of a road section or journey (km)
L_i	length of a road link i (km)
L_{det}	detection zone length (m)
L_{veh}	average vehicle length (m/veh)
LKDI	lane-km duration indicator (km.h)
LKR	total lane-kms of roadway (km)
LOS	level of service (-)
M	vehicle mass (kg)
n_s	average number of stops per vehicle (veh ⁻¹)
$n_{s,un}$	mean number of stops per vehicle due to uniform arrivals (veh ⁻¹)
$n_{s,of}$	mean number of stops per vehicle due to overflow conditions (veh ⁻¹)
n_s^*	average number of stops per vehicle per unit distance (km ⁻¹)
N_s	total number of stops per unit time (h ⁻¹)
Ω	percent occupancy (%)
PF	progression factor (-)
P_{HDV}	proportion of heavy-duty vehicles in the traffic stream (-)
P_{LDV}	proportion of light-duty vehicles in the traffic stream (-)

P_{idle}	proportion of time spent idling (-)
P_{acc}	proportion of time spent in acceleration (-)
P_{dec}	proportion of time spent in deceleration (-)
P_{cruise}	proportion of time spent in cruise (-)
$P_{m,y}$	proportion of total VKT of vehicle class m
PKE	positive acceleration kinetic energy (m/s^2)
q	traffic flow rate (veh/h.lane)
q_a	arrival or demand flow rate (veh/h.lane)
\bar{Q}	average queue length (m, veh)
\bar{Q}_{int}	average queue length (“maximum back of queue”) (veh)
QTFI	quality of traffic flow index (-)
r^*	effective red time (s)
r	effective red time ratio (-)
RCI	roadway congestion index (-)
RDR	relative delay rate (-)
S	saturation flow rate (veh/h.lane)
SRCI	speed reduction congestion index (-)
σ_{at}	acceleration noise (m/s^2)
σ_{vt}	speed noise (km/h)
τ	observation period (s, min or h)
T	travel time of an individual vehicle (s, min or h)
T_{idle}	stopped time of an individual vehicle (min)
\bar{T}	mean travel time of a traffic stream (s, min or h)
\bar{T}_{idle}	mean stopped time (min)
\bar{T}^*	average unit travel time (min/km)
\bar{T}_{idle}^*	average unit stopped time (min/km)
\bar{T}_{ff}	mean travel time under free-flow conditions (min)
\bar{T}_{ff}^*	mean unit travel time under free-flow conditions (min/km)
\bar{T}_{zf}^*	mean unit travel time under zero-flow conditions (min/km)
\bar{T}_q^*	mean unit travel time in queue (min/km)

T_{run}	running time (s, min, h)
TAD	total absolute second-to-second difference in speed per km (m/s.km)
v	average travel speed of an individual vehicle (km/h)
\bar{v}	mean travel speed of a traffic stream (km/h)
\bar{v}_i	mean travel speed for link i (km/h)
\bar{v}_{ff}	mean travel speed under free-flow conditions (km/h)
\bar{v}_{zf}	mean travel speed under zero-flow conditions (km/h)
\bar{v}_n	mean network travel speed (km/h)
v_{run}	running speed of an individual vehicle (km/h)
\bar{v}_{run}	mean running speed (km/h)
\bar{v}_{space}	space mean speed (km/h)
\bar{v}_{time}	time mean speed (km/h)
v_t	(second-by-second) instantaneous speed (m/s)
$v_{t,a}$	initial instantaneous speed in an acceleration manoeuvre (km/h)
$v_{t,b}$	final instantaneous speed in an acceleration manoeuvre (km/h)
V	traffic volume (veh/h.lane)
V_i	traffic volume on road link i (veh/h.lane)
V_n	mean network traffic volume (veh/h)
VHT	vehicle-hour of travel (veh.h)
VKT	vehicle-kilometre of travel (veh.km)
VKTKM	VKT per lane.km or per km^2 (VKT/lane.km or VKT/ km^2)
ω	shock wave speed (km/h)

GLOSSARY OF TERMS

A/F ratio	air-to-fuel ratio (- ¹)
bottleneck	site-specific constriction on road capacity
cycle time	period of time of one complete sequence of signal phases
driving pattern	a time series of speed points (speed-time profile)
downstream	same direction of traffic
effective green time	displayed green time corrected for start loss and end gain
HDV	heavy-duty vehicle
LCV	light-commercial vehicle
LDV	light-duty vehicle
link	line between two points in a road network representing a one-way stretch of road, as commonly used in transport models
movement	a stream of through traffic leading to an intersection that is characterised by its direction, lane usage and right of way provision
overflow queue	queue left from previous signal cycles
pce	passenger car equivalent
queue	temporary storage of vehicles upstream of a bottleneck
saturated	traffic demand exceeds capacity
signal phase	state of signal during which one or more movements receive right of way
traffic demand	the number of vehicles that would pass a point in the road network without the presence of capacity constraint
unsaturated	traffic demand is less than capacity
upstream	opposite direction of traffic
vehicle trajectory	movement of a vehicle in space and time

¹ i.e. dimensionless

Acknowledgements

First of all, I would like to thank Professor Lex Brown, Dr. Andrew Chan and Dr. Joseph Affum for their supervision, and for providing me with the opportunity to explore this very interesting area of research. I would like to express my gratitude to the Australian Research Council (ARC) and the Queensland Department of Transport (Industry Partner) for providing me with a scholarship.

Mr. Marc Thompson and Mr. Haemisch Middleton (National Environment Protection Council service Corporation), Mr. Jon Real (Federal Office of Road Safety), Mr. David Brzezinski (US EPA, United States Environmental Protection Agency), Mr. Lawrence C. Larsen, Mr. Jeff Long and Mr. Ben Hancock (California Air Resources Board), Professor Zissis C. Samaras (Aristotle University Thessaloniki), Dr. M. Weilenmann (EMPA, Swiss Federal Laboratories for Materials Testing and Research), Dr. Tim Barlow (TRL, Transport Research Laboratory) and Mr. Erik van de Burgwal (TNO, Netherlands Organisation for Applied Scientific Research) are all acknowledged for kindly providing relevant driving cycle speed-time data.

Mr. Neil Jones, Mr. Matthew Buckham and Mr. Peter Fitzgerald (Brisbane City Council, Traffic Management Centre), Mr. Adrian Gibbons and Mr. Cameron Glassford (Brisbane City Council, Transport & Traffic Branch), Ms. Aurelia Cartacai (Brisbane City Council, Policy & Planning Unit), Mr. Adam Pekol and Mr. Mac Hulbert (Adam Pekol Consulting, Brisbane), Mr. Ross Blinco, Mr. Barry Henderson, Mr. Mark R. Logan, Mr. Mark Henaway and Mr. A. De Weger (Queensland Government Department of Main Roads), Mr. David Wainwright and Dr. Josef Ischtwan (Queensland Government Environmental Protection Agency) are all greatly acknowledged for providing the necessary urban network data and patiently addressing the many questions I had. Without their help this work could not have been done.

I would like to thank Dr. Emanuelle Negrenti (ENEA, Italy) in particular for providing me with the opportunity to explore his TEE model and apply it to the Brisbane network. A special thanks is directed at Mr. William Lilley (CSIRO) for our regular discussions throughout the Ph.D. and who provided me with the necessary answers regarding CSIRO's power-based emission model. I would also like to thank Professor Janet Chaseling and Dr. James McBroom (Griffith University, Brisbane) for their very helpful advice on statistical matters.

I would also like to extend my appreciation to the many interesting people with whom I have discussed different issues, whom have sent me relevant information and/or whom I have met in person, including (but not limited to) Professor Rahmi Akçelik (Akçelik & Associates, Melbourne), Dr. Eva Ericsson (University of Lund, Sweden), Professor Lidia Morawska and Professor Luis Ferreira (Queensland University of Technology), Mr. Tom Carlson (Sierra Research), Dr. Jeremy Woolley and Dr. Rico Zito (Transport Systems Centre), Dr. Peter Hidas (University of New South Wales) and Mr. Peter Anyon (AQT).

Finally I would like to express my greatest gratitude and love to my dear family: Alexandra, Nimue and Yasmin, who have continued to support me all the way through. Without them, this low speed, almost congested, journey would not have happened.

Robin Smit

Declaration

I declare that this work has not previously been submitted for a degree or a diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

A handwritten signature in black ink, appearing to be 'RS', enclosed within a large, loopy oval shape.

Robin Smit
March 2006

1 INTRODUCTION

1.1 Air Pollution From Urban Road Traffic

Urban air quality is an issue that is currently on top of air pollution agendas around the world (e.g. Colvile *et al.*, 2001). Estimates are that, worldwide, nearly one billion people in urban environments are continuously being exposed to health hazards from air pollutants (Ahrens, 2003).

Air pollutants are airborne substances that occur in concentrations high enough to cause adverse effects on health, the environment and/or outdoor structures (amenity, property, cultural). Air pollutants can affect health in different ways and in varying degrees of severity ranging from minor irritation through serious illness to premature death (e.g. Dickey, 2000).

Air pollutant emissions come from both natural (e.g. biogenic emissions) and anthropogenic sources. Although emissions from natural sources can be substantial², and are indeed the dominant source in non-urban areas, this study specifically investigates (anthropogenic) road traffic emissions in urban areas.

The emission of air pollutants has led to several air quality issues such as photochemical smog, acid rain, visibility degradation and nuisance. Although major efforts have been made over the past decades to reduce air pollution and improve air quality, these issues have proven to be quite persistent and continue to exist, despite the implementation of several air quality strategies (e.g. Mitchell *et al.*, 2002). A major factor in this is the strong and continued growth in road traffic (Ahrens, 2003).

² For instance, it has been estimated that biogenic emissions of VOCs constitute around 64% of total VOC emissions in the South-East Queensland Region (QGEPA, 2000).

Road transport emits air pollution from the combustion of liquid or gaseous fossil fuels. Although thousands of air pollutants from road traffic can be identified, most of them can be classified in the following major groups according to their origins and formation processes:

- products of incomplete combustion, including carbon monoxide (CO), particulate matter (PM) and hydrocarbons (HCs);
- products of high-temperature combustion processes, including nitrogen oxides (NO_x);
- by-products of combustion due to impurities in the fuel, including heavy metals and sulphur oxides (SO_x);
- non-combustion products, including evaporative hydrocarbons;
- secondary air pollutants such as photochemical oxidants, including tropospheric ozone (O₃) and peroxyacetyl nitrate (PAN); and
- greenhouse gases³, including carbon dioxide (CO₂) and methane (CH₄).

Around the world, and particularly for CO, NO_x and HC, road traffic is the dominant, if not the most important, anthropogenic source of air pollution in urban areas (e.g. Fenger, 1999). This is not only because of the magnitude of its emissions, but also because pollutants are emitted in close proximity to human receptors, which enhances exposure levels. By means of an example, Figure 1 shows the relative contribution of road traffic to anthropogenic emissions of key primary air pollutants in the South-East Queensland Region, estimated for the year 2000 (data derived from BCC/QGEPA, 2004).

³ Greenhouse gases are not of concern with respect to air pollution, but are important with respect to climate change (greenhouse effect).

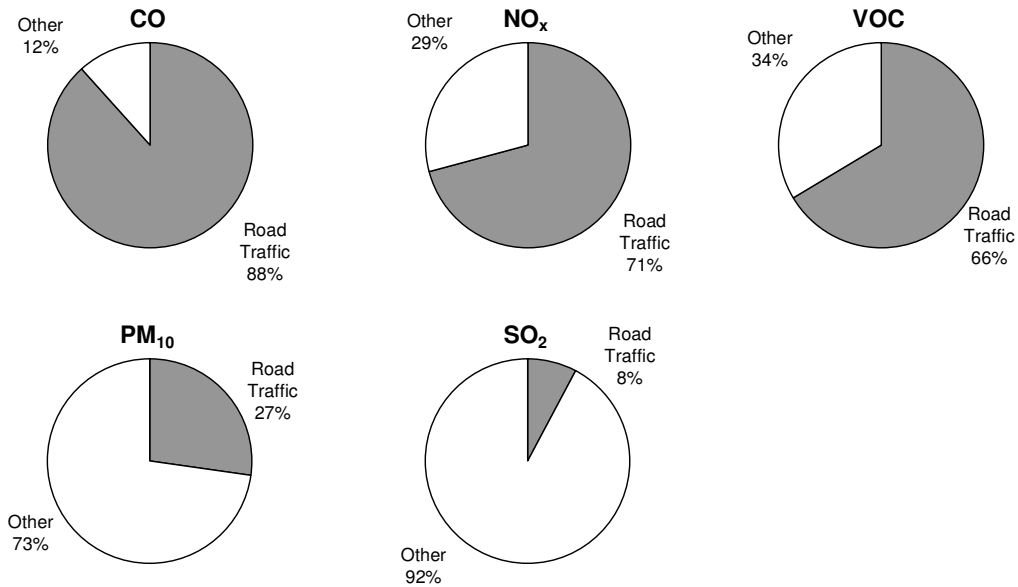


Figure 1 – Relative Contribution of Road Traffic to Anthropogenic Emissions in South-East Queensland (2000)

The relationship between air pollution from road traffic and its effects is complex. This is illustrated in Figure 2, which shows how air pollution is generated and exerts its effects through different steps. The multidisciplinary character of the relationship is clear.

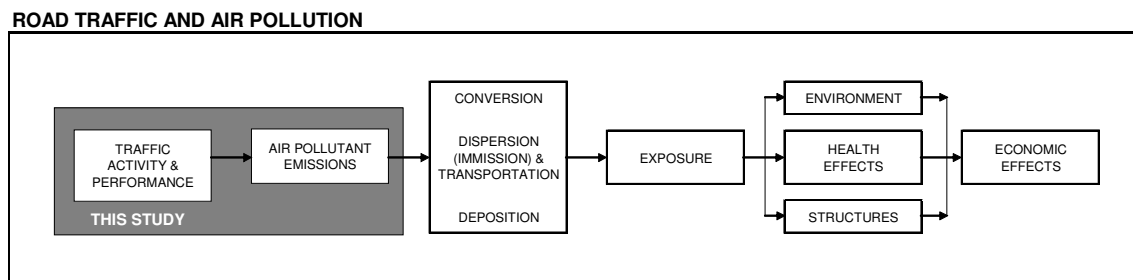


Figure 2 – Relationships Between Air Pollution and its Effects

Emissions of air pollutants are a function of the intensity and spatial distribution of human and economic activity (land use) within an area, which creates a demand for

transport. How, where and to what extent this demand is met depends on the supply of transport, i.e. the transport infrastructure. The interaction between supply and demand determines the level and distribution of transport activity in an area, which is the starting point for the modelling of road transport impacts on air quality.

The magnitude, spatial and temporal distribution of emissions are determined by traffic activity and traffic performance. Traffic activity describes the *quantity* of traffic flow and is quantified with measures such as traffic volume and vehicle-kilometres of travel. Traffic performance describes the *quality* of traffic flow and is quantified with measures such as travel speed, number of stops and queue length.

Once these emissions are released into the atmosphere, dispersion processes transport and dilute these emissions. In addition to dispersion, pollutants can also undergo (chemical) transformation and deposition. Depending on the ground level location, these processes results in certain ambient concentration levels, which are referred to here as immissions (Harssema, 1987), the extent of which is a function of meteorological conditions, topographical characteristics and distance between source and receptor.

The level of exposure to air pollutants depends on ambient concentration levels and where sensitive receptors (e.g. population) are situated in time and place. Health effects then depend on dose-effect relationships, which may be obtained from epidemiological or clinical studies. The magnitude of the effects subsequently determine the economic effects (costs) of air pollution.

This study is concerned with the first two steps in the assessment of air quality impacts from road traffic, namely traffic activity/performance and air pollutant emissions, and in particular the role of congestion in the prediction of these emissions.

As will be seen later, traffic data have been measured in real-time and through traffic studies (section 2.5.6) and vehicle emissions have been measured in both laboratories and in field experiments (section 3.2.1). However, these measured data are often only available for limited time and locations in urban areas. As a consequence, traffic models and/or emission models are commonly needed to fill in the data gaps (e.g. Namdeo, Mitchell & Dixon, 2002; Borrego *et al.*, 2003). This is particularly evident when large urban road networks are considered, *which is the scale of interest of this study*. Models are also required for prediction of (relative) emission

levels for situations that do not yet exist and cannot be measured (e.g. future years, after implementation of control measures).

This study is concerned with the assessment of emissions from traffic streams on “road links” in large urban road networks. This scale is essential for effective air quality management and policy making, which requires the identification, quantification, forecasting and control of all air pollutant emission sources (e.g. Lindley *et al.*, 1999). There are various purposes for which traffic emission information on links is required (e.g. Affum & Brown, 1999), for instance:

- evaluation of existing air quality control strategies (trend analysis, forecasting);
- assessment of effectiveness of alternative policy options (scenario testing);
- assessment of importance of road traffic to overall air pollution (priorisation of sources);
- development (planning and design) of transport policies;
- impact assessments of changes in land use (scenario testing);
- identification of high-priority areas or locations with severe air pollution;
- international obligations/negotiations (e.g. with respect to greenhouse gas emissions);
- forecasting of air pollution episodes; and
- assessment of urban air quality - photochemical smog levels (large areas).

A review of the literature showed a large number of studies which are concerned with traffic emission modelling in road networks. An overview of 57 reviewed studies (1979-2004) is presented in Table 1. It is noted that this table and the terminology and abbreviations it contains are used and explained later in this thesis. At this point, some general observations are made on page 11. It is noted that Table 1 is further discussed in section 3.2.3.

Table 1 – An Overview of Air Emission Modelling Studies, The Air Emission Models that Were Used, and the Traffic Data/Models used in Modelling Air Emissions

Reference	Country	Spatial Scale & Temporal Resolution of Air Emission Modelling	Traffic Data Used in Emission Modelling		Emission Model Used in Air Emission Modelling
			Field Data	Model Used	
Tobin, 1979	USA	Metropolitan Area, Daytime Periods ²⁾	-	SPM	ASM
Neylon & Collins, 1982	Australia	Metropolitan Area, 24h & Hourly	VKT ¹⁾ , Road/Flow Type	-	TSM
Taylor & Anderson, 1982	Australia	Small Urban Network, Peak Hour	-	SPM (URPOL)	ASM
Taylor & Anderson, 1984	Australia	Metropolitan Area, Peak Hour	-	SPM (URPOL)	ASM
Matzoros, 1990	UK	4 Adjacent Road Sections, Hourly	VKT ¹⁾ , Signal Settings	-	MAT
Carnovale <i>et al.</i> , 1992	Australia	Metropolitan Area, 24h & Hourly	VKT, Road/Flow Type	-	TSM
Ingham, 1992	South Africa	Country, Annual & Daytime Periods ²⁾	VKT, v	-	ASM
Keenan & Escarpeta, 1994	USA	Regional, Hourly	v	SPM	ASM (MOBILE)
EC, 1995	Europe	Small Urban Network, Peak Hour	-	DNM (SATURN)	AMM
EC, 1995; Negrenti, 1998	Europe	Several Urban Networks, N/A ³⁾	-	SPM (EMME2/TRANUS)	TEE-KCF
Samaras <i>et al.</i> , 1995	Greece	Metropolitan Area, Daytime Periods	VKT, v	-	ASM (COPERT)
Anderson <i>et al.</i> , 1996	Canada	Metropolitan Area, Peak Hour	-	SPM (EMME2)	ASM (MOBILE)
IPCC, 1996	International	National, Annual	VKT, TFC	-	AWM, FBM
Robertson <i>et al.</i> , 1996	UK	5 Adjacent Links, Daytime Periods	V, L, T	TPM (TRANSYT)	IMM

v = Mean Travel Speed, V = Traffic Volume, SPM = Strategic Planning Model, DNM = Dense Network Model, TPM = Traffic Performance Model, ASM = (Average) Travel Speed Model, TSM = Traffic Situation Model, MAT = Matzoros Model, AMM = Aggregate Modal Model, TEE-KCF = TEE-KCF Model, IMM = Instantaneous Modal Model, FBM = Fuel Based Model

¹⁾ VKT (Vehicle Kilometres Travelled) is obtained through multiplication of road lengths with corresponding traffic count data.

²⁾ A commonly used breakdown in daytime periods is peak, off-peak and night-time conditions.

³⁾ N/A = information is not available.

Table 1 (Continued) - An Overview of Air Emission Modelling Studies, The Air Emission Models that Were Used, and the Traffic Data/Models used in Modelling Air Emissions

Reference	Country	Spatial Scale & Temporal Resolution of Air Emission Modelling	Traffic Data Used in Emission Modelling		Emission Model Used in Air Emission Modelling
			Field Data	Model Used	
Bachman <i>et al.</i> , 1996	USA	Metropolitan Area, Hourly	V, L	SPM	ASM
Moragues & Alcaide, 1996	Spain	Metropolitan Area, Daily	Road Type	SPM (TRIPS)	AWM
NSW EPA & Coffey, 1997	Australia	Metropolitan Area, Hourly	-	Unspecified Model	TSM
Sturm <i>et al.</i> , 1997	Austria	Metropolitan Area, Hourly	-	Unspecified Model	ASM
Sturm <i>et al.</i> , 1997	Austria	Region, Daily	-	National Statistics	AWM
Metz <i>et al.</i> , 1997	Germany	Motorway, Daytime Periods	T, Traffic Situation ⁴⁾	-	TSM
TRB, 1997	USA	Metropolitan Area, Hourly	VKT	SPM	ASM (MOBILE)
Scott <i>et al.</i> , 1997	Canada	Metropolitan Area, Peak Hour	-	SPM	ASM (MOBILE)
Mullen <i>et al.</i> , 1997	USA	National Highway Network, Annual	VKT, v	-	ASM (MOBILE)
AGO, 1998; 2003	Australia	National, Annual	VKT, TFC	-	AWM, FBM
Gualtieri & Tartaglia, 1998	Italy	Metropolitan Area, Peak Hour	-	SPM	ASM (COPERT)
Schmidt <i>et al.</i> , 1998	Germany	Regional Area, N/A	Traffic Situation ⁴⁾	BTM (SIMTRAP)	TSM
Saleh <i>et al.</i> , 1998	UK	Small Urban Network, Annual	-	DNM (CONTRAM)	AMM
Seika <i>et al.</i> , 1998	Germany	Metropolitan Area, Annual	VKT	SPM	ASM

v = Mean Travel Speed, V = Traffic Volume, T = Travel Time, SPM = Strategic Planning Model, DNM = Dense Network Model, BTM = Basic Traffic Stream Model, ASM = Travel Speed Model, TSM = Traffic Situation Model, AMM = Aggregate Modal Model, AWM = Area-Wide Emission Model, VKT = Vehicle Kilometres Travelled, TFC = Total Fuel Consumption, FBM = Fuel Based Model

⁴⁾ It is not clear from the publication how this variable was quantified.

Table 1 (Continued) - An Overview of Air Emission Modelling Studies, The Air Emission Models that Were Used, and the Traffic Data/Models used in Modelling Air Emissions

Reference	Country	Spatial Scale & Temporal Resolution of Air Emission Modelling	Traffic Data Used in Emission Modelling		Emission Model Used in Air Emission Modelling
			Field Data	Model Used	
Mensink & De Vlieger, 1998	Belgium	Regional Area, Annual	VKT, Road Type	-	TSM
Hallmark & Guensler, 1999	USA	Intersection, 2 Links, 1 h	-	MSM (NETSIM)	SFM (MEASURE)
Beamon & Griffin, 1999	USA	Metropolitan Highway Network, 24h	-	SPM	ASM
Rebolj & Sturm, 1999	Austria	Regional Major Road Network, Annual	VKT, Traffic Situation ⁴⁾	SPM	TSM
Lindley <i>et al.</i> , 1999	UK	Regional Area, Annual	VKT	-	TSM
Sturm <i>et al.</i> , 1999	Austria	Metropolitan Area, Hourly	Traffic Situation ⁴⁾	SPM	TSM
Zachariadis & Samaras, 1999	Greece	Metropolitan Area, Hourly	VKT, v	-	ASM (COPERT)
Owen <i>et al.</i> , 1999 & 2000	UK	Metropolitan Area, Hourly	VKT, v ⁴⁾	-	ASM
Hao <i>et al.</i> , 2000	China	Urban Main Road Network, Hourly	VKT, v ⁴⁾	-	ASM (MOBILE) ⁵⁾
Reynolds & Broderick, 2000	Ireland	Urban Network, Daytime Periods	V, D, v, \bar{Q} (SCATS)	DNM (SATURN)	ASM
EA, 2000	Australia	Gridded Network, Annual	VKT, Road Type	-	TSM
Daniel & Bekka, 2000	USA	Regional Highway Network, Annual	-	SPM (TRANPLAN)	ASM (MOBILE)

v = Mean Travel Speed, V = Traffic Volume, L = Link Length, T = Travel Time, D = Delay, \bar{Q} = Average Queue Length, SPM = Strategic Planning Model, DNM = Dense Network Model, MSM = Microscopic Simulation Model, ASM = Travel Speed Model, TSM = Traffic Situation Model, SFM = Speed Fluctuation Model, VKT = Vehicle Kilometres Travelled

⁴⁾ It is not clear from the publication how this variable was quantified.

⁵⁾ The emission model is based on the principles of or a modified or augmented version of the model that is mentioned.

Table 1 (Continued) - An Overview of Air Emission Modelling Studies, The Air Emission Models that Were Used, and the Traffic Data/Models used in Modelling Air Emissions

Reference	Country	Spatial Scale & Temporal Resolution of Air Emission Modelling	Traffic Data Used in Emission Modelling		Emission Model Used in Air Emission Modelling
			Field Data	Model Used	
Borrego <i>et al.</i> , 2000	Portugal	Metropolitan Area, Daily	VKT, Road Type	-	TSM
Mensink <i>et al.</i> , 2000	Belgium	Urban City Network, Peak Hour	-	SPM	ASM (COPERT)
Taylor, 2000	Australia	Synthetic Urban Network	-	DNM (TRAFIKPLAN)	ASM (RUNNING)
Tate & Bell, 2000	UK	5-Link Urban Network, Peak Period	-	DNM (SATURN)	AMM
	UK	5-Link Urban Network, Peak Period	-	MSM (DRACULA)	AMM
Lehmuskoski <i>et al.</i> , 2000	Finland	Two Streets, Ring Road (2.5 km), N/A	-	MSM (HUTSIM)	IMM
TNO, 2001	Netherlands	Motorway Network	v_{space} , VKT, V, SL	-	CRM TNO
Romanini & Mangia, 2001	Italy	Regional Area, N/A	-	SPM (QRS)	ASM (COPERT)
Mensink <i>et al.</i> , 2001	Belgium	Urban City Network, Hourly	-	SPM	ASM (COPERT)
Park <i>et al.</i> , 2001	UK	13-Link Urban Network, 15 min	-	MSM (VISSIM)	IMM (MODEM), ASM
Corvalán <i>et al.</i> , 2002	Chile	Metropolitan Area, Daytime Periods	-	SPM (ESTRAUS)	ASM (COPERT) ⁵⁾
Saija & Romano, 2002	Italy	Urban Areas, Annual	VKT ⁴⁾ , Road Type ⁴⁾	-	TSM

v_{space} = Space Mean Speed, V = Traffic Volume, SPM = Strategic Planning Model, DNM = Dense Network Model, TPM = Traffic Performance Model, MSM = Microscopic Simulation Model, ASM = Travel Speed Model, TSM = Traffic Situation Model, AMM = Aggregate Modal Model, IMM = Instantaneous Modal Model, VKT = Vehicle Kilometres Travelled

⁴⁾ It is not clear from the publication how this variable was quantified.

⁵⁾ The emission model is based on the principles of or a modified or augmented version of the model that is mentioned.

Table 1 (Continued) - An Overview of Air Emission Modelling Studies, The Air Emission Models that Were Used, and the Traffic Data/Models used in Modelling Air Emissions

Reference	Country	Spatial Scale & Temporal Resolution of Air Emission Modelling	Traffic Data Used in Emission Modelling		Emission Model Used in Air Emission Modelling
			Field Data	Model Used	
Eissfeldt <i>et al.</i> , 2002a	Germany	Urban City Network, Hourly	-	MQM (Q-MODEL)	TSM
Namdeo <i>et al.</i> , 2002	UK	Metropolitan Area, Hourly	-	DNM (SATURN)	ASM (COPERT) ⁵⁾
Brown & Affum, 2002	Australia	Small Urban Network, Annual	-	SPM	ASM
Mitchell <i>et al.</i> , 2002	UK	Metropolitan Area, Hourly	-	DNM (SATURN)	ASM (COPERT) ⁵⁾
Akçelik & Besley, 2003	Australia	Intersection	-	TPM (SIDRA)	IMM (Biggs- Akçelik)
BCC/QGEPA, 2004	Australia	Metropolitan Area, Daytime Periods	-	SPM (EMME2)	ASM (MOBILE) ⁵⁾

MQM = Microscopic Queuing Model, SPM = Strategic Planning Model, DNM = Dense Network Model, TPM = Traffic Performance Model, ASM = Travel Speed Model, TSM = Traffic Situation Model, IMM = Instantaneous Modal

⁵⁾ The emission model is based on the principles of or a modified or augmented version of the model that is mentioned.

Table 1 shows that emission models are commonly applied in various countries around the world to predict emissions from road networks of different size. The spatial scale ranges from very small urban networks (only a few adjoining links) to large city or regional road networks, and in a few cases even national road networks (the latter limited to main roads, e.g. highways). The majority of studies (55%), however, is concerned with emission modelling of large urban networks, which highlights the relevance of this type of activity in air pollution modelling. The following observations are made from Table 1:

- The so-called average (travel) speed emission model (ASM) is the type of emission model that is most often used (50%). It is also the dominant type of model that is applied to large urban networks (72%).
- Two particular ASMs, COPERT and MOBILE, stand out in that they are the most commonly used ASMs (59%). Together, they are also the most commonly applied emission models (53%) for large urban networks.
- Traffic data are generally obtained from traffic models (52%) or solely obtained from field measurements (31%), or a combination of the two (17%). The majority of the traffic models that are used (73%) are so-called strategic planning models (SPMs).

These observations indicate that specific types of emission models and traffic models are of particular interest to this study, given their common usage in the prediction of road traffic emissions in urban networks.

1.2 Congestion and Air Pollution

Road transport has grown rapidly over the last decades. For instance, in Australia over a period of twenty years (1979-1998) (Austroads, 2000):

- the total number of vehicle-kilometres travelled by cars has increased by 56%; and
- the total number of tonne- kilometres by trucks has increased by a factor of 3.

As a consequence, traffic-related emissions and air pollution have increased substantially (e.g. Burmich, 1989), despite the increasing use of abatement measures such as catalytic converters (Namdeo, Mitchell & Dixon, 2002). Due to the growth in road traffic, congested traffic conditions have become increasingly common and severe worldwide, particularly in major cities (e.g. Austroads, 2000). A strong further increase in the demand for transport and congestion is projected around the world (e.g. Fenger, 1999), including Australia (e.g. BTE, 2000).

Traffic congestion has been indicated as being one of the main contributors to environmental impacts in urban areas (e.g. Woolley *et al.*, 1997). Various publications explicitly state that congestion has an adverse effect on either traffic emissions, air quality or both in urban areas (e.g. Shefer, 1994; Donaghy & Schintler, 1998). For example, Oduyemi and Davidson (1998) remark that:

“traffic related air pollution is most severe in urban areas and particularly city centres, where large traffic volumes and congestion commonly result in a significant degradation of the air quality in these areas”.

Empirical evidence supports this. A review of the literature (Table 2) shows that different types of empirical studies all indicate that congestion increases vehicle emissions, and in particular CO and HC emissions.

Table 2 – Reported Effect of Congestion on Air Pollution

Reference	Study Type	Reported Results
Claggett, Shrock & Noll (1981)	Monitoring of hourly kerbside CO concentrations at different sites on an arterial road and on a freeway.	<ul style="list-style-type: none"> - CO concentrations measured in the queue zone at the intersection were on average four times higher than at midblock. - The maximum concentration measured at the freeway site was 43% lower than the maximum concentration measured in the queuing zone, despite the fact that traffic volumes on the freeway were 3.2 times higher.
Watson (1995)	Laboratory emission tests.	Lowest emissions of CO, HC and NO _x from Australian catalyst and non-catalyst cars, expressed as g/km, occur at steady constant speeds between about 40 and 60 km/h (CO, HC) and 20 and 40 km/h (NO _x), with increased emissions outside this range of steady-state speeds and with increased levels of speed fluctuation.
Sjödin <i>et al.</i> (1998)	Tunnel study.	CO and HC emission factors (g/km) increase with up to a factor of 10 in congested driving conditions with average speeds at 20 km/h, when compared to uncongested smooth driving conditions in the range of 60-70 km/h.
De Vlieger <i>et al.</i> (2000)	On-board emissions tests.	For a catalyst petrol car, emission factors (g/km) increased by about 60% (CO) and 10% (HC) when measurements in rush hour traffic were compared to measurements in smooth traffic conditions, whereas NO _x emission factors did not change.
Carr <i>et al.</i> (2002)	Monitoring of kerbside air pollutant concentrations	Statistical models were developed to describe the variation in near road ambient pollutant concentrations (annual mean) of benzene, toluene, NO ₂ , and soot in an urban area. It was found that two traffic characteristics, i.e. traffic volume and percent traffic jam, adequately described concentration levels.

The studies presented in Table 2 refer to small sections of roadways or individual vehicles. Of all the studies conducted at network level that were reported in Table 1, only two of them *explicitly* compared road networks in both congested and uncongested conditions:

- Anderson *et al.* (1996) compared emissions in the morning peak hour in the Hamilton metropolitan area (Canada) and found an increase in total predicted CO, HC and NO_x emissions of a factor of 1.71, 1.53 and 1.04, respectively, when uncongested conditions (all roads at free-flow speed) were compared to actual more congested conditions.
- Tobin (1979) compared total daily fuel consumption⁴ in the Milwaukee metropolitan area (USA) and found a slight reduction (4%) in predicted fuel consumption when uncongested conditions (all roads at free-flow speed) were compared to actual more congested conditions.

These two studies suggest that congestion increases emissions from traffic streams in road networks (although the effect appears to be smaller than the effect measured in some empirical studies presented in Table 2), and hence that congestion could be a significant contributor to traffic emissions and air quality problems in urban areas. However, skeptics (for instance Barth, Johnston & Tadi, 1996) have expressed concern over the claims that higher emissions in large networks are associated with congestion as they are not substantiated at the scientific level.

As will be shown later in this thesis (Chapter 3), congestion is not explicitly mentioned in the majority of emission models, despite the importance of congestion in the traffic engineering profession. This raises the question if, and to what extent, congestion is taken into account in current emission models. It also raises the question in what situations congestion actually matters in traffic emission estimation.

Given the importance of urban air quality, the dominant role of road traffic in it, and the projected increases in both travel and congestion, a thorough understanding of the relationship between congestion and air emission models is of major importance.

⁴ It has been reported that fuel consumption is correlated with emissions under normal operating conditions (An, Barth & Norbeck, 1996).

1.3 The Rationale and Research Objectives of This Study

1.3.1 The Rationale for this Research Project

Firstly, from what I have presented in this introductory chapter it is clear that there is a large amount of interest in models that predict the emission of air pollutants over a network of roadways in urban areas. This can be seen from the four pages of tables and 55 references to such models that I have just described. Secondly, congested flow conditions appear to produce significantly different emissions to those that are produced by the same vehicles moving in uncongested conditions. The fundamental question addressed by this thesis arises from the following:

- If congested flow does change the emissions of vehicles; and
- if congestion on urban road networks is common, and continuing to increase; and
- because there is a great deal of interest in using models to predict emissions over such urban road networks:

How and to what extent do models that are used to predict emissions over urban road networks include the effects of congestion on emissions?

Thus, this thesis is an exploration of the role of congestion in urban road network air pollution emission modelling.

1.3.2 The Research Approach

It will be seen that addressing this question is by no means a simple task, and one that can only partially be answered within the resource constraints of a doctoral program.

The following summarises my approach to this complex issue and the structure of this thesis:

- Firstly, as my background is in air pollution, not traffic engineering, I needed to understand how traffic engineers define and measure congestion, and, in fact, how they measure most aspects of traffic flow, because traffic flow variables are used in emission models. There is quite a gap between the traffic engineering literature and the emission modelling literature. While congestion in everyday life is easily recognised, for this thesis' purposes it needs to be quantified. Therefore, the road traffic engineering literature needs to be examined in-depth to clarify the measures of congestion and to provide unambiguous definitions of all relevant traffic terms and traffic flow variables that are related to congestion, and to air emission modelling generally. Chapter 2 presents my review of the relevant aspects of traffic engineering for this project, and attempts to put the interface between emission modelling and traffic engineering on a rigorous footing for my subsequent work.
- Next, I reviewed (Chapter 3) the air pollution literature to understand the factors that influence vehicle emissions and which of these factors are affected by congestion, and then, in detail, reviewed the construction of the various emission models for vehicles that have been developed in different parts of the world. This was a necessary base from which I could examine if, how, and to what extent, congested traffic flow conditions are included in emission model development and application. Part of this was to compare the input and output of different models and their linkage to traffic models. This review leads to my identification of three categories, or types, of emission models with respect to the way they address congestion. An additional differentiation (two groups) of models in terms of explicit or implicit consideration of congestion will be proposed and will be shown to be a critical distinction. Here, **explicit** means that the effects of congestion are modelled by variables that are related to congestion and whose values can be modified by the user. **Implicit** means that the effects of congestion are inherently considered in the model, but that level of congestion cannot be modified and is therefore beyond the control of the model user.

- Chapter 4 presents a detailed examination, to the extent that I was able to gain access to the necessary data, of selected emission models that are often used in practise for which Chapter 3 has concluded that they are not explicit models. It was, however, not possible in on the basis of literature review alone (Chapter 3), to determine if these models implicitly (or do not) incorporate congestion. Chapter 4 attempts to determine this. The chapter focuses on the driving cycle data used in the development of those emission models, and the extent to which congested conditions form a part of those driving cycles. The work in this chapter represents a further exploration of the research question and will show that it is likely that the selected models do implicitly incorporate congestion.
- After having addressed the research question, to the extent possible, in Chapters 2 to 4, I finally applied two different types of emission models, type I implicit and type II explicit, to the same real urban road network (Brisbane) in Chapter 5, as a case study. The purpose was not to investigate which model type produced better results in congested conditions⁵, but to:
 - ➔ shed light on the importance of congestion in urban network modelling; and
 - ➔ examine if the different way in which and different extent to which congestion was built into the emission models produced results that were much different in practice.

For both research objectives, direction, magnitude and location of (the differences in) emission predictions was examined. Finally, I will elaborate, by inference, on the need for further work in this field.

- The final Chapter 6 draws together the conclusions from this work.

⁵ This would have been a most desirable aim, but without appropriate secondary data being available, and the scope of a necessary primary data collection project way beyond the resources of a doctoral project, testing of predictions against measurement was not feasible.

2 THE NATURE OF CONGESTION

This chapter presents my review of the relevant aspects of the road traffic engineering literature for this project in order to:

- define congestion;
- clarify the different measures of congestion;
- provide unambiguous definitions of all relevant traffic terms;
- provide unambiguous definitions of all traffic flow variables:
 - ➔ that are related to and quantify congestion; and
 - ➔ that are used in air emission modelling generally; and
- explore the interaction between congestion, traffic flow and, in anticipation to Chapter 3, road traffic emissions.

Both traffic engineering handbooks and traffic flow theory have been explored to address these objectives. In addition, a number of relevant empirical and simulation studies were found in the literature and they are discussed as well. It is noted that important terms are underlined.

Since both traffic models and traffic field data are used in emission modelling, as was shown in Chapter 1 (Table 1), the chapter is concluded with a concise description of these models and field data. The discussion will focus on the input requirements, their output and their linkage to emission models and also provide relevant background information.

2.1 Introduction to Congestion

This section provides a general introduction to the congestion phenomenon. In anticipation of a more detailed analysis in subsequent sections, it briefly describes what congestion is (including types of congestion), what causes it and finally provides a general definition.

Generally speaking, traffic congestion results when the number of vehicles attempting to use a network or network element (e.g. road, intersection) exceeds the capacity or ability of the infrastructure to carry the load (e.g. Van Arem *et al.*, 1997). In practice, there are a variety of situations from which congestion may emerge, and these situations often work together to create or increase congestion (Wright & Huddart, 1989). For instance, congestion may be caused by (a combination of) high traffic densities, temporary reductions in normal road capacity (e.g. accidents, vehicle breakdowns, severe weather), conflicts among road users (e.g. parking manoeuvres) or among different types of traffic (e.g. trucks, pedestrians) and improper use of traffic controls. Given the variety of situations that may lead to congestion, a classification of different types of congestion is useful. Two basic types of congestion can be distinguished:

- recurring; and
- non-recurring congestion.

Recurring congestion results from traffic patterns that occur cyclically on a relatively stable and predictable basis, e.g. every weekday or weekends day (Laetz, 1990). Recurring congestion generally occurs at the same place and time due to excessive traffic volumes (due to high traffic demand), which is most obvious during morning and afternoon peak hours when a large number of people travel to and from work. In this respect, road junctions are frequently the capacity 'pinchpoints' or bottlenecks in the urban road network from where queues and congestion can form and spread (Hounsell & McDonald, 2001). In fact, signalised intersections are often the principal source of congestion along arterial roads and in urban networks (Hensher & Button, 2000).

Non-recurring congestion can result from special events such as planned roadworks, concerts and sport meetings and from unpredictable sources that occur on a random basis such as accidents, traffic signal failures, adverse weather and vehicle breakdown (e.g. Cottrell, 1998).

There are some indications that the contribution of traffic accidents to traffic congestion is substantial. A few studies report that even 40 to 65% of congestion delay is incident based (e.g. AATSE, 1997). It is noted, however, that traffic models that are used in air emission modelling generally predict the effect of recurring congestion, as will be seen later, simply because non-recurring congestion cannot be predicted or because its presence at a specific location is only temporary.

There are several effects of congestion on traffic performance. An effect of increased congestion commonly reported in the literature is an increase in travel times, and hence delays, and departure from smooth flow conditions (e.g. TRB, 1992; Austroads, 1993). Other commonly reported effects of congestion such as lower travel speeds and increased queuing (e.g. Taylor, Bonsall & Young, 2000) are all closely related to increased travel times or delay, as will be shown in this chapter.

Congestion is a regional phenomenon that is concentrated in highly urbanised and densely populated areas (Bovy & Salomon, 1999). Congestion is most evident in large urban (metropolitan) areas. Previous studies found that the most severe congestion usually occurs in the central city or CBD area and that congestion diminishes significantly from central to outer urban areas (e.g. Smeed, 1970; Newman, Kenworthy & Lyons, 1988).

The level of congestion in a network is a function of travel demand. A large demand for travel will increase the level of congestion. There is, however, substantial variability in travel demand in time and subsequently in traffic flow. This variability occurs on an hourly, daily, weekly, monthly and seasonal basis and travel demand is often strongly peaked in the morning and afternoon peak periods (Hensher & Button, 2000). As a result, the most frequently observed and greatest level of congestion usually occurs during the morning (a.m.) and afternoon (p.m.) peak periods, where the peaking pattern may be most pronounced in the morning period (Bullock *et al.*, 2003).

Now that some general aspects of congestion have been introduced (and will be discussed in more detail in subsequent sections), it is time to provide a general

definition of congestion. Relatively few publications have explicitly defined congestion, which is surprising given the importance of this phenomenon. Also, the definitions that were found in the literature reveal different interpretations of congestion. It is therefore not possible to find an exact, consistent, universally recognised and widely accepted definition of congestion in the literature, which is a notion that has also been reported by other researchers (e.g. Levinson & Lomax, 1996; Schallaböck & Petersen, 1999).

Nevertheless, congestion definitions in the literature also share common and recurring elements, which, together with the information presented in this section, can be used to construct a definition of congestion for use in this study:

Congestion is the deterioration of the quality of traffic flow (i.e. departure from smooth free-flow driving conditions) on a network element or in an entire road network due to increased travel demand and/or reduced capacity for traffic movement, which may be observed in terms of different interrelated measures including, but not limited to, increased traffic density, increased travel times, increased delays, lower travel speeds and increased queuing.

2.2 Congestion from a Traffic Engineering Perspective

In this section the traffic engineering literature, which includes traffic flow theory, is explored and used to describe the nature of traffic flow and how it is affected by the causes of congestion from both a theoretical and an empirical perspective. This section explores in more detail and defines the various traffic flow terms and variables (some of them have already been mentioned in the previous section) that have relevance towards congestion and air pollution modelling. Traffic variables that are “good” indicators of congestion will be identified. In this respect the qualification “good” refers to a variable that shows a consistent and unambiguous relationship with the level of congestion in a traffic stream.

An important notion in the traffic engineering literature is the existence of two regimes of traffic flow, namely uninterrupted and interrupted traffic flow (e.g. Gipps,

1984). This distinction arises from three main types of interaction⁶, which a vehicle may encounter when it travels on a road:

1. Interactions with the actual *road environment*, the level of which is determined by geometric design of the road, road grade, pavement condition, the character of roadside activity (land use) and speed restrictions.
2. Interactions with *other vehicles*, the level of which is determined by the total number of vehicles on the road, the proportion of heavy vehicles or other road users (e.g. bicycles) on the road, parking and turning movements.
3. Interactions with *traffic control devices at road intersections*, the level of which is determined by intersection density, type of control and, in the case of traffic signals, signal settings.

Uninterrupted traffic flow occurs in a traffic stream that is only affected by “internal” traffic stream interactions, i.e. interactions with other vehicles inside the traffic stream and (minor) interactions with the road environment. Traffic on non-urban roads such as motorways, expressways, freeways, (rural) highways and multilane suburban roads is typically uninterrupted. Hence, these roads are referred to as uninterrupted roads in this thesis. Uninterrupted flow conditions may also be observed on parts of urban roads (e.g. midblock).

Interrupted traffic flow occurs when there are also significant “external” influences on a traffic stream that cause interruptions to the flow of traffic. Interrupted traffic flow is a hallmark of urban road networks, where urban roads include (sub)arterial roads, collector roads, local roads and inner-city or central business district (CBD) roads. Hence, these roads are referred to as interrupted roads in this thesis.

⁶ It is noted that (many) other interactions may affect local traffic flow situations, such as driving style, human factors (e.g. fatigue, driving under the influence of alcohol) and adverse weather conditions. Here, the discussion is restricted to the dimensions that are considered to be the main factors by traffic engineers (TRB, 2000).

Most commonly, interrupted flow occurs at road junctions where two or more traffic streams intersect. At intersections fixed elements such as traffic signals and traffic signs cause traffic to stop periodically, often forcing vehicles in the traffic stream to decelerate (brake), idle and accelerate again. This happens irrespective of the amount of traffic.

Traffic signals are especially important since they are a major form of urban traffic control and management, which is particularly so at major intersections where large traffic volumes converge (Taylor, Bonsall & Young, 2000). It is noted that there are other (may be less obvious) manifestations of interrupted flows. For instance, compression of flow on multilane roads into a smaller number of lanes may cause interruptions.

A wealth of information is available on the many different aspects of traffic flow. Different theories and empirical studies will now be used to further explore and understand the changes in traffic flow as a result of congestion:

- **Section 2.2.1:** the basic traffic stream model is used to describe the effects of congestion on traffic flow in uninterrupted conditions.
- **Section 2.2.2:** shock wave theory is used to describe the effects of congestion on traffic flow, and the motion of individual vehicles, in interrupted conditions.
- **Section 2.2.3:** traffic performance models are used to explore quantitatively the effects of traffic demand, road capacity and signal settings on congestion on urban roads.
- **Section 2.2.4:** congestion functions are reviewed and used quantitatively to describe the effects of congestion on traffic flow on links in (large) urban road networks.
- **Section 2.2.5:** empirical studies are discussed that describe the relationships between the level of speed fluctuation and congestion.
- **Sections 2.2.6 to 2.2.8:** remaining congestion indicators are presented and discussed.

Mathematical models have been taken from various traffic flow theory textbooks and used in calculations to illustrate the characteristics of traffic flow in urban areas. For the

purpose of readability, presentation of these formulae (and their derivations) has been restricted where possible, and instead reference is made to the relevant textbooks.

2.2.1 Basic Traffic Stream Model

Figure 3 is possibly the most important diagram in macroscopic traffic flow theory. Macroscopic theory considers the performance and behaviour of a traffic stream, whereas microscopic traffic flow theory considers the motion of individual vehicles. This basic traffic stream model applies to uninterrupted flow situations in steady-state traffic conditions, and is presented in Figure 3.

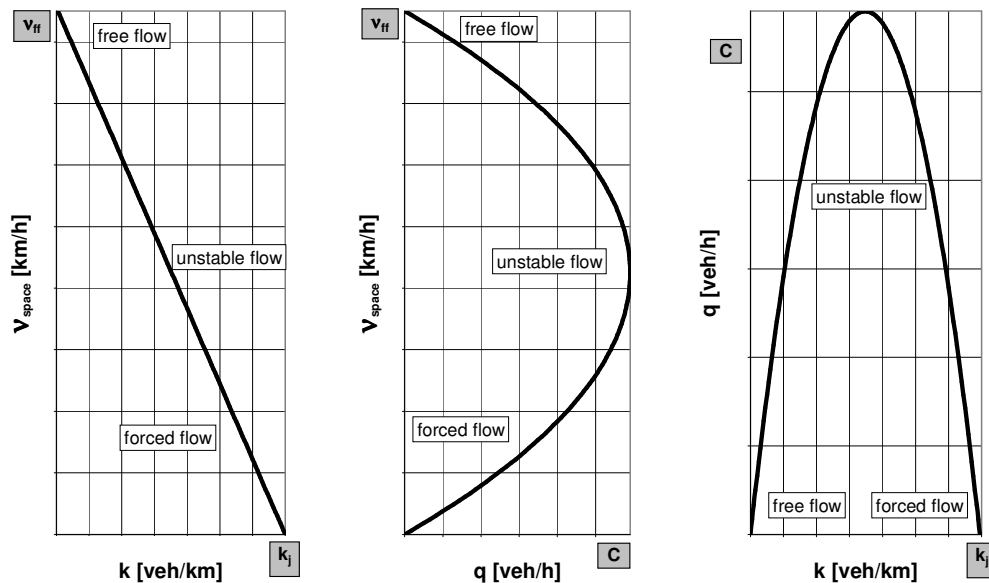


Figure 3 – Fundamental Macroscopic Relationships of Uninterrupted Traffic Flow

Figure 3 presents the theoretical relationships between the three basic traffic variables that are common descriptors of a traffic stream:

- traffic volume (V) or flow rate (q);

- average speed (\bar{v}_{space}); and
- traffic density (k).

These variables are interrelated by the following simple equation, which is commonly referred to as the “continuity of flow equation” (e.g. Lighthill & Whitlam, 1955):

$$q = k \bar{v}_{\text{space}} \quad \text{Equation 2-1}$$

In the construction of Figure 3, the linear speed-density relationship (“Greenshields’ model”) has been taken from May (1990). A continuum of traffic flow situations can be observed in Figure 3, where the actual situation depends on the level of interaction (reflecting the various degrees of constraint) that is experienced within the traffic stream on a particular section of road.

At low traffic densities, traffic conditions can be described as free-flow conditions (indicated with \bar{v}_{ff} in Figure 3, which is the mean free-flow speed, i.e. the average of the desired speeds at which vehicles travel). Drivers can choose to travel at their own preferred speeds within the restrictions of the road environment as imposed by e.g. road characteristics and speed limits.

When traffic volume increases, most vehicles still experience little or no interaction with other vehicles, although mean speed drops slightly. When traffic flow increases further, the proportion of the traffic travelling at their desired speed decreases and so does the mean speed. This is so because there are less opportunities for vehicles to overtake and speeds of most vehicles are limited by the speed of the preceding vehicle. In addition, drivers decrease their speeds as the number of cars around them increases for safety reasons (Gerlough & Huber, 1975).

When the traffic volume approaches the road capacity C (shown in Figure 3), which is the maximum volume that the road can accommodate under prevailing conditions, the traffic stream enters a transitional regime between non-congested and congested flow conditions. Near capacity, most of the traffic is unstable and strongly influenced by the vehicles around them (Bell & Lida, 1997). When density increases further, traffic flow may become extremely interacted, which results in breakdown (traffic jam) or low

speed stop-and-go conditions (Schallaböck & Petersen, 1999). These conditions with continuous change between standstill (stationary queue indicated with k_j in Figure 3, which is the maximum density or jam density) and driving at slow speed represent forced flow or congested flow conditions. This implies that the presence of queues is a good indicator of congestion.

As will be discussed in Chapter 3, speed data are important for air quality assessments since vehicle emissions are a function of speed. “Speed” specifies the distance travelled by a vehicle per unit time and typically has units of meters per second or kilometres per hour. “Speed”, however, is an ambiguous term and care is needed to clearly define it. There are two ways in which the average speed of a traffic stream can be defined:

1. time mean speed; or
2. space mean speed.

Time mean speed (\bar{v}_{time}) is the arithmetic mean of measured speeds (“spot speeds”) of all vehicles passing a fixed roadside point over a *short* measured distance L during a given time interval, i.e.:

$$\bar{v}_{\text{time}} = \sum_n \left(\frac{L}{T} \right) \div n \quad \text{Equation 2-2}$$

In this equation, T is the travel time of an individual vehicle in the traffic stream and n is the total number of vehicles sampled. Travel time is a directly measurable physical quantity and it is the time required for a vehicle to traverse distance L. T will depend on many factors such as length of road (or journey), speed limits, presence of parked vehicles, traffic composition and number of vehicles on the road.

Space mean speed (\bar{v}_{space}), which is used in the basic traffic stream model, is the arithmetic mean of the measured travel times (\bar{T}) over a short measured distance L of all vehicles passing a fixed roadside point during a given time interval, in other words distance divided by mean travel time, i.e:

$$\bar{v}_{\text{space}} = L \div \frac{\sum T}{n} = \frac{L}{\bar{T}} \quad \text{Equation 2-3}$$

It is noted that time mean speed is always greater than or equal to space mean speed. Equation 2-2 and 2-3 show that speed and travel time are (mathematically) related and can be expressed as a function of each other.

Traffic volume (V) or flow rate (q), commonly expressed as veh/h or veh/h.lane, are two measures that quantify the amount of traffic passing a point on a road or lane⁷ during a given time interval. Traffic volume is an important traffic variable for air quality assessments as total emissions are a direct function of the number of vehicles that pass over a (section of) of road. In fact, vehicle kilometres travelled (VKT) is the traffic variable that is commonly needed for emission estimation. This variable is derived from traffic volume and road length data, as will be seen later (refer to Equation 2-31, page 66).

Traffic density (k), commonly expressed as veh/km or veh/km.lane, quantifies the number of vehicles located in a given length of roadway or lane averaged over time. Traffic density is related to percent occupancy and can be estimated by (May, 1990):

$$k = \frac{0.19 \Omega}{L_{\text{veh}} + L_{\text{det}}} \quad \text{Equation 2-4}$$

where L_{veh} is the average vehicle length (m), L_{det} is the detection zone length (m) and Ω is percent occupancy time (%). Ω is defined as the percent of time a point or a short section of roadway is occupied, which may vary from 0% (absence of vehicles) to 100% (vehicle completely stopped over a point or short section of roadway).

As is obvious from Figure 3, a low traffic volume can indicate the occurrence of either a stationary traffic jam or free-flow conditions. In contrast, traffic density provides

⁷ A traffic lane is defined as that portion of a carriageway used for the passage of a single stream of vehicles.

a specific indication of flow conditions in terms of speed and volume. Density is therefore a good indicator of congestion, whereas traffic volume is not.

It is noted that the precise shapes of the three diagrams on a given road segment depend on various factors such as speed limit, number and width of lanes, weather, traffic composition, etc. (Hensher & Button, 2000). Furthermore, Figure 3 is a coarse and simplified approximation of empirical evidence. In fact, the characteristic shape of these curves is sometimes difficult to observe in real data plots, particularly with respect to forced flow conditions (Papageorgiou, 1998; Wright & Lupton, 2001). Despite this, the basic traffic stream model illustrates that a continuum of traffic flow situations exists and shows the important and fundamental effect on mean speed and volume when density increases in uninterrupted conditions.

Although the basic traffic stream model specifically applies to uninterrupted conditions, the basic shapes of the fundamental relationships are still observed in interrupted conditions, if space mean speed is replaced with mean running speed, as was shown by Dick (1966). Mean running speed (\bar{v}_{run}) is defined as the average speed when vehicles are moving. In other words, it is the overall speed between two points excluding stopped time, i.e.:

$$\bar{v}_{run} = \frac{L}{\bar{T} - \bar{T}_{idle}} \quad \text{Equation 2-5}$$

Here, \bar{T}_{idle} is the average stopped time. Mean stopped time is the average time vehicles remain stationary (idle) during travel on a section of road or journey. It will be seen in section 2.2.4 that the basic shape of fundamental relationship between speed and volume (albeit with a different definition of traffic volume) also holds when speed is taken as the mean travel speed.

2.2.2 Shock Wave Theory

Shock wave theory is an important tool in the analysis of traffic flow and traffic performance. It is particularly useful to predict queue variables at bottlenecks⁸. Queues essentially are a stationary or moving chain of excess vehicles that are temporarily stored upstream of a bottleneck and whose departures are delayed to a later time period.

Shock wave theory is used in this section to illustrate the concept of traffic flow through signalised intersections and the effects of increased traffic demand (one of the causes of congestion) on measures of traffic performance⁹. It is noted on beforehand that shock wave theory can also be applied to other kinds of bottlenecks such as lane drops and merge areas on freeways, toll plazas, slow-moving vehicles, etc. (e.g. May, 1990), but, given the importance of signalised intersections with respect to congestion in urban networks, a signalised intersection has been selected to illustrate the theory.

Shock wave theory was introduced by Lighthill and Whitham (1955). The theory considers that a specific state of density, speed and flow may change in time and space. When these changes of state occur, a disturbance in flow conditions is established that demarks the time-space domain of one state to another. This boundary or “flow discontinuity” is transmitted in space and time in the form of a kinematic shock wave.

Shock wave analysis requires a basic traffic stream model, which was discussed in the previous section, and a specified flow state of the traffic stream approaching the bottleneck. To illustrate this concept, Figure 4 (next page) shows a distance-time (x-t) diagram at a one-lane intersection approach and a fundamental flow-density diagram.

It is noted on beforehand that Figure 4 specifically applies to unsaturated traffic flow conditions. Unsaturated means that traffic demand in each signal cycle does not exceed intersection capacity. Traffic demand is defined as the number of vehicles that would pass a point in the road network without the presence of capacity constraint.

⁸ Bottlenecks are site-specific constrictions on road capacity where queues form once traffic volume exceeds capacity.

⁹ It is noted that queuing theory could have been used as an alternative (Berka & Boyce, 1994). However, shock wave theory has the advantage that it can be readily used to graphically show the (simplified) microscopic movement of vehicles in time and space. Moreover, queuing theory forms the basis of traffic performance models that are discussed in the next section.

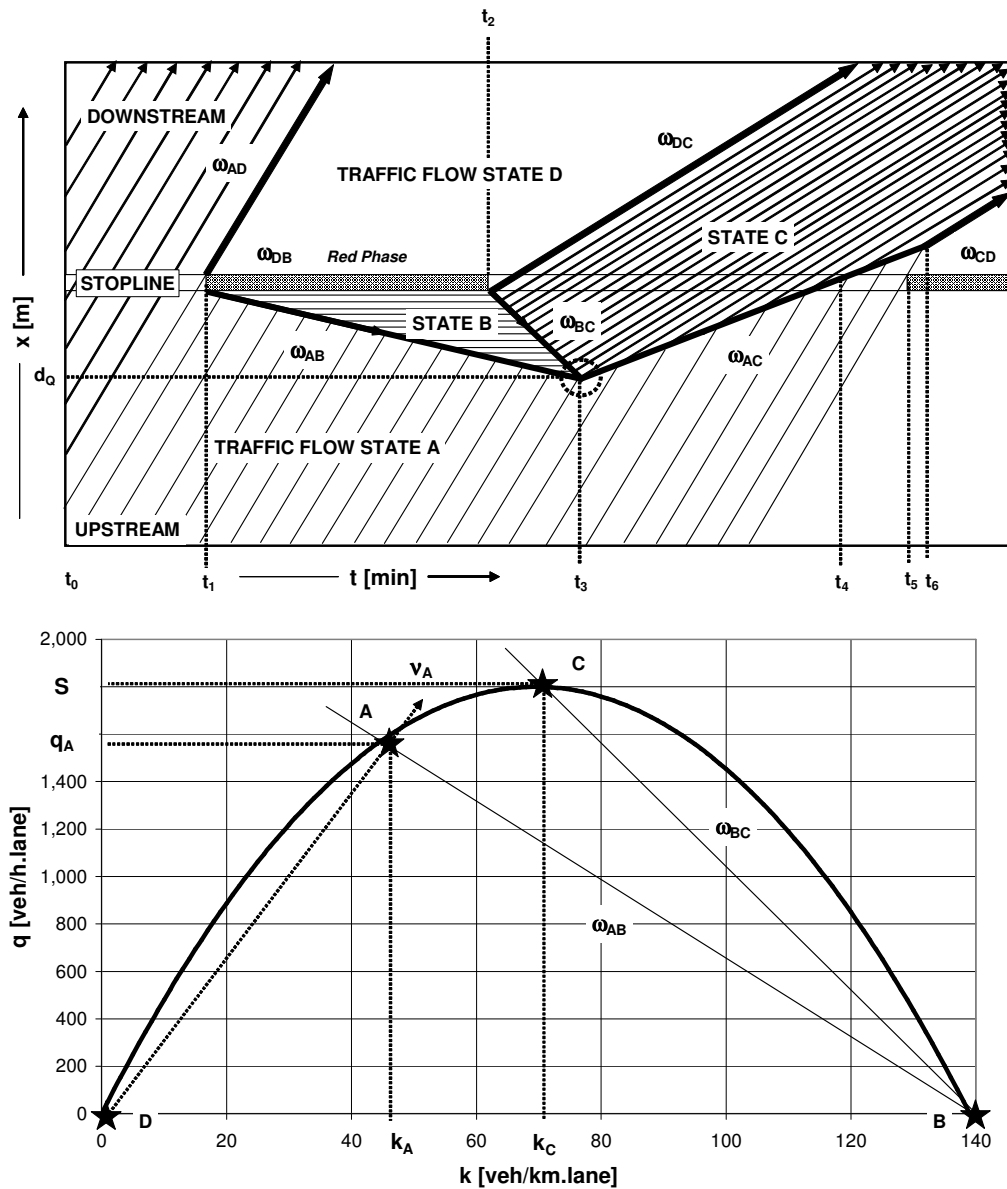


Figure 4 – Shock waves at an Unsaturated Signalled Intersection

In the distance-time diagram, the thin arrows represent vehicle trajectories and the thick arrows represent shock waves. A vehicle trajectory represents the movement of a vehicle in a traffic stream in space and time. The slope of the arrows ($\partial x/\partial t$) represent the speed of a vehicle or a shock wave. The stop line on the intersection approach is

shown with a traffic signal band that indicates either a green phase (light strip) or red phase (dark strip).

During t_0 and t_1 the signal is green and traffic proceeds uninterrupted under traffic flow state A upstream and downstream of the intersection. Traffic flow state A is characterised by flow rate q_A (veh/h.lane), space mean speed v_A (km/h) and density k_A (veh/km.lane), which can be seen in the flow-density diagram. In Figure 4, traffic demand is equivalent to q_A .

At time t_1 , the signal changes to red and the flow immediately upstream of the stop line changes to flow state B, which represents standing queue conditions (traffic jam) with zero speed. At the same time, the flow downstream of the stop line changes to flow state D, which demarks a space unoccupied by vehicles. It is noted that the length of time an individual vehicle idles is represented by the length of the horizontal line in Figure 4. Clearly, the first vehicle that arrives when the signal changes to red has to idle for the longest time (equal to the red time). Shock wave theory dictates that the speed of the shock wave (ω , km/h) is equal to the change in flow divided by the change in density:

$$\omega = \frac{\Delta q}{\Delta k} \quad \text{Equation 2-6}$$

Hence, the speed of the shock wave is equal to the slope of the line that connects the two points in the basic traffic stream model that define the two traffic flow situations. It is noted that vehicle speeds are equal to the slope of the line that connects the origin to current traffic flow state. When ω is positive, zero or negative, the shock wave is called a forward-moving, stationary or backward-moving shock wave, respectively. Three shock waves start at time t_1 at the stop line:

- a forward moving shock wave (ω_{AD});
- a frontal stationary shock wave (ω_{DB}); and
- a backward moving shock wave (ω_{AB}).

ω_{AB} represents the movement of the *end of the queue* in space and time. Hence, queue length at time t_x is equal to the vertical distance between the stop line and ω_{AB} at time t_x . A new flow state C is introduced at the stop line at t_2 when the signal changes to green. At t_2 the flow at the stop line increases from zero flow to saturation flow (S). S is the maximum flow rate achieved by vehicles departing from a queue during the green period under prevailing conditions. This causes two new shock waves ω_{DC} and ω_{BC} , while ω_{DB} is terminated.

The movement of the *head of the queue* through space and time is represented by ω_{BC} . The shock waves ω_{AB} and ω_{BC} move backwards in space, intercept at a certain distance behind the stop line and are terminated. This point of interception in space defines the furthest point from the stop line where vehicles queue and the point in time (t_3) at which the queue dissipates.

At time t_3 , a new forward moving shock wave (ω_{AC}) is formed. At time t_4 , the forward moving shock wave ω_{AC} crosses the stop line and the flow at the stop line changes from a saturation flow (S) to arrival flow rate q_A . At time t_5 , the red phase starts again and the shock wave pattern upstream of the traffic signal begins to repeat itself. No vehicle has to wait longer than one signal cycle.

It is noted that the shock wave pattern downstream of the signal deviates from the earlier pattern. Although ω_{AD} is again formed at the beginning of red, it travels downstream only until it intercepts shock wave ω_{AC} at time t_6 , after which both shock waves are terminated and a new shock wave is ω_{CD} formed.

As long as the traffic demand and signal settings remain unchanged, the shock wave pattern will repeat itself every signal cycle¹⁰. At the start of any particular cycle, there is no queue left from any previous cycles (overflow queue), which makes the growth and decay of queues periodical and independent of time.

A number of important observations can be made from all this. Firstly, congestion, which, in this case, is caused by a temporary reduction in road capacity due to a red signal, changes the (individual) trajectories of vehicles in a traffic stream.

¹⁰ It is noted that this is not the case for modern vehicle actuated (and coordinated) traffic signals, where signal settings will vary from cycle to cycle in response to demand (e.g. TRB, 2000).

These changes can be quite large, for instance when vehicles arrive at the back of the queue and vehicle speed drops to zero (i.e. a change from moving to idle conditions).

Similarly, but less dramatic, when vehicles reach a cluster of traffic of high density and lower speed (moving queue), vehicle speeds are adjusted to this lower speed. Traffic density clearly affects individual vehicle speeds, which is line with the effect on average space mean speed of a traffic stream, as was shown in the basic traffic stream model.

Secondly, any changes in signal settings (e.g. a shorter or longer green phase) or the flow state of the approaching traffic stream (i.e. a higher or lower traffic demand) would impose a change in the x-t diagram and would thus change the proportion of time vehicles would spend in the different states of traffic flow. For instance, a longer red phase would force vehicles to wait longer before they can proceed and, in addition, more vehicles would be affected by queuing since the queuing triangle B would become larger. This is illustrated by applying shock wave in more congested saturated conditions, i.e. when traffic demand exceeds intersection capacity.

In this situation queues cannot be completely discharged during the green time period. As a result, queue length grows in time and some vehicles may have to queue over subsequent cycles, depending on the period of time that saturated conditions exist. This is because the portion of the queue that is not discharged in one cycle is carried over to the next cycle (overflow queue). Under these circumstances the growth in queuing area B is dependent on the time period that saturated conditions exist. Figure 5 shows shock waves and flow states over subsequent signal cycles in saturated conditions.

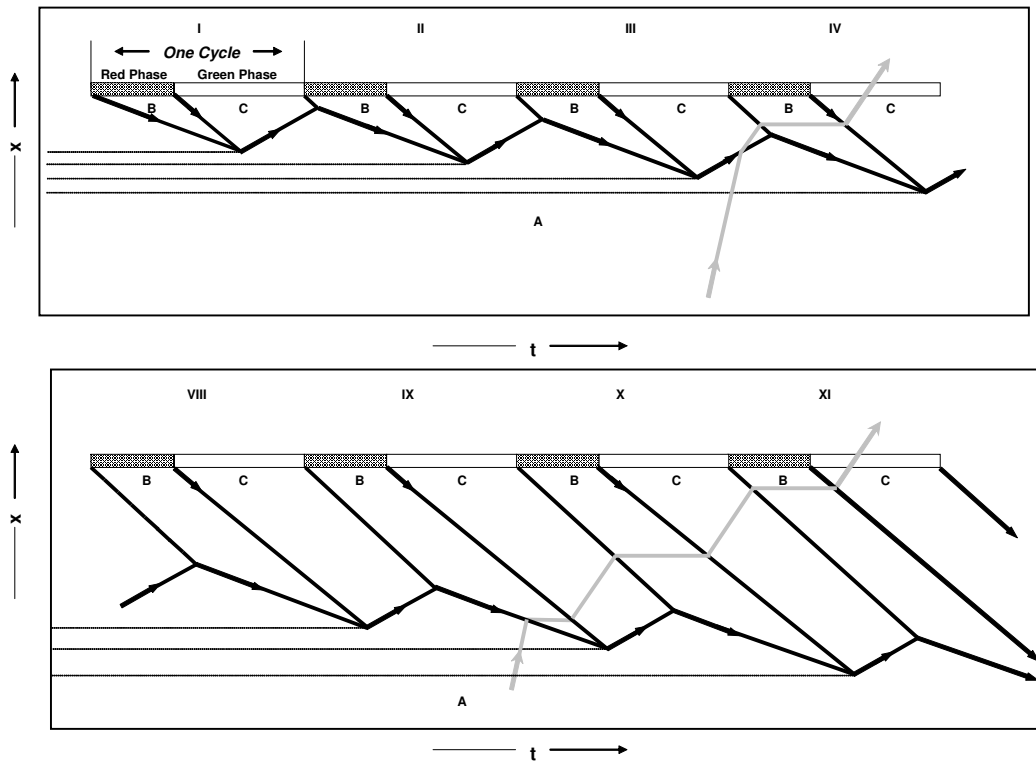


Figure 5 – Shock waves in Saturated Conditions

Cycle I is the first cycle in saturated conditions, followed by the next saturated cycle II, and so forth. From an emissions perspective, the size of queuing area B is important because it shows the location where vehicle idle (are stopped) and the proportion of time vehicles idle. Idling results in increased emissions, expressed as mass of pollutant emitted per unit distance, simply because the vehicle is not moving towards its destination, but is still emitting. Idling emissions can thus be regarded as excess emissions.

Although shock wave theory is based on the simplifying assumption of physically impossible instantaneous speed changes (and hence does not consider acceleration and deceleration patterns that occur in the real world), it can be perceived that queuing area B also approximately shows where vehicles are decelerating from and accelerating to cruise speed. As will be seen later, these driving modes are important with respect to emissions. A large queuing area B implies that a larger number of

vehicles go through deceleration-idle-acceleration sequences, which will affect the total emission level from a traffic stream.

A few vehicle trajectories (grey arrows) are included in Figure 5, showing a vehicle going through the different flow states in time. It can be seen that if saturated conditions extend over a large enough number of cycles, vehicles have to move through the queue over several cycles before they can cross the stop line. All vehicles now experience several stops and periods of idling, instead of none or only one as was the case in unsaturated conditions. It is clear that a change in traffic demand or capacity affects the vehicle trajectories of individual vehicles.

Finally, it is noted that shockwave theory is based on a number of simplifying assumptions that would affect its accuracy (i.e. how close a prediction is to the true value). For instance, all vehicles are considered through traffic (i.e. no turning), to arrive uniformly and to travel at exactly the same speed. Also, the examples discussed in this section apply to relatively simple isolated fixed-time traffic signals. In reality, however, advanced traffic control systems such as SCATS, BLISS and TRACS are in use in Australian cities (Ogden & Taylor, 1996). These systems use coordinated signal technology with dynamic control, in which the control system continually adapts the traffic signal settings (within predetermined ranges) in response to traffic activity in different parts of the network (AATSE, 1997). Nevertheless, shockwave theory is useful for the purpose for which it was used in this section, i.e. to illustrate the concept of traffic flow and individual vehicle movement on an urban road with a signalised intersection.

2.2.3 Traffic Performance Models

Traffic performance models for both interrupted and uninterrupted flow conditions are explored in this section to gain insight into the traffic flow variables that are commonly used by traffic engineers to quantify the effects of congestion. The mathematical models presented in this section are used in computations to illustrate the effect of changes in traffic demand and capacity (signal settings) on traffic performance.

Traffic performance models are an important practical tool in the analysis of intersection operation. Several analytical models have been developed in time to estimate average vehicle delay at (isolated fixed time) signalised intersections as a function of traffic demand and signal settings (e.g. Webster, 1958; Webster & Cobbe, 1966; Miller, 1978).

This section is confined mainly to a discussion of a set of performance models that are currently used. These models emerged from much of the earlier work. The equations were developed using both deterministic queuing theory for saturated conditions and a steady-state expression for unsaturated conditions (Miller, 1963), the latter which showed good agreement with field observations. The models are incorporated in the SIDRA (Signalised Intersection Design and Research Aid) model (Akçelik, 1980; Akçelik, 1981; ARRB, 1990), which is widely used by traffic engineers for intersection performance analysis in Australia and overseas.

It is noted that there are strong similarities with other current performance models, such as used in the US Highway Capacity Manual (TRB, 2000), which is a standard guide in the field of traffic engineering all over the world, and as used in the network model TRANSYT, which is widely used for signal optimisation (e.g. Robertson, Wilson & Kemp, 1996). Also, performance models used for *unsignalised* intersections (sign-controlled, roundabouts) show strong similarities with the models presented in this section (e.g. Berka & Boyce, 1994; Akçelik & Troutbeck, 1991; Akçelik, Christensen & Chung, 1998). Thus, the use of other models than SIDRA would have generated similar insights.

The Performance Models

Four different measures of traffic performance are predicted by SIDRA:

- delay;
- queue length (interrupted flow);
- density (uninterrupted flow); and
- number of stops.

Since these measures are a function of the principal causes of congestion, i.e. high traffic demand and/or low capacity, as will be seen later, they are also indicators of congestion. A congestion indicator is defined as a variable that has explanatory power towards a traffic congestion response.

Delay, which is expressed as either total (traffic stream) delay (D) or average vehicle delay (\bar{d}), is defined as the difference between “delayed” and “undelayed” (i.e. steady-state cruise) travel time and it includes:

- delay due to deceleration from and acceleration to cruise speed;
- queue move-up manoeuvres (stop-go-stop); and
- stopped time (idle).

Queue length at the intersection (\bar{Q}_{int}) provides information on the maximum space occupied by the queuing process (“maximum back of queue”) where vehicles spent time idling. Density describes the proximity of vehicles to one another and reflects the freedom and ability to manoeuvre within the traffic stream (level of interaction).

Finally, number of stops provides information on the average (n_s) and total (N_s) number of “d-i-a” (deceleration-idle-acceleration) or stop-start manoeuvres that are conducted in the traffic stream. It is noted that, by definition, number of stops is zero in uninterrupted conditions, although under traffic jam conditions all vehicles will practically stop.

All these variables also have relevance with respect to air quality assessments since emissions are a function of idle time, speed and speed fluctuation, as will be seen in subsequent chapters, which are (indirectly) reflected in the four measures.

Mean intersection delay (\bar{d}_{int} , s/veh) is computed as the sum of two delay terms:

$$\bar{d}_{int} = \bar{d}_{un} + \bar{d}_{of} = \frac{0.5c(1-g)^2}{1-\phi g} + \frac{3600 \bar{Q}_{of}}{C} \quad \text{Equation 2-7}$$

Here, \bar{d}_{un} is the average uniform delay, which is the delay due to regular arrivals in unsaturated conditions. \bar{d}_{of} is the average overflow delay, which is the additional delay due to 1) saturated conditions and 2) random arrivals in unsaturated conditions. Random arrivals in unsaturated conditions cause some signal cycles to be saturated, which results in temporary overflow queues.

In Equation 2-7, c represents the cycle time (s), which is the period of time that is required for one complete sequence of signal phases. A signal phase is a state of signal during which one or more movements receive right of way. A movement is defined as an approach to the intersection that is characterised by its direction, lane usage and right of way provision (Akçelik, 1981). The effective green time ratio g is defined as the ratio of g^* to c . Here, effective green time (g^* , s) is equivalent to the displayed green time, which is adjusted for the effects of start loss (i.e. time loss due to vehicles accelerating to saturation speed) and end gain (i.e. time gain due to yellow signal), as will be shown in Chapter 5.

The volume-to-capacity ratio ϕ^{11} is defined as the ratio of arrival flow rate q_a to capacity (C), i.e.:

$$\phi = \frac{q_a}{C} \quad \text{Equation 2-8}$$

¹¹ Also referred to as degree of saturation.

In this case C represents the intersection capacity, which is determined by the maximum flow rate (S) and signal settings (g):

$$C = S g$$

Equation 2-9

The volume-to-capacity ratio is a good congestion indicator, since it combines the two principal causes of congestion (traffic demand and capacity, thus indirectly signal settings) into one variable. Because of the wide availability of volume and capacity figures for network links and widespread acceptance by most transport agencies, ϕ has been widely used as a fundamental congestion indicator (e.g. Berry, 1987; BTCE, 1996).

There is a difference in definition of traffic volume used in the basic traffic stream model and in traffic performance models (Akçelik, 1996). In the basic traffic stream model, volume represents the traffic flow rate measured at a certain reference point along the road. This volume is measured, for instance, with loop detectors, and it cannot exceed the capacity of the road at this point. In traffic performance models (and also in congestion functions for that matter, which are discussed in the next section) volume represents the *demand* flow rate, which presents the input to a link that would exist without capacity constraint. Demand flow rate can exceed bottleneck or (critical) road capacity.

For this research, we are interested in the speed-flow relationship that is measured over a section of road because this corresponds best to the average travel speed that is used to predict emission factors. This means that when ϕ is used as a congestion indicator, care is needed to ensure that the V (or q) and C values represent the appropriate parameters, i.e.:

- Volume should represent the demand flow rate and not the measured flow rate at a point. Traffic models predict travel demand (as will be seen later), and thus the correct flow rate.
- Capacity should be the “bottleneck” capacity, which is intersection capacity in most cases and not mid-block capacity.

However, the use of demand flow rate in emission modelling may also introduce errors in emission prediction. This issue is discussed further in section 2.5.1. Mean overflow delay is a function of the mean overflow queue (\bar{Q}_{of} , veh), which is the average number of vehicles left in the queue at the end of the green period.

$$\bar{Q}_{of} = 0.25 C \tau \left\{ (\phi - 1) + \sqrt{(\phi - 1)^2 + \frac{12(\phi - \phi_0)}{\tau C}} \right\} \quad \text{Equation 2-10}$$

for $\phi > \phi_0$ (zero otherwise)

$$\phi_0 = 0.67 + 0.001667 S g^* \quad \text{Equation 2-11}$$

Here, τ is the observation period (h) and ϕ_0 is the degree of saturation below which the mean overflow queue is approximately zero. Total intersection delay of a traffic stream (D_{int}) is simply calculated as the product of τ , q_a and \bar{d}_{int} .

Queue length (veh) is computed as the sum of uniform queue and overflow queue:

$$\bar{Q}_{int} = \bar{Q}_{un} + \bar{Q}_{of} = \frac{q_a r^*}{3600 \left(1 - \frac{q_a}{S} \right)} + \bar{Q}_{of} \quad \text{Equation 2-12}$$

Here, r^* is the effective red time, which is equivalent to c minus g^* . The average number of stops per vehicle (n_s , veh^{-1}) is calculated by:

$$n_s = 0.9 (n_{s,un} + n_{s,of}) = 0.9 \left(\frac{1-g}{1-\phi g} + \frac{\bar{Q}_{of}}{c q_a} \right) \quad \text{Equation 2-13}$$

$n_{s,un}$ is uniform stop rate (major stop-start manoeuvre) and $n_{s,of}$ is multiple stops in queue (queue move-up stops). The total number of stops in a traffic stream per unit time (N_s, h^{-1}) is calculated as the product of n_s and q_a .

Mean delay in *uninterrupted* conditions, i.e. cruise delay ($\bar{d}_c, s/veh$), is a function of road length (L) and the degree of saturation and computed by:

$$\bar{d}_c = 720L\tau \left\{ (\phi - 1) + \sqrt{(\phi - 1)^2 + \frac{4\phi}{\tau C}} \right\} \quad \text{Equation 2-14}$$

Here, C represents *midblock* capacity, which may be taken to be equivalent to S (ARRB, 1990) and here ϕ represents the ratio of volume to the capacity of the *midblock* section of road. Finally, average traffic density k (veh/km) is computed by:

$$k = \frac{q_a (\bar{T}_{ff} + \bar{d}_c)}{3600 L} \quad \text{Equation 2-15}$$

Here, \bar{T}_{ff} is the average free-flow travel time.

The Effects of the Principal Causes of Congestion on the Quality of Traffic Flow

Now that all performance models have been presented it is clear that traffic engineers only use a limited number of variables in the computation of the traffic performance measures. They can be summarized as:

- traffic demand (q_a);
- capacity (C);
- signal setting variables (c, g^* , r^*); and
- road and intersection characteristics (S, L, \bar{T}_{ff}).

The analytical models can now be used to investigate the effects of increasing traffic demand and reduced capacity (the principal causes of congestion), which both are combined into the variable ϕ , on traffic performance measures. Figure 6 shows the relationships between ϕ (using intersection capacity) versus delay and number of stops. The relationships were computed assuming $g^* = 80$ s, $c = 100$ s, $S = 1800$ veh/h.lane, $L = 1$ km, $\bar{T}_{ff} = 60$ s, and $\tau = 1$ h.

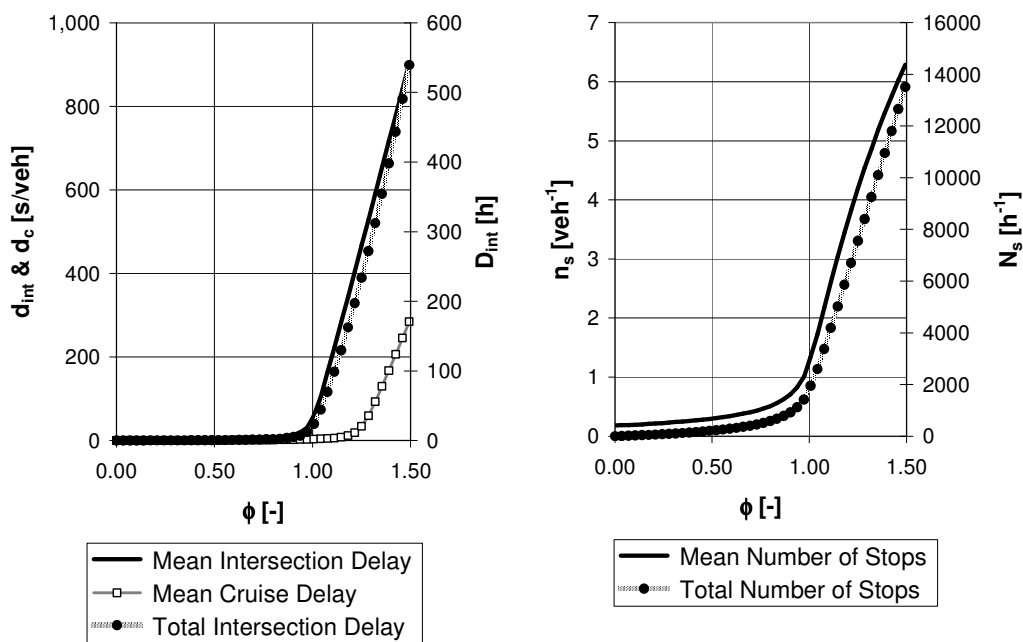


Figure 6 – Congestion Relationships (Delay & Number of Stops) on Urban Roads using Traffic Performance Models

Figure 6 shows that the quality of traffic flow is hardly affected by increasing traffic demand or decreasing capacity, as long as volume-to-capacity ratio remains slightly below unity (unsaturated conditions). However, once demand approaches or exceeds capacity (i.e. saturated conditions, $\phi > 1$), the quality of traffic flow quickly deteriorates in quite a dramatic fashion. This is evident from the step increase in the congestion indicators delay and number of stops.

One interesting aspect of Figure 6 is the relatively small value of uninterrupted (midblock) cruise delay compared to interrupted (intersection) delay. As a result, the

relative contribution of cruise delay to total link delay (i.e. the sum of total intersection and total cruise delay) is minor as well.

In addition to differences in delay models, this can be explained by the larger capacity of midblock sections of road when compared to intersections. For instance, in the computations that led to the construction of Figure 6, intersection capacity is equal to 80% (i.e. 100 g) of midblock capacity. As a consequence, saturated conditions on the midblock section are only reached when the intersection is already significantly oversaturated. Thus, the strong deterioration of midblock traffic flow conditions starts at a higher level of traffic demand, which can be seen in Figure 6.

The relative contribution of cruise delay to total link delay would have been larger when a longer link length and larger effective green time were used in the computations. It is noted, however, that the values used in the construction of Figure 6 are conservative in this respect. For instance, 96% of the urban links in the Brisbane network that is used in Chapter 5 are equal to or shorter than 1 km, whereas 97% of the urban links have an effective green time ratio equal to or less than 0.80.

It is concluded that, on the basis of computations using traffic performance models, delay at intersections, and not vehicle interactions, would generally dominate overall delay along urban roads. This finding is consistent with the literature (e.g. Beard & McLean, 1974, TTI, 1993).

Figure 7 shows the computed relationships between ϕ versus intersection queue length and mean traffic density at midblock location.

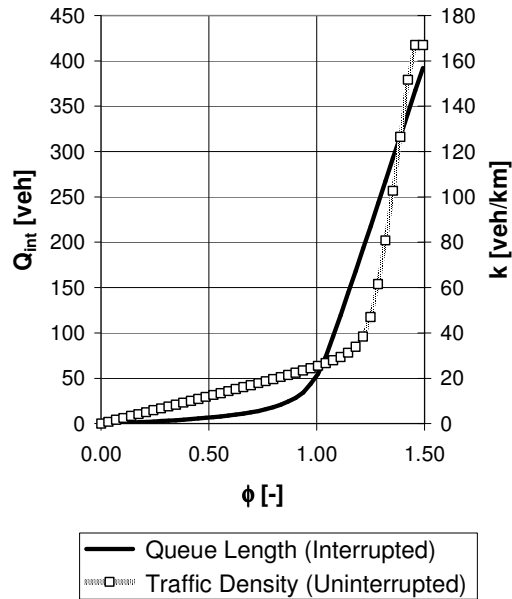


Figure 7 – Congestion Relationships (Queue Length & Density) on Urban Roads using Traffic Performance Models

Again, the strong non-linear deterioration in traffic performance is observed in terms of queue length when traffic demand approaches and exceeds intersection capacity. Traffic density linearly increases with ϕ , due to increasing traffic demand, up to the point where the midblock section becomes saturated ($\phi = 1.25$), after which density quickly increases until jam density is reached. This strong increase is due to the strong increase in cruise delay as was seen in Figure 6.

Finally, the performance models lend themselves for illustration of the effects of signal settings on congestion (delay). Figure 8 shows the effect of signal settings in terms of cycle time and effective green time ratio at two volume-to-capacity ratios (0.0 and 1.0).

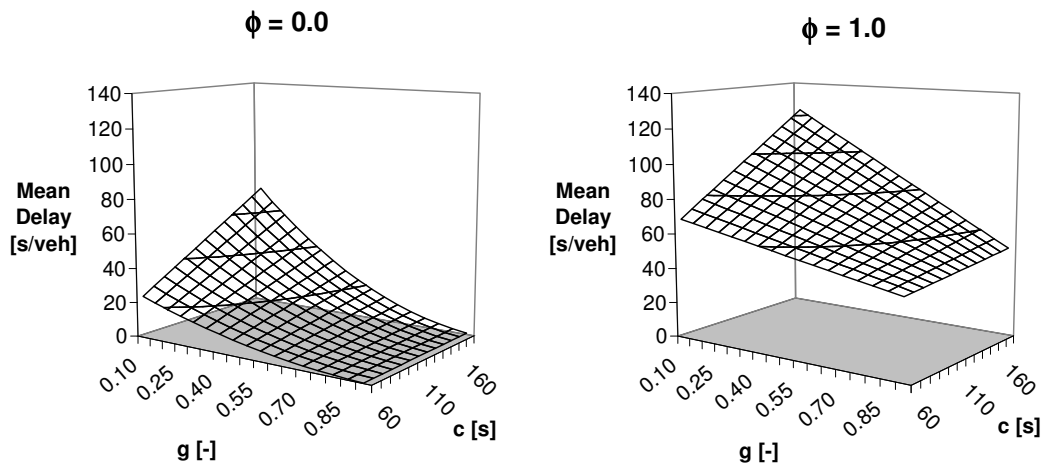


Figure 8 – Relationship Between Congestion and Signal Settings

It is obvious that mean vehicle delay is very sensitive to these signal characteristics, and in particular to the effective green time ratio, which can increase mean vehicle delay by a factor of up to 2.4 over its range of values. Cycle time has a small effect on mean delay at values of g above 0.80, but then an increasingly larger influence up to a factor of 1.8 at low g values.

2.2.4 Congestion Functions

As will be seen in Chapter 3, link travel speeds play a crucial role in the estimation of emissions in urban networks. In this respect, congestion functions¹² are important because they are commonly used to predict link travel speeds in large urban road networks. In this study the term “travel speed” will be frequently used. The travel speed

¹² It is noted that various other names are used in practice such as travel time functions, link capacity functions and link cost functions.

of an individual vehicle (v) is defined as the overall speed between two points, including all delays, and is computed by:

$$v = \frac{L}{T} \quad \text{Equation 2-16}$$

Here, T (h) is overall travel time and L (km) represents any traversed distance, which may vary between a short section of road to a complete journey. Average travel speed of a traffic stream (\bar{v}) is then computed using average travel time \bar{T} (e.g. TTI, 1993):

$$\bar{v} = \frac{L}{\bar{T}} \quad \text{Equation 2-17}$$

Hence, by definition average travel speed is equivalent to space mean speed (Equation 2-3, p. 28). However, in this dissertation \bar{v}_{space} and \bar{v} are explicitly used as two different terms. This is done to recognise the different spatial and temporal resolution at which travel time data are obtained. Whereas space mean speed is based on travel time data collected at a fixed roadside *point* over a short measured distance (say up to 30 m), mean travel speed is based on travel time data collected over a longer stretch of road (e.g. a road link) or even over an entire journey.

Extrapolation of point-based space mean speeds to longer sections of road inherently assumes that traffic conditions remain the same for the section of road under consideration (i.e. road section is uniform), which may or may not be a valid assumption depending on the circumstances. It is, for instance, not difficult to conceive that space mean speed measured at a midblock location would deviate substantially from travel speed measured over a longer stretch of road that includes delay experienced at a signalised intersection. In this respect, it is noted that average travel speed can also be expressed in terms of mean free-flow travel time and mean delay:

$$\bar{v} = \frac{L}{(\bar{T}_{ff} + \bar{d})}$$

Equation 2-18

Equation 2-18 shows that for a particular road, where L and \bar{T}_{ff} may be taken as constants, mean travel speed is purely a function of mean congestion delay \bar{d} (s/veh), which is defined as additional travel time due to interactions with other vehicles and traffic control devices (TRB, 2000).

Congestion functions are mathematical relationships between mean unit travel time \bar{T}^* (min/km), which is the reciprocal of \bar{v} , and traffic conditions. Their development goes a long way back (e.g. Walker, 1956; Campbell, Keefer & Adams, 1959) and they have evolved in time. Different congestion functions have been used in practice. An overview of congestion functions that have been widely used in urban network modelling or have been developed over the last few decades or so is presented in Table 3.

Table 3 – Overview of Congestion Functions

Year of Development	Name	Analytical Model(s)	Reference(s)	Remarks
1964	BPR ¹³ (or FHWA ¹⁴) function	$\bar{T}^* = \bar{T}_{ff}^* \left\{ 1 + 0.15 (1.33 \phi)^4 \right\}$	Spiess, 1990; Tisato, 1991; Dowling & Skabardonis, 1992	One of the best-known and most commonly used congestion function in the US, Europe and Australia
1966	Davidson Function	$\bar{T}^* = \bar{T}_{zf}^* \left\{ 1 + \left(\frac{J_D \phi}{1 - \phi} \right) \right\}$	Davidson, 1966; Potts, 1966; Golding, 1977; Akçelik, 1978a; 1978b Taylor, 1977; Akçelik, 1991	The function is based on the concepts of steady-state stochastic queuing theory and hence gives only realistic results when $\phi \ll 1$
1991	Modified Davidson Function	$\bar{T}^* = \bar{T}_{zf}^* \left(\frac{1 - (1 - J_D) \phi_c}{1 - \phi_c} \right) + 30 \tau (\phi - \phi_c)$	Tisato, 1991	The function based on consideration of deterministic traffic flow theory and applies to cases where or $\phi > \phi_c$
1991	Akçelik Function	$\bar{T}^* = \bar{T}_{zf}^* + 0.25 \tau \left\{ (\phi - 1) + \sqrt{(\phi - 1)^2 + \frac{8 J_A \phi}{\tau C}} \right\}$	Akçelik, 1991	Function arose from earlier work on traffic performance models (refer to section 2.2.3)

\bar{T}_{ff}^* = free-flow unit travel time (min/km), ϕ = volume-to-capacity ratio (-), \bar{T}_{zf}^* = minimum unit travel time under zero-flow conditions (min/km), J_D = Davidson delay parameter (-), ϕ_c = critical volume-to-capacity ratio (-), τ = time period over which flow exceeds capacity (min), J_A = Akçelik delay parameter, C = road capacity (veh/h)

¹³ Bureau of Public Roads

¹⁴ Federal Highway Administration

Table 3 (continued) – Overview of Congestion Functions

Year of Development	Name	Analytical Model(s)	Reference(s)	Remarks
1992	“Updated” BPR function	$\bar{T}^* = \bar{T}_{zf}^* \left\{ 1 + 0.05 \phi^{10} \right\}$ $\bar{T}_{zf}^* = \bar{T}_{ff}^* + (\phi \bar{d}_{un} PF)$	Dowling & Skabardonis, 1992; Skabardonis & Dowling, 1997; Dowling, Singh & Cheng, 1998	Update of original BPR function for predictions in non-freeway conditions
1992	Post-processor Function	$\bar{T}^* = \frac{\bar{T}_q^* \bar{Q} + \bar{T}_{bpr10}^* (L - \bar{Q})}{L}$ $\bar{T}_q^* = \frac{60 k_j}{C} \quad \bar{T}_{bpr.10}^* = \bar{T}_{ff}^* \left\{ 1 + 0.15 \phi^{10} \right\}$ $\bar{Q} = \text{MAX} \left\{ 0, \frac{\bar{Q}_{initial} + (q_a - C) \tau \times 1000}{2 k_j} \right\}$	Dowling & Skabardonis, 1992	Set of functions ¹⁵ developed with the specific aim to improve the analysis of air quality impacts of new highway projects in the US. Queue length is computed using deterministic queuing theory for saturated conditions. The functions are subject to $\bar{Q} \leq L$, otherwise $\bar{T}^* = \bar{T}_q^*$

\bar{T}_{ff}^* = free-flow unit travel time (min/km), ϕ = volume-to-capacity ratio (-), \bar{T}_{zf}^* = minimum unit travel time under zero-flow conditions (min/km), ϕ = intersection density (signals/km), \bar{d}_{un} = average uniform intersection delay (s, refer to Equation 2-7), PF = traffic progression factor (-), \bar{T}_q^* = mean unit travel time in queue (min/km), \bar{T}_{bpr10}^* modified BPR function, \bar{Q} = average queue length (m), $\bar{Q}_{initial}$ = initial queue length (m), q_a = traffic demand flow rate (veh/h), C = road capacity (veh/h), k_j = jam density (veh/km)

¹⁵ It is noted that the original congestion function as presented in Dowling and Skabardonis (1992) exhibits a few typos, which have been corrected here.

Table 3 shows that congestion functions have evolved from relatively simple functions to more complex (sets of) equations. This development was often inspired by issues (e.g. theoretical inconsistencies, unrealistic or inaccurate predictions) that arose from the use of earlier functions (e.g. Golding, 1977; Davidson, 1978a-b; Dowling & Skabardonis, 1992). In an attempt to address these issues certain aspects of traffic flow theory (e.g. queuing theory) have been incorporated in the congestion functions.

The original BPR function has been commonly used in strategic planning model applications (e.g. Boyce, Janson & Eash, 1981; Dowling, Singh & Cheng, 1998). The (modified) Davidson function has also found considerable use, particularly in Australia, in a variety of applications (e.g. Starrs & Starkie, 1986; Helali & Hutchinson, 1994). The use of more recently developed congestion functions in strategic planning models such as the Akçelik function have rarely been reported in the literature (e.g. Horowitz, 1997; Singh, 1999).

Compared to traffic performance models, congestion functions are more simplified models. This is, for instance, reflected in the absence of signal setting variables in congestion functions. Instead signal settings are reflected in the capacity values and, in some functions, also in calibration parameters such as J_A and J_D , which take on different values for different road types.

Traffic demand volume and road capacity¹⁶ play a central role in the prediction of mean unit travel time in all congestion functions. In addition, all congestion functions include a variable representing *uncongested* unit travel time (min/km), which can be either free-flow unit travel time \bar{T}_{ff}^* or zero-flow unit travel time \bar{T}_{zf}^* . When traffic demand volume is zero, mean unit travel time is equal to \bar{T}_{ff}^* or \bar{T}_{zf}^* .

Zero-flow is not the same as free-flow. The term zero-flow unit travel time is used to denote minimum unit travel time that reflects the effects of both road environment *and* traffic control, whereas free-flow reflects the effects of road environment alone. This distinction is relevant for interrupted roads where there is always a (small) component of congestion due to capacity reduction at traffic signals, even when there are almost no vehicles on the road. Zero-flow travel speed is lower than free-flow travel

¹⁶ Here, road capacity is the critical capacity of the road (i.e. bottleneck capacity).

speed on interrupted roads¹⁷, whereas they are equivalent on uninterrupted roads. Hence, zero-flow speed is a more realistic estimate of maximum achievable travel speed in interrupted flow conditions than free-flow speed. However, free-flow speed is a better estimate of uncongested travel speed.

The congestion functions presented in Table 3 can be used to investigate the effect of different levels of congestion as reflected by different values for ϕ on travel speed. Using the input data presented in Table 4, Figure 9 shows the results for both interrupted and uninterrupted roads.

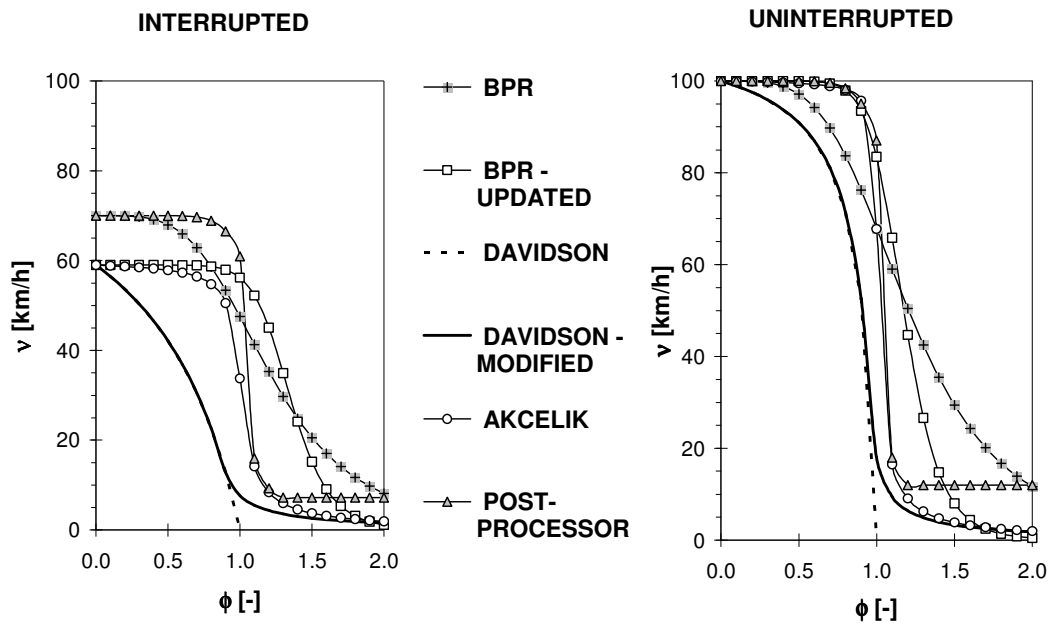


Figure 9 – Effect of Congestion on Travel Speed

Figure 9 shows that different levels of congestion have a large effect on mean travel speed, although the magnitude of the change in \bar{v} clearly depends on the level of congestion.

¹⁷ The actual difference between zero-flow and free-flow travel speeds depends on signal density (the number of signals per km) and signal settings and can vary from insignificant to quite substantial. For example, Irwin & Von Cube (1962) measured differences of 0 km/h up to 22 km/h between the mean free-flow speed (\bar{v}_{ff}) and the mean zero-flow speed (\bar{v}_{zf}).

All congestion functions exhibit an inverted S-shape relationship between volume-to-capacity ratio and mean travel speed. For ϕ values below about 0.8 most functions predict small changes in mean travel speed. Some functions use a different starting point, either free-flow speed or zero-flow speed, which leads to different travel speed predictions for interrupted roads, but not for uninterrupted roads.

Between ϕ values of 0.8 and 1.5, a substantial drop in mean travel speed can be observed for most functions. At higher values of ϕ all functions predict low travel speeds. The largest difference between congestion functions in the prediction of \bar{v} can be found when traffic demand is near road capacity ($\phi \sim 1$), which in this case is 54 km/h for interrupted roads and 85 km/h for uninterrupted roads. This is an interesting result since emission predictions are a function of travel speed. This finding implies that that the use of different congestion functions in a traffic model could possibly lead to substantially different emission predictions.

Table 4 shows an overview of representative parameter values that were used in the construction of Figure 9, and will also be used in the construction of charts that are presented later in this dissertation. The representative parameter values have been selected from the available literature (Menon *et al.*, 1974; Taylor, 1984; Akçelik, 1991), and are partly based on experimental data.

Table 4 – Representative Parameter Values for Three Basic Road Types

Flow Type	\bar{v}_{ff}	\bar{v}_{zf}	C	g^*	C	L
CBD	60	34	750	50	100	0.25
Interrupted	70	59	1200	60	100	1.00
Uninterrupted	100	100	2000	-	-	1.00
Flow Type	ϕ	PF	ϕ_c	K_j	J_D/J_A	τ
CBD	4.0	0.9	0.86	167	0.9/1.2	1.00
Interrupted	1.3	0.9	0.91	167	0.4	1.00
Uninterrupted	0.0	1.0	0.94	167	0.1	1.00

In Table 4 three basic road types are distinguished (e.g. Chang & Herman, 1978; BTCE, 1995; 1996): uninterrupted roads, interrupted roads and CBD roads. CBD roads are taken as a special case of interrupted roads since they are typically more interrupted than other urban roads due to a relatively large amount of turning movements at intersections, pedestrian conflicts and other lane obstructions such as stopping taxis, buses, trucks and parking vehicles.

Some researchers have suggested (e.g. Hamilton, 1977) that mean travel speed is a good indicator of congestion. Although mean travel speed is clearly affected by congestion, it is not necessarily a good indicator of congestion in all circumstances. This is illustrated in Figure 10 where the range of mean travel speeds is plotted for each major road type, including three volume-to-capacity ratios and corresponding mean travel speeds for each road type. Figure 10 has been constructed using the Akçelik congestion function and Table 4.

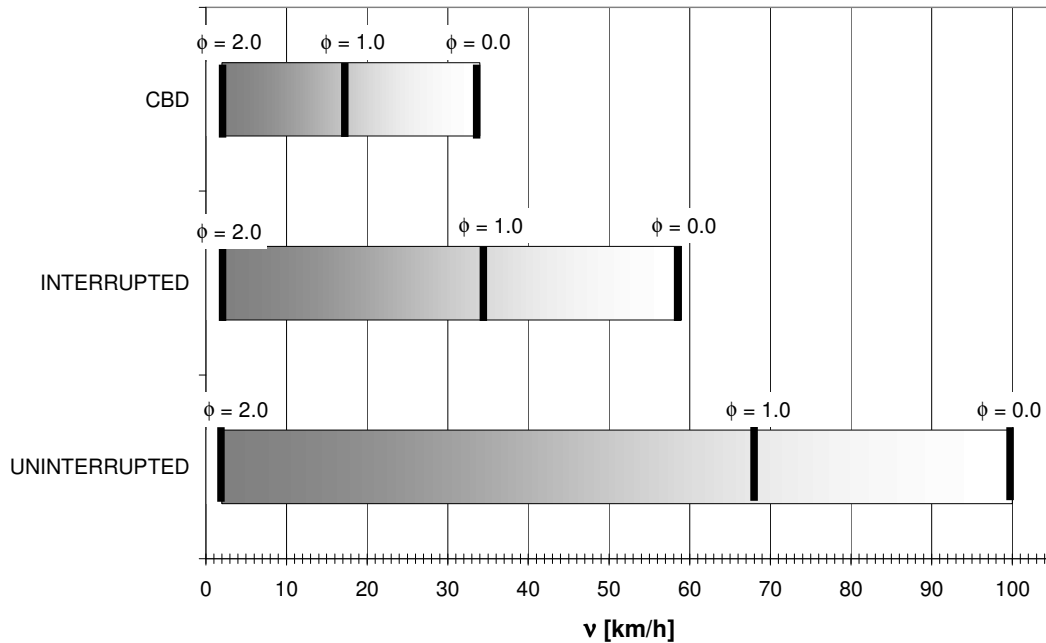


Figure 10 – Mean Travel Speed as an Indicator of Congestion

Figure 10 shows that mean travel speed is not a good congestion indicator in the travel speed range roughly between 15 and 60 km/h. For instance, an average travel speed

of 60 km/h on an arterial road would represent uncongested free-flowing conditions ($\phi \sim 0$), whereas the same speed on a freeway would represent much more congested conditions ($\phi > 1$), possibly involving low speed stop-and-go conditions. Outside this range of travel speeds, \bar{v} is a good indicator for congestion. For speeds below 15 km/h all road types are very congested and speeds above 60 km/h apply to freeway conditions only.

It is noted that the three road types presented here are a simplistic representation of reality. For instance, arterial roads may approach uninterrupted driving conditions and have zero-flow speeds that are higher than 60 km/h. Nevertheless, the issue with \bar{v} being an inadequate indicator, in certain speed intervals, for comparison of congestion levels on different road links (or networks) remains.

Of course, mean travel speed is a good congestion indicator when the same road, similar types of roads or the same network are compared in different situations (e.g. Leung, Lee & Wong, 1997). When congestion levels between (different types of) links are compared, a congestion indicator that takes the *deviation* from free-flow travel speeds (or unit travel time) into account should be used (e.g. Chang & Horowitz, 1979). The magnitude of the difference between (mean) travel speed and free-flow speed then reflects the level of congestion.

An obvious candidate is mean congestion delay \bar{d} , which was discussed at the beginning of this section. However, delay on a road link is a function of distance, as was shown in Equation 2-14 (p. 42). Delay could be large because of long road length and not necessarily because of high congestion levels. It is therefore appropriate to use delay normalised for distance when congestion levels on different roads are compared. This variable is the average delay rate (\bar{d}^* , min/km) and is computed as:

$$\bar{d}^* = \frac{\bar{d}}{L} \tag{Equation 2-19}$$

It is noted that this argument does not only apply to delay, but also to other congestion indicators that are a function of distance. As a consequence, stopped or idle time (\bar{T}_{idle}) and number of stops (n_s) are not used as congestion indicators in subsequent

chapters. Instead their equivalents, expressed per unit distance, i.e. average unit idle time (\bar{T}_{idle}^* , sec/km) and normalised number of stops (n_s^* , km⁻¹), are used.

Other congestion indicators that also reflect the deviation from free-flow travel speeds were found in the literature (TRB, 1992; Turner, Lomax & Levinson, 1996). The delay ratio (d_{ratio}) is calculated as the ratio of \bar{d}^* to mean unit travel time:

$$d_{ratio} = \frac{\bar{d}^*}{\bar{T}^*} \quad \text{Equation 2-20}$$

The relative delay rate (RDR) is calculated as the ratio of mean delay per unit distance (min/km) to mean unit travel time in free-flow conditions:

$$RDR = \frac{\bar{d}^*}{\bar{T}_{ff}^*} \quad \text{Equation 2-21}$$

Another congestion indicator that reflects the deviation from free-flow travel speed actually follows from the congestion functions themselves. These functions can be rewritten to compute the dimensionless ratio of mean travel time to mean travel time under free-flow conditions. This ratio is called the congestion index (CI) and it has been used by different researchers (e.g. Richardson & Taylor, 1978; Lyons *et al.*, 1996; Taylor; 2000). CI is calculated as:

$$CI = \frac{\bar{T}}{\bar{T}_{ff}} = \frac{\bar{v}_{ff}}{\bar{v}} \quad \text{Equation 2-22}$$

A similar congestion indicator, the speed reduction congestion index (SRCI) is an index which is normalised to a scale of 0 to 10. It is based on mean travel speed reduction due to congestion using the mean free-flow travel speed as a reference (WSA, 2000).

$$\text{SRCI} = \frac{(\bar{v}_{\text{ff}} - \bar{v})}{\bar{v}_{\text{ff}}} \quad \text{Equation 2-23}$$

2.2.5 Speed Fluctuation

As will be discussed in detail in Chapter 3, the level of speed fluctuation, i.e. the frequency and amplitude of instantaneous speed changes, affects emissions rates of individual vehicles. Measures of speed fluctuation are therefore included in a number of emission models, as will be seen later. Quantification of speed fluctuation requires the analysis of second-by-second driving pattern data. A driving pattern is defined as a time series of speed points, i.e. a speed-time profile.

Although measures of speed fluctuation are not commonly used as congestion indicators in practice, a limited number of studies, based on empirical data or simulation, show that they are related to other indicators of congestion. This section will discuss the available evidence.

The use of speed fluctuation measures as congestion indicators can be justified by considering them as measures of the *smoothness* of a driving pattern, or traffic flow for that matter. As the number of vehicles or the number of interruptions on the road increase, traffic becomes less smooth since vehicles are forced to decelerate and accelerate repeatedly. Driving patterns become increasingly unstable and oscillatory as drivers attempt to adjust in response to neighbouring vehicles, and hence the level of speed fluctuation increases (e.g. Barth, Johnston & Tadi, 1996). In this respect it is noted that number of stops (n_s , N_s), a congestion indicator that has been discussed in section 2.2.3, can also be regarded as a measure of speed fluctuation.

The first (published) attempts to quantify speed fluctuation (Greenshields, 1955; 1965) led to the development of the quality of traffic flow index (QTFI). QTFI attempted to incorporate driver effort and satisfaction and it is computed as a function of average

travel speed divided by speed changes per unit distance and the frequency of speed changes per unit distance. It is noted that QTFI cannot be used later in this study because there is no information that relates QTFI values to level of congestion.

A few studies have investigated the effect of congestion on acceleration noise (σ_{at}).

Acceleration noise is the standard deviation of instantaneous acceleration (a_t):

$$\sigma_{at} = \sqrt{\frac{\int_0^{T_{run}} (a_t - a)^2 dt}{T_{run}}}$$

Equation 2-24

where a (m/s^2) is the average acceleration rate (excluding zero acceleration when stopped), which is zero if final speed equals initial speed, and T_{run} is the running time (s), which is defined as travel time minus stopped time. σ_{at} is a function of the number, duration and rate of vehicle speed fluctuations (accelerations and decelerations).

Jones and Potts (1962) measured acceleration noise on a 7.2 km long stretch of suburban divided arterial road with different levels of congestion using the floating car technique¹⁸. These workers found that acceleration noise increased with increasing congestion levels, which were caused by higher traffic volumes and parked cars. In the most uncongested situation (off-peak period), σ_{at} had an average value of $0.21 m/s^2$, whereas in the more congested situations (peak period with and without parking ban) σ_{at} had an average value of 0.34 and $0.39 m/s^2$, respectively. Since both travel time and acceleration noise increase with increasing traffic, these two variables would be expected to be positively correlated. This was confirmed by Jones and Potts (1962).

More recently, Greenwood and coworkers (Greenwood & Bennett, 1996; Greenwood, Dunn & Raine, 1998; Greenwood, 2003) developed models that show the relationship between volume-to-capacity ratio and acceleration noise for different road types.

¹⁸ The survey vehicle attempts to simulate an average vehicle in the traffic stream.

These relationships were developed explicitly for uninterrupted driving conditions, since σ_{at} was measured on uniform sections of road, excluding interruptions such as intersections, change in lane configuration and change in the level of side friction. In addition, the driving patterns used to compute σ_{at} were selected in such a way that there was no net acceleration. Driving patterns were measured with a length ranging from 0.5 to 8.5 km and a mean length of 1.8 km. Values for ϕ were calculated using measured traffic count data and assumptions on road capacity. The relationships between σ_{at} and ϕ for three basic road types is illustrated in Figure 11. In order to run the models, assumptions need to be made with respect to road capacity and traffic volumes below which the effect of traffic interactions on travel speed are deemed negligible. Values for these variables were taken from Table 4 (p. 53).

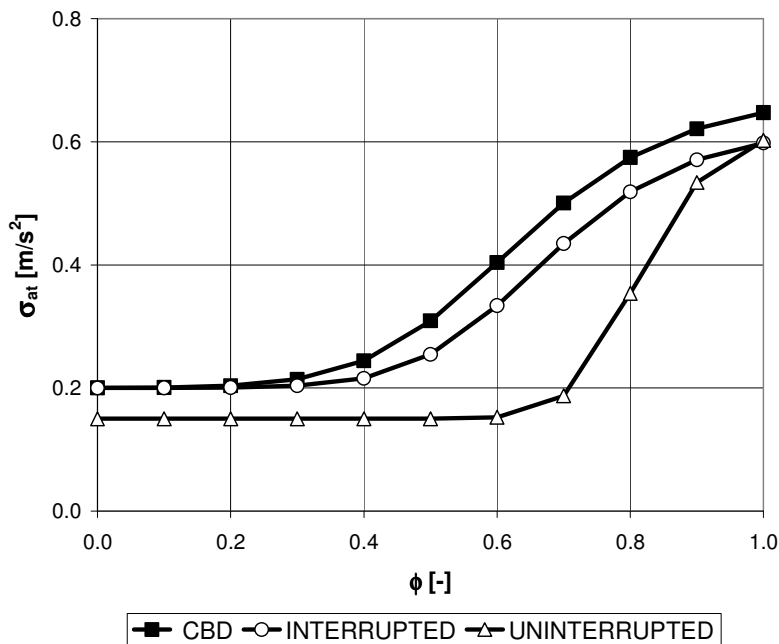


Figure 11 – Acceleration Noise versus Volume-to-Capacity Ratio by Road Type for Uninterrupted Conditions

Figure 11 shows that low σ_{at} values are predicted for low ϕ values. Here, “natural” acceleration noise due to e.g. geometric design and pavement condition dominates total noise. It also shows that “natural” acceleration noise is lower for freeway driving

than urban driving. This is in line with the expectation that accelerations are less pronounced at high speeds due to limitations in engine power in these conditions.

At high ϕ values acceleration noise due to traffic interaction dominates total noise, which is highest for CBD roads. The influence of traffic interaction on total noise at intermediate ϕ values depends on road type, where CBD roads show interaction effects at lower ϕ values than arterials and freeways. Freeways maintain low σ_{at} values until relatively high ϕ values are reached.

Jones and Potts (1962) remark that, since acceleration noise depends on many factors such as road type, road condition, roadside friction and driving style, it is safer to use it as a comparison test rather than attach too much significance to its actual values. Nevertheless, the different studies discussed in this section suggest that a value of less than 0.2 m/s^2 typically indicates uncongested conditions with minor speed fluctuations (“natural” noise).

Barth, Johnston and Tadi (1996) investigated the relationships between a number of microscopic speed fluctuation measures, which were calculated from driving patterns collected by a GPS-equipped instrumented vehicle, and macroscopic traffic variables that were measured by traffic detectors on a freeway. The following measures of speed fluctuation were selected:

- PKE (positive acceleration kinetic energy);
- TAD (total absolute second-to-second difference in speed per km); and
- COV_{vt} (coefficient of variation of instantaneous speeds).

PKE is expressed as m/s^2 and represents the work done per unit distance:

$$\text{PKE} = \frac{\sum (v_{t,a}^2 - v_{t,b}^2)}{L} \quad \text{subject to } a_t > 0 \text{ m/s}^2 \quad \text{Equation 2-25}$$

where $v_{t,a}$ and $v_{t,b}$ are the initial and final instantaneous speed in an acceleration manoeuvre (km/h) and L is the length of the driving pattern. Smooth driving patterns will have low PKE values, whereas driving patterns with large and frequent speed fluctuations will have high PKE values. It is noted that PKE increases only during

positive acceleration manoeuvres. Strong accelerations increase PKE substantially more than weak accelerations, due to the quadratic form of the PKE equation. Similarly, TAD is calculated as:

$$\text{TAD} = \frac{\sum |v_{t,a} - v_{t,b}|}{L} \quad \text{Equation 2-26}$$

TAD is a measure of overall wiggle per unit distance. Every time a vehicle changes its speed (whether up or down), TAD increases. Finally, the coefficient of variation of speed (COV_{vt}) is computed as:

$$\text{COV}_{vt} = \frac{\sigma_{vt}}{v} \quad \text{Equation 2-27}$$

where v (km/h) is the mean speed of a particular driving pattern, which is denoted as travel speed, and σ_{vt} represents speed noise. Speed noise is defined as the standard deviation of instantaneous speed (v_t).

$$\sigma_{vt} = \sqrt{\frac{\int_0^T (v_t - v)^2 dt}{T}} \quad \text{Equation 2-28}$$

where T is the total journey time (h). These relationships, taken from Barth, Johnston and Tadi (1996), are graphically depicted in Figure 12 for the range of measured data points. It is noted that these curves were fitted to datum points with averaging times of 60 seconds.

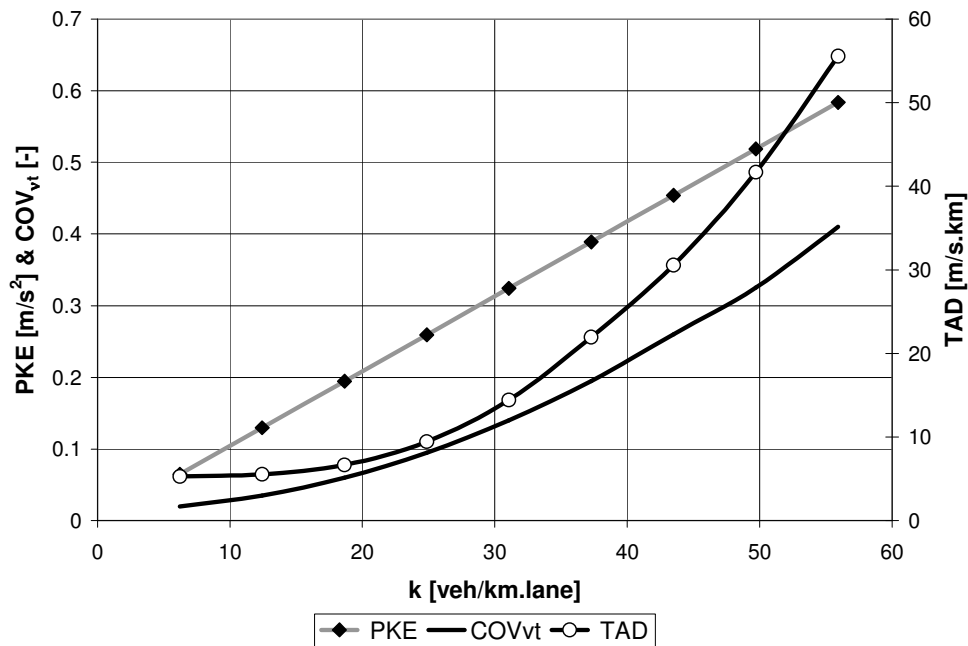


Figure 12 – Relationship between Speed Fluctuation and Density on a US Freeway (Data Derived From Barth, Johnston & Tadi, 1996)

Figure 12 shows that for uninterrupted conditions the level of speed fluctuation increases with increasing density. Although this information is not available for interrupted conditions, it is expected that similar relationships, at least in terms of direction, would exist for urban roads.

As will be discussed in more detail in section 3, emissions rates are a function of “driving mode”, which may refer to the four fundamental driving modes (i.e. cruise, idle, deceleration, acceleration). The modal activity distribution provides the proportion of time spent in each driving mode (P_{idle} , P_{acc} , P_{dec} , P_{cruise} are the proportions of time spent idling, accelerating, decelerating and cruising, respectively). Although modal activity distribution is not used as a congestion indicator in practice, there is one publication (Skabardonis, 1997) that shows that it is related to other congestion indicators. These results are presented here (Table 5, next page).

Table 5 – Effect of Congestion on Modal Activity Distribution in Traffic Streams

Road Type	ϕ [-]	v [km/h]	P _{idle} [%]	P _{acc} [%]	P _{dec} [%]	P _{acc} + P _{dec} [%]	P _{Cruise} [%]
Freeway	0.50	92	0.2	22.7	21.2	43.9	55.9
	0.75	90	0.4	23.6	22.4	46.0	54.6
	0.95	87	0.5	23.7	22.7	46.4	53.2
	> 1.00	52	7.7	31.0	26.5	57.5	34.6
Arterial	~ 1.00	-	52.0	24.0	13.0	37.0	11.0
CBD	-	-	26.0	-	-	-	-
	-	-	33.0	-	-	-	-

Table 5 shows that the modal distribution for a traffic stream on a freeway changes with different levels of ϕ . Particularly the increase in percent idle time and acceleration time and the reduction in cruise time is evident. In addition, the percent of time that speed fluctuates (denoted as P_{acc} + P_{dec}) increases with traffic intensity. For urban roads no such information is available, but is observed that idle time is very high for a congested arterial. It is noted that Table 5 does not present actual field data, but that it is the result of simulation using microscopic vehicle interaction models (these models are discussed in section 2.5.4).

All measures of speed fluctuation presented in this section show a consistent increase in their values with increasing levels of congestion, except for QTFI, for which the relationship with congestion has not been quantified. On the basis of the available literature, it is therefore concluded that σ_{at} , PKE, TAD, COV_{vt} and {P_{acc} + P_{dec}} are all good congestion indicators.

2.2.6 Level of Service (LOS)

Level of service (LOS) has been widely used as a surrogate for congestion assessment (TRB, 1992). LOS is a qualitative traffic quality measure, based on a letter grading scale from A to F, describing a range of operating conditions within a traffic stream, where A represents free-flow conditions and F most congested conditions. The determination of LOS is based on a number of assumptions and computational techniques (TTI, 1993).

LOS is determined by traffic variables such as traffic density, travel time and delay, which may be measured in the field, or alternatively computed using established traffic engineering procedures (e.g. Austroads, 1988b; TRB, 2000). As an example, Table 6 and Table 7 show the traffic variables with associated threshold values that are used for different Australian road types (Austroads, 1988b) to determine LOS E and LOS F. The principal traffic variables that define LOS conditions are indicated in bold.

LOS for freeway and uninterrupted multi-lane roads is principally determined by density value ranges, although minimum travel speed values for different free-flow speeds are also indicated. LOS for urban streets (arterial/collector) is principally determined by average travel speed ranges, which depend on the free-flow speed. Thus, provided that the congestion indicators on which LOS is based are used instead, the use of LOS as a congestion indicator is superfluous.

Table 6 – Traffic Variables with Values for LOS E Conditions (Level Terrain)

Road Type	v [km/h]	k [pce/km.lane]	Percent Time Delayed [%*]	ϕ [-]
Uninterrupted Two-Lane Two-Way Roads (DS [#] ≥ 100 km/h)	72 – 80	-	> 75	0.57 - 1.0
Uninterrupted Multi-Lane Roads (DS = 100-110 km/h)	48-64	26.3 - 41.9	-	0.80 - 1.0
Uninterrupted Multi-Lane Roads (DS = 80 km/h)	45-56	26.3 - 41.9	-	0.76 - 1.0
Freeways (DS = 100-110 km/h)	48 – 67/74	26.3 - 41.9	-	0.84/0.94 - 1.0
Freeways (DS = 80 km/h)	45 – 64	26.3 - 41.9	-	0.83-1.00
Interrupted Urban Arterial Roads (FFS ^{##} = 55 to 70)	20 – 25	-	-	-
Interrupted Urban Arterial Roads (FFS ^{##} = 50 to 55)	15 – 20	-	-	-
Interrupted Urban Arterial Roads (FFS ^{##} = 40 to 55)	10 – 15	-	-	-

Table 7 – Traffic Variables with Values for LOS F Conditions (Level Terrain)

Road Type	v [km/h]	k [pce/km.lane]	Percent Time Delayed [%*]	ϕ [-]
Uninterrupted Two-Lane Two-Way Roads (DS [#] ≥ 100 km/h)	< 72	-	100	[> 1.0]
Uninterrupted Multi-Lane Roads (DS = 80-110 km/h)	< 45-48	> 41.9	-	[> 1.0]
Freeways (DS = 80-110 km/h)	< 45-48	> 41.9	-	[> 1.0]
Interrupted Urban Arterial Roads (FFS ^{##} = 55 to 70)	< 20	-	-	-
Interrupted Urban Arterial Roads (FFS ^{##} = 50 to 55)	< 15	-	-	-
Interrupted Urban Arterial Roads (FFS ^{##} = 40 to 55)	< 10	-	-	-

[#] Design Speed

^{##} Range of Free-Flow Speeds

* Average percent of time that all vehicles are delayed while travelling in platoons due to their ability to overtake.

2.2.7 Network Congestion Indicators

A number of congestion indicators were found in the literature that are specifically used to quantify the level of network congestion. These network indicators correspond to traffic variables that were found to be good congestion indicators in previous sections. As will be seen shortly, these indicators are (slightly) modified to enable estimation of aggregate congestion levels. Congestion indicators presented in this section will be used in Chapter 5.

Total network delay (D , h) has been commonly used (e.g. TRB, 1992; Dargay & Goodwin, 1999) and is computed by:

$$D = \sum_i (\tau V_i \ell_i \bar{d}_i) \quad \text{Equation 2-29}$$

where \bar{d}_i is mean vehicle delay for link i (h/veh), τ is the observation period (h), V_i is traffic volume on link i (veh/h.lane) and ℓ_i is the number of lanes on link i . Since total delay is a function of total network length, total network delay should be normalised for distance. In this respect, total delay can be expressed on a VKT basis (TTI, 1993), which is denoted as DVKT (h/veh.km):

$$DVKT = \frac{D}{VKT} \quad \text{Equation 2-30}$$

Here, total VKT (vehicle-kilometres of travel), expressed as veh.km, is computed as:

$$VKT = \sum_i (\tau V_i \ell_i L_i) \quad \text{Equation 2-31}$$

Average network travel speed (km/h) is computed as (Mahmassani, Jayakrishnan & Herman, 1990):

$$\bar{v}_n = \frac{VKT}{VHT} \quad \text{Equation 2-32}$$

Total VHT or vehicle-hours of travel, expressed as veh.h, is computed as:

$$VHT = \sum_i \left(\frac{\tau V_i \ell_i L_i}{\bar{v}_i} \right) \quad \text{Equation 2-33}$$

where \bar{v}_i is mean travel speed for link i. Mean network density (k_n , veh/km) is calculated by (Mahmassani, Williams & Herman, 1987):

$$k_n = \frac{VHT}{\tau LKR} \quad \text{Equation 2-34}$$

where LKR represents the total number of lane-kilometres of roadway in the network. The congestion index CI, which has been discussed before, can be used for a road network, but summation of link CI values must take into account link traffic volumes (e.g. Van Vuren & Leonard, 1994):

$$CI_n = \frac{\sum (CI_i V_i \ell_i L_i)}{\sum (V_i \ell_i L_i)} \quad \text{Equation 2-35}$$

Finally, VKT per kilometre (or alternatively per km²), which is denoted as VKTKM, has been used by a number of researchers (Smeed, 1970; Turner, 1992; Dargay & Goodwin, 1999), and is computed as:

$$VKTKM = \frac{VKT}{LKR}$$

Equation 2-36

VKTKM is a gauge of the travel intensity for a particular urban (sub)area.

2.2.8 Other Congestion Indicators

Other less commonly used congestion indicators have been published and, for the sake of completeness, they are listed below. These indicators cannot be used in subsequent chapters of this thesis for various reasons, which are discussed below.

- The degree of congestion (DC) has specifically been developed as an indicator for traffic conditions at signalised intersections using output from the Sydney Coordinated Adaptive Traffic system (SCATS), such as traffic count and vehicle occupancy data from vehicle detector loops and signal control data (Nguyen, Lilley & Williams, 2000). The complete set of algorithms used for computation of DC is not published in the literature (RTA, 2000a; 2000b). Hence, DC cannot be used in this study.
- Different empirical studies have indicated that variation in travel time is a function of mean unit travel time (e.g. Smeed, 1968; Herman & Lam, 1974; Menon *et al.*, 1974). Richardson and Taylor (1978) specifically investigated this and measured an increase in the variation of travel time with level of congestion. Although this is an interesting congestion indicator, this variable is not computed by traffic models or (commonly) measured in the field and can therefore not be used in this study.
- AADT-to-capacity Ratio (AADT/C ratio), is defined as the ratio of average annual daily traffic volume to road capacity and has been used by some researchers (Van Toorenburg, 1991; Turner, 1992; Cottrell, 1998). This congestion indicator may be useful, in addition to ϕ , when there is no distinct peak and high hourly flows are spread out more uniformly during the day (Polus & Craus, 1997). This is not the case for the Brisbane network (which is the test network used in Chapter 5), and hence this indicator will not be used.

- The delay rate index (DRI) is an index with values between 0 and 10 and it can be read from a chart using average delay per unit distance (min/km) as input (e.g. Levinson & Lomax, 1996). Use of this congestion indicator to estimate congestion levels on links would be quite laborious. Also, similar indicators such as RDR and d_{ratio} will be used in subsequent chapters.
- The roadway congestion index (RCI) is an empirically derived formula that weighs the daily VKT per lane-km for main road types (“freeway”, “arterial”) by its respective amount of daily VKT (e.g. DeCorla-Souza & Schoeneberg, 1992). It is questionable if this formula can be similarly applied to other networks.

A few *network* indicators that are less commonly used are:

- Congested travel (CT, veh.km) has been used by a number of researchers (TRB, 1992, Turner, Lomax & Levinson, 1996) and it is the amount of travel in an urban area, expressed as vehicle-kilometres travelled (VKT), that occurs in congested conditions. It is calculated by multiplying the length of congested links by traffic volume associated with the appropriate time period, then summing the congested travel over all links.
- Congested roads (CR, km) has been used by a number of researchers (TRB, 1992, Turner, Lomax & Levinson, 1996) and it is the total length of congested roads.
- The lane-km duration indicator (LKDI, km.h) is computed by the product of the number of congested lane kilometres and the duration of congestion (TRB, 1992; Turner, 1992).

These three network indicators all require the selection of threshold values for volume-to-capacity values, which as will be seen in section 2.4, is quite arbitrary. It is therefore better to use the network indicators presented in section 2.2.7 that do not require this threshold value.

- The Congestion Severity Indicator (CSI, $\text{veh.h}/10^6 \text{ veh.km}$) is the ratio of total vehicle-hours of delay per million VKTs by main road type, i.e. freeway or arterial

(Lindley, 1987; 1989; TRB, 1992, Turner, 1992). This indicator is not used in Chapter 5 since interrupted and uninterrupted roads are investigated separately.

2.3 Congestion Indicators in Air Emission Modelling

The previous sections have shown that a large number of congestion indicators can be found in the literature. In anticipation of the next chapters, it is now possible to investigate which congestion indicators are explicitly used in current air emission modelling. Table 8 is used for this evaluation and it shows, for each congestion indicator, at which level of analysis it is (typically) used and which type of emission model explicitly use this indicator as an input variable. The following levels of analysis are distinguished:

- point (P);
- driving pattern (DP);
- intersection/link (I/L); and
- network (N).

The second level of analysis (DP) is concerned with individual vehicle movement in time and space (i.e. microscopic), whereas the first, third and fourth level (P, I/L and N) consider traffic stream characteristics (i.e. macroscopic), although at different spatial scales.

An X in Table 8 indicates that application of a congestion indicator has been observed in the available literature. Table 8 shows that a number of congestion indicators are used as input in emission modelling. This suggests that congestion is reflected in emission predictions of at least a number of emission models. Of course, the input variables used in the modelling process depend on the actual emission model that is considered. It is possible that certain emission models may not include congestion indicators, whereas others may include only one or a few congestion indicators. This point is discussed in detail in Chapter 3.

Table 8 – Overview of Congestion Indicators, Level of Analysis and Use in Emission Models

Congestion Indicator	Level of Analysis				Emis. Model
	P	DP	I/L	N	
\bar{v}_{space}	X				X
\bar{v}_{time}	X				
Ω (k)	X				
σ_{at}		X			
COV_{vt}		X			
TAD		X			
PKE		X			X
QTFI		X			
LOS		X	X		X
ϕ			X		
AADT/C			X		
VIT ¹⁾			X		
\bar{Q}, \bar{Q}_{int}			X		X
c			X		X
g, g*, r, r*			X		X
DC			X		
CT				X	
DVKT				X	
CR				X	
LKDI				X	
RCI				X	
VKTKM				X	
CSI				X	

¹⁾ Variation in Travel Time

Table 8 (Continued) – Overview of Congestion Indicators, Level of Analysis and Use in Emission Models

Congestion Indicator	Level of Analysis				Emis. Model
	P	DP	I/L	N	
\bar{d}^*			X		
RDR			X		
d_{ratio}			X		
DRI			X		
SRCI			X		
\bar{T}^*		X	X		
CI, CI_n		X	X	X	
k, k_n		X	X	X	X
\bar{T}_{idle}^*		X	X		X
MAD ²⁾		X	X		X
\bar{v}_{run}		X	X		X
n_s^*, N_s^*		X	X	X	X
d, D			X	X	X
\bar{v}, \bar{v}_n		X	X	X	X

²⁾ Modal Activity Distribution

2.4 Quantification of Congestion in this Study

Quantification of congestion is required in two chapters of this study:

1. assessment of the extent to which congestion is included in driving patterns (Chapter 4); and
2. assessment of the level of network congestion (Chapter 5).

Congestion levels are assessed in both an *absolute* manner (i.e. below or above a prespecified threshold value) and in a *relative* manner (i.e. intercomparison of congestion levels in different situations - trends are important) in Chapter 4 and 5.

Traffic engineers commonly need congestion thresholds to quantify *absolute* congestion levels on roads and in road networks (e.g. TRB, 1992). A congestion threshold is a particular value of a congestion indicator that establishes the point at which congestion begins. Information on absolute congestion levels creates insight in the size of the congestion problem in certain locations and areas. Congestion thresholds are not needed in the *relative* comparison of congestion levels on links or in networks.

The basic traffic stream model may have created the impression that the point at which the congested regime starts is in fact quite clear and that this point can be readily quantified in terms of speed, volume and density. In practice, however, this point can hardly be determined from field data (e.g. May, 1990, p. 291-292). Moreover, congestion thresholds may vary greatly between sites since they are dependent on many factors such as the geometric design, weather conditions, proportion of heavy vehicles, and so forth. For example, Oguchi, Taniguchi and Morita (1995), determined the onset of congested conditions for different segments of the same Tokyo Metropolitan Expressway based on measured flow-speed curves in each road segment. These workers established a wide range of threshold speeds (36-68 km/h) for different sections of the same expressway.

Clearly, it is not feasible to establish congestion threshold values this way for a small road network, let alone a large metropolitan road network. Here, threshold values

need to be selected that are believed to be reasonably representative. This has led to often arbitrary selection of quite different threshold values. Two examples will illustrate this:

- Different threshold values for ϕ have been used in practice, for instance 0.75 (FHWA, 1992a), 0.77 (Lindley, 1987 & 1989), 0.8 (e.g. Ogden & Taylor, 1996), 0.85-0.95 (Akçelik, 1978a; 1978b), 0.975 (Cottrell, 1992), 0.8-0.9 (Akçelik, 2000), 1.0 (e.g. TRB, 2000), 1.15 (TRB, 1997) and 1.25 (e.g. WSA, 2000).
- Different threshold values for \bar{v} have been used in practice, for instance 10 km/h (Schallaböck & Petersen, 1999), 15 km/h (NEPC, 1999b), 48 km/h (FHWA, 1992b), 52 km/h (BTCE, 1996), 33% of free-flow speed (BTE, 2000), 50% of free-flow speed (Spiess, 1990), 60-70% of free-flow speed (RTA, 2000a; 2000b) and 25 km/h below the speed limit (TTI, 1993).

It is thus impossible to find a single universally accepted and consistently used threshold value. The differences in threshold values can partly be explained by a different *perception* of what a “congested situation” is. Although the concept of congestion is thus perceived in many different ways, as was already clear from the many different congestion thresholds that have already been presented in this section, three important approaches were identified in the literature:

- Congestion is strictly defined as low speed “stop-and-go” traffic conditions (e.g. NEPC, 1999b).
- Congestion is defined as the degradation of travel conditions beyond a level that is perceived “acceptable” or “tolerable” to the general public (e.g. Turner, Lomax & Levinson, 1996).
- Congestion is defined as departure from light or free-flow travel conditions (e.g. Laetz, 1990).

This third approach aligns with the definition of congestion used in this study. The first and second approach both exclude traffic conditions with a significant level of interaction (congestion) from the definition of a congested situation, which appears to

be a rather arbitrary decision. The third approach effectively defines an “uncongested situation” and considers all other situations as being congested. Although some assumptions on threshold values still need to be made (see below), this approach likely includes the majority of traffic situations with significant levels of interaction, and would therefore more accurately define a congested situation.

It is noted that the choice for a certain approach will clearly affect the estimated extent and duration of congestion in a network, and, as a consequence, the predicted effects of congestion on emissions. For example, Schallaböck and Petersen (1999) defined congestion as low speed stop-and-go traffic conditions only, which accounts only for a minor part of total travel, in this case 1% of total VKT on German Roads. As a result, congested conditions were found to account only for a small part of the total fuel consumption and emissions of NO_x and HC (2.3, 2.2 and 4.4% respectively). In contrast, Anderson *et al.* (1996) defined congestion as average speeds other than free-flow speed. As a result, congested conditions caused an increase in emissions of a factor of 1.71, 1.53 and 1.04 for CO, HC and NO_x, respectively, when compared to a free-flowing network.

Another issue in the quantification of congestion levels is that different studies have demonstrated that it is not possible to capture congestion by means of a single congestion indicator (Dougherty, Kirby & Boyle, 1993; RTA, 2000a; 2000b). To illustrate this point, Jones and Potts (1962) remarked that acceleration noise may give a better measure of traffic congestion in some traffic situations than stopped time, for example on a congested shopping street where actual stopped time was small, but acceleration noise large. In this case, travel time and speed fluctuation would increase, but not idle time. It is possible that in other traffic situations stopped time would be a better congestion indicator, for instance, when a vehicle is embedded in a severe traffic jam and idle time would be large, but level of speed fluctuation small.

It is thus appropriate to use multiple congestion indicators in this study to quantify congestion levels, instead of only a single one. The use of a set of congestion indicators would result in a better capability to identify uncongested conditions and would reduce the chance that the congestion level in a particular traffic situation is over- or underestimated. It is, however, not immediately clear which set of congestion indicators should be used to adequately quantify the level of congestion.

Also, as was seen in section 2.2, many congestion indicators are interrelated. In this respect, a large set of congestion indicators may appear to quantify congestion better, but in fact provide redundant information. For instance, the volume-to-capacity ratio may incorporate signal settings (cycle time and green time) in its computation, which makes the use of effective green time or effective red time as separate congestion indicators unnecessary. Although several congestion indicators are clearly correlated (e.g. PKE, TAD and COV_{vt}) it is not possible, on the basis of the available information, to determine which specific indicator would be the best congestion indicator. Thus, the redundancy criterion cannot be used.

The decision on which congestion indicators are to be used thus needs to be made on other grounds. Two additional selection criteria are used:

- the selected traffic variable should be applicable at the level of analysis; and
- the selected traffic variable could or should not be used for various reasons that have been discussed in previous sections.

As is clear from Table 8 (p. 71), the set of congestion indicators that can be used is a function of level of analysis. It can be seen that use of certain congestion indicators is restricted to a specific level of analysis, whereas others can be applied to two or more levels of analysis. For instance, the volume-to-capacity ratio cannot be quantified in driving pattern analysis since there is no information on traffic volumes. When the two criteria are combined, the following set of traffic variables, presented in Table 9 (next page) can be used at the levels of analysis that apply to Chapters 4 and 5 (provided that they are available from traffic models or field data).

An “X” sign in Table 9 means that a variable is suitable and that application has been observed in the literature, whereas an “(+)” sign indicates that a particular variable is suitable, although its application at this level has not been found in the literature. In this respect, five variables have been added at DP level. This was done to include congestion indicators that specifically reflect the deviation from free-flow speed in the set of congestion indicators.

Table 9 – Overview of Congestion Indicators to Be Used in Chapters 4 & 5

Congestion Indicator	Level of Analysis		Congestion Indicator	Level of Analysis	
	DP	N		DP	N
σ_{at}	X		\bar{d}^*	(+)	
COV_{vt}	X		RDR	(+)	
TAD	X		d_{ratio}	(+)	
PKE	X		SRCI	(+)	
MAD	X		CI, CI_n	(+)	X
\bar{v}_{run}	X		\bar{v} , \bar{v}_n	X	X
n_s^*	X		k_n		X
\bar{T}^*	X		VKTM		X
\bar{T}_{idle}^*	X		DVKT		X

In the course of section 2.2 several traffic variables were found to be “good” congestion indicators, i.e. traffic variables that show a consistent and unambiguous relationship with the level of congestion in a traffic stream. A congestion indicator must show a consistent relationship with level of congestion to allow for examination whether one situation is more congested than another one. A clear example of an ambiguous congestion indicator, which should not be used in Chapters 4 and 5, is traffic volume (refer to section 2.2.1), which may be low in both congested and uncongested conditions.

Literature indicates that all congestion indicators presented in Table 9, except travel speed, are good congestion indicators. Travel speed is an ambiguous indicator in a certain range (roughly between 15 and 60 km/h) and \bar{v} and \bar{v}_n can therefore only be used to compare congestion levels for the same road or the same road network in different situations.

Finally, a set of quantitative criteria is needed in Chapter 4 that defines “uncongested” conditions. It was considered, on the basis of information presented in this chapter, that the occurrence of uncongested conditions would be reflected in the combination of the following indicator values:

- travel speed is close to free-flow speed (hence, CI value is close to unity and SRCl, d^* , d_{ratio} and RDR values are all low and close to zero);
- running speed is close or equal to travel speed;
- modal activity distribution would reflect a large proportion of cruise and no idle;
- number of stops per km is zero;
- idle time per km is zero.
- an acceleration noise value of less than 0.20 m/s^2 on interrupted roads;
- an acceleration noise value of less than 0.15 m/s^2 on uninterrupted roads;
- a PKE value of about 0.2 m/s^2 or less;
- a TAD value of about 7 m/s.km or less; and
- a COV_{vt} value of about 6% or less.

Deviation from these values would indicate (more) congested conditions. It is noted that the PKE, TAD and COV_{vt} values were determined from their relationships with traffic density presented in Figure 12, assuming that the start of LOS C conditions represents the upper boundary of uncongested flow conditions. According to Austroads (1988b), LOS C represents conditions of stable flow, with most drivers being restricted to some extent in their freedom to select their desired speeds and to manoeuvre within the traffic stream. These conditions correspond to a traffic density of 18.8 passenger car equivalents/km.lane.

It is noted that the relationship between a number of speed fluctuation indicators (i.e. σ_{at} , PKE, TAD, COV_{vt}) and congestion is based on more limited empirical data than the relationship between other indicators and congestion. For instance, the quantitative relationship between PKE, TAD and COV_{vt} and traffic density is based on empirical data of one study that was restricted to freeway driving conditions only. Hence, it has to be assumed that similar relationships exist for lower speed uninterrupted conditions and interrupted conditions. Although this appears to be a

reasonable assumption, it is not based on field observations. In contrast, the relationship between CI and level of congestion has been studied much more extensively, which is reflected in its discussion in traffic flow theory (e.g. congestion functions) and the number of empirical studies.

2.5 Traffic Models & Traffic Field Data

This section provides a brief introduction to different types of traffic models and traffic field data, which are commonly or less commonly used in the emission modelling process. These models generate (intermediate) output that is used as input to emission models, or alternatively traffic field data acts directly as emission model input, as was seen in Table 1 (p. 6). Traffic models and field data are therefore important aspects in the emission modelling process. This section discusses the input requirements for traffic models, provides some relevant information on the traffic models and discusses the interface with (stand-alone or incorporated) emission models.

2.5.1 Strategic Planning Models (SPMs)

Strategic planning models (SPMs) are used for the assessment of current and future efficiency and performance of metropolitan road networks. SPMs are intended to determine (long term) corridor- or area-wide (network) effects of different policy options (BTE, 1998). Strategic planning models are commonly referred to as strategic network models, urban transport models or travel demand models, and examples of such models are UTPS, EMME2, TRANSTEP, MINUTP and TRIPS (e.g. NCTR, 1997; Brindle *et al.*, 2000).

In SPMs the road network is represented by a set of links and nodes and urban space is divided into zones. Each zone is represented by a centroid node, which is a point inside the zone. Here, all zone trips are assumed to begin and end. Nodes usually represent an intersection, but may also represent a change in road characteristics. Links form the one-way connections between nodes and they usually represent actual roads in the network or they represent centroid connectors (dummy links).

Different road characteristics such as capacity are coded on the links. SPMs consist of several submodels that work together to generate the required output for each link, i.e. traffic volume, mean travel speed, volume-to-capacity ratio and VKT. Other data that are used as input to the modelling process (e.g. Sbayti *et al.*, 2001), for instance type of road, link length, number of lanes, free-flow speed, link capacity and speed limit, can be extracted as well.

In the strategic planning modelling process, congestion functions, which have been discussed in section 2.2.4, are commonly used iteratively in a procedure that assigns traffic volumes to the road network. Once traffic assignment reaches an equilibrium, congestion functions are used to compute mean link travel speeds. A further description of the modelling process is provided in Appendix A.

Although (new) SPMs may incorporate emission prediction capabilities (Taylor & Anderson, 1982; 1983; 1984; TRT, 2005), often data extracted from strategic planning models are used as input to stand-alone emission models to generate emission predictions (e.g. TRB, 1997; Noriega & Florian, 2005). This was already shown in Table 1, in which models such as MOBILE and COPERT are often used in combination with SPMs.

Although SPMs have been extensively used there are several assumptions and issues which affect its accuracy¹⁹ and limit their application. One issue that has been reported (Helali & Hutchinson, 1994; Grant, Gillis & Guensler, 2000), and which is relevant with respect to air emission modelling, is that substantial errors in the estimated mean travel speed may exist.

¹⁹ An accurate model implies to be precise (i.e. small confidence limits) and have a lack of bias in the model predictions. Bias is the tendency for emission estimates to be, on average, consistently higher or consistently lower than "true" emission values.

The likelihood for this to occur may be larger when a relatively simple congestion function, such as the original BPR-function, has been used.

It was discussed in section 2.2.3 that congestion functions use *demand* flow rates, which are subsequently assumed to be equivalent to actual link volumes. This may lead to incorrect link emission predictions when ϕ (significantly) exceeds unity. For instance, if the demand flow rate is larger than link capacity, and if it is accepted that the value taken for link capacity is accurate, only part of the traffic volume can be “serviced” within the observation period (e.g. a two hour peak period) and the remaining part would still be physically present on the link (in a queue) at the end of the observation period. Thus, total link VKT would be lower than predicted (and link emissions would be overpredicted) since not all vehicles traverse the entire link.

On the other hand, the number of trips between each zone are predicted for each observation period (presented in so-called origin-destination matrices) and queues that would exist at the end of one observation period are not carried over to the next period (Bell & Lida, 1997). As a consequence, link emissions are possibly underestimated when total emissions are investigated that include various daytime observation periods (e.g. over a week day). For prediction of total emissions in large congested urban networks this issue may be of importance, but this would depend on the time of day and city location.

If link length is not long enough to store all the excess vehicles, part of the queue may even be physically present on other adjacent links, due to spill-over effects, and produce emissions on these links. Queues spilling over from one link to another are not taken into account in strategic planning models. Thus, in cases where spill-over queues are present, emissions are not correctly allocated in space. This would particularly be an issue when local effects of congestion on emissions are assessed (e.g. dispersion modelling in a small city area - a number of adjacent links).

For instance, in the Brisbane road network, which is used as a case-study in Chapter 5, 29% of the links has a V/C ratio > 1 in the morning peak period, whereas this is 16% in the off-peak period and 0% in the night period. It has been estimated by the author, using link data for the Brisbane network, that no link in the night period would experience queue spill-over, i.e. (volume minus capacity) times average queue

space²⁰ is larger than link length, whereas this can be up to 25% (CBD), 10% (Inner City) and 5% (Outer City) of the total number of links in the peak period.

Another possibly relevant issue with respect to air emission modelling, is that the modelled network often only includes major roads. As a consequence, local effects of congestion on air quality may not be correctly predicted, since the distribution of emissions over a local area is not sufficiently resolved.

It is finally considered (although no such suggestion has been seen in the literature) that traffic volumes (and hence congestion levels) may be “systematically” overestimated on links, because total travel is distributed over a modelled network that is smaller than the real road network. On the other hand, total travel demand in an area may be underestimated as intrazonal trips are not (properly) assigned to the network (intrazonal trips never leave their centroid). This may offset overestimated traffic volumes due to a smaller network in the modelling process.

The overall effect is, however, difficult to determine since modelled traffic volumes are often only validated (and calibrated) for a few links, i.e. by comparing modelled values to observations for a limited number of natural “screenlines” such as bridges (e.g. QGEPA, 2002), as will be seen in Chapter 5.

2.5.2 Dense Network Models (DNMs)

To address some of the issues with SPMs, more complex models have been developed, such as dense network models. Dense network models are particularly useful for evaluation of alternative plans for traffic control and traffic management²¹ in a (small) study area. Traffic management is commonly used to improve traffic flow conditions, reduce congestion and enhance safety on a road or in an area (Taylor, 1999b).

²⁰ Average queue space is taken to be 6 meters for light-duty vehicles and 12 meter for heavy duty vehicles (ARRB, 1990).

²¹ Many traffic management or traffic control techniques are available and they include (dynamic) urban traffic control (e.g. signals, signs, coordination, speed limits), control of on-street parking, allocation of road space to specific road user groups, widening of streets, one-way streets, road closure and turn bans, central area traffic restraints (e.g. pedestrianisation) and traffic calming (e.g. reduced speed limits, road humps).

Dense network models require more detailed data (e.g. signal settings, type of intersection), more model setup time and more computing power than strategic planning models. As a consequence, their application is typically restricted to smaller urban areas, but with a more detailed coverage of the actual road system compared to strategic planning models. A commonly used dense network model is SATURN (Hall, Van Vliet & Willumsen, 1980; Van Vliet, 1982), but similar models exist as well such as TRAFIKPLAN (Taylor, 1979; 1980; 1999a; 2000) and CONTRAM (Taylor, 2003).

The main difference between dense network models and strategic planning models is the focus on turning movements and the calculation of intersection (node) delays in the assignment step instead of link delays. For instance, SATURN (Simulation and Assignment of Traffic to Urban Road Networks) uses flow-delay models which express intersection delay as a function of volume and zero-flow delay in unsaturated conditions and uses deterministic queuing theory to estimate delay in saturated conditions (Matzoros *et al.*, 1988).

DNMs may incorporate emission prediction capabilities. For example, SATURN uses a postprocessor emission model called LANES (Links and Network Emissions from SATURN), which computes emissions as a function of VKT, cruise speed, total delay and total number of primary (major) and secondary stops (queue move-up). LANES (EC, 1995; Tate & Bell, 2000) incorporates a modal emission model (refer to section 3.2.2.1).

2.5.3 Traffic Performance Models (TPMs)

Traffic performance models have been discussed in detail in section 2.2.3. These models require detailed data on the geometric layout of roads and intersections, signal settings, signal phasing, signal coordination, and so forth.

Some TPMs incorporate emission prediction algorithms. For instance, the SIDRA model incorporates additional models for computation of acceleration and deceleration distances and times (Açkelik & Besley, 2003). From this information speed-time profiles of an average vehicle are constructed consisting of a series of cruise, acceleration, deceleration and idling elements. These profiles will be different for different

intersection types, different signal settings and different traffic demand. Fuel consumption and emissions are then estimated using a modal emission model (refer to section 3.2.2.1), which is also part of the SIDRA model.

2.5.4 Microscopic Simulation Models (MSMs)

Microscopic simulation models (MSMs) are used to study and evaluate the performance of road networks at the operational level, for example for analysis and development of urban traffic management schemes. Several microscopic traffic simulation models exist and examples of such models are FRESIM, NETSIM, AIMSUN, PARAMICS and ARTEMIS (e.g. EC, 2000; Barceló, 2002). MSMs require detailed input data, similar to TPMs.

In MSMs the first step is determination of travel demand and traffic assignment (route choice or turning percentages). These data are usually imported from external models such as EMME2 and SATURN. The second step is microscopic modelling of vehicle behaviour, which is controlled by a set of detailed microscopic rules governing car-following, lane changing, queue discharge and gap acceptance.

Car-following models are a fundamental part of all microscopic simulation models (Brackstone & McDonald, 1999). These models describe the acceleration-speed behaviour of individual vehicles in a traffic stream on a single lane as a function of its leader, when vehicles are travelling in close proximity of each other and cannot overtake (Dijkster, Bovy & Vermijs, 1998). To illustrate this, a generalised car following models is given by:

$$a_{t+\Delta t,i} = b_1 \frac{\Delta v (v_{t+\Delta t,i})^{b_2}}{(\Delta x - L_{veh,i-1})^{b_3}} \quad \text{Equation 2-37}$$

where $\Delta v = (v_{t,i-1} - v_{t,i})$ and $\Delta x = (x_{t,i-1} - x_{t,i})$

where $a_{t+\Delta t,i}$ is the instantaneous acceleration of the i^{th} vehicle at time $t+\Delta t$ (m/s^2), Δt represents reaction time (time lag, s), $v_{t,i-1}$ and $v_{t,i}$ are the instantaneous speed (m/s) of

the leading and following vehicle, respectively, $x_{t,i-1}$ and $x_{t,i}$ represent the location on the road (m) of the leading and following vehicle, respectively, $L_{veh,i-1}$ is the length of the leading vehicle and b_1 , b_2 and b_3 are calibration parameters.

Equation 2-37 shows that the magnitude of acceleration of a vehicle at time t depends on:

- the speed differential between it and the leading vehicle; and
- the separation distance between the two vehicles.

The magnitude of acceleration and the deviation from the desired speed reflects the level of interaction between subsequent vehicles. Thus, car-following models can simulate changes in speed and speed fluctuation of individual vehicles in a traffic stream due to changes in congestion level.

There have been several new developments in car-following models, resulting in more complex and (possibly) more accurate models such as collision avoidance models (e.g. Eissfeldt, Metzler & Wagner, 2000) and car-following models for interrupted flow conditions that include platoon dispersion effects (e.g. Hidas, 1998).

With respect to congestion in emission modelling, however, the most important feature of MSMs is that they simulate the movement in terms of speed and acceleration of individual vehicles in space and time. Although microscopic simulation models typically generate macroscopic traffic performance variables as output (e.g. mean vehicle delay, mean travel time and speed), it is possible to generate (simplified, i.e. straight line) vehicle trajectory or speed-time information of individual vehicles, which can be readily combined with modal emission models (refer to section 3.2.2.1) to estimate emission levels. Indeed, many MSMs incorporate these kind of emission models in the overall modelling process and are able to produce emission estimates (e.g. NRC, 2000; EC, 2000).

Microscopic traffic simulation is an emerging approach to modelling of traffic streams in networks and emission prediction (e.g. Lehmuskosi, Niittymäki & Silfverberg, 2000), due to its ability to reflect stochastic behaviour of traffic and its ability to deal with complex systems without the need for simplifying assumptions. Continuously increasing computing power has facilitated this development. However,

there are also indications that further model development is required. For instance, Hallmark and Guensler (1999) compared emission predictions based on measured driving patterns and modelled vehicle trajectories. Their study indicates that microscopic simulation modelling may not adequately represent actual vehicle trajectories for use in (modal) emission modelling.

2.5.5 Other Traffic Models

A few traffic models were found in the literature that are less commonly applied in practice, but have been used in the modelling of emissions in urban networks:

- Schmidt and coworkers (Schmidt & Schäfer, 1998; Schmidt, Schäfer & Nökel, 1998) developed the SIMTRAP model for large networks where travel speeds of individual vehicles are predicted as a function of density using a fundamental speed-density relationship.
- Matzoros and Van Vliet (refer to section 3.2.2.3) developed a model that uses shock wave theory to predict queue lengths at signalised intersections. This information along with other traffic data are then used to estimate traffic emissions on links.
- Xu (1998) applied shock wave theory to signalised intersections in a similar fashion, estimating idle time, number of stops and VKTs in cruise, acceleration and deceleration mode. This information is then subsequently used to estimate emissions utilizing appropriate input traffic data and emission factors.
- Eissfeldt and coworkers (Eissfeldt & Schrader, 2002; Eissfeldt, Lubrichs & Sentuc, 2002a; 2002b) have developed a simplified microscopic model (Q-Model) that is not based on simulation like MSMs, but considers macroscopic queuing characteristics on links to estimate travel times for individual vehicles.

2.5.6 Traffic Field Data

The use of traffic field data as input in emission modelling of urban networks has a clear advantage in terms of accuracy when compared to modelled data. However, it may be quite acceptable (e.g. from the point of view of cost-effectiveness), depending on the modelling purposes (e.g. screening study²²), to use less accurate output from traffic models. In addition, there may be a practical limitation on the use of field data in the modelling of air pollutant emissions in urban networks.

It will be shown below (and in chapter 5) that availability of important traffic field data is often restricted to certain points in the road network. There are, however, certain kinds of traffic data, which are important to emissions modelling, that are (in principle) available for every road in a network, such as speed limit, type of road, road length, type of intersection and signal settings. It is noted that the interfacing between emission models, traffic models and traffic field data is discussed in section 3.2.3.

As modelling of emissions requires input data for all (or at least the majority of) roads in the network, traffic models are usually the only means to generate (or complement) the full set of these data. Several kinds of traffic data are measured in the field, and they are described below.

- Traffic counts are most commonly measured in road networks. Traffic count data show the number of vehicles passing a point on a road in a specified time period. These data are readily aggregated to traffic volume (and thus VKT) on a link, provided that the number of vehicles leaving and entering at intermediate points along the link are not significant. Count data can be collected by manual count surveys or automatic traffic detection devices (Austroads, 1993), such as passage detectors (e.g. pneumatic tubes) and presence detectors (e.g. induction loop detectors). Most urban traffic control (UTC) systems are based exclusively around induction loop detectors implanted in the road surface

²² Emission models applied for screening purposes do not have to be accurate, they only have to be conservative.

(Dougherty, Kirby & Boyle, 1993) and they allow for comprehensive real-time data acquisition of traffic volumes²³.

- Delay may be measured directly as part of a travel time study or through path tracing of individual vehicles, input-output surveys or queue length and delay surveys. Similar to queue data, delay data may only be available for specific points in the network (Richardson, 1982).
- Space mean speed data is directly measured by dual-loop detectors (i.e. two closely spaced induction loop detectors), which may be used on major roads (e.g. freeways). In case of single-loop detectors, space mean speed may be estimated from measured traffic volume and occupancy data (Hellinga, 2002). Speed data for short sections of road may be collected manually using e.g. enoscopes, radar guns or video analysis (Taylor, Bonsall & Young, 2000).
- (Mean) travel times, and thus (mean) travel speeds, can be measured on specific segments of road or entire routes using travel time studies (Turner, Lomax & Levinson, 1996, Bullock *et al.*, 2003). These studies are commonly conducted on major roads, for example, to measure the effectiveness of a transport system (Herman & Lam, 1974).
- Direct measurement of density in the field is often difficult, requiring a vantage point for photographing or videotaping in order to observe significant lengths of roads. However, density can be estimated using percent occupancy, which is measured by presence loop detectors. Alternatively, density may be computed from using field data on traffic volume and speed (e.g. TRB, 2000, p. 23-12).
- Basic vehicle classification data (e.g. light vehicle, heavy vehicle, perhaps a few heavy vehicle sub classes) is usually available for major roads (Taylor & Young, 1988). More comprehensive classification data, which, as will be shown in chapter 5, is needed for emission estimation, is more difficult to obtain since they are usually collected by less common manual classified counting surveys or video image surveys (Taylor, Bonsall & Young, 2000). For a detailed breakdown of traffic composition additional data therefore need to be extracted from other sources such as the National Bureau of Statistics or separate

²³ In addition, video cameras mounted at strategic points on the network may be used in traffic control centres to provide visual information on traffic conditions.

modelling of fleet age distributions and linkage to specific vehicle categories is required (an example is shown in section 5.1.2).

- Queue data may be collected by manual surveys (e.g. vehicle-in-queue counts, input-output surveys) or video image surveys. Observing queue variables is usually a laborious, site-specific and time-specific task and it is only practical to measure queues in individual situations (TRB, 1992)²⁴.

It is clear that several kinds of traffic data are collected in the field, although the extent to which this is done varies substantially. This affects the use of field data in emission modelling and this is discussed further in section 3.2.3.

²⁴ Most UTC systems provide only information on points in the network and variables such as queue length, link occupancy and link density cannot be directly measured. In case of advanced UTC systems such as SCOOT and SCATS (e.g. Hounsell & McDonald, 2001) these variables are estimated using data from two detectors per lane, one at the stop line (departure flow profile) and the other beyond the maximum back of queue (arrival flow profile). However, most UTC systems use only one detector per lane (and some use one detector for several lanes), largely due to the cost of installing and maintaining induction loop detectors (Luk, 1992). In these cases these variables cannot be estimated.

2.6 Discussion & Conclusion

In this study, congestion is defined as the deterioration of the quality of traffic flow, i.e. a departure from smooth free-flowing driving conditions, on a network element, or in an entire road network, due to increased travel demand and/or reduced capacity for traffic movement. Congestion is a phenomenon that is most prevalent in urban areas, and particularly in morning and afternoon peak periods. As a consequence, the effects of congestion on emissions would be expected to be largest in the morning (typically 7:00 to 9:00 am) and afternoon (typically 4:00 to 6:00 pm) peak periods.

Traffic flow theory, traffic engineering handbooks and empirical evidence show that congestion affects both macroscopic and microscopic characteristics of traffic streams. Three main types of interaction can be distinguished that affect traffic flow conditions, namely interactions with the road environment (“capacity”), with other vehicles (“travel demand”) and with traffic control devices (also “capacity”). In *uninterrupted* traffic (typically non-urban roads), traffic flow is only affected by the road environment and other vehicles in the traffic stream, whereas in *interrupted* conditions (typically urban roads) traffic flow is affected by all three main types of interaction.

Intersections are “capacity pinchpoints” in an urban road network, where vehicles have to stop periodically irrespective of the number of vehicles on the road. Once a vehicle is stopped (e.g. for a red light or a priority sign), subsequent vehicles will have to stop as well (vehicle interaction) until the vehicle in front is able to proceed. Delay at intersections is *the* major factor in the reduction of mean travel speeds of traffic streams on urban roads, and not delay due to vehicle interactions on uninterrupted parts of these roads, as was shown in this chapter. As a consequence, signal settings (cycle time, effective green time) are a particularly important aspect with respect to congestion in urban areas, because they directly determine intersection (and therefore link) capacity.

The review of traffic engineering literature (e.g. shock wave theory) showed that different levels of congestion in traffic streams will be reflected in *driving patterns* of individual vehicles. This is an important finding for this study because it leads to the

conclusion that congestion exerts its effect on traffic emissions through changes in driving patterns of individual vehicles in a traffic stream.

The occurrence of congestion is reflected in a continuum of traffic flow situations, which can be measured and quantified using several variables that are often interrelated. It is proposed that these variables, or congestion indicators, are categorized into two main types (this classification is used in Chapter 4):

1. those based on travel time; and
2. those not based on travel time.

The first category includes (unit) travel time, all “speed” variables (reflecting the different definitions of “speed”), variables reflecting the amount of deviation from free-flow speed (e.g. delay and derived variables), and also density. The second category includes variables that reflect the level of speed fluctuation, queuing measures and variables that reflect traffic demand and/or road capacity such as volume-to-capacity ratio and signal settings. LOS belongs to both types of indicators because it is a derived congestion indicator that actually uses one the two types of congestion indicators, depending on the type of road that is considered.

These variables can be used in an absolute manner, in which (the extent of) departure from free-flow conditions is considered, or in a relative manner, in which the level of congestion of two situations is compared. It was found in this chapter that travel speed can only be used as a congestion indicator to compare congestion levels for the *same* road, *same* type of road or *same* network in different situations.

From the traffic engineering literature, traffic flow theory and empirical studies it became clear that increasing congestion leads to the following consistent quantitative effects:

- a drop in “speed” (all definitions);
- an increase in mean unit travel time;
- an increase in queue length at intersections;
- increased deviation from free-flow speed (e.g. increased delay);
- an increase in the number of stops;

- an increase in speed fluctuation; and
- an increased proportions of time that is spent idling (stopped).

The rate of increase (or decrease) in these variables is initially very small (at relatively small volume-to-capacity ratios), but becomes suddenly much stronger once traffic demand approaches capacity. When this strong non-linear increase occurs, the quality of traffic flow quickly deteriorates and congestion increases strongly.

Due to the complexity of the congestion phenomenon it is appropriate to use multiple congestion indicators in subsequent chapters. This would increase the chance that the level of congestion for a particular situation is accurately quantified. The usefulness of each congestion indicator for use in subsequent chapters was assessed in the course of this chapter. This led to the determination of 20 congestion variables (Table 9, p. 72) for use in subsequent chapters.

It became clear that one particularly important variable for this study, i.e. (mean) travel speed (which is commonly used in emission modelling, as will be seen in Chapter 3), is not an adequate congestion indicator in certain speed intervals. This variable should therefore only be used to compare congestion levels for the same road, similar road types or the same network.

In anticipation of Chapter 3 it was also observed that a number of congestion indicators are explicitly used in emission modelling. This suggests that congestion may be taken into account in emission modelling, although this would depend on the actual emission model that is considered.

Finally, several observations were made (and some issues were raised) in the course of this chapter that concern the interface between traffic data and traffic air emission modelling.

- A number of traffic variables can be defined in different ways and although traffic data used as input in emission modelling appears, on first sight, to be based upon the same definitions, this does not have to be the case. An example is the use of “speed” for which five different definitions (space mean speed, time mean speed, running speed, travel speed, instantaneous speed) were identified. A mismatch between definitions used in the generation of traffic

data and those used in emission modelling could possibly lead to significant errors in emission predictions.

- Several kinds of traffic data are collected in the field at a representative grid of points in the road network. Some kinds of traffic data such as traffic volume are collected more commonly than others such as point speeds and travel speeds, whereas other kinds of traffic data are rarely measured (e.g. speed-time profiles, link density). Traffic models are needed to fill in the data gaps and to predict network performance characteristics for situations that do not yet exist.
- Although it is possible to simulate non-recurrent congestion in traffic models (e.g. an incident can be modelled by modifying "normal" road capacity), in practice this is only done in specific projects (e.g. TNO, 2004b)²⁵. There may, for instance, be a particular interest in repeated incidents such as football matches. Usually, only the effects of *recurring* congestion on traffic activity (e.g. volume) and traffic performance (e.g. mean link speed) are modelled since (estimates of) "average day" road capacities are used in the modelling process to simulate normal traffic patterns in the network. Hence, the overall effects of congestion on air pollutant emissions are potentially underestimated when emission models use output from traffic models.
- A number of issues with the commonly used strategic planning models (SPMs) were identified from the literature with respect to emission prediction. These issues include the accuracy of predicted link speeds, the use of demand flow rate in congested conditions and spatial allocation of emissions. Although these issues may have been addressed to some extent in more detailed traffic models, these models also require more input data, which effectively restricts their application to (relatively) small road networks. This will be discussed further in section 3.2.3.

²⁵ One notable exception is the specific use of real-time traffic data as input to (modified) traffic models. These field data obviously take into account both recurrent and non-recurrent congestion. An example is "MOLA" (Motorway On Line Advisor), which is an enhanced version of the CONTRAM traffic model (Strong *et al.*, 2002). MOLA calculates the effects of different diversion plans and provides advice to traffic operators at a control centre on the best diversion strategy to use in case of an incident, road work, etc. on the network.

- The use of different congestion functions in the predictions of mean link travel speeds in SPMs can lead to quite different results. These differences are largest in congested conditions and they depend on the specific congestion functions that were used in the modelling process. This implies that emission predictions for the same network but based on traffic data from two different SPMs could possibly lead to quite different emission predictions.

3 CURRENT VEHICULAR EMISSION MODELS FOR ROAD TRAFFIC

This chapter starts with an introduction to vehicular emissions to clarify the complexities that are associated with emission modelling. The introduction will discuss the various factors that influence emissions at different levels of analysis, and will discuss which of these factors are relevant with respect to congestion, and are thus important to this study.

It then examines, on the basis of literature review, (current) vehicular emission models that have been developed in different parts of the world and are used or have been used in practise. The focus is directed at the construction of these models, or more specifically, the empirical model base and assumptions, model formulation, data input and model output.

This detailed analysis then leads to a partial answer of the research question if, how, and to what extent, congested traffic flow conditions are included in current emission models. The chapter is concluded with a proposed emission model classification scheme. This scheme is based on the manner and the extent to which the possible effects of congestion are incorporated in modelling process.

3.1 Introduction to Vehicle Emissions and Congestion

This section provides a general introduction to vehicle emissions and answers the question: what are the factors that influence vehicle emissions and how are these factors, and particularly those that are affected by congestion, taken into account in current emission prediction? Three main types of vehicular emissions can be distinguished (e.g. Eggleston *et al.*, 1993):

- hot running emissions;
- cold start exhaust emissions; and
- evaporative emissions.

Hot running emissions are exhaust emissions that occur under “hot stabilized” conditions, which means that the engine and the emission control system (e.g. catalytic converter) have reached their typical operating temperatures (e.g. Faiz, Weaver & Walsh, 1996). Vehicles are generally assumed to have achieved hot stabilised operation by the time the engine temperature has reached 70-80 °C (e.g. LeBlanc *et al.*, 1995).

Cold start emissions are exhaust emissions²⁶ of CO, HC and CO₂ that occur in addition to hot running emissions. These excess emissions occur because cold engine and cold catalyst operate in a non-optimal manner (e.g. Singer *et al.*, 1999).

Evaporative emissions consist of hydrocarbon losses through the vehicle’s fuel system, and different kinds of evaporative HC emissions (i.e. hot soak, diurnal, running loss, resting loss) are distinguished (TRL, 1999). Evaporative emissions are particularly relevant for spark-ignition (SI²⁷) vehicles, but less important for compression-ignition (CI²⁸) vehicles due to the lower volatility of diesel fuel (Bosch, 2000).

²⁶ In the case of catalyst vehicles, NO_x exhaust emissions are increased due to reduced catalyst efficiency during the cold start period. In the case of non-catalyst technology, NO_x exhaust emissions can be lower than in hot running conditions (e.g. Laurikko, 1995).

²⁷ The spark-ignition engine (petrol, LPG, natural gas) derives its power from explosion of the air-fuel mixture.

²⁸ The diesel or compression-ignition engine the fuel burns rather than explodes.

This chapter will show that all emission models predict hot running emissions, but that only a few models explicitly (or implicitly) predict cold start and evaporative emissions. It will also be shown that, even if a model is capable of predicting cold start and evaporative emissions, these predictions are often taken to be independent of driving patterns, and thus congestion.

This means that the possible effects of (changing levels of) congestion on cold start and evaporative emissions are often not (fully) taken into account in current emission models. This may potentially lead to an underestimation of the predicted effects of congestion on emissions. Although the importance of this issue needs to be clarified, the following comments can be made:

- For evaporative emissions this issue may be of limited importance. This is because hot soak, diurnal and resting loss emissions are not affected by congestion, since they occur while a vehicle is parked. The exception are running loss emissions, which occur when the vehicle is being driven. It has been reported that running loss emissions are critically dependent on the driving pattern (Pierson *et al.*, 1999), which indicates that congestion effects should be included in the emission modelling process for this part of evaporative emissions.
- With respect to cold start emissions, there appears to be some controversy on the matter, which needs to be resolved. Some publications specifically state or suggest that cold start emissions are not significantly affected by driving patterns and traffic congestion (e.g. Burmich, 1989). However, other research (e.g. INRETS, 1999b) indicates that cold start emissions are dependent on driving patterns, among several other factors (e.g. trip length, ambient temperature).

Prediction of vehicle emissions is complex because of the combined influence of the vehicle, the driver and local conditions.

In line with section 2.3, three levels of analysis can be distinguished:

1. vehicle;
2. traffic stream (road link);
3. network.

Irrespective of the level of analysis, total emissions (E , unit mass) are predicted by multiplication of an emission factor with appropriate traffic activity data. Emission factors quantify the amount of pollutant emitted and they are usually expressed as mass per unit distance (e_x) at link and network level, although mass per kg of fuel burned may be used instead, and as mass expressed per unit time (e_t) at vehicle level, as will be seen later in this chapter. The corresponding traffic activity data follows from these units, i.e. VKT in the case of e_x and total time spent in particular conditions in the case of e_t .

In emission models, emission factors are a function of various influencing factors, which are discussed below. However, the extent of which these factors are taken into account depends on the actual emission model that is considered, as will be seen later. Figure 13 (next page, prepared by the author) shows which factors are usually considered in emission estimation at which level of analysis.

Vehicle Level

Figure 13 shows that emissions from an individual vehicle in a traffic stream depend on a number of factors, such as:

- use of auxiliary equipment such as air conditioning (Enns *et al.*, 1994);
- engine tuning (Zhang *et al.*, 1995);
- fuel characteristics (CONCAWE, 1999);
- deterioration of engine and emission control components such as catalytic converters, “ageing” effects (INRETS, 1999a);
- ambient temperature and humidity (Laurikko, 1997); and
- geographic location in terms of air density or altitude (Sturm *et al.*, 1996).

These factors may be interrelated and influence different types of emissions. For instance, ambient temperature and humidity affect air conditioning use (US EPA, 1998c), and thus hot running emissions, but also affect the magnitude of evaporative emissions (US EPA, 2001b).

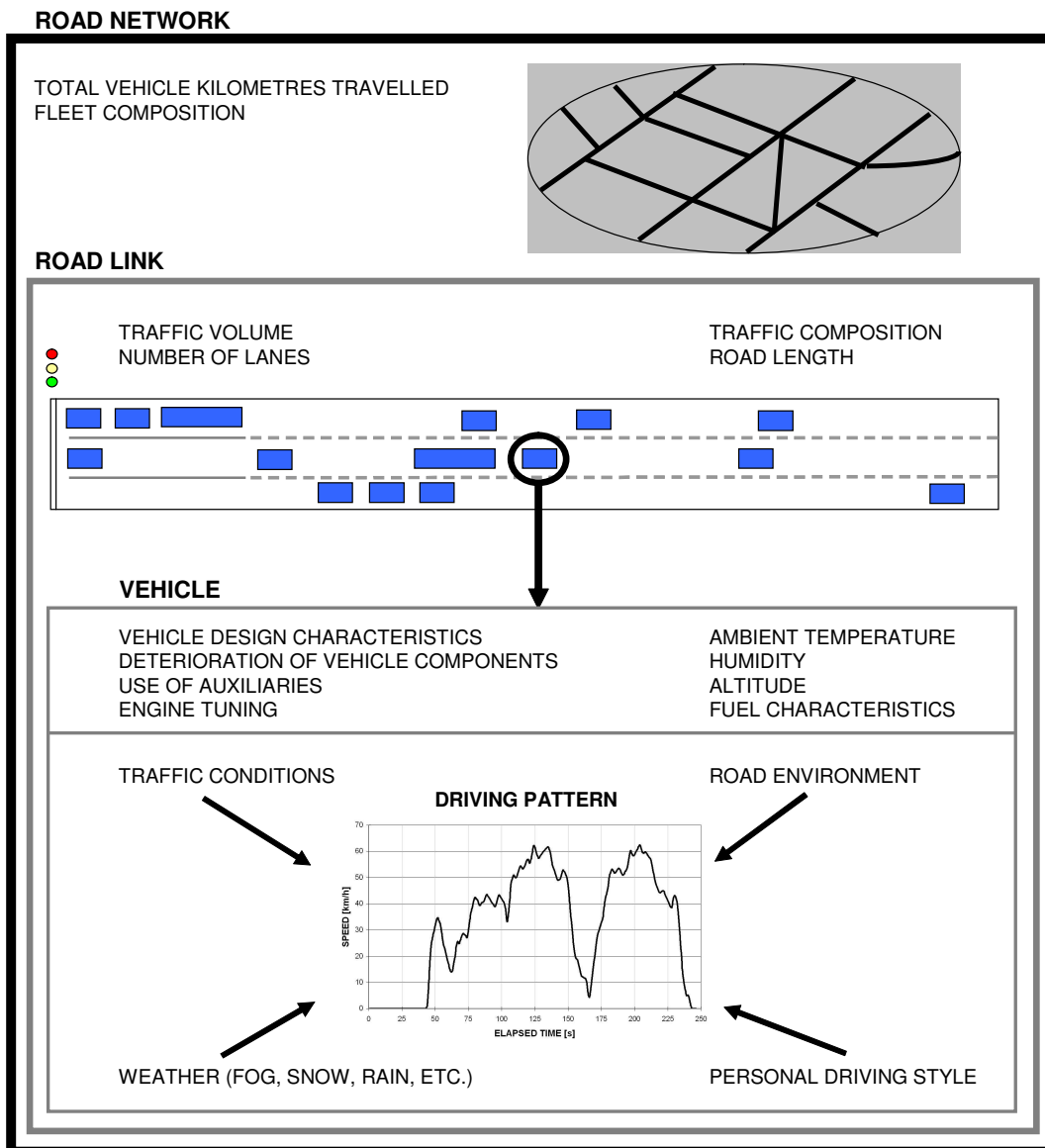


Figure 13 – Influential Factors Included in Emission Modelling at the Different Scales of Individual Vehicle, Road Link and Road Network

Air pollutant emissions vary substantially with vehicle design characteristics, which include (but are not limited to) vehicle size and weight, engine type, type of fuel, presence and type of emission control technology, transmission and aerodynamic characteristics (e.g. frontal area, shape).

It has been observed in empirical studies (e.g. Watson, 1973; Kunselman *et al.*, 1974; Hansen, Winther & Sorenson, 1995) that the influence of driving patterns on emissions and fuel consumption is significant. A general finding (e.g. Watson, 1995; Joumard *et al.*, 1995) is that smooth driving patterns with average speeds typically in the range of 30-60 km/h achieve the best fuel economy (l/km) and lowest emissions (g/km). Empirical evidence identifies the following operating conditions with elevated emission levels:

- emission rates (g/s) of HC and particularly CO increase strongly in the case of (high) *accelerations* and high speeds (Kelly & Groblicki, 1993; LeBlanc *et al.*, 1994);
- emissions rates (g/s) of CO and particularly HC increase strongly during (high) *decelerations* (Koupal & German, 1995; An *et al.*, 1998);
- emission rates (g/s) of CO and HC are higher during *idling* in older cars to help with combustion stability (Heywood, 1997).

These elevated emission from spark-ignition vehicles levels are explained by the air-to-fuel ratio (A/F ratio). Figure 14 (next page) shows how CO, HC and NO_x engine-out exhaust emissions vary with this variable.

Spark-ignition engines normally operate at A/F ratio values between about 13 and 18. At very lean combustion conditions (A/F ratio > 18) concentrations are low for all pollutants. These conditions are, however, not feasible since combustion quality becomes poor and engine operation becomes erratic. Combustion conditions should be close to stoichiometric (A/F ratio ~ 14.6) for smooth and reliable engine operation (Heywood, 1988). The A/F ratio is directly affected by driving conditions (engine load). Fuel-rich engine operation (high CO and HC) occurs in cold-start conditions and during high engine load events such as sharp accelerations, high speeds or steep grades. Fuel-lean operation (high NO_x) may occur during deceleration manoeuvres.

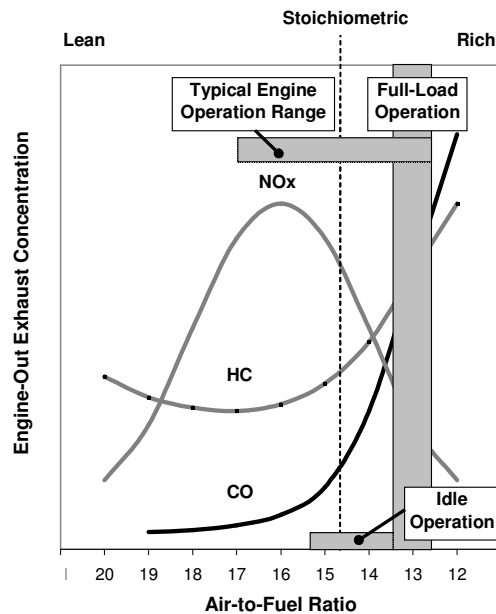


Figure 14 – Variation of Engine-Out Exhaust Emission Concentrations with A/F ratio (Source: Heywood, 1988, p. 571)

The presence of emission control technology such as exhaust catalysts and oxygen sensors further complicates the relationship between vehicle operating conditions and emissions. The now commonly used three-way catalyst (TWC) in spark-ignition vehicles has reportedly reduced CO, HC and NO_x emissions by 70% to over 95% (e.g. Singer *et al.*, 1999). However, the presence of exhaust after-treatment technology makes vehicles very sensitive to the actual shape of driving patterns (e.g. Austin *et al.*, 1993; Barth, Johnston & Tadi, 1996), and thus congestion. This is explained by the fact that catalysts work only well within a few percent change of stoichiometric A/F ratio and a correct catalyst temperature (e.g. Singh & Huber, 2000). Departure from these conditions that occur in practise during short periods of fuel-rich or fuel-lean operation result in short emission peaks that together account for a major part of total vehicle emissions (De Haan & Keller, 2000).

Compared to spark-ignition vehicles, compression-ignition (diesel) vehicles always operate under lean operation conditions. As a consequence, three-way catalytic converters cannot be used in diesel engines (Bosch, 2000) and other forms of emission

control are used instead (e.g. EGR – exhaust gas recirculation). CO and HC emissions from diesel vehicles are typically low when compared to SI vehicles (due to overall lean combustion), whereas PM and NO_x are relatively high (Heywood, 1988).

The latter can be explained by the combustion of a less homogeneous air-fuel mixture and use of a fuel with a higher boiling point when compared to SI-engines. PM (mainly soot) forms in the fuel-rich unburned fuel containing core of the injected fuel spray, whereas NO_x forms in the high temperature fuel-lean and stoichiometric burned gas regions.

Diesel emissions are a function of engine load (TNO, 2004a). For instance, high engine loads increase PM emissions (e.g. Hickman & Graham, 1993). Hence, similar to vehicles with SI engines, the actual shape of the driving pattern (and thus congestion) affects emissions from diesel vehicles (e.g. Hausberger *et al.*, 2003)

The factor “driving pattern” is itself a function of various factors, as can be seen in Figure 13. Importantly, it connects vehicle emissions to congestion, because traffic conditions and road environment (reflected in capacity) directly affect these driving patterns, as has been discussed in Chapter 2 and has been reported in different empirical studies (e.g. Rainford *et al.*, 1987; Newman, Kenworthy & Lyons, 1992; Ericsson, 2000). It is also shown that factors other than congestion affect driving patterns. Examples are road environment (e.g. road grade, Cicero-Fernández *et al.*, 1997), personal driving style, including gear shift behaviour (TNO, 2000), and weather related conditions (Morawska *et al.*, 2001).

Traffic Stream Level

Factors that are relevant at the individual vehicle level do, of course, similarly affect emissions at road link level. However, the situation becomes more complex since a large number of vehicles (traffic stream) need to be considered. As a consequence, two additional model variables are required.

First of all, road emissions are a direct function of the number of vehicles on the road. Thus traffic volume, number of lanes and road length (effectively VKT) must be taken into account.

Secondly, the distribution of vehicles with different vehicle design characteristics within the traffic stream must be considered. A vehicle classification scheme is normally used in emission modelling to take differences in vehicle design characteristics into account to the extent that is considered both sufficient and practical. The vehicles in each class should display sufficient homogeneity to be treated as a single group.

In emission modelling of traffic streams, vehicle technology classes are usually defined by a combination of a few factors such as broad “vehicle type” (e.g. passenger car, heavy-duty vehicle, motorcycle), fuel type and the emission standards that were applicable at the time of production resulting in certain “age groups” (e.g. EA, 2000). The term traffic composition is used to denote the distribution of the different vehicle classes in a traffic stream.

Network Level

At the level of road network, emissions may be computed by aggregation of road link emissions (as is done in Chapter 5), or emissions may be computed at the network level, as will be discussed in sections 3.2.2.7 and 3.2.2.8, for instance by using information on total travel (VKT) and fleet composition (e.g. Moragues & Alcaide, 1996). The fleet composition reflects the distribution of the different vehicle classes within the on-road fleet.

3.2 Review of Emission Models

3.2.1 Introduction to the Empirical Base of Emission Models

Emission models are developed from emission measurements. There are different emission measurement methods available, namely laboratory engine bench testing, laboratory chassis dynamometer testing, on-road measurements, road measurements and tunnel studies. These methods and their use with respect to emission modelling are briefly reviewed and discussed in this section. It will be seen that current emission models are primarily based on laboratory measurements.

Laboratory Measurements

When exhaust emissions are measured in a laboratory, a vehicle (or dismantled engine) is fixed to and operated on a chassis (or engine) dynamometer according to a specific driving cycle, which simulates certain driving conditions (e.g. driving in an urban area). A driving cycle is a predefined driving pattern in which operating conditions in terms of instantaneous speed, and in some cases gearshift points, are specifically defined. Driving cycles are models of driving behaviour that are thought to be representative of certain conditions (e.g. urban driving) and which are developed for a specific class of vehicles (e.g. cars, trucks) and for a specific period of the day (e.g. entire day, peak hour). The test-driver “drives” the vehicle in such a way that the speed-time profile follows, within specified tolerances, the driving cycle that is displayed on a driver's aid placed in view of the driver.

The chassis (or engine) dynamometer is a test bed on which a vehicle (or engine) is fixed with the wheels (or krukas) in contact with a system of fly-wheels and a power absorption unit. These replicate the load experienced by a vehicle as speed varies (e.g. due to inertia, aerodynamic drag and rolling resistance), as would be the case if the vehicle (or engine) had driven on the road.

Typically, a constant volume sampling (CVS) system is used to collect the exhaust gases. The diluted exhaust gases are directly fed to analysis equipment or collected in sample bags for later analysis (e.g. Mole, 1982). The CVS system dilutes the exhaust gases to prevent condensation and maintains a constant total flow rate (Kvatch, Dravitzki & Brown, 1998). Instantaneous or average emission rates can be obtained by multiplication of the total CVS flow with instantaneous or average bag pollutant concentrations. Two approaches of laboratory vehicle exhaust emission measurement may be distinguished:

- Exhaust emissions are collected in a sample bag using CVS and are analysed after completion of the driving cycle.
- Exhaust emissions are measured continuously during the driving cycle using either diluted (CVS) or raw exhaust gas.

The first method, which will be called “bag” sampling (referring to the tedlar bags in which exhaust is stored for analysis), is the dominant approach used for emission model development. It has been used worldwide in emission testing procedures prescribed by emission standards. For example, the commonly used US Federal Test Procedure (FTP72 and FTP75 city and highway cycle), its equivalent Australian test procedures (AS 2077, ADR 27, ADR 37 and AS 2877) and the New European Driving Cycle (NEDC, consisting of an urban part - ECE-15 or UDC, and a non-urban part - EUDC) both use this methodology. It is therefore not surprising that a large body of measurement data based on this method is available and has been used in the development of emission models. The FTP city and NEDC driving cycles are depicted in Figure 15 (next page).

The second method of instantaneous emission measurements is required for the development of instantaneous emission models. This method is now becoming increasingly common for environmental emission factor calculation and engine development (Weilenmann, Bach & Rüdý, 2000). There are some additional aspects that specifically concern this second method such as correction for the time lag in the sampling and analysis system before measured emission values can be correlated with driving conditions (Atjay, Weilenmann & Soltic, 2005).

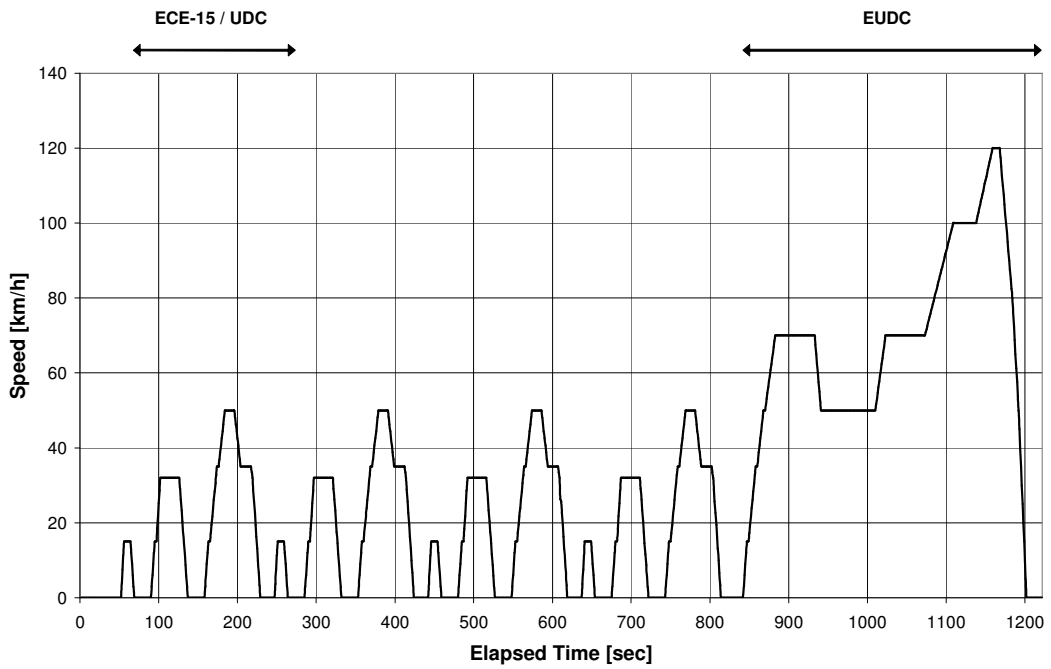
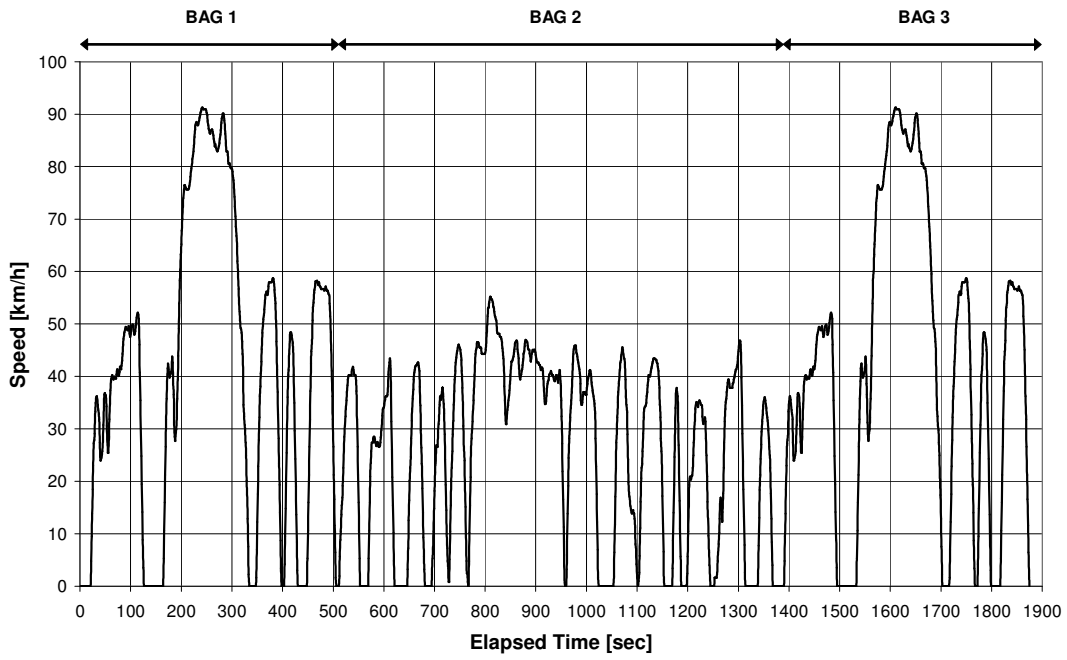


Figure 15 – Standard Driving Cycles (US FTP75 City and EU NEDC)

An advantage of laboratory measurements is that they are conducted under controlled conditions. This enables investigation of specific aspects that influence emissions such as driving pattern and ambient temperature. A disadvantage of this method is the limitation on the number of vehicles or engines that can be tested due to time and budget constraints. Furthermore, the driving cycle employed during testing may not necessarily represent driving conditions that are encountered on the road. This may lead to biased emissions, which will be reflected in the emission models based on these measurements.

For instance, the ECE-15 and EUDC driving cycles are simplified representations of urban and non-urban driving, respectively. Both cycles consists of perfectly constant speeds, ignoring minor speed fluctuations that naturally occur in the real-world, linked by constant accelerations and decelerations, which are also quite low for typical urban driving (e.g. Austin *et al.*, 1993). It has been reported that emission factors based on the ECE-15 and EUDC cycles underestimate emissions in “real-world” driving by up to 50-60% (e.g. Joumard *et al.*, 2000).

Also the FTP city driving cycle, which was developed in the early 1970s, is thought not to be representative of modern urban driving due to low acceleration rates and limited speeds present in the cycle (e.g. St. Denis *et al.*, 1994). For instance, Watson (1995) found that hydrocarbon emission levels in “real-world” driving (i.e. as presented by the AUC or Australian Urban Cycle, which has been developed in the 1990s) are considerably higher than might be expected from the FTP cycle test, i.e. a factor of 2.2 for catalyst vehicles and a factor of 1.5 for non-catalyst vehicles. Similarly, recent experimental data published by DoTRS (2001) shows even higher AUC/FTP ratios for individual catalyst vehicles of up to a factor of 16. This demonstrates again the sensitivity of emissions, from modern vehicles in particular, to the driving pattern.

On-Board Measurements

In addition to dynamometer testing, researchers have used vehicles with on-board measurement systems to collect emissions and driving pattern data while they are driving on the road. In this way real-world exhaust emissions may be collected in a sample bag (e.g. Kvatch, Dravitzki & Brown, 1998), which can be analysed after

completion of the trip to obtain average emission rates (g/km). Alternatively, emissions may be analysed and data processed and stored in real-time to obtain instantaneous emission rates (g/s) (e.g. Staab & Schürmann, 1987).

Although research of this sort has provided valuable insights in real world vehicle emissions, it has not been used to date in the development of current emission models²⁹, with possibly the only exception being the emission model introduced by Rose *et al.* (1965), which is also the first emission model published in the literature.

This may be due to the costs, the size and weight of these on-board systems, which have prohibited general application of this method in emission measurements. Another issue has been the quality of the on-road measurements. It has been shown that on-road measurements can deviate substantially (up to a factor of five) from laboratory measurements and that on-road systems can experience measurement problems such as calibration drift, "out of range" errors and cross-sensitivity of certain pollutants (Elst, Smokers & Koning, 2004). Another disadvantage may be the lack of control over certain factors (e.g. wind speed, temperature) that affect emission rates.

Nevertheless, this method now seems to be evolving towards more general application. For example, US EPA (US EPA, 2002b & 2002c) regards this method as the future for their vehicle emission measurements and emission modelling, as more realistic emission rates for e.g. acceleration and deceleration conditions can be obtained using this methodology. Further advances in measurement technology such as portable on-road instruments (Frey, Unal & Chen, 2002) clearly support this development.

Road Measurements

Three types of road measurements were identified in the literature:

- remote-sensing;
- in-traffic immission sampling; and
- fixed-point immission sampling.

²⁹ It is noted that various fuel consumption models (e.g. Watson, Milkins & Marshall, 1980; Post *et al.*, 1984; Bowyer, Açkelik & Biggs, 1985; Taylor & Young, 1996; Leung & Williams, 2000) are (partly) based on experimental on-road data.

Remote-sensing provides a practical approach to routinely measure instantaneous on-road exhaust emissions from large fleets of individual vehicles at certain locations in the road network resulting in fuel-based emission factors, i.e. g/kg of fuel (Zhang *et al.*, 1995), which can be used in emission modelling as will be shown later. Remote-sensing has contributed to an increased understanding of real world emission behaviour of vehicles (e.g. high emitters) and it is a promising technique for emission model validation purposes (e.g. Sjödin & Lenner, 1995).

There are however some issues with this approach that complicate its use for emission model development such as the representativeness of the remote sensing measurements for the entire fleet, the limited range of operating conditions that are usually measured, and correct apportionment of fuel-use activity data within the study area (e.g. Singer & Harley, 2000).

In-traffic immission sampling was reported in only one study (EPAV, 1999). A vehicle in a moving traffic stream was used to sample air about 1 meter above the vehicle and emissions computed by making assumptions about average fuel consumption and the ratio of pollutant concentrations to CO₂. This approach was an innovative way of determining average vehicle fleet emissions, but its accuracy limited by its assumptions and its application limited to a few road sections (expensive) and operating conditions (e.g. idle not included). It may therefore be most useful as a validation tool.

Fixed-point immission sampling has been used for indirect estimation of mean emission factors from traffic streams (“inverse” dispersion modelling). Ambient air pollutant concentrations are monitored at the kerbside (e.g. Zweidinger *et al.*, 1988) or at a point above the road (e.g. Morawska *et al.*, 2001). Measurements of background concentrations, traffic data and meteorological data are collected concurrently.

Emission factors are subsequently computed through consideration of dispersion processes and traffic conditions (e.g. volume, composition, speed). Simplifying assumptions need to be made, for instance perfect mixing or steady-state speeds. This approach provides point measurements of a few sites in a network and a comprehensive set of data generally do not exist. This complicates its use for emission model development. Furthermore, certain operating conditions may not be measured

(e.g. queuing) and it may not be possible to develop more disaggregated emission factors, e.g. for different types of vehicles or for different types of emissions (e.g. cold start). This approach, too, may therefore be most useful as a validation tool.

Tunnel Studies

A large number of tunnel studies have been conducted to date (e.g. Duffy & Nelson, 1996; Miguel, Kirchstetter & Harley, 1998; Staehelin *et al.*, 1998). These studies have been used to measure emissions from a large fleet sample, reflecting traffic composition, state of maintenance, driving behaviour, road grade effects etc. An advantage of tunnel studies is that emissions are determined from a large fleet sample, which also includes badly maintained vehicles. Moreover, measurements are carried out in relatively controlled conditions compared to, for example, road measurements.

This technique has been used for model validation purposes. However, a disadvantage of tunnel studies is that they represent only a limited range of operating conditions, typically smooth uncongested high speed driving, which might not translate to other driving conditions, for example urban driving on arterial roads with several intersections. This limits the use of tunnel studies in the development of emission models. In addition, tunnel study results rely on indirect measurements, rather than direct exhaust measurements, which may introduce unknown errors (e.g. Rogak *et al.*, 1998).

3.2.2 A Review of Emission Models

Several vehicle emission models are used worldwide to estimate road traffic emissions. This section reviews the various models that were found in the literature. Models are discussed with respect to empirical model base and the manner in which emissions are predicted (model structure). Emission models have been grouped based on similarities in model structure. The following categories of emission models were identified from the literature:

1. modal emission models (section 3.2.2.1);
2. speed and speed fluctuation emission models (section 3.2.2.2);
3. queuing emission model - Matzoros model (section 3.2.2.3);
4. reconstructed speed-time profile emission model - TEE model (section 3.2.2.4);
5. travel speed emission models (section 3.2.2.5);
6. traffic situation emission models (section 3.2.2.6);
7. area-wide emission models (section 3.2.2.7); and
8. fuel-based emission models (section 3.2.2.8).

The information presented in this section is based on the available literature and on personal communication with professionals in the field of emission modelling.

3.2.2.1 Instantaneous and Aggregate Modal Emission Models

The term “modal” model is used to denote emission models that explicitly simulate the effect of different operating modes (NRC, 2000). The earliest work on emission models was directed at developing modal models. Over recent years, international research has focused more strongly on the development of modal emission models as it is believed by some researchers (e.g. TRL, 1999; US EPA, 2001a) that this will lead to more accurate emission assessments at local scale compared to more aggregate models. Five categories of modal emission models can be distinguished in the literature:

1. instantaneous acceleration-speed matrix model;
2. instantaneous engine speed/load matrix model;
3. instantaneous analytical speed-acceleration functions;
4. instantaneous power based model; and
5. aggregate modal emission model.

A characteristic feature of these models is that they all require a substantial amount of input data. This is particularly so for the first four types of modal model, which need

instantaneous (usually second-by-second) speed-time data as input and often require information on vehicle-specific parameters. The last type of modal model requires a modal activity distribution, which can also be presented in terms of a simplified driving pattern consisting of a predetermined sequence of fundamental driving modes.

Instantaneous Acceleration-Speed Matrix Model

This model category basically is a lookup table (matrix) that provides instantaneous emission factors (grams per unit time). The most common form of this lookup table is two-dimensional, with rows representing a speed interval and the columns representing an acceleration interval, which are typically expressed as either “acceleration” or “acceleration × speed” (e.g. St. Denis & Winer, 1994; TRL, 1999). The emission factors (g/s) presented in the matrix show the mean of a distribution of second-by-second emission factor values that were obtained from continuous emission sampling over (a) driving cycle(s) (e.g. Watson *et al.*, 1983).

Kent, Post and coworkers (Kent, Post & Tomlin, 1982; Post *et al.*, 1983, 1984 & 1985) developed Australian matrix models (i.e. instantaneous acceleration versus speed) for hot running fuel consumption and emissions. Their models were based on continuous dynamometer testing of 164 spark-ignition (leaded petrol) and 16 compression ignition (diesel) passenger cars using the ADR 27 (CoA, 1984a-c) and AS 2077 driving cycles (FORS, 1996). Analysis of these matrices reportedly revealed good linear correlations between matrix emission factor values and instantaneous power output of the vehicle (Post *et al.*, 1983, 1984 & 1985), which led to the subsequent development of power based models, which are discussed later in this section.

A more current overseas model of this type is the European DRIVE-MODEM³⁰ hot running emission model (Joumard *et al.*, 1995; Joumard, Jost & Hickman, 1995; André & Pronello, 1996 & 1997; TUG, 1998). The model presents emission factors in a speed and “acceleration × speed” matrix. It is based on continuous dynamometer testing of 129 petrol (catalyst and non-catalyst) and 21 diesel passenger cars using 14 “MODEM”

³⁰ The MODEM model (Modelling of Emissions and Fuel Consumption in Urban Areas, DRIVE Project V1053) was derived from the DRIVE research program.

driving cycles, which were developed from on-road measurements in six European urban areas using instrumented vehicles.

Instantaneous Engine Speed/Load Matrix Model

These type of modal models are steady state or transient emission and fuel consumption matrices, which tabulates instantaneous emission factors (g/s) as functions of engine speed (rpm) and engine load (torque).

Steady state matrices are developed from measurements of fuel consumption and emissions using engine or vehicle dynamometer testing at certain constant target engine speed and load combinations, whereas transient maps incorporate steady state (cruise) as well as transient (i.e. accelerating and decelerating) conditions. They are essential tools for vehicle manufacturers in optimising vehicle design (e.g. Watson, Milkins & Marshall, 1979).

The emission matrices need to be combined with additional models to simulate gear shift behaviour and to compute engine load and engine speed from speed-time data, gear shift and road gradient data. Information such as gear ratios and wheel size are also needed, before total fuel consumption and emissions can be estimated for the prescribed driving pattern (Watson, 1980; Barth *et al.*, 1996).

The US VEMISS model is an example of a current steady-state emission and fuel consumption map (Koupal & German, 1995). This model is based on dynamometer testing of 29 passenger cars using three driving cycles, including the FTP city cycle, and steady-state tests. The vehicle simulation model DCMOD (Orbital, 1995) is an Australian example of this type of model and it is specifically designed to predict emissions over a pre-specified driving cycle. This model is based on dynamometer testing of passenger cars using the FTP city and highway driving cycles, the EDC and steady-state tests.

PHEM (Passenger car and Heavy-duty vehicle Emission Model) is a recent European example that is nearing completion (Zalinger, Ahn & Hausberger, 2005). This model is based on dynamometer testing of an unspecified number of passenger cars using 15 driving cycles and an unspecified number of heavy-duty vehicle engines using a number of unspecified driving cycles.

Instantaneous Analytical Speed-Acceleration Functions

The earliest work on emission models resulted in the development of analytical functions for the fundamental driving modes using instantaneous speed and acceleration. In the US, Kunselman *et al.* (1974) developed the “Modal Analysis Model” for 11 vehicle classes, which established instantaneous emission factor models (g/s) for HC, CO and NO_x for the four fundamental modes of driving:

Equation 3-1

$$e_t = b_1 + b_2 v_t + b_3 a_t + b_4 v_t a_t + b_5 v_t^2 + b_6 a_t^2 + b_7 v_t^2 a_t + b_8 v_t a_t^2 + b_9 v_t^2 a_t^2$$

where v_t and a_t are the (second-by-second) instantaneous speed (m/s) and acceleration (m/s²). The b_1 - b_9 model parameters are regression constants, which are a function of driving mode (i.e. steady-state cruise, idle, acceleration). This model is based on dynamometer emission testing on 1020 (petrol) light-duty vehicles using the SDS (Surveillance Driving Sequence) driving cycle. This driving cycle is defined in terms of 37 distinct driving modes, which can be idle, steady-state cruising at different speeds or (constant) acceleration/deceleration manoeuvres from a specified initial to a final speed.

Kent and Mudford (1979) developed a similar Australian model for prediction of hot running HC, CO, NO_x and CO₂ emission factors (g/s). The model is based on continuous dynamometer testing of 28 passenger cars using a modified US SDS driving cycle.

The European model developed by Cernuschi *et al.* (1995) is another example of this kind of modal model. Here, a second-order polynomial relationship between instantaneous speed and the combined hot running and cold start emission factor (mg/s) was developed for five different acceleration classes. The model is based on continuous dynamometer testing using four driving cycles, i.e. the ECE-15 driving cycle and three other cycles developed from on-road measurements in Milan, Italy. Eight (catalyst and non-catalyst) petrol passenger cars and two diesel passenger cars were tested.

Instantaneous Power Based Model

Compared to the empirical instantaneous models discussed in previous sections, power based modelling provides a different approach where emissions are expressed as a function of several causal variables. Power based modelling is based on the theoretical consideration that engine power is required to overcome different resistive forces. These energy sinks consist of power required to run certain engine and vehicle accessories (e.g. air conditioning) and power required to overcome engine friction, drivetrain resistance, tire resistance, air drag, road gradient and vehicle inertia (Post *et al.*, 1984). In power based modelling fuel consumption and exhaust emissions are predicted as a function of instantaneous power expended by a vehicle.

Power-based emission modelling has been used in Australia for quite some time. Kent, Post and coworkers (Kent, Post & Tomlin, 1982; Post *et al.*, 1983, 1984 & 1985) developed a power based model from hot running instantaneous fuel consumption and emission maps, which were based on continuous dynamometer testing of 164 petrol and 13 diesel passenger cars using the ADR 27 driving cycle. The model is based on a linear relationship between instantaneous fuel consumption or HC and NO_x emissions and required engine power output. It was found that CO did not show any simple power demand relationship.

The energy-related Biggs-Akçelik model (Biggs & Akçelik, 1985; 1986; Akçelik & Besley, 2003) is another example of an Australian hot running power-based model. This model is very similar to the power based model developed by Kent, Post and coworkers, with the main difference being an additional model term to better account for hard accelerations and a different approach to calibrate model parameters. However, a problem with these two models is that their emission prediction algorithms have not been updated for new vehicle technologies (e.g. cars with catalytic converters) that have been introduced into the Australian vehicle fleet in time.

An example of a current power based model that has been calibrated with recent Australian emissions data is CVEM or CSIRO Vehicle Emissions Model (Williams *et al.*, 1994, Williams, Shenouda & Carras, 1994; Leung & Williams, 2000; Lilley, Williams & Carras, 2001). CVEM is an extension and modification of the model developed by

Kent, Post and coworkers. Hot running exhaust CO, HC and NO_x emission factors (g/s) for spark-ignition (petrol) and compression ignition (diesel) vehicles are computed by:

$$e_t = \gamma EC + \beta Z_t \quad \text{Equation 3-2}$$

where γ is a variable that represents the emission rate at idle conditions (g/min.l), EC is the engine capacity (l) and β is a measure of the efficiency of power generation (ml/min.kW). γ and β are vehicle technology and pollutant specific parameters, which are calibrated using dynamometer test data. The total instantaneous power Z_t (kW) is calculated as:

Equation 3-3

$$Z_t = \left(b_1 v_t^2 M \right) + \left(b_2 v_t M + b_3 v_t^2 M \right) + \left(b_4 v_t^3 A C_d \right) + \left(b_5 v_t M \left[a_t + g \text{ SIN}(\theta) \right] \right)$$

where M is vehicle mass (kg), C_d is the aerodynamic drag coefficient, A is the frontal area of the vehicle (m²), g is the gravitational constant (9.81 m/s²) and θ is the road gradient. The b_1 - b_5 model parameters are constants. In addition, CVEM incorporates further models for cold start and catalyst performance.

The CVEM model parameters have been calibrated through integration over the ADR 27 and ADR 37 driving cycles and subsequent fitting to emissions data based on dynamometer testing using these driving cycles. Recent emissions data for 611 petrol passenger cars (FORS, 1996) has been used for calibration of CVEM. For diesel vehicles, the experimental dynamometer emissions data provided from a more recent study (NEPC, 2000) have been processed to determine the best fit model coefficients.

A renewed interest in the United States in power based modelling has led to the recent development of CMEM or Comprehensive Modal Emissions Model (Barth *et al.*, 1996; An *et al.*, 1997; Williams *et al.*, 1999; Schulz, Younglove & Barth, 2000). CMEM is an extension and modification of earlier work by An and Ross (An & Ross, 1993 a-c, Ross & An, 1993), and it uses several engine-related variables such as engine speed,

thermal efficiency and engine power output (Z_t) to model instantaneous fuel consumption (g/s). Z_t is computed in a similar fashion as Equation 3-3.

Hot running and cold start *engine-out* emissions (g/s) are computed as a function of instantaneous fuel consumption and air-to-fuel ratio. Hot running and cold start *exhaust* emissions are then modelled using the instantaneous engine-out emissions and a catalyst performance algorithm. CMEM is calibrated using test data from continuous dynamometer testing of 340 light-duty petrol vehicles (catalyst, non-catalyst), which are based on three driving cycles, including the FTP cycle.

Aggregate Modal Emission Models (Fundamental Driving Mode)

More aggregate modal models have been developed as well. The elemental Biggs-Akçelik model (Biggs & Akçelik, 1985) is an example of this type of model. The model estimates the emissions over any road section by the sum of the hot running emissions during each fundamental driving mode (cruise, idle, acceleration, deceleration) over that section. The minimum input data required are cruise speed (that is, assuming that the initial speed in acceleration and the final speed in deceleration are both zero), average grade, total section distance and stopped time. This model is used in the intersection model SIDRA (Akçelik & Besley, 2003).

Similarly, the LANES (Links and Network Emissions from SATURN) model is an aggregate modal model. This model is a postprocessor emission model for the (dense network) SATURN model. Emissions are estimated using an analytical function that uses as input VKT, cruise speed, total delay and total number of primary (major) and secondary stops (queue move-up). LANES (EC, 1995; Tate & Bell, 2000) uses an augmented version of the modal DRIVE-MODEM emission model.

Other aggregate modal emission models were also identified in the literature. Ludwig, Sandys & Moon (1973) used an exponential CO emission factor model for steady-speed driving and a constant emission factor for idling. In addition, CO emissions for each vehicle stop and subsequent start were computed using an exponential function of the steady-speed driving speed.

The US road traffic dispersion model CALINE4 (FHWA, 1989) utilises algorithms for intersection analysis that convert hot running CO emission factors (g/km) from travel

speed models to modal CO emission rates (g/s). Different algorithms were developed for acceleration, which uses average acceleration and travel speed for the acceleration manoeuvre, and cruise, which uses (constant) cruise speed. These algorithms were based on dynamometer testing of 81 light-duty vehicles using the US 37-Mode SDS driving cycle. Idle emission factors are also input to the model and deceleration emission rates are assumed to be 1.5 times the idle rates (Benson, 1992).

Taylor and Young (1996) developed a model to enable estimation of fuel consumption and hot running CO emissions for a current Australian catalyst passenger car. The CO emissions per unit distance (g/km) or $e_{x,CO}$ are computed as follows:

Equation 3-4

$$e_x = \frac{b_1 t_{idle} + (b_2 + b_3 v_c + b_4 v_c^2 - b_5 v_c^3) t_c + b_6 \exp(b_7 v_{af}) t_a + (b_8 v_{di} + b_9 v_{di}^2) t_d}{L}$$

where t_{idle} , t_c , t_a and t_d are time spent (s) in idle, cruise, acceleration and deceleration mode, respectively, v_c is (constant) cruise speed (m/s), v_{af} is acceleration final speed (km/h), v_{di} is deceleration initial speed (km/h), L is the total section distance (km) and the other parameters either have a fixed value or are a function of cruise speed, acceleration or deceleration rate. The model is based on “modal” dynamometer testing of one catalyst petrol car, i.e. emission measurements over the four fundamental driving modes, using the FTP75 driving cycle and continuous dynamometer testing of several steady speeds and acceleration and deceleration manoeuvres.

3.2.2.2 Speed and Speed Fluctuation Emission Models

These type of models incorporate variables that reflect the level of speed and speed fluctuation averaged over an entire driving cycle. In practice, these models require instantaneous driving pattern data to compute cycle variable values.

Following earlier work by Evans, Herman and Lam (1976), the PKE-average speed model was developed by Watson and co-workers (Watson, Milkins & Marshall, 1980; Watson, 1980; Watson *et al.*, 1983). Watson, Milkins and Marshall (1980) introduced

the kinetic energy term “PKE”, which stands for “positive acceleration kinetic energy”. Computation of PKE (m/s²) needs the lowest and peak speed values of all accelerations (refer to Equation 2-25, page 60), which effectively means that speed-time profiles are required as input.

The PKE model was derived as an extension of the average travel speed model with the new PKE term added to increase its accuracy (Biggs & Akelik, 1985). The hot running emissions per unit distance or e_x (g/km) is computed as follows (Watson *et al.*, 1982; Watson, Holyoake & Milkins, 1983):

Equation 3-5

$$e_x = k_1 + \frac{k_2}{v_{run}} + k_3 v_{run} + k_4 v_{run}^2 + \frac{k_5 T_{idle}}{L} + k_6 PKE + \frac{k_7 PKE}{v_{run}} + k_8 PKE^2$$

where the k_1 - k_8 model parameters are fixed constants. Watson *et al.* (1982) presented parameter values for two petrol cars for the prediction of CO, HC and NO_x emissions using Equation 3-5. These coefficients were obtained through regression of laboratory test data based on a range of steady speed driving tests and the segmented (microtrip) ADR 27, Melbourne Initial and Sydney driving cycles. Coefficients required to run the PKE - average speed emission model for model years after 1979 were not found in the literature.

Fomunung and co-workers (Fomunung, Washington & Guensler, 1999; Fomunung *et al.*, 2000) reported on the development of an aggregate modal emission modelling technique that is being incorporated into the MEASURE³¹ modelling framework. The model is based on dynamometer testing using 20 different driving cycles. MEASURE needs speed-time profile data as input and then predicts instantaneous hot running exhaust emission factors (g/s) for different light-duty vehicle classes as a function of a variety of selected variables, which depend on the pollutant considered. For example, CO emission factors (g/s) are computed by:

³¹ Mobile Emissions Assessment System for Urban and Regional Evaluation.

$$e_x = b_1 \text{FTP}_{\text{bag2}} \times 10^{\{b_2 v + b_3 A + b_4 I1 + b_5 I2 + b_6 I3 + b_7 T1 + b_8 T2 + b_9 F1 + b_{10} C + b_{11} S + b_{12} F2\}} \quad \text{Equation 3-6}$$

where FTP_{bag2} are emissions obtained over the second subcycle of the FTP driving cycle (g/s), v is average (cycle) speed (mph), A is the proportion of the driving cycle with accelerations exceeding 3 mph/s (1.34 m/s²), $I1$ is the proportion of the driving cycle with “acceleration × speed” exceeding 60 mph²/s, $I2$ is an interaction variable between the proportion of the driving cycle with “acceleration × speed” exceeding 45 mph²/s and a vehicle with no air injection, $I3$ is an interaction variable for a vehicle with automatic transmission on the proportion of the driving cycle with “acceleration × speed” exceeding 90 mph²/s, $T1$ is an interaction variable for a three-speed manual transmission at idle, $T2$ is an interaction variable for a five-speed manual transmission vehicle with mileage below 25000 miles, $F1$ is an interaction variable for a vehicle that has throttle body fuel injection and pump air injection, C is an interaction variable for a vehicle with automatic transmission and three-way catalyst, S is an interaction variable for a vehicle with four-speed manual transmission and pump air injection and $F2$ is a flag used to tag a vehicle emitting high CO emissions.

Smit, Smokers and Schoen (2005) and Smit *et al.* (2006a) recently reported on the development of a new generation emission model for passenger cars (VERSIT+). VERSIT+ requires speed-time profile data as input, which are then used to calculate various cycle variables that are subsequently input to regression equations to predict average hot running exhaust emission factors (g/km) for different vehicle classes. The model is based on a large number of dynamometer emission tests (about 12000) over 126 different driving cycles.

Rexeis and Hausberger (2005) recently reported on the development of the “Network Emission Model” (NEMO). This model uses five cycle variables (average speed, maximum and minimum speed, average acceleration and deceleration) and vehicle specifications to compute the cycle average engine power, which is subsequently used to compute emission factors for different model classes. The model is based on data produced by the models PHEM and HBEFA, the latter which is discussed later.

3.2.2.3 Queuing Emission Model (Matzoros Emission Model)

Matzoros and Van Vliet (Matzoros, 1990; Matzoros & Van Vliet, 1992) developed a model that accepts as input traffic data from the SATURN traffic model and instantaneous emission factor matrices (refer to section 3.2.2.1). The model uses traffic flow theory to predict the change in queue variables in time and distinguishes between three intersection types, namely signalised, priority and roundabouts.

The Matzoros emission model uses shock wave theory (refer to section 2.2.2) to predict queue lengths at signalised intersections. Queue length is then used to predict the time spent idling, accelerating, decelerating and cruising of all vehicles in the traffic stream at any point along the road. Stochastic queuing theory is used to model air pollutant emissions from road traffic streams at unsignalised intersections, i.e. priority intersections or roundabouts. A matrix with emission factors (which may include both hot running and cold start emissions, but this is up to the user) for the four fundamental driving modes is used to predict link emissions.

The model's main purpose is to estimate the distribution of emissions along road links with a minimum amount of input data. In order to run, the model requires input data such as (constant) cruise speed, intersection type and signal settings.

3.2.2.4 Reconstructed Speed-Time Profile Emission Model (TEE Model)

Since this model will be used in Chapter 5 (on the basis of selection criteria that are discussed later), it is discussed in more detail than the models that have been discussed in previous sections. The European TEE (Traffic Energy and Emission) model is a modelling framework that incorporates different emission models (EC, 1995; Negrenti, 1996; 1998; 1999; 2001; Negrenti & Zanini, 1999; Negrenti & Parenti, 2002; 2003):

- a detailed speed cycle model;
- a reconstructed simplified cycle model (TEE-REC);
- a corrected average speed model (TEE-KCF); and
- average speed model.

The detailed speed cycle model is equivalent to the instantaneous DRIVE-MODEM model (refer to section 3.2.2.1.) and the average speed model is equivalent to the COPERT model (refer to section 3.2.2.5). In this section, the two remaining emission models, i.e. TEE-REC and TEE-KCF, are discussed to the extent as is possible from the available literature and personal communication with the model developer. It is noted that the reconstructed simplified cycle model is regarded as an intermediate model in the development of the TEE-KCF model.

In the reconstructed simplified cycle model (TEE-REC) a speed-time profile or driving pattern is “reconstructed” inside the TEE model in terms of the four fundamental driving modes with predefined instantaneous speed and acceleration levels. Hot running link emissions are then calculated by using the reconstructed speed-time profile as input to the instantaneous DRIVE-MODEM emission factors.

The TEE model generates reconstructed speed-time profiles as a function of travel speed, traffic density, green time ratio and link length. The reconstructed cycle is divided into a free-flow segment and an intersection segment. The shape of the free-flow segment depends on traffic density, whereas the intersection segment depends on

the duration of the green phase and cycle time at the traffic light. Traffic density (veh/km.lane) is computed by the model as (pers. comm., Dr. E. Negrenti, 22-02-04):

$$k = \frac{q_y}{v N_l} \quad \text{Equation 3-7}$$

where q_y is traffic volume on link y (veh/h) and N_l is the number of lanes. Normalised traffic density is then computed by dividing k by 140 veh/km.lane (pers. comm., Negrenti, 22-02-04). Normalised density represents the presence of other vehicles and is used to calculate the fractions of time spent in each fundamental driving mode using the relationship shown in Figure 16.

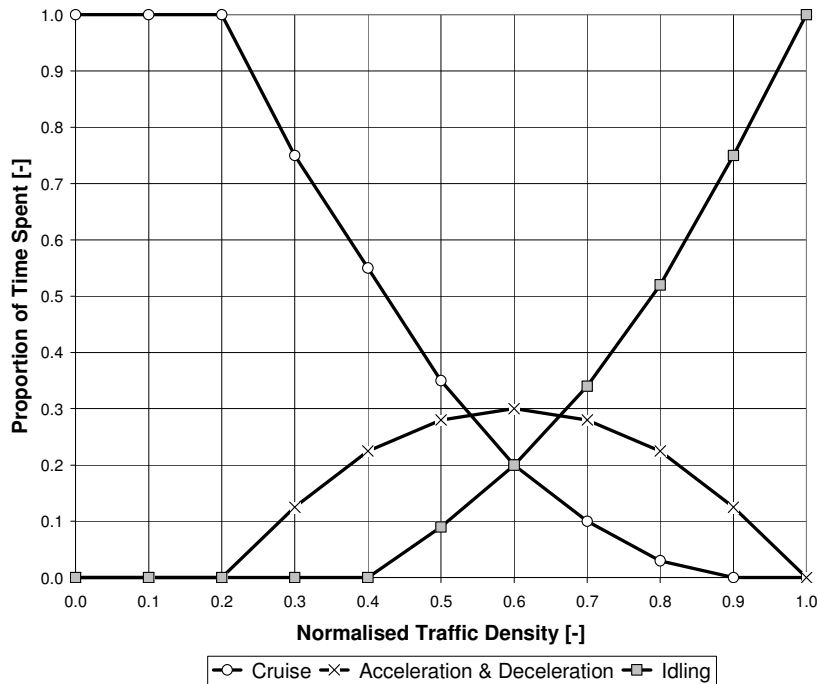


Figure 16 – Fundamental TEE Model Relationship for Uninterrupted Conditions

This relationship between density and time spent in each fundamental driving mode is a hypothetical one that needs validation. It is based on information from the traffic engineering literature, i.e. the US Highway Capacity Manual (point when traffic flow

departs from smooth driving conditions), driving pattern data (maximum time spent in acceleration/deceleration) and anecdotal evidence (all time spent in idling in traffic jams) (pers. comm., Dr. E. Negrenti, 18-09-02). To date, the TEE-KCF model has undergone several verification tests and limited model validation (EC, 1995; Negrenti, 1998), which are discussed in section 5.5.2.

The time spent in acceleration and deceleration is used to estimate the number of acceleration events on the basis of hypothesis of driver behaviour and acceleration rates derived from driving pattern data. In order to account for power limitation of vehicles, acceleration rates are speed dependent.

The presence of a traffic light is simulated by an additional deceleration-idle-acceleration speed-time segment. This combined information then results in a reconstructed speed-time profile, which reflects a set of constant acceleration and deceleration rates and steady-state cruise or idling.

Two examples of reconstructed cycles are presented in Figure 17. These cycles were reproduced from Negrenti (1998, Figure 2). The “High Speed Cycle” would represent a typical cycle for a link with low traffic density and no traffic light. The “Low Speed Cycle” would represent a typical cycle for a link with high traffic density and no traffic light.

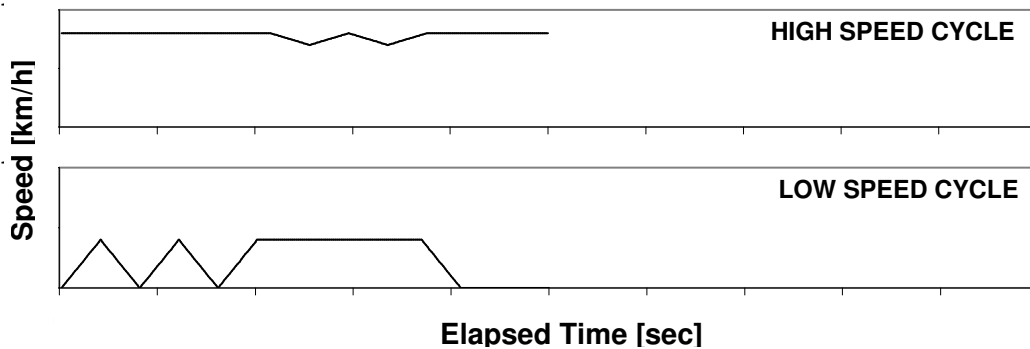


Figure 17 – Reconstructed TEE Cycles

The corrected average speed model (TEE-KCF) corrects output emission factors generated by the COPERT III travel speed emission model for different levels of speed

fluctuation around the mean value due to congestion. The corrected average speed model uses a “kinematic correction factor” or “congestion correction factor” (KCF) in the following way:

$$e_{x,corrected} = KCF \times e_x \quad \text{Equation 3-8}$$

where e_x is the hot running emission factor (g/km) computed by COPERT and $e_{x, corrected}$ is the hot running emission factor (g/km) corrected for the effects of congestion. This model was developed because different combinations of the fundamental driving modes in a speed-time profile can give the same value for average travel speed, but significantly different emission factors. The kinematic correction factor for CO emissions³² is calculated with the following model:

Equation 3-9

$$KCF = b_1 \times \left(b_2 + b_3 \text{EXP} \left(\frac{k}{b_4} \right) \right) \times \left(b_5 + b_6 \text{EXP} \left(\frac{-g}{b_7} \right) \right) \times \left(b_8 + b_9 \text{EXP} \left(\frac{-L}{b_{10}} \right) \right) \\ \times \left(b_{11} + b_{12} \text{EXP} \left(\frac{-v}{b_{13}} \right) \right)$$

where k is the (mean) traffic density (veh/km), g is the effective green time ratio of intersection at the end point of the link, L is link length (km) and v is average link travel speed (km/h). The determination of the constants b_1 - b_{13} is discussed below.

It is noted that the reconstructed simplified cycle model and the corrected average speed model require the same input data. The difference between these models is that the simplified cycle model uses solely modal emission factors, whereas the corrected average speed model also uses travel speed emission factor data generated by the COPERT model.

³² At this stage of its development, TEE-KCF only simulates the effects of congestion on CO emissions.

The KCF values were calculated in five steps:

1. Predefined combinations of link density, average link speed, green fraction and link length were used to calculate reconstructed speed profiles for 500 links.
2. The travel speeds of these 500 links were used to calculate total emissions for each link with the COPERT emission model.
3. These 500 reconstructed speed profiles were then combined with the DRIVE-MODEM emission model to calculate total emissions for each link.
4. The KCFs for each link were calculated as the ratio of link emissions determined by DRIVE-MODEM to link emissions determined by COPERT.
5. The KCF model constants b_1 - b_{13} were finally determined by fitting Equation 3-9 to the generated data set of calculated KCF values for the 500 links, using a specifically developed software program that optimised the lowest average correlation error to this data set.

It is clear from the discussion that the TEE model considers the presence of other vehicles and the presence of a traffic lights as the fundamental cause for speed fluctuation. This is in line with traffic flow theory. It also aligns with the definition of congestion used in this study, where increased traffic demand would be reflected in the density variable and the green time ratio and the link length (i.e. intersection density) variables reflect a common cause (signalised intersections) for reduced capacity in urban areas. There are, however, two aspects of the TEE model that do not seem to correspond entirely to what would be expected from traffic flow conditions under congested conditions on urban roads:

- In section 2 it became clear that signalised intersections, and not vehicle interactions on the free-flow portion of the links leading to these intersections, are the major cause for congestion on urban roads. In congested (saturated) conditions, vehicles may have to move through the queue (multiple stops, slow speed) over several subsequent signal cycles before they can cross the stop line. However, in the TEE model intersections are simply modelled as a single additional stop-and-go driving pattern. It may be possible that the intersection effects are

partly included in free-flow portion of the reconstructed cycle, but it is not clear if this is the case.

- When normalised traffic density is equal to unity, Figure 16 shows that traffic is at stand-still (idling) hundred percent of the time. It is questionable if this is an accurate representation of reality, since vehicles may have to stop regularly and for certain periods of time, but they would normally also exhibit some movement in traffic jams. This would result in a very low travel speed, but not a travel speed of zero.

3.2.2.5 (Average) Travel Speed Emission Models

Since current travel speed models are further investigated in Chapter 4 and will be used in Chapter 5, these models are discussed in similar detail as the TEE model. (Average) travel speed emission models are commonly referred to as average speed emission models. As we will see in due course in this section, these models predict average emission factors for a vehicle class that are driven over a number of different driving patterns, which are characterised in terms of journey travel speed. It is often assumed that this travel speed corresponds to the average travel speed of the entire traffic stream, since the driver simulated “average” traffic behaviour at the time of data collection (e.g. Evans, 1978). It seems more appropriate, however, to refer to these models as travel speed models since they produce mean emission factors for a journey with a certain mean speed. A “true” mean travel speed emission model would incorporate emission factors that were based on a (properly weighted) collection of driving patterns recorded in a traffic stream under homogeneous traffic conditions (e.g. in terms of traffic density and road type) with a certain mean travel speed.

Early Travel Speed Models

Possibly the earliest emission model was published by Rose *et al.* (1965) who found an empirical relationship between HC, CO and CO₂ emissions per unit distance (e_x) and journey travel speed (v) that was well correlated (r between 0.57 and 0.84), but not for

NO_x. Experimental data were obtained by driving a small fleet of light-duty vehicles on four predetermined routes in two US cities, including all types of road and during peak and off-peak hours, while sampling exhaust emissions in sample bags. The bags were analysed in a laboratory after the journey had ended. It was found that the relationship between HC and CO emissions (pounds/mile) and journey travel speed less than about 80 km/h was best satisfied by using a power function:

$$e_x = b_1 v^{-b_2} \quad \text{Equation 3-10}$$

This model formed the basis for the prediction of CO emissions from road traffic in the 1970s (e.g. Kurtzweg, 1973; Ludwig, Sandys & Moon, 1973; Wigan, 1976) and emission factor models of similar form for CO and HC were used in an emission inventory for Sydney, while the emission factor for NO_x was taken as a constant (Iverach *et al.*, 1976).

Evans (1978) found a simple linear relationship between unit travel time T* (sec/km) and hot running engine-out HC emissions (g/km):

$$e_x = b_1 + b_2 T^* \quad \text{or} \quad e_x = b_1 + \frac{b_2}{v} \quad \text{Equation 3-11}$$

The model was based on laboratory dynamometer emission test data from a 12 catalyst cars using the 18 individual segments of the FTP driving cycle. Exhaust emission factors showed large variability and low correlation with this equation due to additional variability associated with catalyst performance. No consistent relations between CO and NO_x and travel speed emerged from the analysis of the data. The work used to accelerate the vehicle (which may be expressed as e.g. PKE) was found to be a better predictor.

Kent & Mudford (1979) collected driving pattern data in Sydney by driving an instrumented vehicle repeatedly on predetermined routes including several types of roads (expressways, arterials, CBD, suburbs) during peak and off-peak hours using the

chase car technique³³. These data were then combined with their instantaneous modal model (refer to 3.2.2.1) to predict average hot running emissions and fuel consumption per km for the driving pattern data points, each representing 10 km of driving. It was found that NO_x emissions can be modelled by a linear function of travel speed and that CO and HC emissions (g/km) for passenger cars could be predicted by Equation 3-10.

Current Travel Speed Models (MOBILE, EMFAC, COPERT & QGEPA)

The emission and fuel consumption models discussed in the previous section have not been updated with respect to new vehicle technologies. This section discusses current travel speed models. These models are MOBILE (US), EMFAC (California), COPERT (EU) and QGEPA (Australia). It is noted that some of these models are also used, possibly in a modified or augmented form, in other countries. For instance, COPERT is used in non-EU countries in Central and Eastern Europe (Zachariadis & Samaras, 1999) and South-America (Corvalán, Osses & Urratia, 2002) and MOBILE is used in Canada (Scott *et al.*, 1997) and Asia (Hao *et al.*, 2000; Mukherjee & Viswanathan, 2001).

The two primary emission models currently in use in the United States are MOBILE and EMFAC (Schulz, Younglove & Barth, 2000). Although a few alternative travel speed emissions models to MOBILE have been developed in the US (e.g. Singh & Huber, 2000), they are in fact similar in the way in which they treat the effect of vehicle operation on emissions.

It will be shown in this section that the US models use basic hot running emission factors in combination with algorithms that are used to correct for travel speed and that the European model uses travel speed directly to compute hot running emission factors. The Australian QGEPA model uses both methods. All models are based on laboratory emission testing using driving cycles, although different cycles are used in different models. It will be seen that driving cycles play a vital role in the development of current travel speed models. They are fundamental building blocks since they form the basis for emissions testing data, which is subsequently used for mathematical model development using statistical techniques.

³³ The survey vehicle follows a randomly selected vehicle in the traffic stream.

MOBILE

US EPA's mobile source emission factor model called "MOBILE" was first developed as MOBILE1 in 1978 and since then has been periodically updated to reflect the ongoing development in emission factor testing, emission control systems, test procedures, emission standards, regulations and improved understanding of in-use emission levels and the factors that influence them. In time, several technical reviews were conducted for the different model versions, which were inspired by field observations that indicated a disagreement between model predictions and actual emission measurements (NRC, 2000).

The most recent version of MOBILE is MOBILE 6 (US EPA, 1998a-c; 1999b-i, 2001b-j; 2002a). The model is based on a large body of experimental data involving thousands of emission tests and a large number of vehicles (pers. comm., US EPA, 26-02-04). MOBILE 6 computes so-called basic emission rates (BERs) for a travel speed of 31.5 km/h, expressed as g/mile, for light-duty petrol vehicles (cars and light "trucks"), which are classified in terms of model year and vehicle technology. These BERs were computed as follows:

1. Total hot running exhaust emissions (g) that were generated during the laboratory test procedure using the FTP72 urban driving cycle (Figure 15, p. 72, bag 1 and 2 only) were divided by total cycle length (mile) to arrive at emission factors (g/mile) for individual vehicles.
2. BERs were computed as the mean emission factor values of the individual vehicle data points in the test fleet.

Speed correction factor (SCF³⁴) algorithms are used to adjust BERs for travel speeds other than 31.5 km/h. These SCFs were created for three different pollutants (CO, HC and NO_x), four road types (freeway, arterial, freeway ramp and local streets) and three vehicle "emission levels" (TIER0 normal-emitter, TIER1 normal-emitter and TIER0

³⁴ The SCF is defined as the ratio of the predicted emission factor at any travel speed to the predicted emission factor at 31.5 km/h for the same vehicle in freeway driving conditions.

high-emitter³⁵). These SCF models are based on an experimental emissions data set, which was created from dynamometer emissions testing of 63 petrol passenger cars and 22 petrol light-duty trucks using a total of eleven road and congestion specific driving cycles and the New York City cycle (US EPA, 1997; 2001a).

The actual SCF algorithms were developed using piece-wise linear regression over predefined speed ranges on the collection of log transformed emission data points of individual test vehicles (pers. comm., US EPA, 11-04-03). Similar to the computation method used for BERs, these emission data points represent the average emission factors in g/mile (> 30 mph) or g/hour (< 30 mph) over each cycle, for each emission level and road type. Assumptions were made on the effect of travel speed on emission factors for the speed ranges for which no emissions data were available (i.e. < 13.1 mph for freeways, < 11.6 mph and > 24.8 mph for arterials). For extremely low travel speeds (< 7.1 mph, 11.4 km/h) and idle conditions speed correction factors were directly taken from MOBILE 5.

MOBILE 6 uses the following algorithm for freeways and arterials to compute hot running emissions per unit distance (e_x) as a function of travel speed for 5 mph speed increments:

$$e_x = \text{SCF} (\text{BER} + \text{EO}) \quad \text{Equation 3-12}$$

where EO is the emission offset, which is a correction factor to account for BER “off-cycle” emissions, i.e. additional emissions due to high power operation which are not included in the BER. EO is a model variable that is calculated as a second order function of BER. Discrete SCF values for arterials and freeways can be found in lookup tables in MOBILE 6 documentation (US EPA, 1999a; 2001a). Figure 18 shows these SCFs for TIER0 normal-emitter vehicles.

³⁵ “TIER” refers to US emission standards where TIER0 (issued in 1981) refers to light-duty vehicles with closed loop carburettor or electronic fuel injection systems and three-way catalysts and TIER1 (issued in 1994) refers to light-duty vehicles with electronic fuel injection systems, EGR (exhaust gas recirculation) and three-way catalysts. TIER1 and TIER0 have similar standards for CO and HC, but a different standard for NO_x (0.25 instead of 0.62 g/km).

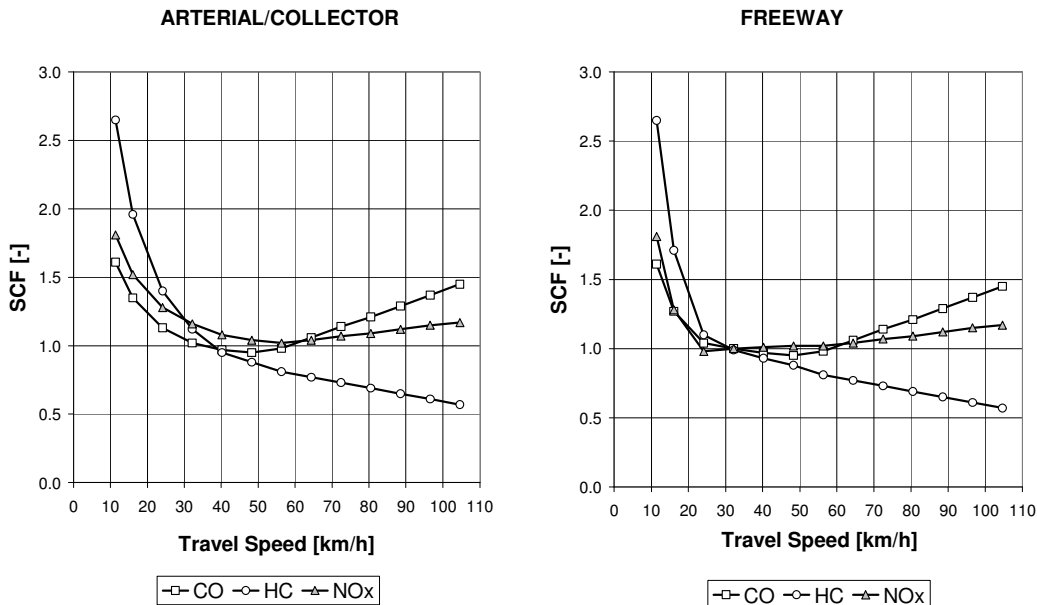


Figure 18 – MOBILE 6 Speed Correction Factors for Light-Duty Catalyst Petrol Vehicles

For diesel vehicles, heavy-duty petrol vehicles and motorcycles MOBILE 6 uses speed correction factors that were previously used in MOBILE 5. No technical reports are available on the development of speed correction factors for diesel vehicles, heavy-duty petrol vehicles and motorcycles, but according to US EPA (pers. comm., 11-11-03) for light-duty vehicles they were derived from chassis dynamometer testing using a few (unspecified) cycles and for heavy-duty vehicles they were derived from engine dynamometer testing using one segmented cycle.

Correction factor algorithms are also used to adjust BERs for other factors including ambient temperature, in-use deterioration, air-conditioning, high emitting vehicles, petrol volatility and implementation of I/M programs. A separate set of algorithms is used in MOBILE 6 to estimate particulate emission factors (US EPA, 2003). These algorithms are not speed-dependent and are quite similar to the previous "PART 5" model that was used to estimate PM emissions. It is noted that separate models for start (cold and hot) and evaporative emissions are incorporated in MOBILE

6. Speed correction factors for three travel speeds are used for evaporative running loss emissions (US EPA, 1994), but not for cold start emissions where excess start emissions (expressed as grams) have been derived from test data on only one driving cycle (FTP) (US EPA, 1999c).

EMFAC

EMFAC (Emissions FACTor model) is a US on-road mobile sources emission factor model developed by the California Air Resources Board (CARB). This model is one of four Motor Vehicle Emission Inventory (MVEI) models that are used together to develop emission inventories in California. EMFAC accepts input from CALIMFAC, which provides basic emission rates, and WEIGHT, which estimates vehicle activity by model year, to produce emission factors, which are then corrected in EMFAC for several factors. The last model BURDEN combines vehicle travel data (VKT, number of starts, number of vehicles) with EMFAC's emission factors to produce the emission inventory.

EMFAC has been periodically updated and has been around since at least 1988 when the first major improvements were reported. The version of EMFAC examined in this thesis is EMFAC 2000 (CARB, 2000; Lin & Niemeier, 2002). Although more recent versions of EMFAC exist (e.g. CARB, 2002), the model structure of EMFAC 2000 has not been changed and the modifications³⁶ are not relevant to this thesis.

EMFAC 2000 model computes basic hot running emission rates (BERs), expressed as g/mile, for light-duty petrol vehicles (< 8500 lbs), which are classified in terms of model year, vehicle technology (carbureted, throttle-body injected and fuel-injected) and "emissions level regime" (normal, moderate, high, very high and super) and for three different air pollutants (CO, HC and NO_x) and CO₂. These BERs have been based on dynamometer testing using either the Unified Cycle (UC) or the FTP72 city cycle, where FTP emissions data has been expressed as "UC-equivalents".

Similar to the BERs in MOBILE 6, BERs are computed as the mean emission factor values of the individual vehicle data points in the test fleet, which were calculated

³⁶ These most recent versions reflect minor modifications to a few specific model components such as mileage accrual rate and I/M assumptions.

as the total emissions (g) that were generated during the laboratory test procedure using the UC driving cycle divided by total cycle length (mile).

The exact number of vehicle tests on which these BERs have been based is not specified, but it is clear that they will involve thousands of tests. For example, model documentation shows that 3151 FTP emission tests for the model years 1975-1992 are incorporated in the model. It also mentions that 1300 emission tests on both the FTP and UC cycles were used to develop a correction factor algorithm which converts FTP based emission factors to UC-equivalents.

Correction factor algorithms are used to adjust BERs for travel speeds that differ from the UC travel speed (39.9 km/h). Speed correction factors (in EMFAC: cycle correction factors) have been developed from 12 driving cycles, which are referred to as the Unified Correction Cycles or UCCs (Gammariello & Long, 1996).

The SCF models are based on an experimental data set based on dynamometer emissions testing of more than 130 vehicles using the UCCs. Mean correction cycle emission factor values were derived from the individual vehicle data points in the test fleet, which were calculated as the total emissions (g) that were generated during the laboratory test procedure using the respective UCC driving cycle divided by total cycle length (mile). The actual SCF models were developed from regression on the UCC/UC ratios of mean data, i.e. the ratios of the mean correction cycle emission factor (g/mile) to the mean of the “Unified Cycle” emission factor (i.e. basic emission rate).

EMFAC 2000 uses the following algorithm to compute hot running emissions per unit distance (e_x) as a function of travel speed:

$$e_x = \text{BER} \times \text{SCF} = \text{BER} \times \text{EXP} \left[b_1(v - 27.4) + b_2(v - 27.4)^2 \right] \quad \text{Equation 3-13}$$

where b_1 and b_2 are model parameters and v is expressed as mph. Figure 19 shows these SCFs for the three technology groups. It is noted that carbureted vehicles (“CARB”) refer to both non-catalyst and oxidation catalyst vehicles, whereas throttle-body (“TBI”) and fuel injected (“FI”) vehicles have three-way catalysts.

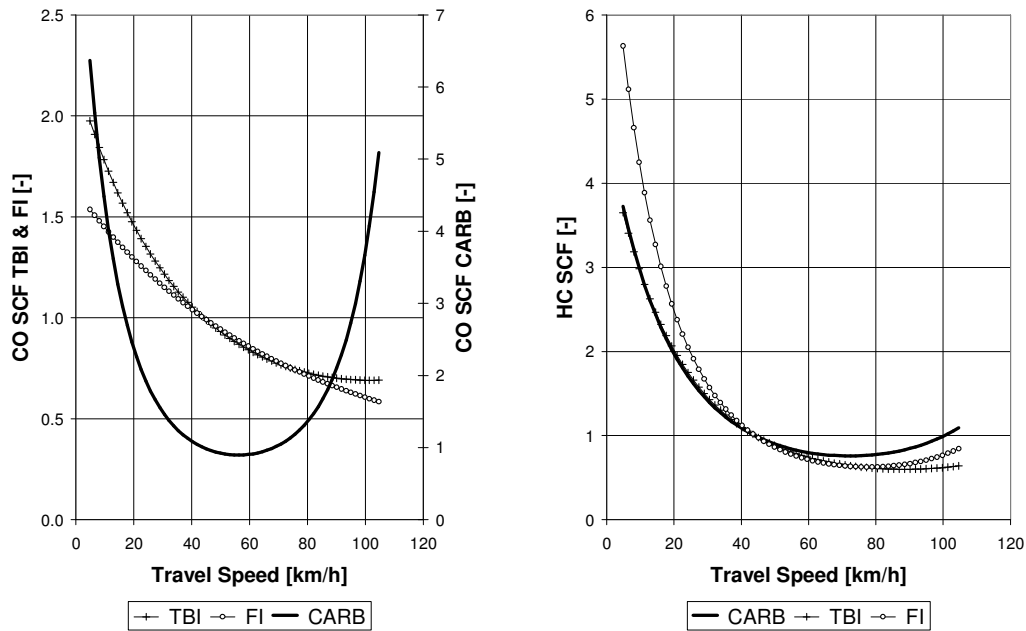


Figure 19 – EMFAC 2000 Cycle Correction Factors for Light-duty Petrol Vehicles

In EMFAC 2000, emission factors for heavy-duty diesel trucks were developed from dynamometer tests using the FTP city cycle for 20 medium diesel trucks (8501-14001 lbs GVW or 3856-6351 kg) and using the EPA Urban Dynamometer Driving Schedule for Heavy-duty Vehicles (UDDS, Test D) for 50 heavy diesel trucks (> 14001 lbs GVW or 6351 kg). Since only one driving cycle was used for each vehicle class, no speed correction factors were developed for heavy-duty diesel trucks.

Correction factor algorithms are also used to adjust BERs to different factors including ambient temperature, in-use deterioration, air-conditioning, humidity, altitude, petrol volatility, fuel composition and implementation of I/M programs. It is noted that separate models for start (cold and hot) and evaporative emissions are also incorporated in EMFAC 2000. No speed correction factors are used for evaporative running loss emissions and for start emissions. It is noted that running loss emissions are modelled as a function of total engine-on time, which is indirectly related to travel speed.

COPERT

The first real European initiative for developing emission inventory methodologies beyond local initiatives was the CORINAIR working group on emission factors for calculating emissions from road traffic. The working group began in 1987 with the aim of developing a methodology for the estimation of vehicle emissions in the reference year 1985. This methodology was transformed into the computer program “COPERT” (Computer Programme to Calculate Emissions from Road Traffic), which was released in 1989 (Eggleston *et al.*, 1993). New versions of COPERT have been released in 1991 (COPERT 90), 1997 (COPERT II) and the most recent in-use version in 2000 (COPERT III). COPERT IV is expected to be released by the end of 2006 (pers. comm., Professor Z. Samaras, 11-01-06). The COPERT model is used in many EU countries and it brings together the results of several studies carried out in both individual EU member states and at the European level.

COPERT III (EEA, 2000) computes hot running fuel consumption rate and CO, HC, PM and NO_x emission factors, expressed as g/km, as a direct function of travel speed. Different statistical models (e.g. linear, exponential, logarithmic, polynomial) are incorporated in COPERT for several technology classes of light-duty vehicles (petrol, diesel and LPG), heavy-duty vehicles (petrol and diesel) and motorcycles. The COPERT III models were developed through regression on emission data points (i.e. average emission factor in g/km over each cycle) of individual test vehicles for each vehicle technology class.

The COPERT models are based on 2836 dynamometer emission tests using several driving cycles. These tests involve mainly petrol passenger cars, but also include diesel and LPG cars and light petrol and diesel vehicles (< 3.5 tonnes). The actual driving cycles that have been used are not documented for all vehicle classes, but it is clear that the models are based on dynamometer emission tests using at least 41 non-legislative driving cycles and one standard driving cycle (FTP Highway cycle).

The hot running emission models for heavy-duty vehicles are based on the Swiss/German Handbook of Emission Factors (refer to section 3.2.2.6). It is noted that COPERT specifies separate models for the prediction of cold start and evaporative emissions. It also provides emission factors (unit mass/km) for a range of non-

regulated pollutants such as speciated hydrocarbons, N₂O, NH₃ and PAHs. Speed correction is incorporated for three ranges of travel speeds for start emissions, but no speed correction is considered for non-regulated pollutant emissions and evaporative running loss emissions. In addition, correction factor algorithms are specified in COPERT to adjust hot running emission factors for in-use deterioration, fuel composition, road gradient and heavy-duty vehicle load.

QGEPA

The Queensland Government Environmental Protection Agency (QGEPA) recently developed an Australian travel speed emission model for use in the air emissions inventory for South-East Queensland (QGEPA, 2002).

The QGEPA model (QGEPA, 2002) consists of a hot running emission factor database (CO, HC, PM and NO_x), expressed as g/km, where emission factors are a function of travel speed (i.e. eleven travel speed points). Emission factors are available for several technology classes of light-duty vehicles (petrol, diesel and LPG), heavy-duty vehicles (diesel, CNG, LPG) and motorcycles.

In the development of the Australian QGEPA model a distinction was made between spark-ignition (petrol, LPG) and compression-ignition vehicles (diesel). For spark-ignition vehicles, 899 Australian dynamometer emission tests based on the FTP72 city cycle have been used to develop basic emission rates (BERs) for each legislative and fuel category. BERs were computed as the mean emission factor values of the individual vehicle data points in the test fleet, which were calculated as the total emissions (g) that were generated during the laboratory test procedure using the FTP72 urban driving cycle divided by total cycle length (km). The SCFs in MOBILE 6 were then used to correct hot running CO, HC and NO_x BERs for travel speeds different from 31.5 km/h.

For compression-ignition vehicles, 950 Australian dynamometer hot running emission tests based on four CUEDC (Composite Urban Emission Drive Cycles) subcycles and DT80 test cycle were used to develop mean emission rates for each

diesel vehicle category³⁷. DT80 emissions data were expressed as CUEDC-equivalents. Regression analysis was then employed to determine the curve of best fit through 6 data points, each with its own travel speed:

- the whole CUEDC cycle;
- the four CUEDC subcycles;
- a freeway “anchor” data point.

The freeway “anchor” data point is an artificial data point at 80 km/h that was used to generate the characteristic gradual upward swing of emission factors at speeds beyond 60 km/h. This data point presents a 10% increase in emissions compared to the mean emission factor for the highway subcycle (51-75 km/h, depending on the vehicle class). In order to facilitate the addition of new test data to the model, the curve of best fit was then linearised with the line intercepts fixed at 10, 30, 60 and 80 km/h. Through linear interpolation and extrapolation (e.g. beyond 80 km/h), mean emission factors were finally calculated for eleven travel speed points.

It is noted that the QGEPA model uses separate emission factors for the prediction of cold start and evaporative emissions. It also provides emission factors (unit mass/km) for a range of non-regulated pollutants such as speciated hydrocarbons, N₂O, NH₃ and PAHs. Speed correction factors for the eleven travel speeds are used for evaporative running loss emissions, but not for start emissions. Emission factors were directly taken from other publications or models such as COPERT III in cases where no Australian emissions test data were available (e.g. motorcycles, CNG and LPG heavy-duty vehicles, specific pollutants).

³⁷ Passenger cars, light goods vehicles with a gross vehicle weight (GVW) below 3.5 tonnes, medium goods vehicles (> 3.5 tonnes GVW), buses, heavy goods vehicles (12-25 tonnes GVW) and heavy goods vehicles (> 25 tonnes GVW).

3.2.2.6 Qualitative and Quantitative Traffic Situation Models

These models use discrete emission factors for predefined “traffic situations”. Some model only use a few traffic situations, whereas others are quite extensive as will be seen below. Traffic situations may be defined either:

1. qualitatively, i.e. in terms of verbal descriptions; or
2. quantitatively, i.e. by a set of quantitative variables.

In terms of input data, traffic situation models require information on vehicle kilometres travelled and determination of which particular traffic situation apply to which specific road link(s). It is noted that application of qualitative traffic situation models may present some difficulties with respect to the last point. This is because the boundaries between traffic situations are not clearly established. For instance, the extent to which “stop-and-go” conditions apply to particular links in a network, or the decision that perhaps another traffic situation would be more suitable, is a matter of opinion of the model user. This is not an issue for quantitative traffic situation models because traffic situation boundaries are clearly defined.

Qualitative Traffic Situation Models

In Australia, traffic situation emission models have been used extensively in the development of urban emission inventories (e.g. Neylon & Collins, 1982; NSW EPA & Coffey, 1997). In the development of these models, the FTP city cycle was arbitrarily divided into a series of segments that would reflect four different flow types, namely “free-flow freeway”, “free-flow main roads (arterials)”, “free-flow unclassified roads (residential and minor roads)” and “forced or congested peak hour flow”. Neylon and Collins (1982) subsequently used these four subcycles in dynamometer emissions testing of 37 non-catalyst petrol cars and calculated the mean hot running emission factors (g/km) for each flow-road type³⁸. Williams *et al.* (1994) later presented mean

³⁸ It is noted that the residential/minor road type combines both hot running and cold start emissions.

emission factors derived from dynamometer testing of 1500 Australian petrol cars using the segmented FTP city cycle.

A current Australian example is the Emissions Estimation Technique Manual for Aggregated Emissions from Motor Vehicles (EA, 2000). This manual provides emission factors for three road types (arterial, freeway, residential).

An overseas traffic situation emission model is the Swiss/German/Austrian Handbook of Emission Factors (“Handbuch der Emissionsfaktoren des Strassenverkehrs”) or HBEFA³⁹. The manual, model description and background information on HBEFA are not available in English (only in German), so information on this model had to be extracted indirectly from other documentation.

HBEFA provides emission factors for a variety of traffic situations (e.g. stop-and-go driving, driving at low acceleration) and road types for each pollutant and vehicle type (TUG, 1998). The development of the Handbook has principally been based on two separate parts.

The first part was driving cycle development. Real-world driving patterns were measured using instrumented vehicles for a wide range of driving conditions from high speed Autobahn conditions to stop-and-go traffic in urban centres. Statistical analysis of these data resulted in 43 driving cycles for different road types and congestion levels (i.e. 13 urban, 3 rural, 14 highway and 13 special driving conditions). The second part was the development of exhaust emission maps, which were based on continuous chassis dynamometer testing of more than 300 light-duty petrol and diesel vehicles using several driving cycles (e.g. FTP, NEDC, German Autobahn cycles)

With respect to heavy-duty vehicles, the Handbook is based on dynamometer testing of 36 diesel engines using different test cycles (13-mode, US Transient and TÜV-FIGE cycles) to produce emission maps. Subsequently, instantaneous road speed, engine speed and engine torque were recorded for 25 commercial heavy-duty vehicles during normal operation on different road types with different congestion levels, road gradients and vehicle loads. Combination of these data with the emission maps resulted in the emission factors that are presented in the Handbook for a wide range of situations.

³⁹ <http://www.hbefa.net/>

Several studies (NEPC 1999a-c; 2000) have been conducted in Australia which are to be used for emission inventory development and in-service emission testing. Diesel hot running emission factors have been developed from dynamometer exhaust emissions testing of 80 diesel vehicles using the CUEDC cycles for four types of road and traffic flow (“congested”, “minor road”, “arterial”, “highway”). These emission factors (named the “NEPC” model) for diesel vehicles have been incorporated into the QGEPA 2002 emission model, as was discussed in section 3.2.2.5.

The CUEDC cycles were constructed from on-road driving pattern data in Sydney collected by instrumented vehicles. In the cycle development process, driving patterns were allocated to each road/flow type according to arbitrarily selected ranges of travel speed and idle time that were considered appropriate.

Currently, a new traffic situation model is being developed in Europe (Keller, 2005). The ARTEMIS/COST 346 Fleet Emission model defines a traffic situation according to speed limit, road type, area type and congestion level (“free-flow”, “heavy”, “saturated”, “stop + go”). This way a total of 276 situations are defined and for each situation a driving cycle is developed for which emission factors are computed using the instantaneous PHEM model. The model is expected to become available in 2006.

Quantitative Traffic Situation Models

The United States Environmental Protection Agency (US EPA, 1997) developed several road type and congestion specific driving cycles. This work resulted in six freeway driving cycles, three arterial driving cycles, one local road cycle and one freeway ramp cycle. Subsequently, US EPA (2001a) conducted hot running laboratory emission tests on a sample of light-duty vehicles using these “congestion and road type” specific driving cycles. Mean emission factors (g/mile) were presented by technology level, road type and congestion level (i.e. LOS category).

These data were then used in the development of MOBILE 6 SCF models (these were discussed in section 3.2.2.5), so the US EPA traffic situation emission model may be regarded as being an intermediate model. Although LOS itself is a qualitative congestion variable, it is determined by quantitative variables such as average travel

speed (refer to section 2.2.6). Hence, the US EPA model is considered to be a quantitative traffic situation model.

Similar to US EPA, the Netherlands Organisation for Applied Scientific Research or TNO (TNO, 2001; Veurman *et al.*, 2002) developed nine congestion specific driving cycles for motorway driving. Subsequent chassis dynamometer testing of 19 petrol, diesel and LPG catalyst and non-catalyst passenger cars resulted in mean hot running emission factors (g/km) by congestion level. Nine levels of congestion are distinguished, which are defined in terms of (ranges of) traffic volume, space mean speed and speed limit.

3.2.2.7 Area-Wide or National Emission Models

This model is the most aggregate emission model. It uses a top-down approach where aggregate traffic activity data for an entire area is combined with a single emission factor, expressed as for example g/km, to compute total area emission levels. Traffic activity data on annual VKTs may be derived from national statistics (e.g. Sturm *et al.*, 1997). Spatial and temporal disaggregation may be performed by assuming that local emissions are proportional to some other variable (e.g. population density, typical traffic flow pattern over a day).

A recent example is the Energy Workbook for Transport (AGO, 1998; 2003), which is used to calculate Australia's annual national greenhouse gas and other emissions from the transport sector. In this Workbook the exhaust emission factors (g/km) for road vehicles are directly derived from dynamometer testing using the FTP city cycle (thus both cold start and hot start are included). Since these type of models assume that fuel consumption and emissions occur at a constant average rate, they are best used for studies that investigate emissions at low spatial (e.g. national, state, area) and temporal resolution (e.g. year).

3.2.2.8 Fuel Based Emission Models

Fuel based emission models use emission factors that are expressed as g of pollutant emitted per kg of fuel burned. These emission factors are derived from on-road emission measurements such as those from remote sensing studies and tunnel studies. A reported advantage of expressing emission factors in these units is that they vary substantially less as driving patterns change when compared to the conventional way of expressing emission factors in g/km.

To estimate emissions, emission factors are then combined with data on the amount of fuel consumed, i.e. fuel sales data. An Australian example is the Energy Workbook for Transport (AGO, 1998). Another well-known example is the IPCC method for national greenhouse gas inventories (IPCC, 1996).

Fuel based emission models have also been used in the US as an independent method for comparison with emissions predictions by the EMFAC and MOBILE travel speed emission models (e.g. Singer & Harley, 1996; Singer *et al.*, 1999; Pokharel, Bishop & Stedman, 2002).

In Europe, a different approach is used in which emission inventories based on the COPERT travel speed emission model are verified using data on total fuel sales. In order to do this, total fuel consumption calculated by using COPERT is compared to actual fuel consumption data. The emission inventory may then be “calibrated” by changing model variables that are expected to be most uncertain, for example total VKT, cold start VKT or actual emission factors (e.g. Samaras, Kyriakis & Zachariadis, 1995; Zachariadis & Samaras, 1999).

3.2.3 Discussion and Conclusions

The previous section has examined the construction of different (types of) emission models that were found in the literature. Many of these (types of) models have been used in practical applications, as was evident from Table 1 (p. 6). This section will now summarize the differences (and similarities) between emission models that were found

in the previous section and will discuss the (practical) implications of these differences for the modelling of congestion effects on emissions in urban networks. It is noted that investigation of emission models has sometimes been complicated by insufficient documentation or a lack of documentation.

Current emission models share a common base; practically all models are based on laboratory measurements. With respect to congestion this is relevant for models that have (solely) used standard driving cycles (e.g. FTP cycles, NEDC) in the model development process. A number of these models have been identified from the literature. Use of standard driving cycles may lead to biased emission models, which in turn would bias the assessment of congestion effects on emissions.

There are various factors that influence emissions from vehicles in traffic streams. The extent to which these factors are taken into account is reflected in emission model complexity, which varies substantially among (types of) emission models. This complexity is not only determined by the number of influencing factors that are included in the model, but also by the number of pollutants and types of emissions that are considered.

For instance, emission models vary in the number and types of correction factor algorithms they may include for e.g. road grade and air-conditioning and additional options they may include (e.g. impact assessment of inspection & maintenance programs).

For this study, however, the focus is on the factor “driving pattern”, which is key because it connects vehicle emissions to congestion. Given the importance of this factor, its use in emission models is discussed separately in section 3.3. One further remark is made here with respect to driving patterns. It has been reported that modern passenger cars with advanced emission control systems are particularly sensitive to changes in driving patterns (and thus congestion). As a consequence, it can be expected, on the basis of this observation, that the increasing penetration of these vehicles in the on-road fleet, could result in a significantly larger (relative) effect of congestion on traffic stream emissions.

The majority of models only predict emissions of regulated pollutants (CO, HC, NO_x, in some cases PM₁₀), and only a few models are explicitly capable of predicting emissions of a number of non-regulated emissions. Even if a model is capable of

predicting emissions of non-regulated emissions (e.g. N₂O, NH₃), these predictions are often independent of driving patterns. An important exception are speciated hydrocarbon emissions (e.g. benzene, toluene, etc.), which are often computed using "hydrocarbon profiles". These profiles represent the hydrocarbon composition and they are commonly expressed as mass fractions of individual compounds relative to total HC or PM (Smit, Bawden & Ormerod, 2002). As a consequence, speciated hydrocarbons are (or can be made) indirectly dependent on driving patterns⁴⁰, provided that modelled HC and PM are sensitive to driving patterns.

This means that if a model incorporates congestion in the modelling process, the effects of congestion can usually be assessed for regulated pollutants and speciated hydrocarbons, but not for other non-regulated pollutants.

All models predict hot running emissions, but only a limited number of models explicitly (or implicitly) predict cold start and evaporative emissions. Even if a model is capable of predicting cold start or evaporative emissions, these predictions are often taken to be independent of driving patterns. As a consequence, the possible effects of congestion on cold start and evaporative emissions are usually not taken into account in current emission models, which may potentially lead to an underestimation of the predicted effects of congestion on total emission levels.

The modelling of emissions from traffic streams requires consideration of all relevant vehicle classes with respect to the air pollutant that is considered. Although all emission models use a certain vehicle classification scheme, which may show different levels of detail, they often are "incomplete" in that they predict emissions for specific vehicle categories only (e.g. passenger cars). Use of incomplete models restricts the assessment of the effects of congestion on emissions to a specific part of traffic streams.

A related aspect is the use of up-to-date emission factors in emission models. Up-to-date models include vehicles with new emission and fuel management systems⁴¹. However, some models use seriously outdated emission factors and their use is therefore limited to a small portion (e.g. only non-catalyst cars) of the current vehicle

⁴⁰ The advantage of these HC profiles is that they have been reported to be remarkably stable for most HCs under different conditions, particularly with respect to HC classes and the more abundant species (Smit, Bawden & Ormerod, 2002).

⁴¹ They may also better reflect the effect of the deterioration on emissions performance.

fleet. For example, the aggregate modal US “Modal Analysis Model” and the modal CALINE4 algorithms have not been updated since 1977 (FHWA, 1989). Similarly, the Australian Biggs-Akçelik family of models use emissions data that were measured in the mid 1980s (Taylor & Young, 1996) and the Australian PKE-speed model has not been updated since 1979 (Watson *et al.*, 1982), which restricts their application to relatively old vehicles in traffic streams.

Examples of complete and up-to-date models are COPERT and MOBILE, and this in part has probably resulted in their common use in air emission modelling, as was shown in Table 1 (p. 6). Another important aspect of emission modelling that affects model application is the interface between emission models, traffic models and field data. Table 1 showed for several studies, what type of traffic data and which type of emission model were employed in the assessment, which leads to the following observations:

- Area-wide and fuel based emission models are applied at metropolitan or regional level, but are have sometimes been used in air emission modelling in practise (7%).
- Travel speed emission models have most often been used in air emission modelling (50%), and they are dominant (72%) in the construction of large (urban, regional, national) emission inventories. Input traffic data have generally been obtained from strategic planning models (62%), although more complex traffic models have been used as well (14%). Traffic data may also be obtained solely from field measurements (21%).
- Traffic situation models have also been regularly used in air emission modelling (24%). When they are applied they are always used for the computation of large emission inventories and in most cases they run on traffic field data alone. In some cases these models are also combined with output from strategic planning models.
- Modal emission models have been used in air emission modelling (14%), and they are always applied to small urban networks. Application of modal emission models is always done in combination with traffic models that are more complex than strategic planning models, i.e. dense network models, analytical delay models or microscopic simulation models.

- Other emission model types such as the Matzoros model, the TEE model and speed fluctuation models have found some limited practical application in air emission modelling (together 5%).

The (predominant) application of certain combinations of emission and traffic models (or traffic field data) at different spatial scales that is observed in Table 1 can be explained by the interaction between purpose of emission modelling and differences in emission model complexity.

The specific purpose of emission predictions affect the choice for certain emission models. Firstly, the purpose determines the size of the study area (and thus size of the modelled road network, i.e. the number of links and nodes) that needs to be considered. For instance, modelling of photochemical smog formation requires consideration of a large regional area (e.g. Helali & Hutchinson, 1994), whereas an air quality assessment in the direct vicinity of a new road requires consideration of only a small road network or possibly a single road (e.g. Meng & Niemeier, 1998).

The size of the study area (i.e. road network) affects input data availability, which subsequently determines the possibility of application of different emission model types. This is because the level of complexity of an emission model is reflected in the extent and level of detail of input data it requires to run. The more complex a model is, the more input data it generally needs. Input data to emission models are generated by traffic models and/or provided by traffic field measurements. However, traffic models are also subject to different levels of complexity and traffic field data is subject to different levels of availability, as was discussed in section 2.5.

More complex traffic models generate more comprehensive output data. For instance, the microscopic simulation model can provide data that are sufficient to run all emission model types. However, more complex traffic models require more comprehensive input data themselves, which, in practise, leads to a reduction in the size of the modelled network in order to keep use of resources within practical and manageable limits (TRB, 1997, p. 62).

Thus, the demand for resources (costs, labour, computer runtime) to generate and process input data to emission models from either traffic models, field data or both, increases with network size. As a consequence, the extent and the level of detail of

available input data is effectively reduced when network size increases (Taylor & Gipps, 1982). In simple terms, complex models can only be applied at small networks and large networks require less complex models. The trade-off between emission model complexity and network size and its consequences for model choice are further discussed in section 5.5.

Finally, from the review of emission models a hierarchy of emission models can be distinguished in terms of the minimum spatial and temporal resolution:

- Instantaneous modal emission models operate at the highest temporal (and therefore spatial) resolution of typically 1 second.
- Both the aggregate modal emission models and the Matzoros queuing model operate at a minimum spatial and associated temporal scale of the fundamental driving mode.
- The speed fluctuation models, travel speed models⁴², reconstructed speed-time profile model (TEE) and traffic situation models operate at the spatial and temporal scale of a driving pattern, which may consist of (a part of) a road or several adjacent roads (journey).
- Area wide and fuel based emission models operate at network resolution for the time period during which driving patterns were sampled in an area.

This hierarchy shows that the most complex emission models with respect to driving pattern input requirements predict emissions at the highest spatial and temporal resolution. A reduction in model complexity is accompanied by a reduction in spatial and temporal resolution. Now the question arises: what is the appropriate minimum spatial and temporal resolution in the modelling of the effects of congestion on emissions in urban networks?

⁴² With respect to the minimum spatial resolution of travel speed models a distinction should be made between MOBILE 6 and the other models. MOBILE 6 was specifically developed to generate link-specific emissions estimates for planning purposes (US EPA, 2001a), and hence its minimum spatial resolution is link level. In contrast, EMFAC 2000 and COPERT III predict emissions for a journey (driving cycle) with a given travel speed, as will be seen in Chapter 4. Their appropriate minimum resolution would appear to be journey level or perhaps at the level of a number of connected links in a network. In practice, however, these models have been used at higher resolution such as area level (CARB, 2000, EEA, 2000), but also at lower resolution to estimate emissions for individual roads (Winther, 1998; Carslaw & Beevers, 2002). In these smaller scale applications, there is a clear difference in spatial and temporal scale of the application (road section) and the model base (journey), which may result in prediction errors.

Traffic flows in urban areas and on roads are by nature highly variable in time and space (Taylor, Bonsall & Young, 2000). As a consequence, so are the levels of congestion in the road network. Because of this large variability, emissions from road traffic are highly variable as well and, in order to capture this variability, emission modelling requires a high temporal and spatial resolution.

In practice, a time resolution of one hour is generally regarded as being sufficient because it aligns with air quality standards for which averaging times ranging from 1 hour to 1 year are of practical interest (Reynolds & Broderick, 2000). This time resolution also aligns with the time period in which highest congestion levels are commonly observed in road networks, i.e. peak hour or peak period. All emission models can be applied at this temporal resolution as long as emission model input data is provided at this resolution.

It appears logical to use link level as a minimum spatial resolution for assessment of the effects of congestion on emissions because at this level, on the one hand, major differences in minimum road capacity (e.g. differences in intersection lay-out and signal settings) are taken into account, and on the other hand, capacities at different points along a link (road environment conditions) would be relatively constant. Furthermore, traffic models generate data at this level. This resolution is in line with the scope of this study as was discussed in section 1.1.

It is noted that, depending on the study purpose, a higher spatial resolution may or may not be appropriate. For instance, when immission levels at certain receptor points near an intersection are predicted, the spatial distribution of emissions along links is probably most appropriate. In contrast, when photochemical smog formation is predicted, emissions data are required for area grid cells (e.g. Harley *et al.*, 1993) and average link emissions seem more appropriate.

It is clear that area-wide and fuel based emission models cannot be applied at this minimum spatial resolution of link level. In addition, they have been rarely used in practise as became clear from Table 1. These families of models are therefore not considered further in the remainder of this thesis.

3.3 Classification of Emission Models With Respect To Congestion

The previous sections introduced and discussed the full range of emission models available. This section now specifically looks at those models in terms of how and to what extent congested flow conditions are addressed or incorporated in the model, based on information presented in the literature. For this I develop a typology of emission models with respect to congestion.

From the models that were reviewed, a number of models explicitly mention congestion to be part of the emission modelling process:

- the TEE corrected average speed model;
- five traffic situation models (US EPA, TNO, CUEDC, FTP, HBEFA, ARTEMIS/COST346 model).

This does not necessarily mean that the other models do not take congestion into account, since they may e.g. implicitly consider congestion in the modelling process. As discussed before, congestion exerts its effect on emissions through changes in driving patterns of vehicles in a traffic stream. Thus, emission models which include driving pattern data in the modelling process have the potential to take congestion into account.

All emission models discussed in section 3.2 include driving pattern data in the modelling process, but this is done in different ways. In this respect, I make a distinction between three main categories of emission models, i.e. models which:

1. have *incorporated* driving pattern data in the development phase of the model (Type I);
2. *generate* driving pattern information in the actual emission modelling process (Type II); or
3. *require* driving pattern data as input (Type III).

Figure 20 shows how these three categories use driving pattern data to predict the effects of congestion on emissions.

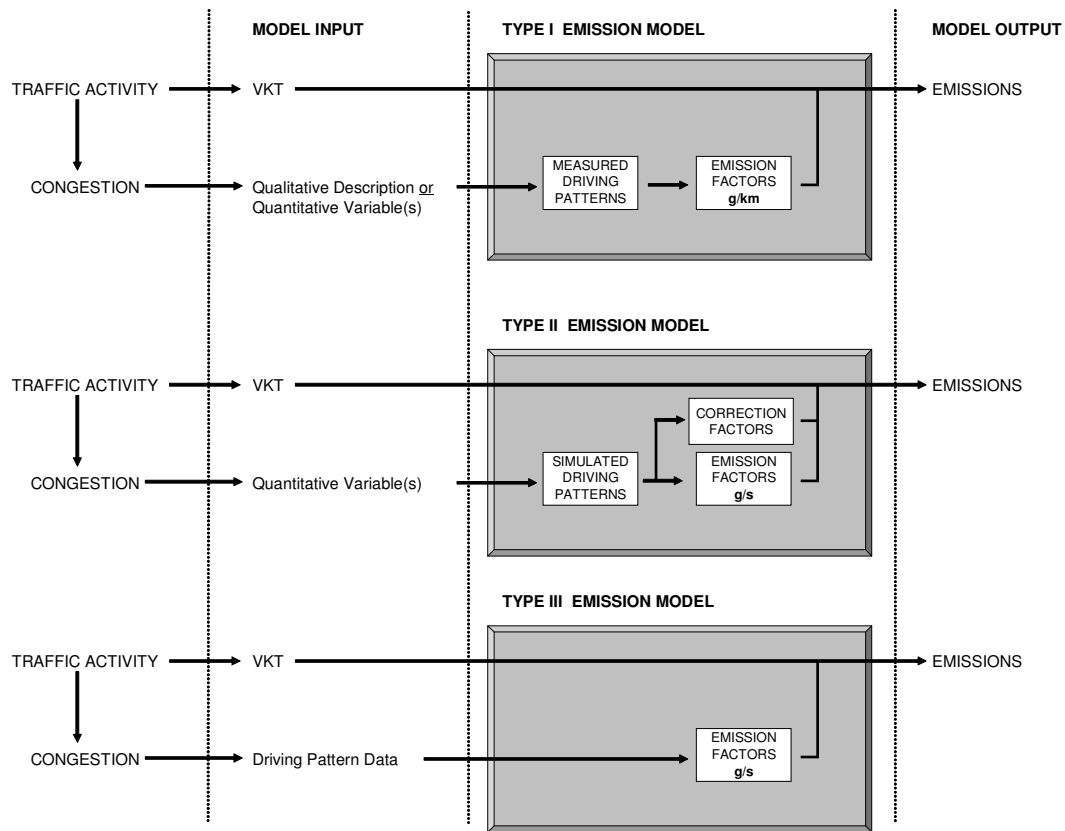


Figure 20 – Type I, II & III Emission Models

In addition to a classification with respect to the manner in which congestion is incorporated in an emission model (type I, II, III), the extent to which congestion is incorporated in an emission model is considered. In this respect, three groups are distinguished:

- congestion is not included (“none”);
- congestion is implicitly included (“implicit”); and
- congestion is explicitly included (“explicit”).

Implicit means that the effects of congestion are inherently considered in the model, but that level of congestion cannot be modified and is therefore beyond the control of the model user. Explicit means that the effects of congestion are modelled by variables that are related to congestion and whose values can be modified by the user.

Type I models have used measured driving pattern data (driving cycles) to develop distance-based emission factors (g/km, which is equivalent to g/VKT). Type I models comprise of area-wide models, fuel-based models, travel speed models and traffic situation models. Emission factors used in type I models are either constant, as is the case for area-wide and fuel-based models, or are a function of:

- one continuous quantitative driving pattern variable (travel speed model);
- a discrete quantitative or qualitative description of a traffic situation (traffic situation model).

Vehicle activity data (VKT) are required as model input, which may be obtained from national statistical data or through combination of traffic volume data with corresponding number of lanes and road lengths. An important feature of type I models is that the driving cycles are fixed and cannot be changed.

Importantly, for all type I models, except the quantitative traffic situation model, it is not immediately obvious what level of congestion is contained in the driving cycles that were used during model development since they are “hidden” in the model. For instance, it may be that the driving cycles that were used are smooth speed-time profiles with almost constant speed (uncongested) or, alternatively, they may have been profiles with large speed fluctuations indicating congested conditions, but this is not evident. Further analysis of the used driving cycles would be required to investigate to what extent (“none” or “implicit”) congestion is incorporated in these type I models, and to address the research question.

It is noted that this does not entirely apply to qualitative traffic situations models, since these models likely reflect, to a large extent, the different congestion levels (traffic situations) that they verbally describe in the model. However, given the often arbitrary nature of cycle development, it would still be useful to investigate and quantify the actual level of congestion that has been incorporated in these cycles.

This is not the case for quantitative traffic situation models, which explicitly include congestion-related variables in the modelling process. Here, prespecified ranges of congestion-related variables are related to fixed driving cycles. It is clear that these type I models do take congestion into account.

Type II emission models *generate* driving pattern data as a function of a number of macroscopic traffic activity and traffic performance variables and road infrastructure characteristics. The reconstructed speed-time profile model (TEE) and Matzoros queuing model are type II models. All type II models require input data on link volume, link length, type of intersection and signal settings (cycle time, effective green time). In addition, the Matzoros queuing model requires information on cruise (free-flow) speed and number of lanes and the TEE model requires information on mean travel speed and traffic density. A further distinction can be made between the TEE and Matzoros queuing (MAT) models, i.e. simulated driving pattern data are used:

- to compute a correction factor for a type I travel speed model (TEE-KCF); or
- to estimate emissions directly using instantaneous emission factors (MAT, TEE-REC).

Strictly speaking, the TEE-KCF model is a type I model since the driving patterns are fixed and cannot be changed. However, it distinguishes itself from type I models by its unique approach and by the consideration of a large number of generated driving patterns (500) that have been used in the development of the correction algorithm. Hence, the model is classified as a type II model. Type II models use different congestion related variables in the emission modelling process and therefore explicitly take congestion into account.

Type III models require actual driving pattern data (modal emission models) or specific congestion variables (speed/speed fluctuation models) as input to determine emission factor values. Modal emission models combine emission factors (g/s) with information on how long these emission factors apply and information on VKT. The speed/speed fluctuation models require driving pattern data to quantify the required input variables (e.g. PKE) and subsequently use VKT data to estimate emissions. Emission models that require driving pattern data as input are fully capable of

modelling the effects of congestion on emissions. Type III models explicitly take congestion into account through their use of actual driving pattern data in the emission modelling process.

With respect to the use of driving pattern data in the modelling process, a further categorisation can be made in terms of the use of simplified or real-world driving pattern data. Simplified refers to the fact that driving patterns are presented as a set of constant speed and constant acceleration segments (i.e. fundamental driving modes: cruise, idle, acceleration, deceleration). This is a simplistic representations of reality because in real driving, e.g.:

- acceleration rates initially increase and then gradually diminish as the desired cruising speed is approached; and
- almost constant variations in throttle position cause minor natural variations in speed.

It has been found that simplified cycles lead to substantially different (lower) emissions than real world cycles (e.g. Joumard *et al.*, 2000). In modelling the effects of congestion on emissions, the preferred approach would be to use real-world instead of simplified driving pattern data to prevent bias. The use of real-world driving pattern data would account for small effects of congestion on instantaneous speed that are not considered in simplified driving patterns.

Finally, emission models can also be classified according to their consideration of different kinds of interactions in traffic streams. As was discussed in section 2.2, congestion may be due to vehicle interactions or traffic control interactions or a combination of both. Emission models that consider both types of interaction are better suited to model congestion effects in urban areas than emission models that would consider only one type of interaction.

The type III models use driving pattern data as input and thus are capable of taking into consideration both types of interaction. As will be seen later, the type II TEE model explicitly takes both types of interaction into account through modelling of the effects of both traffic density and signal settings on the modal activity distribution. In contrast, the type II Matzoros queuing model simulates the effect of signalised and unsignalised

intersections, but does not consider vehicle interactions within the traffic stream. As a result this model cannot be used for uninterrupted urban driving conditions

With respect to the type I models it is not clear if both types of interactions are taken into account. The exception is the TNO traffic situation model which was developed for motorway driving only, and thus cannot be used for interrupted urban driving conditions. For the other type I models it seems very likely that both types of interactions are considered, since these models are commonly based on driving patterns that were collected in urban areas and on different types of roads (as will be shown in section 4.1). This suggests that the other type I models would take both types of interaction into account.

The following table presents my classification of the different types of emission models that were reviewed in section 3.2 according to the various congestion-related aspects that were discussed in this section.

Table 10 – Emission Model Classification With Respect to the Use of Driving Pattern Data

		Interrupted	Uninterrupted	Interrupted & Uninterrupted
Type I Implicit or None	Simplified	-	-	-
	Real-World	-	-	FBM, AWM, ASM
Type I Explicit	Simplified	-	-	-
	Real-World	-	TSM-Q ¹⁾	TSM-V, TSM-Q ²⁾
Type II Explicit	Simplified	MAT	-	TEE
	Real-World	-	-	
Type III Explicit	Simplified	-	-	AMM
	Real-World	-	-	IMM, SFM

¹⁾ Specifically, the TNO motorway model.

²⁾ Specifically, the US EPA model.

Abbreviations used: fuel based model (**FBM**), area-wide emission model (**AWM**), qualitative traffic situation emission model (**TSM-V**), quantitative traffic situation emission model (**TSM-Q**), travel speed emission model (**ASM**), Speed/Fluctuation model (**SFM**), analytical modal emission model (**AMM**), TEE emission model (**TEE**), Matzoros queuing emission model (**MAT**), instantaneous modal emission model (**IMM**)

3.4 Conclusions

This section has reviewed several emission models and has investigated several aspects of the emission modelling process. It was found emission models have been constructed in different ways, which translates into:

- different input requirements;
- a different extent to which influencing factors are included in the model;
- a different extent to which major vehicle classes are considered;
- a different extent to which pollutants and types of emissions are considered; and
- operation at different spatial and temporal resolution

These differences in model complexity affect the interfacing with traffic models and traffic field data. It was found that an increase in network size reduces the availability of emission model input data. As a consequence, practical application of emission models is restricted to certain combinations of (measured or modelled) traffic data and emission models.

A typology of emission models has been developed in this section that reflects the way in which congestion is incorporated in these models. The manner in which driving patterns (or driving cycles) are used in the modelling process or have been used in the development of these models is key to assessing the manner in which and the extent to which congestion is incorporated in current models. The type of model (manner) is determined on the basis of whether an emission model has:

- incorporated driving pattern data in the model development phase (type I);
- generates driving pattern data in the modelling process (type II); or
- requires driving pattern data as input to the modelling process (type III).

With respect to the extent to which congestion has been incorporated (none, implicit, explicit – real-world versus simplified driving patterns – vehicle interactions versus traffic control interactions), the following conclusions follow from this section:

- Type II and III models can use either real-world or simplified driving pattern data, or both, and one particular type II model does not consider vehicle interactions. All type I models are based on real-world driving patterns, and one particular type I model does not consider traffic control interactions.
- All type II and type III models explicitly take congestion into account in the modelling process through their use of actual driving pattern data in the modelling process. The difference between these two model types lies in the level of detail with respect to input data. Whereas type III models require highly detailed microscopic driving pattern data as model input, type II models generate these patterns themselves, although in simplified form, in the modelling process, on the basis of several (macroscopic) traffic stream and road infrastructure variables.
- One family of type I models, quantitative traffic situation models, explicitly take congestion into account through their use of congestion-related variables, which are in turn related to fixed discrete emission factors.
- Another family of type I models, qualitative traffic situation models, also explicitly take congestion into account through verbal description, which includes road types and congestion-related words such as "congested" and "free-flow".
- The other type I models may or may not implicitly take congestion into account, but this is unknown. Given the extensive use of travel speed models in current emission modelling (refer to Table 1, p. 6), it is most important to answer the research question for these models.

The family of type I qualitative traffic situation models, which are regularly applied in emission modelling, has been excluded from further analysis in Chapter 4 and 5 for different reasons. The current NEPC model has been incorporated in the QGEPA 2002 model, which is investigated in Chapters 4 and 5. With respect to the current HBEFA model, there was a practical limitation (language) in terms of analysis and application since it is a German model.

Chapter 4 will now attempt to answer the research question for current travel speed models. This will be done through a detailed analysis of the driving cycles that have been used in the development of these models.

4 CONGESTION IN CURRENT TRAVEL SPEED EMISSION MODELS

The purpose of this chapter is to conduct a further in-depth analysis of a specific family of type I models that is extensively used in practise, i.e. current travel speed emission models (MOBILE 6, EMFAC 2000, COPERT III, QGEPA 2002). This is done to address a part of the research question, which could not be fully addressed in the previous Chapter, specifically for these models:

To what extent (implicit or none) do current travel speed emission models take congestion into account?

The analysis is build up in three parts. Firstly, the development of the driving cycles that have been used in current travel speed models is examined, based on the available literature. This is done to investigate how congestion may be reflected in these cycles from the perspective of cycle construction. It will be seen that this work provides insufficient information to answer the research question of this section, although some important conclusions can be drawn.

Therefore, further examination of the actual driving cycles used in the model development process is conducted. The second part of the analysis examines the driving cycle data (to the extent that they could be obtained from various organisations) in a *qualitative* way, i.e. by visual comparison of cycles used in emission model development with other cycles for which congestion levels are known. It will be seen that this approach goes a long way to answering the research question, but that there remains a need to further substantiate the conclusions that follow from the qualitative approach.

The third part, therefore, consist of a *quantitative* analysis in which mean congestion levels are quantified for each driving cycle, using the congestion indicators that were selected in section 2.4. These mean congestion levels allow for a relative analysis (are there any trends that emerge from the data?) and absolute analysis (does a particular cycle reflect uncongested conditions?) of the driving cycles.

4.1 Driving Cycle Construction and Congestion

The construction of driving cycles can be separated into two parts:

- collection of driving pattern data; and
- cycle construction methods.

It is noted that for the MOBILE, EMFAC and COPERT models, this section is necessarily restricted to a discussion of driving cycles for light-duty vehicles, because the available documentation is limited to this vehicle class. This is not the case for the QGEPA model for which cycle development has been well-documented for both light-duty and heavy-duty vehicles.

Driving Pattern Data Collection

Various methods of driving pattern data collection exist. The US emission models (MOBILE6, EMFAC 2000) for light-duty vehicles have mainly employed the chase car strategy with distance correction using a forward looking laser (US EPA, 1997; Austin *et al.*, 1993; Gammariello & Long, 1996). The chase car strategy dictates that the driver follows randomly selected target vehicles in the traffic stream and attempts to mimic their behaviour by maintaining a constant distance to the target vehicle. Data were collected in large urban areas such as Los Angeles over several predetermined routes and at different times of day and involve travel on all types of road.

An important aspect of data collection was that, in addition to second-by-second speed-time measurements, visual observations regarding roadway type and “perceived” traffic congestion (defined in terms of LOS) were recorded. This means that congestion has *explicitly* been considered as an influencing factor in the data collection process that has eventually led to the development of MOBILE 6 and EMFAC 2000.

With respect to a number of light vehicle classes, which includes petrol passenger cars with three-way catalysts (EURO I), the COPERT III model is based on a collection

of 42 driving cycles that were developed by several European institutions and one standard US cycle (e.g. EC, 1998; TRL, 1999). These institutions⁴³ have been contacted, but it has been difficult to trace back specific information on cycle construction methods used in the development of all these 42 cycles. Therefore, only a portion of the COPERT III cycles can be discussed in detail. A substantial portion of the COPERT III cycles is based on the DRIVE-MODEM driving pattern database⁴⁴ that were collected for a month by 58 privately-owned vehicles with on-board instrumentation in six European cities. Vehicle owners were instructed to drive like they normally would.

The driving pattern data that were used in the QGEPa 2002 model were collected using a small fleet of instrumented vehicles (light-duty and heavy-duty diesel vehicles). These vehicles followed several preselected routes within 60 km radius of Sydney city centre on different road types and at different times of day (NEPC, 1999b).

Cycle Construction Methods

After collecting substantial amounts of driving pattern data, the next step is to compress these data into a driving cycle of acceptable duration for laboratory emissions testing that still reflects the characteristics of the overall survey data. There are different methods in use to do this. Early driving cycle development was particularly influenced by practical restrictions and based on somewhat arbitrary decisions. This was mainly due to a lack of computing power and equipment limitations in those days.

For instance, the LA4 driving cycle, which is used in the FTP city cycles, is a measured driving pattern of a single driver, which was selected since it came closest to the average travel time of 6 driving patterns by 6 different drivers that were collected in total. The final cycle was an edited (shortened) version of the original driving pattern in order to reflect the average journey length at the time. In addition, the maximum allowed acceleration and deceleration rates were artificially limited to 3.3 mph/s due to limitations of the dynamometers in use at the time (Kruse & Huls, 1973).

⁴³ TRL in the UK, EMPA in Switzerland, TÜV in Germany, University of Thessaloniki in Greece, INFRAS in Switzerland, UBA in Germany, INRETS in France.

⁴⁴ These cycles are fourteen MODEM cycles (André *et al.*, 1994; 1995) and four additional representative European cycles, referred to here as the INRETS cycles (INRETS, 1998).

Over the last few decades the process of cycle development has become more sophisticated. Although the details of cycle development will vary among the models, the method of driving cycle development does follow a number of generic steps.

The first step is to attribute the driving pattern data to a number of bins or categories according to prespecified criteria (e.g. Magbuhat & Long, 1996; Gammariello & Long, 1996). With respect to these criteria, MOBILE 6 used congestion level (LOS) and road type, QGEPA 2002 travel speed and idle time, EMFAC 2000 travel speed and COPERT III used a combination of statistical classification techniques (i.e. principal component analysis, dynamic cluster classification and hierarchical classification).

The second step is to (randomly) select driving pattern segments from each bin according to prespecified criteria until a required cycle length and/or cycle duration is reached. Several “candidate” cycles are constructed this way. The driving pattern segments represent stop-to-stop speed traces for all models, except MOBILE 6. In MOBILE 6, driving pattern segments are defined as speed traces whose endpoints were determined by either a change in road type or change in congestion level, or when the vehicle came to rest.

Different criteria are used by the models. The US models (MOBILE6, EMFAC 2002) and the Australian QGEPA 2002 used so-called SAPDFs or speed-acceleration probability density functions (Austin *et al.*, 1993; NEPC, 1999b). A SAPDF is a two-dimensional matrix which represents the frequency of operation at all possible combinations of instantaneous speed and acceleration with an arbitrarily selected bin size. Candidate cycles are forced to match most closely the “survey” SAPDF, which represents all observed driving patterns. The MODEM and INRETS cycles used in COPERT III are based on a probability matrix which show the probability of succession of driving pattern segments from each specific bin (e.g. André *et al.*, 1995; Joumard, Jost & Hickman, 1995).

As the last step, the final cycle is determined from the set of candidate cycles. This final cycle provides the best match to the criteria that were set on beforehand. In some cases, some final manual editing (e.g. shortening) is performed (e.g. INRETS, 1998).

Discussion & Conclusion

The driving cycles used in current travel speed models are based on driving pattern data that were collected in real-world driving conditions in urban areas. These cycles therefore reflect actual driving behaviour in the field. The methods used for the development of these driving cycles are quite sophisticated and involved with respect to data collection and analysis. They follow a generic stepwise approach to cycle construction, although there are differences in the detail among the models such as the actual criteria used.

The US and Australian models are based on a set of driving cycles that were developed using generally more transparent methods. The COPERT III model is based on a large collection of driving cycles that were developed independently by a number of mainly European institutions.

It is not possible to address the research objective of this chapter by means of published literature alone because of a (common) lack of:

1. published information; and
2. information on congestion levels during driving pattern data collection.

Further examination of the driving cycles used in the model development process is required to address the research objective and this will be done in subsequent sections. Nevertheless, some useful remarks can be made on the basis of information presented in this section:

- Since the driving cycles used in MOBILE 6 are based on separate subsets of driving pattern data that were explicitly categorized according to measured “congestion level” and major “road type”, it is concluded that this model does implicitly take different levels of congestion into account. The term implicit is used to indicate that it is not immediately obvious that MOBILE 6 takes congestion into account, because it uses an ambiguous congestion indicator (travel speed) as model variable.

- With respect to the other three models this conclusion cannot be drawn because “congestion level” was not used as a variable in the cycle construction process. Since the driving pattern data were collected in urban areas it seems likely that each cycle reflects travel on different road types and that it contains driving patterns with different levels of congestion. It is clear that at least part of the cycles will not present continuous smooth (constant) speed driving, because they are based on a sequence of stop-driving-stop driving patterns.

In order to determine more precisely how much congestion is reflected in the driving cycles used in current travel speed models, further analysis of the actual driving cycles is required. This analysis is conducted in two parts, a qualitative analysis (section 4.2) and a quantitative analysis (4.3).

The *qualitative* analysis examines the driving cycle data that could be obtained from various organisations by visual comparison of cycles used in emission model development with other cycles for which congestion levels are known.

The *quantitative* analysis then examines the driving cycle data by computation of congestion indicator values for each cycle. This way mean congestion levels contained in the driving cycles can be quantified and subsequently investigated in both a relative and absolute manner.

Driving cycles are sometimes presented as charts in model documentation (e.g. US EPA, 1997; EC, 1998), but this information is not available for all relevant cycles and not sufficient for quantitative driving cycle analysis where the actual second-by-second speed-time data is needed. In an attempt to collect these speed-time for all relevant driving cycles, various organisations were contacted by phone or e-mail in the period of September 2003 to May 2004.

These organisations were (grouped by geographic region):

- United States & California: US EPA⁴⁵, CARB⁴⁶, NCSU-CTE⁴⁷ and Sierra Research.
- Europe: AUT⁴⁸ in Greece, TRL⁴⁹ in the UK, EMPA⁵⁰ in Switzerland, TNO⁵¹ in the Netherlands, TÜV⁵² in Germany, INFRAS in Switzerland, Umweltbundesamt in Germany and INRETS⁵³ in France.
- Australia: QGEPA⁵⁴, FORS⁵⁵ and AQT⁵⁶.

4.2 Qualitative Analysis of Congestion in Travel Speed Models

In this section, the driving cycles used in current travel speed models are analysed qualitatively. This is done in two steps:

- determination of what effects congestion has on the actual shape of driving patterns; and
- by visual observation, determination of how congested the driving cycles in current travel speed models appear to be.

⁴⁵ US Environmental Protection Agency

⁴⁶ California Air Resources Board

⁴⁷ North Carolina State University – Centre for Transportation and the Environment

⁴⁸ Aristotle University of Thessaloniki

⁴⁹ Transport Research Laboratory

⁵⁰ Swiss Federal Laboratories for Materials Testing and Research

⁵¹ Netherlands Organisation for Applied Scientific Research

⁵² Technische Überwachungs Verein – Technical Inspecting Agency

⁵³ Institut National de Recherche sur les Transports et leur Securite - French National Institute for Transport and Safety Research

⁵⁴ Queensland Government Environmental Protection Agency

⁵⁵ Federal Office of Road Safety

⁵⁶ Air Quality Technologies

Publicly available data that directly relates driving patterns to congestion indicators such as traffic density, LOS and delay is scarce. From the literature, three studies were identified that show the effect of congestion level on the shape of driving patterns:

1. congestion specific driving cycles (freeways/arterials) in California (Effa & Larsen, 1994);
2. congestion specific driving cycles (freeways/arterials) in the US (US EPA, 1997); and
3. congestion specific driving cycles (motorways) in The Netherlands (TNO, 2001; Veurman *et al.*, 2002).

It is noted that the second and third study formed the basis for the speed correction factors used in MOBILE 6 (LDV – light-duty vehicle) and the TNO traffic situation model, respectively. In section 4.2.1 these driving cycles are visually displayed and discussed. Section 4.2.2 then uses this information to assess the level of congestion that is reflected in the driving cycles used in the development of the remaining travel speed models EMFAC 2000, COPERT III and the QGEPA model.

4.2.1 Known Levels of Congestion in Driving Cycles

The speed-time data for the US EPA, CARB and TNO cycles are presented in graphical form and discussed in this section. Driving cycles for uninterrupted (freeway/motorway) and interrupted (arterial) roads are discussed in separate sections.

Driving Cycles for Uninterrupted Roads

Figure 21 shows the six MOBILE 6 freeway driving cycles for each congestion level. From top to bottom, cycles are presented in order of increasing congestion level. Thus, the least congested cycle is presented in the top chart and the most congested cycle is presented in the bottom chart. This way of presenting the cycles is maintained

throughout this section. It is noted that the original cycle names used in the literature are retained as well.

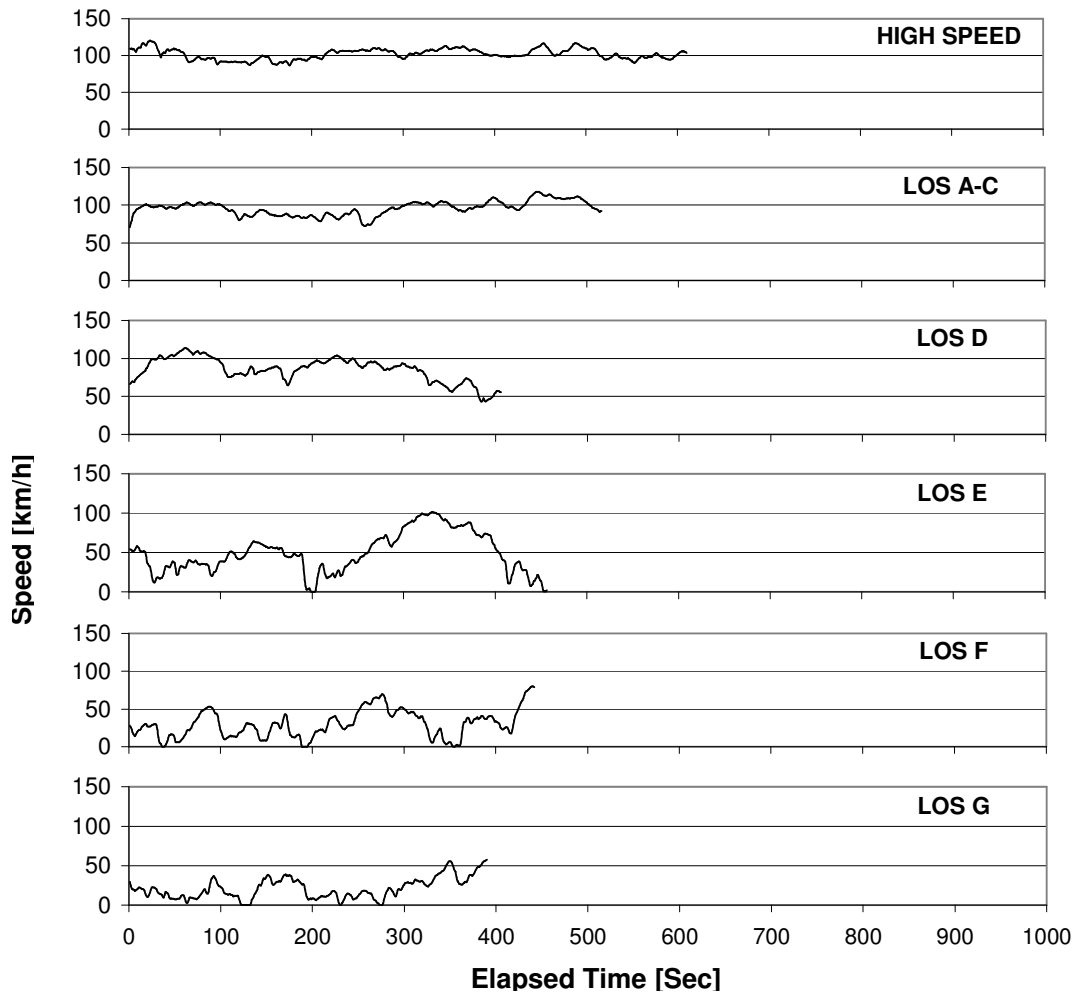


Figure 21 – MOBILE 6 Freeway Driving Cycles

Figure 21 shows that, as congestion level (indicated by traffic density) increases, speed drops and speed fluctuations are becoming more frequent and stronger (more erratic profile). At a certain level of congestion, short idle periods start to appear in the driving profiles, and these periods appear to become more frequent and longer in more congested conditions. Under the most congested condition, speed is generally below 50 km/h and overall driving occurs at speeds much lower than this speed. In contrast,

in cycles that would present most closely free-flow conditions, speeds are high and fluctuate around the 100 km/h.

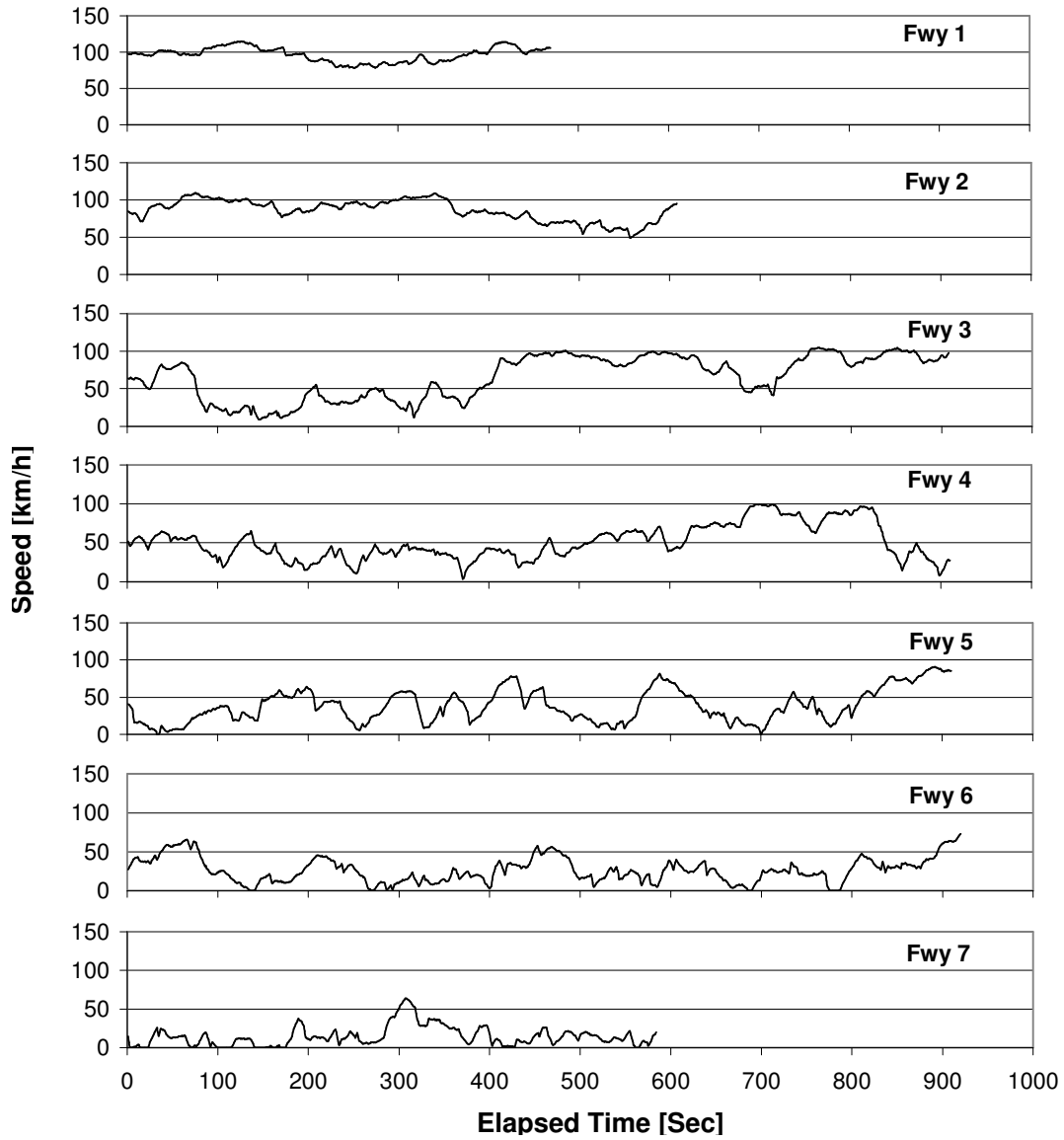


Figure 22 – CARB Freeway Driving Cycles

Figure 22 shows the freeway driving cycles that were developed by CARB in order of increasing traffic density from top to bottom. Similar observations that were made with

respect to the MOBILE 6 freeway cycles can be made for these CARB cycles. It is noted that the driving pattern data used in the development of the MOBILE 6 and these CARB cycles overlaps for a substantial part, but that the actual cycle construction process was different as was discussed before. This difference in construction method apparently does not affect the observed impact of congestion on driving profiles.

Figure 23 (next page) shows the motorway driving cycles that were developed by TNO for the different congestion categories.

Again, similar observations can be made for the TNO cycles, as were made with respect to the previous cycles. The TNO cycles do appear to reflect more extreme driving behaviour. The high speed 2E cycle shows higher speed driving than in the CARB and MOBILE 6 cycles. This cycle also shows relatively steady driving and a long continuous deceleration at the end, which may present an off-ramp. At the other extreme, cycle 1AA appears more congested than the LOS G and Fwy 7 cycles, which compare better to TNO's 1A cycle. Cycle 1AA presents extremely slow driving behaviour with a maximum speed of 27 km/h and most driving conducted below 10 km/h.

The cycles presented in this section were all derived from freeway and motorway data, which, in uncongested conditions, are characterised by high speed driving patterns with relatively minor and infrequent speed fluctuations. As was discussed in section 2.2, these kind of roads typically have uninterrupted traffic flow, which means that flow conditions, and thus driving patterns, are only affected by interactions between vehicles and with the road environment.

Although there is no data to support this, it may be expected that lower speed uninterrupted roads segments (e.g. midblock section of a long arterial road) would exhibit similar congestion effects as observed for freeways and motorways. The main difference would then only be that driving patterns under free-flow conditions would be characterised by lower speeds, for instance close to the speed limit.

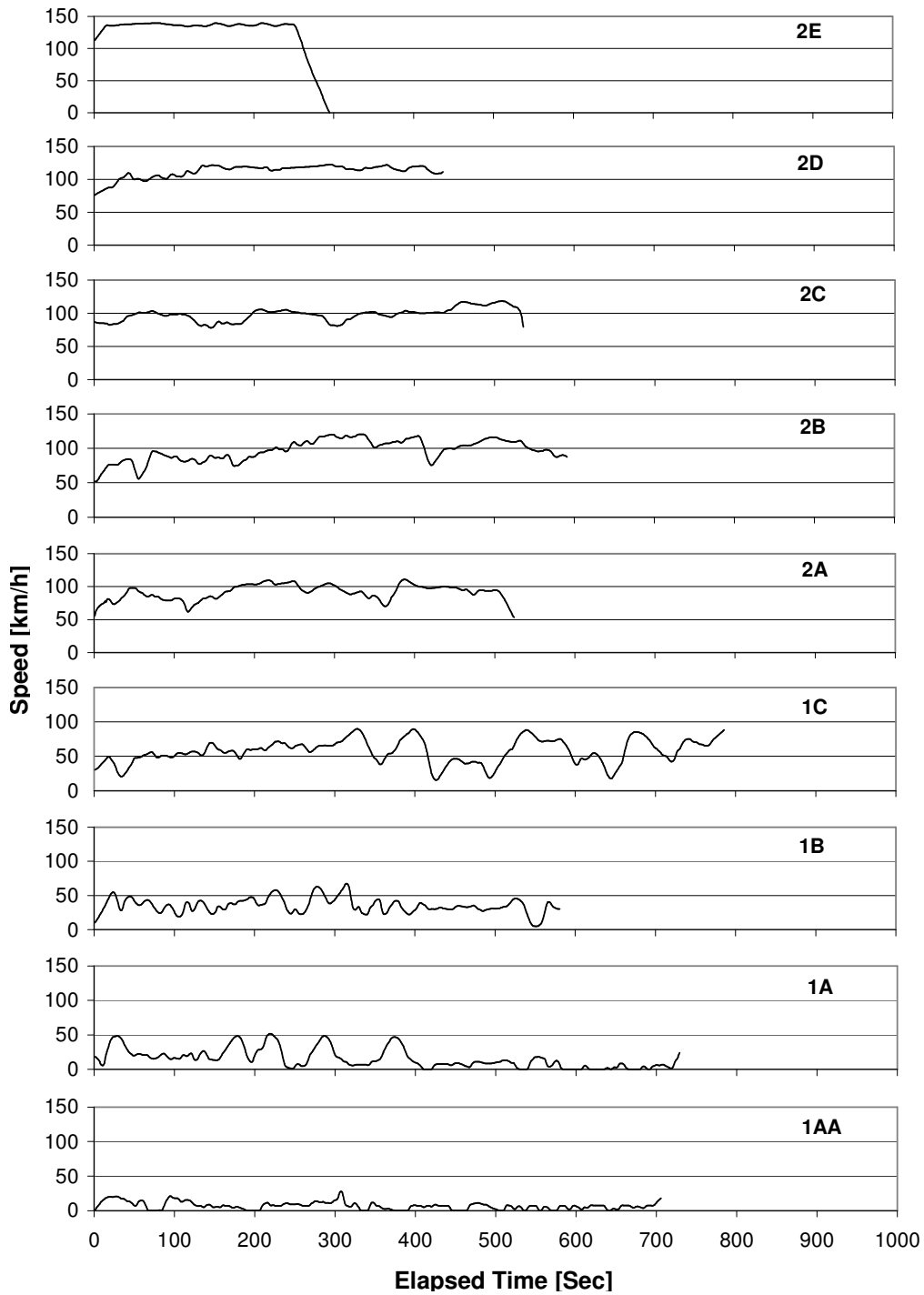


Figure 23 – TNO Motorway Driving Cycles

Driving Cycles for Interrupted Roads

Compared to the previous section, there is less information available with respect to the effects of congestion on driving patterns in urban driving conditions. US EPA developed three arterial driving cycles for use in MOBILE 6. In addition, the NYCC, representing congested driving in New York city, was used as well. These cycles are presented in Figure 24.

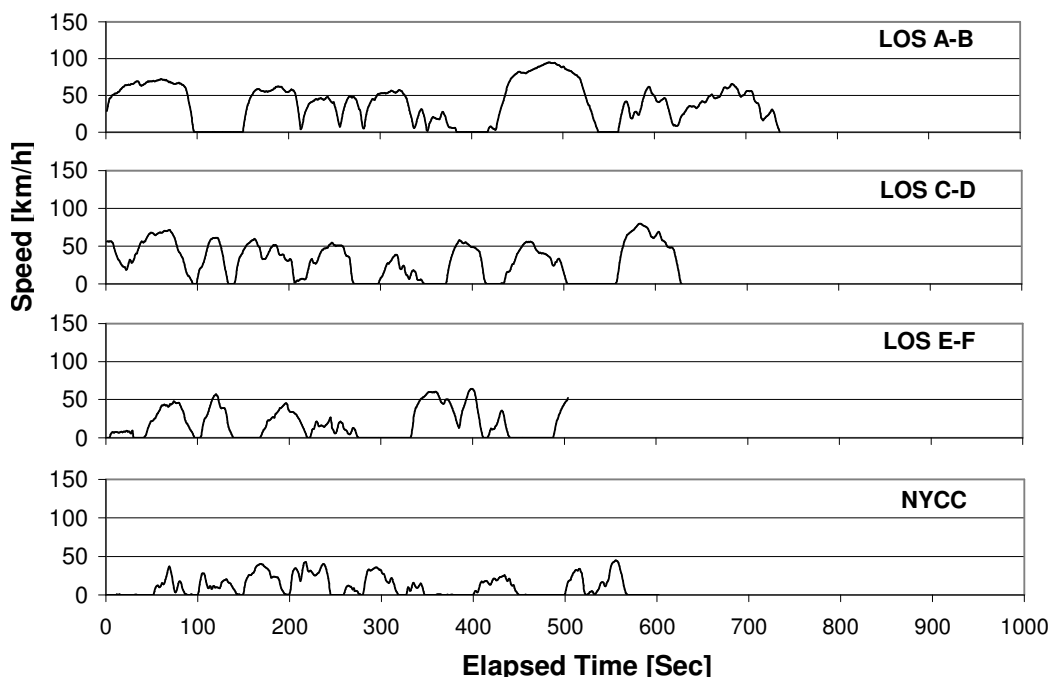


Figure 24 – MOBILE 6 Arterial Driving Cycles

It can be observed that, irrespective of the level of congestion, arterial driving is characterised by stop-and-go driving and periods of standstill. This was already to be expected from traffic flow theory, which shows that the presence of interruptions (e.g. intersections) in urban traffic results in (partial) stops, low speed driving and queuing. The frequency of (partial) stops and the extent of queuing and low speed driving would be expected to increase when the number of vehicles on the road increase. This should be particularly evident once traffic demand approaches road capacity.

This trend can be observed in the arterial cycles, but the effects of increased congestion levels appear to be less dramatic than for uninterrupted roads. When the least congested arterial cycle is compared with the most congested arterial cycles, the following remarks can be made:

- The LOS A-B cycle exhibits relatively wide stop-and-go “humps” with maximum speeds that are maintained for relatively long periods of time, indicating sustained periods of cruise conditions that are perhaps close to free-flow speeds. In contrast, the LOS E-F and NYCC cycles shows much narrower stop-and-go “humps” with sharp peaks. These “humps” appear to be more erratic and have low maximum speeds. This indicates that, in congested conditions, free-flow conditions are encountered for very short periods of time or may not have been achieved at all.
- Although the number of idle segments is larger in the LOS E-F and NYCC cycle, the LOS A-B cycle also incorporates long idle segments.

In the next table, additional information is presented with respect to the arterial cycles. US EPA (1997) analysed the effects of controlled intersections (signs, signals) on the second-by-second speed-time data in these cycles by video review. “Intersection effects” were somewhat loosely defined as stopping for a red light, queuing in front of a red light, multiple stops in queue, not achieving free-flow speed because of a queue and turning movements.

Table 11 – The Influence of Controlled Intersections in Arterial Cycles

Arterial Cycle	Total Number of Inter-sections	Mean Inter-section Density [int./km]	Proportion of Time		Proportion of Distance	
			Intersection Influenced	Other	Intersection Influenced	Other
LOS A-B	13	1.6	37%	63%	18%	82%
LOS C-D	17	3.2	59%	41%	31%	69%
LOS E-F	7	2.7	83%	17%	55%	45%

Table 11 shows that the proportions of time and distance in the cycles that were affected by controlled intersections increase with increasing levels of congestion, as would have been expected from traffic flow theory. This trend may, to a certain extent, be caused by higher intersection densities, which are higher for the more congested cycles. Another factor that was not investigated by US EPA, but which is expected to have had an effect on the LOS ratings that were recorded during driving pattern data collection, is signal settings (e.g. cycle time, green time, coordination).

Thus, the trend of stop-and-go humps becoming narrower with increasing congestion may be due to several reasons, such as short intersection-to-intersection distance (e.g. CBD road) or long queue lengths at intersections because of high traffic density and/or unfavourable signal settings limiting the road section where free-flow is possible.

Figure 25 shows the arterial cycles that were developed by CARB. Similar to the US EPA cycles, arterial driving is characterised by stop-and-go driving and periods of standstill.

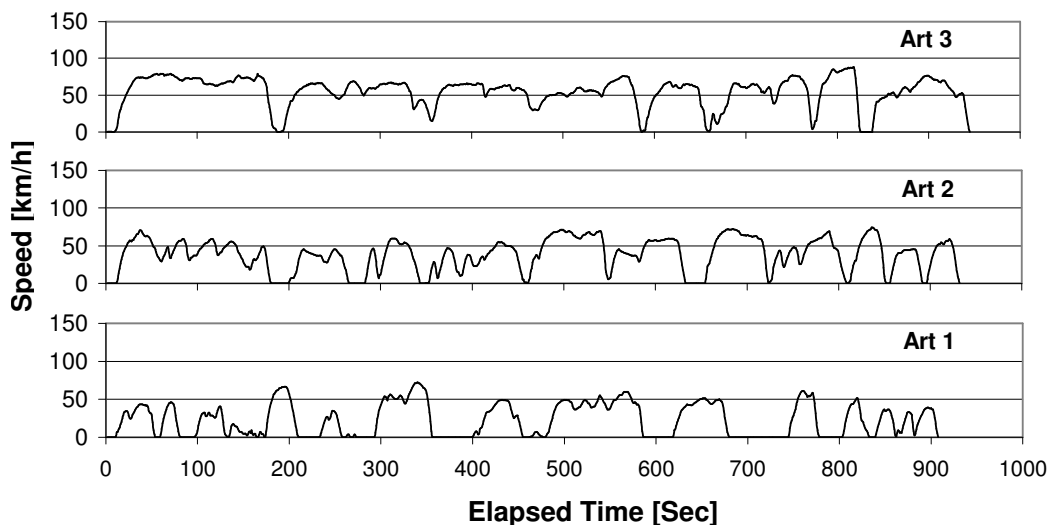


Figure 25 – CARB Arterial Driving Cycles

The CARB arterial cycles show that as travel speed between major intersections (snippets) drops for whatever reason (e.g. increased density, unfavourable signal settings, increased signal density), the characteristics of stop-and-go “humps”

progressively change in a general sense from being relatively wide with relatively high speeds (block shape) to relatively narrow “humps” with sharp peaks (triangular shape) or sometimes erratic low speed “humps” (crown shape). The frequency and magnitude of idle segments increases with a drop in segment travel speeds.

Discussion & Conclusion

This section has examined the effect of different levels of congestion on the shape of driving cycles. It is emphasized that the speed-time data in driving cycles reflect recorded driving patterns that, at the time of data collection, were likely affected by rather unique combinations of a large number of factors. Despite this, it can be observed that, at first sight, different levels of congestion have substantially different speed-time profiles (as would have been expected from the information presented in Chapter 2). Increased congestion consistently results in rather obvious changes in the characteristics of driving patterns.

Investigation of driving cycles for high-speed uninterrupted roads (freeways, motorways) reveals that, as congestion levels increase, the actual speed-time data shows the following characteristics:

- speed drops;
- data becomes more erratic (more fluctuation);
- zero speed periods (idle) appear after a certain level of congestion;
- zero speed periods appear more frequently and for longer periods;

It may be expected that similar effects would be observed at lower speed uninterrupted roads.

Investigation of driving cycles for interrupted urban roads reveals that, irrespective of the level of congestion, speed-time data exhibits stop-and-go driving (microtrips) and periods of zero speed. As congestion levels increase, the actual speed-time data shows that the shape of microtrips generally changes from block shape with maximum speeds in the order of 50-100 km/h to triangle or crown shapes with maximum speeds

below approximately 50 km/h. The effect of congestion on speed-time profiles is, however, less clear than for high-speed uninterrupted roads.

4.2.2 Congestion in COPERT, QGEPA and EMFAC

This section will investigate the driving cycles that were used in the development of the COPERT III, QGEPA 2002 and EMFAC 2000 models.

COPERT III Driving Cycles

Examination of COPERT driving cycles is restricted to light-duty vehicle cycles. Attempts to obtain the heavy-duty vehicle cycles (HBEFA model) were not successful. COPERT III is based on a substantial number of light-duty vehicle driving cycles, 42 in total. The actual driving cycles used for emission model development depend on vehicle class. This is shown in Table 12. The largest number of driving cycles is used for EURO I petrol cars (i.e. passenger cars with closed loop three-way catalyts).

The emission factor algorithms for pre-EURO I petrol cars were developed using the same methodology as the EURO I petrol cars (Eggleston *et al.*, 1988). However, inspection of the various publications on the different versions of COPERT (Eggleston *et al.*, 1988; 1993; EEA, 2000) provided no information on the actual driving cycles used for pre-EURO I petrol cars. After contacting one of the model developers (pers. comm., Professor Z. Samaras, 12-05-04), it became clear that this specific information cannot be traced back. The emissions data used in this process came from different European institutions, and at the time, the actual cycles that had been used were not specified (only average cycle speed was provided). It was mentioned that the actual cycles used for the pre-EURO I petrol cars were not different from the ones used for the EURO I petrol cars. Therefore, Table 12 (next page) presents all driving cycles that have been used for light-duty vehicles in the development of COPERT III.

Table 12 – Driving Cycles used for each COPERT Vehicle Class

Driving Cycle Category	Passenger Car				Light-Duty vehicles			
	EURO I Petrol	EURO I Diesel	Pre-EURO Petrol	Pre-EURO Diesel	EURO I Petrol	EURO I Diesel	Pre-EURO Petrol	Pre-EURO Diesel
DRIVE-MODEM Cycles (14)	14	1	<i>Information is Not Available</i>		1	1	0	0
INRETS Cycles (4)	4	3			2	2	3	3
U-Cycles (2)	2	0			0	0	0	0
Route 2 Cycle (1)	1	0			0	0	0	0
Autor Cycle (1)	1	0			0	0	0	0
TRL Cycles (6)	0	0			0	0	0	6
WSL Congested Cycle (1)	1	0			1	0	1	1
WSL Cycles (3)	3	3			0	3	0	0
US FTP Highway (1)	1	1			1	1	1	1
T-Cycles (3)	3	0			2	0	0	0
BAB Autobahn Cycles (3)	2	1			2	2	2	2
C-Cycles (3)	3	0			2	0	0	0
TOTAL	35	9					11	9

After contacting the relevant European organisations (p. 194), most of the speed-time data for the driving cycles in Table 12 were obtained. Several attempts to obtain the 6 TRL cycles and 3 C-cycles were not successful⁵⁷ and these cycles could therefore not be included in the analysis. It is noted that the 6 TRL cycles were only used in the development of the pre-EURO light-duty diesel vehicles. The 33 COPERT III cycles are presented in Figure 26 (next pages) in order of decreasing travel speed.

The eight COPERT cycles with the highest travel speeds (T-cycles, BAB cycles, WSL Motorway, mM) give the impression of reflecting free-flow conditions. Six of these cycles exhibit continuous high-speed driving with no stops and two of these cycles seem to include ramp operation. When cycle speeds drop, maximum speed drops, the frequency of stops appears to increase and driving patterns becomes more erratic. At the other extreme, the four cycles with the lowest travel speeds (Modem 4, 9, 6, Urbain Lent 2 and WSL Congested) resemble the TNO 1AA cycle and they appear to be very congested.

It seems that the COPERT cycles reflect driving on different road types and reflect a vehicle journey. For instance, the MODEM 11 cycle contains a long microtrip with large speed fluctuations, which appears to be quite similar to the long freeway segment in the LOS E Freeway cycle that is used in MOBILE 6. Similarly, the urban segments in the NYCC cycle (MOBILE 6 Arterial) are not unlike the other microtrips observed in MODEM 11. This observation seems in line with the fact that driving pattern data for the MODEM cycles were collected in urban areas, which contain different road types.

⁵⁷ None of the people that were contacted at the relevant organisations knew anything about these cycles.

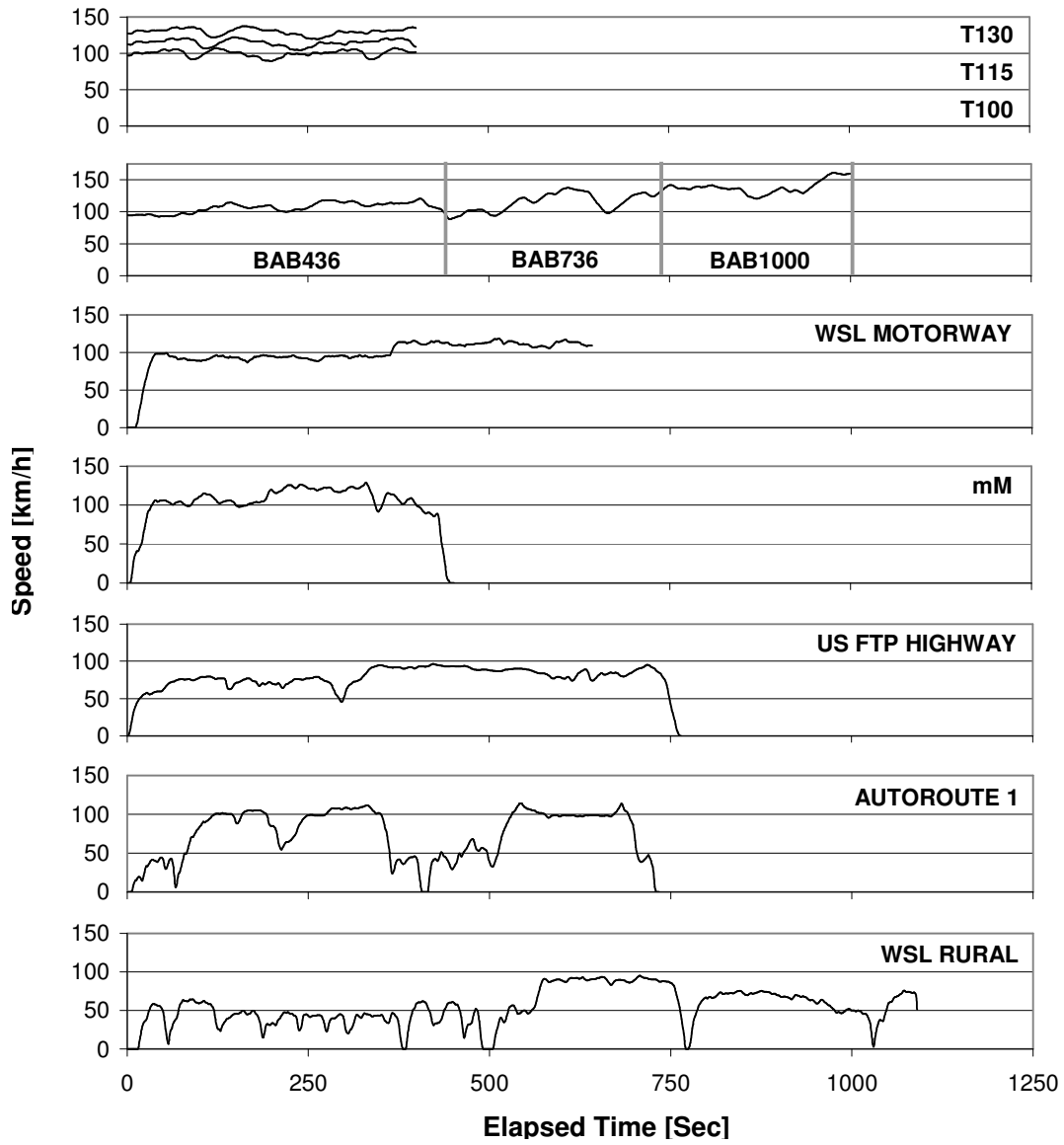


Figure 26 – COPERT Driving Cycles (Travel Speeds 130-56 km/h)

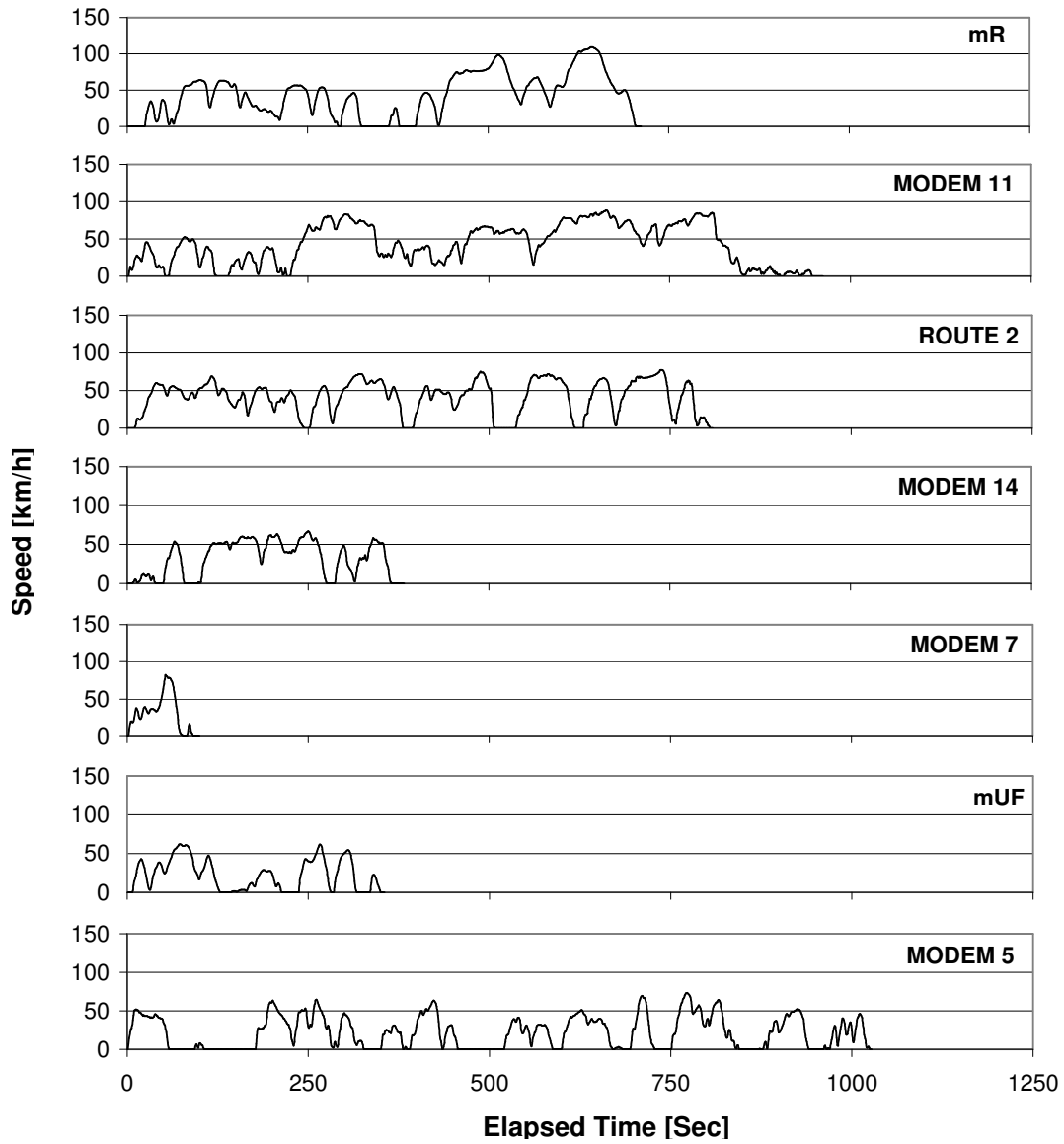


Figure 26 (Continued) – COPERT Driving Cycles (Travel Speeds 43-22 km/h)

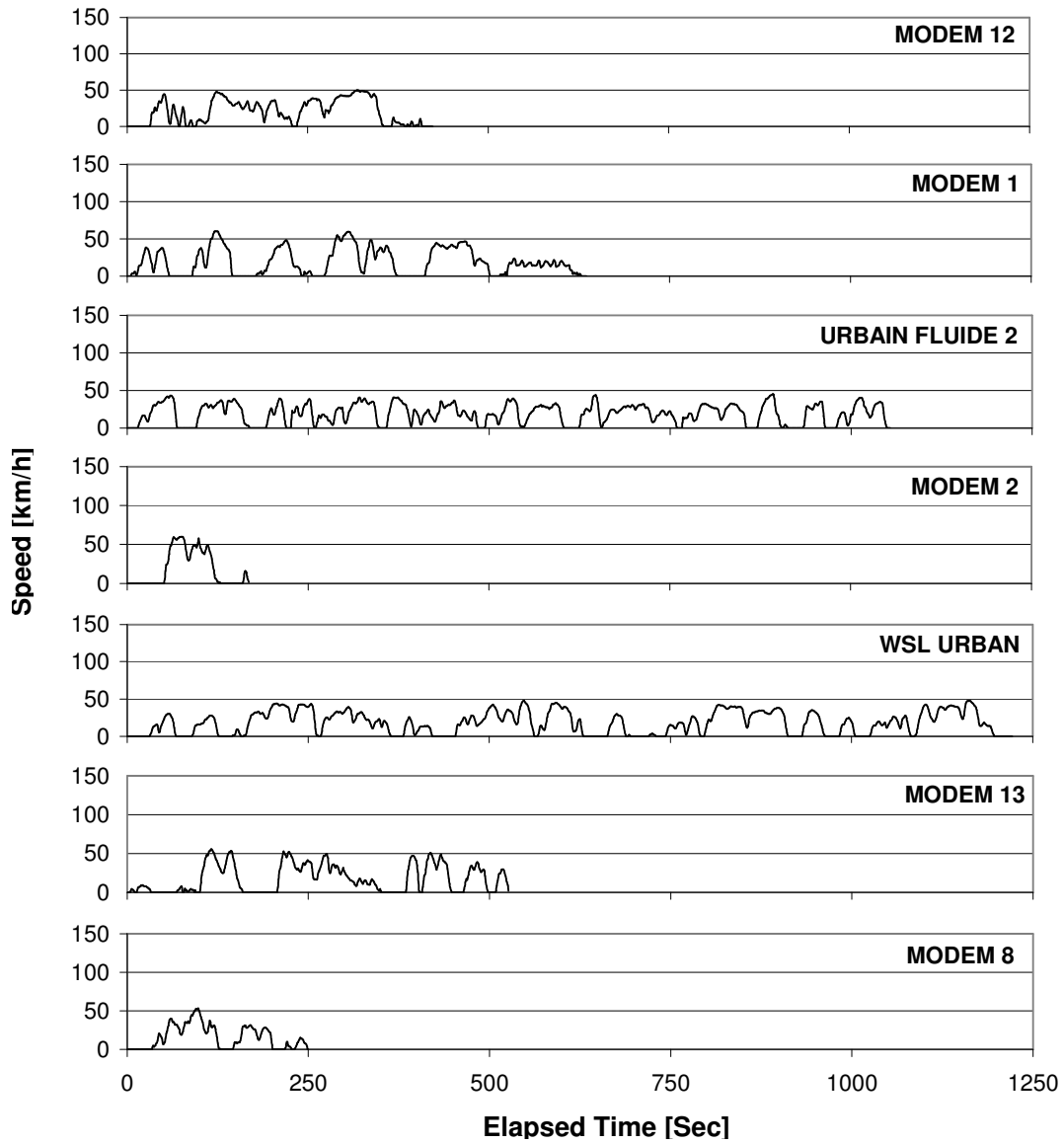


Figure 26 (Continued) – COPERT Driving Cycles (Travel Speeds 21-16 km/h)

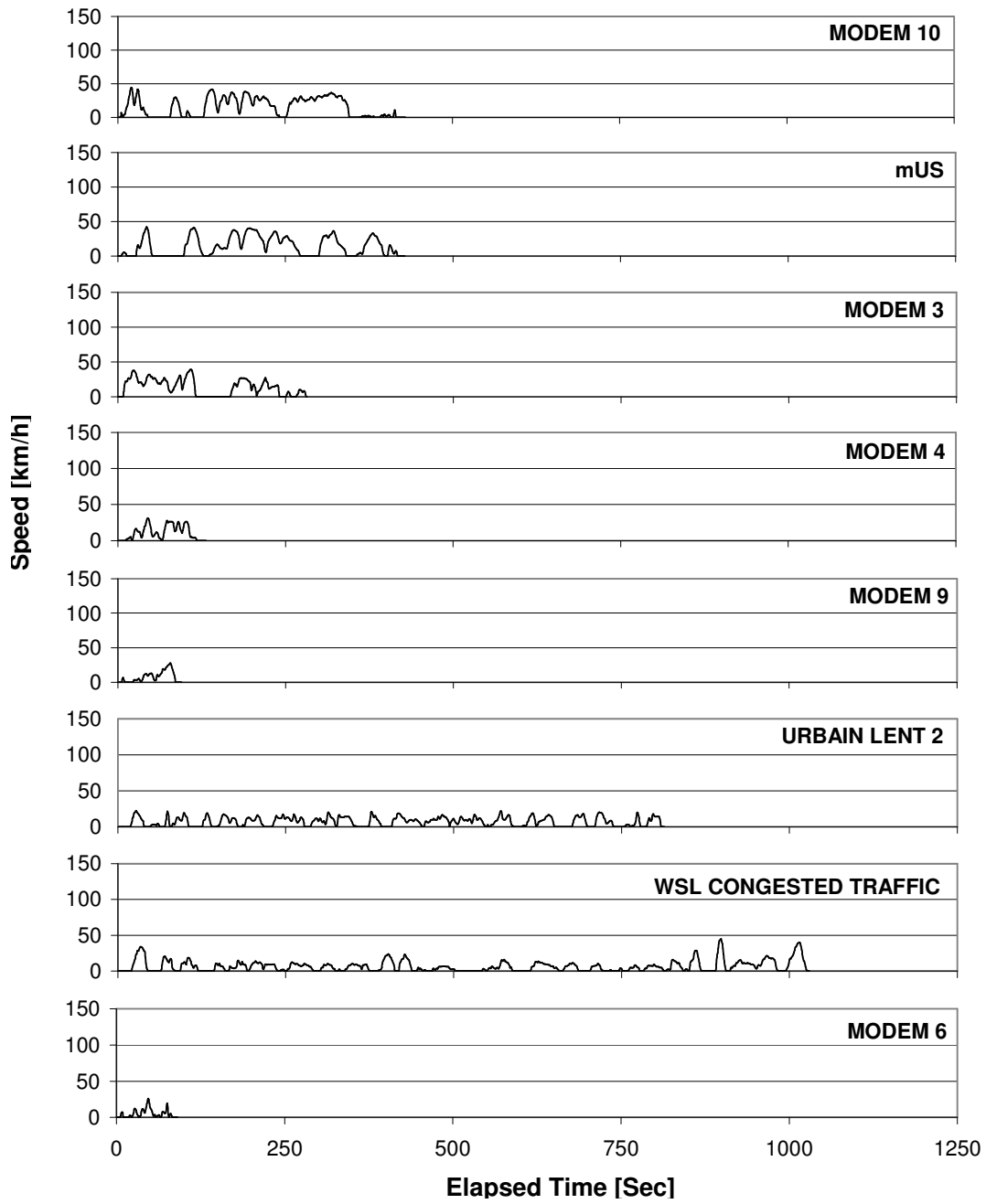


Figure 26 (Continued) – COPERT Driving Cycles (Travel Speeds 16-5 km/h)

QGEPA Driving Cycles (Diesel Vehicles)

The 24 driving cycles used for the development of the diesel vehicle emission factors in the QGEPA cycle are shown in Figure 27. The six vehicle categories, including legislative vehicle codes, are indicated at the right side of the chart. It is noted that the full CUED cycle is presented by the four subcycles combined.

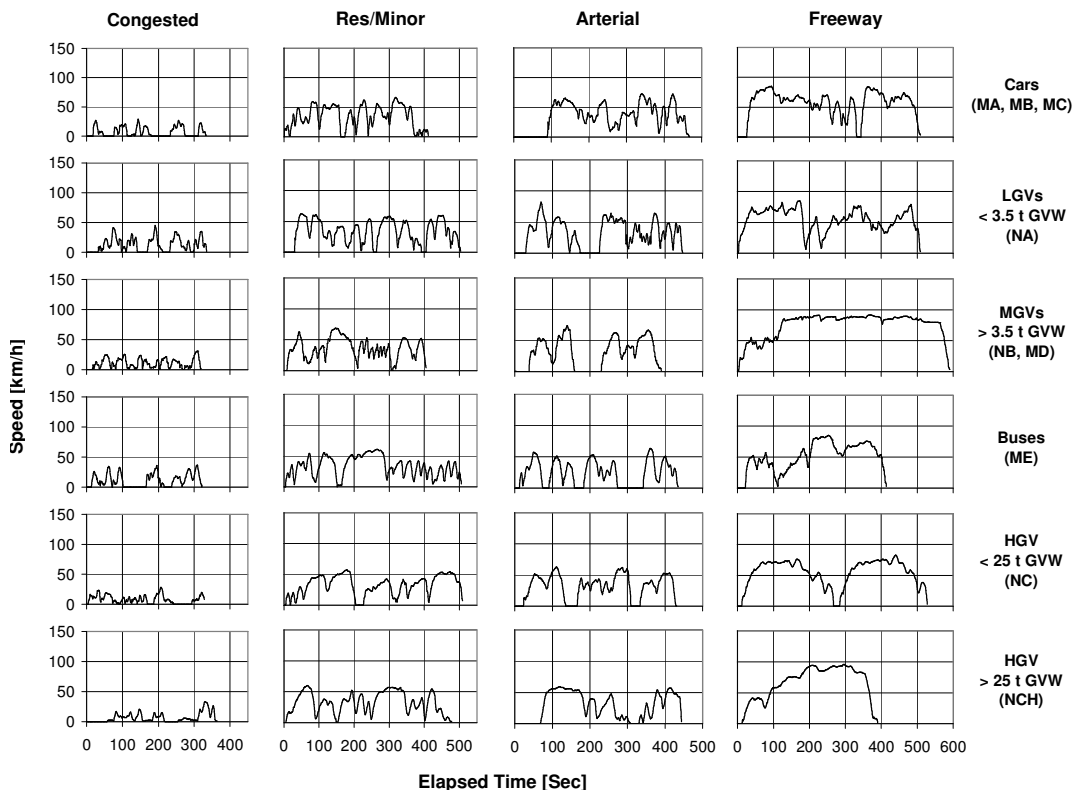


Figure 27 – QGEPA Diesel Vehicle Driving Cycles (Travel Speeds 7-75 km/h)

It can be seen that none of the freeway driving cycles present continuous steady-speed driving, although the freeway cycle for MGVs does approach this behaviour for a substantial part of its speed-time profile. The other freeway cycles appear to be quite congested with substantial speed fluctuation, and in some cases quite low speeds (e.g. buses). The arterial and residential/minor cycles all appear to be quite congested since they mainly consist of triangle and crown shaped microtrips. The congested cycles give

the impression of being very congested with very low speed driving and a large number of stops.

EMFAC 2000 Driving Cycles

The fourteen EMFAC 2000 cycles are presented in Figure 28 (next pages) in order of decreasing travel speed. It is clear that all cycles reflect stop-and-go driving patterns. This is not surprising since every cycle represents a typical journey for its respective journey speed bin, which would by its nature involve driving on different road types, including urban roads.

The high speed cycles are generally characterised by a number of high speed microtrips with little speed fluctuations (apart from on-ramp and off-ramp operation), which would suggest that these microtrips were recorded in uncongested conditions. When cycle speed drops, these high speed microtrips become less frequent and the proportion of lower speed microtrips with more speed fluctuation increases. These low speed microtrips can have all kinds of shapes and maximum speed can be significantly above and below 50 km/h. It is therefore not possible to distinguish a clear trend in the shape of lower speed microtrips in the UCC 65 to UCC 20 cycle range. This would suggest that, in this cycle range, these microtrips were recorded in a variety of congestion levels.

In the cycle range UCC 15 to UCC 5 microtrips with maximum speeds higher than about 50 km/h do not occur any more and clearly speed drops and idle periods increase. The UCC 5 cycle appears particularly congested, with a profile that comes closest to the TNO 1AA cycle.

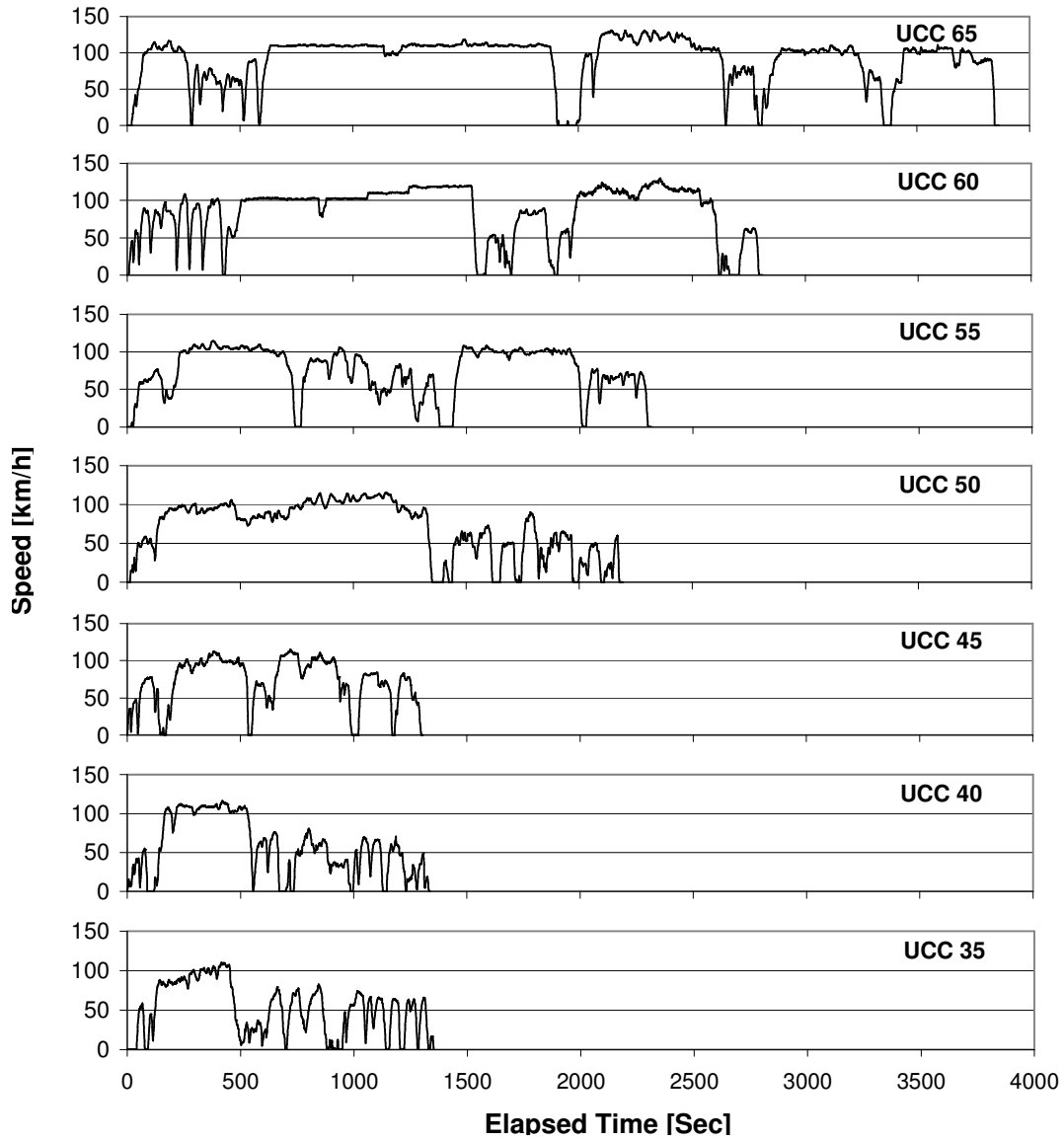


Figure 28 – EMFAC Driving Cycles (UCC 65 – UCC 35)

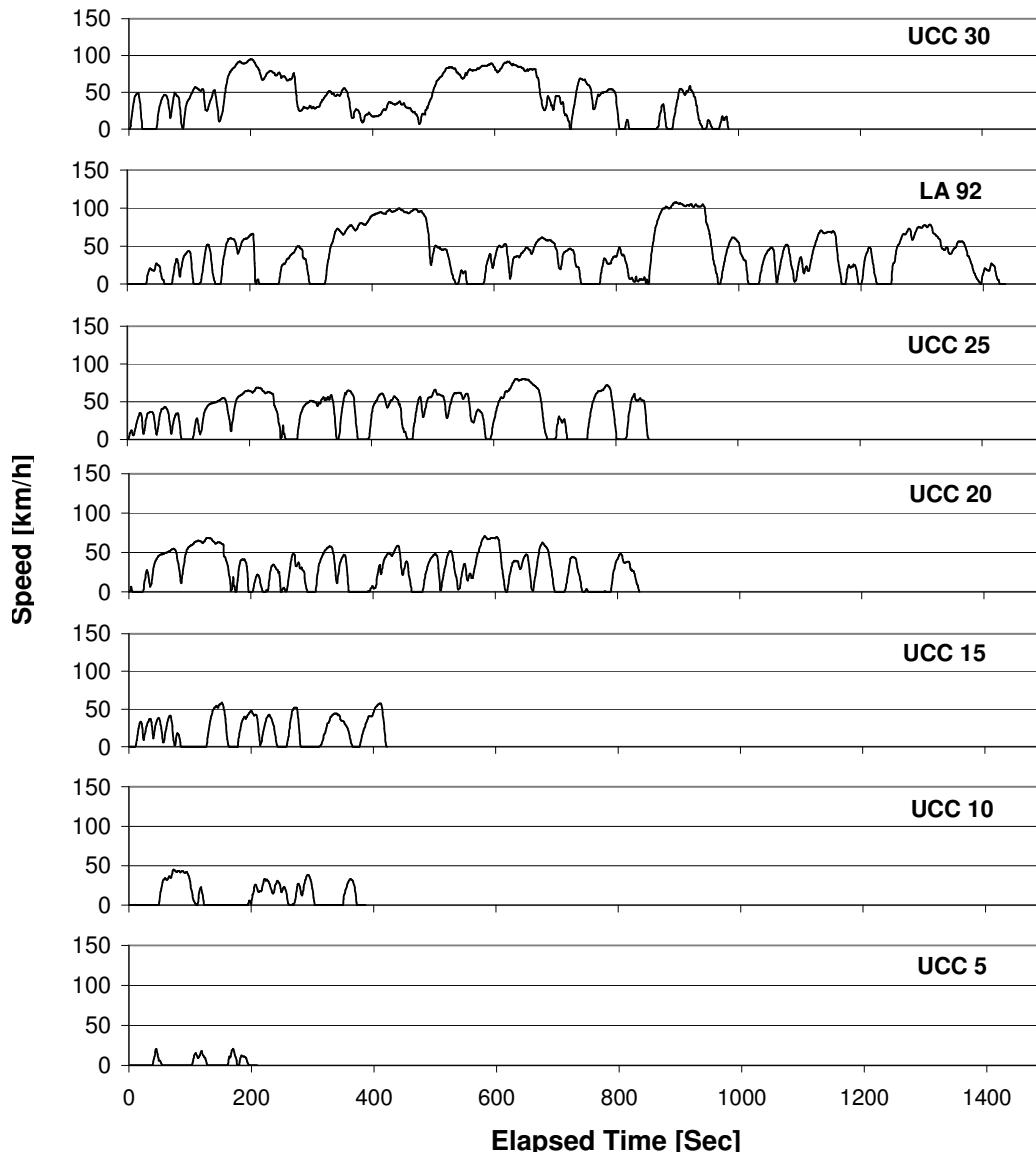


Figure 28 (Continued) – EMFAC Driving Cycles (UCC 30 – UCC 5)

It is evident that none of the EMFAC 2000 cycles represent continuous speed-time traces with minor speed fluctuations, which would represent free-flow conditions. The highest speed cycle (UCC 65) appears to reflect the largest proportion of time with these uncongested speed time traces. In contrast, the lowest speed cycle (UCC 5) reflects long periods of standstill and very low speed stop-and-go driving, which indicates very congested conditions. There seems to generally exist a progressive

change from one extreme to the other for the intermediate cycles, but this change is difficult to observe visually between adjacent cycles.

After the construction of the EMFAC cycles, CARB performed additional analysis with respect to road type for a number of cycles. The results were provided by CARB (pers. comm., 18-02-04) and are presented in Table 13.

Table 13 – Percent Distance Driven by Road Type for EMFAC 2000 Cycles

EMFAC Cycle	Urban	Freeway	Freeway Ramp
UCC 10	100%	0%	0%
UCC 15	100%	0%	0%
UCC 20	99%	1%	0%
UCC 25	100%	0%	0%
UCC 30	28%	61%	11%
UCC 35	42%	44%	14%
UCC 40	45%	51%	4%
UCC 45	24%	60%	16%
UCC 50	18%	77%	5%
UCC 55	7%	89%	4%
UCC 65	2%	96%	2%

This information shows that the proportion of freeway driving increases with cycle travel speed, where, at the extremes, the low speed cycles contain only urban driving and the high speed cycles contain mainly freeway driving. Intermediate speed cycles contain a mix of urban and freeway driving.

4.2.3 Conclusions of the Qualitative Analysis

Investigation of the effect of congestion on the shape of driving cycles and subsequent visual inspection of the cycles used in the development process of four current travel speed models leads to the following conclusions:

- None of the four travel speed models are based on driving cycles with continuous constant speed driving.
- The majority of driving cycles contain stop-to-stop driving segments, which appear to reflect driving on different types of road with varying levels of congestion.
- The high speed cycles in COPERT III are the only cycles that appear to reflect free-flow driving conditions on high-speed uninterrupted roads (i.e. continuous speed-time traces with only minor speed fluctuations).
- All the other cycles appear to reflect congested conditions of varying intensity.

However, it is possible that visual examination of speed-time profiles alone may overlook important differences between driving cycles. Hence, a further quantitative examination of congestion levels in the model cycles is warranted. This is done in the next section.

4.3 Quantitative Analysis of Congestion in Travel Speed Models

In this section, the level of congestion in the driving cycles is investigated quantitatively. This is done to see to what extent the findings in the previous sections are supported, or perhaps contradicted.

4.3.1 Methodology

In order to quantify the level of congestion that is contained in the driving cycles, cycle variables are needed that are related to congestion. Section 2.4 discussed in detail the various congestion indicators that were found in the literature and should be used in this section. These indicators can be separated into two groups:

- indicators that are based on travel time; and
- indicators that reflect the level of speed fluctuation.

The first group contains the following cycle variables:

- travel speed (v)
- running speed (v_{run})
- unit idle time (T^*_{idle})
- delay rate (d^*)
- delay ratio (d_{ratio})
- relative delay rate (RDR)
- congestion index (CI)
- speed reduction congestion index (SRCI)

It was demonstrated in Chapter 2 that congestion is consistently related to these variables, where increased levels of congestion result in increased travel time and

increased idle time, and hence a decrease in travel and running speed and an increase in delay (d , d^* , d_{ratio} , RDR), CI and SRCI. The first three variables can be directly computed using speed-time data as input to the corresponding equations presented in Chapter 2 (equations 2-5, 2-16). It is noted that idle time is determined by the total time a vehicle is stopped (the definition of a “stop” is discussed below), which is subsequently divided by cycle distance, to arrive at unit idle time.

The last five variables, however, require average free-flow speed in their computation, as was shown in Chapter 2 (equations 2-19 to 2-23), which is not provided by the speed-time data. Thus, a methodology needs to be developed to estimate free-flow speed for driving pattern segments. This is discussed later in this section. The second group contains the following cycle variables:

- acceleration noise (σ_{at})
- positive acceleration kinetic energy (PKE)
- total absolute second-to-second difference in speed per km (TAD)
- coefficient of variation of instantaneous speeds (COV_{vt})
- modal activity distribution (cruise, idle, acceleration, deceleration)
- number of stops per unit distance (n_s^*)

These variables can be quantified directly using the speed-time data as input. The first four cycle variables are computed using the equations presented in Chapter 2 (equations 2-24, 2-28 to 2-30). The modal activity distribution (percent of time spent in each fundamental driving mode) and number of stops per unit distance require specification of the boundaries between the fundamental driving modes and definition of a stop.

There are three remaining aspects that need further discussion. The first aspect is the definition of a stop. The second aspect is the different ways in which instantaneous acceleration can be estimated and the effect this has on the computation of congestion indicator values. The third aspect is the estimation of free-flow speeds in driving cycles for which a method has been developed by the author and validated (to the extent that this is possible). These three aspects are now discussed.

Definition of Fundamental Driving Modes and a Stop

In the literature, fundamental driving modes and a vehicle stop have been defined in different ways in an arbitrary manner (e.g. Rainford *et al.*, 1987; Effa & Larsen, 1994; Lin & Niemeier, 2003). In this study, the boundaries that are chosen for the fundamental driving modes align with the ones used in the TEE model (pers. comm., Dr. E. Negrenti, 22-02-04) and in another study (Tong, Hung & Cheung, 1999). These boundaries are as follows:

- “idle” is defined as $v_t = 0$ km/h and $a_t = 0$ m/s²;
- “acceleration” is defined as $v_t > 0$ km/h and $a_t > +0.1$ m/s²;
- “deceleration” is defined as $v_t > 0$ km/h and $a_t < -0.1$ m/s²; and
- “cruise” is defined as $v_t > 0$ km/h and $-0.1 \leq a_t \leq +0.1$ m/s².

The variable “number of stops per km” (n_s^*) is simply defined as the number of times a vehicle becomes stationary ($v_t = 0$ km/h) in a driving pattern, divided by the total driving distance.

Estimation of Instantaneous Acceleration in Driving Cycles

In the computation of the speed fluctuation variables instantaneous acceleration is required. Instantaneous (second-by-second) acceleration must be estimated from the speed-time data. In addition, the travel time based variable T_{idle}^* , which uses the amount of idle time requires estimates of instantaneous acceleration, as is clear from the definition of idle conditions.

There are different methods available to estimate instantaneous acceleration. Some researchers calculate acceleration as the difference in instantaneous speed between two subsequent speed-time data points divided by the time interval (e.g. Greenwood, 2003).

$$a_{t,t} = \frac{(v_{t,t+1} - v_{t,t})}{(t_{t+1} - t_t)} \quad \text{Equation 4-1}$$

where $v_{t,t+1}$ and $v_{t,t}$ are instantaneous speeds at time t_{t+1} and t_t , respectively. Others have estimated the instantaneous (second-by-second) acceleration rate at time t as follows (e.g. Austin *et al.*, 1993):

$$a_{t,t} = \frac{(v_{t,t+1} - v_{t,t-1})}{(t_{t+1} - t_{t-1})} \quad \text{Equation 4-2}$$

In order to test the sensitivity of the study outcomes to these different methods, both methods have been used in the computation of the cycle statistics for comparison. The percent difference between the methods, which is computed as 100 times (equation 4-1 minus equation 4-2) divided by equation 4-2, are presented for each relevant variable in Table 14.

Table 14 – Percent Difference in Cycle Statistics Due to Different Acceleration Computation Methods

	Min	Max	Mean
σ_{at}	+1	+38	+9
PKE	+1	+14	+5
TAD	+1	+19	+5
COV_{vt}	-1	+3	0
Modal Distribution	-14	+11	0
T^*_{idle}	0	+75	+8

Table 14 shows that different acceleration computation methods can lead to substantial differences in computed congestion indicator values for individual cycles. On average, however, the percent differences for all cycles together are small within about 10 percent. The use of equation 4-2 results in consistently lower absolute values for the indicators σ_{at} , PKE, TAD and T^*_{idle} .

In general, no clear trend was observed between the magnitude of percent difference and level of congestion. Only for COV_{vt} there appeared to be an increase in the magnitude of percent difference with increasing level of congestion. However, actual differences for this variable are quite small, within a few percent, as is shown in Table 14. It will be shown that the outcomes of this chapter are not affected by the method that is chosen to compute instantaneous acceleration levels.

Estimation of Free-Flow Speeds in Driving Cycles

A number of congestion indicators that are used in this analysis require the quantification of mean free-flow speed. However, driving cycle data do not provide information on free-flow speeds. Three cases can be distinguished for which mean free-flow speed can be estimated using different methods:

1. For some driving cycles, the speed limits that applied at the time of driving pattern data collection are known, and free-flow speeds can be estimated using this information. This is the case for the TNO cycles that have been discussed early in this chapter. The posted speed limit on a road may be taken as being roughly equivalent to the free-flow speed. The posted speed limit may be considered as the maximum safe driving speed on the road section and therefore the nominal undelayed speed (Taylor, Bonsall & Young, 2000). Watson *et al.* (1990) suggested that drivers tend to comply with a margin of 8 to 15 km/h above the speed limit in free-flowing traffic conditions. Harkey *et al.* (1990) measured free-flow speeds at 50 locations on different types of roads in urban and rural areas and found that, on average, posted speed limits were exceeded by 2 to 13 km/h. Ogden and Taylor (1996) remark that operating speeds depend on drivers' perceived appropriateness of the speed zone and that they are commonly 10 km/h more than the speed limit in 60, 70, 80 and 100 km/h zones. Based on this information, two estimates of free-flow speed are used in this study to indicate their possible range: the actual speed limit for a section of road, and the speed limit plus 15 km/h.

2. In some cases, only the types of road on which a driving cycle is based is known. This is the case for the MOBILE 6 cycles, where a cycle can be either an arterial or a freeway cycle. Here, free-flow speeds can be estimated by consideration of the national speed limits for these roads. The speeds limits used are national statutory speed limits that generally apply to various types of roads. It is noted that, in practice, speed limits may be raised above or lowered below the general speed limit by local authorities on the basis of traffic engineering studies and traffic surveys. Thus, it must be assumed that the general speed limits applied in most cases during driving pattern data collection. This approach seems most appropriate for freeway cycles since speed limits on these roads would vary less in practise than speed limits on urban roads.
3. For the remaining cycles, no additional information on speed limit or road type is known. Here, a new procedure is needed to estimate mean free-flow speeds.

The last case applies to the cycles used in COPERT III, QGEPA 2002 and EMFAC 2000. The following procedure has been developed in this thesis in order to estimate mean free-flow speeds for each cycle.

It is presumed that for most driving patterns, free-flow speeds will be achieved at least once in the speed-time segments (e.g. stop-to-stop pattern) that are investigated. This point would be represented by the maximum instantaneous speed that is encountered in the speed time data. It is assumed that even in quite congested conditions there will normally be some small period of time in which free-flow conditions are achieved.

Clearly, this last approach will not always work, for instance, in very congested conditions where only low speed driving occurs. In these conditions, free-flow speeds could be anything from high speed freeway driving to low speed residential driving, but this cannot be determined from the speed-time data. Therefore, additional assumptions need to be made for these conditions.

To address this issue, it is considered that free-flow speed cannot be lower than the minimum national speed limit that are used in the area where the driving pattern

data were collected⁵⁸. It is noted that this assumption is only valid as long as driving cycles do not consist of artificial constant low speed driving. Hence, a visual inspection is required for cycles with maximum speeds lower than the general speed limit to verify the validity of this assumption.

It was already concluded in the previous sections that none of the driving cycles investigated in this study showed constant steady-speed driving at low travel speeds and that they are based on real-world data where speed limits would apply. Therefore the assumption of a minimum free-flow speed can be used in this study.

Using this procedure, (the range of) free-flow speeds have not been estimated for one complete driving cycle, but for several driving segments that together make up the speed-time profile. This is done because these segments would better represent driving on *homogeneous* sections of road (e.g. from intersection to intersection), where the speed limit is not likely to change.

Following the findings from Lyons, Kenworthy & Newman (1990) and Newman, Kenworthy & Lyons (1992), it was considered that large changes in speed are generally associated with controlled intersections resulting in either complete or “approach” stops, i.e. a decrease in speed from free-flow cruise speed by more than 33%. The drop in “cruise” speed in the driving segments only applied if maximum speed was higher than the general minimum speed limit.

This resulted in the separation of the driving cycles into stop-go-stop segments, and in some cases, driving segments shorter than stop-go-stop segments, where one or both segment boundaries were determined as being “approach stops”. It is thus assumed that free-flow speeds (speed limits) are constant for the duration of these driving segments, or in other words, that driving took place within a specific speed zone. This assumption seems reasonable as minimum zone lengths are used in practice, which may be up to 10 km long for high speed limits (e.g. Vicroads, 1993; AS, 1999).

⁵⁸ In California, the general minimum speed limit on urban streets is 25 mph or 40 km/h (NHTSA, 2004). In the US, the general minimum speed limit on urban streets varies from 25 to 30 mph or 40 to 48 km/h, depending on the State (NHTSA, 2004). In Europe, the general minimum speed limit on urban streets is 50 km/h (EC, 2004), but it may be 60 km/h in some European countries (Umweltbundesamt, 1998). In Australia, the general urban speed limit is 60 km/h (AS, 1999).

Furthermore, differences in posted speed limits between speed zones are generally relatively small as speed limits are generally applied in increments of 10 km/h between adjacent speed zones.

For almost all cycles used in the four models, average free-flow speed for the entire cycle was computed by dividing the sum of free-flow travel times for each cycle segment by total cycle length. This was not done for the freeway cycles used in MOBILE 6 for which the maximum statutory speed limit of 65 mph (NHTSA, 2004) has directly been used as the free-flow speed (i.e. both 105 and 120 km/h).

Validation of Free-Flow Speed Method

The method to estimate free-flow speed when no information on speed limits is available is hypothetical and needs to be validated. The speed limits for each of the TNO motorway cycles are known (either 100 or 120 km/h) and these cycles can be used for validation. For each TNO cycle, the 5 congestion indicators that use free-flow speed as input were calculated using the method discussed previously and compared to the “true value”, i.e. the known speed limit plus 15 km/h. The reason for not using the speed limit is that the speed limit plus 15 km/h maximizes the possible error in the estimation method, making the validation more robust. In addition, for one TNO cycle the travel speed was higher than the known speed limit, which for instance resulted in negative delays and CI values lower than one. This indicates that, in this case, the free-flow speed is actually higher than the speed limit.

The results of this validation are presented in Figure 30 (next page). Scatter plots are shown between range-standardized estimated and “true” values, including a 45° line that presents a perfect fit. The x- and y-axes have been standardised over the range of indicator values. It can be seen that estimated indicator values generally correlate reasonably well with the “true” values, but that some indicators seem to perform better than others. The largest errors occur in more congested conditions (i.e. higher indicator values). However, direction (i.e. increase or decrease) is predicted correctly by all indicators in these conditions.

From the scatter plots it appears that d^* is able to predict true values well in all conditions. This is in contrast with CI and RDR that appear to provide biased

(underestimated) results in more congested conditions. This is confirmed by the fact that d^* has the lowest root-mean-square-error value of all five indicators for both free-flow speed estimates, whereas CI and RDR have the highest values.

Further validation is not possible because there are no other datasets for which the speed limit is known for each cycle. It is expected, however, that the estimation method would perform better in situations where lower speed limits would apply than in the TNO motorway cycles (e.g. on urban roads), because the difference between free-flow speed and travel speeds is substantially lower. As a result, errors in the estimation of free-flow speed would have a smaller impact on congestion indicator values. The validation using TNO cycle data is therefore considered to be a worst-case assessment of method performance.

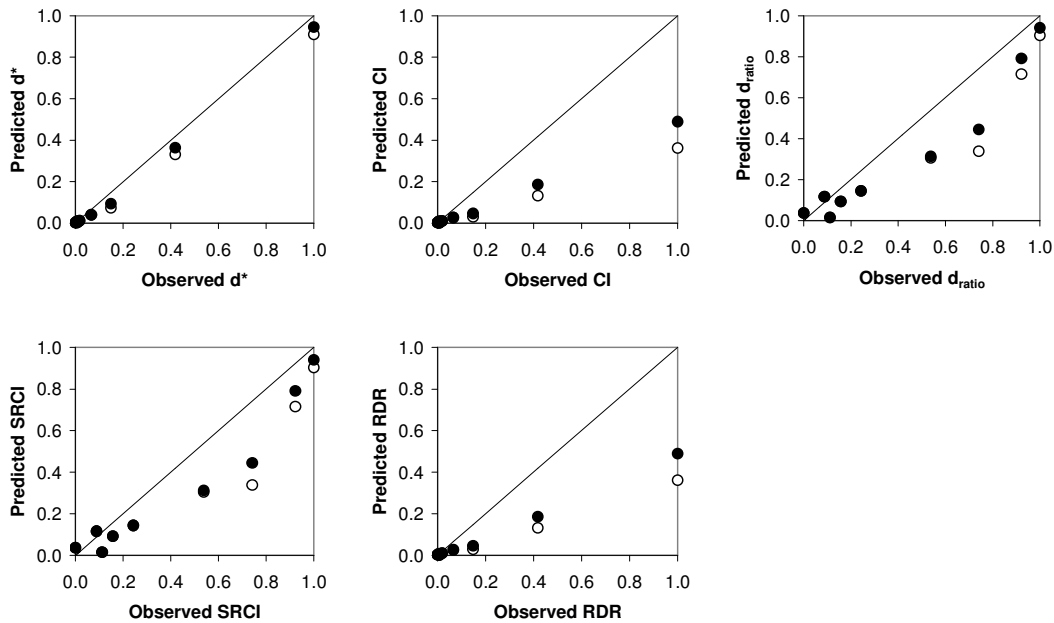


Figure 29 – Validation of Estimation Method for Free-Flow Speeds Developed in This Section

(Open Dots Represent Method Using Minimum Urban Speed Limit,
Black Dots Represent Method Using Minimum Urban Speed Limit + 15 km/h)

This limited validation exercise indicates that the free-flow speed estimation procedure developed in the previous section generally gives acceptable results for at least one congestion indicator, delay rate (d^*), which is predicted most accurately. With respect to the other four indicators, and particularly CI and RDR, the estimation method gives biased results in more congested conditions. However, in relative terms, all indicators predict indicator “direction” correctly in more congested conditions.

Although the definition of free-flow speed as the speed limit *plus* 15 km/h performs better with respect to the TNO motorway cycles than the definition of free-flow speed as only the speed limit, this may not always be the case. For example, for roads with radar control (speed enforcement) it seems likely that the second definition would perform better than the first one, because vehicles would generally adhere to the speed limit. Therefore, both definitions are retained for the quantification of congestion levels in driving cycles. As a consequence, a range is presented in Table 15 to Table 21 for the indicators that use free-flow speed as input. The range presents a minimum value, which is based on the general minimum urban speed limit, and a maximum value, which is based on the same limit plus 15 km/h.

4.3.2 MOBILE 6

Table 15 and Table 16 present the calculated congestion indicator values for each driving cycle used in the MOBILE 6 emission model. The three MOBILE 5 low-speed urban cycles (LSP 1-3) used in MOBILE 6 have been included.

Table 15 – Congestion Indicator Values (Travel Time Based) for MOBILE 6 Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI	d*	d_{ratio}	RDR	SRCI
	km/h	km/h	sec/km	(Range) -	(Range) sec/km	(Range) -	(Range) -	(Range) -
HS	101.8	101.8	0.0	1.03 - 1.18	1 - 5	0.03 - 0.15	0.03 - 0.18	0.3 - 1.5
FWY A-C	96.0	96.0	0.0	1.09 - 1.25	3 - 7	0.09 - 0.20	0.09 - 0.25	0.9 - 2.0
FWY D	85.1	85.1	0.0	1.23 - 1.41	8 - 12	0.19 - 0.29	0.23 - 0.41	1.9 - 2.9
FWY E	49.0	49.6	0.6	2.14 - 2.45	39 - 43	0.53 - 0.59	1.14 - 1.45	5.3 - 5.9
FWY F	30.0	30.7	1.9	3.50 - 4.00	86 - 90	0.71 - 0.75	2.50 - 3.00	7.1 - 7.5
FWY G	21.2	22.1	5.7	4.96 - 5.67	136 - 140	0.80 - 0.82	3.96 - 4.67	8.0 - 8.2
ART A-B	39.8	46.8	13.1	1.69 - 1.75	37 - 39	0.41 - 0.43	0.69 - 0.75	4.1 - 4.3
ART C-D	30.9	39.3	23.5	1.98 - 2.03	58 - 59	0.50 - 0.51	0.98 - 1.03	5.0 - 5.1
ART E-F	18.7	27.8	60.5	2.76 - 3.08	123 - 130	0.64 - 0.68	1.76 - 2.08	6.4 - 6.8
NYCC	11.4	17.6	102.7	3.60 - 4.84	229 - 252	0.72 - 0.79	2.60 - 3.84	7.2 - 7.9
LSP 3	4.1	6.4	288.6	9.73 - 13.37	785 - 810	0.90 - 0.93	8.73 - 12.37	9.0 - 9.3
LSP 2	3.5	5.9	384.8	11.29 - 15.52	926 - 950	0.91 - 0.94	10.29 - 14.52	9.1 - 9.4
LSP 1	2.5	4.7	629.4	15.92 - 21.89	1343 - 1367	0.94 - 0.95	14.92 - 20.89	9.4 - 9.5

Table 16 – Congestion Indicator Values (Speed Fluctuation Based) for MOBILE 6 Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s [*]	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
HS	36	37	0	28	0.00	0.30	0.22	7.8	7
FWY A-C	39	38	0	22	0.00	0.30	0.23	8.6	10
FWY D	45	39	0	16	0.00	0.39	0.28	12.4	19
FWY E	44	41	1	14	0.16	0.68	0.36	33.2	52
FWY F	50	38	2	11	0.81	0.69	0.53	59.0	61
FWY G	43	39	3	14	1.31	0.53	0.44	66.3	63
ART A-B	40	33	15	13	0.49	0.79	0.42	43.1	68
ART C-D	36	36	20	7	1.48	0.85	0.50	58.5	77
ART E-F	34	27	31	7	2.68	0.85	0.65	87.4	104
NYCC	28	28	32	12	9.48	0.82	0.62	127.5	113
LSP 3	26	27	33	15	22.08	0.30	0.24	139.8	108
LSP 2	24	26	38	12	25.47	0.29	0.22	148.2	116
LSP 1	18	20	44	18	35.76	0.23	0.16	143.0	123

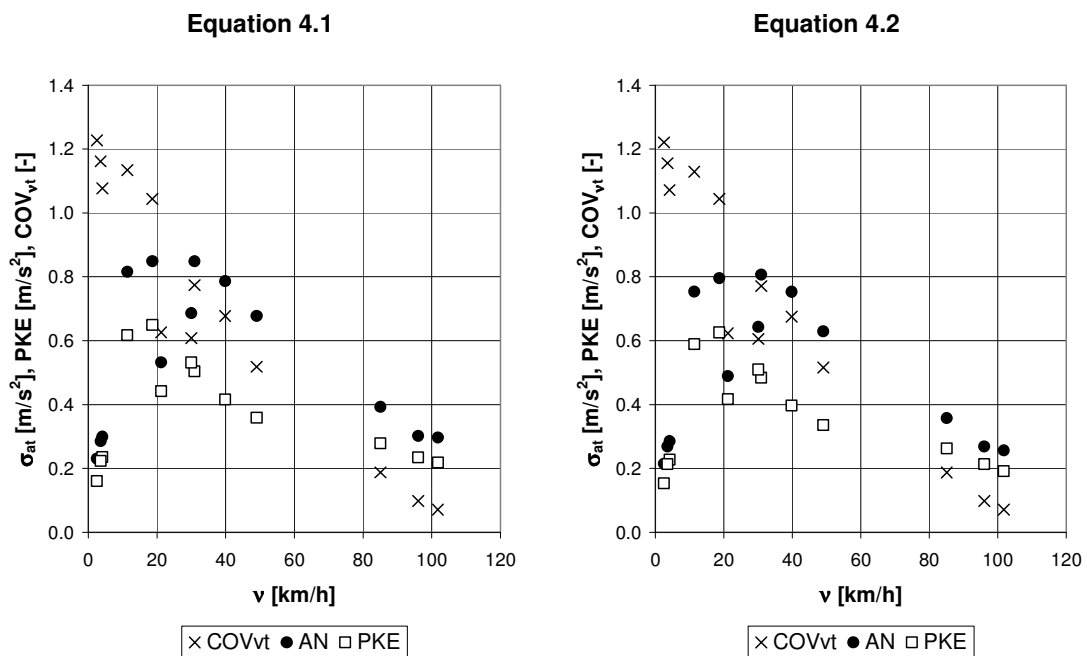
The following observations can be made from the information presented in these tables. None of the MOBILE 6 cycles qualifies as being “uncongested” according to the criteria that were defined in section 2.4. The cycle with the lowest level of speed fluctuation (i.e. Freeway High Speed Cycle - HS) still exceeds the criteria for σ_{at} , PKE, TAD and COV_{vt} . Other congestion indicators indicate relatively uncongested conditions for this cycle. For instance, the number of stops per km is zero, the estimated free-flow speed is very close to both travel speed and running speed ($CI \sim 1$ and $SRCI \sim 0$) and delay is very low (d^* , d_{ratio} and RDR are all approximately zero).

Generally a consistent increase is observed in the mean cycle values of all congestion indicators with decreasing travel speed, with the exceptions being the speed fluctuation indicators σ_{at} and PKE (and occasionally TAD and COV_{vt}), which show an opposite trend (decrease) in these values for the most congested freeway (FWY G) and the most congested arterial cycles (NYCC, LSP 1-3). Similarly, the percent of time spent in acceleration and deceleration mode (i.e. $P_{acc} + P_{dec}$) shows a decrease for these cycles. As will be shown later, this reduction in these speed fluctuation indicators in the most congested cycles is also observed in other driving cycles, and it does not mean that the level of congestion is reduced.

Figure 30 (next page) shows combined scatter plots of various congestion indicators versus travel speed. In Appendix B the trends that are visible in Figure 30 have been quantified for each congestion indicator individually through regression analysis. In this Appendix scatter plots are presented which include the “lines of best fit” and the coefficients of determination (R^2). The relationships between travel speed and the various congestion indicators are generally strong with an average R^2 value of 0.85.

Quantification of the congestion indicators is affected by the equation that is used to estimate instantaneous acceleration (equation 4-1 or 4-2, section 4.3.1). It can be seen that absolute values are slightly different when the two equations are compared. However, the pattern of data points is retained irrespective of the equation used. As a consequence, relative comparisons of cycle variables will lead to equivalent results, whichever equation is used. This result was also found for the other travel speed models.

The only case where the method may affect the analysis results is when absolute values are compared to preset criteria, which is the case for the identification of uncongested conditions. For the MOBILE 6 model, both equations lead to the conclusion that none of the MOBILE 6 cycles qualifies as being “uncongested”, since none of the criteria are met.



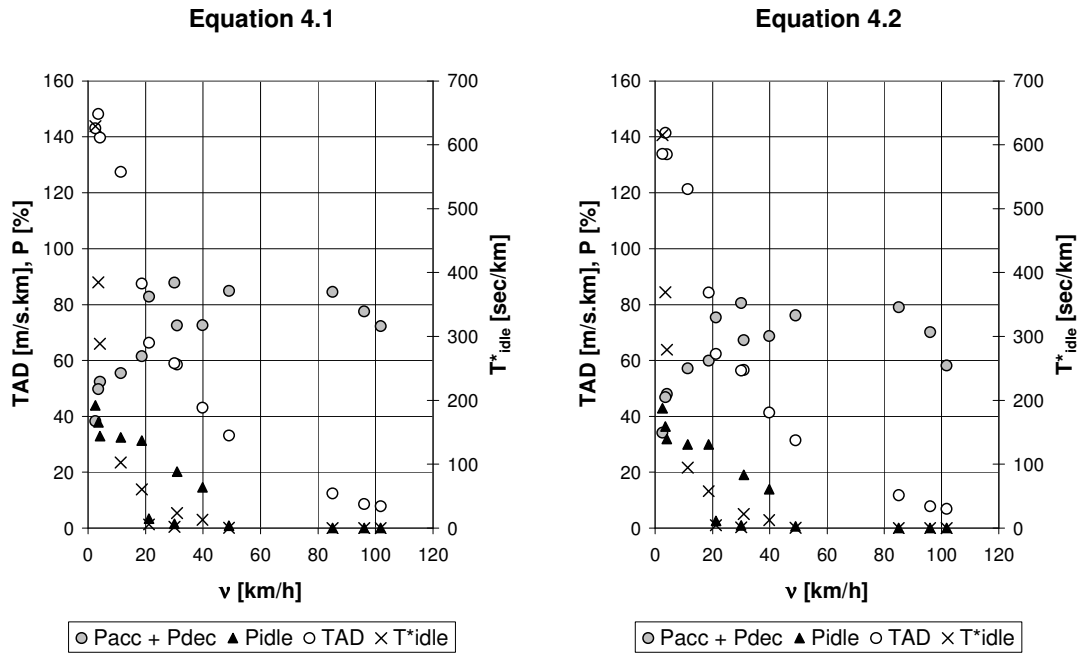


Figure 30 – Comparison of Two Different Methods to Compute Instantaneous Acceleration (MOBILE 6 Cycles)

The information presented in Table 15 and Table 16 indicates that travel speed is inversely related to level of congestion in the MOBILE 6 model. In other words, the relative levels of congestion increase with a decrease in travel speed. Since emission factors are computed as a function of travel speed, this implies that the emission factors used in MOBILE 6 also reflect different levels of congestion. In addition, none of the emission factors used in MOBILE 6 appears to reflect entirely uncongested conditions. These findings are in line with the previous sections. It is concluded that MOBILE 6 takes varying levels of congestion into account, where level of congestion increases with a reduction in travel speeds.

4.3.3 EMFAC 2000

Table 17 and Table 18 present the calculated congestion indicator values for each driving cycle used in the EMFAC 2000 emission model.

Table 17 – Congestion Indicator Values (Travel Time Based) for EMFAC 2000 Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
UCC65	91.8	95.8	1.5	1.23 - 1.23	7 - 7	0.19 - 0.19	0.23 - 0.23	1.9 - 1.9
UCC60	85.9	90.2	1.9	1.29 - 1.30	9 - 10	0.23 - 0.23	0.29 - 0.30	2.3 - 2.3
UCC55	75.8	80.4	2.6	1.32 - 1.32	11 - 11	0.24 - 0.24	0.32 - 0.32	2.4 - 2.4
UCC50	69.0	74.7	3.8	1.39 - 1.41	15 - 15	0.28 - 0.29	0.39 - 0.41	2.8 - 2.9
UCC45	71.8	75.1	1.9	1.34 - 1.35	13 - 13	0.25 - 0.26	0.34 - 0.35	2.5 - 2.6
UCC40	57.2	61.1	3.6	1.47 - 1.53	20 - 22	0.32 - 0.35	0.47 - 0.53	3.2 - 3.5
UCC35	51.4	56.4	5.7	1.66 - 1.68	28 - 28	0.40 - 0.40	0.66 - 0.68	4.0 - 4.0
UCC30	43.3	48.0	7.4	1.70 - 1.75	34 - 36	0.41 - 0.43	0.70 - 0.75	4.1 - 4.3
LA92	39.6	47.4	13.9	1.79 - 1.88	40 - 42	0.44 - 0.47	0.79 - 0.88	4.4 - 4.7
UCC25	36.9	43.3	13.1	1.70 - 1.75	40 - 42	0.41 - 0.43	0.70 - 0.75	4.1 - 4.3
UCC20	28.5	34.7	20.4	1.98 - 2.11	63 - 66	0.50 - 0.53	0.98 - 1.11	5.0 - 5.3
UCC15	21.5	30.3	46.5	2.26 - 2.61	94 - 103	0.56 - 0.62	1.26 - 1.61	5.6 - 6.2
UCC10	12.3	23.9	136.7	3.41 - 4.47	207 - 227	0.71 - 0.78	2.41 - 3.47	7.1 - 7.8
UCC5	3.5	10.3	649.6	11.31 - 15.55	928 - 953	0.91 - 0.94	10.31 - 14.55	9.1 - 9.4

Table 18 – Congestion Indicator Values (Speed Fluctuation Based) for EMFAC 2000 Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
UCC65	23	22	4	51	0.08	0.48	0.18	9	34
UCC60	25	21	4	50	0.12	0.60	0.23	13	41
UCC55	27	26	5	42	0.12	0.44	0.20	12	41
UCC50	32	28	7	33	0.19	0.54	0.22	15	51
UCC45	41	35	4	21	0.27	0.70	0.32	21	44
UCC40	41	33	6	21	0.42	0.73	0.34	28	64
UCC35	40	36	8	16	0.62	0.74	0.39	33	64
UCC30	40	33	9	18	0.85	0.79	0.43	41	66
LA92	38	34	15	12	1.01	0.88	0.45	47	80
UCC25	42	32	13	12	1.26	0.98	0.53	59	66
UCC20	41	32	16	10	1.96	1.00	0.58	78	78
UCC15	39	26	28	7	2.38	1.05	0.67	99	89
UCC10	23	24	47	6	5.29	0.81	0.53	100	121
UCC5	14	18	64	4	19.39	0.71	0.57	215	164

The following observations can be made from the information presented in these tables. None of the EMFAC 2000 cycles qualifies as being “uncongested”. The cycle with the lowest level of speed fluctuation (i.e. UCC 65) as indicated by PKE, TAD, COV_{vt} and n_s^* (but not σ_{at}) still exceeds the criteria that were defined in section 2.4. This finding does not change when the values are based on a different method of calculation of acceleration (not shown). This observation is in line with the values for other congestion indicators. For instance, the estimated free-flow speed deviates slightly from travel speed ($CI > 1$ and $SRCI > 0$) and delay (d^* , d_{ratio} and RDR) is slightly larger than zero.

At first sight, there appears to be a consistent increase of level of congestion with decreasing travel speed. However, closer inspection of the tables shows that this is not always the case. For instance, according to the free-flow speed based indicators the cycles UCC 45 and UCC 25 both show a small reduction in congestion level. Similarly, the cycles UCC 55 and UCC 50 exhibit lower σ_{at} and PKE values than the higher travel speed UCC 60 cycle, although these cycles do show a consistent increase in number of stops and COV_{vt} with travel speed.

Similar to MOBILE 6, the lowest speed cycles show a reduction in σ_{at} , PKE and $\{P_{acc} + P_{dec}\}$ values, which would suggest a reduction congestion levels. This is illustrated in Figure 31. This behaviour of these specific congestion indicators in the most congested conditions was also observed in the MOBILE 6 cycles and, as will be seen in the next section, is also present in the COPERT III and QGEPA cycles. This behaviour and its consequences for the analysis of congestion levels in driving cycles are discussed in detail in the next section.

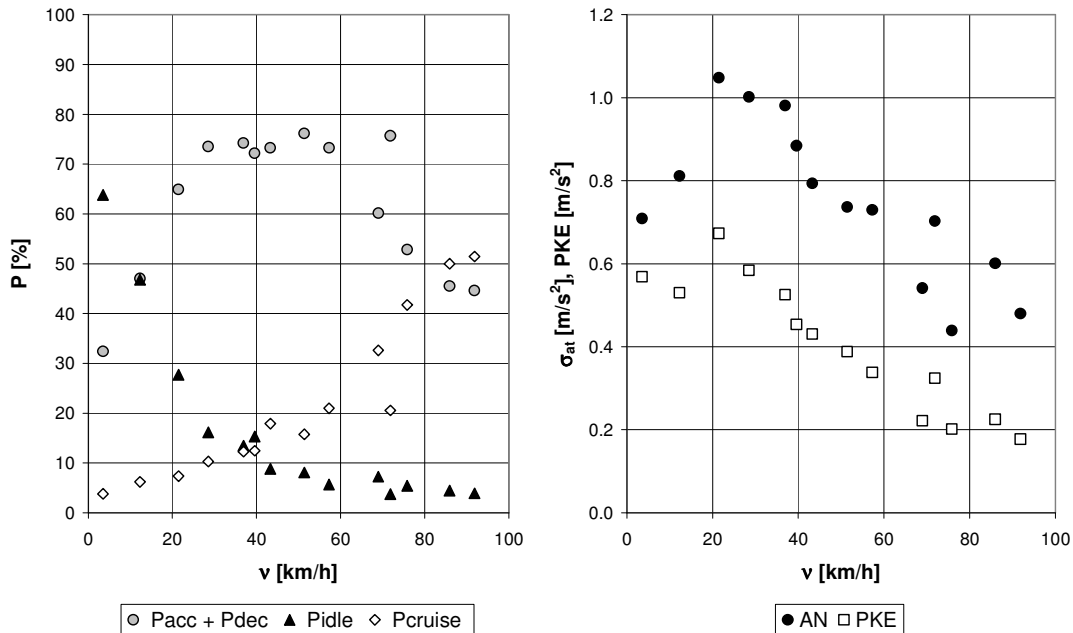


Figure 31 – Modal Activity Distribution and Speed Fluctuation in EMFAC 2000 Cycles

In Appendix B the trends that are visible in Figure 31 have been quantified for each congestion indicator individually through regression analysis. The relationships between travel speed and the various congestion indicators are generally strong with an average R^2 value of 0.93.

Table 17 and Table 18 indicate that none of the cycles (and thus emission factors) used in EMFAC 2000 appears to entirely reflect uncongested conditions. It is emphasized that this does not mean that uncongested conditions are never present in the cycles. It is possible that certain parts of the driving cycle are in fact uncongested. To illustrate this point, Figure 32 presents the UCC 65 cycle, with a section of the driving cycle that represents uncongested conditions. Congestion indicator values for this specific section are all below the criteria values that were set in section 2.4.

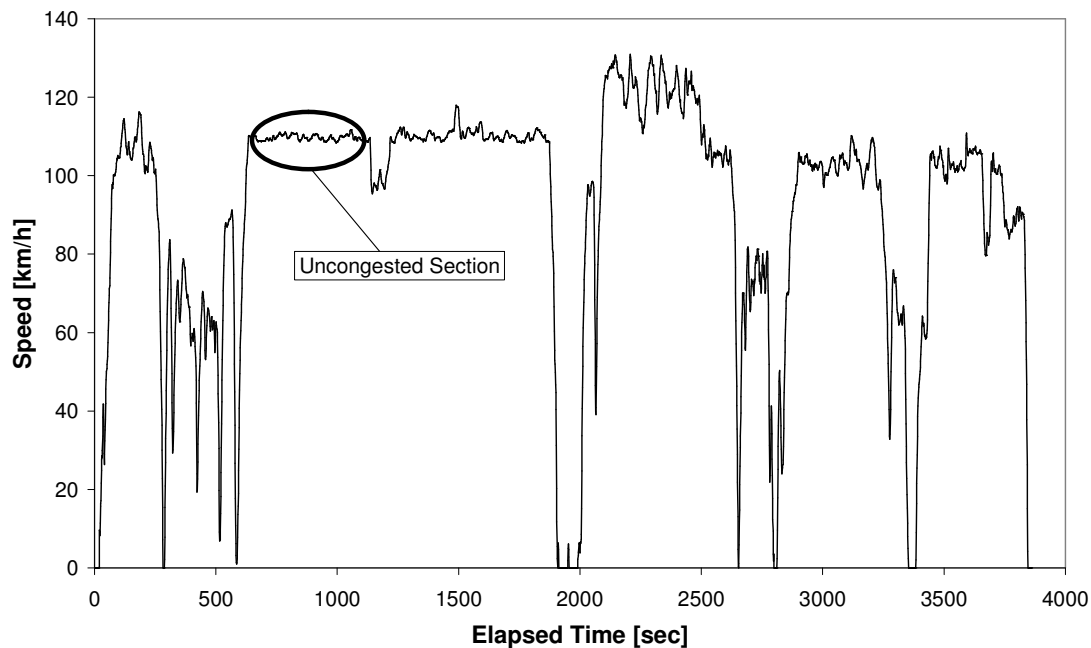


Figure 32 – Example of an Uncongested Part in the UCC 65 Cycle

However, since emission factors are based on the entire driving cycle, and not on specific parts of the driving cycle, mean congestion levels are of interest.

In contrast to the MOBILE 6 model, the cycles used in the development of the EMFAC 2000 model do not always show a consistent relationship between level of congestion and travel speed. It is concluded that EMFAC 2000 takes different levels of congestion into account and that there appears to be an overall trend of increasing congestion levels with a decrease in travel speeds.

4.3.4 COPERT III

Table 19 and Table 20 present the calculated congestion indicator values for each driving cycle used in the COPERT III emission model.

Table 19 – Congestion Indicator Values (Travel Time Based) for COPERT III Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
T130	130.0	130.0	0.0	1.06 - 1.06	2 - 2	0.06 - 0.06	0.06 - 0.06	0.6 - 0.6
BAB1000	117.5	117.5	0.0	1.16 - 1.16	4 - 4	0.14 - 0.14	0.16 - 0.16	1.4 - 1.4
T115	115.0	115.0	0.0	1.06 - 1.06	2 - 2	0.06 - 0.06	0.06 - 0.06	0.6 - 0.6
BAB736	110.0	110.0	0.0	1.16 - 1.16	4 - 4	0.14 - 0.14	0.16 - 0.16	1.4 - 1.4
BAB436	106.8	106.8	0.0	1.13 - 1.13	4 - 4	0.12 - 0.12	0.13 - 0.13	1.2 - 1.2
MM	101.0	103.5	0.8	1.27 - 1.27	8 - 8	0.22 - 0.22	0.27 - 0.27	2.2 - 2.2
T100	100.0	100.0	0.0	1.07 - 1.07	2 - 2	0.07 - 0.07	0.07 - 0.07	0.7 - 0.7
WSL MW	98.5	100.2	0.6	1.20 - 1.20	6 - 6	0.17 - 0.17	0.20 - 0.20	1.7 - 1.7
US HWAY	77.6	78.1	0.2	1.16 - 1.16	6 - 6	0.14 - 0.14	0.16 - 0.16	1.4 - 1.4
AUTO 1	74.2	76.0	1.1	1.38 - 1.40	13 - 14	0.27 - 0.28	0.38 - 0.40	2.7 - 2.8
WSL RUR	54.4	56.0	1.7	1.32 - 1.41	16 - 19	0.24 - 0.29	0.32 - 0.41	2.4 - 2.9
MR	42.9	49.6	10.8	1.85 - 1.92	39 - 40	0.46 - 0.48	0.85 - 0.92	4.6 - 4.8
MOD 11	42.5	44.8	4.0	1.74 - 1.82	36 - 38	0.43 - 0.45	0.74 - 0.82	4.3 - 4.5
ROUTE 2	41.3	45.4	7.4	1.57 - 1.68	32 - 35	0.36 - 0.41	0.57 - 0.68	3.6 - 4.1

Table 20 (Continued) – Congestion Indicator Values (Travel Time Based) for COPERT III Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
MOD 14	32.1	38.5	17.6	1.90 - 2.04	53 - 57	0.47 - 0.51	0.90 - 1.04	4.7 - 5.1
MOD 7	30.2	36.9	19.1	2.69 - 2.71	75 - 75	0.63 - 0.63	1.69 - 1.71	6.3 - 6.3
MUF	22.8	28.6	29.4	2.54 - 2.85	96 - 103	0.61 - 0.65	1.54 - 1.85	6.1 - 6.5
MOD 5	22.2	31.3	44.5	2.55 - 2.96	99 - 107	0.61 - 0.66	1.55 - 1.96	6.1 - 6.6
MOD 12	20.8	25.3	28.2	2.41 - 3.13	101 - 118	0.58 - 0.68	1.41 - 2.13	5.8 - 6.8
MOD 1	19.5	25.4	40.3	2.71 - 3.33	116 - 129	0.63 - 0.70	1.71 - 2.33	6.3 - 7.0
UFLUI 2	19.2	23.0	28.7	2.61 - 3.39	116 - 132	0.62 - 0.70	1.61 - 2.39	6.2 - 7.0
MOD 2	18.8	36.3	90.1	3.12 - 3.46	130 - 136	0.68 - 0.71	2.12 - 2.46	6.8 - 7.1
WSL URB	18.1	23.5	43.1	2.76 - 3.59	127 - 143	0.64 - 0.72	1.76 - 2.59	6.4 - 7.2
MOD 13	17.9	25.7	56.9	2.87 - 3.62	131 - 145	0.65 - 0.72	1.87 - 2.62	6.5 - 7.2
MOD 8	15.9	21.9	57.8	3.25 - 4.08	156 - 170	0.69 - 0.75	2.25 - 3.08	6.9 - 7.5
MOD 10	15.6	21.0	54.6	3.20 - 4.16	158 - 175	0.69 - 0.76	2.2 - 3.16	6.9 - 7.6
MUS	14.3	20.9	75.1	3.49 - 4.53	179 - 196	0.71 - 0.78	2.49 - 3.53	7.1 - 7.8
MOD 3	13.8	19.0	67.5	3.62 - 4.71	189 - 205	0.72 - 0.79	2.62 - 3.71	7.2 - 7.9

Table 20 (Continued) – Congestion Indicator Values (Travel Time Based) for COPERT III Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
MOD 4	11.1	13.8	61.7	4.52 - 5.88	254 - 270	0.78 - 0.83	3.52 - 4.88	7.8 - 8.3
MOD 9	7.6	10.8	129.4	6.57 - 8.53	401 - 417	0.85 - 0.88	5.57 - 7.53	8.5 - 8.8
ULENT 2	7.4	9.8	110.1	6.77 - 8.80	415 - 432	0.85 - 0.89	5.77 - 7.80	8.5 - 8.9
WSL CON	6.7	10.0	163.5	7.47 - 9.71	466 - 483	0.87 - 0.90	6.47 - 8.71	8.7 - 9.0
MOD 6	5.2	6.4	114.9	9.68 - 12.59	625 - 642	0.90 - 0.92	8.68 - 11.59	9.0 - 9.2

Table 20 – Congestion Indicator Values (Speed Fluctuation Based) for COPERT III Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
T130	16	10	0	74	0.00	0.09	0.08	2	3
BAB1000	30	18	0	53	0.00	0.15	0.14	4	14
T115	17	15	0	68	0.00	0.11	0.08	3	4
BAB736	27	18	0	55	0.00	0.16	0.14	4	11
BAB436	18	14	0	69	0.00	0.11	0.09	3	7
MM	34	33	2	31	0.08	0.48	0.23	10	27
T100	23	17	0	60	0.00	0.12	0.10	3	5
WSL MW	19	13	2	66	0.00	0.26	0.14	5	20
US HWAY	28	21	1	50	0.06	0.30	0.14	8	21
AUTO 1	41	31	2	26	0.13	0.61	0.28	18	43
WSL RUR	36	32	3	29	0.18	0.61	0.28	24	43
MR	36	35	13	16	0.47	0.76	0.45	41	69
MOD 11	43	37	5	15	0.53	0.69	0.42	40	64
ROUTE 2	43	34	9	14	0.54	0.84	0.50	47	54

Table 21 (Continued) – Congestion Indicator Values (Speed Fluctuation Based) for COPERT III Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
MOD 14	38	35	16	12	1.17	0.82	0.51	57	71
MOD 7	35	42	16	7	2.38	1.09	0.82	84	83
MUF	38	34	19	9	2.67	0.82	0.60	82	88
MOD 5	33	34	27	6	2.68	1.00	0.69	88	94
MOD 12	36	35	16	12	2.87	0.81	0.49	84	80
MOD 1	34	34	22	11	2.03	0.79	0.55	83	91
UFLUI 2	38	35	15	11	2.31	0.79	0.49	90	68
MOD 2	21	24	47	7	1.14	0.97	0.70	77	121
WSL URB	33	30	22	15	2.77	0.66	0.43	76	82
MOD 13	30	36	28	6	3.43	0.92	0.70	100	99
MOD 8	32	33	26	9	3.61	0.74	0.58	97	95
MOD 10	30	35	24	11	4.28	0.82	0.58	103	90
MUS	30	33	30	7	4.11	0.73	0.51	99	96
MOD 3	37	29	26	8	3.70	0.78	0.53	110	84

Table 21 (Continued) – Congestion Indicator Values (Speed Fluctuation Based) for COPERT III Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
MOD 4	38	35	19	8	2.47	0.78	0.64	154	90
MOD 9	39	29	27	4	9.95	0.59	0.44	159	105
ULENT 2	30	33	23	15	11.37	0.61	0.44	167	85
WSL CON	24	28	30	17	16.19	0.60	0.46	152	117
MOD 6	33	38	16	12	15.32	0.84	0.86	357	117

The following observations can be made from the information presented in these tables. A number of high speed COPERT III cycles (T130, T115, T100, BAB436) qualify as being “uncongested”. These cycles are within all the criteria that were set in section 2.4. The other high speed cycles (BAB1000, BAB736) meet most of the criteria, but have σ_{at} and COV_{vt} values that are slightly higher than the criteria that were set for these indicators. Examination of indicator values based on a different method of calculation of acceleration (not shown) leads to similar conclusions.

Unlike MOBILE6, there is no consistent increase of level of congestion with decreasing travel speed in the COPERT III model. The level of congestion as quantified by the various indicators fluctuates significantly. This is illustrated in Figure 33 and Figure 34 (next page). Although there appears to be a general trend of increasing congestion levels with a reduction in travel speed, there is also significant scatter, which indicates that for small changes in travel speed the level of congestion may go either up or down.

In Appendix B the trends that are visible in Figure 33 and Figure 34 have been quantified for each congestion indicator individually through regression analysis. The relationships between travel speed and the various congestion indicators are, despite the sometimes scattered datapoints, generally strong with an average R^2 value of 0.89.

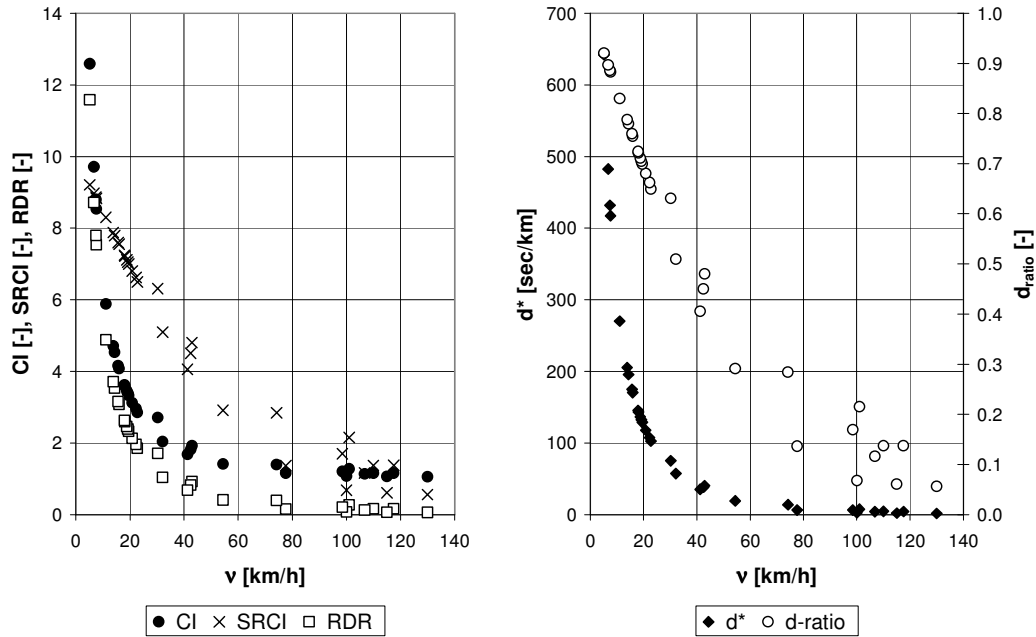


Figure 33 – Travel Time Based Congestion Indicator Values for COPERT Driving Cycles

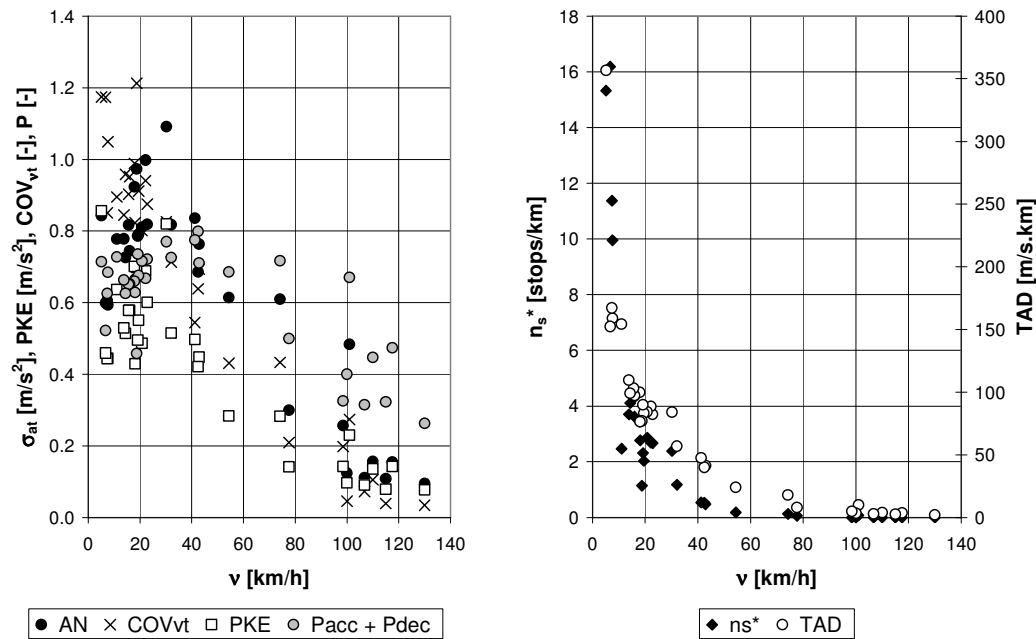


Figure 34 – Speed Fluctuation Based Congestion Indicator Values for COPERT Driving Cycles

Figure 34 indicates that at low travel speeds (below about 20 km/h), the computed values for the acceleration based indicators PKE, σ_{at} and $\{P_{acc} + P_{dec}\}$ are more scattered, including data points that have values that are lower than (or at least similar to) those observed at higher travel speeds. On average, values for $\{P_{acc} + P_{dec}\}$ and σ_{at} appear to be actually reduced, which was also observed in the previous sections.

The relationships between PKE and σ_{at} and level of congestion that were discussed in section 2.2.5 showed a consistent increase in these indicators with increasing congestion levels (i.e. density and volume-to-capacity ratio). Thus, these relationships would suggest that congestion levels in the COPERT cycles are reduced at very low travel speeds. However, this is contradicted by the other three speed fluctuation measures and the other five travel time based indicators in Figure 33 and Figure 34, which all show a quite consistent further increase in congestion levels.

In order to investigate why the relationships in section 2.2.5 do not show a reduction (or stabilization) in PKE and σ_{at} at very high levels of congestion the actual data points to which the relationships were fitted were re-examined. The model developed by Greenwood (2003) is based on only a few data points with travel speeds below 20 km/h, with large scatter in observed σ_{at} values at higher speeds. It is possible to visually fit a more hyperbolic relationship to these data. It appears reasonable to conclude that the data on which these relationships are based do not contradict the observation made in this study that at very high congestion levels PKE and σ_{at} are reduced.

It is hypothesized that PKE and σ_{at} are reduced due to a limited ability of vehicles to accelerate freely and strongly in very congested conditions. The absence of strong accelerations and large speed fluctuations would particularly reduce the values of PKE and σ_{at} , which are a function of “squared deviation in speed” and “squared deviation from mean acceleration”, respectively. In contrast to PKE and σ_{at} , the other measures of speed fluctuation (TAD, COV_{vt} and n_s^*) do indicate a consistent increase in congestion level with decreasing travel speed. These variables reflect overall speed fluctuation and they are not as sensitive to omission of strong accelerations and large speed fluctuations as PKE and σ_{at} .

In order to test this hypothesis, the acceleration distribution of two specific cycles were compared. The Urbain Lent 2 and Modem 7 cycle have different levels of speed fluctuation (refer to Table 20). Figure 35 shows the acceleration and deceleration distributions for these two cycles.

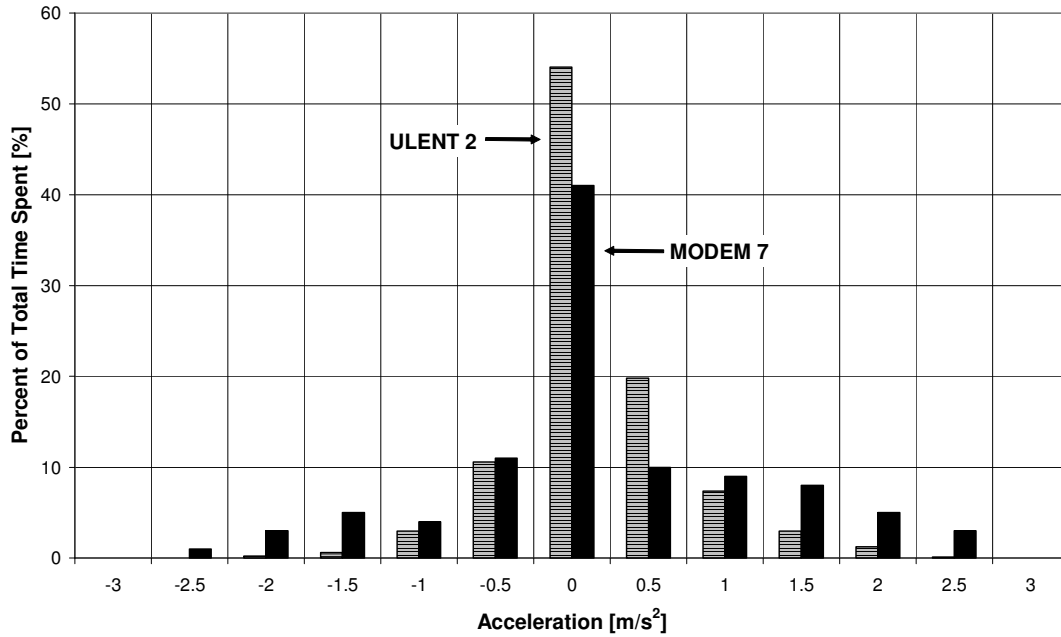


Figure 35 – Acceleration Distributions for two COPERT Driving Cycles

It can be seen that the MODEM 7 cycle experiences stronger and more frequent accelerations compared to the "Urbain Lent 2" cycle. This cycle also has higher PKE, σ_{at} and $\{P_{acc} + P_{dec}\}$ values, which lends support for the hypothesis. It is logical to conclude that the reduction in PKE, σ_{at} and $\{P_{acc} + P_{dec}\}$ at low travel speeds does not implicate a reduction in congestion levels, but rather is the result of restricted vehicle movement in these conditions.

A logical explanation for the reduction in $\{P_{acc} + P_{dec}\}$ values at low travel speeds appears to be the strong increase in percent of time spent idling, which leaves less time that can be spent in the other driving modes (acceleration, deceleration and cruise).

The quantitative analysis suggests that the high speed cycles with travel speeds higher than about 105 km/h (and thus emission factors) used in COPERT III reflect uncongested conditions. Below this travel speed, cycles experience some congestion where a general trend of increasing congestion levels with decreasing travel speeds can be observed. However, in contrast to the MOBILE 6 model, the relationship between level of congestion and travel speed is not as consistent. Depending on the change in travel speed, congestion may increase or decrease with decreasing travel speed.

It is concluded that COPERT III takes varying levels of congestion into account and that free-flow speed conditions exist for travel speeds above 105 km/h. There appears to be a trend of increasing level of congestion with lower travel speed.

4.3.5 QGEPA 2002

Table 21 and Table 22 present the calculated congestion indicator values for each driving cycle used for diesel vehicles in the QGEPA 2002 emission model. Since the QGEPA model for non-diesel vehicles is based on MOBILE6, the findings of section 4.3.2 apply to these vehicles.

Table 21 – Congestion Indicator Values (Travel Time Based) for QGEPA Diesel Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
CUED MC	35.3	42.2	15.9	2.01 - 2.20	51 - 55	0.50 - 0.54	1.01 - 1.20	5.0 - 5.4
CUED NA	35.1	39.9	11.7	1.98 - 2.22	51 - 56	0.50 - 0.55	0.98 - 1.22	5.0 - 5.5
CUED NB	43.5	47.5	6.5	1.81 - 1.94	37 - 40	0.45 - 0.48	0.81 - 0.94	4.5 - 4.8
CUED ME	30.9	36.3	16.8	2.11 - 2.47	61 - 69	0.53 - 0.60	1.11 - 1.47	5.3 - 6.0
CUED NC	34.1	38.4	10.9	2.00 - 2.25	53 - 59	0.50 - 0.56	1.00 - 1.25	5.0 - 5.6
CUED NCH	33.4	38.0	12.8	2.17 - 2.50	58 - 65	0.54 - 0.60	1.17 - 1.50	5.4 - 6.0
CON MC	7.2	12.5	207.1	8.39 - 10.49	443 - 455	0.88 - 0.90	7.39 - 9.49	8.8 - 9.0
CON NA	13.0	17.3	64.9	4.63 - 5.79	218 - 230	0.78 - 0.83	3.63 - 4.79	7.8 - 8.3
CON NB	11.0	11.8	19.6	5.48 - 6.85	269 - 281	0.82 - 0.85	4.48 - 5.85	8.2 - 8.5
CON ME	11.2	16.3	98.2	5.38 - 6.72	263 - 275	0.81 - 0.85	4.38 - 5.72	8.1 - 8.5
CON NC	8.0	10.1	90.8	7.52 - 9.40	391 - 403	0.87 - 0.89	6.52 - 8.40	8.7 - 8.9
CON NCH	6.7	9.1	135.4	8.93 - 11.16	476 - 488	0.89 - 0.91	7.93 - 10.16	8.9 - 9.1
RES MC	34.5	35.8	3.0	1.84 - 2.17	47 - 56	0.46 - 0.54	0.84 - 1.17	4.6 - 5.4
RES NA	32.8	36.5	10.5	1.84 - 2.29	50 - 62	0.46 - 0.56	0.84 - 1.29	4.6 - 5.6
RES NB	35.8	37.0	2.7	1.78 - 2.09	44 - 53	0.44 - 0.52	0.78 - 1.09	4.4 - 5.2

Table 22 (Continued) – Congestion Indicator Values (Travel Time Based) for QGEPA Diesel Driving Cycles

Cycle Name	v	v_{run}	T*_{idle}	CI (Range)	d* (Range)	d_{ratio} (Range)	RDR (Range)	SRCI (Range)
	km/h	km/h	sec/km	-	sec/km	-	-	-
RES ME	33.3	33.7	0.9	1.81 - 2.25	48 - 60	0.45 - 0.56	0.81 - 1.25	4.5 - 5.6
RES NC	32.4	34.0	4.2	1.85 - 2.32	51 - 63	0.46 - 0.57	0.85 - 1.32	4.6 - 5.7
RES NCH	32.6	33.1	1.4	1.84 - 2.30	51 - 63	0.46 - 0.57	0.84 - 1.30	4.6 - 5.7
ART MC	33.9	41.9	19.9	2.00 - 2.21	53 - 58	0.50 - 0.55	1.00 - 1.21	5.0 - 5.5
ART NA	32.0	38.9	19.4	2.05 - 2.38	57 - 65	0.51 - 0.58	1.05 - 1.38	5.1 - 5.8
ART NB	29.9	41.0	32.2	2.29 - 2.51	68 - 73	0.56 - 0.60	1.29 - 1.51	5.6 - 6.0
ART ME	23.7	32.9	41.2	2.55 - 3.17	92 - 104	0.61 - 0.68	1.55 - 2.17	6.1 - 6.8
ART NC	31.5	38.3	19.3	1.96 - 2.38	56 - 66	0.49 - 0.58	0.96 - 1.38	4.9 - 5.8
ART NCH	28.1	35.4	25.6	2.13 - 2.67	68 - 80	0.53 - 0.62	1.13 - 1.67	5.3 - 6.2
FWY MC	55.7	59.8	4.1	1.41 - 1.45	19 - 20	0.29 - 0.31	0.41 - 0.45	2.9 - 3.1
FWY NA	54.5	54.7	0.1	1.48 - 1.48	21 - 21	0.33 - 0.33	0.48 - 0.48	3.3 - 3.3
FWY NB	75.3	75.3	0.0	1.22 - 1.22	9 - 9	0.18 - 0.18	0.22 - 0.22	1.8 - 1.8
FWY ME	50.8	53.7	3.6	1.45 - 1.54	22 - 25	0.31 - 0.35	0.45 - 0.54	3.1 - 3.5
FWY NC	54.2	57.4	3.4	1.46 - 1.46	21 - 21	0.32 - 0.32	0.46 - 0.46	3.2 - 3.2
FWY NCH	65.2	67.3	1.6	1.47 - 1.47	18 - 18	0.32 - 0.32	0.47 - 0.47	3.2 - 3.2

Table 22 – Congestion Indicator Values (Speed Fluctuation Based) for QGEP Diesel Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
CUED MC	32	37	16	16	0.65	0.90	0.50	51	73
CUED NA	38	36	11	15	0.63	0.93	0.52	57	66
CUED NB	30	27	8	35	0.39	0.75	0.30	33	71
CUED ME	37	32	14	16	0.70	0.79	0.43	55	74
CUED NC	35	31	10	24	0.70	0.58	0.30	37	69
CUED NCH	33	26	12	29	0.39	0.53	0.27	34	85
CON MC	21	24	41	14	7.56	0.79	0.55	160	118
CON NA	27	35	23	14	4.16	0.99	0.68	147	90
CON NB	35	29	6	30	4.12	0.80	0.44	150	73
CON ME	33	29	30	7	3.01	0.85	0.62	145	98
CON NC	30	30	20	20	2.75	0.57	0.41	149	85
CON NCH	22	21	25	32	1.47	0.45	0.39	117	116
RES MC	43	45	3	9	0.25	0.97	0.60	71	54
RES NA	36	37	10	17	0.44	0.94	0.53	64	59
RES NB	38	36	3	23	0.25	1.01	0.55	63	47

Table 23 (Continued) – Congestion Indicator Values (Speed Fluctuation Based) for QGEPA Diesel Driving Cycles

Cycle Name	P _{acc}	P _{dec}	P _{idle}	P _{cruise}	n _s *	σ _{at}	PKE	TAD	COV _{vt}
	%	%	%	%	stops/km	m/s ²	m/s ²	m/s.km	%
RES ME	48	35	1	16	0.21	0.75	0.45	58	48
RES NC	37	29	4	30	0.87	0.56	0.28	40	49
RES NCH	45	32	1	22	0.23	0.61	0.38	49	52
ART MC	27	33	19	21	0.00	0.99	0.58	55	67
ART NA	40	35	17	8	0.25	1.20	0.72	78	68
ART NB	26	27	27	20	0.62	0.88	0.49	49	80
ART ME	33	34	27	6	1.05	0.92	0.60	79	82
ART NC	38	32	17	13	0.53	0.73	0.43	48	62
ART NCH	30	25	20	25	0.29	0.63	0.33	43	78
FWY MC	35	41	6	18	0.25	0.80	0.40	30	41
FWY NA	44	36	0	19	0.00	0.62	0.40	29	33
FWY NB	24	18	0	57	0.00	0.36	0.16	10	27
FWY ME	32	28	5	36	0.00	0.67	0.31	25	45
FWY NC	33	32	5	29	0.13	0.46	0.23	19	40
FWY NCH	31	24	3	42	0.00	0.35	0.17	12	44

The following observations can be made from the information presented in these tables. None of the diesel cycles qualifies as being entirely “uncongested”. The cycle with the lowest level of congestion is the freeway cycle for medium goods vehicles (FWY NB). This cycle has no stops (and thus no idle time) and a large proportion of cruise. Although it experiences the lowest level of speed fluctuation of all diesel cycles, only the PKE value is below the congestion threshold value.

Similar to the COPERT and EMFAC models, there is no consistent increase of level of congestion with decreasing travel speed in the QGEPA model. This is illustrated in Figure 36 and Figure 37, which compares all diesel cycles simultaneously.

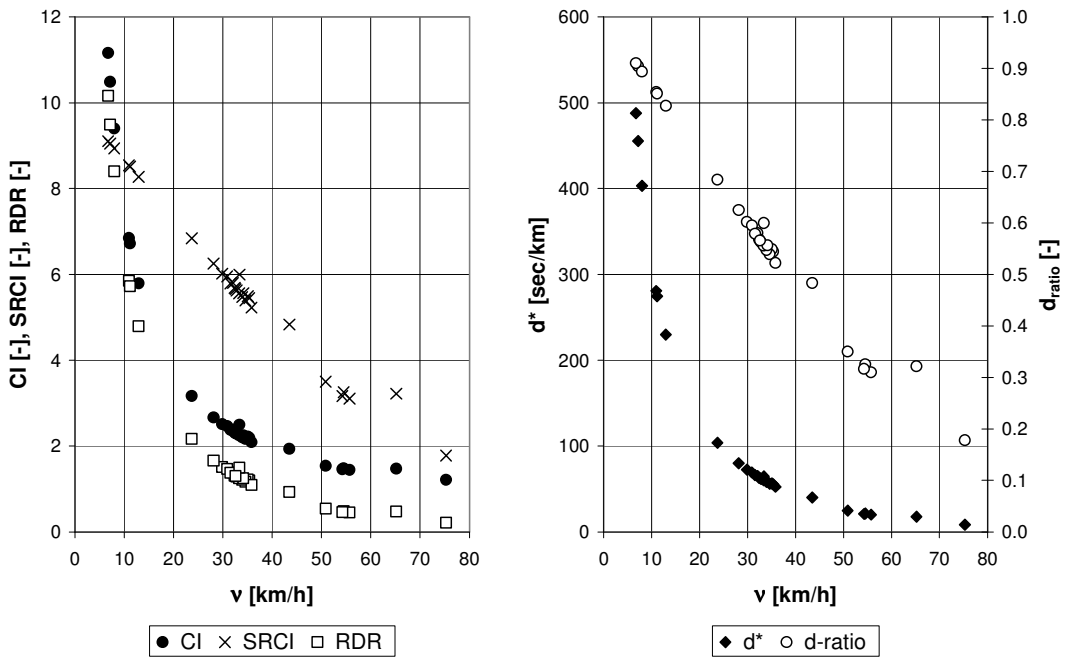


Figure 36 – Travel Time Based Congestion Indicator Values for QGEPA Diesel Driving Cycles

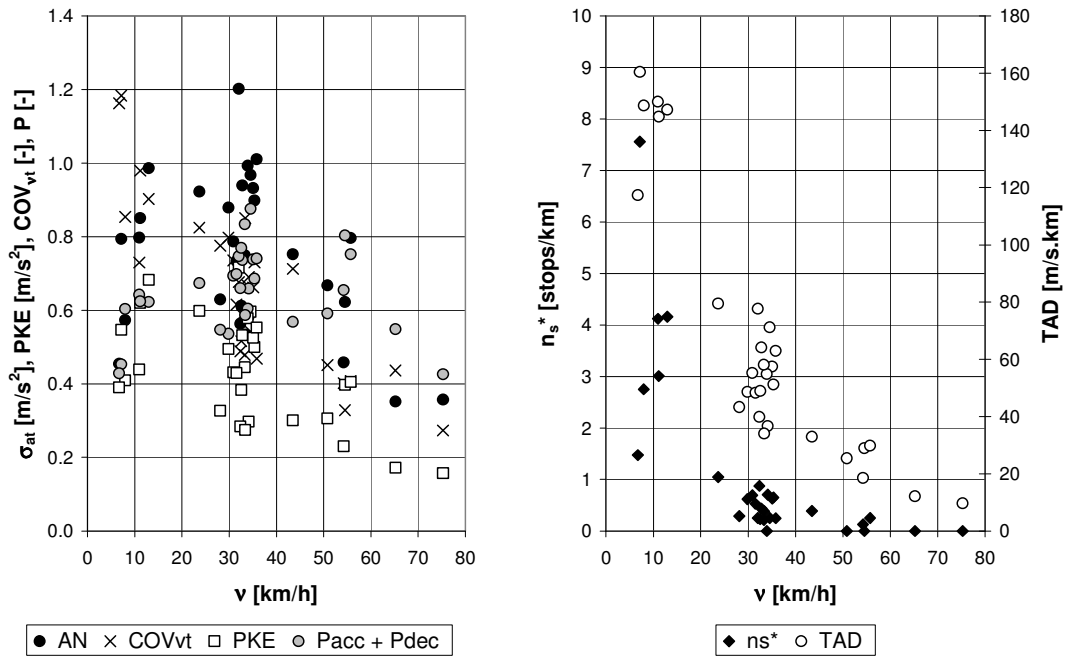


Figure 37 – Speed Fluctuation Congestion Indicator Values for QGEPA Diesel Driving Cycles

Although there appears to be a general trend of increasing congestion levels with a reduction in travel speed, there is also significant scatter in the 20-70 km/h travel speed range, which indicates that for small changes in travel speed the level of congestion may go either up or down.

In Appendix B the trends that are visible in Figure 36 and Figure 37 have been quantified for each congestion indicator individually through regression analysis. The relationships between travel speed and the various congestion indicators are, despite the sometimes significantly scattered datapoints, generally strong with an average R² value of 0.74.

It is concluded that the QGEPA model takes different levels of congestion into account. The quantitative analysis suggests that none of the diesel cycles (and thus emission factors) used in the QGEPA model entirely reflect uncongested conditions. The relationship between level of congestion and travel speed is not consistent, although a rough trend of increasing congestion levels with decreasing travel speeds can be distinguished.

4.4 Discussion & Conclusion

The research objective of this chapter was defined as an examination of to what extent (none or implicitly) a particular family of type I emission models, i.e. (four) current travel speed emission models, take congestion into account.

It was found that the information presented in the available literature was not sufficient to address the research objective for these models. Further analysis of the driving cycles that were used in the development of the respective emission models was necessary to determine more precisely how much congestion is included in these models. A method was developed to assess the mean level of congestion in driving cycles using both a qualitative (visual examination) and a quantitative approach. The re-examination of the driving cycles made use of various congestion indicators for which literature (i.e. traffic flow theory or empirical evidence) has shown that they are a function of level of congestion. Both the qualitative and quantitative analysis of the driving cycles showed consistent results.

In the driving cycles that were investigated for each model, an overall trend was observed of increasing congestion levels with decreasing travel speeds. Only a few high speed cycles in the COPERT III model qualify as being uncongested, according to a set of prespecified criteria that quantify smooth uninterrupted driving conditions. Based on the material presented in this chapter, it is concluded that:

all travel speed models examined in this chapter implicitly take varying, but fixed, levels of congestion into account, the level of which is dependent on the actual driving cycle that is reflected by the variable "travel speed" in the model.

This conclusion is subject to two limitations:

First of all, the driving cycle analysis had to be restricted mainly to light-duty vehicles due to lack of information and limited availability of speed-time data with respect to heavy-duty vehicles. The exception is the QGEPA model for which these data were

available. Hence, it was only possible for the QGEPA model to assess the level of congestion in the driving cycles for all vehicle types. For one model (COPERT) not all driving cycle data for light-duty vehicles could be obtained.

For air pollutants that are predominantly emitted by light-duty vehicles, such as CO and HC (e.g. BCC/QGEPA, 2004), it can be safely assumed, on the basis of this work, that application of current travel speed models would (largely) reflect the effects of congestion on emissions. However, for air pollutants for which heavy-duty vehicles are important contributors, such as NO_x and PM₁₀ (e.g. BCC/QGEPA, 2004), this statement can only be made with respect to the QGEPA 2002 model.

In terms of future work, researchers that do have access to the “missing” cycle data could apply the methodology presented in this chapter and complete the analysis.

Secondly, since driving patterns are also a function of other factors, it is possible that the change in congestion indicator values is not (only) a result of congestion but (partly) a result of these other factors. Several of such factors can be distinguished (Ericsson, 2000), such as driving style influenced by human factors (attitude, experience, gender, etc.), vehicle factors (power-to-mass ratio, size, etc.) and weather (visibility, precipitation, etc.). The extent to which driving cycles have been affected by these non-congestion related factors could not be determined.

The nature of the cycle construction process, however, *suggests* that congestion was a major, if not the most important, factor influencing the driving patterns on which the driving cycles are based. This is because the investigated cycles used in the models are all based on driving pattern data that were collected in urban areas where congestion is naturally prevalent. For a few models (MOBILE 6 and thus part of QGEPA 2002, EMFAC 2000), level of congestion (indicated by LOS) was even part of the driving pattern data collection process, and thus clearly an important factor.

Although it is not precisely known to what extent non-congestion related factors affect driving patterns, traffic engineering literature dictates that these non-congestion related factors are less important than congestion related factors (that is: road environment, vehicle interactions, intersections), as has been discussed in section 2.2. Also, Ericsson (2000) investigated the variability in driving pattern data and concluded that variation in the type of urban road had the largest influence on driving patterns when compared to human factors (gender, different drivers).

Therefore, it seems likely that the driving cycles used in the development of current travel speed models do at least for a large part reflect different levels of congestion. In terms of future work, it appears very important to investigate the relative importance of all factors (there are perhaps even more factors than the ones discussed in section 3.1 that we do not yet know about) that influence driving patterns. If it would be confirmed that congestion is by far the most important factor, this would corroborate the suggestion made by earlier studies (as was discussed in section 1.2) that congestion is a significant contributor to traffic emissions.

So, if it is assumed that the findings for the vehicle classes for which cycle data could not be obtained are similar to those for which cycles were examined⁵⁹, and when these conclusions are combined with the conclusions of section 3.4, an overall conclusion can be made with respect to the research question:

The majority of current air emission models that are applied at link level in urban networks and that have been investigated in detail in this thesis include the effects of congestion on emissions through either explicit or implicit consideration of (changes in) driving patterns.

So what are the implications for the use of emission models for networks that have congestion in them? If all models include congestion, although in different ways and to a different extent, which model should one use? The choice for a particular model could, in principle, be made on different grounds, such as the (required) level of model accuracy and practical considerations (e.g. model input requirements versus data availability).

As will be shown in section 5.5, validation of any emission model is difficult. In my research methodology I would have liked to examine whether models that explicitly incorporated congestion had higher validity than models that do this implicitly, but if others have been unable to do it generally, clearly I cannot within resources of a doctoral program.

⁵⁹ This does not seem to be an inappropriate assumption given the consistent way in which current driving cycles are developed and the consistency in the results with respect to the cycles that were examined.

Therefore, as I will show in Chapter 5, the approach I have adopted will be to compare the outputs of different models on a real transport network. This will be a limited assessment, but I flag here that it is a clever way to advance knowledge in this field within the resources available.

Now that congestion *within* current emission models and their interfacing with traffic data has been examined, to the extent possible, the focus in Chapter 5 is shifted to actual *application* of current emission models to large urban networks. Chapter 5 will examine, in a case-study setting, the (predicted) importance of congestion in urban networks with respect to emissions and whether *application* of different types of emission models produce results that are much different when applied to a large urban network.

The models that are selected for application in Chapter 5 have to comply with a number of criteria, which largely follow from the discussion in Chapter 3 (in particular section 3.2.3):

- The model must have been updated within the last ten years.
- The model must be capable of predicting emissions at the required spatial (link) and temporal resolution (1 hour).
- The model must include the effects of congestion in their predictions, either implicitly or explicitly.
- The model must be able to run on input data that can be feasibly collected at the level of a large urban network.
- The model must include all major vehicle categories⁶⁰.
- The model must consider both interrupted and uninterrupted flow conditions.

Table 23 presents an overview of the reviewed emission models that meet the first three criteria, i.e. they have been updated within the last ten years⁶¹, they can be applied at link level and hourly intervals and they implicitly or explicitly include

⁶⁰ These are catalyst and non-catalyst passenger cars and light-duty vehicles running on petrol, diesel and LPG, heavy-duty vehicles running on diesel.

⁶¹ It is noted that three models that were discussed in chapter 3 (PHEM, ARTEMIS/COST 346, VERSIT+) are not included in this chapter, because, at the time of model selection for chapter 5 (mid 2004), information on these models was not found in the literature. These models are now (becoming) available.

congestion (as has been shown in this Chapter 3 and Chapter 4). A shaded cell with an “X” means that a specific model meets one of the last three criteria.

Table 23 – Summary of the Appropriateness of Emission Models for Application in Chapter 5

	Runs on Input Data Available for a Large Road Network	Predicts Emissions for All Major Vehicle Categories	Considers Both Interrupted and Uninterrupted Flow
CVEM			X
CMEM			X
MEASURE			X
TEE-KCF 2002	X	X	X
MATZOROS			
MOBILE 6	X		X
EMFAC 2000	X		X
QGEPA 2002	X	X	X
COPERT III	X	X	X
TNO CRM	X	X	

Table 23 shows that three models meet the criteria for application in Chapter 5: one explicit type II model (TEE-KCF) and two implicit type I models (COPERT III and QGEPA 2002). It is noted that the MOBILE 6 model has been incorporated in the QGEPA 2002 model.

5 PRACTICAL NETWORK APPLICATION OF EMISSION MODELS

This chapter addresses the last two research objectives of this study:

by examination of an urban road network (Brisbane) as a case study;

- 1) investigate the importance of congestion in urban network modelling, and*
- 2) investigate when and where implicit and explicit emission models predict different effects of congestion on traffic emissions.*

With respect to the first research objective it is noted that only two studies were found that applied emission models to urban networks specifically in both congested and uncongested conditions (Tobin, 1979 and Anderson *et al.*, 1996, as was discussed in section 1.2). These studies both used type I travel speed models and their results showed that congestion in urban networks leads to elevated network emission levels. However, because the models are different (Tobin, 1979) and/or older (e.g. MOBILE 5 was used by Anderson *et al.*, 1996) compared to current travel speed models, it is not clear if similar results are achieved when current models are applied.

With respect to the second research objective it is noted that there is some evidence (Zachariadis & Samaras, 1997; Hallmark & Guensler, 1999; Bart *et al.*, 2001; Festa & Mazzulla, 2002) that implicit and explicit models predict different results. It is, however, unknown under which circumstances these differences occur in urban network modelling (e.g. congested or uncongested networks, different types of road) when current emission models are used.

So what are the possible implications of the testing that is conducted in this chapter? First of all, it is emphasized that the conclusions that follow from this chapter are limited by the *number* of emission models that were applied⁶².

⁶² This is not only because of restricted availability of input data, as was discussed in section 3.2.3, but also because of practical considerations: application of one particular emission model costs substantial amounts of time due to the different steps that are required, e.g. collection of all relevant data from different sources, preparation of input files (e.g. right format), running the model and processing its output data.

It is possible that different results would have been produced when other emission models had been applied. Therefore, general conclusions that would apply to all current explicit and implicit models cannot be made.

Secondly, the case-study network that is used in this chapter uses information from a particular travel demand traffic model (EMME2) for a particular urban area (Brisbane) and field data on signal settings that specifically apply to Brisbane. The work had to be restricted to this single case-study for practical reasons (as will be explained later).

It is noted that the use of other traffic models (e.g. SATURN) or similar traffic models that use other congestion functions could lead to substantially different emission predictions, due to differences in (the distribution of) computed link speeds. Differences in link speeds will also be reflected in different levels of (network) congestion. Therefore, this chapter will look into the effects of different levels of (sub)network congestion on both the importance of congestion and the differences between models.

It is possible that consideration of another urban network with a significantly different *network configuration* or *fleet composition* would lead to different results. Since the effects of different levels of network congestion are investigated, this only concerns certain aspects of network configuration, i.e. those aspects that affect emission predictions, but do not affect predicted level of (network) congestion⁶³.

1. The distribution of speed limits by road type (free-flow speeds in congestion functions), may vary substantially depending on the country (e.g. 40 to 60 km/h for urban roads, as was discussed in section 4.3.1) and may thus substantially affect travel speed distributions, but not necessarily level of network congestion (e.g. in terms of deviation from free-flow speed).

⁶³ It is noted that differences in other aspects of network configuration that are reflected in the level of (network) congestion (i.e. the distribution of road capacities and V/C ratios by road type, total road kilometres by road type), and also network size (total number of links, total road kilometres), are not important because the outcomes of this study are not sensitive to these differences.

2. The distribution of signal settings (effective green time, cycle time) on urban roads affects emission predictions made by the TEE-KCF model, but does not affect level of network congestion predicted by travel demand models since they do not use signal settings data in the computation of link travel speeds.

The extent of these differences in final results is not assessed in this study, but it is already suggested here that, in terms of further research, similar investigations should be conducted with other traffic models in other countries to see if comparable results are generated. Despite these issues, there are some valuable observations that can be made from the results of this chapter, for instance:

- if results are similar in congested and uncongested situations (provided that these are present in the case-study network), then this would *suggest* that congestion is not an important issue in urban network modelling; or
- if explicit and implicit models predict similar results in certain situations, then this would *suggest* that the way in which congestion is incorporated in an emission model is trivial with respect to urban network modelling in these situations.

It is noted that if different model types produce similar results, then the implicit model, which has the advantage of requiring less input data, can be used instead of the explicit model. In situations where emission models predict different results, one would have to choose which model would be best to use based on a number of predefined criteria such as sensitivity to specific variables and model accuracy. A possible procedure for the determination of the most appropriate model is discussed in section 5.5.

Section 5.1 will now first discuss the preparation of the test network input data and subsequent emission modelling. After this, the two research objectives are addressed in sections 5.2 to 5.4 through analysis of the modelling results. The chapter ends with a presentation of the conclusions.

5.1 Network Preparation and Emission Model Application

The Brisbane road network was selected for model application, because all required input data could be feasibly collected (e.g. signal data were collected at local traffic management centres as will be discussed later) for this test network. Brisbane, with a resident population of 1.7 million, is a large metropolitan area with an obvious CBD area, and hence congestion would very likely be present (as will be shown later this is the case), particularly during peak hours. The network also contains interrupted and uninterrupted roads, which allows for investigation whether the different mechanisms through which congestion manifests itself actually leads to different results in emission predictions.

The availability of traffic field data for this research was investigated. It was found that different publicly available information sources (BCC & ABACUS Surveys, 2000; QGDMR, 2002) provide important field data for the Brisbane road network. These sources provide mid-block and intersection count data, information on basic traffic composition (percent light-duty and heavy-duty vehicles, LDV and HDV) and travel time survey data (travel times, travel speeds)⁶⁴. However, these data are restricted to major roads in the network and morning and afternoon peak periods. In addition, travel speed data are usually provided for route sections, which consist of several links. Since the focus of this chapter is on comparison of emission models, rather than *accurate* estimation of emissions, the use of modelled network data, which provides a higher coverage of the actual network and data for non-peak periods, is the preferred option.

Recently, a travel demand model (EMME2) has been developed for the South-East Queensland Region (QGEPA, 2002), which includes the Brisbane Metropolitan Region. The Queensland Government Environment Protection Authority provided the required EMME2 link data for this research. The EMME2 traffic model has employed the BPR congestion function in its simulations (pers. comm., A. Pekol, 2-6-2004).

⁶⁴ Other field data on traffic performance such as vehicle trajectory data, queue length, number of stops were not available.

It is noted that traffic models that use congestion functions that substantially deviate from the BPR function (e.g. Akçelik function, section 2.2.4) may generate substantially different predictions of link speed and hence may produce substantially different link emissions. However, different predictions of link speed also result in different levels of (network) congestion. Hence, the relationship between (a change in) the level of network congestion and (a change in) the level of network emissions, which is investigated later in this chapter, should, to a large extent, remain in tact irrespective of the traffic model that is used. The term “to a large extent” is used here because a difference in the definition of uncongested travel speed (i.e. free-flow speed or zero-flow speed) may significantly affect emission predictions, but not congestion level.

The EMME2 data did not provide the complete set of required input data and data on signal settings and fleet composition needed to be extracted from other sources. Signal data has been extracted from two traffic signal coordination systems in Brisbane. This was done through several visits at the traffic management centres of both BCC⁶⁵ and DMR⁶⁶, who use separate systems, i.e. BLISS (BCC) and STREAMS/TRACS (DMR). These data, which consist of intersection plans, signal phasing diagrams and intersection data sheets, were then processed to determine intersection cycle times and (effective) green times for each approaching traffic stream (link) or movement. The effective green time ratio (g) is computed by (Akçelik, 1981):

$$g = \frac{g^*}{c} = \frac{\Gamma + I - a + b}{c} \quad \text{Equation 5-1}$$

where Γ is the displayed green time (sec), I is the intergreen time (i.e. amber and all-red period, sec), a is start loss, b is end gain and c is cycle time (sec). It is noted that the nominator represents the effective green time g^* (sec). Extracted signal intersection data provided values for cycle time and the sum of Γ and I for each movement at signalised intersections. Representative values for a and b were taken from Akçelik (1981).

⁶⁵ Brisbane City Council (denoted as BCC), which is responsible for local government-controlled roads.

⁶⁶ Queensland Government Department of Main Roads (denoted as DMR), which is responsible for state-controlled roads.

These two databases were consolidated into a single emission model input database. In addition, the distance of the link (mid-point) to the city centre was computed. The actual test network was defined as the road network modelled by QGEPA for base year 2000 for different times of day, i.e. morning peak (7:00 - 9:00 a.m.), off-peak (9:00 a.m. - 4:00 p.m, 6:00 – 10:00 p.m.), afternoon peak (4:00 - 6:00 p.m.), night (10:00 p.m. - 7:00 a.m.) with a radius of about 10 km from the city centre. For each network link and time of day the following data items were available:

- link length;
- road type;
- distance to city centre;
- number of lanes;
- direction of travel;
- traffic volume;
- proportion of light-duty and (commercial) heavy-duty vehicles;
- free-flow speed (posted speed limit);
- link capacity;
- travel speed;
- cycle length;
- effective green time; and
- effective green time ratio.

This database contains all input data that are required to run the travel speed and TEE-KCF emission models, except for a detailed traffic composition on the links. This information needs to be extracted from other data sources and this will be discussed in section 5.1.2.

Finally, congestion indicator values were calculated (equations 2-8, 2-19 to 2-23, 3-9) and added to the database for each link. This information has been used for the examination of network congestion levels and for later analysis of the results.

The congestion indicators that were calculated using the data items listed above are (refer to Chapter 2):

- volume-to-capacity ratio (ϕ);
- delay rate (d^*);
- delay ratio (d_{ratio});
- relative delay rate (RDR);
- congestion index (CI);
- speed reduction congestion index (SRCI); and
- mean density (veh/km.lane).

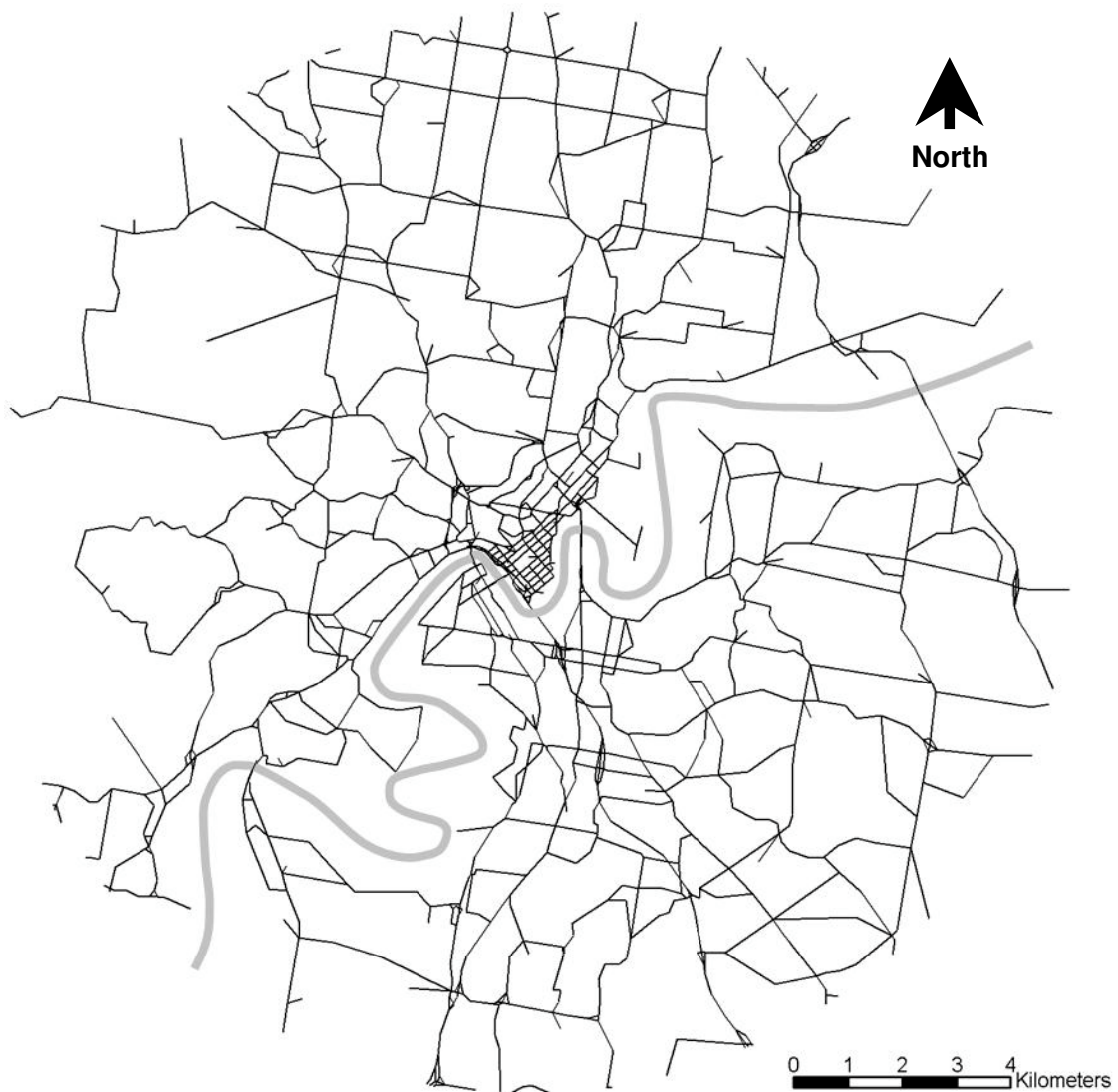
In addition the five network congestion indicators that were selected in section 2.4, i.e. DVKT, \bar{v}_n , k_n , CI_n and VKTKM (equations 2-32, 2-34, 2-36 to 2-38) were computed for different parts of the Brisbane network and different times of day (this will be discussed in the next section).

5.1.1 Test Network Characteristics and Level of Congestion

Two conditions must be met before the two objectives of this chapter can be addressed. Firstly, the selected emission models should include congestion. This was investigated in the first part of the thesis and it was concluded that this is the case for the TEE-KCF model and (most likely) the case for the COPERT III and QGEPA 2002 models. Secondly, the urban network should reflect at least two different situations, i.e. an uncongested and a congested network. The extent to which the second condition is met, is discussed in this section. In addition, relevant network features are discussed.

Network Structure

The Brisbane test network is depicted in Figure 38. The test network consists of a total of 2731 links and 479 signalised intersections. Of the total number of network links, 1223 links end with a signalised intersection (for which real signal data has been extracted), 169 links represent freeway driving and 1339 links end with a particular road feature (e.g. curve, bridge, tunnel).

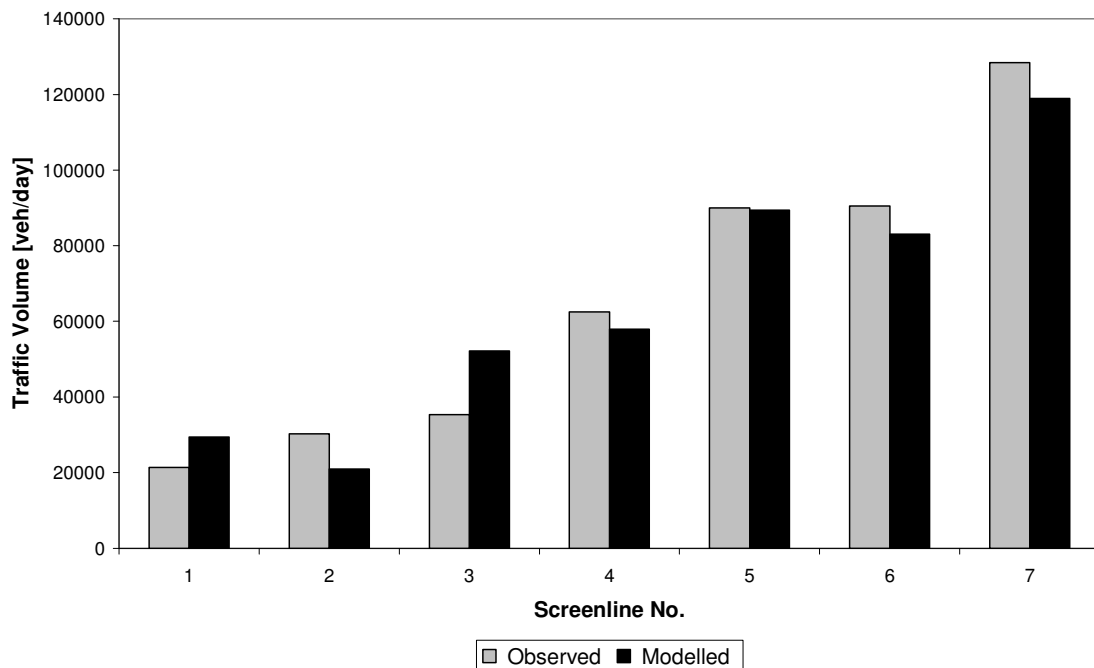


**Figure 38 – Brisbane Test Network
(Thick Grey Line Represents the Brisbane River)**

Comparison to the Real Network

In terms of coverage of the real Brisbane road network, the test network includes all higher order roads (e.g. arterial, sub-arterial and distributors), whereas most of the local access streets have been excluded⁶⁷. This means that all major traffic carrying roads are included whereas roads that tend to serve an access function (and carry much less traffic) are excluded (pers. corr., A. Pekol, APC, 14-10-2005).

Comparison to VKT data from the Australian Bureau of Statistics (ABS) suggests that the bulk of motor vehicle travel has been estimated by the travel demand model. Total VKT for Brisbane as predicted by the model was 3% lower than total VKT reported by ABS (QGEPA, 2002). This difference may be due to the exclusion of local roads, which implies that omission of local roads in the modelled network has only a small effect on total network emission predictions. Comparison of modelled traffic volumes to observations (average weekday) at seven screenlines (bridges) in Brisbane showed differences varying between -31% to +48%, as is shown in Figure 39.



⁶⁷ The length of the actual road network is 5700 km, whereas the length of the modelled network is 1100 km (pers.corr, A. Pekol, APC, 18-9-2006).

Figure 39 – Validation of Travel Demand Model

On average the difference between observations and model estimates was -1.4%. Although this validation is clearly restricted to a very small number of roads, it provides some level of confidence that the modelled network reflects traffic volumes (and hence level of congestion) on the real network of major roads sufficiently well.

Congestion in the Test network

Figure 40 shows the distribution of volume-to-capacity ratios of all links in the test network at different times of day.

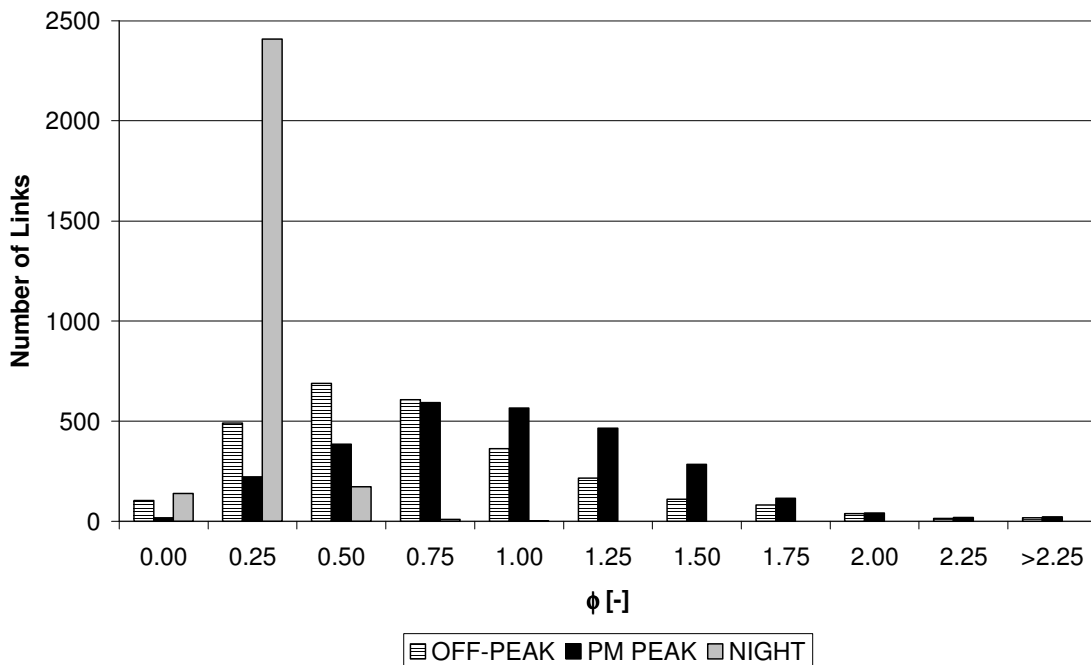


Figure 40 – Link Volume-to-Capacity Ratios in the Test Network

(Note: for clarity reasons the a.m. peak is not shown since it is almost equivalent to the p.m. peak)

Figure 40 shows that there are marked differences between the times of day. As expected, the night period is characterised by low volume-to-capacity ratios and here the majority of links are relatively uncongested. This is in contrast with the peak period in which a large proportion of the links (32%) experiences ϕ values that exceed unity.

Thus, *temporal separation* of the Brisbane network allows for comparison of emission predictions in a practically free-flowing uncongested network (night) to those in (more) congested networks (peak, off-peak).

In addition, *spatial separation* of the Brisbane network by *geographical location* and *basic road type* will further maximize the difference in congestion levels, and thus maximize the scope for comparison of emission predictions. This separation of the test network in time and space also enables examination when and where consideration of congestion is important and when and where (possible) differences between the particular explicit and implicit models occur in practise.

Geographical location is defined in terms of three geographical subdivisions:

- the Central Business District (CBD) area, as defined by the Brisbane City Council Road Hierarchy Plan (BCC, 2000);
- the Inner City Area, as defined by the part of the metropolitan area that was developed before the advent of mass motorisation (i.e. before 1939), but excluding the CBD area (Kenworthy & Laube, 1999); and
- the Outer City Area, as defined by the area that lies outside the inner area and is less than 10 km distance from the city centre.

The Brisbane inner city area is roughly defined as the city area within a 6.5 km radius from the city centre (Kenworthy & Laube, 1999). For *basic road types*, the two fundamental traffic flow regimes are used, i.e. interrupted and uninterrupted roads. For each link basic road type was determined based on the road typology provided by the travel demand model, i.e. interrupted roads are considered equivalent to “arterial”, “subarterial”, “collector”, “distributor” and “local road”, whereas uninterrupted roads are considered equivalent to “highway” and “freeway”. Table 24 (next page) presents the values of the five network congestion indicators by time of day, city area and road type.

Table 24 – Levels of Network Congestion and Other Features of the Test Network by City Region, Road Type and Time of Day

City Region	Road Type	Time Period	DVKT [sec/VKT]	Cl _n [-]	k _n [veh/lnkm]	VKTKM [VKT/lnkm.h]	v _n [km/h]	Mean P _{HDV} [-]	Total VKT [VKT]
Entire Network		A.M. peak	59	2.0	23	711	31	0.044	1,073,783
		Off-peak	2	1.0	8	527	63	0.056	795,446
		P.M. peak	56	2.0	23	740	32	0.030	1,117,712
		Night	0	1.0	1	88	65	0.070	133,541
CBD	Interrupted	A.M. peak	67	2.1	24	657	28	0.075	19,638
		Off-peak	5	1.1	10	557	54	0.080	16,659
		P.M. peak	48	1.8	21	693	33	0.050	20,728
		Night	0	1.0	1	77	57	0.123	2,288
Inner City	Interrupted	A.M. peak	78	2.3	26	679	26	0.042	514,194
		Off-peak	2	1.0	9	513	58	0.054	388,337
		P.M. peak	75	2.3	27	711	27	0.028	538,627
		Night	0	1.0	1	84	60	0.069	63,874
	Uninterrupted	A.M. peak	71	2.6	40	1252	32	0.038	75,994
		Off-peak	1	1.0	13	1086	83	0.037	65,940
		P.M. peak	57	2.3	35	1272	36	0.031	77,219
		Night	0	1.0	2	203	86	0.044	12,330
Outer City	Interrupted	A.M. peak	39	1.7	16	583	37	0.045	325,950
		Off-peak	1	1.0	7	431	61	0.057	241,322
		P.M. peak	19	1.7	17	618	36	0.029	345,718
		Night	0	1.0	1	72	62	0.069	40,055
	Uninterrupted	A.M. peak	26	1.6	24	1347	56	0.039	138,007
		Off-peak	0	1.0	9	812	91	0.057	83,189
		P.M. peak	19	1.5	21	1322	62	0.033	135,420
		Night	0	1.0	2	146	93	0.073	14,994

The differences in congestion between the peak and non-peak periods are still clear for the entire network and for all parts of the network, with higher congestion levels in the peak periods and low congestion levels in the non-peak periods, particularly at night. In fact, Table 24 shows that the night period presents a practically free-flowing network (except for intersection effects on urban links) with very low density (one or two vehicles per lane-km) and zero delay (DVKT = 0, $CI_n = 1.0$)

Highest congestion levels are found for the collection of freeways (uninterrupted roads) in the inner city area in the morning peak period (highest CI_n and k_n values) and collection of arterials (interrupted roads) in the inner city area in the morning peak period (highest DVKT value).

Interestingly, the highest VKTKM value is found for uninterrupted roads in the outer city area during the morning peak. However, in terms of deviation from free-flow speed (DVKT, CI_n) this subnetwork has the lowest values during the morning peak and with respect to traffic density only interrupted roads in the outer city area have lower values. This indicates that uninterrupted roads in the outer city area actually experience relatively low congestion levels, which is supported by the high \bar{v}_n value. This, however, is in contrast with the high VKTKM value.

This discrepancy can be explained by the fact that uninterrupted roads in general are high capacity roads that carry relatively high volumes of traffic. This results in high VKT values. As a result VKTKM values are by nature higher for freeways when compared to arterials. When freeways in the inner and outer city areas in the morning period are compared, freeways in the outer city area have on average the highest link capacity, which means that relatively high traffic loads are required before deviation from free-flow speed occurs. This explains the smaller values of DVKT and CI_n .

For the comparison of subnetworks, DVKT, CI_n and k_n are considered to be better indicators of congestion than VKTKM and \bar{v}_n . DVKT and CI_n are both measures of the magnitude of deviation from uncongested (free-flow) travel speed. k_n includes in its computation a measure of both traffic activity (link traffic volume) and traffic performance (link travel speed). These three congestion indicators can be used to compare road (sub)networks since they take into account the effects of different road features (e.g. type of road, capacity) on congestion.

VKTKM and \bar{v}_n do not do this. As a consequence, comparison of congestion levels between different subnetworks using one of these indicators is not meaningful. However, individual use of these congestion indicators is still useful for comparison of the *same* subnetwork at different times of day, or useful for *different* networks as long as VKTKM and \bar{v}_n values are considered together⁶⁸, as will be seen below.

Comparison to Other Urban Networks

It is now clear that the Brisbane test network, differentiated in time and space, includes a free-flowing network and subnetworks with varying levels of congestion. Although the most congested network values presented in Table 24 appear to be high, it is difficult to say to what extent they can be considered high values in practise. It is conceivable that other networks (e.g. in East Asia) would show higher levels of congestion than Brisbane.

Information on other urban networks around the world is scarce. One study (Kenworthy & Laube, 1999), can, to a certain extent, be used for this purpose. This study lists basic urban data for a global sample of 46 metropolitan cities for base year 1990. The only network congestion data that are available from this publication are a measure of travel intensity, i.e. VKTKM (based on annual VKT for cars only), and \bar{v}_n for the entire metropolitan network, and they are plotted in Figure 41.

Figure 41 shows that the *overall* level of congestion in the Brisbane metropolitan test network is generally higher than those in urban areas in the United States, Canada and Australian cities in 1990, but lower than a number of Asian and European cities. The most congested part of the Brisbane test network (i.e. inner city area, including both types of road, morning peak) has a network speed of 27 km/h and an annual travel intensity of 2 482 498 car VKT/km, as is shown in Figure 41 (indicated with “I”).

⁶⁸ For instance, urban networks with a high VKTKM value and a small proportion of high capacity freeways would be congested, which would translate into a low mean network speed. Alternatively, urban networks with a similarly high VKTKM value but also a high proportion of high capacity freeways would be relatively uncongested, which would translate into a high mean network speed.

This subnetwork appears to be quite congested compared the other urban networks, and only two cities (Bangkok, Paris) appear to have network levels (i.e. higher VKTKM and lower network speed) that are higher. This is corroborated by the high proportion of links (35%) in this subnetwork that experience ϕ values that exceed unity.

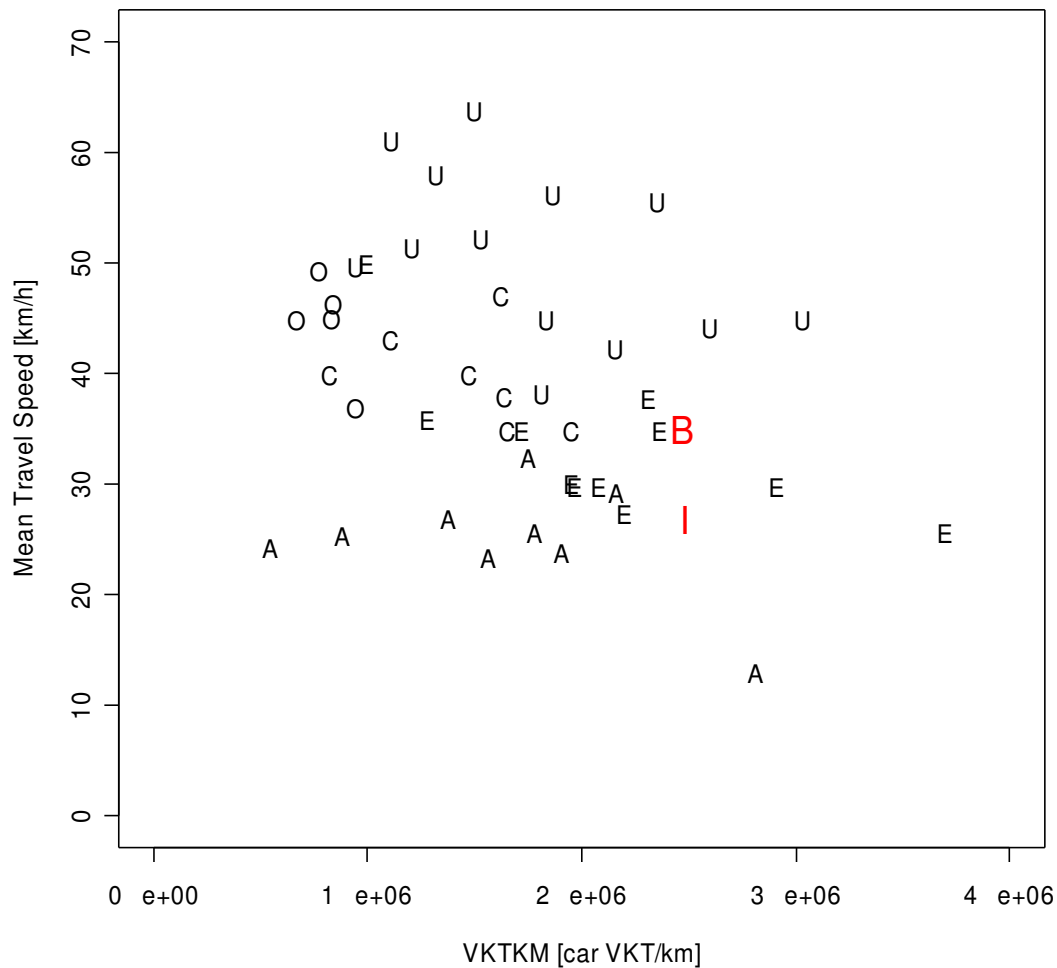


Figure 41 – International Comparison of Urban Network Congestion

(B = Brisbane Test Network, I = Inner City Brisbane Test Network (a.m. peak), O = Australian City, E = European City, A = Asian City, C = Canadian City, U = US City)

This information suggests that the urban test network used in this study, differentiated in time and space, includes network congestion levels that can be considered to be relatively high when compared to other urban networks around the world (although higher network congestion levels do exist).

As a consequence, it seems likely that the conclusions that will follow from this chapter would not significantly change when the selected emission models are applied to other urban networks, provided that:

- the fleet composition is similar to the fleet composition in Queensland; and
- certain aspects of network configuration (speed limits, signal settings) are similar to the Brisbane sub(networks).

Other Factors

Finally, the last two columns in Table 24 show that congestion is not the only variable that varies by location and time of day. Percent heavy-duty vehicles is highest in the night period, and particularly high in the CBD area, and lowest in the peak periods. Total VKT is a function of the total number of links and link length distribution of each subnetwork, but always highest in the peak periods and lowest in the night period. These two variables (traffic activity, basic traffic composition) are key variables with respect to emission estimation, as will be seen later. Therefore, it will be investigated to what extent a change in emission levels can be attributed to a change in congestion level, or a change in the other two variables.

5.1.2 Preparation of a Detailed Traffic Composition

As was discussed in section 3.1, vehicle emissions are a function of several vehicle characteristics like weight, type of fuel, emission control technology and the age of the vehicle. In the modelling of traffic stream emissions, vehicle categories are used, which are assumed to reflect the major differences in these characteristics that occur in traffic streams. Depending on the emission model, a large number of vehicle categories can be defined. For instance, COPERT III incorporates 106 different vehicle categories and the QGEPA model defines a total of 73 different vehicle categories.

As a consequence, emission models require link VKT data broken down by the various vehicle categories used in the respective emission models. In the Brisbane test network, link VKT data are available for only two major vehicle categories (LDVs and HDVs). Additional information is thus needed to arrive at the required breakdown of link VKT data for emission modelling.

This kind of information is not available at link level, but it is available at more aggregate network level. Therefore, with respect to a further breakdown of link VKT data, fleet composition data are used to estimate average traffic composition for all the links in the network. Different information sources were employed to estimate a further breakdown of LDV and HDV traffic volumes.

As a first step, fleet composition data from the Australian Bureau of Statistics (ABS) was examined. ABS publishes annual data on VKTs and fuel consumption, broken down by vehicle type and fuel type. ABS (2000) provides information on total VKT by area of operation (e.g. “capital city”, “interstate”), vehicle type and fuel type. ABS (2000) also provides information on total travel by year of manufacture (≤ 1979 , 1980-1989, ≥ 1990) and vehicle type for each Australian State. This information is, however, not detailed enough to develop a representative traffic composition for LDVs and HDVs that would correspond to the vehicle categories used in current emission models. This is because the years of manufacture used by ABS do not correspond to the definitions of the major technology classes.

In anticipation of the final results of this section, Table 25 shows an overview of these major technology classes for base year 2000, which are described by vehicle type, fuel type, year of manufacture, engine technology, emission control technology and emission standard. The following remarks are made with respect to Table 25:

- Australian passenger cars and light commercial vehicles running on petrol or LPG of model years *prior to* 1986 (ADR 26, ADR 27) correspond to the fleet of Australian non-catalyst cars. These cars generally have carburettors rather than fuel injection systems and may use a variety of non-catalytic emission controls such as exhaust gas recirculation for NO_x reduction (DoTRS, 2001). These vehicles run on leaded petrol.
- Australian passenger cars and light commercial vehicles running on petrol or LPG manufactured *after* January 1986 (ADR 37, 37/00 and 37/01) generally have computer controlled engine management systems, fuel injection and are fitted with a catalyst (DoTRS, 2001). In order to prevent poisoning of the catalyst, these vehicles require unleaded petrol. A further distinction can be made with respect to the type of catalytic converter. Light vehicles of model years 1986 to 1988 predominantly have two-way catalyst technology, whereas light vehicles manufactured from 1989 onwards predominantly have three-way catalyst (FORS, 1996; AGO, 1998). It is noted that ADR 37/01 imposes more stringent emission standards compared to ADR 37/00. The ADR 37/01 standards are achieved through a combination of better engine management and slightly larger exhaust catalysts (AATSE, 1997).
- Most Australian buses, articulated and rigid trucks, i.e. vehicles with a gross vehicle weight above 3.5 tonnes, are diesel fuelled. Prior to the introduction of ADR 70/00 in the period 1995-1996 Australian vehicles with light-duty or heavy-duty diesel engines were effectively uncontrolled and required only to be certified to ADR 30, which sets limits for smoke opacity. Nevertheless, from around 1990 onwards, diesel engines sourced from some countries such as the US and Europe often embodied some of the emission control systems (but not exhaust after-treatment) required in their country of origin. Prior to 1990, most diesel vehicles had no specific emission controls (Parsons, 1998; CONCAWE, 1999).

Table 25 – Major Vehicle Classes for This Study (LDVs)

Vehicle Type	Fuel Type	Year of Manufacture	Engine Technology	Emission Control Technology	Emission Standard ²⁾
Passenger vehicles	LP, LPG ¹⁾	≤ 1985	Spark-Ignition	Non-catalyst	ADR 26, 27
Passenger vehicles	ULP, LPG ¹⁾	1986 – 1988	Spark-Ignition	2-Way catalyst	ADR 37
Passenger vehicles	ULP, LPG ¹⁾	1989 – 1996	Spark-Ignition	3-Way catalyst	ADR 37/00
Passenger vehicles	ULP, LPG ¹⁾	1997 – 2000	Spark-Ignition	3-Way catalyst	ADR 37/01
Passenger vehicles	Diesel	≤ 1989	Compression-Ignition	Non-catalyst	Uncontrolled
Passenger vehicles	Diesel	1990 – 1996	Compression-Ignition	Non-catalyst	Controlled (overseas)
Passenger vehicles	Diesel	1997 – 2000	Compression-Ignition	Non-catalyst	ADR 70/00
Light-commercial vehicles	LP, LPG ¹⁾	≤ 1985	Spark-Ignition	Non-catalyst	ADR 26, 27
Light-commercial vehicles	ULP, LPG ¹⁾	1986 – 1988	Spark-Ignition	2-Way catalyst	ADR 37
Light-commercial vehicles	ULP, LPG ¹⁾	1989 – 1996	Spark-Ignition	3-Way catalyst	ADR 37/00
Light-commercial vehicles	ULP, LPG ¹⁾	1997 – 2000	Spark-Ignition	3-Way catalyst	ADR 37/01
Light-commercial vehicles	Diesel	≤ 1989	Compression-Ignition	Non-catalyst	Uncontrolled
Light-commercial vehicles	Diesel	1990 – 1996	Compression-Ignition	Non-catalyst	Controlled (overseas)
Light-commercial vehicles	Diesel	1997 – 2000	Compression-Ignition	Non-catalyst	ADR 70/00
Motorcycles	Petrol	All Years	Spark-Ignition	Non-catalyst	Uncontrolled

LP = leaded petrol, ULP = unleaded petrol, LPG = liquefied petroleum gas

¹⁾ No Australian emission standards apply to LPG-fuelled vehicles for these years of manufacture.

²⁾ Australian Design Rules (ADRs) are national standards for motor vehicles, covering vehicle emissions and safety.

Table 27 (Continued) – Major Vehicle Classes for This Study (HDVs)

Vehicle Type	Fuel Type	Year of Manufacture	Engine Technology	Emission Control Technology	Emission Standard ¹⁾
Rigid trucks	Diesel	≤ 1989	Compression-Ignition	Non-catalyst	ADR 30/00
Rigid trucks	Diesel	1990 – 1996	Compression-Ignition	Non-catalyst	Controlled (overseas)
Rigid trucks	Diesel	1997 – 2000	Compression-Ignition	Non-catalyst	ADR 70/00
Articulated trucks	Diesel	≤ 1989	Compression-Ignition	Non-catalyst	ADR 30/00
Articulated trucks	Diesel	1990 – 1996	Compression-Ignition	Non-catalyst	Controlled (overseas)
Articulated trucks	Diesel	1997 – 2000	Compression-Ignition	Non-catalyst	ADR 70/00
Buses	Diesel	≤ 1989	Compression-Ignition	Non-catalyst	ADR 30/00
Buses	Diesel	1990 – 1996	Compression-Ignition	Non-catalyst	Controlled (overseas)
Buses	Diesel	1997 – 2000	Compression-Ignition	Non-catalyst	ADR 70/00

¹⁾ Australian Design Rules (ADRs) are national standards for motor vehicles, covering vehicle emissions and safety.

Since ABS (2000) did not provide sufficient information, other sources of information have been employed to estimate the distribution of vehicle travel over the different vehicle classes, as defined in Table 25. Two factors needed to be taken into account (NEPC, 1999a):

1. the total number of vehicles in a specific age group decreases due to disposal; and
2. the annual distance travelled decreases with vehicle age.

Vehicle registration data (August, 2001) were obtained from Queensland Transport showing the number of vehicles registered by vehicle type, fuel type and year of manufacture. Data on annual mileage by model year were extracted from EA (2000) for passenger cars. These data were combined to estimate the proportion of total VKT that was driven by cars for each model year. For the other vehicle types, data on annual mileage were not found and the distribution of travel by vehicle age was directly taken from NEPC (1999a). The results are presented in Figure 42 (next page)⁶⁹.

⁶⁹ It is noted that the proportion of total travel for model year 2000 is lower because vehicles are purchased during this year and vehicles purchased later in the year travel less compared to the other model years for which vehicles always travel the full year.

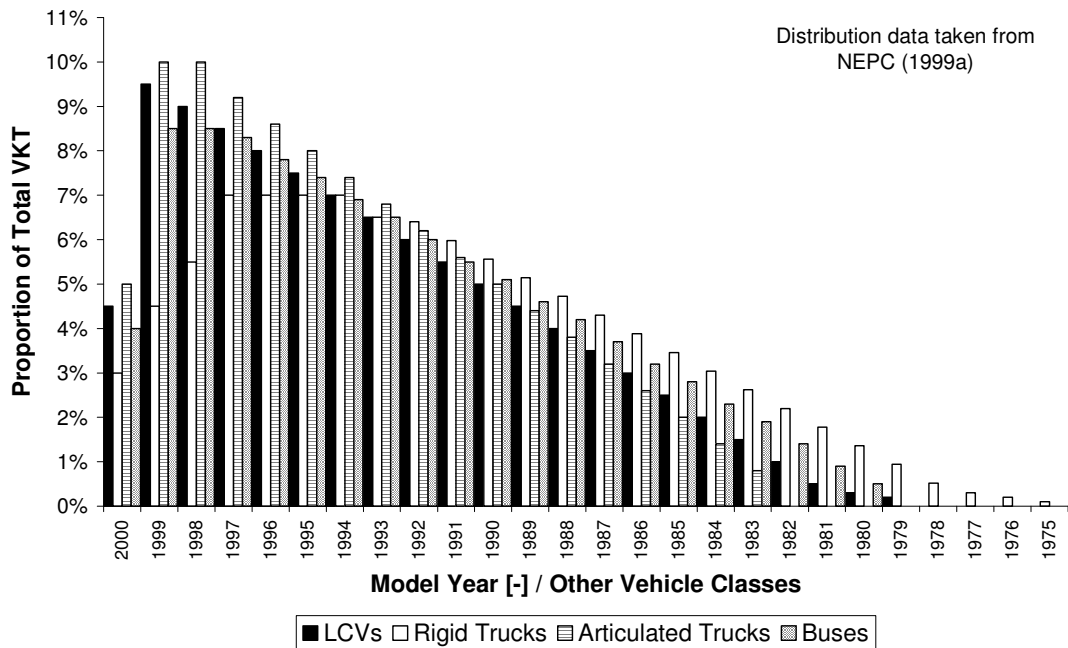
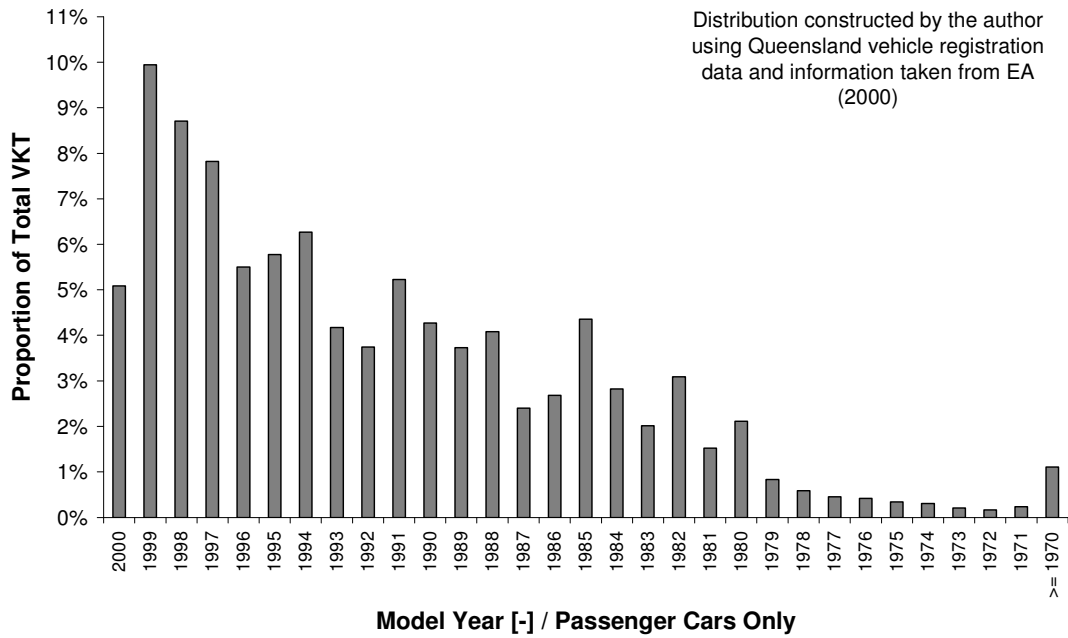


Figure 42 – Distribution of Total Travel by Vehicle Type and Model Year in the Year 2000

To verify these computations with the available ABS data, these distributions have been used to calculate the percent of total VKT for the three ABS model year ranges. The difference between the percent of total VKT provided by ABS and the percent of total VKT as estimated using the detailed information presented in Figure 42 was computed for each vehicle type separately. The results are shown in Table 26.

Table 26 – Differences Between ABS data and Predictions Based on Travel Distributions

Type of Vehicle	≤ 1979	1980 - 1989	≥ 1990
Passenger vehicles	0.57%	-1.39%	0.82%
Light-commercial vehicles	-3.92%	0.08%	3.84%
Rigid trucks	-4.25%	-0.36%	4.61%
Articulated trucks	-4.22%	2.33%	1.89%
Buses	-5.45%	1.80%	3.65%
Motor cycles	N/A	N/A	N/A

It can be seen that in most cases, the percent difference is small within a few percent. This is particularly so for passenger vehicles, which indicates that the use of Queensland vehicle registration data leads to a similar breakdown of the fleet composition. The largest differences are found for old light and heavy commercial vehicles, with a maximum difference of about 5%. However, these vehicles together account for only 1% of total VKT and the effect of this difference on emission predictions would therefore be small. Table 26 indicates that the detailed travel distributions align with the ABS data, which confirms the validity for use in this study.

The data presented in Figure 42 were subsequently used to compute the share of total travel (VKT) for each of the 32 major vehicle classes. The final result of this work is presented in Table 27.

Table 27 – Percent of Total VKT by Major Vehicle Class for the Base Year 2000

Main Vehicle Class ¹⁾	Vehicle Type	Fuel Type	≤ 1985	1986 - 1988	1989 - 1996	1997 - 2000	≤ 1989	1990 - 1996	1997 - 2000	TOTAL
LDV	Passenger vehicles	ULP	-	7.3%	31.0%	25.3%	-	-	-	63.7%
		LP	15.8%	-	-	-	-	-	-	15.8%
		LPG	1.2%	0.5%	2.2%	1.8%	-	-	-	5.6%
		Diesel	-	-	-	-	0.3%	0.6%	0.4%	1.3%
	Light commercial vehicles	ULP	-	0.8%	4.0%	2.5%	-	-	-	7.4%
		LP	1.6%	-	-	-	-	-	-	1.6%
		LPG	0.1%	0.2%	0.9%	0.6%	-	-	-	1.8%
		Diesel	-	-	-	-	0.5%	1.0%	0.7%	2.2%
	Motor cycles	Petrol	-	-	-	-	0.1%	0.5%		0.5%
	Total LDV			18.7%	8.9%	38.1%	30.2%	0.9%	1.8%	1.3%
HDV	Rigid trucks	Diesel ²⁾	-	-	-	-	22.8%	30.0%	13.2%	65.9%
	Articulated trucks	Diesel ²⁾	-	-	-	-	3.6%	9.4%	6.8%	19.8%
	Buses	Diesel ²⁾	-	-	-	-	3.6%	6.4%	4.2%	14.2%
Total HDV			-	-	-	-	30.0%	45.8%	24.1%	100.0%

LP = leaded petrol, ULP = unleaded petrol, LPG = liquefied petroleum gas

¹⁾ It is noted that LDVs account for 95% of total VKT and HDVs 5%.

²⁾ Includes CNG and petrol (less than 0.06 % of total VKT).

Since data on link VKT was already differentiated by basic vehicle type (i.e. LDV and HDV), two detailed traffic compositions, one for LDVs and one for HDVs, are presented in Table 27 and have been used to compute a breakdown into all major vehicle categories for each link in the network. These results have been incorporated in the emission model input database.

Petrol vehicles, which almost entirely consist of light-duty vehicles (i.e. cars, light-commercial vehicles and motorcycles), dominate total travel in Brisbane since they account for 95% of total travel. Heavy-duty vehicles (i.e. rigid trucks, articulated trucks and buses) account for about 5% of total travel. Catalyst cars (i.e. model years of 1986 and later) account for a large part of total travel in Brisbane (about 65%) and non-catalyst cars are less important with 15% of total travel. However, in terms of total emissions load, non-catalyst cars will still contribute significantly to total network emissions, because emissions are typically a factor of 2 to 10 higher compared to their catalyst counterparts, depending on e.g. the pollutant, catalyst technology and level of maintenance (e.g. Faiz, Weaver & Walsh, 1996).

The Queensland fleet composition is an important input variable in the computation of total emissions (as will be shown in the next section). This means that the outcomes of this chapter may not apply to urban areas in countries with a fleet composition that is significantly different from the one that was used in this chapter.

A final task was to construct a “vehicle class equivalency” table for the models used in this chapter. The QGEPA 2002 model uses descriptions of major vehicle class that are equivalent to Table 25. The TEE-KCF 2002 and COPERT III models, however, use other descriptions. Hence, it was necessary to develop a table that shows which Australian vehicle classes correspond to which classes used in the European models. Table 28 shows the results. This table was constructed using information (e.g. emission control technology) on European vehicle classes presented in EEA (2000).

Table 28 – Corresponding Australian and European Vehicle Categories Used in This Study

QGEPA 2002 Model	TEE-KCF 2002 & COPERT III Models
Passenger Vehicles, Leaded Petrol, Non-Catalyst, ADR 26, 27	Passenger Vehicles, Leaded Petrol, Non-Catalyst, ECE15/03
Passenger Vehicles, Unleaded Petrol, Catalyst, ADR 37, 37/00, 37/01	Passenger Vehicles, Unleaded Petrol, TWC, 1.4-2.0 l, EURO I
Passenger Vehicles & LCVs, LPG, Non-Catalyst, ADR 26, 27	LPG Vehicles < 2.5 tonne, LPG, Non-Catalyst, "Conventional"
Passenger Vehicles & LCVs, LPG, Catalyst, ADR 37, 37/00, 37/01	LPG Vehicles < 2.5 tonne, LPG, TWC, EURO I
Passenger Vehicles, Diesel, Non-Catalyst, ≤ 1989	Diesel Vehicles < 2.5 tonne, Diesel, Non-Catalyst, "Conventional"
Passenger Vehicles, Diesel, Non-Catalyst, 1990-2000	Diesel Passenger Cars < 2.5 tonne, Diesel, Non-Catalyst, EURO I
LCVs, Leaded Petrol, Non-Catalyst, ADR 26, 27	LDVs < 3.5 tonne, Leaded Petrol, Non-Catalyst, "Conventional"
LCVs, Unleaded Petrol, Catalyst, ADR 37, 37/00, 37/01	LDVs < 3.5 tonne, Unleaded Petrol, TWC, EURO I
LCVs, Diesel, Non-Catalyst, ≤ 1989	LDVs < 3.5 tonne, Diesel, Non-Catalyst, "Conventional"
LCVs, Diesel, Non-Catalyst, 1990-2000	LDVs < 3.5 tonne, Diesel, Non-Catalyst, EURO I
Motorcycles, Petrol, Non-Catalyst, All Years	Motorcycles, Petrol, Non-Catalyst, 250-750 cc, "Conventional"
Rigid & Articulated Trucks, Diesel, Non-Catalyst, ≤ 1989, ADR 30/00	Diesel HDVs > 3.5 tonne, Diesel, Non-Catalyst, "Conventional"
Rigid Trucks, Diesel, Non-Catalyst, 1990-1996, Controlled	Diesel HDVs, Diesel, Non-Catalyst, 7.5-16.0 tonne, EURO I
Rigid Trucks, Diesel, Non-Catalyst, 1997-2000, ADR 70/00	Diesel HDVs, Diesel, Non-Catalyst, 7.5-16.0 tonne, EURO II
Articulated Trucks, Diesel, Non-Catalyst, 1990-1996, Controlled	Diesel HDVs, Diesel, Non-Catalyst, 16-32 tonne, EURO I
Articulated Trucks, Diesel, Non-Catalyst, 1997-2000, ADR 70/00	Diesel HDVs, Diesel, Non-Catalyst, 16-32 tonne, EURO II
Buses, Diesel, Non-Catalyst, ≤ 1989, ADR 30/00	Urban Buses/Coaches, Diesel, Non-Catalyst, "Conventional"
Buses, Diesel, Non-Catalyst, 1990-1996, Controlled	Urban Buses/Coaches, Diesel, Non-Catalyst, EURO I
Buses, Diesel, Non-Catalyst, 1997-2000, ADR 70/00	Urban Buses/Coaches, Diesel, Non-Catalyst, EURO II

5.1.3 Computation of Link and Network Emissions (Model Application)

The three emission models used in this chapter, i.e. the TEE-KCF 2002 model (Negrenti & Parenti, 2003), the COPERT III model (EEA, 2000) and the QGEPA 2002 model (QGEPA, 2002), compute link emissions (E_y) using two fundamental variables (TRL, 1999), i.e. a composite emission factor for link y ($e_{x,y}$), expressed as grams of pollutant per kilometre, and a measure of travel activity (VKT_y), expressed as vehicle kilometres of travel (VKT) for link y . Total network emissions (E) are then computed by aggregation of link emissions, i.e. by summing the products of composite emission factors and traffic activity for all links (e.g. Negrenti, 1999; EEA, 2000; QGEPA, 2002):

$$E = \sum_y \{ VKT_y \times e_y \} = \sum_y \left\{ VKT_y \times \sum_m (e_{x,m,y} \times P_{m,y}) \right\} \quad \text{Equation 5-2}$$

The composite emission factor e_y for road link y presents the “mean traffic stream emission factor” and it is equal to the sum of the emission factors for all vehicle classes m ($e_{x,m,y}$) and the VKT-based proportion of these classes in the traffic stream ($P_{m,y}$). Since the available link input data is restricted to basic traffic composition (i.e. LDV and HDV), equation 5-2 can be rewritten as:

$$E = \sum_y \left\{ VKT_y \times \sum_m (e_{x,LDV,y} \times P_{LDV,y} + e_{x,HDV,y} \times P_{HDV,y}) \right\} \quad \text{Equation 5-3}$$

Equation 5-3 shows that total link and network emissions are determined by three basic variables: VKT_y , $e_{x,m,y}$ and $P_{m,y}$. As was discussed in Chapter 3, the modelled effect of congestion on total emissions is reflected by $e_{x,m,y}$, whose value is determined as a function of travel speed in COPERT III and QGEPA 2002 and as a function of travel speed, signal settings, traffic density and link length in TEE-KCF 2002.

In anticipation of a more detailed analysis in section 5.5, Figure 43 shows, as an example, the modelled effects of speed (congestion) on the mean traffic emission factors for the three models that are used in this chapter. Clearly, congestion has a substantial effect on composite emission factors in all three models.

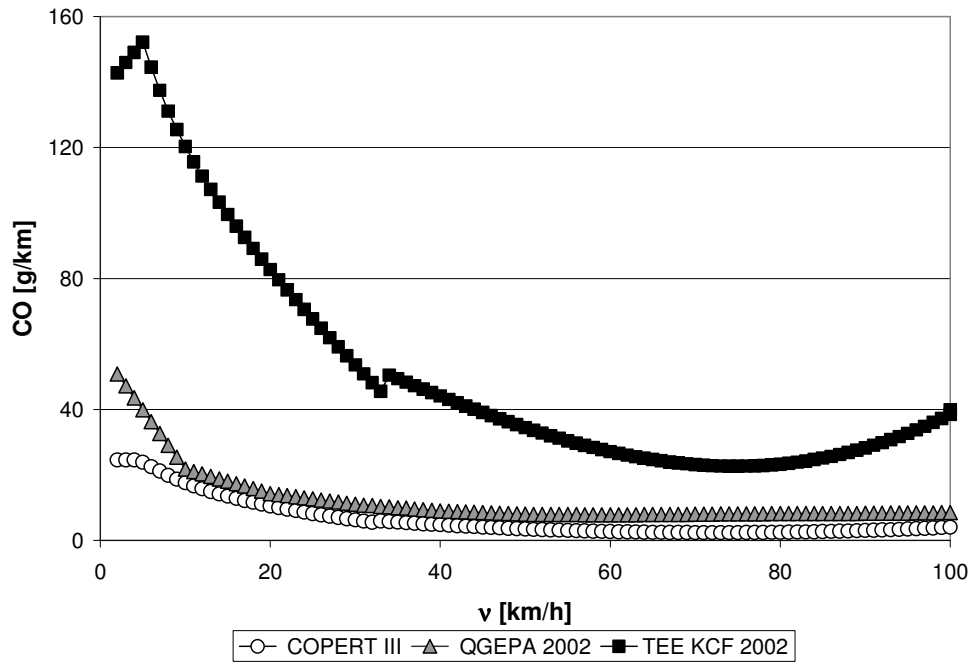


Figure 43 – Relationship Between Travel Speed (Congestion) and Composite Emission Factors for Three Models

In order to compute emissions, the test network input database was fed into the three models. The input data and modelling results were then imported in a spreadsheet for further analysis. Table 29 shows a section (three links) of this emission modelling input and output database.

Table 29 – Section of Emission Modelling Input and Output Database

Data Category	Variable	Unit	Link Number			
			1	2	etc.	10924
OUTPUT TRAFFIC MODEL	I Node Number	-	40870	41107	etc.	42988
	J Node Number	-	40908	41112	etc.	42888
	Link Number	-	1	2	etc.	2731
	City Area	-	OUTER	OUTER	etc.	CBD
	Time of Day	-	AM	AM	etc.	NIGHT
	Road Type	-	Arterial	Freeway	etc.	Local
	Basic Road Type	-	1	U	etc.	1
	Link Length	km	1.074	0.567	etc.	0.225
	Posted Speed Limit	km/h	60	90	etc.	80
	Number of Lanes	-	2	2	etc.	2
	Link Capacity	veh/h.ln	900	1,500	etc.	1,000
	Traffic Volume	veh/h	1,502	2,292	etc.	297
	Mean Link Travel Speed	km/h	49	79	etc.	80
	Proportion LDV	-	0.98	0.98	etc.	0.88
	Proportion HDV	-	0.02	0.02	etc.	0.12
	OUTPUT TRAFFIC SIGNAL COORDINATION SYSTEM	Intersection Code	-	B0244	BLANK	etc.
Cycle Time		sec	120	90	etc.	120
Effective Green Time		sec	14	90	etc.	84
Effective Green Time		-	0.12	1.00	etc.	0.70
CONGESTION (COMPUTED)	V/C Ratio	-	0.8	0.8	etc.	0.1
	Mean Density	veh/km.ln	15	15	etc.	2
	Mean Delay Rate	sec/km	13.5	5.6	etc.	0.0
	Congestion Index	-	1.2	1.1	etc.	1.0
	Delay Ratio	-	0.2	0.1	etc.	0.0
	Relative Delay Rate	-	0.2	0.1	etc.	0.0
	Speed Reduction Congestion Index	-	1.8	1.2	etc.	0.0
	Distance to City Centre	m	9,886	8,019	etc.	9,986
	Vehicle Kilometres of Travel	veh.km/h	1,612	1,299	etc.	67
	Vehicle Hours of Travel	veh.h/h	33	16	etc.	1
	Lane Kms	ln.km	2,147	1,134	etc.	0,450
	Density x Lane Kms	veh	32.9	16.4	etc.	0.8
	Mean Vehicle Delay	sec/veh	14.5	3.2	etc.	0.0
	Link Delay	h	6.0	2.0	etc.	0.0
Cl x VKT	-	1,974	1,480	etc.	67	
FLEET COMPOSITION (COMPUTED)	Passenger Car, LP, Non-Catalyst, ADR26/27	%	15.8	15.8	etc.	15.8
	Passenger Car, ULP, Catalyst, ADR37	%	7.3	7.3	etc.	7.3
	etc.	etc.	etc.	etc.	etc.	etc.
	Buses, Diesel, ADR70/00	%	4.2	4.2	etc.	4.2
EMISSIONS (PREDICTED)	CO Link Emissions QGEPa	kg/h	13.6	11.1	etc.	0.5
	CO Link Emissions COPERT	kg/h	5.7	3.1	etc.	0.2
	CO Link Emissions TEE-KCF	kg/h	12.4	11.4	etc.	0.5
	HC Link Emissions QGEPa	kg/h	1.1	0.8	etc.	0.0
	HC Link Emissions COPERT	kg/h	0.7	0.3	etc.	0.0
	NOx Link Emissions QGEPa	kg/h	2.4	1.9	etc.	0.2
	NOx Link Emissions COPERT	kg/h	1.3	1.2	etc.	0.1

The results of the analysis are now presented and discussed in two separate sections, each section addressing one of the research objectives of this chapter.

5.2 The Importance of Congestion in Urban Network Modelling

This section presents and discusses the modelling results of the three models with respect to hot running emissions of carbon monoxide (CO) hydrocarbons (HCs) and

nitrogen oxides (NO_x)⁷⁰. With respect to the explicit TEE-KCF model, the analysis has been restricted to CO emissions since, at this stage of its development, the model only simulates the effects of congestion on emissions of this pollutant.

These modelling results are used to investigate the importance of congestion in urban network modelling. This is done by examining the magnitude and direction of disparities in emission predictions at different times of day and different network location (geographic location, basic road type).

Both absolute (arithmetic difference) and relative (ratio or percentage change) measures of disparity have been investigated. This is important since they provide complementary information about the magnitude and direction of a difference (Schoenbach, 2002; Keppel *et al.*, 2005). In anticipation of the next section, differences between type I implicit and type II explicit models are indicated and briefly discussed.

Peak Period versus Night Time Period Emissions

Figure 44 shows total CO emission predictions for the entire road network by the three models by time of day. Two points are clear from this chart. Firstly, all models predict significantly higher emissions in a congested network (i.e. peak periods) when compared to the same but uncongested network (i.e. night period). In fact, total network CO emissions are a factor of 16 (COPERT), 11 (QGEPA) and 18 (TEE-KCF) higher in peak periods when compared to the night time period. This indicates that differences in total emission levels correlate with differences in network congestion levels.

⁷⁰ Although an important air pollutant, PM emissions are not discussed because 1) PM emissions are not computed for all vehicle classes in COPERT III (only for diesel vehicles: EEA, 2000, Table 5.2), and 2) the MOBILE 6 SCFs used in the QGEPA 2002 model do not include PM (they have only been developed for CO, HC and NO_x).

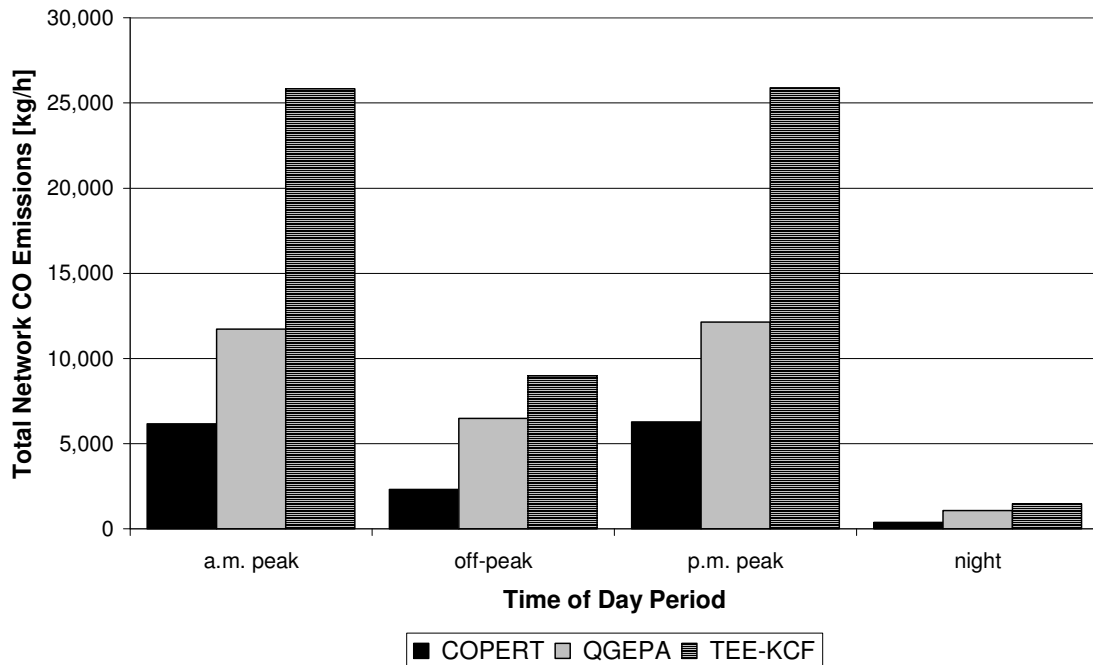


Figure 44 – Total Network CO Emission Predictions by Three Models

Secondly, there are substantial differences in total emission predictions by the three models. The COPERT model predicts an additional total CO emission of 5848 kg/h when the peak and night time periods are compared, whereas this is 10864 kg/h for the QGEPA model and 24397 kg/h for the TEE-KCF model. This indicates that there are large differences between implicit and explicit models, but also between implicit models, in terms of the predicted impact of congestion on total emission levels.

Figure 45 and Figure 46 show total HC and NO_x emission predictions, respectively, for the entire road network by the two implicit models by time of day. Again, the models predict significantly higher network emissions in the peak periods when compared to night period: a factor of 13 (COPERT) and 12 (QGEPA) for HC and a factor of 7 (COPERT) and 8 (QGEPA) for NO_x. The differences between ratio values are less pronounced than those that were found for CO.

There are also substantial differences in total emission predictions by the implicit models. The COPERT model predicts an additional 548 kg/h total HC emission and 824 kg/h total NO_x emission when the peak and night time periods are compared, whereas this is 934 kg/h for HC and 1628 kg/h for NO_x for the QGEPA model.

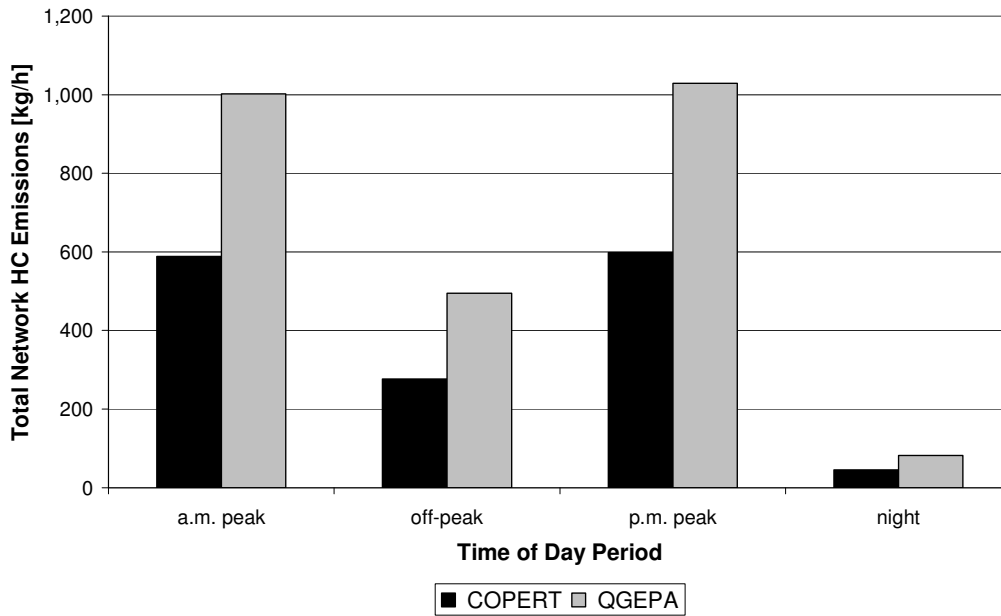


Figure 45 – Total Network HC Emission Predictions by Two Implicit Models

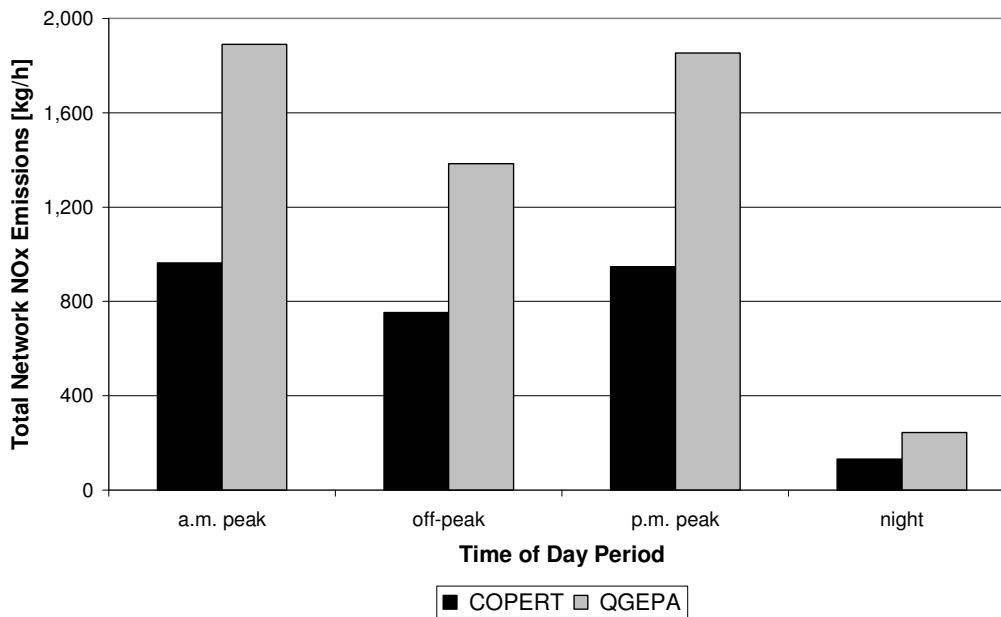


Figure 46 – Total Network NO_x Emission Predictions by Two Implicit Models

The information presented so far indicates the *possibility* that congestion is an important issue in modelling of CO, HC and NO_x emissions in urban networks. It appears that consideration of congestion in emission modelling of the test network is most relevant for CO and least relevant for NO_x. However, the predicted increase in network emissions by all three models, when the same subnetworks change from an uncongested (night) to a congested (peak) situation, could be due to reasons other than congestion. These other reasons follow from equation 5-3, and they are:

- a change in the amount of travel in a network (VKT); and
- a change in basic traffic composition⁷¹ on links in a network.

The effects of congestion (i.e. changes in driving patterns) on network emissions are reflected in changes of (composite) emission factors for each road link in the network as a function of congestion-related input variables travel speed, traffic density, intersection density, cycle time and effective green time.

So the question arises: what is the relative importance of congestion (and the other two variables) with respect to the change in emission levels when the test network changes from an uncongested to a congested state, and are any location effects present? Sensitivity analysis (SA) is a method that can be used to investigate the relative importance of the three input factors (traffic activity, basic traffic composition and congestion) with respect to emission predictions (e.g. TRB, 1997).

⁷¹ i.e. the relative proportions of HDVs and LDVs.

Sensitivity Analysis

The difference in the model output due to the change in the input variable is referred to as the sensitivity of the model to that particular input variable. The relative importance of the input variables “traffic activity” (i.e. distribution of link VKT), “traffic composition” (i.e. distribution of proportions of heavy-duty vehicles on links) and “congestion” (i.e. multivariate distribution of the *set* of input variables that *together* affect congestion: travel speed, cycle time, effective green time, traffic density and intersection density) is investigated in this section.

The SA method used in this section is a mathematical one-at-a-time (OAT) sensitivity analysis (Frey & Patil, 2001). Mathematical methods assess the sensitivity of a model output to the *possible range* of a specific input through computation. OAT means that one particular input factor is varied each time, while all the other input factors are held constant. This method is a relatively simple method that is applicable to deterministic models. It is particularly useful for identification of the most important inputs. This method only considers main effects and assumes that interactions are negligible (Saltelli, Chan & Scott, 2000). Percentage difference is used as the measure of sensitivity S_i (e.g. Buckland & Middleton, 1999):

$$S_i = \frac{E_{\text{ref},i} - E_{\text{ref}}}{E_{\text{ref}}} \quad \text{Equation 5-4}$$

where E_{ref} is the predicted total emission in the reference situation and $E_{\text{ref},i}$ is the predicted total emission in the alternative situation. The most congested network situation (i.e. morning or afternoon peak period), has been chosen as the reference situation. For alternative situations, the link values for each (set of) input variable(s) were varied one-at-a-time by changing them to the values that applied to the uncongested network situation (i.e. night time period). S_i thus presents a relative measure of disparity between a congested and an uncongested network. Subsequently, link and (sub)network emissions have been predicted. Table 30 (next page) shows the results and presents the mean sensitivity values of the two peak periods by city region and road type.

Table 30 – Sensitivity of Total Emission Predictions to Range Variation of Relevant Input Variables

City Region	Road Type	Change	CO COPERT	CO QGEPa	CO TEE	HC COPERT	HC QGEPa	NO _x COPERT	NO _x QGEPa
Entire Network		Traffic Activity	-88%	-88%	-88%	-88%	-88%	-88%	-88%
		Traffic Composition	1%	-2%	-2%	6%	0%	22%	20%
		Congestion	-51%	-25%	-53%	-39%	-34%	2%	-10%
CBD	Interrupted	Traffic Activity	-88%	-88%	-88%	-88%	-88%	-88%	-88%
		Traffic Composition	3%	-5%	-3%	10%	-1%	39%	34%
		Congestion	-52%	-27%	-51%	-37%	-33%	-8%	-10%
Inner City	Interrupted	Traffic Activity	-88%	-88%	-88%	-88%	-88%	-88%	-88%
		Traffic Composition	0%	-2%	-2%	6%	0%	26%	20%
		Congestion	-61%	-33%	-61%	-44%	-40%	-3%	-14%
	Uninterrupted	Traffic Activity	-85%	-84%	-85%	-85%	-85%	-83%	-84%
		Traffic Composition	0%	-1%	-2%	3%	0%	11%	11%
		Congestion	-44%	-19%	-55%	-48%	-38%	14%	-4%
Outer City	Interrupted	Traffic Activity	-88%	-88%	-88%	-88%	-88%	-88%	-88%
		Traffic Composition	1%	-2%	-2%	5%	0%	18%	19%
		Congestion	-47%	-20%	-43%	-33%	-26%	0%	-8%
	Uninterrupted	Traffic Activity	-89%	-89%	-89%	-89%	-89%	-89%	-89%
		Traffic Composition	1%	-2%	-2%	6%	0%	14%	22%
		Congestion	2%	1%	-3%	-28%	-15%	19%	4%

Clearly, traffic activity has the largest effect on emission predictions. A decrease in total VKT always results in a decrease in total emissions. This is the case because emissions are directly proportional to the number of vehicles on the road. The information presented in Table 24 shows that total network VKT is a factor of 6 to 9 higher in the peak periods compared to the night period (the actual value depends on city region and road type). Table 30 shows that changes in network emission levels are of similar magnitude.

Compared to the change in traffic activity, the effect of a change in basic traffic composition (i.e. the percentage of heavy-duty vehicles in the traffic stream) is small. This is particularly so for CO where total emissions vary by practically zero to only a few percent (less than 5%). For HC the variation is slightly higher (less than 10%). For both pollutants the change can be either positive or negative, despite the fact that the proportion of heavy-duty vehicles is always lower in the peak period when compared to the night period (Table 24 shows a factor of 1.2 to 2.5 depending on city region and road type).

In fact, the direction (sign) of the effect depends on the model that has been used. The COPERT model predicts a small increase in CO and HC emissions with an (on average) increasing proportion of heavy-duty vehicles, whereas the opposite effect is predicted by the QGEPA and TEE-KCF models. Thus, although all models predict a small effect of a change in basic traffic composition on total network emissions, the *direction* of the effect is predicted differently by the three models.

Compared to CO and HC, the effects of a change in basic traffic composition on NO_x emissions are larger, i.e. between 11 and 39% depending on city region and road type, as indicated in Table 30. All models consistently predict an increase in NO_x emissions when the proportion of heavy-duty vehicles increases (i.e. when the basic traffic composition of the night time period is used in the reference situation).

Table 30 also shows that the effect of a change in basic traffic composition on CO, HC and NO_x emissions on uninterrupted roads (“freeways”) is generally smaller than the effect that is predicted for interrupted roads (“arterials”). The largest effect of a change in basic traffic composition (about 35-40% for NO_x) is predicted for the CBD area, which is the area with the largest mean proportion of heavy-duty vehicles at night

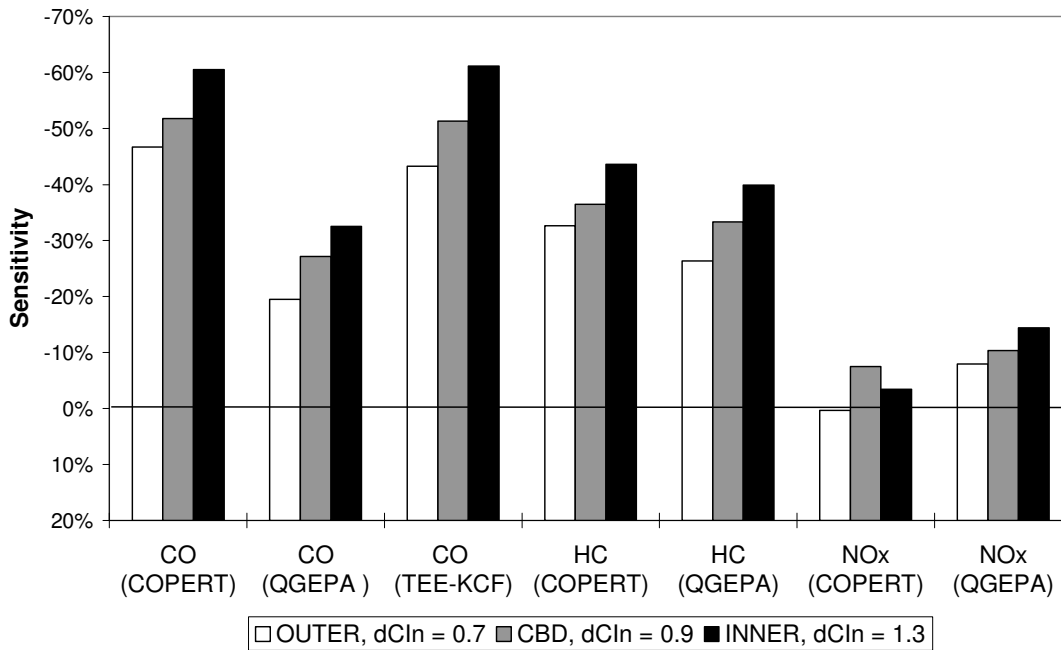
(about 12%) and the largest change in this proportion (approximately a factor of two) when the peak period is compared to the night time period.

The information presented in Table 24 shows that network congestion (Cl_n) is a factor of 1.5 to 2.6 higher in the peak periods compared to the night period (the actual value depends on city region and road type). Table 30 shows that congestion generally has a substantial effect on network emissions of CO and HC. A change from peak period congestion levels to generally free-flowing travel speeds and night time signal settings results in a reduction of CO network emissions by a factor of about 1.0 to about 2.5 (COPERT, TEE-KCF) or somewhat lower 1.0 to 1.5 (QGEPA). For HC, the two implicit models predict similar results: a reduction of HC network emissions by a factor of about 1.2 to 1.9.

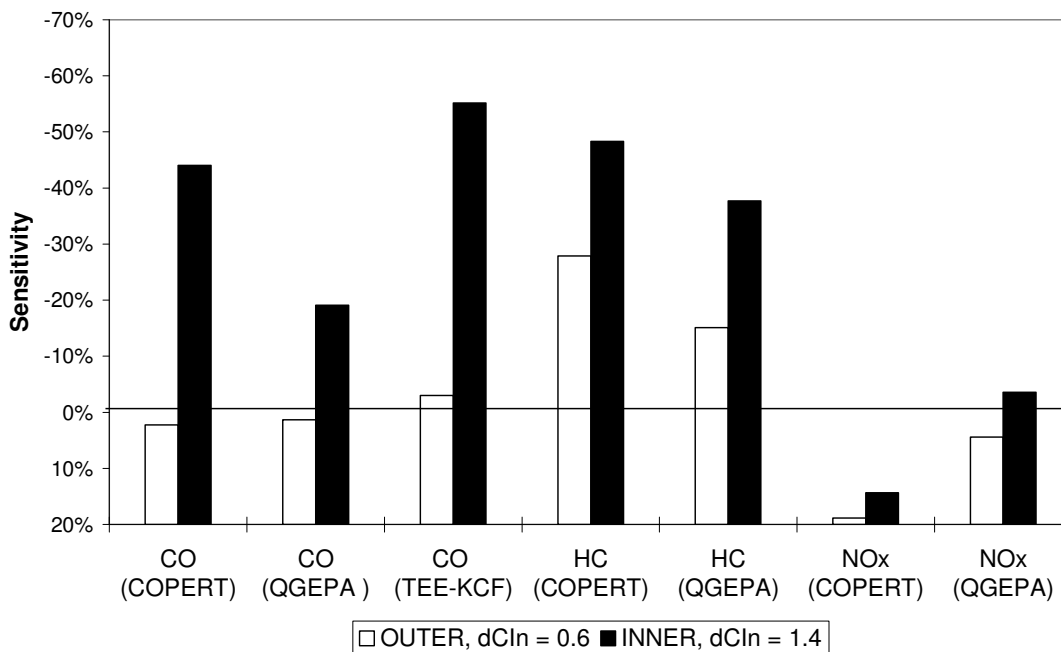
The largest sensitivity of network emissions of CO and HC to congestion is found for the most congested inner city area. All models, no matter if they are implicit or explicit models, show this result. In fact, when the different subnetworks are considered separately, the results consistently show that the higher the subnetwork congestion levels in the reference situation (Table 24), the larger the reduction in network emissions of CO and HC when night time flow conditions exist.

In other words, a positive relationship exists between (the difference in) level of network congestion and (the change in) network emissions of HC and CO. These findings are illustrated in Figure 47 and Figure 48 (next page), where the sensitivity is plotted against the *difference between Cl_n values* in the peak period and the night period (denoted as dCl_n).

This indicates that predicted total emissions for (sub)networks that are more congested than the test (sub)network(s) that have been used in this chapter (but assuming approximately similar fleet composition and network configuration) would likely depart to a greater extent from the uncongested situation than this test network. Similarly, if non-recurrent congestion were somehow included in the traffic model, both predicted network congestion levels and network emissions would be expected to increase.



**Figure 47 – Sensitivity of Network Emissions towards Congestion
(Interrupted Roads)**



**Figure 48 – Sensitivity of Network Emissions towards Congestion
(Uninterrupted Roads)**

Interrupted roads in the inner city area show a larger sensitivity to CO emissions than uninterrupted roads. With respect to HC emissions, the sensitivity of both road types is similar. An interesting point that becomes clear from the charts is that a change in congestion level in the uninterrupted road network has no significant effect on CO emissions in this subnetwork in the outer city area, i.e. total emissions are only marginally increased, or even decreased, despite an increase in network congestion. This is in contrast with the more congested uninterrupted road network in the inner city area, where all models predict substantial increases in CO emissions due to increased (differences in) congestion levels.

Compared to CO and HC, the effects of congestion on NO_x emissions are mixed. On interrupted roads, an increase in network congestion generally results in a consistent but relatively small increase (or no effect) in NO_x emissions. On uninterrupted roads an increase in network congestion results often in a relatively small reduction or a marginal increase in NO_x emissions. Interestingly, the effect of basic traffic composition on NO_x emissions is often larger or of similar magnitude than the effect of congestion.

It is noted that the predicted effects of congestion compare well to the study conducted by Anderson *et al.* (1996), which was discussed in Chapter 1. These workers found that a change from free-flowing conditions to peak conditions in an urban network in Canada increased total predicted CO, HC and NO_x emissions by a factor of 1.71, 1.53 and 1.04, respectively.

The information presented so far has shown that, in terms of *relative* changes in emission predictions for (parts of) urban networks due to different levels of travel demand, the one explicit and two implicit models show surprisingly similar results in general. For all three models, traffic activity is by far the most important factor in the prediction of emissions. For CO and HC, level of network congestion is the second most important factor, whereas for NO_x this generally is basic traffic composition.

It is concluded that, on the basis of three emission models that were applied to a particular urban network, congestion is an important factor that influences total network emissions of CO and HC in this network. In terms of future research work it is important, however, to investigate whether these findings are confirmed when the same and other emission models are applied to other urban networks.

5.3 Disparities in Predictions between Implicit and Explicit Models

This section investigates in more detail when and where disparity exists between implicit and explicit emission models with respect to emission predictions for urban networks. To investigate whether the direction and magnitude of disparities between implicit and explicit models are dependent on time of day and location the absolute and relative differences in normalised network CO emissions are compared.

Normalised network emissions, or mean network CO emission factors, are computed by dividing total subnetwork emissions by total subnetwork VKT (Table 24). Hence, total emissions are corrected for subnetwork size (number of links). Mean network emission factors are used since they enable comparison of disparities (arithmetic difference and ratio) among different subnetworks⁷². The results are presented in Table 31. The results are also graphically shown in Figure 49 and Figure 50.

⁷² Comparison of the arithmetic difference in emission levels between subnetworks is not meaningful, since total emissions in a subnetwork are dependent on network size. For instance, the CBD network with 97 links is much smaller than the inner city interrupted network with 1612 links. Hence, (differences in) total emissions on the inner city interrupted network are always much larger than those for the CBD due to differences in network size.

Table 31 – Disparities between Normalised Network CO Emissions (g/VKT) of the Explicit and Implicit Models by Geographic Location, Road Type and Time of Day

City Region	Road Type	Time Period	Ratio of TEE-KCF to COPERT	Ratio of TEE-KCF to QGEPA	TEE-KCF minus COPERT	TEE-KCF minus QGEPA
Entire Network		A.M. peak	4.2	2.2	18	13
		Off-peak	3.9	1.4	8	3
		P.M. peak	4.1	2.1	18	12
		Night	3.9	1.4	8	3
CBD	Interrupted	A.M. peak	5.3	3.0	28	23
		Off-peak	4.4	1.8	11	6
		P.M. peak	4.5	2.3	19	14
		Night	4.6	1.8	11	6
Inner City	Interrupted	A.M. peak	4.3	2.4	23	17
		Off-peak	4.1	1.4	9	4
		P.M. peak	4.3	2.4	22	17
		Night	4.1	1.4	8	3
	Uninterrupted	A.M. peak	4.7	2.6	23	18
		Off-peak	3.6	1.3	8	3
		P.M. peak	4.4	2.4	18	14
		Night	3.6	1.4	8	3
Outer City	Interrupted	A.M. peak	3.8	1.8	14	9
		Off-peak	3.9	1.3	8	3
		P.M. peak	3.8	1.9	14	9
		Night	3.9	1.3	8	3
	Uninterrupted	A.M. peak	3.6	1.5	9	4
		Off-peak	3.2	1.3	7	2
		P.M. peak	3.3	1.2	7	2
		Night	3.2	1.3	8	3

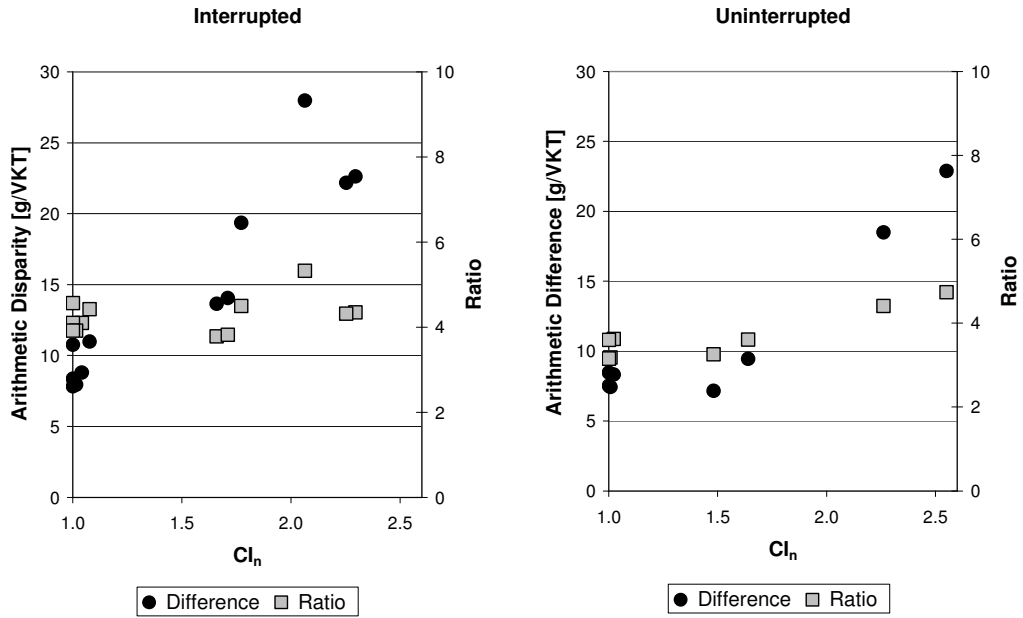


Figure 49 – Disparity Between Normalised Network CO Emissions of TEE-KCF 2002 and COPERT III

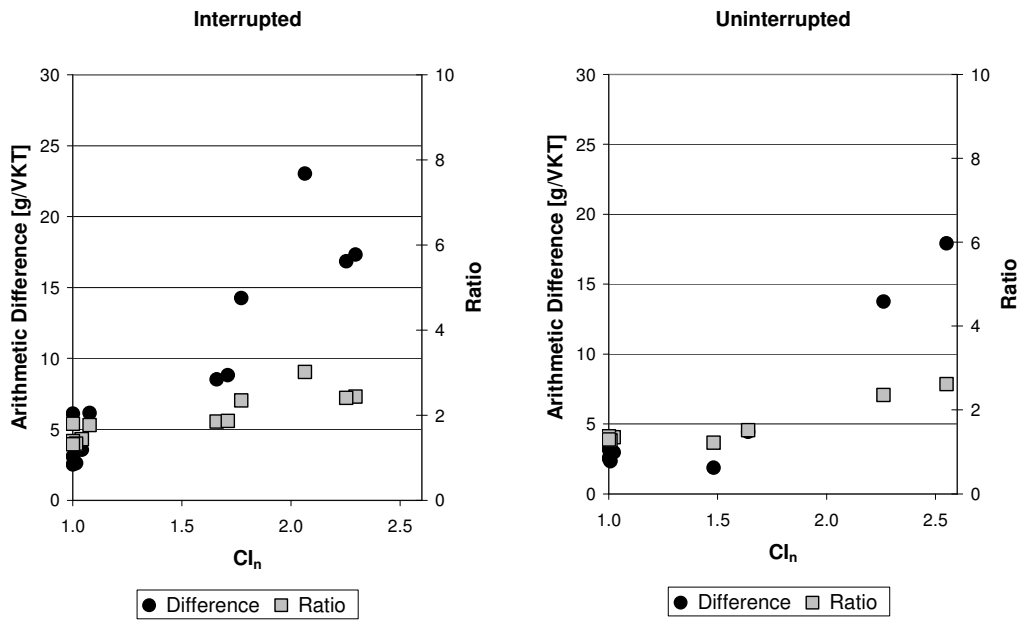


Figure 50 – Disparity Between Normalised Network CO Emissions of TEE-KCF 2002 and QGEPa 2002

Arithmetic Differences

In terms of absolute disparity in emission predictions, there are substantial differences between the three models. Figure 44 (page 72) already showed that the explicit TEE-KCF model always predicts higher network CO emissions than the two implicit models and that the largest absolute differences in network emissions occur in the peak periods. Figure 49 and Figure 50 confirm this and show that absolute differences between models increase with an increasing level of network congestion. This is the case for both interrupted and uninterrupted roads, although there appears to exist a level of congestion (CI_n about 1.5) for uninterrupted roads below which no substantial change in the arithmetic difference is observed.

This last point is in line with an earlier finding from the sensitivity analysis (Figure 48, page 72) that all models predict only a marginal change in total network emissions when the uncongested uninterrupted network in the outer city area becomes more congested (that is, provided that traffic activity and traffic composition do not change). Because network predictions by the three models hardly change in this case, the differences between these predictions hardly change either.

Since the three models use the same input data on traffic activity, traffic composition and level of network congestion, arithmetic differences in predictions must be caused by differences in composite emission factors for links. In the models, these composite link emission factors are a function of:

- 1) basic traffic composition; and
- 2) level of congestion on the link.

It was found in the previous section that level of congestion (and not traffic composition) was generally *the* major factor influencing CO emission predictions. As a consequence, differences between models are largely due to two factors:

1. Differences in predicted effects of congestion on (composite) emission factors due to differences in the way (and extent) congestion is build into the model (type I versus type II), but also, within the particular family of travel speed

emission models, differences in e.g. driving cycles and statistical methods that were used in model development.

- (Systematic) differences due to unknown reasons other than congestion that are reflected in the test data on which the model is based, but which cannot be examined here.

The last point is illustrated in Figure 51, where disparities between COPERT III and QGEPA 2002 are graphically depicted. These models are based on driving cycles that have roughly similar congestion levels at comparable travel speeds, as will be discussed in the next section. Despite this, the QGEPA model utilizes mean network CO emission factors that are systematically higher (irrespective of level of network congestion) by a rather constant margin (about 5 g/VKT). Factors other than congestion must play a role here, and although one can speculate on possible reasons (as will be done in the next section), it is unknown if these reasons are the main cause for the observed difference between the COPERT and QGEPA models.

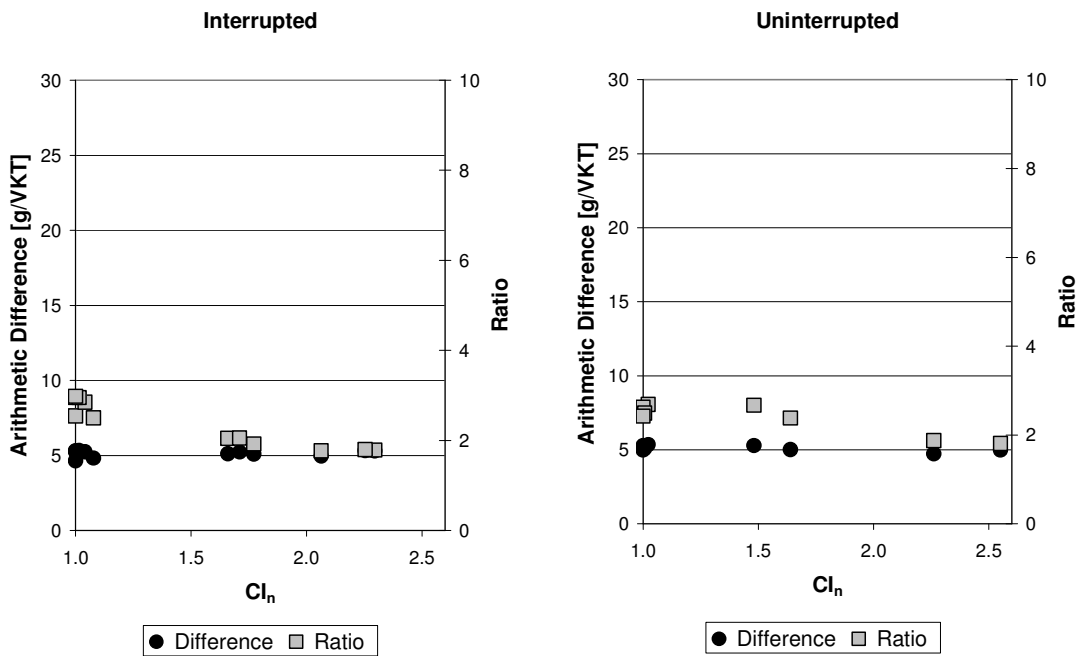


Figure 51 – Disparity Between Normalised Network CO Emissions of COPERT III and QGEPA 2002

Figure 49 and Figure 50 show that TEE-KCF also uses systematically higher mean network CO emission factors, which is due to differences in the methodology used to predict effects of congestion on (composite) emission factors (type II versus type I), but also probably due to the emissions test data on which the model is based (DRIVE-MODEM), as will be discussed in the next section.

Ratios

In contrast to absolute difference, Figure 49 and Figure 50 show that the change in relative difference (ratio) between the explicit and implicit models is quite stable for interrupted roads. For uninterrupted roads the ratio appears to increase only slightly with increasing level of network congestion above a particular level of congestion. The small change in the relative difference in interrupted conditions is particularly evident for the COPERT model, which is the model that TEE-KCF aims to correct for congestion. This indicates that the relative difference between implicit and explicit models in predicting network emissions is rather insensitive to level of network congestion.

This finding is in line with the results that have been presented in the previous section where the sensitivity analysis showed that the explicit TEE-KCF model generally predicts similar relative effects of congestion on CO network emissions when compared to one implicit model (COPERT), irrespective of network location, whereas the other implicit model (QGEPA) deviates substantially from both models, but at a constant level (about 50% of the effect of congestion as predicted by COPERT and TEE-KCF in all subnetworks).

Conclusions

On the basis of the information presented in this section it is concluded that, wherever network congestion levels change (irrespective of geographical location and basic road type), the different manner in which congestion has been incorporated in the models (i.e. explicit versus implicit models) leads to:

- substantially different predictions of absolute CO emission levels, but
- only minor differences in relative CO emission levels.

This means that, if a particular study is only interested to assess the relative effects of congestion, it may not be necessary to use the TEE-KCF model (which demands more input data) when the COPERT model is already used. However, before this conclusion can be drawn, it would be necessary to use both model types in other urban networks around the world with different fleet composition and network configuration and to compare the results.

5.4 Analysis of Composite Emission Factors

To further explore the reasons behind the findings presented in this Chapter so far, composite emission factors for each model are further investigated and compared. Figure 52 to Figure 55 present scatter plots with travel speed on the x-axis and composite emission factors on the y-axis. Travel speed is used on the x-axis since it determines the emission factor value for implicit models and partly determines the emission factor value for the explicit model, where emission factors also depend on mean traffic density, cycle time, effective green time and intersection density (link length).

Two boundary conditions have been defined for the explicit model. The boundary conditions are a “high congestion” ($k = 140$ veh/km.lane, $c = 240$ s, $g = 0.05$, $L = 0.013$ km) and a “low congestion” situation ($k = 1$ veh/km.lane, $c = 40$ s, $g = 1.00$, $L = 2.332$ km). The k , c , g and L boundary values reflect the minimum and maximum values that occur in the test network. For basic traffic composition two values were used, i.e. 0.5% and 15.0% HDV. These percentages present the minimum and maximum values that were used for the (discrete) traffic composition classes that are required as input to the TEE-KCF 2002 model (Negrenti & Parenti, 2003).

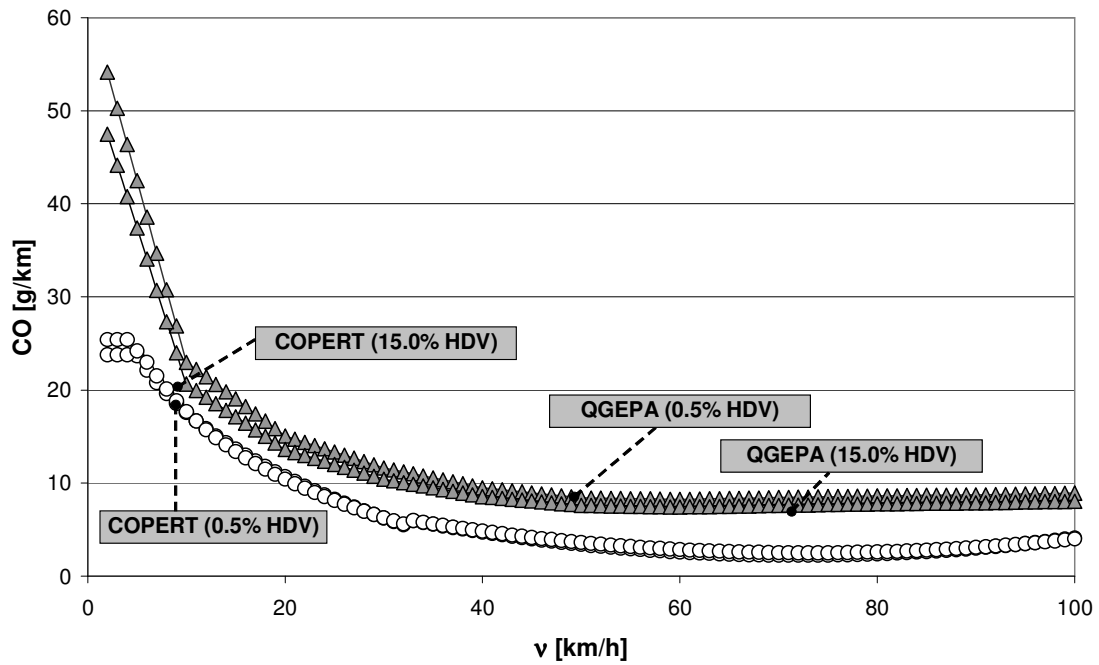


Figure 52 – Composite CO Emission Factors of the Implicit Models

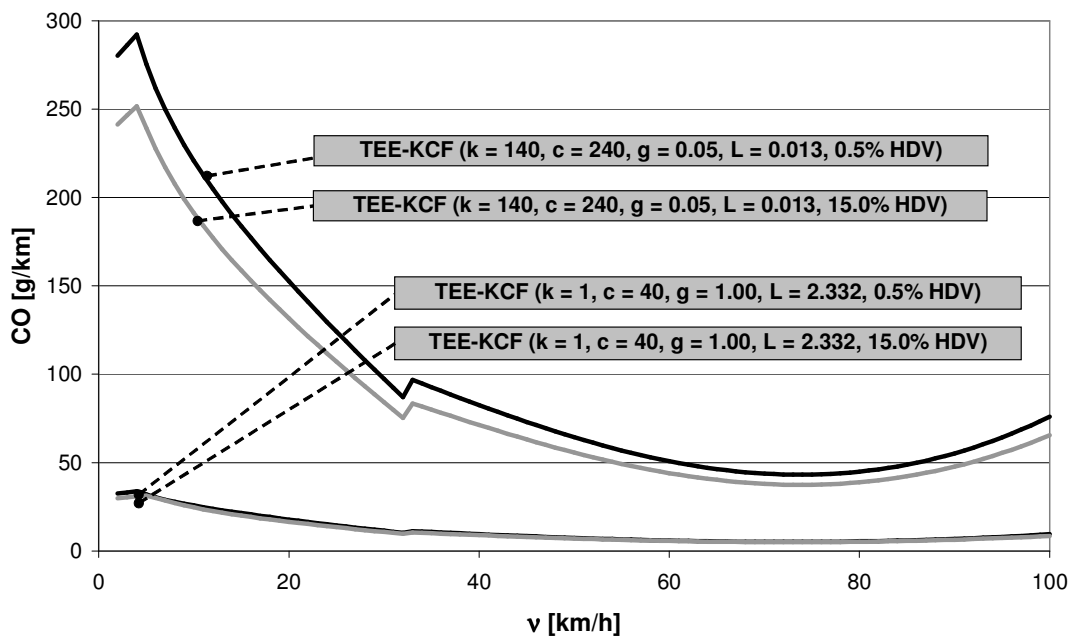


Figure 53 – Composite CO Emission Factors of the Explicit Model

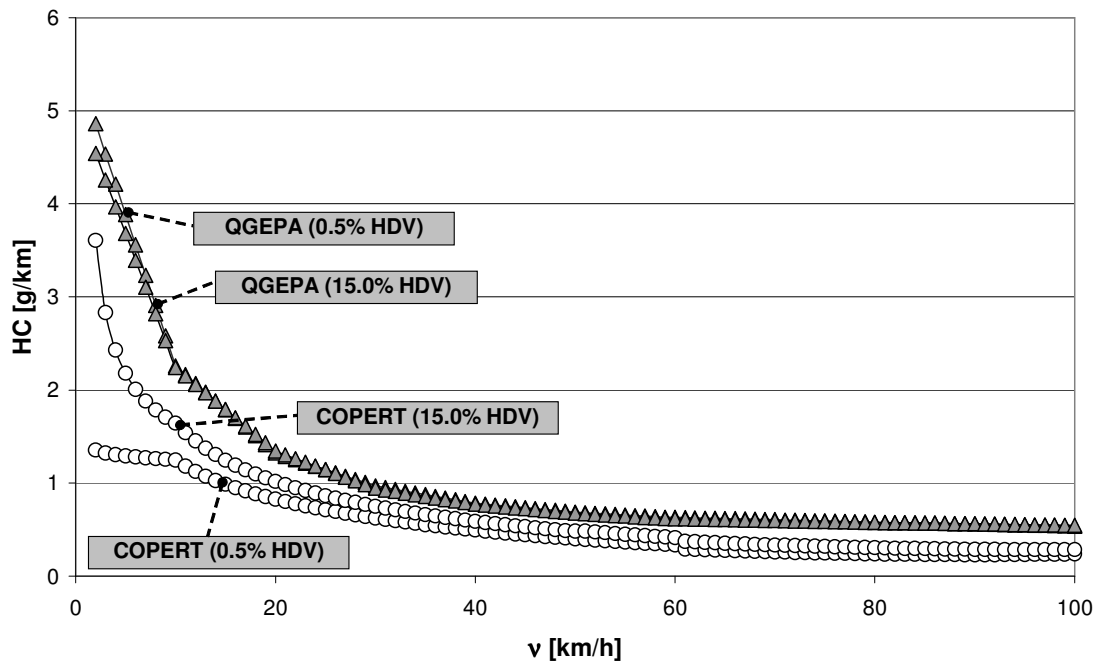


Figure 54 – Composite HC Emission Factors of the Implicit Models

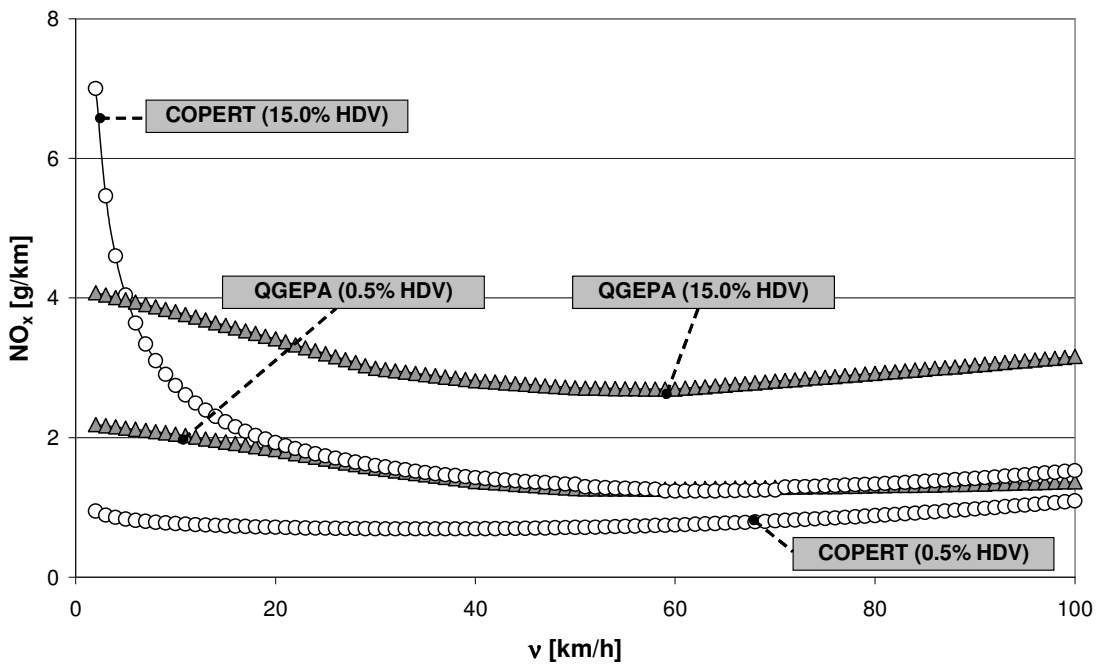


Figure 55 – Composite NO_x Emission Factors of the Implicit Models

Effects of Congestion

When the high congestion and low congestion situation that were defined for the TEE-KCF model are compared, and when it is considered that a general trend of increasing congestion levels with decreasing travel speeds was found for the COPERT and QGEPA emission models in Chapter 4, it is clear that congestion has a large effect on composite CO and HC emission factors for the three models (both explicit and implicit). This effect is particularly strong at low travel speeds, where emission factors increase in a non-linear fashion. This explains why all models consistently predict that congestion is an important factor for these emissions.

Difference in Shape

At first sight, the *shape* of the relationship between the composite emission factors of CO, HC and travel speed is quite similar for all three models. For NO_x, the shape of the relationship between composite emission factors and travel speed is somewhat different for the two implicit models. Here, only the COPERT model shows a relatively steep increase at low travel speeds when the proportion of heavy-duty vehicles is high.

It has been observed in the previous sections that a change in congestion level in the uninterrupted road network has no significant effect on CO emissions in the outer city area. When it is considered that the outer city uninterrupted subnetwork has an average network speed of 93 km/h at night time and about 60 km/h in the peak periods (Table 24), it becomes clear from Figure 52 and Figure 53 that there is relatively little change in composite CO emission factors in this speed range. In fact, there is a small reduction in composite CO emission factors when travel speeds drop from 100 to about 70 km/h.

This explains why network CO emissions only increase when a substantial proportion of network links experience low speeds, as is the case for the uninterrupted subnetwork in the inner city area where 19% of the links experience travel speeds below 30 km/h in the peak period (this is 8% for the outer city uninterrupted network in the peak period).

However, small differences in shape can have significant impacts on the overall results. For instance, the QGEPA model uses almost constant composite CO emission factors for travel speeds larger than about 40 km/h, whereas the COPERT model shows a more curvilinear shape with a minimum at about 70 km/h. As a consequence, the ratio between the composite emission factor for travel speeds at 2 and 70 km/h is higher for the COPERT model (approximately 13) when compared to the QGEPA model (approximately 7). Hence, COPERT predicts a larger *relative* effect of an increasingly congested network on total CO emissions. Thus, emission models can predict relative congestion effects that are quite different in magnitude, despite the fact that congestion is built into the model in the same way.

Effects of Traffic Composition

For CO and HC, the effect of changing traffic composition on composite emission factors is generally small for all travel speeds (less than about 10%), with the exception being the composite HC emission factor for COPERT for travel speeds below 15 km/h where values can be up to a factor of about three higher. There is however a difference in direction between the three models. The COPERT model generally uses higher CO and HC emission factors for heavy-duty vehicles than for light-duty vehicles.

In contrast, the QGEPA and TEE-KCF models use higher CO and HC emission factors for light-duty vehicles. Hence, for COPERT composite emission factors of CO and HC are generally higher when the proportion of heavy-duty vehicles in the traffic stream increases, whereas the opposite is true for the other models. This difference between the models is reflected in the different direction (sign) of the effect of traffic composition on network CO and HC emissions that was observed earlier in this section.

A physical explanation for the different effect of basic traffic composition on composite emission factors in COPERT cannot be given here⁷³, but it is speculated that the differences between models may have been caused by differences in driving cycles (e.g. more dynamic driving) that were used in the development of the models for heavy-duty vehicles. Further analysis of these cycles would be necessary to verify this hypothesis.

Absolute Difference in Composite Emission Factors

Figure 52 to Figure 55 show that the QGEPA model uses composite emission factors of CO and HC that are systematically higher than those used by COPERT. This is the same for NO_x, except for link conditions with a high proportion of heavy-duty vehicles and travel speed below 5 km/h. As a consequence, the QGEPA model predicts test network emissions that are higher than those predicted by COPERT.

Differences in composite emission factors between the two models may be partly explained by a difference in congestion level in the driving cycles used in their development. When the values of the different congestion indicators that were computed in Chapter 4 for the driving cycles used in QGEPA 2002 (Table 15 and Table 16) and COPERT III (Table 19 and Table 20) are compared for similar travel speeds, both model appear to incorporate roughly similar levels of congestion. The QGEPA model appears to be only *slightly* more congested for travel speeds above 20 km/h. As a consequence, higher emission factors would be expected for this model in this speed region, which is the case.

This, however, does not explain the large differences at low speeds. As a consequence, factors other than congestion must attribute to the differences. These factors cannot be investigated here, but possible factors are differences between Australia and Europe with respect to legislative emission standards. This, in turn, could be reflected in differences in level of emission control technology (e.g. size of catalysts, catalyst materials) and calibration of the engine and emission control systems. These differences have been reported to significantly impact on emissions (e.g. DoTRS, 2001). Other factors may be the presence (or absence) of national Inspection and

⁷³ As was mentioned before, the driving cycles for heavy-duty vehicles could not be obtained for COPERT.

Maintenance (I/M) programmes. Finally, differences in model fitting procedures may also have significantly contributed to these differences.

These observations have implications for the definition of corresponding vehicle classes, which is needed to run emission models from different countries. Although an equivalence table can be constructed on the basis of the best available information, as was shown in Table 28 (page 72), vehicle classes will never correspond completely. As a consequence, it seems most appropriate to use (if available) the (implicit) emission model that is based on local emissions test data, since it (probably) best reflects the local situation. For Brisbane this would be the QGEPA model.

Compared to CO and HC, the effect of the proportion of heavy-duty vehicles on composite NO_x emission factors is much larger. This is because both models used NO_x emission factors for heavy-duty vehicles that are substantially larger than those for light-duty vehicles across the entire speed range, which is in line with the literature (e.g. Faiz, Weaver & Walsh, 1996). This explains why for NO_x the relative effect of traffic composition is often larger than the relative effect of congestion.

Figure 52 and Figure 53 show that the explicit model employs composite CO emission factors that are substantially higher in the “high congestion” situation than those used by the implicit models. Figure 56 (next page) shows that the average (absolute) differences between composite emission factors of the explicit model and the implicit models⁷⁴. Clearly, these differences are largest in low speed conditions on links. Hence, arithmetic differences in predicted CO network emissions between the explicit and implicit models will become larger when the proportion of (congested) low speed links in a network will become larger, as would be the case when a network becomes more congested.

⁷⁴ This chart has been constructed from Figure 52 and Figure 53. In order to present an orderly graph, *average* values have been used for the different situations presented in these figures.

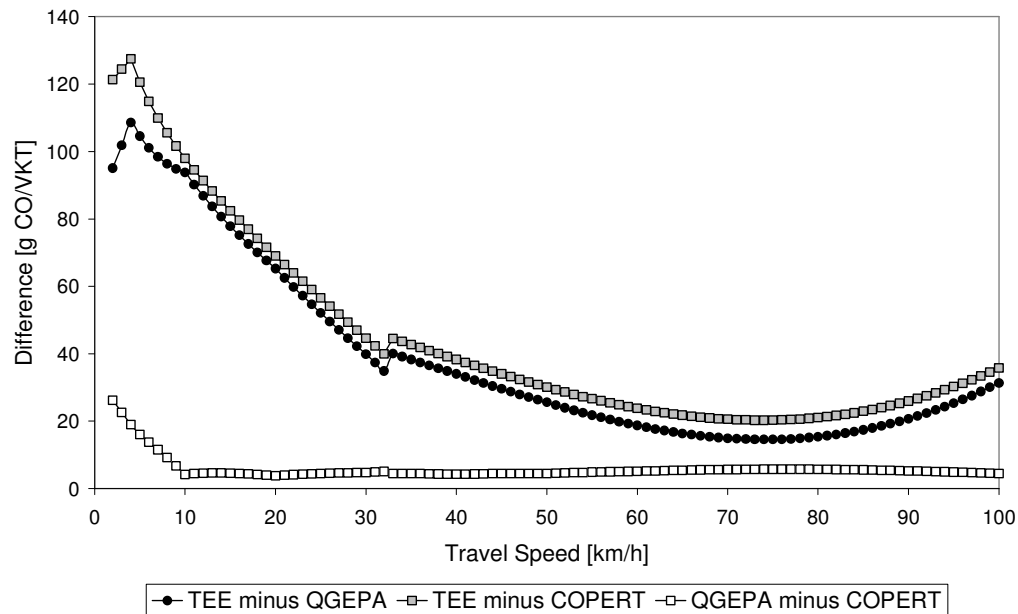


Figure 56 – Difference in Composite CO Emission Factors Between Models

For the “low congestion” situation, composite emission factors are approximately similar to QGEPA emission factors, but always higher than the COPERT emission factors. As a result, the explicit model predicts network CO emissions that are always higher than those predicted by the two implicit models.

The fact that the TEE-KCF model employs composite emission factors that are systematically higher than COPERT emission factors is somewhat peculiar since COPERT emission factors below about 105 km/h are based on driving cycles that already reflect varying levels of congestion (as was discussed in Chapter 4). Since literature indicates that increased levels of congestion lead to increased emissions of CO (Chapter 1), one would expect that COPERT emission factors would lie somewhere within the boundaries of the TEE-KCF emission factors, but this is not the case. There is no clear explanation for this.

Perhaps it has to do with the DRIVE-MODEM model, which was used in the development of TEE-KCF. It has been reported elsewhere that DRIVE-MODEM systematically predicts higher emissions than COPERT (e.g. Zachariadis & Samaras, 1997). In the development of TEE-KCF, the KCF factors have been computed by directly dividing DRIVE-MODEM predictions by COPERT predictions (as was discussed in section 3.2.2.4). It therefore seems logical that the use of the DRIVE-MODEM model is the main reason for the systematically higher emission factors in TEE-KCF. If the aim of TEE-KCF is to correct COPERT only for different levels of congestion, then it appears necessary to recalibrate TEE-KCF model to the COPERT model in order to reflect the level of congestion that is already present in COPERT III.

5.5 Best Model Choice

In the introduction to this chapter, the issue of model selection was brought up: how does one determine the "best" or most appropriate model for use in a particular study, given the variety of emission models that are available? It will be shown in this section that this is not an easy task. Section 5.5.1 starts with a general discussion on various criteria that could be used in the process of model selection. Section 5.5.2 then uses this discussion as a base for selecting the most appropriate model of the three models used in chapter 5. It will become clear that several gaps in knowledge still exists that will need to be addressed in the future. Consequently, further research in this area is clearly required.

5.5.1 Aspects that Affect Model Choice

Emission model choice is a function of different (interrelated) aspects⁷⁵:

1. modelling objectives;
2. available input data;
3. appropriate resolution;
4. sensitivity to variables that are investigated;
5. level of accuracy.

This section discusses these factors separately.

Modelling Objectives

There are many practical applications at different levels of analysis for which emission modelling is required. In this respect, three main objectives can be distinguished:

⁷⁵ It is noted that other factors such as the available budget and project planning (deadlines) for a particular study and cost-effectiveness of different options would also clearly affect model choice, but these are not discussed here.

- One objective is emission (and subsequently dispersion) modelling to verify compliance with air quality standards, now or in future situations. This objective may also be directed at different levels of analysis. An important scale is the assessment of *local* air quality impacts (e.g. Nagendra & Khare, 2002) due to, for instance, existing emission "hot spots" such as intersections, new transport projects (e.g. environmental impact assessments with respect to new roads or re-alignment of existing roads) or the implementation of traffic management measures (e.g. lower speed limits, traffic signal coordination). Another important scale is the assessment of *regional* or urban air quality, which is commonly based on emission inventories. This may involve modelling of any key pollutants such as NO_x and SO₂ (e.g. Owen *et al.*, 1999; 2000), but is often directed towards the analysis and prediction of photochemical smog levels (e.g. Harley *et al.*, 1993).
- A second objective is the development and evaluation of emission reduction policies through urban, national or global emission inventories, which are needed when (future) air quality problems have been identified or are needed to verify compliance with international agreements (e.g. national emission ceilings, greenhouse gas emissions). This objective requires prioritisation of emission sources (also non-road), evaluation of existing emission control strategies (trend analysis, forecasting) and the assessment of the effectiveness of alternative policy options (scenario testing).
- A third objective is the evaluation of air quality impacts of transport scenarios in the development stages (planning and design) of transport policies. Although transport planning was traditionally concerned with issues of investment and congestion, there has been an increasing interest to assess the air pollution impacts of (major) changes in land use at the network level (e.g. Taylor, 1992; Affum & Brown, 1999).

It is clear from this list that emission models have to operate at different scales, which could vary from a national/global, regional, urban to local road networks, and that the actual study objective determines the size of the study area (and thus size of the modelled road network, i.e. the number of links and nodes) that needs to be considered.

For instance, modelling of photochemical smog formation requires consideration of a large regional area (e.g. Helali & Hutchinson, 1994), whereas an air quality assessment in the direct vicinity of a new road requires consideration of only a small road network or possibly a single road (e.g. Meng & Niemeier, 1998). This leads to the following aspect of model selection: available input data.

Available Input Data

The size of the study area (i.e. road network) affects the availability of emission model input data. As was discussed in section 3.2.3, the demand for resources (costs, labour, computer runtime) to generate and process input data for emission models from either traffic models, field data or both, increases with network size. As a consequence, the extent and the level of detail of *available* input data are effectively reduced in practise when network size increases (Taylor & Gipps, 1982). On the other hand, the amount and types of *required* input data are a function of emission model complexity. More complex models impose a larger demand for input data on the model user.

The trade-off between emission model complexity and network size can be observed in Table 32 (next page, constructed by the author), which shows the interface between emission models, traffic models and field data. This summary table has been constructed using information presented in sections 2.5 and 3.2.2.

Table 32 – Interface Between Types of Emission Models, Traffic Models and Traffic Field Data

AVAILABILITY OF TRAFFIC FIELD DATA	REQUIRED INPUT FOR EMISSION MODELS	TYPE I			TYPE II			TYPE III				
		FBM	AWM	ASM	TSM	TSM	TSM	TEE	MAT	AMM	SFM	IMM
					EPA	TNO						
	Microscopic Driving Patterns	MICROSCOPIC SIMULATION MODELS										
4	Space Mean Speed											
3	"Typical" Driving Pattern	TRAFFIC PERFORMANCE MODELS										
4	Number of Queue Move-Ups											
4	Number of Major Stops											
4	Delay											
4	Green Time											
1	Cycle Time											
1	Intersection Type											
1	(Free-Flow) Cruise Speed											
4	LOS											
3	Mean Travel Speed											
3	"Traffic Situation"											
-	Speed Limit											
1	Basic "Road Type"											
1	Link Volume											
2	Number of Lanes											
1	Link Length											
1	Basic Traffic Composition											
2	Link VKT											
2	Network VKT											
2	Detailed Traffic Composition											
3	Detailed Fleet Composition											
1	Fuel Sales											
1												

Abbreviations used: strategic planning model (SPM), (macroscopic) dense network model (DNM), traffic performance model (TPM), microscopic simulation model (MSM), area-wide emission model (AWM), traffic situation emission model (TSM), US EPA traffic situation emission model (TSM-EPA), TNO traffic situation emission model (TSM-TNO), travel speed emission model (ASM), speed/fluctuation model (SFM), analytical modal emission model (AMM), reconstructed speed time profile emission model (TEE), Matzoros queuing emission model (MAT), instantaneous modal emission model (IMM), available for every road (1), commonly available for many roads (2), commonly available for major roads (3) and rarely available (4).

Four levels of traffic field data availability have been distinguished in Table 32, i.e. “available for every road” (1), “commonly available for many roads” (2), “commonly available for major roads” (3) and “rarely available” (4). As was shown in this chapter, input data for emission models are not restricted to actual output data from traffic models (e.g. link VKT, link travel speed), but may also concern input data to traffic models (e.g. link length, free-flow speed). From the perspective of emission modelling, traffic models may be regarded as a data source from which several kinds of emission model input data can be extracted.

The summary table may be useful for air pollution modellers who quickly want to examine (in a general sense) what the required input data for a particular type of emission model is and what the availability of these input data from all possible data sources is. For instance, if one selects the TEE column in the table, it becomes clear that the required input data (indicated with shaded cells) may be obtained from either a dense network model or perhaps from a strategic planning model with additional field data on cycle time, green time and intersection type.

Appropriate Resolution

As was discussed in section 3.2.3, a hierarchy of emission models can be distinguished in terms of the minimum spatial and temporal resolution. The most complex emission models predict emissions at the highest spatial and temporal resolution of typically one second, whereas the least complex models operate at network level.

The appropriate resolution for a particular study would clearly depend on the study objectives and the situation that is being investigated. It would be determined on the basis of logical arguments. For instance, when concentration levels at certain receptor points near an intersection are predicted, it seems appropriate to model at a high resolution. This would be necessary to account for the distribution of emissions along the roads near the intersection. However, for local air quality impact assessments of roads with relatively homogeneous traffic conditions (e.g. part of a freeway), a higher resolution (e.g. link level) seems suitable.

When photochemical smog formation is predicted, emissions data are usually required for area grid cells and average link emissions seem the appropriate minimum resolution. For national emission predictions higher resolutions (e.g. network level) appear to be reasonable.

It is important to note that, although reasonable, decisions on the appropriate resolution are made in a rather arbitrary manner. This is because this decision ideally needs to be balanced using information on other aspects such as model accuracy. As will be seen later in this section, there is not enough information available (yet) on e.g. model accuracy to substantiate a general scheme on the appropriate resolution for each type of emission model.

It is, for instance, not clear if it is actually *possible* to accurately predict emissions at very short time intervals, and there are indications that this might not be the case (e.g. TRL, 1999). Another example, which was discussed in section 3.2.3, is that the *validity* of applying emission models that are based on journey-level driving cycles to shorter sections of road (links) is yet to be determined.

Sensitivity to Variables that are Investigated

The *basic* constituents of emission modelling, i.e. the amount of vehicle kilometres travelled by vehicle class and by the particular "traffic situation" (including congestion, road type) that are of interest, should always be included in air pollution modelling.

Usually, one would like to use emission models that are "complete", i.e. models that include all (major) vehicle classes, since emissions from entire traffic streams are usually of interest (e.g. to assess effects on local air quality). In some cases incomplete models may be useable. For instance, the aim of a project may be to determine the effects of vehicle class specific measures on emissions (e.g. implementation of a new bus corridor).

In addition to these basic constituents, emission models should *at least* be sensitive to the issues that are investigated in a particular study. Otherwise, these issues cannot be effectively assessed. The specific aim of a study determines which other variables are relevant and should be included in the model. For instance, if emission models are used to assess the emissions (and air quality) effects of implementation of different

speed limits on highways, the emission model should (at least) be sensitive to the variable “speed limit”.

Level of Accuracy

The required level of accuracy would depend on the type of study. An emission model used for “screening” purposes would not be required to be accurate, but instead would be required to be conservative. For other “non-screening” applications, accurate emission predictions may well be important. For instance, accurate emission predictions would be necessary to compute local air quality at critical locations (e.g. new residential area near a highway).

Emission Model Accuracy

Because complex emission models are *sensitive* to many factors they would be expected to be more accurate than less complex models. On the other hand, the sensitivity to many factors would also create additional uncertainty because more (types of) input data are needed, each with its own inherent uncertainty.

In addition, there are several other aspects of emission models that would affect model accuracy (and could thus be used as selection criteria) such as number of measurements (precision), the use of simplified or real world cycles (bias) and the use of up-to-date emissions test data (bias), as was discussed in section 3.3, and perhaps several other factors such as the use of local emissions test data (bias). In this respect, less complex models such as travel speed models may actually be more accurate than more complex emission models, because they use the largest empirical database, use real-world cycles and are regularly updated.

Also, peculiar behaviour may be present in certain emission models, but this may not be directly clear. For instance, the TEE-KCF model uses emission factors that are always higher, irrespective of the level of congestion on a link, than those used by the implicit model it is supposed to correct, which already includes congestion.

In order to assess the accuracy of emission models, one would like to compare the results from different emission models to independent observations from the system

being modelled, i.e. the process of model validation. It is, however, not possible to validate traffic emission models in a strict scientific sense, since true road traffic emission values are unknown and cannot practically be determined by measurement (e.g. Horowitz, 1982).

Some partial emission model validation is possible where road traffic emissions data are available for specific *localised* situations with certain traffic conditions during relatively short time periods, such as in tunnels (e.g. Pierson *et al.*, 1996), during specific vehicle journeys (e.g. Mensink, De Vlioger & Nys, 2000) or at specific points along a road using either remote-sensing (e.g. Kuhns *et al.*, 2004) or kerbside air quality measurements (e.g. Vogel *et al.*, 2000). Here, certain aspects of emission models (e.g. emission factors) can be validated for particular local situations, but this information cannot be used to arrive at an overall emission model evaluation (e.g. at network level).

It is impossible to directly measure emissions at network level due to the large number of vehicles and traffic situations involved. Therefore, other means are needed to validate traffic emission models at area level. The only possible way of doing this is to compare model results to ambient air pollutant concentration data (e.g. Fujita *et al.*, 1992; Panitz, Nester & Fiedler, 2002). Since these model results arise from the combination of traffic models, emission models and dispersion models, these studies validate the model chain and do not directly assess the accuracy of emission models.

This is an important consideration, because there may have been several reasons for discrepancies found between modelled and ambient concentration data (e.g. Harley *et al.*, 1993; Panitz, Nester & Fiedler 2002). For instance, a factor of two between predicted and observed values is often considered “satisfactory” in the field of air pollution dispersion modelling (Marmur & Mamane, 2003), but larger errors are commonly observed (e.g. Matzoros, 1990). These other error sources may have offset or amplified emission modelling errors, but the magnitude and direction of these errors in the validation studies are unknown.

In addition, local vehicle fleet characteristics (e.g. fleet composition, fleet age, maintenance, etc.) that were current at the time of the evaluation programme continuously change in time and this significantly affects emissions observations (e.g. Pokharel, Bishop & Stedman, 2002). Thus, a model may have performed well a

number of years ago, but this may no longer be the case for the current situation. Also, model validation is not possible for situations for which there is a lack of empirical data (e.g. future years).

It is clear that the determination whether one model is more accurate than another one is not an easy task, and would require information from different sources. It will be seen in section 5.5.2 that it is not possible for the three models used in Chapter 5 to establish, on the basis of available information (and the complexity of assessing emission model accuracy in general), which emission model is most accurate.

Input Data Accuracy

The quality of emission model input data is obviously an important factor with respect to the accuracy of emission predictions. The use of traffic field data as input in emission modelling of urban networks has a clear advantage in terms of accuracy when compared to modelled data. However, as was seen before, there may be practical limitations with respect to the use of field data and data from traffic models may be the only source that can be used.

Each (type of) traffic model would have its own accuracy issues, as was discussed in section 2.5. Examples are the prediction of link speeds by and spatial network resolution in strategic planning models and validity of predicted vehicle trajectories by microscopic simulation models.

Efforts to improve the quality of emission model input data should focus on variables that have shown to have a large effect on emission predictions. In this respect, section 5.3 showed that the amount of travel (VKT) is a particularly important input variable. As a consequence, particular attention should be directed at obtaining accurate information on traffic volumes. Other important input variables are level of congestion and traffic composition, and any improvements in the accuracy of these input data would certainly lead to better emission predictions, particularly at the local level.

5.5.2 Best Model Choice for Chapter 5

The objectives of Chapter 5 were to investigate the importance of congestion in urban network modelling and to compare the results from different model (types). Through the use of logical arguments it was decided in section 3.2.3 that hourly intervals and link level would be the appropriate minimum temporal and spatial resolution for the assessment of the effects of congestion on emissions.

The size of the test network and additional requirements for up-to-date and complete models that can model both interrupted and uninterrupted flow conditions restricted the analysis to three models. It was already verified in Chapter 3 and 4 that each of these models incorporated "congestion" as a variable (either explicitly or implicitly). All three models are thus sensitive to the "variable" congestion.

With respect to the three models that have been used in this chapter (COPERT III, QGEPA 2002, TEE-KCF 2002), only one study (EC, 1995) was found that compared predictions by two of these particular models to observed data. Here, CO immissions were predicted by a dispersion model, using emission estimates from both COPERT and the TEE-KCF model for a small road network with an area of about 0.16 km² that contained several links. These predictions were subsequently compared with ambient concentration levels at two kerbside locations in a city. The results are presented in Table 33.

Table 33 – TEE-KCF Model Validation Test Results (Source: EC, 1995)

	Measured CO Concentration [$\mu\text{g}/\text{m}^3$]	Predicted CO Concentration [$\mu\text{g}/\text{m}^3$] By TEE-KCF – ADMS Urban	Predicted CO Concentration [$\mu\text{g}/\text{m}^3$] By COPERT – ADMS Urban
Site 1	6.0	6.5	1.5
Site 2	6.0	9.0	2.5

This exercise showed that the TEE-KCF model overpredicted concentrations at two sites within a factor of 1.5, whereas the COPERT model consistently underestimated concentrations within a factor of 4. There are however, some questions and issues that remain with respect to these findings:

- It is not clear how the models perform with respect to other pollutants such as HC and NO_x.
- It is not clear where the kerbside monitors were located along the link. There is empirical evidence that emissions are not evenly distributed along a link and that CO emissions are elevated near intersections and lowest at midblock (e.g. Claggett, Shrock & Noll, 1981; Al-Suleiman & Al-Khateeb, 1996). It is therefore likely that the actual location along the link would have influenced the outcomes of the validation testing.
- Both TEE-KCF and COPERT are used to predict total (g) and average (g/km) link emissions. Given that emissions are not evenly distributed along a link, the use of a single point measurement site may not correspond well to predicted average link emissions. Instead, averaged values from several measurement sites along the link may have been a more appropriate approach.
- The number of cold-start vehicles cannot be controlled and their proportion in the traffic stream is unknown. It was thus *assumed* that a certain cold start percentage (30%) applied to this situation. Because traffic stream CO emissions may vary substantially with the proportion of vehicles that operate in cold start conditions (e.g. Marsden, Bell & Reynolds, 2001) and the distribution of fuel types in the traffic stream⁷⁶, it seems likely that other assumptions⁷⁶ on this percentage would lead to different results.

⁷⁶ For instance, diesel vehicles have substantially lower cold start CO emissions than petrol vehicles and (Smit, 2006b).

- Dispersion models are themselves subject to uncertainty, which may influence the outcomes of this emission model validation studies. For instance, Vardoulakis *et al.* (2002) observed that dispersion models may use inappropriate values for model parameters. As a consequence, comparing model results with experimental data might be falsely interpreted as unsatisfactory emission predictions or meteorological input. With respect to the ADMS dispersion model (the model used in EC, 1995), validation studies have shown that the fraction of predicted immissions that are within a factor of 2 of observed values varies between approximately 30% to 80% and that overall accuracy varies between -24% and +14% (Ellis *et al.*, 2001; CERC, 2003a; 2003b). This source of error may have offset or amplified emission modelling errors, but the magnitude and direction of these errors are unknown.

These issues demonstrate the (general) difficulty in the determination of the “best” emission model in terms of its capability to predict the (unknown) true emission values.

There is thus some limited evidence that suggests that the use of the type II TEE-KCF model may lead to better (local) emission predictions for a specific situation than current type I travel speed models. However, the results of this study are based on limited testing and are necessarily based on assumptions with respect to factors that are known to strongly influence emissions (e.g. percent cold vehicles).

It is therefore concluded that there is insufficient information to state that the type II TEE-KCF model has a higher accuracy than the type I COPERT model. As a consequence, a choice for one of these models cannot be made on the grounds of (proven) improved accuracy.

On the other hand, TEE-KCF is clearly sensitive to more factors that are known to influence congestion levels (i.e. signal settings, intersection spacing, traffic density) than COPERT and QGEPA. One particular weakness of the travel speed model appears to be its use of average speed alone to reflect the effect of driving conditions on emissions. This means that emission factors are fixed for a certain travel speed and that they only reflect one particular level of congestion for that average speed, possibly differentiated by basic road type.

Literature has shown (EC, 1995; Negrenti, 1998) that the same average travel speed can have a (substantial) difference in emissions of up to a factor 4, depending on the actual level of speed variation that is encountered during the journey. This implies that application of current travel speed models to assess the effect of congestion on emissions is valid as long as level of congestion does not substantially depart from the values used by the model.

From this perspective, the TEE-KCF model would have more validity than the travel speed models, since it offers more flexibility to differentiate emission factors according to (local) traffic conditions. Because TEE-KCF uses more link-specific and congestion-related input data than the COPERT and QGEPA models, the TEE-KCF model is *expected* to perform better in practical applications at local scales.

However, it is possible that other factors such as the use of local emissions test data (as was the base for the QGEPA model), is in fact more important with respect to model validity than improved modelling capabilities, but this is unknown. In addition, peculiar behaviour⁷⁷ in the TEE-KCF model may also reduce the validity of this particular model. It is thus impossible on the basis of the available information and reflection based on arguments to make a well-founded statement on the *best* model for use in chapter 5.

The procedure for selection of the best emission model that was presented in this section can be used, to some extent, for model selection. However, due to gaps in knowledge, which were identified and discussed in this section, it will generally be difficult to determine and select the most appropriate model for a particular study.

To resolve this issue, the procedure for selection of the most appropriate model will require more information on (proven) emission model accuracy (preferably using different approaches such as tunnel studies and air quality measurements) and will require further research into the relative importance of the various factors that contribute to emission model accuracy.

⁷⁷ TEE-KCF uses emission factors that are always higher, irrespective of the level of congestion on a link, than those used by the implicit model it is supposed to correct, which already includes congestion.

5.6 Conclusions

This Chapter has investigated 1) the importance of congestion in urban network modelling and 2) possible disparities in predictions between explicit and implicit emission models, by applying a number of current emission models to a case-study urban network in Australia (Brisbane). This network has been differentiated in time (day time periods) in order to contrast network congestion levels (uncongested versus congested) and differentiated in space (city area, basic road type) to examine location effects.

Given the large number of emission models that exist around the world, general conclusions that would apply to all current explicit and implicit models can logically not be made from this work. Also, the extent of differences that could potentially exist between the results that follow from this Chapter and outcomes from studies conducted in a similar fashion, but based on other urban networks with different characteristics (fleet composition, network configuration) cannot be assessed here. It is therefore suggested that, in terms of further research, similar investigations should be conducted with other traffic models in other countries in order to see if the outcomes of this chapter are confirmed.

With these limitations in mind, the results of this chapter *suggest* that:

1. congestion is an important issue in urban network modelling of emissions of specific pollutants; and
2. differences between explicit and implicit models can be large or small (trivial), depending on the type of disparity (absolute or relative) that is considered.

This section has shown that level of network congestion in the Brisbane network is an important factor in the prediction of network emissions of CO and HC. When the network changes from uncongested to congested conditions total emissions increase by approximately an order of magnitude.

This large increase is, in the first place, largely due to the principal cause of congestion, i.e. increased traffic densities (more vehicles) on network links. In the

second place, congestion or the deterioration of the quality of traffic flow conditions (i.e. changes in driving patterns), also has a large effect on total network emissions, i.e. predicted emissions of CO and HC can more than double. For NO_x, congestion has a much smaller impact on total emissions, and for this pollutant basic traffic composition appears to be a more important factor.

It was also observed that the effect of congestion on predicted emissions of CO and HC becomes larger when the (difference in) level of network congestion increases. This was the case for all city areas and road types, with one exception. On uninterrupted roads (“freeways”) there appears to be a congestion level below which no effect of changing congestion levels on subnetwork CO emissions (not HC) is observed.

When the predicted relative effects of congestion on network CO emissions by the three models are compared, the outcomes from this chapter indicate that the different model types (type I implicit and type II explicit) can produce quite similar results. In contrast, differences in predicted relative effects can be quite large when the two implicit models are compared. Thus, the different way in which (type I, II) and the *extent* to which (implicit, explicit) congestion is incorporated into the models does not seem to have a significant effect on relative emission predictions.

This implies that the use of different implicit models, which have the advantage of requiring less input data than the explicit models, may be sufficient for studies whose purpose is to compare relative emission levels in urban networks (e.g. to compare different future scenarios).

When the effects of congestion on network emissions are compared in an absolute sense (e.g. total emission load in the peak hour), the results in this chapter show that the different model types can produce substantially different results. The explicit model predicts higher network emissions than the implicit models in all circumstances, but the differences between model types increase when network congestion increases, which is the case for both road types.

Interestingly, substantial differences in absolute emission predictions were also observed for similar model types (travel speed models). The causes for these differences could not be clarified, but it is suggested that country specific differences in

e.g. emission legislation and I/M programmes and perhaps (small) differences in model development methodology may have contributed to these differences.

The substantial differences in absolute emission predictions imply that there might be an issue with the selection of the “best” emission model when the principal focus of a study is on producing absolute emissions data (e.g. for the assessment of photochemical smog levels in a region). In this case, one may wish to use the most accurate model. Emission model accuracy is, however, not easily determined, and for the models that have been used in this chapter there is insufficient information to establish which model is most accurate.

One could argue that the TEE-KCF model has more validity than travel speed models on the basis of improved modelling capabilities (at least from a theoretical perspective). The methodology behind the TEE-KCF 2002 model, although partly based on hypothetical assumptions, approaches the congestion issue largely from a traffic engineering perspective. This incorporation of theoretical aspects of traffic flow is rather unique in air emission modelling, and it contributes to confidence in TEE-KCF model’s predictions.

In contrast to current travel speed models that reflect the effect of a fixed level of congestion for a particular link speed on emissions, the TEE-KCF model (and all type II and type III models for that matter) has the additional capability to predict the effects of varying levels of congestion at a particular link speed. The TEE-KCF model would therefore have more validity in general than travel speed models to assess emissions in local traffic conditions.

On the other hand, it is possible that other factors such as the use of local emissions test data (QGEPA in this case) or the use of simplified driving patterns (TEE-KCF) are in fact more important with respect to model validity than the improved modelling capabilities mentioned before. Hence, determination of the most appropriate model is not possible, and further research into the relative importance of the various factors that contribute to emission model accuracy is required.

6 SUMMARY OF CONCLUSIONS

The level of air pollution in urban areas, which is largely affected by road traffic, is an issue of high political relevance. Congestion is most prevalent in urban areas and a common and increasingly present phenomenon worldwide. This study has investigated the role of congestion in urban road network air pollution emission modelling. Specifically, it has addressed the following research question:

How and to what extent do models that are used to predict emissions over urban road networks include the effects of congestion on emissions?

Congestion

Congestion is defined as the deterioration of the quality of traffic flow away from free-flow conditions on a network element, or in an entire road network, due to increased demand for travel and/or reduced capacity for traffic movement. Road capacity is determined by the road environment and presence of traffic control devices. In urban road networks minimum road capacity regularly occurs at (signalised) intersections, which makes signal settings particularly important variables with respect to congestion.

The relationship between congestion and its causes is non-linear, and this is particularly evident on uninterrupted roads (e.g. freeways). At relatively small volume-to-capacity ratios the quality of traffic flow is good and relatively stable (no congestion), but traffic flow quickly deteriorates when traffic demand approaches (or exceeds) capacity.

There are many different (but interrelated) traffic variables (congestion indicators) that are used to quantify congestion (48 variables were identified in this study). They may be assigned to two main groups, i.e. those based on travel time (e.g. “speed”, deviation from free-flow speed, time spent idling) and those not based on travel time (e.g. queue length, speed fluctuation, number of stops). In order to sufficiently identify (more) congested traffic conditions, it is necessary to use a set of different indicators, and not one single indicator.

Traffic and Emission Modelling

Air emission modelling is a multidisciplinary exercise since it combines the results from traffic modelling (or traffic field data collection) with emission (factor) models. Because both fields have largely been developed independently of each other, answering the research question is a complex task, which requires a systematic approach.

In this respect, one particular point of attention is the possible differences in definition of variables that are relevant to air emission modelling. A number of these variables can be defined in different ways and although traffic data used as input in emission modelling appears, on first sight, to be based upon the same definitions, this is not always the case. An important example is “speed” which can be defined and measured in different ways. This study showed that the definition of “average speed” used in common traffic models corresponds to the definition used in current average (travel) speed emission models. In contrast, certain methods of traffic field data collection (e.g. loop detectors) employ different definitions of speed. This mismatch between definitions could potentially lead to significant errors in emission predictions.

Another example is traffic volume. In traffic models demand flow rate is commonly used, which can exceed the physical capacity of a road. Direct use of demand flow rate in emission predictions may lead to incorrect prediction and incorrect allocation of emissions in congested situations in the network.

Several emission models were identified from the literature (38 in this study) and they differ in the extent to which the different aspects of vehicle emissions (e.g. type of emission, vehicle categories) have been incorporated into the model. They also have different input requirements, which, in practise:

- affects the interfacing with traffic models; and
- affects their temporal and spatial resolution.

Since an increase in network size (number of links) often reduces the level of detail in the output data from traffic models, a “scale effect” is visible in air emission modelling, i.e. a trade-off between network size and emission model complexity. In practical applications, complex (traffic and) emission models are effectively applied to small

networks only and large road networks require less complex (traffic and) emission models due to reduced data availability.

A reduction in emission model complexity is also accompanied by a reduction in spatial and temporal resolution. A spatial resolution of link level is considered to be a "natural" minimum resolution for the assessment of congestion effects on emissions, since major differences in minimum road capacity (e.g. differences in intersection layout and signal settings) are taken into account and because capacities at different points along a link (road environment conditions) would be relatively constant.

Most emission models are able to operate at link level, although it is suggested that the validity of application of emission models, which are based on journey-level driving cycles, at this spatial resolution should be further investigated. It became clear that two types of emission models ("area-wide", "fuel based") fell beyond the scope of this study since they cannot operate at link level.

Development of an Emission Model Typology

Congestion and traffic emissions are linked to each other through one fundamental key aspect: vehicle movement in time and space, which is described in terms of vehicle trajectories or, more commonly, driving patterns. Congestion causes changes in driving patterns of individual vehicles in a traffic stream, and these changes are subsequently reflected in changes in congestion indicators and changes in emission levels.

This consideration has led to a proposed "congestion typology" of emission models, and it reflects the different ways in which congestion can be incorporated in these models (the "how" in the research question). Three main types have been distinguished. An emission model has either:

- incorporated driving pattern data in the model development phase (type I);
- generates driving pattern data in the modelling process (type II); or
- requires driving pattern data as input to the modelling process (type III).

A further important distinction is made with respect to explicit, implicit or no consideration of congestion in an emission model (the "extent" in the research

question). Here, explicit means that the effects of congestion are modelled by variables that are related to congestion and whose values can be modified by the user. Implicit means that the effects of congestion are inherently considered in the model, but that level of congestion cannot be modified and is therefore beyond the control of the model user.

Two additional distinctions with respect to the “extent” in the research question have been proposed, i.e. whether an emission model is based on real-world or simplified driving pattern data, which would affect model accuracy, and whether an emission model considers vehicle interaction and/or traffic control interactions, which determines to which road types a model can be applied. Type II and III models can use either real-world or simplified driving pattern data, or both, and one particular type II model does not consider vehicle interactions. All type I models are based on real-world driving patterns, and one particular type I model does not consider traffic control interactions.

All type II and type III models explicitly take congestion into account in the modelling process through their use of actual (location specific) driving pattern data in the modelling process. The difference between these two model types lies in the level of detail with respect to input data. Whereas type III models require highly detailed microscopic driving pattern data as model input, type II models generate these patterns themselves in the modelling process, on the basis of several (macroscopic) traffic stream and road infrastructure variables.

For type I models the results are mixed. One family of type I models, the so-called quantitative traffic situation models, also explicitly take congestion into account through their use of congestion-related variables, which are in turn related to fixed discrete emission factors.

For another family of type I models, the so-called travel speed models (“average speed models”), which are used extensively in urban network modelling, the research question could not be fully answered on the basis of literature review alone. The problem follows from the sole use of “average speed” to quantify traffic flow conditions:

- The relationship between average speed and level of congestion is road (type) specific. Travel speed is therefore an ambiguous congestion indicator in a certain range of travel speeds (low to medium).

- It is (at least theoretically) possible that any particular travel speed could represent flow conditions that are somewhere in between two extreme situations, i.e. smooth (uncongested) flow conditions – which would correspond to no consideration of congestion in the model – or highly dynamic (very congested) flow conditions with many interactions.

As a consequence, it is not clear to what extent congestion (no or implicit consideration) is incorporated in these models. The extent has been investigated in this study through analysis of driving pattern data (and other information with respect to e.g. data collection) that were used in the development of these models. Since information on congestion level was usually not collected concurrently with driving pattern data, there was no *direct* way of establishing the congestion level in current commonly used travel speed emission models.

Therefore an *indirect* approach was needed to examine congestion levels in these models. A method was developed to assess the mean level of congestion in driving cycles using both a qualitative (visual examination) and a quantitative approach. The re-examination of the driving cycles made use of various congestion indicators for which literature (i.e. traffic flow theory or empirical evidence) has shown that they are a function of level of congestion. The analysis was restricted to current commonly used travel speed emission models. Both the qualitative and quantitative analysis of the driving cycles showed consistent results.

It is concluded that all four travel speed models (COPERT III, MOBILE 6, QGEPA 2002, EMFAC 2000) examined in this thesis implicitly take varying (but fixed) levels of congestion into account. An overall trend was observed of increasing congestion levels with decreasing travel speeds. Only a few high speed cycles in the COPERT III model qualified as being “uncongested”, according to a set of prespecified criteria. These findings are subject to two important limitations:

1. The cycle analysis was mainly restricted to light-duty vehicles (passenger cars, light-commercial vehicles), since driving cycles for heavy-duty vehicles (trucks, buses) could not be obtained for all models (only for the QGEPA 2002 model). For air pollutants that are predominantly emitted by light-duty vehicles (e.g. CO, HC), it

can be safely assumed, on the basis of this work, that application of these models would (largely) reflect the effects of congestion on emissions. However, for air pollutants for which heavy-duty vehicles are important contributors (e.g. NO_x), this statement can only be made with respect to QGEPA 2002. In terms of future work, the analysis could be completed once access to the “missing” cycle data is granted.

2. Since driving patterns are also a function of other factors (e.g. driving style, weather), it is possible that the observed change in congestion levels in driving cycles is not (only) a result of congestion, but (partly) a result of these other factors. The extent to which driving cycles have been affected by these non-congestion related factors, and their relative importance with respect to congestion-related effects could not be determined. However, when the nature of the cycle construction process, current traffic engineering practise and one particular publication (Ericsson, 2000) are considered, it appears likely that congestion was a major, if not the most important, factor influencing the driving patterns on which the driving cycles are based.

With these limitations in mind, it is concluded that the majority of emission models that were investigated in this thesis, and which are applied to urban networks at link level, explicitly consider congestion in the modelling process, although this is done in different ways, and that a small number of emission models (travel speed models), which are often used in practice, implicitly consider congestion in the modelling process for at least one major vehicle class (LDV).

For one particular family of type I emission models, i.e. qualitative traffic situation models, the driving cycles were not further examined for practical reasons. These models do explicitly include congestion, but additional cycle analysis could shed light on the actual extent to which congestion has been included.

Partial Prediction of Congestion Effects

An important finding of this study is that prediction of (the effects) of congestion in both traffic models and emission models is generally restricted to certain modelling dimensions, i.e.

- traffic models (and thus emission predictions) usually only consider recurrent congestion;
- emission models consider the effects of congestion on regulated pollutants (CO, HC, NO_x, sometimes PM₁₀), and indirectly (through hydrocarbon profiles) the effects on speciated hydrocarbons, but not the effects on other unregulated pollutants;
- emission models consider the effects of congestion on hot running emissions, but often not the effects on cold start and running loss emissions.
- emission models often consider the effects of congestion for certain vehicle classes (due to deliberate exclusion of particular classes or due to lack of regular model updates), and not always for all major vehicle classes.

This leads to the conclusion that in current air emission modelling, the effects of congestion are only partially predicted. Although it seems likely that, as a consequence, the effects of congestion on emissions are now underestimated, the magnitude of this error is not clear. Given the increasing importance of congestion, it appears vital to extend current traffic and emission models with algorithms that enable the prediction of the effects of congestion on emissions for all dimensions.

Application of Emission Models

The second part of the thesis addressed two research objectives, which followed from answering the research question, i.e.:

1. *to investigate the importance of congestion in urban network modelling, and*
2. *to investigate when and where different types of emission models predict different effects of congestion on traffic emissions.*

The first objective attempted to address the question whether congestion is actually an important issue in urban network emission modelling or not. The second objective attempted to address the question if different types of emission models (type I, II, III and implicit versus explicit) actually predict different results. Before the analysis was conducted it was verified that 1) the selected emission models include congestion (this was investigated and confirmed in the first part of the thesis), and 2) the urban network reflect both an uncongested and a congested situation.

On the basis of a number of selection criteria, two types of models were compared, i.e. one type II explicit model (TEE-KCF 2002) and two type I implicit models (COPERT III, QGEPA 2002). The research objectives have been addressed by applying these emission models to a case-study urban network in Australia (Brisbane).

The test network represented an actual urban road network with a radius of 10 km from the city centre. Different sources of information, i.e. traffic model, traffic field data, publications and national/state statistics, have been used to create an input database that was sufficient to run the emission models. The network has been differentiated in time (day time periods - morning peak, afternoon peak, off-peak, night) in order to contrast network congestion levels (“uncongested” versus “congested”) and differentiated in space (city area, basic road type) to examine location effects. In terms of city area, the urban area was divided into three city regions: the central business district, an inner city area and an outer city area. In terms of basic road type, a distinction was made between interrupted (urban roads - “arterial”) and uninterrupted (non-urban roads - “freeway”) roads. On the basis of this work it is concluded that:

- Changes in traffic activity (i.e. distribution of vehicle kilometres travelled on network links) over the day appear to have the largest effect on predicted traffic emissions.
- Congestion appears to be an important factor in urban network modelling of emissions of specific pollutants (CO and HC). For the most congested parts in the urban network that have been investigated, congestion can more than double predicted emissions of CO and HC.
- Congestion is not so relevant with respect to NO_x emissions. Here, (a change in) basic traffic composition is generally a more (and sometimes equally) important factor.
- Disparities between different types of emission model can be large in case of *absolute* (arithmetic) differences or small (trivial) in case of *relative* differences (ratio or percent difference). The different *manner* in which and *extent* to which congestion is incorporated into the models (type I implicit versus type II explicit) does not have a significant effect on relative emission predictions, but does have a substantial effect on absolute emission predictions.

The presence and extent of location effects is dependent on the pollutant and the type of effect that is considered. With respect to city area, the following conclusions are made:

- A positive relationship exists between level of network congestion and total emissions of CO and HC. Hence, the largest effects of congestion on CO and HC emissions are found in the inner city area, where the largest change in the level of network congestion occurs when peak period and night time period are compared.
- With respect to the effects of basic traffic composition, which is an important factor with respect to NO_x emissions, the largest effect on the emissions of all three pollutants is consistently observed in the CBD area, where the largest change in the proportion of heavy-duty vehicles occurs when peak period and night time period are compared.

With respect to road type, differences in the effects of network congestion on emissions are dependent on the pollutant:

- For CO emissions the effects of network congestion are larger on interrupted roads, when compared to uninterrupted roads in the same city area.
- On uninterrupted roads there appears to be a congestion level below which no effect of changing congestion levels on subnetwork CO emissions is observed. This is not the case for interrupted roads, where a change in congestion level always has an effect on network emissions.
- For HC emissions, differences between road types with respect to the effects of network congestion are not consistent and a location effect is not evident.
- For NO_x emissions, differences between road types with respect to the effects of network congestion are observed in terms of the direction (sign) of the effect. On interrupted roads, emissions generally increase when network congestion increases, whereas the opposite result often occurs on uninterrupted roads.

These findings are limited by the fact that they follow from one urban network with particular characteristics (fleet composition, signal settings, speed limits) and application of particular emission models.

Depending on the purpose of the study (e.g. to compare different future scenarios) it may be sufficient to apply less complex (implicit) emission models, which have the advantage of requiring less input data than more complex (explicit) emission models. However, when differences between models are substantial, for instance in case of absolute emission predictions (e.g. total emission load in the peak hour) or relative emission predictions between models of the same type, a choice needs to be made which model predictions are finally used.

It is not entirely clear what causes the differences between emission models. An obvious reason for the differences between type I and II models is the different way in which and extent to which congestion has been built into the models. However, this is not a full explanation, because differences between models of the same type can also be substantial. The causes for these differences and their relative importance could not be clarified, although some suggestions have been made. For instance, country

specific differences in e.g. emission legislation and I/M programmes and perhaps (small) differences in model development methodology may have contributed to these differences.

Irrespective of these model differences, an objective selection criterion is model accuracy. However, it has not been possible, on the basis of available information (and the complexity of assessing emission model accuracy in general), to establish which model type was most accurate.

Instead, model selection could be performed on the basis of argument. This, however, is a subjective approach. For instance, one could argue that type II and III models have more validity than travel speed models, because of their capability to predict the effects of varying levels of congestion at a particular link speed. However, it is possible that other factors such as the use of local emissions test data are in fact more important with respect to model validity than improved modelling capabilities. In addition, peculiar behaviour may be present in emission models, but this may not be directly clear. For instance, the TEE-KCF model uses emission factors that are always higher, irrespective of the level of congestion on a link, than those used by the implicit model it is supposed to correct, which already includes congestion.

Further Work

In terms of the need for further work and new directions, the following comments are made:

- Given the increasing importance of congestion, it appears vital to extend current traffic and emission models with algorithms that enable the prediction of the full effects of congestion on emissions for all dimensions.
- Further investigation into the causes for the differences between emission models and further research into the relative importance of the various factors that contribute to emission model accuracy are required. This future work may aid in determination of the most valid model for each (network) situation.

- It is suggested that application of different emission models in various urban networks around the world are conducted in a similar fashion to see if the outcomes of this study are confirmed.
- The methodology presented in this chapter could be applied to the driving cycles used in current qualitative traffic situation models to further investigate the level of congestion contained in these cycles and fully address the research question. It is already clear, however, on the basis of the verbal descriptions used in these models, that congestion has explicitly been incorporated in these models.
- In current emission prediction link emissions are predicted on the basis of mean link travel speed alone. Consideration of a *distribution* of travel speeds within a traffic stream in emission estimation may lead to different (and more accurate) predictions. It is possible that these differences would be significant due to the non-linear relationship between (particularly CO and HC) emission factors and travel speed, which is particularly evident in congested conditions. Investigation of the relationship between level of congestion and the shape (mean, dispersion) of travel speed distributions would precede further investigation into this matter.
- Traffic models that use congestion functions in the predictions of mean link travel speeds (strategic planning models, SPMs) can predict quite different results. These differences are largest in congested conditions and they depend on the specific congestion functions that have been used in the modelling process. This implies that emission predictions for the same network, but based on traffic data from two different SPMs (or different types of traffic model for that matter) could possibly lead to quite different emission predictions. To assess the magnitude of absolute and relative differences, it is suggested that output from different traffic models for the same urban network are used as input to emission models and that the results are compared. It is expected, on the basis of this work, that if a particular traffic model predicts more congested network conditions, total network emissions of CO and HC would increase.
- The magnitude of possible errors in emission predictions due to different definitions of traffic variables that may be used in air emission modelling was not examined in this thesis. It is suggested that this could be investigated by comparing emission

predictions for links with varying levels of congestion using both traffic field data and traffic model data.

- Given the difficulties associated with assessing emission model accuracy, it seems important to employ different techniques (e.g. tunnel study, laboratory measurements, on-road measurements, remote-sensing, fixed-point immission sampling) in the process of emission model validation, where each technique has its own strengths and weaknesses, as has been discussed in section 3.2.1, and not to assess overall model accuracy with one particular method.

It is finally suggested that, given the increasing importance of congestion in the future, level of congestion (traffic density, signal settings), and also important road features (road type, signal density) are recorded during driving pattern data collection. This would simplify the assessment to what extent a travel speed model incorporates congestion, would remove the uncertainties that are associated with the indirect method employed in this thesis, and would also allow for examination to what extent specific local situations correspond to the particular situations that are simulated by the travel speed model.

REFERENCES

- AATSE (1997) *Urban Air Pollution in Australia - Transport Logistics*, Australian Academy of Technological Sciences and Engineering, Supporting Report No. 3, Task Group 5.
- ABS (2000) *Survey of Motor Vehicle Use*, Australian Bureau of Statistics (ABS), ABS Catalogue No. 9210.0.55.001, Belconnen, ACT 2616, Australia.
- Affum, J.K. & Brown, A.L. (1999) Estimating urban air pollution levels from road traffic in TRAEMS, *Journal of Eastern Asia Society for Transportation Studies*, Vol. 3, No. 1, pp. 139-150.
- AGO (1998) *Energy Workbook for Transport (Mobile Sources)*, Australian Greenhouse Office, National Greenhouse Gas Inventory Committee, Workbook 3.1 with Supplements, ISBN 1 876 53642 X.
- AGO (2003) *Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2003 – Energy (Transport)*, Australian Greenhouse Office, National Greenhouse Gas Inventory Committee, ISBN 1 928040 16 8.
- Ahrens, C.D. (2003) *Meteorology Today – An Introduction to Weather, Climate and the Environment*, 7th Edition, Thomson Brooks/Cole, ISBN 0 534 39771 9.
- Akçelik, R. (1978a) Discussion on Davidson's flow-rate/travel time relationships, *Australian Road Research*, Vol. 8, No. 1, pp. 41-44.
- Akçelik, R. (1978b) A new look at Davidson's travel time function, *Traffic Engineering & Control*, Vol. 19, No. 10, pp. 459-463.
- Akçelik, R. (1980) *Time-Dependent Expressions for Delay, Stop Rate and Queue Length at Traffic Signals*, Australian Road Research Board, Internal report AIR 367-1.
- Akçelik, R. (1981) *Traffic Signals: Capacity and Timing Analysis*, Australian Road Research Board, Research Report ARR No. 123.
- Akçelik, R. & Troutbeck, R. (1991) Implementation of the Australian roundabout analysis method in SIDRA, *Proceedings of the International Symposium on Highway Capacity*, Karlsruhe, July 1991, Brannolte, U. (ed.), A.A. Balkema, Rotterdam, pp. 17-34.

- Akçelik, R. (1991) Travel time functions for transport planning purposes: Davidson's function, its time-dependent form and an alternative travel time function, *Australian Road Research*, Vol. 21, No. 3, pp. 49-59.
- Akçelik, R. (1996) Relating flow, density, speed and travel time models for uninterrupted and interrupted traffic, *Traffic Engineering + Control*, Vol. 37, No. 9, pp. 511-516.
- Akçelik, R., Christensen, B. & Chung, E. (1998) A comparison of three delay models for signalized controlled intersections, *Proceedings of the 3rd International Symposium on Highway Capacity*, Copenhagen, Denmark, 22-27 June 1998, pp. 35-56.
- Akçelik, R. (2000) *Extract From: aaSIDRA User Guide*, Akçelik & Associates Pty Ltd, Greythorn, Victoria, Australia, September 2000, Confidential.
- Akçelik, R. & Besley, M. (2003) Operating cost, fuel consumption and emission models in aaSIDRA and aaMOTION, *Proceedings of the 25th Conference of Australian Institutes of Transport Research (CAITR 2003)*, Adelaide, 3-5 December 2003, pp. 1-15.
- Al-Suleiman, T.I. & Al-Khateeb, G.G. (1996) Effect of traffic movement and delay on air pollution, *Road & Transport Research*, Vol. 5, No.4, pp. 84-98.
- An, F. & Ross, M. (1993a) A model of fuel economy and driving patterns, *SAE Technical Paper Series*, Paper No. 930328, pp. 63-79.
- An, F. & Ross, M. (1993b) The use of fuel by spark ignition engines, *SAE Technical Paper*, Paper No. 930329, pp. 81-90.
- An, F. & Ross, M. (1993c) Model of fuel economy with applications to driving cycles and traffic management, *Transport Research Record*, No. 1416, pp. 105-114.
- An, F., Barth, M. & Norbeck, J. (1996) A comparison between emission speed correction factors and vehicle fuel consumption, *Proceedings of the 6th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, 18 March 1996, pp. 2.23-2.40.
- An, F., Barth, M., Scora, G. & Younglove, T. (1996) Catalyst cold-start characterization and modeling, *Proceedings of the 6th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, 18 March 1996, pp. 2.1-2.21.

- An, F., Barth, M. & Norbeck, J. (1997) Development of a comprehensive modal emissions model: Operating under hot-stabilized conditions, *Transportation Research Record*, No. 1587, pp. 52-62.
- An, F., Barth, M., Scora, G. & Ross, M. (1998) Modelling enleanment emissions for light-duty vehicles, *Transportation Research Record*, No. 1641, Washington, USA, TRB Paper 981287, pp. 48-57.
- Anderson, W.P., Pavlos, S.K., Miller, E.J. & Buliung, R.N. (1996) Simulating automobile emissions in an integrated urban model, *Transportation Research Record*, No. 1520, pp. 71-80.
- André, M., Hickman, J., Hassel, D. & Joumard, R. (1995) Driving cycles for emission measurements under European conditions, *SAE Technical Paper Series*, Paper No. 950926, Society of Automative Engineers Inc., Warrendale, PA, USA.
- André, M. & Pronello, C. (1996) Speed and acceleration impact on pollutant emissions, *SAE Technical Paper Series*, No. 961113, pp. 1-8.
- André, M. & Pronello, C. (1997) Relative influence of acceleration and speed on emissions under actual driving conditions, *Int. J. Vehicle Design*, Vol. 18, No. 3/4 , Special Issue, pp. 340-353.
- ARRB (1990) *Calibrating SIDRA*, Australian Road Research Board, by Akçelik, R., ARR Research Report No. 180.
- AS (1999) *Manual of Uniform Traffic Control Devices – Part 4: Speed Controls*, Australian Standard, AS 1742.4.
- Atjay, D.E., Weilenmann, M. & Soltic, P. (2005) Towards accurate instantaneous emission models, *Atmospheric Environment*, Vol. 39, pp. 2443-2449.
- Austin, T.C., DiGenova, F.J., Carlson, T.R., Joy, R.W., Gianolini, K.A. & Lee, J.M. (1993) *Charactization of Driving Patterns and Emissions from Light-Duty Vehicles in California*, Prepared by Sierra Research for California Air Resources Board, Final report, Contract No. A932-185, November, 1993.
- Austroads (1988b) *Guide to Traffic Engineering Practice - Part 2 Roadway Capacity*, Sydney, NSW, Australia, ISBN 0 85588 233 9.
- Austroads (1993) *Guide to Traffic Engineering Practice - Part 7 Traffic Signals*, Sydney, NSW, Australia, ISBN 0 85588 436 3.

- Austroads (2000) *Roadfacts 2000 - An Overview of the Australian and the New Zealand Road Systems*, Austroads Incorporated, Sydney, Australia, ISBN 0 85588 484 3.
- Bachman, W., Sarasua, W. & Guensler, R. (1996) Geographic Information System framework for modeling mobile-source emissions, *Transport Research Record*, No. 1551, pp. 123-132.
- Barceló, J. (2002) Dynamic network simulation with AIMSUN, Yokohama Symposium, <http://www.tss-bcn.com>, pp. 1-24.
- Barth, M., An, F., Norbeck, J. & Ross, M. (1996) Modal emission modeling: A physical approach, *Transportation Research Record*, No. 1520, pp. 81-88.
- Barth, M.J., Johnston, E. & Tadi, R.R. (1996) Using GPS technology to relate macroscopic and microscopic traffic parameters, *Transportation Research Record*, No. 1520, pp. 89-96.
- Barth, M., Malcolm, C., Younglove, T. & Hill, N. (2001) Recent validation efforts for a comprehensive modal emissions model, *Transportation Research Record*, No. 1750, pp. 13-23.
- BCC (2000) *Brisbane City Council Road Hierarchy Plan*, Brisbane City Council (BCC), March 2000, Rev 0001.
- BCC & ABACUS Surveys (2000) 2000 Annual Travel Time Survey - Main Report, Annual Road Network Performance Study, Brisbane City Council, Brisbane.
- BCC/QGEPA (2004) *Air Emissions Inventory South-East Queensland Region*, Brisbane City Council and Queensland Government Environmental Protection Agency.
- Beamon, B.M. & Griffin, P.M. (1999) A simulation based methodology for analyzing congestion and emissions on a transportation network, *Simulation*, Vol. 72, No. 2, pp. 105-114.
- Beard, C.L. & McLean, J.R. (1974) Speed flow relationship for nine 4-lane roads in Melbourne, *Proceedings of the 7th ARRB Conference*, Vol. 7, No. 4, pp. 39-53.
- Bell, M.G.H. & Lida, Y. (1997) *Transport Network Analysis*, John Wiley & Sons Ltd., Chichester, England, ISBN 0 471 96493 X.
- Benson, P.E. (1992) A review of the development and application of the CALINE3 and 4 models, *Atmospheric Environment*, Vol. 26B, No. 3, pp. 379-390.

- Berka, S. & Boyce, D.E. (1994) Implementation and solution of a large asymmetric network equilibrium model, *Paper presented at Tristan 2 Conference*, The Triennial Symposium on Transportation Analysis, Capri, Italy, <http://ais.its-program.anl.gov/advance/reports/REPORTS.HTML/adv36/index.html>.
- Berry, D.S. (1987) Using the volume-capacity ratio to supplement delay criteria at traffic signals, *Transportation Research Record*, No. 1112, pp. 23-28.
- Biggs, D.C. & Akçelik, R. (1985) *Further Work on Modelling Car Fuel Consumption*, Australian Road Research Board, Internal Report AIR 390-10.
- Biggs, D.C. & Akçelik, R. (1986) An energy-related model of instantaneous fuel consumption, *Traffic Engineering + Control*, Vol. 27, pp. 320-325.
- Borrego, C., Tchepel, O., Barros, N. & Miranda, A.I. (2000) Impact of road traffic emissions on air quality of the Lisbon region, *Atmospheric Environment*, Vol. 34, pp. 4683-4690.
- Borrego, C., Tchepel, O., Costa, A.M., Amorim, J.H. & Miranda, A.I. (2003) Emission and dispersion modelling of Lisbon air quality at local scale, *Atmospheric Environment*, Vol. 37, pp. 5197-5205.
- Bosch, R. (2000) *Automotive Handbook*, 5th Edition, Robert Bosch GmbH, Stuttgart, Germany, ISBN 0 8376 0614 4.
- Bovy, P.H.L. & Salomon, I. (1999) *Traffic Congestion in Europe*, Economic Research Centre, Report of the 110th Round Table of Transport Economics, European Conference of Ministers of Transport, Paris, France, 12-13 March 1998, OECD Publications Service, ISBN 92-821-1248-9, pp. 85-153.
- Bowyer, D.P., Akçelik, R. & Biggs, D.C. (1985) *Guide to Fuel Consumption Analyses for Urban Traffic Management*, ARRB Transport Research Ltd, Sydney, Australia, Report ARRB SR32, ISBN 0 86910 220 6.
- Boyce, D.E., Janson, G.N. & Eash, R.W. (1981) The effect of equilibrium trip assignment of different link congestion functions, *Transpn Res.-A*, Vol. 15A, No. 3, pp. 223-232.
- Brackstone, M. & MacDonald, M. (1999) Car-following: a historical review, *Transportation Research Part F*, Vol. 2, pp. 181-196.

- Brindle, R., Ashley, D., Johnston, D., Milthorpe, F., Smith, N., Taylor, M.A.P. & Young, W. (2000) *Improving Urban Transport Demand Models and Their Use*, Austroads, Sydney, Australia, Report AP-R164/00, ISBN 0 85588 551 3.
- Brown, A.L. & Affum, J.K. (2002) A GIS-based environmental modelling system for transportation planners, *Computers, Environment and Urban Systems*, Vol. 26, pp. 577-590.
- BTCE (1995) *Urban Congestion: Modelling Traffic Patterns, Delays and Optimal Tolls*, Bureau of Transport and Communications Economics, Commonwealth of Australia, Canberra, Australia, ISBN 0 642 22679 2.
- BTCE (1996) *Traffic Congestion and Road User Charges in Australian Capital Cities*, Bureau of Transport and Communications Economics, Commonwealth of Australia, Canberra, Australia, BTCE Report 92, ISBN 0 644 36066 6.
- BTE (1998) *Urban Transport Models: A Review*, Bureau of Transport Economics, Department of Transport and Regional Services, Canberra, Australia, Working Paper 39, ISBN 0 642 28305 2.
- BTE (2000) Urban congestion – the implications for greenhouse gas emissions, by Cosgrove, D., *Bureau of Transport Economics*, Canberra, ACT, Australia, Information Sheet 16, pp. 1-4.
- Buckland, A.T. & Middleton, D.R. (1999) Nomograms for calculating pollution within street canyons, *Atmospheric Environment*, Vol. 33, pp. 1017-1036.
- Bullock, P., Stopher, P., Pointer, G. & Jiang, Q. (2003) *GPS Measurements of Travel Times, Driving Cycles, and Congestion*, Institute of Transport Studies (ITS), University of Sydney, Australia, Working Paper ITS-WP-03-07, ISSN 1440 3501.
- Burmich, P. (1989) *The Air Pollution-Transportation Linkage: How Vehicle Travel on our Roads and Highways Affects the Air We Breathe*, California Air Resources Board (CARB), USA.
- Campbell, E.W., Keefer, L.E. & Adams, R.W. (1959) A method for predicting speeds throughout signalised street sections, *Highw. Res. Bd. Bulletin*, Vol. 230, pp. 112-115.
- CARB (2000) *Public Meeting to Consider Approval of Revisions to the State's On-Road Motor Vehicle Emissions Inventory – Technical Support Document*, California

Air Resources Board, May 2000, http://www.arb.ca.gov/msei/on-road/doctable_test.htm.

- CARB (2002) EMFAC 2002, *California Air Resources Board's Emission Inventory Series*, September, 2002, http://www.arb.ca.gov/msei/on-road/latest_version.htm, pp. 1-12.
- Carnovale, F., Alviano, P., Carvalho, C., Deitch, G., Jiang S., Macaulay D. & Summers, M. (1992) Air emissions inventory for the Port Phillip control region, *Clean Air*, Vol. 26/4, pp. 134-144.
- Carr, D., Von Ehrenstein, O., Weiland, S., Wagner, C., Wellie, O., Nicolai, T. & Von Mutius, E. (2002) Modelling annual benzene, toluene, NO₂, and soot concentrations on the basis of road traffic characteristics, *Environmental Research Section A*, Vol. 90, pp. 111-118.
- Carslaw, D.C. & Beevers, S.D. (2002) The efficacy of low emission zones in central London as a means of reducing nitrogen dioxide concentrations, *Transpn. Res.-D*, Vol. 7, pp. 49-64.
- CERC (2003a) ADMS-Urban and ADMS-Roads validation, <http://www.cerc.co.uk/software/publications.htm>, pp. 1-8.
- CERC (2003b) ADMS-Roads validation, <http://www.cerc.co.uk/software/publications.htm>, pp. 1-8.
- Cernuschi, S., Giugliano, M., Cemin, A. & Giovannini, I. (1995) Modal analysis of vehicle emission factors, *The Science of the Total Environment*, Elsevier Science BV, Vol. 169, pp. 175-183.
- Chang, M.F. & Herman, R. (1978) An attempt to characterize traffic in metropolitan areas, *Transportation Science*, Vol. 12, No. 1, pp. 58-79.
- Chang, M.F. & Horowitz, A.J. (1979) Estimates of fuel savings through improved traffic flow in seven US cities, *Traffic Engineering & Control*, Vol. 20, No. 2, pp. 62-65.
- Cicero-Fernández, P., Long, J.R. & Winer, A.M. (1997) Effects of grades and other loads on on-road emissions of hydrocarbons and carbon monoxide, *J. Air & Waste Manage. Assoc.*, Vol. 47, pp. 898-904.
- Claggett, M., Shrock, J. & Noll, K.E. (1981) Carbon monoxide near an urban intersection, *Atmospheric Environment*, Vol. 15, No. 9, pp. 1633-1642.

- CoA (1984a) *Australian Design Rule 27 for Vehicle Emission Control*, Commonwealth of Australia, Australian Transport Advisory Council, Department of Transport, February 1984, ACT 2608, Australia.
- CoA (1984b) *Australian Design Rule 27A for Vehicle Emission Control*, Commonwealth of Australia, Australian Transport Advisory Council, Department of Transport, February 1984, ACT 2608, Australia.
- CoA (1984c) *Australian Design Rule 27B for Vehicle Emission Control*, Commonwealth of Australia, Australian Transport Advisory Council, Department of Transport, February 1984, ACT 2608, Australia.
- Colville, R.N., Hutchinson, E.J., Mindell, J.S. & Warren, R.F. (2001) The transport sector as a source of air pollution, *Atmospheric Environment*, Vol. 35, pp. 1537-1565.
- CONCAWE (1999) *Fuel Quality, Vehicle Technology and Their Interactions*, CONCAWE, by McArragher, J.S., Becker, R.F., Bennett, P.J., Claus, G., Graham, J., Lang, G., Van Leeuwen, C.J., Rickeard, D., Schuermann, F. & Heinze, P., Brussels, Belgium, Report No. 99/55.
- Corvalán, R.M., Osses, M. & Urrutia, C.M. (2002) Hot emission model for mobile sources: application to the metropolitan region of the city of Santiago, Chile, *J. Air & Waste Management*, Vol. 52, No. 2, pp. 167-174.
- Cottrell, W.D. (1992) Comparison of vehicular emissions in free-flow and congestion using MOBILE4 and Highway Performance Monitoring System, *Transportation Research Record*, No. 1366, pp. 75-82.
- Cottrell, W.D. (1998) Estimating the probability of freeway congestion recurrence, *Transportation Research Record*, No. 1634, pp. 19-27.
- Daniel, J.I. & Bekka, K. (2000) The environmental impact of highway congestion pricing, *Journal of Urban Economics*, Vol. 47, pp. 180-215.
- Dargay, J.M. & Goodwin, P.B. (1999) *Traffic Congestion in Europe*, Economic Research Centre, Report of the 110th Round Table of Transport Economics, European Conference of Ministers of Transport, Paris, France, 12-13 March 1998, OECD Publications Service, ISBN 92-821-1248-9, pp. 155-200.
- Davidson, K.B. (1966) A flow travel time relationship for use in transportation planning, *Proceedings of 3rd ARRB Conference*, Vol. 1, pp. 183-194.

- Davidson, K.B. (1978a) The theoretical basis of a flow travel time relationship for use in transportation planning, *Australian Road Research*, Vol. 8, No. 1, pp. 32-35.
- Davidson, K.B. (1978b) Letter to the editor, *Australian Road Research*, Vol. 8, No. 1, p. 45.
- DeCorla-Souza, P. & Schoeneberg, R. (1992) The transportation-air quality connection: perceptions and realities, *Compendium of Technical Papers – ITE Annual Meeting*, Institute of Transportation Engineers (ITE), Washington D.C., USA, pp. 157-162.
- De Haan, P. & Keller, M. (2000) Emission factors for passenger cars: application of instantaneous emission modelling, *Atmospheric Environment*, Vol. 34, pp. 4629-4638.
- De Vlieger, I., De Keukeleere, D. & Kretzschmar, J.G. (2000) Environmental effects of driving behaviour and congestion related to passenger cars, *Atmospheric Environment*, Vol. 34, pp. 4649-4655.
- Dick, A.C. (1966) Speed/flow relationships within an urban area, *Traffic Engineering & Control*, Vol. 8, No. 6, pp. 393-396.
- Dickey, J.H. (2000) Selected topics related to occupational exposures - Part VII: air pollution: overview of sources and health, *DM Disease-A-Month*, Vol. 46, No. 9, September 2000, pp. 566-589.
- Dijker, T., Bovy, P.H.L. & Vermijs, R.G.M.M. (1998) Car-following under congested conditions - empirical findings, *Transportation Research Record*, No. 1644, TRB Paper 980891, pp. 20-28.
- Donaghy, K.P. & Schintler, L.A. (1998) Managing congestion, pollution and pavement conditions in a dynamic transportation network model, *Transpn. Res.-D*, Vol. 3, No. 2, pp. 59-80.
- DoTRS (2001) *Comparative Vehicle Emissions Study*, Commonwealth Department of Transport and Regional Services, Canberra, Australia, ISBN 0 642 45684 4.
- Dougherty, M.S., Kirby, H.R. & Boyle, R.D. (1993) The use of neural networks to recognise and predict traffic congestion, *Traffic Engineering + Control*, Vol. 34, No. 11, pp. 311-314.

- Dowling, R. & Skabardonis, A. (1992) Improving the average travel speeds estimated by planning models, *Transportation Research Record*, No. 1366, Washington, USA, pp. 68-74.
- Dowling, R.G., Singh, R. & Cheng, W.W.K. (1998) The accuracy and performance of improved speed-flow curves, *Road Transport Research*, Vol. 7, No. 2, pp. 36-51.
- Duffy, B.L. & Nelson, P.F. (1996) Non-methane exhaust composition in the Sydney Harbour Tunnel: A focus on benzene and 1,3 butadiene, *Atmospheric Environment*, Vol. 30, No. 15, pp. 2759-2768.
- EA (2000) *NPI Emissions Estimation Technique Manual for Aggregated Emissions from Motor Vehicles*, Version 1.0, Environment Australia, 22 November 2000, Australia.
- EC (1995) *ESTEEM - European Scenarios on Transport-Energy-Environment for Metropolitan Areas*, The European Commission, Final Report, Contract No. JOE3-CT95-0016.
- EC (1998) *Methodologies for Estimating Air Pollutant Emissions from Transport - Average Hot Emission Factors for Passenger Cars and Light Duty Trucks – Deliverable No. 7*, European Commission – Transport RTD Programme of the 4th Framework Programme, by Samaras, Z. & Ntziachristos, L., Aristotle University Thessaloniki, LAT Report No. 9811.
- EC (2000) *SMARTTEST*, The European Commission, Transport RTD Programme of the 4th Framework Programme, Final Report, Contract No. RO-97-SC.1059.
- EC (2004) *Comparative Study of Road Traffic Rules and Corresponding Enforcement Actions in the Member States of the European Union*, European Commission, Directorate General Energy and Transport, http://europa.eu.int/comm/transport/road/publications/trafficrules/reports/rtr_final_en.pdf
- EEA (2000) *COPERT III Computer Programme to Calculate Emissions From Road Transport - Methodology and Emissions Factors (Version 2.1)*, European Environment Agency, Copenhagen, by Ntziachristos, L., Samaras, Z., Eggleston, S., Gorissen, N., Hassel, D., Hickman, A.-J., Joumard, R., Rijkeboer, R., White, L. & Zierock, K.-H., November 2000, Technical Report No. 49, <http://vergina.eng.auth.gr/mech/lat/copert/copert.htm>.

- Effa, R.C. & Larsen, L.C (1994) Development of real-world driving cycles for estimating facility-specific emissions from light-duty vehicles, *The Emission Inventory: Perception And Reality*, Air & Waste Management Association, pp. 549-568.
- Eggleston, H.S., Gorissen, N., Joumard, R., Rijkeboer, R.C., Samaras, Z. & Zierock, K.-H. (1988) *CORINAIR Working Group on Emission Factors for Calculating 1985 Emissions from Road Traffic, Volume 1: Methodology and Emission Factors*, Final Report No. EUR 12260, Contract No. 88/661/0067, Commission of the European Communities, ECSC-EEC-EAEC, Brussels, Luxembourg.
- Eggleston, H.S., Gaudioso, D., Gorissen, N., Joumard, R., Rijkeboer, R.C., Samaras, Z. & Zierock, K.-H. (1993) *CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 1: Methodology and Emission Factors*, Final Report, Commission of the European Communities, ECSC-EEC-EAEC, Brussels, Luxembourg, ISBN 92 826 5771 X.
- Eissfeldt, N., Metzler, M. & Wagner, P. (2000) Dynamic simulation of traffic and its environmental impact, *Proceedings of 9th IFAC Symposium on Control Transportation Systems*, Vol. 1, No. 392.
- Eissfeldt, N. & Schrader, R. (2002) Calculation of street traffic emissions with a queuing model, *Journal of Computational Technologies*, September 2002, Vol. 7, pp. 1-10.
- Eissfeldt, N., Lubrichs, M. & Sentuc, F.N. (2002a) A breath of fresh air, *Traffic Technology International*, August/September 2002, pp. 76-80.
- Eissfeldt, N., Lubrichs, M. & Sentuc, F.N. (2002b) Investigating emissions of traffic by simulation, *Unpublished Paper*, pp. 1-5.
- Ellis, K., McHugh, C., Carruthers, D. & Stidworthy, A. (2001) Comparison of ADMS-Roads, CALINE 4 and UK DMRB model predictions for roads, *Proceedings of the 7th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Belgirate, Italy, 28-31 May 2001, pp. 1-8.
- Elst, D.A.M.M., Smokers, R.T.M. & De Koning, J.W. (2004) *Evaluation of the Capabilities of On-Board Emission Measurement System for the Purpose of Generating Real-Life Emission Factors*, TNO Report 04.OR.VM.039.1/DE.

- Enns, P., German, J. & Markey, J. (1994) EPA's survey of in-use driving patterns: implications for mobile source emission inventories, *The Emission Inventory: Perception and Reality*, Air & Waste Management Association, pp. 523-534.
- EPAV (1999) *Measurement of Motor Vehicle Pollutants and Fleet Average Emission Factors in Melbourne*, Environment Protection Authority State Government of Victoria, Melbourne, Victoria, Australia, Publication 652, ISBN 0 7306 7556 4.
- Ericsson, E. (2000) *Urban Driving Patterns – Characterisation, Variability and Environmental Implications*, Ph.D. Thesis (Unpublished), Lund University, Bulletin 186, Sweden.
- Evans, L., Herman, R. & Lam, T. (1976) Multivariate analysis of traffic factors related to fuel consumption in urban driving, *Transpn Sci.*, Vol. 10, pp. 205-215.
- Evans, L. (1978) Urban traffic, fuel economy and emissions – consistency of various measurements, *SAE Technical Paper Series*, Paper No. 780934, pp. 1-11.
- Faiz, A., Weaver, C.S. & Walsh, M.P. (1996) *Air pollution from Motor Vehicles - Standards and Technologies for Controlling Emissions*, The World Bank, Washington D.C., ISBN 0-8213-3444-1.
- Fenger, J. (1999) Urban air quality, *Atmospheric Environment*, Vol. 33, pp. 4877-4900.
- Festa, D.C. & Mazzulla, G. (2002) A new simulation model of fuel consumption and pollutant emissions in urban traffic, *Proceedings of the 8th International Conference on Urban Transport and the Environment in the 21st Century*, Wit Press, U.K., ISBN 1 85312 905 4, pp. 581-592.
- FHWA (1989) *CALINE 4 - A Dispersion Model for Predicting Air Pollutant Concentrations Near Roadways*, Federal Highway Administration (FHWA), by P.E. Benson, California Department of Transportation, Sacramento, California, Report No. FHWA/CA/TL-84/15.
- FHWA (1992a) *An Evaluation of Congestion-Reducing Measures Used in Virginia*, Federal Highway Administration (FHWA), by Arnold, E.D., Virginia Transportation Research Council, Charlottesville, Virginia, USA, Report No. FHWA/VA-93-R7.
- FHWA (1992b) *INFORM Evaluation, Volume I: Technical Report*, Federal Highway Administration (FHWA), US Department of Transportation, by Smith, S.A., FHWA/RD Report No. 91-075.

- Fomunung, I., Washington, S. & Guensler, R. (1999) A statistical model for estimating oxides of nitrogen emissions from light-duty vehicles, *Transpn. Res.-D*, Vol. 4, No. 5, pp. 333-352.
- Fomunung, I., Washington, S., Guensler, R. & Bachman, W. (2000) Validation of the MEASURE automobile emissions model: a statistical analysis, *Journal of Transportation and Statistics*, September 2000, pp. 65-84.
- FORS (1996) *Motor Vehicle Pollution in Australia - Report on the National In-Service Vehicle Emissions Study*, Federal Office of Road Safety, by Anyon, P., Jones, D., Jamieson, R. & Real, J., Canberra, ACT2601, Australia, May 1996.
- Frey, H.C. & Patil, S.R. (2001) *Identification and Review of Sensitivity Analysis Methods*, NCSU/USDA Workshop on Sensitivity Analysis Methods, 11-12 June 2001, North Carolina State University.
- Frey, H.C., Unal, A. & Chen, J. (2002) *Recommended Strategy for On-Board Emission Data Analysis and Collection for the New Generation Model*, Computational Laboratory for Energy, Air and Risk, North Carolina State University, Prepared for US EPA, Office of Transportation and Air Quality, 4 February 2002.
- Fujita, E.M., Croes, B.E., Bennett, C.L. & Lawson, D.R. (1992) Comparison of emission inventory and ambient concentration ratios of CO, NMOG and NO_x in California's South Coast Air Basin, *J. Air Waste Manage. Assoc.*, Vol. 42, pp. 264-276.
- Gammariello, R.T. & Long, J.R. (1996) Development of Unified Correction Cycles, *Proceedings of the 6th CRC On-Road Vehicle Emissions Workshop*, San Diego, California, 18 March 1996, pp. 4.15-4.29.
- Gawron, C. (1998) An iterative algorithm to determine the dynamic user equilibrium in a traffic simulation model, *International Journal of Modern Physics C*, Vol. 9, No. 3, pp. 393-407.
- Gerlough, D.L. & Huber, M.J. (1975) *Traffic Flow Theory - A Monograph*, Transportation Research Board, National Research Council, Washington D.C., USA, Special Report No. 165, ISBN 0 309 02459 5.
- Gipps, P.G. (1984) *Traffic Flow Theory*, Monash Series of Short Courses, Department of Civil Engineering, Monash University, ISBN 0 86746 336 8.

- Golding, S. (1977) Discussion on Davidson's flow-rate/travel time relationships, *Australian Road Research*, Vol. 7, No. 3, pp. 36-37.
- Grant, C., Gillis, B & Guensler, R. (2000) Collection of vehicle activity data by video detection for use in transportation planning, *ITS Journal*, Vol. 5, No. 4, pp. 346-361.
- Greenshields, B.D. (1955) Quality of traffic transmission, *Proceedings of 34th Annual Meeting of the Highway Research Board*, National Research Council, Washington D.C., USA, pp. 508-522.
- Greenshields, B.D. (1965) Driveometer determines quality of traffic flow for engineers, *Traffic Engineering*, Vol. 36, No. 2, pp. 28-61.
- Greenwood, I.D. & Bennett, C.R. (1996) The effects of traffic congestion on fuel consumption, *Road and Transport Research*, Vol. 5, No. 2, pp. 18-32.
- Greenwood, I.D., Dunn, R.C.M. & Raine, R.R. (1998) Predicting non-steady speed driving, *Proceedings of the 19th ARRB Transport Research Ltd Conference*, Sydney, New South Wales, Australia, pp. 136-151.
- Greenwood, I.D. (2003) *A New Approach to Estimate Congestion Impacts for Highway Evaluation – Effects on Fuel Consumption and Vehicle Emissions*, Ph.D. Dissertation, Unpublished, University of Auckland, New Zealand.
- Gualtieri, G. & Tartaglia, M. (1998) Predicting urban air pollution: a GIS framework, *Transpn. Res.-D*, Vol. 3, No. 5, pp. 329-336.
- Hall, M.D., Van Vliet, D. & Willumsen, L.G. (1980) SATURN - a simulation-assignment model for the evaluation of traffic management schemes, *Traffic Engineering & Control*, Vol. 21, No. 4, pp. 168-176.
- Hallmark, S.L. & Guensler, R. (1999) Comparison of speed/acceleration profiles from field data with NETSIM output for modal air quality analysis of signalised intersections, *Transportation Research Record*, No. 1664, pp. 40-46.
- Hamilton, R.B. (1977) The consequences of the large congested city on energy for road transport, *Proceedings of Transportation Conference The Way Ahead: New Cities Or Bigger Cities*, National Conference Publication 77/10, Orange, New South Wales, Australia, pp 31-36.
- Hansen, J.Q., Winther, M. & Sorenson, S.C. (1995) The influence of driving patterns on petrol passenger car emissions, *The Science of the Total Environment*, Vol. 169, pp. 129-139.

- Hao, J., He, D., Wu, Y., Fu, L. & He, K. (2000) A study of the emissions and concentrations distribution of vehicular pollutants in the urban area of Beijing, *Atmospheric Environment*, Vol. 34, pp. 453-465.
- Harkey, D.L., Robertson, H.D. & Davis, S.E. (1990) Assessment of current speed zoning criteria, *Transportation Research Record*, No. 1281, pp. 40-51.
- Harley, R.A., Russell, A.G., McRae, G.J., Cass, G.R. & Seinfeld, J.H. (1993) Photochemical smog modelling of the Southern California Air Quality Study, *Environ. Sci. Technol.*, Vol. 27, pp. 378-388.
- Harssema, H. (1987) *Modelling and Measurement of Air Quality (In Dutch: Berekenen en Meten van de Luchtkwaliteit)*, Wageningen Agricultural University, Wageningen, The Netherlands, Report No. R-200.
- Hausberger, S., Rodler, J., Sturm, P. & Rexeis, M. (2003) Emission factors for heavy-duty vehicles and validation by tunnel measurements, *Atmospheric Environment*, Vol. 37, pp. 5237-5245.
- Helali, K. & Hutchinson, B. (1994) Improving Road link speed estimates for air quality models, *Transportation Research Record*, No. 1444, pp. 71-78.
- Hellinga, B. (2002) Improving freeway speed estimates from single-loop detectors, *Journal of Transportation Engineering*, Vol. 128, No. 1, pp. 58-67.
- Hensher, D.A. & Button, K.J. (Eds.) (2000) *Handbook of Transport Modelling*, 1st Edition, Elsevier Science Ltd., Oxford, U.K., ISBN 0 08 043594 7.
- Herman, R. & Lam, T. (1974) Trip time characteristics of journeys to and from work, *Proceedings of the 6th International Symposium on Transportation and Traffic Flow*, Sydney, In D.J. Buckley (Ed.) "Transportation and Traffic Theory", pp. 57-85.
- Heywood, J.B. (1988) *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York, ISBN 0 07 100499 8.
- Heywood, J.B. (1997) Motor vehicle emissions control: past achievements, future prospects, *1997 George Stephenson Lecture*, Institution of Mechanical Engineers, pp. 1-14.
- Hickman, A.J. & Graham, M.A. (1993) Performance related exhaust emissions from heavy duty diesel engines, *The Science of the Total Environment*, Vol. 134, pp. 211-223.

- Hidas, P. (1998) A car following model for urban traffic simulation, *Traffic Engineering + Control*, Vol. 39, No. 5, pp. 300-309.
- Horowitz, A.J. (1997) Intersection delay in regionwide traffic assignment: implications of the 1994 update for the Highway Capacity Manual, *Transportation Research Record*, No. 1572, Paper No. 970463, pp. 1-8.
- Horowitz, J.L. (1982) *Air Quality Analysis for Urban Transportation Planning*, The MIT Press, The Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA, ISBN 0 262 08116 4.
- Hounsell, N.B. & McDonald, M. (2001) Urban network traffic control, *Proceedings Instn. Mech. Engrs.*, Vol. 215, part I, pp. 325-334.
- Ingham, D.J. (1992) Improving the urban environment by means of traffic engineering techniques, *The Civil Engineer in South Africa*, Vol. 34, No. 9, pp. 303-308.
- INRETS (1998) *The Inspection of In-Use Cars in order to Attain Minimum Emissions of Pollutants and Optimum Energy Efficiency – Development of Short Driving Cycles*, by André, M., Hassel, D. & Weber, F.-J., Detailed Report No. 2 (LEN 9809).
- INRETS (1999a) *Methods of Estimation of Atmospheric Emissions from Transport: European Scientist Network and Scientific State-of-the-Art - Action COST 319 Final Report*, Institut National de Recherche sur les Transports et leur Sécurité (INRETS), France, by Joumard, R. (Ed.), Report No. LTE 9901.
- INRETS (1999b) *Modelling of Cold Start Emissions for Passenger Cars*, Institut National de Recherche sur les Transports et leur Sécurité (INRETS), France, by Joumard, R. & Sérié, E., MEET Deliverable No. 8, COST319 Action, Report No. LTE 9931.
- IPCC (1996) *Revised IPCC Guidelines for National Greenhouse Gas Inventories – Reference Manual*, Vol. 3, by Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, I., Griggs, D.J. & Callender, B.A. (Eds.), <http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.htm>.
- Iverach, D., Mongan, T.R., Nielsen, N.J. & Formby, J.R. (1976) Vehicle related air pollution in Sydney, *Journal of the Air Pollution Control Association*, Vol. 26, No. 1, pp. 39-44.

- Jones, T.R. & Potts, R.B. (1962) The measurement of acceleration noise – a traffic parameter, *Operations Research*, Vol. 10, pp. 745-763.
- Joumard, R., Jost, P., Hickman, J. and Hassel, D. (1995) Hot passenger car emissions as a function of instantaneous speed and acceleration, *The Science of the Total Environment*, Vol. 169, pp. 167-174.
- Joumard, R., Jost, P. & Hickman, J. (1995) Influence of instantaneous speed and acceleration on hot passenger car emissions and fuel consumption, *SAE Technical Paper Series*, Paper No. 950928, pp. 207-214.
- Keenan, M. & Escarpeta, D. (1994) Development of a base year on-road mobile source emission inventory for New York State and its application for UAM modelling and examining VOC/NOx emission ratios, *Proceedings of International Specialty Conference*, Raleigh, NC, 1-3 November 1994, Pittsburgh, Air & Waste Management Association, USA.
- Keller, M. (2005) ARTEMIS/COST 346 Fleet Emission Model, *Proceedings of the 14th Symposium Transport and Air Pollution*, Vol. 1, 1-3 June 2005, Graz, Austria, ISBN 3 902465 16 6, pp. 193-200.
- Kelly, N.A. & Groblicki, P.J. (1993) Real-world emissions from a modern production vehicle driven in Los Angeles, *J. Air & Waste Manage. Assoc.*, Vol. 43, pp. 1351-1357.
- Kent, J.H. & Mudford, N.R. (1979) Motor vehicle emissions and fuel consumption modelling, *Transpn. Res.-A*, Vol. 13, pp. 395-406.
- Kent, J.H., Post, K. & Tomlin, J.A. (1982) Fuel consumption and emission modelling in traffic links, *Proceedings of SAE-A/ARRB 2nd Conference on Traffic Energy and Emissions*, Paper No. 82140, pp. 10.1-10.20.
- Kenworthy, J.R. & Laube, F.B. (Eds.) (1999) *An International Sourcebook of Automobile Dependence in Cities, 1960-1990*, The University Press of Colorado, by Kenworthy, J.R., Laube, F.B., Newman, P., Barter, P., Raad, T., Pobooc, C. & Guia, B., ISBN 0 87081 523 7.
- Keppel, K., Pamuk, E. & Lynch, J. et al. (2005) *Methodological Issues in Measuring Health Disparities*, National Center for Health Statistics, Vital and Health Statistics Series 2, No. 141.

- Koupal, J. & German, J. (1995) Real-time simulation of vehicle emissions using VEMISS, *Proceedings of the 5th CRC On-Road Vehicle Emissions Workshop*, 3-5 April, San Diego, California, USA, pp. 2/65-2/94.
- Kruse, R.E. & Huls, T.A. (1973) Development of the Federal Urban Driving Schedule, *SAE Technical paper Series*, Paper No. 730553, pp. 1-8.
- Kuhns, H.D., Mazzoleni, C., Moosmüller, H., Nikolic, D., Keislar, R.E., Barber, P.W., Li, Z., Etyemezian, V. & Watson, J.G. (2004) Remote sensing of PM, NO, CO and HC emission factors for on-road gasoline and diesel engine vehicles in Las Vegas, NV, *The Science of the Total Environment*, Vol. 322, pp. 123-137.
- Kunselman, P., McAdams, H.T., Domke, C.J. & Williams, M. (1974) *Automobile Exhaust Emissions Modal Analysis Model*, US Environment Protection Agency, Office of Air & Water Programs, Office of Mobile Source and Air Pollution, Report No. EPA-460/3-74-005.
- Kurtzweg, J.A. (1973) Urban planning and air pollution: a review of recent research, *Journal of the American Institute of Planners*, Vol. 39, No. 2, pp. 82-92.
- Kvatch, I.A., Dravitzki, V.K. & Brown, D.N. (1998) On-board vehicle emission measurement technique for the determination effect of route attributes on emission rates, *Proceedings of the 19th ARRB Conference*, ARRB Transport Research Ltd, Sydney, Australia, ISBN 0 86910 782 8, pp. 36-50.
- Laetz, T.J. (1990) Predictions and perceptions – defining the traffic congestion problem, *Technological Forecasting and Social Change*, Vol. 38, pp. 287-292.
- Laurikko, J.K. (1995) Ambient temperature effect on automotive exhaust emissions: FTP and ECE cycle responses, *The Science of the Total Environment*, Vol. 169, pp. 195-204.
- Laurikko, J.K. (1997) Exhaust emissions from motor vehicles in low ambient temperature conditions, *Int. J. of Vehicle Design*, Vol. 18, No. 3-4, Special Issue, pp. 280-292.
- Leblanc, D.C., Meyer, M.D., Saunders, F.M. & MulHolland, J.A. (1994) Carbon monoxide emissions from road driving: evidence of emissions due to power enrichment, *Transportation Research Record*, No. 1444, pp. 126-134.

- Leblanc, D.C., Saunders, M., Meyer, M.D. & Guensler, R. (1995) Driving pattern variability and impacts on vehicle carbon monoxide emissions, *Transportation Research Record*, No. 1472, pp. 45-52.
- Lehmuskosi, V., Niittymäki, J. & Silfverberg, B. (2000) Microscopic simulation on high class roads: enhancement of environmental analyses and driving dynamics: practical applications, *Transportation Research Record*, No. 1706, pp. 73-81.
- Leung, D.Y.C, Lee, B.C.H. & Wong D.M.H. (1997) Assessment of traffic congestion in Hong Kong, and prediction of street-level CO concentration using a graphical screening method, *Int. J. Environment and Pollution*, Vol. 8, No. 3-6, pp. 628-637.
- Leung, D.Y.C. & Williams, D.J. (2000) Modelling of motor vehicle fuel consumption and emissions using a power-based model, *Environmental Monitoring and Assessment*, Vol. 65, pp. 21-29.
- Levinson, H.S. & Lomax, T.J. (1996) A travel time based index for evaluating congestion, *Compendium of Technical Papers for the 66th ITE Annual Meeting*, ITE, Minneapolis, Minnesota, USA , pp. 153-157
- Lighthill, M.J. & Whitlam, G.B. (1955) On kinematic waves: II. A theory of traffic flow on long crowded roads, *Proceedings Royal Society A229*, pp. 317-345.
- Lilley, W.E., Williams, D.J. & Carras, J.N. (2001) *Power-Based Motor Vehicle Emissions Modelling Applied to the Sydney Region*, Final Report for AAQFS Appendix 5.4, CSIRO Energy Technology, North Ryde, NSW, Australia.
- Lin, J. & Niemeier, D.A. (2002) An exploratory analysis comparing a stochastic driving cycle to California's regulatory cycle, *Atmospheric Environment*, Vol. 36, No. 38, pp. 5759-5770.
- Lin, J. & Niemeier, D.A. (2003) Regional driving characteristics, regional driving cycles, *Transpn. Res.-D*, Vol. 8, pp. 361-381.
- Lindley, J.A. (1987) Urban freeway congestion: quantification of the problem and effectiveness of potential solutions, *ITE Journal*, Vol. 57, No. 1, pp. 27-32.
- Lindley, J.A. (1989) Urban freeway congestion problems and solutions: an update, *ITE Journal*, Vol. 59, No. 12, pp. 21-23.
- Lindley, S.J., Conlan, D.E., Raper, D.W. & Watson, A.F.R. (1999) Estimation of spatially resolved road transport emissions for air quality management applications

in the North West region of England, *The Science of the Total Environment*, Vol. 235, pp. 119-132.

- Ludwig, F.L., Sandys, R.C. & Moon, A.E. (1973) Preliminary studies of the modelling of air pollution effects from traffic engineering alternatives, *Journal of the Air Pollution Control Association*, Vol. 23, No. 6, pp. 499-504.
- Luk, J.Y.K. (1992) Queue management and monitoring in urban traffic control systems, *Proceedings of the 7th REAAA Conference*, Singapore, 22-26 June, Vol. 1, pp. 20-28.
- Lyons, G.D., McDonald, M., Hounsell, N.B., Williams, B., Cheese, J. & Radia, B. (1996) Urban traffic management: the viability of short term congestion forecasting using artificial neural networks, *Proceedings of the 24th European Transport Forum*, PTRC, pp. 1-12.
- Lyons, T.J., Kenworthy, J.R. & Newman, P.W.G. (1990) Urban structure and air pollution, *Atmospheric Environment*, Vol. 24B, No. 1, pp. 43-48.
- Magbuhat, S. & Long, J.R. (1996) Improving California's motor vehicle emissions inventory activity estimates through use of datalogger-equipped vehicles, *Proceedings of the 6th CRC On-Road Vehicle Emissions Workshop*, March 18-20, San Diego, pp. 1-15.
- Mahmassani, H.S., Williams, J.C. & Herman, R. (1987) Performance of urban traffic networks, *Proceedings of 10th International Symposium on Transportation and Traffic Theory*, Cambridge, Massachusetts, USA, Gartner, N.H. & Wilson, N.H.M (Eds.), 8-10 July 1987, pp. 1-20.
- Mahmassani, H.S., Jayakrishnan, R. & Herman, R. (1990) Network traffic flow theory: microscopic simulation experiments on supercomputers, *Transpn. Res.-A*, Vol. 24, No. 2, pp. 149-162.
- Marmur, A. & Mamane, Y. (2003) Comparison and evaluation of several mobile-source and line-source models in Israel, *Transpn. Res.-D*, Vol. 8, pp. 249-265.
- Marsden, G., Bell, M. & Reynolds, S. (2001) Towards a real-time microscopic emissions model, *Transpn. Res.-D*, Vol. 6, pp. 37-60.
- Matzoros, T., Van Vliet, D., Randle, J. & Weston, B. (1988) A validation of the SATURN and ME2 models using before-and-after survey data from Manchester, *Traffic Engineering + Control*, Vol. 28, January 1990, pp. 641-643.

- Matzoros, A. (1990) Results from a model of road traffic air pollution, featuring junction effects and vehicle operating modes, *Traffic Engineering + Control*, Vol. 31, No. 1, pp. 24-35.
- Matzoros, A. & Van Vliet, D. (1992) A model of air pollution from road traffic, based on characteristics of interrupted flow and junction control: Part 1 - Model description, *Transpn. Res.-A*, Vol. 26, No. 4, pp. 315-330.
- May, A.D. (1990) *Traffic Flow Fundamentals*, Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA, ISBN 0 13 926072 2.
- Menon, A.P.G., Tierney, A.J.H., Blunden, W.R. & Tindall, J.I. (1974) A study on Davidson's flow travel time relationship, *Proceedings of the 7th ARRB Conference*, Vol. 7, No. 4, pp. 5-20.
- Mensink, C. & De Vlieger, I. (1998) Regional-scale modelling of acidification associated with road transport and road transport scenarios, *Int. J. of Vehicle Design*, Vol. 20, No. 1-4, pp. 335-343.
- Mensink, C., De Vlieger, I. & Nys, J. (2000) An urban transport emission model for the Antwerp area, *Atmospheric Environment*, Vol. 34, pp. 4595-4602.
- Mensink, C., Bomans, B. & Janssen, L. (2001) An assessment of urban VOC emissions and concentrations by comparing model results and measurements, *Int. J. Environment and Pollution*, Vol. 16, No. 1-6, pp. 345-356.
- Metz, N., Schlichter, H. & Schellenberg, H. (1997) Positive effects of a traffic control system on fuel consumption and exhaust emissions on the German A9 autoban, *Int. J. of Veh. Design*, Vol. 18, No. 3/4, pp. 354-367.
- Miguel, A.H., Kirchstetter, T.W. & Harley, R.A. (1998) On-road emissions of particulate polycyclic aromatic hydrocarbons and black carbon from gasoline and diesel vehicles, *Environ. Sci. Technol.*, Vol. 32, No. 4, pp. 450-455.
- Miller, A.J. (1963) Settings for fixed-cycle traffic signals, *Operational Research Quarterly*, Vol. 14, No. 4, pp. 373.
- Miller, A.J. (1978) *Signalised Intersections – Capacity Guide*, Australian Road Research Board, ARRB Research Report ARR No. 79, ISBN 0 86910 248 6.
- Mitchell, G., Namdeo, A., Lockyer, J. & May, A.D. (2002) The impact of road pricing and other strategic road transport initiatives on urban air quality, *Proceedings of the*

8th International Conference on Urban Transport and the Environment in the 21st Century, Wit Press, U.K., ISBN 1 85312 905 4, pp. 481-490.

- Mole, J.A. (1982) Modal analysis of vehicle fuel consumption, *Proceedings of the 2nd Conference on Traffic, Energy and Emissions*, SAE Australasia and Australian Road Research Board, Australia, 19-21 May 1982, paper 82133, pp. 3.1-3.15.
- Moragues, A. & Alcaide, T. (1996) The use of a geographical information system to assess the effect of traffic pollution, *The Science of the Total Environment*, Vol. 189/190, pp. 267-273.
- Morawska, L. Ferreira, L., Jamriska, M., Thomas, S. & McGregor, F. (2001) Estimation of motor vehicle emission factors from road measurements of pollutant concentrations, *Urban Transport and the Environment in 21st century*, by Sucharov, L.J. & Brebbia, C.A. (Eds.), Urban Transport VII, WITpress, Southampton, pp. 455-465.
- Mukherjee, P. & Viswanathan, S. (2001) Carbon monoxide modeling from transportation sources, *Chemosphere*, Vol. 45, pp. 1071-1083.
- Mullen, M.A., Wilson, J.H., Gottsman, L., Noland, R.B. & Schroeer, W.L. (1997) Emissions impact of eliminating national speed limits: one year later, *Transportation Research Record*, No. 1587, pp. 113-20.
- Namdeo, A., Mitchell, G. & Dixon, R. (2002) TEMMS: an integrated package for modelling and mapping urban traffic emissions and air quality, *Environmental Modelling & Software*, Vol. 17, No. 2, pp. 179-190.
- Negrenti, E. (1996) TEE: the ENEA traffic emissions and energetics model micro-scale applications, *The Science of the Total Environment*, Vol. 189/190, pp. 167-174.
- Negrenti, E. (1998) The 'corrected average speed' approach in ENEA's TEE model: an innovative solution for the evaluation of the energetic and environmental impacts of urban transport policies, *Proceedings of the 19th ARRB Conference*, ARRB Transport Research Ltd, Sydney, Australia, ISBN 0 86910 782 8, pp. 1-18.
- Negrenti, E. (1999) The 'corrected average speed' approach in ENEA's TEE model: an innovative solution for the evaluation of the energetic and environmental impacts of urban transport policies, *The Science of the Total Environment*, Vol. 235, pp. 411-413.

- Negrenti, E. & Zanini, G. (1999) Combining macroscopic traffic data, average speed emissions and instantaneous emission factors: the kinematics congestion factor as an innovative tool for traffic policies assessment, *ICE99 International Conference*, Capri, September 1999, pp. 385-391.
- Negrenti, E. (2001) Application of advanced transport impacts models on national and local scale: results from COMMUTE, ESTEEM and HESAID projects, *20th ARRB Transport Research Ltd Conference*, 2001, Melbourne, Victoria, Australia, pp. 1-26.
- Negrenti, E. & Parenti, A. (2002) *TEE File System Description*, Version 15th March 2002, ENEA.
- Negrenti, E. & Parenti, A. (2003) *TEE 2002 User Manual – Draft 1*, Version July 2003, ENEA.
- NEPC (1999a) *The Australian Diesel Fleet - Existing Vehicle Characteristics and the Modelling of Transport Demand, Vehicle Populations and Emissions*, by Cox, J., National Environment Protection Council Service Corporation, Australia, ISBN 0 642 32315 1.
- NEPC (1999b) *In-Service Emissions Performance - Drive Cycles*, Vol. 1, by Brown, S., Bryett, C. & Mowle, M., National Environment Protection Council Service Corporation, Australia, ISBN 0 642 32323 2.
- NEPC (1999c) *In-Service Emissions Performance - Drive Cycles*, Vol. 2, by Brown, S., Bryett, C. & Mowle, M., National Environment Protection Council Service Corporation, Australia, ISBN 0 642 32323 2.
- NEPC (2000) *In-Service Emissions Performance - Phase 2 Vehicle Testing*, by Anyon, P., Brown, S., Pattison, D., Beville-Anderson, J., Walls, G. & Mowle, M., National Environment Protection Council Service Corporation, Australia, ISBN 0 642 323 348.
- Newman, P.W.G., Kenworthy, J.R. & Lyons, T.J. (1988) Does free flowing traffic save energy and lower emissions in cities?, *Search*, Vol. 19, No. 5/6, pp. 267-272.
- Newman, P.W.G., Kenworthy, J.R. & Lyons, T.J. (1992) The ecology of urban driving II, driving cycles across a city: their validation and implications, *Transpn Res.-A*, Vol. 26A, No. 3, pp. 273-290.

- Neylon, M. & Collins, B. (1982) Mobile sources emissions inventory for the Melbourne airshed study, *Proceedings of the 2nd Conference on Traffic, Energy and Emissions*, SAE Australasia and Australian Road Research Board, Australia, 19-21 May 1982, Paper 82144, pp. 14.1-14.16.
- Nguyen, V.N., Lilley, W.E. & Williams, D.J. (2000) Development of a technique for estimating traffic emission and fuel consumption from SCATS road networks, *Proceedings of the 15th International Clean Air Conference*, Vol. 1, Clean Air Society for Australia and New Zealand, Sydney, Australia, November 2000, pp. 596-601.
- NHTSA (2004) *Speed Laws – State by State Analysis*, National Highway Traffic safety Administration (NHTSA), United States Department of Transportation.
- Noriega, Y. & Florian, M. (2005) Computing vehicle emissions and display on a fine grid, *Presentation at 2005 EMME/2 Meeting*, Shanghai.
- NRC (2000) *Modeling Mobile-Source Emissions*, National Research Council, National Academy Press, Washington D.C.
- NSW EPA & Coffey (1997) *Metropolitan Air Quality Study - Air Emissions Inventory*, NSW Environment Protection Authority & Coffey, by Carnovale, F., Tilly, K., Stuart, A., Carvalho, C., Summers, M. & Eriksen, P., Australia.
- NCTR (1997) Quality issues in strategic transport modelling, *Transport Engineering in Australia*, Vol. 3, No. 2, pp. 38-42.
- Oduyemi, K.O.K. & Davidson, B. (1998) The impacts of road management on urban air quality, *The Science of the Total Environment*, Vol. 218, No. 1, pp. 59-66.
- Ogden, K.W. & Taylor, S.Y. (Eds.) (1996) *Traffic Engineering and Management*, Dept. of Civil Engineering, Monash University, Clayton, Australia, ISBN 0 7326 0901 1.
- Oguchi, T., Taniguchi, M. & Morita, H. (1995) A method to calculate vehicle fuel consumption allowing for traffic stream fluctuation, *Proceedings of 2nd Steps Forward, Intelligent Transport Systems World Congress*, Yokohama, Japan, VERTIS (Ed.), Vol. 4, p. 2111-2116.
- Orbital (1995) *DCMOD Vehicle Simulation Model Manual*, 1st Edition, March 1995, Confidential.
- Owen, B., Edmunds, H.A., Carruthers, D.J. & Raper, D.W. (1999) Use of a new generation urban scale dispersion model to estimate the concentration of oxides of

nitrogen and sulphur dioxide in a large urban area, *The Science of the Total Environment*, Vol. 235, pp. 277-291.

- Owen, B., Edmunds, H.A., Carruthers, D.J. & Singles, R.J. (2000) Prediction of total oxides of nitrogen and nitrogen dioxide concentrations in a large urban area using a new generation urban scale dispersion model with integral chemistry model, *Atmospheric Environment*, Vol. 34, pp. 397-406.
- Panitz, H.-J., Nester, K. & Fiedler, F. (2002) Mass budget simulation of NO_x and CO for the evaluation of calculated emissions for the city of Augsburg (Germany), *Atmospheric Environment*, Vol. 36, Supplement No. 1, pp. S33-S51.
- Papageorgiou, M. (1998) Some remarks on macroscopic traffic flow modelling, *Transpn. Res.-A*, Vol. 32, No. 5, pp. 323-329.
- Park, J.Y., Noland, R.B. & Polak, J.W. (2001) Microscopic model of air pollutant concentrations – Comparison of simulated results with measured and macroscopic estimates, *Transportation Research Record*, No. 1773, pp. 32-38.
- Parsons (1998) *National Pollutant Inventory – Estimation of Motor Vehicle Emission Factors*, Parsons Australia Pty Ltd, Ninderry, Australia, Prepared for Queensland Department of Environment, September 1998.
- Pierson W.R., Gertler A.W., Robinson N.F., Sagebiel J.C., Zielinska B., Bishop G.A., Stedman D.H., Zweidinger R.B. & Ray W.D. (1996) Real-world automotive emissions - summary of studies in the Fort McHenry and Tuscarora mountain tunnels, *Atmospheric Environment*, Vol. 30, pp. 2233-2256.
- Pierson, W.R., Schorran, D.E., Fujita, E.M., Sagebiel, J.C., Lawson, D.R. & Tanner, R.L. (1999) Assessment of Nontailpipe hydrocarbon emissions from motor vehicles, *J. Air & Waste Manage. Assoc.*, Vol. 49, pp. 498-519.
- Pokharel, S.S., Bishop, G.A. & Stedman, D.H. (2002) An on-road motor vehicle emissions inventory for Denver: an efficient alternative to modelling, *Atmospheric Environment*, Vol. 36, pp. 5177-5184.
- Polus, A. & Craus, J. (1997) Congestion thresholds for lane additions on tollways, *Transportation Quarterly*, Vol. 51, No. 3, pp. 81-91.
- Post, K., Gibson, T.J., Carruthers, N., Tomlin, J.A., Kent, J.H. & Bilger, R.W. (1983) *Motor Vehicle Fuel Economy - Vehicle Maps, Power Demand Models and Unsteady*

State Engine Maps, University of Sydney, Department of Mechanical Engineering, Australia, NERDDC Grant No. 78/2700-80/0313, Technical Note ER-42.

- Post, K., Kent, J.H., Tomlin, J.A. & Carruthers, N. (1984) Fuel consumption and emission modelling by power demand and a comparison with other models, *Transpn Res.-A*, Vol. 18, pp. 191-213.
- Post, K., Kent, J.H., Tomlin, J. & Carruthers, N. (1985) Vehicle characterization and fuel consumption prediction using maps and power demand models, *Int. J. Vehicle Design.*, Vol. 6, No. 1, pp. 72-92.
- Potts, R.B. (1966) Discussion on Davidson's paper, *Proceedings of the 3rd ARRB Conference*, Vol. 3, No. 1, p. 193.
- QGDMR (2002) *Metropolitan District Traffic Info 2002 CD-ROM*, Queensland Government Department of Main Roads (QGDMR), Traffic Operations Business Unit, Network Performance Analysis Section, Australia.
- QGEPA (2000) *A Strategy for Improving Air Quality in South-East Queensland – South East Queensland Regional Air Quality Strategy (SEQRAQS)*, Queensland Government Environmental Protection Agency (QGEPA), Australia.
- QGEPA (2002) *South-East Queensland Motor Vehicle Emissions Inventory – Final Report*, Queensland Government Environmental Protection Agency (QGEPA), Prepared by Adam Pekol Consulting, Parsons Australia, Pacific Air & Environment, Computing in Transportation and Resource Coordination Partnership, 30 September 2002.
- Rainford, H., Lyons, T.J., Kenworthy, J.R. & Newman, P.W.G. (1987) Fuel consumption and road type, *Traffic Engineering + Control*, March 1987, pp. 183-186.
- Rebolj, D. & Sturm, P.J. (1999) A GIS based component-oriented integrated system for estimation, visualization and analysis of road traffic air pollution, *Environmental Modelling & Software*, Vol. 14, pp. 531-539.
- Reynolds, A.W. & Broderick, B.M. (2000) Development of an emissions inventory model for mobile sources, *Transpn. Res.-D*, Vol. 5, No. 2, pp. 77-101.
- Rexeis, M. & Hausberger, S. (2005) Calculation of vehicle emissions in road networks with the model "NEMO", *Proceedings of the 14th Symposium Transport*

and Air Pollution, Vol. 1, 1-3 June 2005, Graz, Austria, ISBN 3 902465 16 6, pp. 118-127.

- Richardson, A.J. & Taylor, M.A.P. (1978) Travel time variability on commuter journeys, *High Speed Ground Transportation Journal*, Vol. 12, No. 1, pp. 77-99.
- Richardson, A.J. (1982) The use of the QDELAY survey method in the estimation of fuel consumption at signalised intersections, *Proceedings of SAE-A/ARRB 2nd Conference on Traffic Energy and Emissions*, pp. 24.1-24.11.
- Robertson, D.I., Wilson, N. & Kemp, S. (1996) The effects of co-ordinated and isolated signal control on journey times and exhaust emissions along the A12 in London, *Traffic Engineering + Control*, January 1996, pp. 4-9.
- Rogak, N., Pott, U., Dann, T. & Wang, D. (1998) Gaseous emissions from vehicles in a traffic tunnel in Vancouver, British Columbia, *J. Air & Waste Manage. Assoc.*, Vol. 48, pp. 604-615.
- Romanini, G. & Mangia, C. (2001) An integrated system for estimating and managing road transport emissions, *Advances in Air Pollution - Air Pollution IX*, AN 2002:217404, ISSN 1369-5886, pp. 337-342.
- Rose, A.H., Smith, R., McMichael, W.F. & Kruse, R.F. (1965) Comparison of auto exhaust emissions in two major cities, *Journal of the Air Pollution Control Association*, Vol. 15, No. 8, pp. 362-371.
- RTA (2000a) Development of a Technique for Estimating Traffic Emission and Fuel Consumption from SCATS Road Networks, Roads and Traffic Authority of New South Wales, Australia, by Nguyen, V.N., 12 February 2000, Report No. RTA/TTB/NN9908a-TC-265.
- RTA (2000b) *Measuring Traffic Congestion from SCATS Road Networks*, Roads and Traffic Authority of New South Wales, Australia, by Nguyen, V.N., 5 April 2000, Report No. RTA/TTB/NN0002-TC-267.
- Saija, S. & Romano, D. (2002) A methodology for the estimation of road transport air emissions in urban areas of Italy, *Atmospheric Environment*, Vol. 36, pp. 5377-5383.
- Saleh, W.S., Nelson, J.D. & Bell, M.H. (1998) Determinants of energy consumption: examination of the alternative transport policies using the TEMIS program, *Transpn. Res.-D*, Vol. 3, No. 2, pp. 93-103.

- Saltelli, A., Chan, K. & Scott, E.M. (Eds.) (2000) What is sensitivity analysis?, *Sensitivity Analysis*, John Wiley & Sons Ltd., Chichester, ISBN 0 471 99892 3, pp. 3-13.
- Samaras, Z., Kyriakis, N. & Zachariadis, T. (1995) Reconciliation of macroscale and microscale motor vehicle emission estimates, *The Science of the Total Environment*, Vol. 169, pp. 231-239.
- Sbayti, H., El-Fadel, M., Kaysi, I. & Baaj, H. (2001) Automotive emissions in developing countries: traffic management and technological control measures, *Environmental Engineering Science*, Vol. 18, No. 6, pp. 347-358.
- Schallaböck, K.O. & Petersen, R. (1999) *Traffic Congestion in Europe*, Economic Research Centre, Report of the 110th Round Table of Transport Economics, European Conference of Ministers of Transport, Paris, France, 12-13 March 1998, OECD Publications Service, ISBN 92-821-1248-9, pp. 5-44.
- Schoenbach, V.J., Keppel, K.G., Lynch, J. & Scott, C. (2002) Absolute (difference) and relative (ratio) measures of disparity: which type to use?, *Conference Proceedings of the 2002 American Public Health Association Annual Meeting*, Philadelphia, PA, USA, Paper No. 39378, pp. 1 – 11.
- Schmidt, M. & Schäfer, R-P. (1998) An integrated simulation system for traffic induced air pollution, *Environmental Modelling & Software*, Vol. 13, pp. 295-303.
- Schmidt, M., Schäfer, R-P. & Nökel, K. (1998) SIMTRAP: Simulation of traffic induced air pollution, *Transactions*, Vol. 15, No. 3, pp. 122-132.
- Schulz, D., Younglove, T. & Barth, M. (2000) Statistical analysis and model validation of automobile emissions, *Journal of Transportation and Statistics*, September 2000, pp. 29-38.
- Scott, D.M., Kanaroglou, P.V. & Anderson, W.P. (1997) Impacts of commuting efficiency on congestion and emissions: case of the Hamilton CMA, Canada, *Transpn. Res.-D*, Vol. 2, No. 4, pp. 245-257.
- Seika, M., Harrison, R.M. & Metz, N. (1998) Effects of traffic-related control strategies on urban air quality, *Int. J. Vehicle Design*, Vol. 20, No. 1-4, pp. 313-325.
- Shefer, D. (1994) Congestion, air pollution and road fatalities in urban areas, *Accid. Anal. and Prev.*, Vol. 26, No. 4, pp. 501-509.

- Singh, R. (1999) Improved speed-flow relationships: application to transportation planning models, *Proceedings of the 7th TRB Conference on Application of Transportation Planning Methods*, Boston, MA, March 1999, pp. 1-20.
- Singh, R.B. & Huber, A.H. (2000) Development of a microscale emission factor model for CO for predicting real-time motor vehicle emissions, *J. Air & Waste Manage. Assoc.*, Vol. 50, pp. 1980-1991.
- Singer, B.C. & Harley, R.A. (1996) A fuel based motor vehicle emission inventory, *J. Air & Waste Manage. Assoc.*, Vol. 46, pp. 581-593.
- Singer, B.C., Kirchstetter, T.W., Harley, R.A., Kensall, G.R. & Hesson, J.M. (1999) A fuel based approach to estimating motor vehicle cold-start emissions, *J. Air & Waste Manage. Assoc.*, Vol. 49, pp. 125-135.
- Singer, B.C. & Harley, R.A. (2000) A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997, *Atmospheric Environment*, Vol. 34, pp. 1783-1795.
- Sjödin, Å. & Lenner, M. (1995) On-road measurements of single vehicle pollutant emissions, speed and acceleration for large fleets of vehicles in different traffic environment, *The Science of the Total Environment*, Vol. 169, pp.157-165.
- Sjödin, Å., Persson, K., Andréasson, K. Arlander, B. & Galle, B. (1998) On-road emission factors derived from measurements in a traffic tunnel, *Int. J. Vehicle Design*, Vol. 20, Nos. 1-4 , Special Issue, pp. 147-158.
- Skabardonis, A. & Dowling, R.G. (1997) Improved speed-flow relationships for planning applications, *Transportation Research Record*, No. 1572, TRB Paper 970996, Washington, D.C., pp. 18-23.
- Smeed, R.J. (1968) Traffic studies and urban congestion, *J. Trans. Econ. and Policy*, Vol. 2, No. 1, pp. 33-70.
- Smeed, R.J. (1970) The capacity of urban road networks, *Proceedings of Australian Road Research Board Meeting*, Vol. 5, Part I, pp. 10-28.
- Smit, R., Bawden, K. & Ormerod, R. (2002) Speciated hydrocarbon emissions from road traffic, *Proceedings of the 16th Clean Air and Environment Conference*, CASANZ, Christchurch, New Zealand, 19-22 August 2002, pp. 746-757
- Smit, R., Smokers, R. & Schoen, E. (2005) VERSIT+ LD: Development of a new emission factor model for passenger cars linking real-world emissions to driving

- cycle characteristics, *Proceedings of the 14th Symposium Transport and Air Pollution*, Vol. 1, 1-3 June 2005, Graz, Austria, ISBN 3 902465 16 6, pp. 177-186.
- Smit, R., Smokers, R., Schoen, E. & Hensema, A. (2006a) *A New Modelling Approach for Road Traffic Emissions – VERSIT+ Light Duty*, TNO Report 06.OR.VM.016.1/RS.
 - Smit, R. (2006b) *Vehicle Technology and Emissions of Air Pollutants*, Road Transport and Air Quality Course, Stichting Postacademisch Onderwijs (Organisation for Postacademic Education), 5 October 2006, Delft, The Netherlands.
 - Spiess, H. (1990) Conical volume-delay functions, *Transportation Science*, Vol. 24, No. 2, pp. 153-158.
 - St. Denis, M.J. & Winer, A.M. (1994) Prediction of on-road emissions and comparison of modeled on-road emissions to the FTP emissions, *The Emission Inventory: Perception And Reality*, Air & Waste Management Association, pp. 495-505.
 - St. Denis, M.J., Cicero-Fernández, P., Winer, A.M., Butler, J.W. & Jesion, G. (1994) Effects of in-use driving conditions and vehicle/engine operating parameters on off-cycle events: comparison with Federal Test Procedure conditions, *J. Air & Waste Manage. Assoc.*, Vol. 44, pp. 31-38.
 - Staab, J. & Schürmann, D. (1987) Measurement of automobile exhaust emissions under realistic road conditions, *SAE Technical Paper Series*, Paper No. 871986, pp. 1-7.
 - Staehelin, J., Keller, C., Stahel, W., Schläpfer, K. & Wunderli, S. (1998) Emission factors from road traffic from a tunnel study (Gubrist Tunnel, Switzerland). Part 3: results of organic compounds, SO₂ and speciation of organic exhaust emissions, *Atmospheric Environment*, Vol. 32, No. 6, pp. 999-1009.
 - Starrs, M.M. & Starkie, D.N.M. (1986) An integrated road pricing and investment model: a South Australian application, *Australian Road Research*, Vol. 16, No. 1, pp. 1-9.
 - Strong, T., Harwood, N., White, J., Flint, A. & Beale, S. (2002) Linking automatic incident detection with diversion strategies using MOLA, *Proceedings of the International Conference on Road Transport Information and Control*, 19-21 March 2002, pp. 131/135.

- Sturm, P.J., Pucher, K., Sudy, C. & Almbauer, R.A. (1996) Determination of traffic emissions - intercomparison of different calculation methods, *The Science of the Total Environment*, Vol. 189/190, pp. 187-196.
- Sturm, P.J., Almbauer, R., Sudy, C. & Pucher, K. (1997) Application of computational methods for the determination of traffic emissions, *J. Air & Waste Manage. Assoc.*, Vol. 47, pp. 1204-1210.
- Sturm, P.J., Sudy, C., Almbauer, R.A. & Meinhart, J. (1999) Updated urban emission inventory with a high resolution in time and space for the city of Graz, *The Science of the Total Environment*, Vol. 235, pp. 111-118.
- Tate, J.E. & Bell, M.C. (2000) Evaluation of a traffic demand management strategy to improve air quality in urban areas, *Proceedings of 10th International Conference on Road Transport Information and Control*, London, UK, pp. 158-162.
- Taylor, M.A.P. (1977) On Davidson's flow rate/travel time relationship - author's reply to discussion, *Australian Road Research*, Vol. 7, No. 4, p. 41.
- Taylor, M.A.P. (1979) Recent Australian experience with a local area traffic model, *Proceedings of Traffic and Environmental Management Seminar*, PTRC Education and Research Services Ltd, London, United Kingdom, pp. 171-194.
- Taylor, M.A.P. (1980) Australian experience with a local area traffic model, *ITE Journal*, Vol. 50, No. 10, pp. 31-32 & 37-41.
- Taylor, M.A.P. & Anderson, M. (1982) Modelling pollution and energy use in urban road networks, *Proceedings of the 11th Conference of the Australian Road Research Board*, Vol. 11, Part 6, pp. 1-17.
- Taylor, M.A.P. & Anderson, M. (1983) A hierarchical approach to modelling network flows, *Papers of 8th Australian Transport Research Forum*, Canberra, May 1983, Vol. 2, pp. 136-149.
- Taylor, M.A.P. (1984) A note on using Davidson's function in equilibrium assignment, *Transpn Res.-B*, Vol. 18, No. 3, pp.181-199.
- Taylor, M.A.P. & Anderson, M. (1984) Energy and emissions in a metropolitan road transport system, *Proceedings of the 12th Conference of the Australian Road Research Board*, Vol. 12, No. 6, pp. 63-78.

- Taylor, M.A.P. & Young, W. (1988) *Traffic Analysis - New Technology & New Solutions*, Hargreen Publishing Company, North Melbourne, Australia, ISBN 0 949905 34 8.
- Taylor, M.A.P. (1992) Modelling environmental impacts of road traffic for transport network analysis, *Papers of the Australasian Transport Research Forum*, Vol. 17, No. 2, pp. 529-549.
- Taylor, M.A.P. & Young, T.M. (1996) Fuel consumption and emissions models for traffic engineering and transport planning applications: some new results, *Proceedings of 18th ARRB Transport Research Conference/ Roads 96 Conference*, Part 6, Christchurch, New Zealand, pp. 189-204.
- Taylor, M.A.P. (1999a). Dense network traffic models, travel time reliability and traffic management I: general introduction. *Journal of Advanced Transportation*, Vol. 33, No. 2, pp.218-233.
- Taylor, M.A.P. (1999b). Dense network traffic models, travel time reliability and traffic management II: application to network reliability, *Journal of Advanced Transportation*, Vol. 33, No. 2, pp. 235-251.
- Taylor, M.A.P. (2000) Network modelling of the traffic, environmental and energy effects of lower urban speed limits, *Road and Transport Research*, Vol. 9, No. 4, pp.48-57.
- Taylor, M.A.P., Bonsall, P.W. & Young, W. (2000) *Understanding Traffic Systems: Data, Analysis and Presentation*, 2nd Edition, Ashgate Publishing Ltd, England, ISBN 0 7546 1248 1.
- Taylor, N.B. (2003) The CONTRAM dynamic traffic assignment model, *Networks and Spatial Economics*, Vol. 3, pp. 297-322.
- Tisato, P. (1991) Suggestions for an improved Davidson travel time function, *Australian Road Research*, Vol. 21, No. 2, pp. 85-100.
- TNO (2000) *Driving Style, Fuel Consumption and Tailpipe Emissions*, TNO Automotive, The Netherlands, by Gense, N.L.J. Report No. 00.OR.VM.021.1/NG.
- TNO (2001) *Emissions and Congestion - Estimation of Emissions on Road Sections and the Dutch Motorway Network*, TNO Automotive, The Netherlands, by Gense, N.L.J., Wilmink, I.R. & Van de Burgwal, H.C., Report No. 01.OR.VM.0441/NG.

- TNO (2004a) *Quickscan Optimale Snelheidslimiet op Nederlandse Wegen* (*Quickscan Optimal Speed Limit on Dutch Roads, in Dutch*), TNO Automotive, The Netherlands, by Riemersma, I.J. *et al.*, Report No. 04.OR.VM.016.1/IJR.
- TNO (2004b) *SMARA: Betrouwbaarheid Voorspellen (In Dutch)*, www.inro.tno.nl.
- Tobin, R. (1979) Calculation of fuel consumption due to traffic congestion in a case-study metropolitan area, *Traffic Engineering & Control*, Vol. 20, No. 12, pp. 590-592.
- Tong, H.Y., Hung, W.T. & Cheung, C.S. (1999) Development of a driving cycle for Hong Kong, *Atmospheric Environment*, Vol. 33, pp. 2323-2335.
- TRB (1992) *Quantifying Congestion: Volume 1 - Final Report*, Transportation Research Board, by Lomax, T., Turner, S., Shunk, G., Levinson, H.S., Pratt, R.H., Bay, P.N. & Douglas, G.B., NCHRP Report 398, Project 7-13 FY 1992, National Academy Press, Washington D.C., ISBN 0 309 06071 0.
- TRB (1997) *Improving Transportation Data for Mobile-Source Emissions Estimates*, Transportation Research Board, by Chatterjee, A., Miller, T., Philpot, J., Wholley, T., Guensler, R., Hartgen, D., Margiotta, R. & Stopher, P., National Research Council, National Academy Press, Washington D.C., NCHRP Report No. 394.
- TRB (2000) *Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington D.C., USA, ISBN 0 309 06681 6.
- TRL (1999) *Methodology for Calculating Transport Emissions and Energy Consumption*, Transport Research Laboratory, UK, by Hickman, J. (Ed.), Hassel, D., Joumard, R., Samaras, Z. & Sorenson, S., Deliverable No. 22 for the Project MEET, EC-DGVII, Brussels, Belgium, Report No. SE/491/98.
- TRT (2005) *TRANS-TOOLS Deliverable 2: Report WP 2*, Commissioned by the European Commission – DG-TREN, 5th Framework Programme.
- TTI (1993) *Congestion Management Systems State-of-the-Practice Review*, Texas Transportation Institute, Texas, USA, by Hamm, R.A., Woods, D.L., Stover, V.G. & Hawley, P.E., Research Report No. 563-1F.
- TUG (1998) *Instantaneous Emission Data and Their Use in Estimating Passenger Car Emissions*, Technical University of Graz, Graz, Austria, by Sturm, P.J., Boulter, P., De Haan, P., Joumard, R., Hausberger, S., Hickman, J., Keller, M., Niederle, W., Ntziachristos, L., Reiter, C., Samaras, Z., Schinagl, G., Schweizer, T. & Pischinger, R. (Ed.), Report VKM-THD Vol. 74, ISBN 3 901351 24 8.

- Turner, S.M. (1992) Examination of indicators of congestion level, *Transportation Research Record*, No. 1360, pp. 150-157.
- Turner, S.M., Lomax, T.J. & Levinson, H.S. (1996) Measuring and estimating congestion using travel time-based procedures, *Transportation Research Record*, No. 1564, pp. 11-19.
- Umweltbundesamt (1998) *European Speed limits*, <http://www.umweltbundesamt.de/uba-info-daten-e/daten-e/speed-limits.htm>.
- US EPA (1994) *User's guide to MOBILE5 (Mobile Source Emission Factor Model)*, US EPA Office of Air and Radiation, Report No. EPA-AA-TEB-94-01.
- US EPA (1997) *Development of Speed Correction Cycles*, by Carlson, T.R & Austin, T.C., Sierra Research, Report No. M6.SPD.001.
- US EPA (1998a) *Hot Soak Emissions as a Function of Soak Time*, US EPA Assessment and Modeling Division, by Glover, L., Report No. EPA420-P-98-018.
- US EPA (1998b) *Air Conditioning Activity Effects in MOBILE6*, US EPA Assessment and Modeling Division, by Koupal, J., Report No. M6.ACE.001.
- US EPA (1998c) *Air Conditioning Correction Factors in MOBILE6 - Draft*, US EPA Assessment and Modeling Division, by Koupal, J., Report No. M6.ACE.002.
- US EPA (1999a) *Facility-Specific Speed Correction Factors - Draft*, US EPA Office of Air and Radiation, by Brzezinski, D.J. & Enns, P. & Hart, C.J., Report No. M6.SPD.002.
- US EPA (1999b) *The Determination of Hot Running Emissions from FTP Bag Emissions - Draft*, US EPA Office of Air and Radiation, by Brzezinski, D.J., Glover, E. & Enns, P., Report No. M6.STE.002.
- US EPA (1999c) *Determination of Start Emissions as a Function of Mileage and Soak Time for 1981-1993 Model Year Light-Duty Vehicles - Draft*, US EPA Office of Air and Radiation, by Glover, E. & Carey, P., Report No. M6.STE.003.
- US EPA (1999d) *Exhaust Emission Temperature Correction Factors for MOBILE6: Engine Start and Running LA4 Emissions for Gasoline Vehicles*, US EPA Office of Air and Radiation, by E.L. Glover & D.J. Brzezinski, Report No. M6.STE.004.
- US EPA (1999e) *Determination of Running Emissions as a Function of Mileage for 1981-1993 Model Year Light-Duty Cars and Trucks - Draft*, US EPA Office of Air and Radiation, by Enns, P., Glover, E., Carey, P. & Sklar, M., Report No. M6.EXH.001.

- US EPA (1999f) *Analysis of Emissions Deterioration Using Ohio and Wisconsin IM240 Data - Draft*, US EPA Office of Air and Radiation, by Enns, P., Glover, E., Carey, P. & Sklar, M., Report No. M6.EXH.002.
- US EPA (1999g) *Basic Exhaust Emission Rates of Open Loop Vehicles for MOBILE6: Exhaust Emissions at High and Low Altitudes for Engine Starts and Running Emissions for Motorcycles, Light Duty Diesel Vehicles and Trucks and Pre-1981 Model Year Light Duty Gasoline Vehicles and Trucks – Draft*, US EPA Office of Air and Radiation, by Brzezinski, D.J. & Gilmore, J., Report No. M6.EXH.005.
- US EPA (1999h) *Comparison of MOBILE6 Basic Emission Rates for 1981-1993 Model Year Cars and Light-Duty Trucks with FTP and IM240 Data - Draft*, US EPA Office of Air and Radiation, by Enns, P., Report No. M6.EXH.010.
- US EPA (2001a) *Final Facility-Specific Speed Correction Factors*, US EPA Office of Air and Radiation, by Brzezinski, D.J. & Enns, P. & Hart, C.J., Report No. M6.SPD.002.
- US EPA (2001b) *Evaluating Resting Loss and Diurnal Evaporative Emissions Using RTD Tests*, Office of Transportation and Air Quality, by Landman. L.C., Report No. M6.EVP.001.
- US EPA (2001c) *Upgrading MOBILE to Include Air Toxic Emission Factors Proposed MOBILE6.2 Project Description*, 15 May 2001.
- US EPA (2001d) *Modeling Hourly Diurnal Emissions and Interrupted Diurnal Emissions Based on Real-Time Diurnal Data*, Office of Transportation and Air Quality, by Landman. L.C., Report No. M6.EVP.002.
- US EPA (2001e) *Evaluating Multiple Day Diurnal Evaporative Emissions Using RTD Tests*, Office of Transportation and Air Quality, by Enns, P., Report No. M6.EVP.003.
- US EPA (2001f) *Update of Hot Soak Emissions*, US EPA Office of Air and Radiation, by Arcadis & Miller Inc., Report No. M6.EVP.004.
- US EPA (2001g) *Estimating Weighting Factors for Evaporative Emissions in MOBILE6*, US EPA Office of Air and Radiation, by Landman, L.C., Report No. M6.EVP.006.
- US EPA (2001h) *Estimating Running Loss Evaporative Emissions in MOBILE6*, US EPA Office of Air and Radiation, by Landman, L.C., Report No. M6.EVP.008.

- US EPA (2001i) *Evaporative Emissions of Gross Liquid Leakers in MOBILE6*, US EPA Office of Air and Radiation, by Landman, L.C., Report No. M6.EVP.009.
- US EPA (2002a) *Technical Description of MOBILE6.2 and Guidance on its Use for Emission Inventory Preparation – DRAFT Report*, US EPA Office of Transportation and Air Quality, by Cook, R. & Glover, E.L., Report No. EPA420-R-02-011.
- US EPA (2002b) *Draft Design and Implementation Plan for EPA's Multi-Scale Motor Vehicle and Equipment Emission System (MOVES)*, US EPA Office of Transportation and Air Quality, by Koupal, J., Cumberworth, M., Michaels, H., Beardsley, M. & Brzezinski, D., Report No. EPA420-P-02-006.
- US EPA (2002c) *Draft Emission Analysis Plan for MOVES GHG*, US EPA Office of Transportation and Air Quality, by Koupal, Hart, C., Brzezinski, D., Giannelli, R. & Bailey, C., Report No. EPA420-P-02-008.
- US EPA (2003) *MOBILE 6.1 Particulate Emission Factor Model Technical Description*, by Glover, E.L. & Cumberworth, M., Report No. M6.PM.001.
- Van Arem, B., Kirby, H.R., Van der Vlist, M.J.M. & Whittaker, J.C. (1997) Recent advances and applications in the field of traffic forecasting, *International Journal of Forecasting*, Vol. 13, No. 1, pp. 1-12.
- Van Toorenburg, J.A.C. (1991) Performance of motorways and trunk routes at high traffic volumes, in U. Brannolte (Ed.), *Highway Capacity and Level of Service*, Rotterdam, Balkema, pp. 413-418.
- Van Vliet, D. (1982) SATURN - A modern assignment model, *Traffic Engineering & Control*, Vol. 23, No. 12, pp. 578-581.
- Van Vuren, T. & Leonard, D.R. (1994) Urban congestion caused by accidents, *Traffic Engineering + Control*, July/August, pp. 422-429.
- Vardoulakis, S., Fisher, B.E.A., Gonzalez-Flesca, N. & Pericleous, K. (2002) Model sensitivity and uncertainty analysis using roadside air quality measurements, *Atmospheric Environment*, Vol. 36, pp. 2121-2134.
- Veurman, J., Gense, N.L.J., Wilmlink, I.R. & Baarbé, H.I. (2002) Emissions at different conditions of traffic flow, *Proceedings of the 8th International Conference on Urban Transport and the Environment in the 21st Century*, Wit Press, U.K., ISBN 1 85312 905 4, pp. 571-580.
- Vicroads (1993) *Speed Zoning Guidelines*, ARRB Transport Research.

- Vogel, B., Corsmeier U., Vogel, H., Fiedler, F., Kühlwein, J., Friedrich, R., Obermeier, A., Weppner, J., Kalthoff, N., Bäumer, D., Bitzer, A. & Jay, K. (2000) Comparison of measured and calculated motorway emission data, *Atmospheric Environment*, Vol. 34, pp. 2437-2450.
- Walker, W.P. (1956) Speed and travel time measurements in urban areas, *35th Annual Proceedings of Traffic Speed and Volume Measurements*, Bulletin 156, Publication No. 491, HRB, National Research Council, Washington DC, pp. 27-44.
- Watson, H.C. (1973) Influence of vehicle driving patterns on localised urban emission sources, *SAE Technical Paper Series*, Paper No. 730566, pp. 1-13.
- Watson, H.C., Milkins, E. & Marshall, G.A. (1979) Controlling traffic flow for minimum energy consumption and emissions, *Transportation Conference*, The Institution of Engineers, Australia, Adelaide, 14-16 November, pp. 116-124.
- Watson, H.C., Milkins, E.E. & Marshall, G.A. (1980) A simplified approach for quantifying fuel consumption of vehicles in urban traffic, *The SAE-Australasia*, Vol. 40, No. 1, pp. 6-13.
- Watson, H.C. (1980) Sensitivity of fuel consumption and emissions to driving patterns and vehicle design, *Proceedings of SAE-A/ARRB Conference "Can Traffic Management Reduce Vehicle Fuel Consumption and Emissions and Affect Vehicle Design Requirements"*, Paper No. 80004, pp 1-29.
- Watson, H.C., Milkins, E.E., Preston, M.O., Beardsley, P. & Chittleborough, C.W. (1982) Further application of the PKE average speed fuel consumption and emissions model, *Proceedings of Joint SAE-A/ARRB 2nd Conference on Traffic, Energy & Emissions*, May 19-21, Melbourne, Paper No. 82139, pp. 9.1-9.14.
- Watson, H.C., Milkins, E.E. & Braunsteins, J. (1982) The development of the Melbourne Peak Cycle, *Proceedings of SAE-A/ARRB 2nd Conference on Traffic Energy and Emissions*, Paper No. 82148, pp. 18.1-18.21.
- Watson, H.C., Holyoake, P.A. & Milkins, E.E. (1983) *The Effects of Cold Starting on Fuel Consumption and Vehicle Component Temperatures*, Department of Mechanical Engineering, University of Melbourne, Australia.
- Watson, H.C., Milkins, E.E., Preston, M.O., Chittleborough, C. & Alimordian, B. (1983) Predicting fuel consumption and emissions, transferring chassis

dynamometer results to real driving conditions, *SAE Technical Paper Series*, Paper No. 830435, pp. 1-24.

- Watson, H.C, Milkins, E.E., Lansell, S. & Challenger, K. (1990) A before and after study of the change to unleaded gasoline – test results from EPA and other cycles, *SAE Technical Paper Series*, Paper No. 900150, pp. 1-28.
- Watson, H.C. (1995) Effects of a wide range of drive cycles on the emissions from vehicles of three levels of technology, *SAE Technical Paper Series*, Paper No. 950221, pp. 119-132.
- Webster, F.V. (1958) *Traffic Signal Settings*, Road Research Laboratory, Department of Scientific and Industrial Research, Her Majesty's Stationary Office, London, Road Research Technical paper No. 39.
- Webster, F.V. & Cobbe, B.M. (1966) *Traffic Signals*, Road Research Laboratory, Ministry of Transport, Her Majesty's Stationary Office, London, Road Research Technical Paper No. 56.
- Weilenmann, M., Bach, C. & Rüdy, C. (2000) Aspects of instantaneous emission measurement, *Proceedings of the 9th International Symposium 'Transport and Air Pollution'*, Avignon, 5-8 June 2000, INRETS, Arcueil, France, pp. 119-126.
- Wigan, M.R. (1976) The estimation of environmental impacts for transport policy assessment, *Environment and Planning A*, Vol. 8, pp. 125-147.
- WSA (2000) *Atlanta Regional Congestion Management System*, Wilbur Smith Associates, Final Report, February 2002, Prepared for Atlanta Regional Commission, USA.
- Williams, D.J., Shenouda, D.A. & Carras J.N. (1994) Modelling air toxic emission from motor vehicles, *Proceedings 1994 Air Toxic Conference*, Vol. 2, National Measurement Laboratories, Lindfield, Sydney, Australia, pp. 31-48.
- Williams, D.J., Carras J.N., Shenouda, D.A., Drummond, M.S. & Lange, A.L. (1994) *Traffic Generated Pollution Near Roads and Highways: Models and Measurements*, CSIRO, Division of Coal and Energy, North Ryde, NSW, Australia, Investigation Report CET/IR238.
- Williams, M.D., Thayer, G., Barth, M.J. & Smith, L.L. (1999) *The TRANSIMS Approach to Emissions Estimation*, Los Alamos National Laboratory, Los Alamos, New Mexico, Report LA-UR 99-471.

- Winther, M. (1998) Petrol passenger car emissions calculated with different emission models, *The Science of the Total Environment*, Vol. 224, pp. 149-160.
- Woolley, J., Klungboonkrong, P., Taylor, M., Yue, W.L. & Kanellos, T. (1997) *Review of the Relationships between Noise and Emissions and Level of Congestion on Urban Roads*, by Transport Systems Centre, University of South Australia, Adelaide, Prepared for ARRB Transport Research, Australia.
- Wright, C. & Huddart, K.W. (1989) *Strategies for Urban Traffic Control*, Rees Jeffreys Road Fund – “Transport & Society”, Middlesex Polytechnic, November 1989, Discussion Paper No. 6.
- Wright, C. & Lupton, K. (2001) Traffic congestion and the fundamental relationships of traffic flow, *Proceedings of the Institution of Civil Engineers - Transport*, Vol. 147, No. 4, pp. 231-238.
- Xu, C.H. (1998) *A Study in Air Pollution from Brisbane Urban Traffic with Development and Application of a Computer Information System for Environmental Management*, Ph.D. Thesis (Unpublished), Faculty of Environmental Science, Griffith University, Brisbane, Australia, April 1998.
- Zachariadis, T.I. & Samaras, Z. (1997) Comparative assessment of European tools to estimate traffic emissions, *Int. J. Vehicle Design*, Vol. 18, No 3/4 , Special Issue, pp. 312-325.
- Zachariadis, T.I. & Samaras, Z.C. (1999) An integrated modeling system for the estimation of motor vehicle emissions, *J. Air & Waste Manage. Assoc.*, Vol. 49, pp. 1010-1025.
- Zalinger, M., Ahn, T.L. & Hausberger, S. (2005) Improving an instantaneous emission model for passenger cars, *Proceedings of the 14th Symposium Transport and Air Pollution*, Vol. 1, 1-3 June 2005, Graz, Austria, ISBN 3 902465 16 6, pp. 167-176.
- Zhang, Y., Stedman, D.H., Bishop, G.A., Guenther, P.L. & Beaton, S.P. (1995) Worldwide on-road vehicle exhaust emissions study by remote sensing, *Environ. Sci. Technol.*, Vol. 29, No. 9, pp. 2286-2294.
- Zweidinger, R.B., Sigsby, J.E., Silvestre, J., Tejada, B., Stump, F.D., Dropkin, D.L., Ray, W.D. & Duncan, J.W. (1988) Detailed hydrocarbon and aldehyde mobile

source emissions from roadway studies, *Environ. Sci. Technol.*, Vol. 22, No. 8, pp. 956-962.

APPENDIX A – STRATEGIC PLANNING MODELLING

The transport modelling process starts with the collection and processing of demographic, land use and socio-economic data and then goes through the following typical steps:

1. modelling of trip generation and attraction;
2. modelling of trip distribution;
3. modelling of mode choice; and
4. modelling of route choice.

The first step (trip generation/attraction) estimates the (typically daily) overall demand for travel, i.e. the number of trips leaving a zone (generation) or entering a zone (attraction) by trip category. A trip category may reflect type of trip (e.g. work, shopping, leisure), vehicle type (e.g. passenger car, commercial) and possibly by time of the day.

The second step (trip distribution) then models the spatial pattern of travel between zones, i.e. where generated trips will go to and where attracted trips come from. This step results in origin-destination (O/D) matrices by trip category and time of day that represent the number of trips between each zone (i.e. centroid node).

The third step (mode choice) subsequently apportions the number of trips to the different modes of transport available in an area (e.g. walk, bicycle, bus, rail, truck, drive alone, high occupancy vehicle). This step results in O/D trip matrices specified for each transport mode.

The fourth and last step (trip assignment) models the route choice and assigns the trip matrices (“transport demand”) to the modelled road network (“transport supply”). This step results in the final planning model output and consists of three separate components (Taylor, Bonsall & Young, 2000):

- shortest route finding algorithm;
- congestion function(s); and
- strategy for route selection.

In the trip assignment model route choice is modelled as a function of the “generalised costs” (in terms of e.g. time, distance, actual costs) of using that route in which travel time is a major factor, particularly in congested conditions. Several decision rules stating the criteria by which users of the system select a route are possible. The simplest one, all-or-nothing assignment, assumes that link costs are fixed independent of flow and assigns trips to links that are part of the least-cost route. This assignment procedure had the tendency to give peculiar and unrealistic results.

This has led to the use of the capacity-constraint equilibrium assignment procedure. This method similarly determines minimum cost routes through the network, but also makes use of congestion functions to estimate mean travel times on links as a function of traffic flow. As flow builds up on a link and hence travel time increases on it, travellers become less inclined to use that link and may want to choose another one. Thus, a feedback loop between traffic flow and travel time is established and traffic volumes are iteratively re-assigned to the network until an equilibrium situation is reached.

A common strategy that is used for reaching this equilibrium situation is Wardrop’s first (user-optimising) principle, which means that no single driver can reduce his own travel time by choosing an alternative route under equilibrium conditions (e.g. Gawron, 1998). Strategic planning models are usually calibrated and validated with household travel survey data and independent field traffic data (traffic counts and speeds).

APPENDIX B – CONGESTION IN DRIVING CYCLES

Section 4.3 showed that non-linear trends are visible between travel speed and different congestion indicators. This Appendix further quantifies the level of association (correlation) between these variables.

Two variables are said to be correlated if changes in one variable are associated with changes in the other variable. A commonly used summary statistic is the Pearson product-moment correlation coefficient. This statistic can be used to quantify the linear relationship between two random variables, i.e. travel speed and different congestion indicators.

Since the relationships are often non-linear, another approach is needed. Therefore, the relationships (trends) are examined through the presentation of scatter plots, which show both the actual data and the “lines of best fit”. Each data point represents a specific driving cycle that was used in the development of a particular model.

The trends have been quantified for each emission model individually through regression analysis. A second order linear regression model with travel speed as the independent variable was fit to the data using the least-squares method:

$$\text{Congestion Indicator} = \beta_0 + \beta_1 v + \beta_2 v^2$$

where v represents travel speed. In some cases, a transformed predictor variable (inverse speed or logarithm of speed) was used to obtain a better regression fit. The coefficient of determination (R^2) has also been computed to quantify the strength of the relationship (goodness-of-fit) and is displayed in these charts.

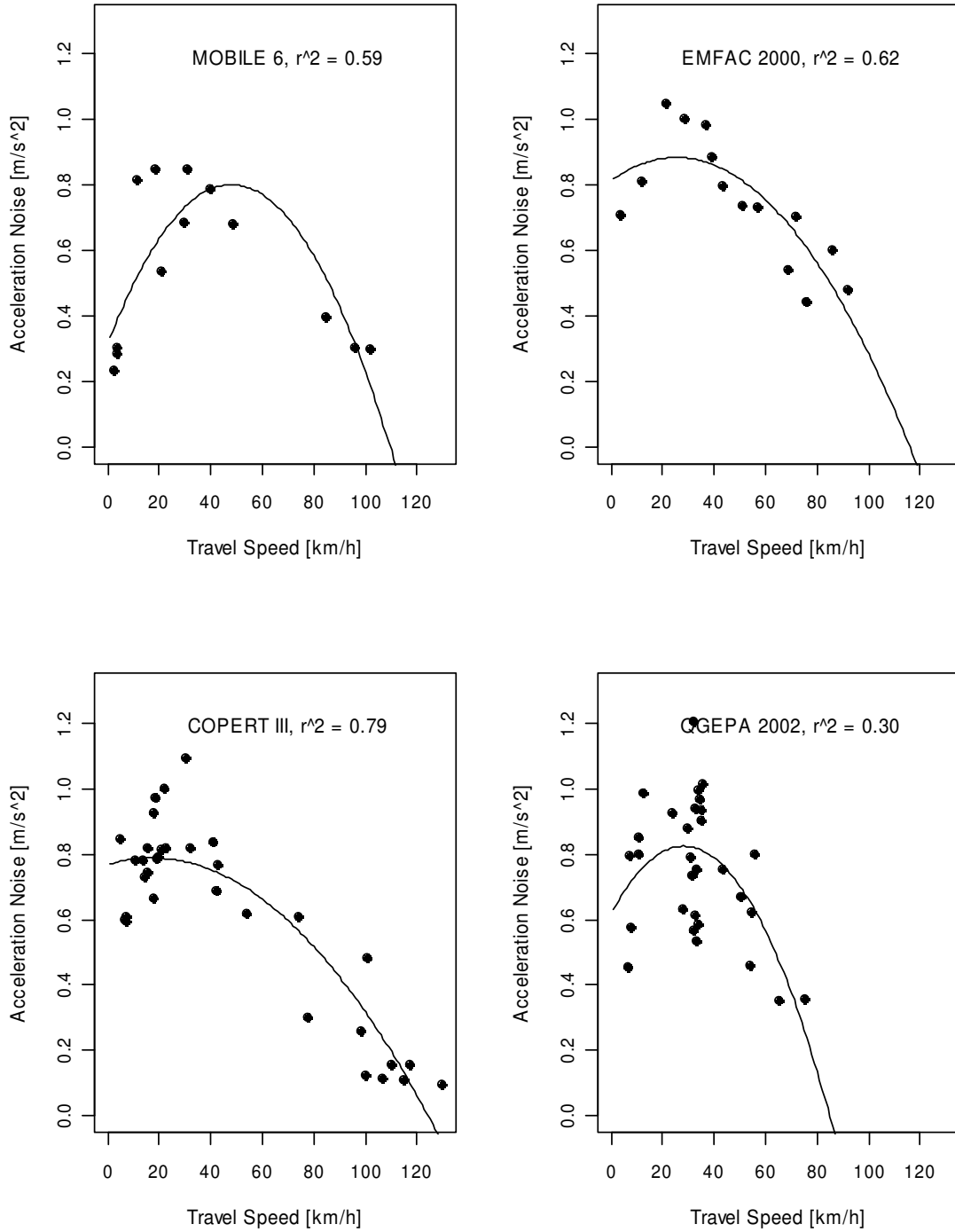


Figure B.1 – Travel Speed versus Acceleration Noise in 4 Emission Models

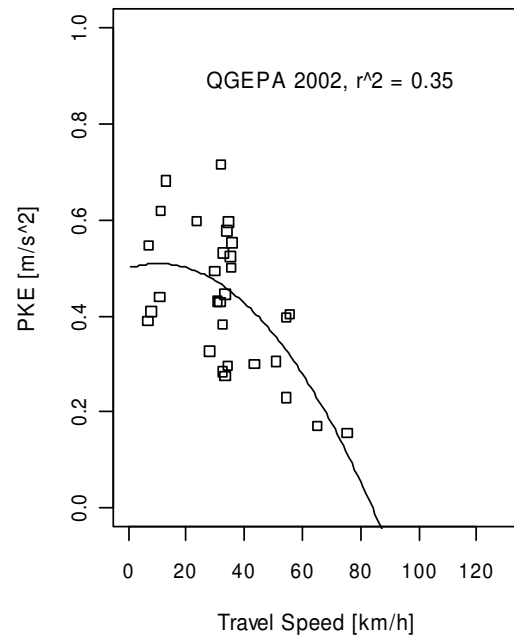
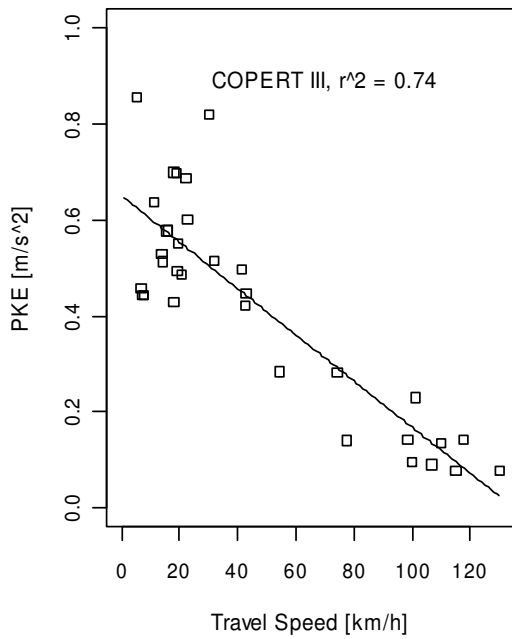
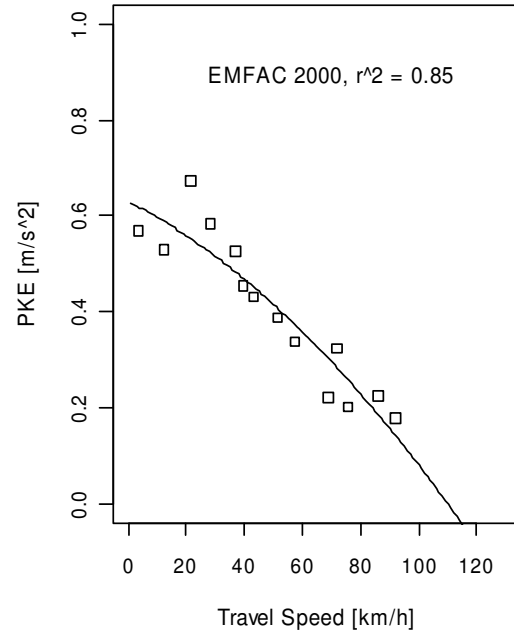
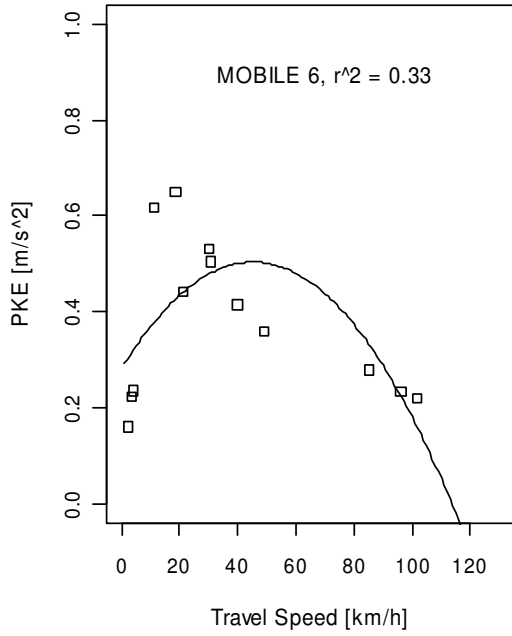


Figure B.2 – Travel Speed versus PKE in 4 Emission Models

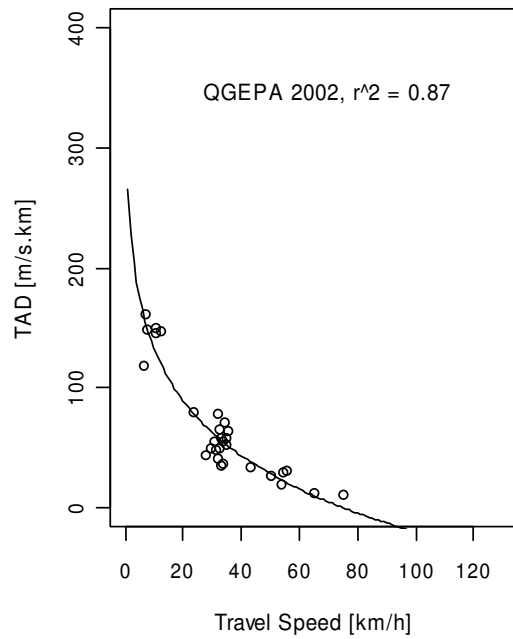
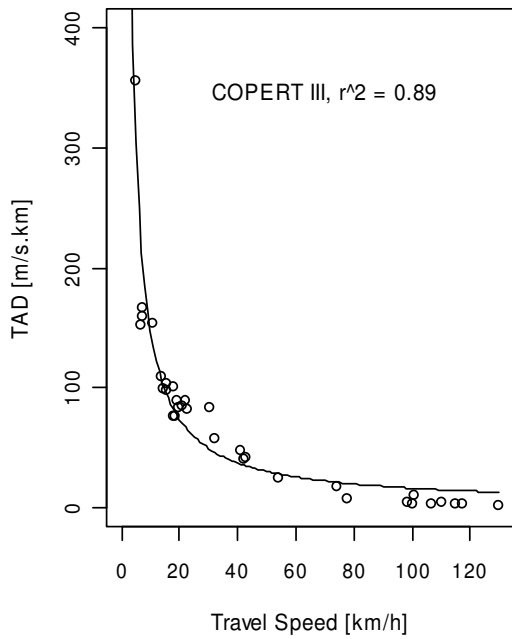
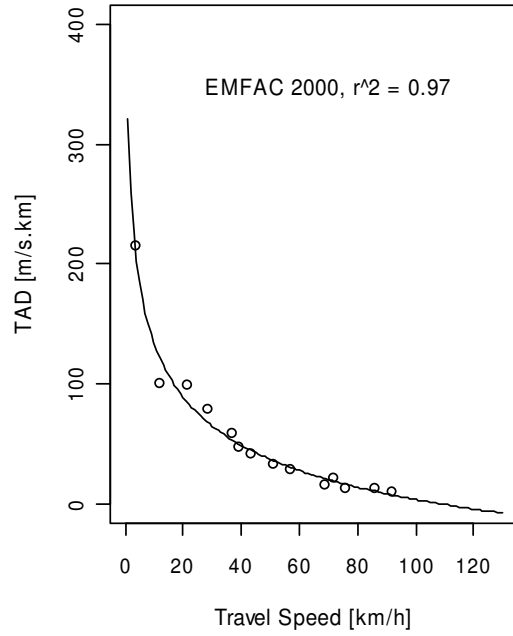
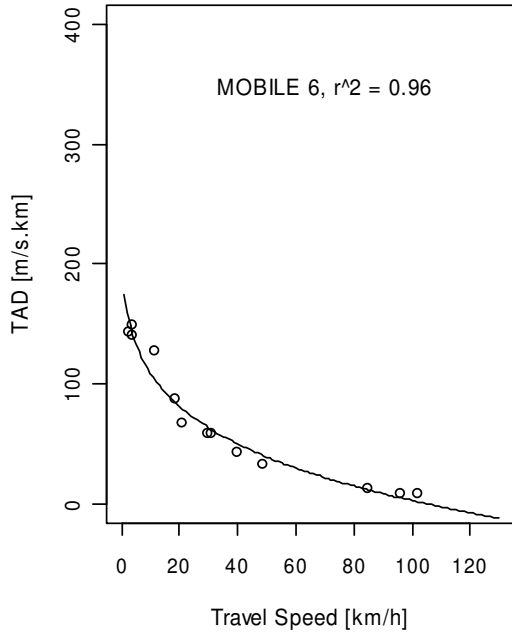


Figure B.3 – Travel Speed versus TAD in 4 Emission Models

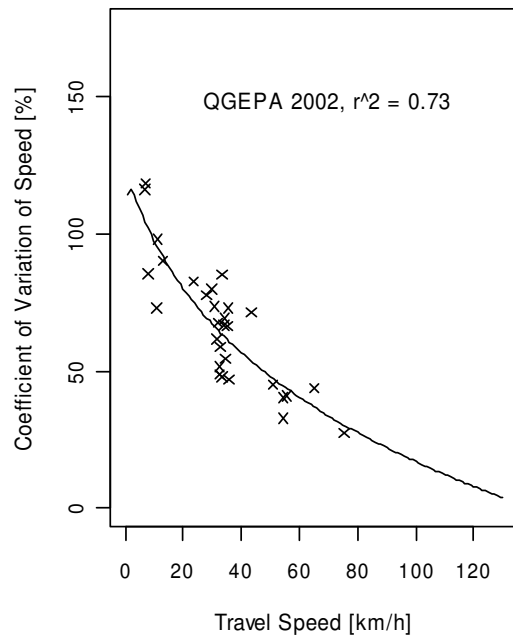
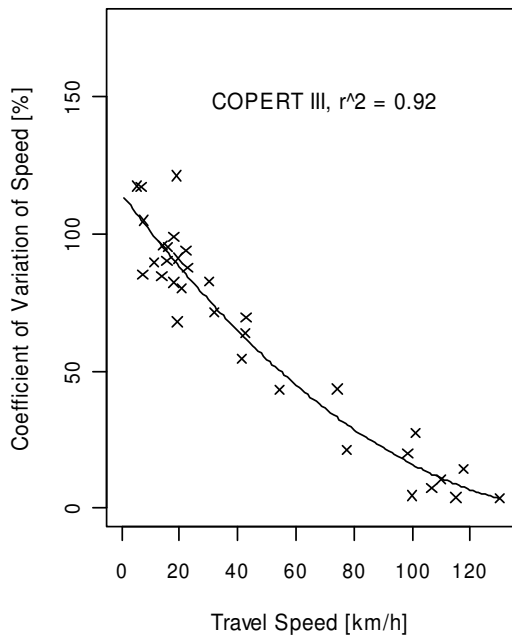
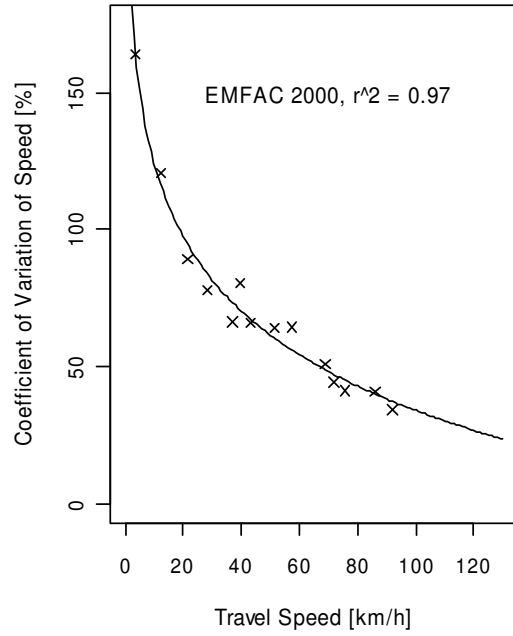
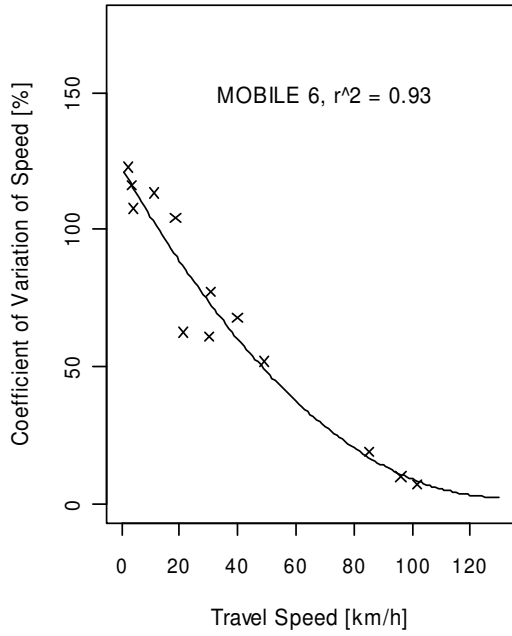


Figure B.4 – Travel Speed versus COV_{vt} in 4 Emission Models

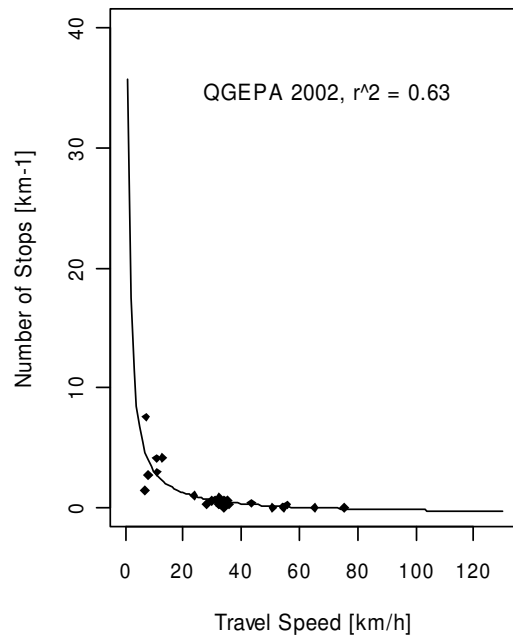
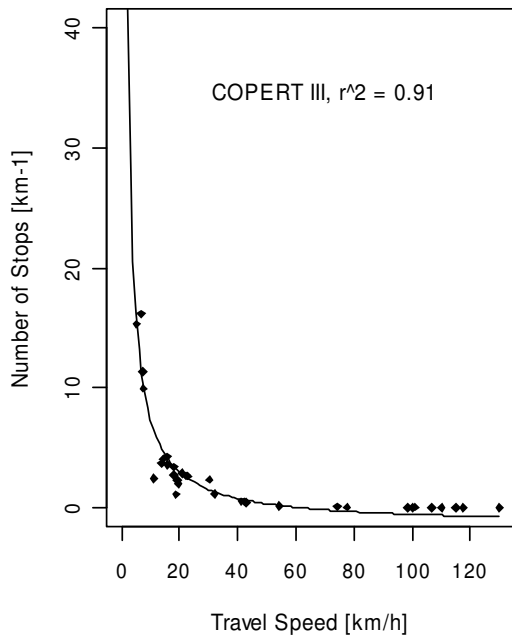
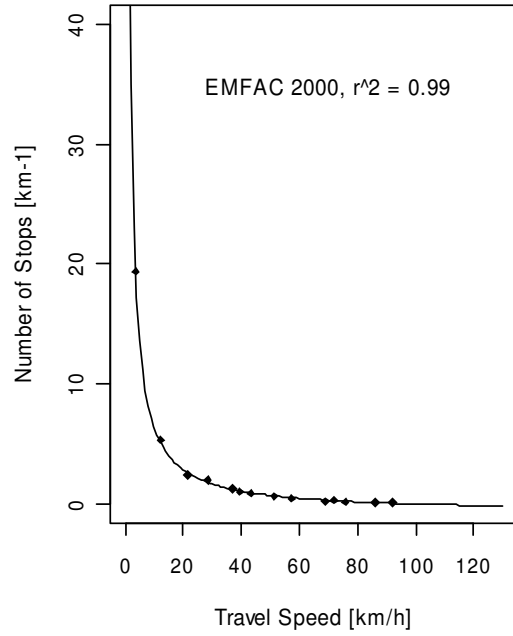
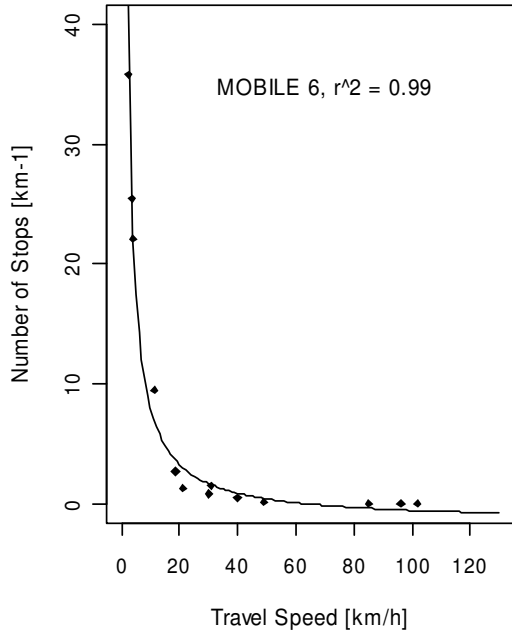


Figure B.5 – Travel Speed versus n_s^* in 4 Emission Models

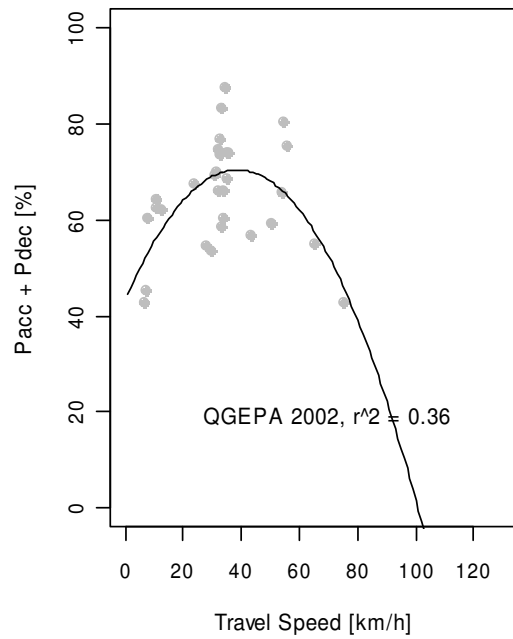
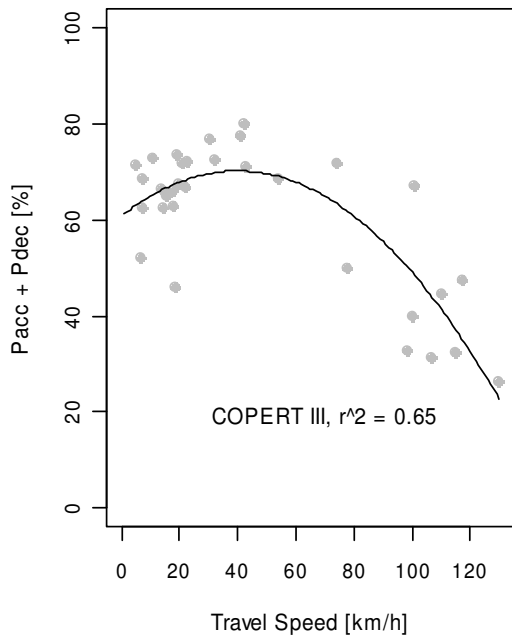
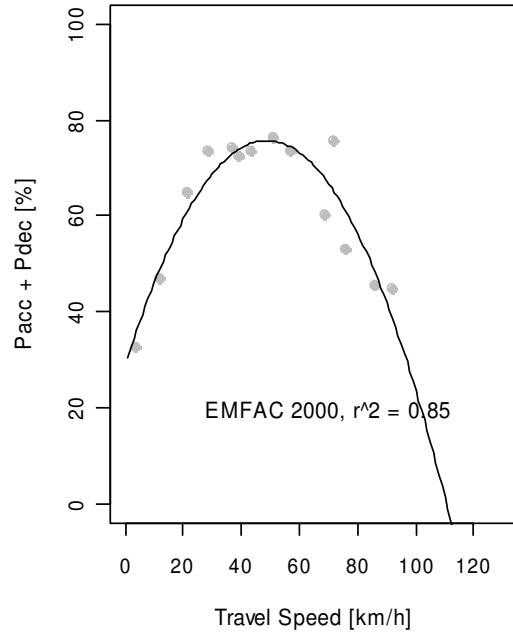
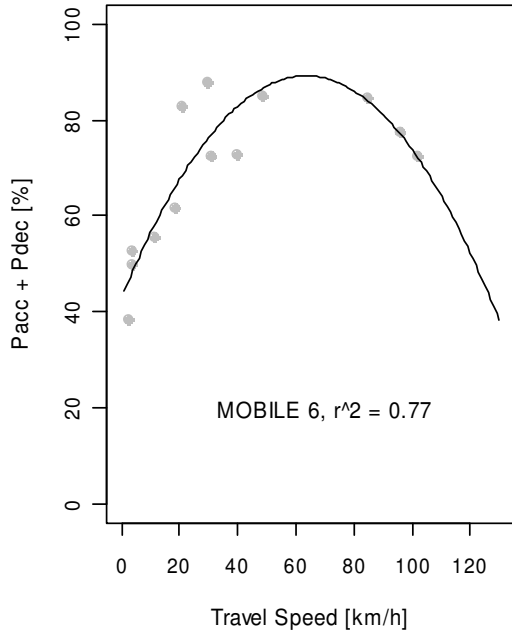


Figure B.6 – Travel Speed versus $\{P_{acc} + P_{dec}\}$ in 4 Emission Models

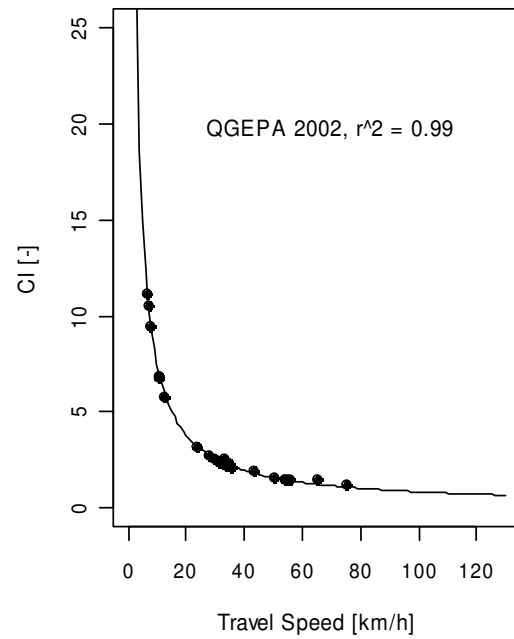
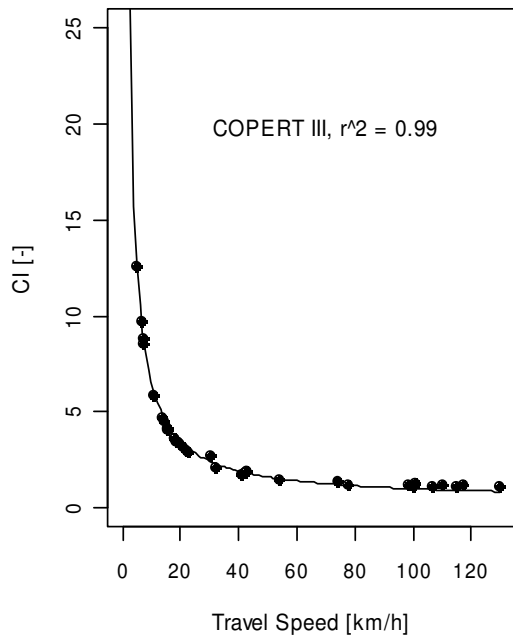
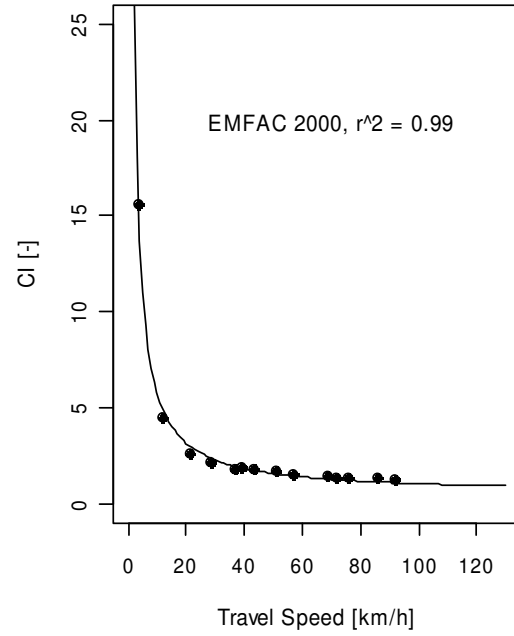
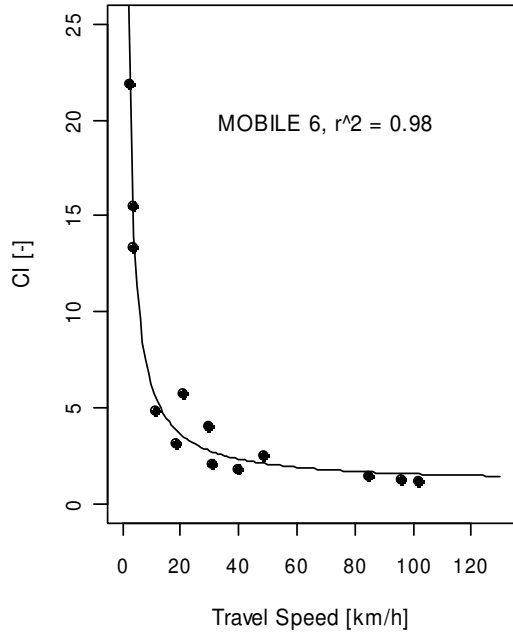


Figure B.7 – Travel Speed versus CI in 4 Emission Models

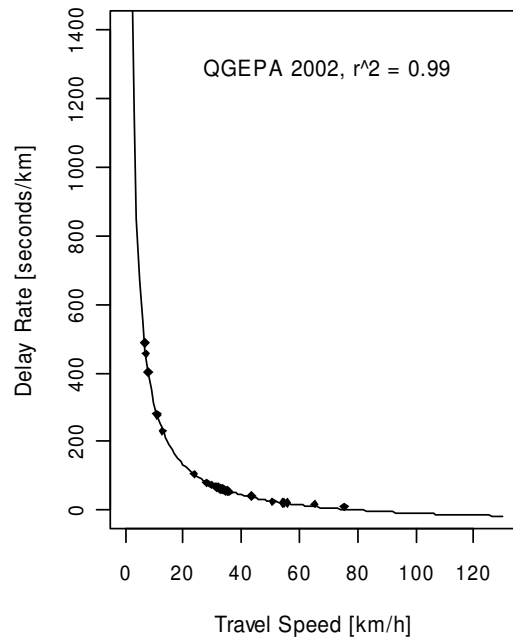
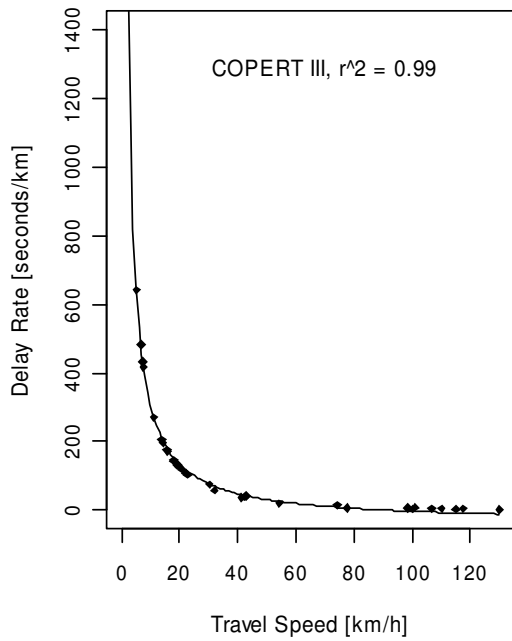
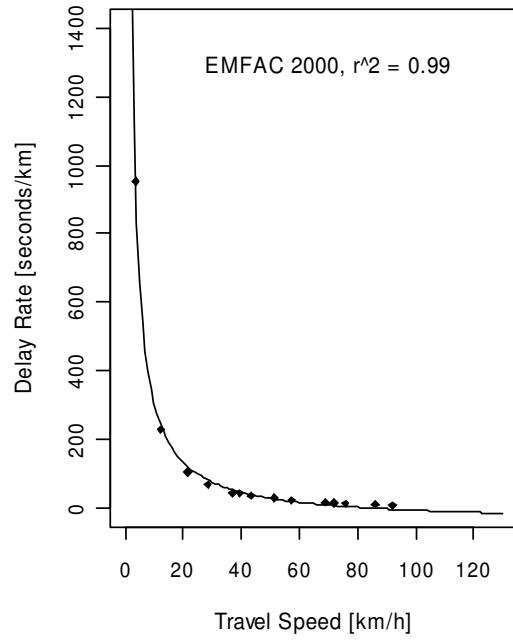
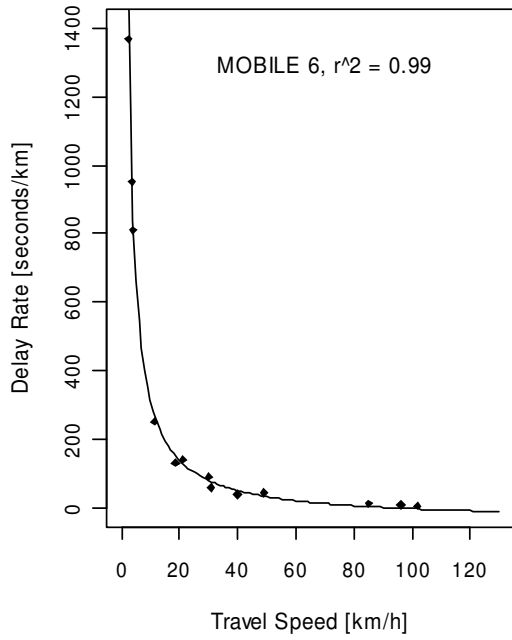


Figure B.8 – Travel Speed versus d^* in 4 Emission Models

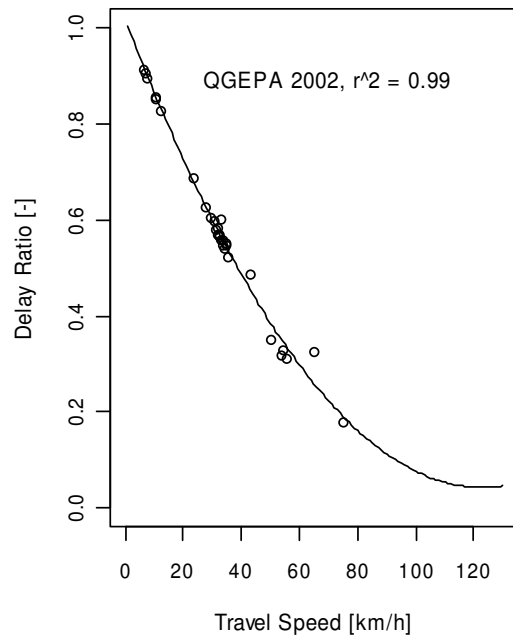
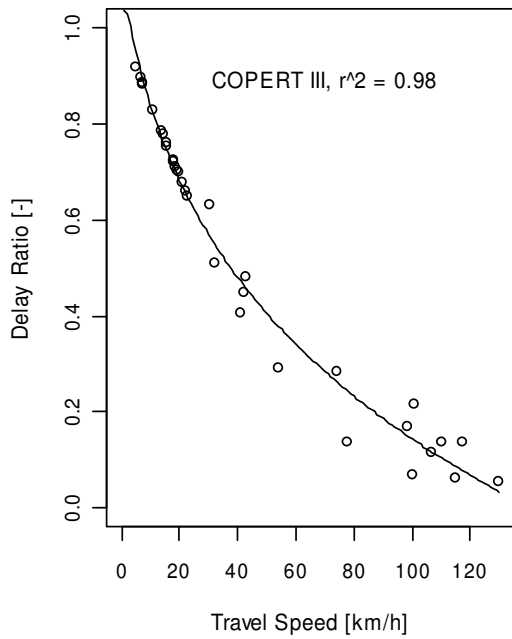
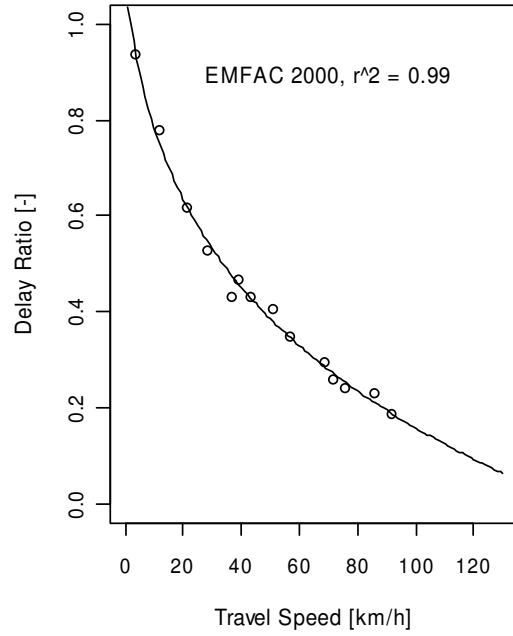
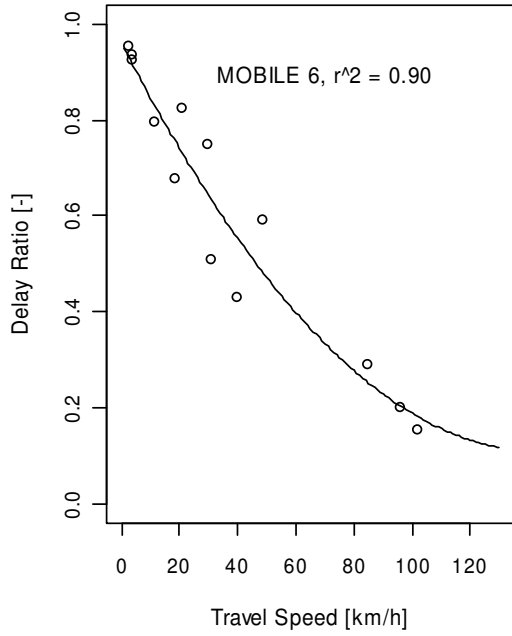


Figure B.9 – Travel Speed versus d_{ratio} in 4 Emission Models

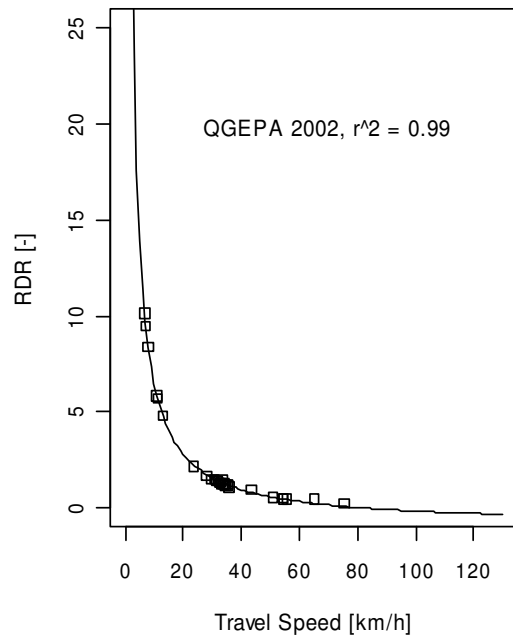
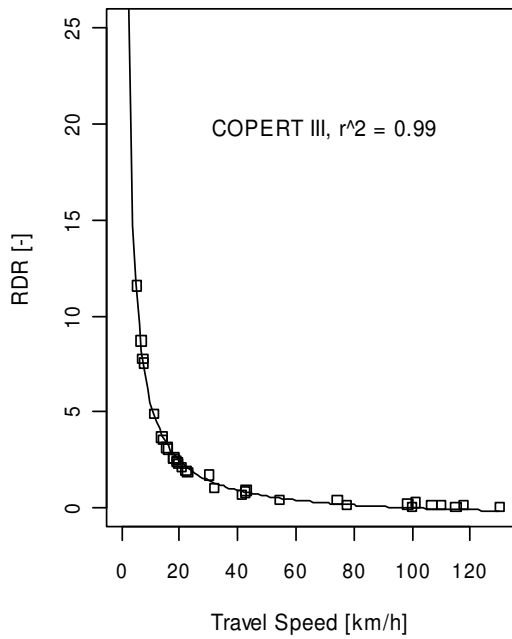
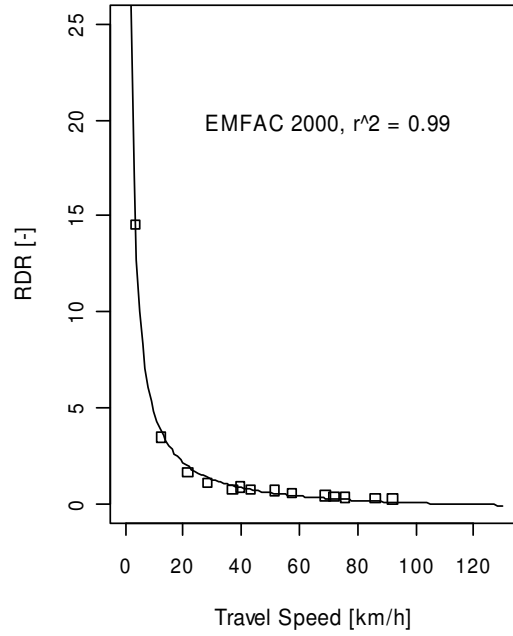
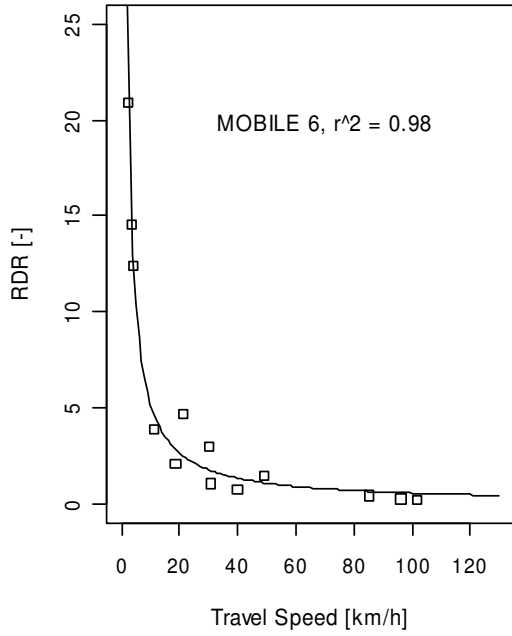


Figure B.10 – Travel Speed versus RDR in 4 Emission Models

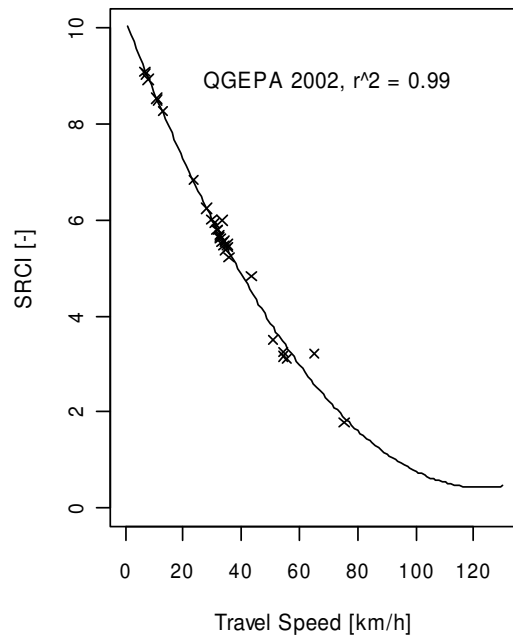
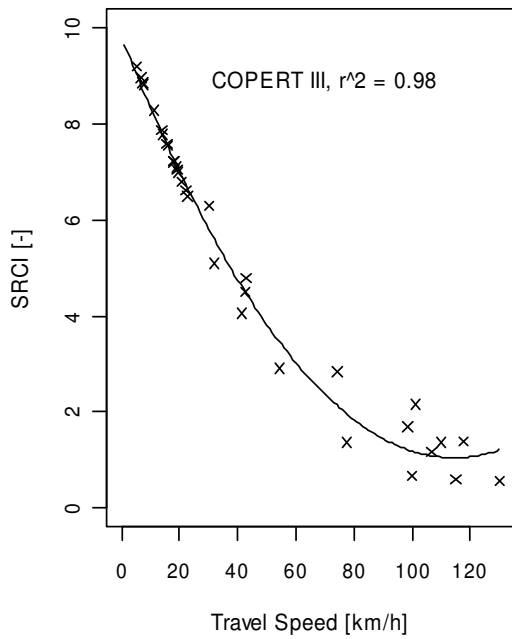
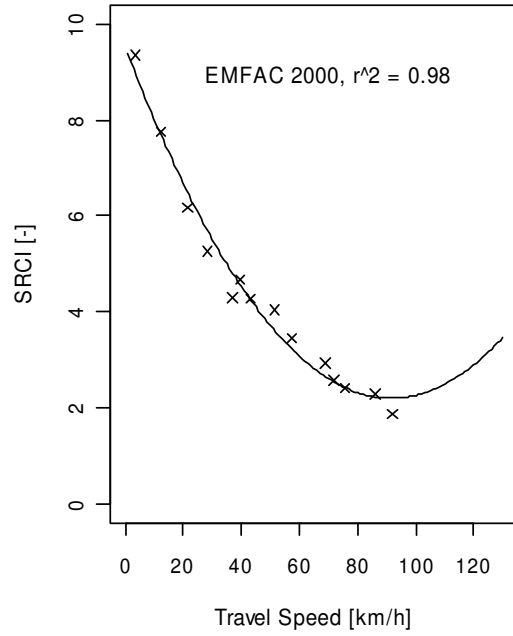
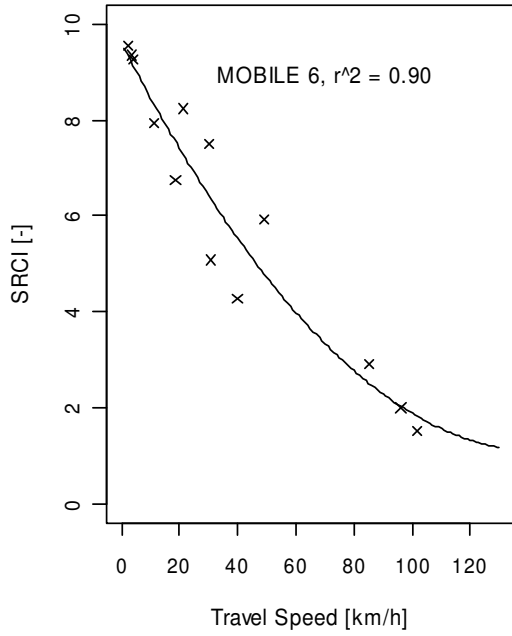


Figure B.11 – Travel Speed versus SRCI in 4 Emission Models

