

REPRINT

Guide to Fuel Consumption Analysis for Urban Traffic Management

D. P. BOWYER, R. AKÇELIK and D. C. BIGGS

REFERENCE:

BOWYER, D.P., AKÇELIK, R. and BIGGS, D.C. (1985). *Guide to Fuel Consumption Analysis for Urban Traffic Management*. Special Report SR No. 32. ARRB Transport Research Ltd, Vermont South, Australia.

NOTE:

This report is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this report, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this report may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research. This report was originally published by the Australian Road Research Board.

Guide to Fuel Consumption Analyses

for Urban Traffic Management

D.P. Bowyer, R. Akcelik and D.C. Biggs



DIRECTORS 1985 - 1986

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BOWYER, D.P., AKCELİK, R. and BIGGS, D.C. (1985) : GUIDE TO FUEL CONSUMPTION ANALYSES FOR URBAN TRAFFIC MANAGEMENT.
Australian Road Research Board. Special Report SR No. 32. 101 pages, including 33 figures, 25 tables and 3 Appendices.

KEYWORDS : Energy conservation/ fuel consumption/ mathematical model/ traffic/ evaluation (assessment)/ vehicle/ urban area/ specifications/ method/ design (overall design)/ estimation*

ABSTRACT : A substantial set of analysis techniques exists for the consideration of fuel consumption in urban traffic management. This report provides a guide to assist the traffic manager in selecting techniques which are appropriate to the various traffic management contexts. It is structured into two parts. Part A presents easy to use functions and graphs for estimating fuel consumption for a typical car. Part B provides a comprehensive guide to the use of techniques for fuel consumption analysis in urban traffic systems. The information requirement for the different phases of the traffic management process (i.e. diagnosis, design, implementation and evaluation) are briefly discussed. The primary interest in this guide is in the design phase, and traffic models which incorporate a fuel consumption model are the only practical means of considering fuel consumption in this phase. Fuel consumption models of four levels of detail are described and numerical examples are given to illustrate their use. The traffic models and associated fuel consumption models are presented as an hierarchy and the scale of traffic system to which each is appropriate is shown. These fuel consumption models are inter-related, forming part of the same modelling framework and the vehicle parameters are explicit at all model levels. Case studies are presented to demonstrate the choice, use and cost-effectiveness of selected traffic models in the design of particular management schemes.

ISBN 0 86910 220 6 Report

ISBN 0 86910 221 4 Microfiche

ISSN 0572 — 144X

OCTOBER 1985

Reprinted December 1986 with minor alterations

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Wholly set up, designed and printed at the Australian Road Research Board, Vermont South, Victoria. 1985

FOREWORD

A recent investigation of fuel consumption related to traffic management (Bowyer, Akcelik, Biggs and Bayley 1984) established that there exists a substantial set of analytical techniques which could assist in considering fuel consumption in urban traffic systems. However, the effective use of these techniques in practice was being limited by the lack of a suitable guide to aid selection of techniques which are appropriate to the various traffic management contexts. This document is intended to meet this need.

The requirement for fuel consumption information is likely to vary significantly across urban traffic management contexts. At one extreme is the micro-assessment of intersection operations under alternative forms of control. At the other is the evaluation of alternative traffic management programs in the total urban area.

The importance of fuel consumption information will also depend on the traffic management objectives which are being pursued. Two energy-related objectives in urban traffic management are the conservation of scarce resources and the maximisation of system efficiency. The importance of energy conservation will vary with the perceived or actual availability of energy resources. System efficiency is, however, a continuing concern in traffic and transport management. Fuel is one element of user costs and, perhaps, the most quantifiable. Thus fuel savings are likely to continue to be an important consideration in urban traffic management.

A major task in the traffic management process is the design of management schemes. This task calls for estimates of the impacts of alternative schemes on travel time, fuel consumption, safety, etc. to enable evaluation of the alternatives. Traffic models are often the only practical means of estimating the impacts of alternative traffic management schemes. The major focus of this guide is on the form and use of models to provide fuel consumption estimates in the scheme design phase. The guide has been structured into two parts in order to make the models as easy as possible to use and to also aid comprehensive assessments, which are appropriate in some traffic management contexts. These two parts are:

PART A: Presents easy to use functions and graphs for estimating fuel consumption. These represent a typical car in urban driving conditions and could provide a means of quickly estimating fuel consumption in a particular traffic situation. The relationship between fuel consumption models and traffic models is also shown.

PART B: Presents a comprehensive guide for the use of techniques for fuel consumption analyses in urban traffic systems. This part contains details of traffic models and fuel consumption functions. It should assist traffic engineers and managers in comprehensive assessments of fuel consumption changes associated with particular forms of traffic management.

ACKNOWLEDGEMENTS

The major funding for development of the guide has been provided through the National Energy Research, Development and Demonstration Program (NERDDP), administered by the Australian Department of Resources and Energy. Development of the guide has been directly assisted by the work of other researchers. In particular, the authors acknowledge the contribution of Dr H. Watson (University of Melbourne) and Mr P. Cotterill (R.J. Nairn and Partners). Valuable comment was also provided by participants in a workshop, conducted to review the guide.



ENERGY CONSERVATION AWARD

The Australian Road Research Board received the Institute of Transportation Engineers (U.S.A.) 1986 Transportation Energy Conservation Award, in memory of Fredrick A. Wagner, for research into energy savings from urban traffic management. This Guide is based on that research.

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NOTATIONS AND DEFINITIONS

		Units
a	Instantaneous acceleration rate (dv/dt)	km/h/s (or m/s ²)
\bar{a}	Mean acceleration rate	km/h/s
α	Fuel consumption per unit time while idling ($\approx t_i/3600$)	mL/s
β_1	Efficiency parameter relating fuel consumption to energy provided by the engine (small values of β_1 indicate high efficiency)	mL/kJ
β_2	Efficiency parameter relating fuel consumption to the product of inertial energy and positive acceleration, i.e. $aR_i dx$ (small values of β_2 indicate high efficiency)	mL/(kJ m/s ²)
d	Delay — the difference between interrupted and uninterrupted travel times which consists of stopped delay and deceleration-acceleration delays due to stops or slowdowns	s
E_k	Change in kinetic energy per unit mass per unit distance during an acceleration or deceleration ($\frac{1}{2}(v_f^2 - v_i^2)/(12960 x)$ where $x = x_a$ for acceleration or x_d for deceleration). Note that E_k is negative for deceleration	J/(kg m)
E_{k+}	Sum of changes in kinetic energy per unit mass per unit distance during positive acceleration(s) ($\approx \frac{1}{2} \sum (v_f^2 - v_i^2)/(12960 x)$ where $v_f < v_i$ and x is x_c for cruise model or x_s for running speed model)	J/(kg m)
EC	Engine capacity	L
F	Total fuel consumption	mL

F_a	Total fuel consumption during acceleration	mL	t	Time	s
F_c	Total fuel consumed while cruising ($= f_c x_c$)	mL	t_a	Acceleration time	s
F_d	Total fuel consumption during deceleration	mL	t_d	Deceleration time	s
F_i	Total fuel consumed while stopped ($= \alpha t_i$)	mL	t_i	Stopped (idling) time	s
f_c	Cruise fuel consumption per unit distance	mL/km	t_s	Time to travel along the total section distance, including all delays	s
$f'_{c,t}$	Constant speed cruise fuel consumption per unit time	mL/s	v	Instantaneous speed ($= dx/dt$)	m/s
$f'_{c,x}$	Constant speed cruise fuel consumption per unit distance	mL/km	v_c	Cruise speed — average speed while cruising uninterrupted by traffic control devices, allowing for speed fluctuations	km/h
f_h	Excess fuel consumption per stop or slowdown	mL/stop	v_f	Final speed of an acceleration or deceleration	km/h
f_i	Fuel consumption per unit time while idling ($= 3600\alpha$)	mL/h	v_i	Initial speed of an acceleration or deceleration	km/h
f_r	Average section fuel consumption per unit distance excluding idle periods	mL/km	v_r	Average running speed which includes the effects of acceleration and deceleration delays due to stops or slowdowns, but excluding the effect of stopped time ($= 3600 x_s/(t_s - t_i)$)	km/h
f_t	Fuel consumption per unit time	mL/s	v_s	Average travel speed along the total section distance, including the effects of all delays ($= 3600 x_s/t_s$)	km/h
f_x	Fuel consumption per unit distance	mL/km (or mL/m)	x	Distance	km (or m)
G	Per cent grade (negative for downhill)		x_c	Part of the total section distance travelled at average cruise speed (v_c) uninterrupted by traffic control devices	km
M	Mass of vehicle including occupants and other load	kg	x_a	Acceleration distance	km
R_T	Total 'tractive' force required to drive the vehicle	kN	x_d	Deceleration distance	km
R_D	Drag force on vehicle	kN	x_s	Total section distance	km
R_i	Inertial force on vehicle ($= Ma/1000$)	kN	$[f]_{a>0}$	$f = f$ if $a > 0$ 0 if $a \leq 0$	
R_G	Force on vehicle due to grade ($= 9.81 M (G/100)/1000$)	kN			

PART A
SUMMARY GUIDE TO ESTIMATION OF
FUEL CONSUMPTION



A.1. INTRODUCTION

There are two primary means of deriving estimates of fuel consumption for use in urban traffic management. These are on-road measurement of fuel consumption and the use of fuel consumption models. For some traffic management tasks and in some traffic systems, on-road measurement of fuel consumption could be the more cost-effective means. This is often the case for post-implementation assessment of a particular scheme. However, for other tasks, such as the design of a particular traffic management scheme, traffic models which incorporate a fuel consumption module will be the only practical means of estimating fuel consumption. This Part of the guide describes and demonstrates the use of four primary fuel consumption models and indicates their links to associated traffic models.

A.2. CAR FUEL CONSUMPTION MODELS

Easy to use functions and graphs for estimating fuel consumption are presented in this Chapter. These have been drawn out of the comprehensive guide to fuel consumption models which is presented in Chapter B.4.

The functions and graphs are given for a 'default car' in urban driving conditions. The car is defined by the parameters in *Table IV*, Section B.4.1 (page 29) and parameters for other cars are given in *Table XXI* (Appendix B). The functions have been calibrated using on-road driving data collected in Sydney, Australia. The models can be adjusted to reflect parameters for other vehicles and procedures for doing this are given in Chapter B.4.

The choice of fuel estimation function will depend on a number of factors. One factor is the availability of traffic variable estimates, either modelled or measured on-road. Another factor is the level of accuracy in fuel estimates which is required for the particular traffic management decision. Both of these factors require a clear understanding of the traffic context in which the management scheme is being considered.

To assist the user in choosing fuel consumption models and estimation procedures appropriate to particular traffic contexts, the areas of possible use and data requirements for each of the four levels of fuel consumption model are described. Worked examples are given showing estimation of fuel consumption for a particular micro-trip, based on the default car. A detailed consideration of the estimation accuracy of the fuel consumption models is given in Appendix C.

A.2.1 An Instantaneous Fuel Consumption Model

Areas of use Detailed assessment of the impacts of proposed traffic management schemes for individual intersections, road sections or small sub-area networks, and where instantaneous traffic data are available.

Data required Estimates of 'instantaneous' speed, v , and grade, G , for a car when driven through the particular traffic system. The time unit is typically 1 second and the speed data must be of sufficient accuracy to calculate the instantaneous acceleration rates, a .

Model The fuel consumption rate (mL/s) for the default car can be estimated by

$$f_t = 0.444 + 0.090 R_T v + [0.054 a^2 v]_{a > 0} \quad \text{for } R_T > 0$$

$$= 0.444 \quad \text{for } R_T \leq 0$$

where

$$R_T = 0.333 + 0.00108v^2 + 1.200a + 0.118G$$

and units are, f_t = mL/s, v = m/s, a = m/s² and G is per cent grade (SI units are appropriate for this level of model).

Example

The speed-time trace in *Fig. 1* represents the instantaneous speeds for a car travelling over a road section comprised of 0.65 km prior to a traffic signal and 1.05 km after the signal. The total micro-trip takes 118 seconds and involves a cruise-deceleration-idle-acceleration-cruise cycle. Assume that there is zero grade. Estimate the total fuel consumed during this micro-trip for the typical car.

Even with this small example there are 118 speed measurements. Thus a computer program considerably reduces the work involved in calculating the instantaneous fuel consumption rates from the above equation. These rates are also plotted in *Fig. 1*.

For example, consider the simple case at the point where $t = 30$ seconds at which speed is constant. The fuel consumption rate is calculated as follows:

$$v = 60 \text{ km/h} = 16.7 \text{ m/s and } a = 0 \text{ m/s}^2$$

$$R_T = 0.333 + 0.00108 \times 16.7 \times 16.7 = 0.6331 \text{ kN}$$

$$f_t = 0.444 + 0.090 \times 0.6331 \times 16.7 = 1.39 \text{ mL/s}$$

By summing the instantaneous values, the total fuel consumption over the complete micro-trip shown in *Fig. 1* is found to be 231 mL.

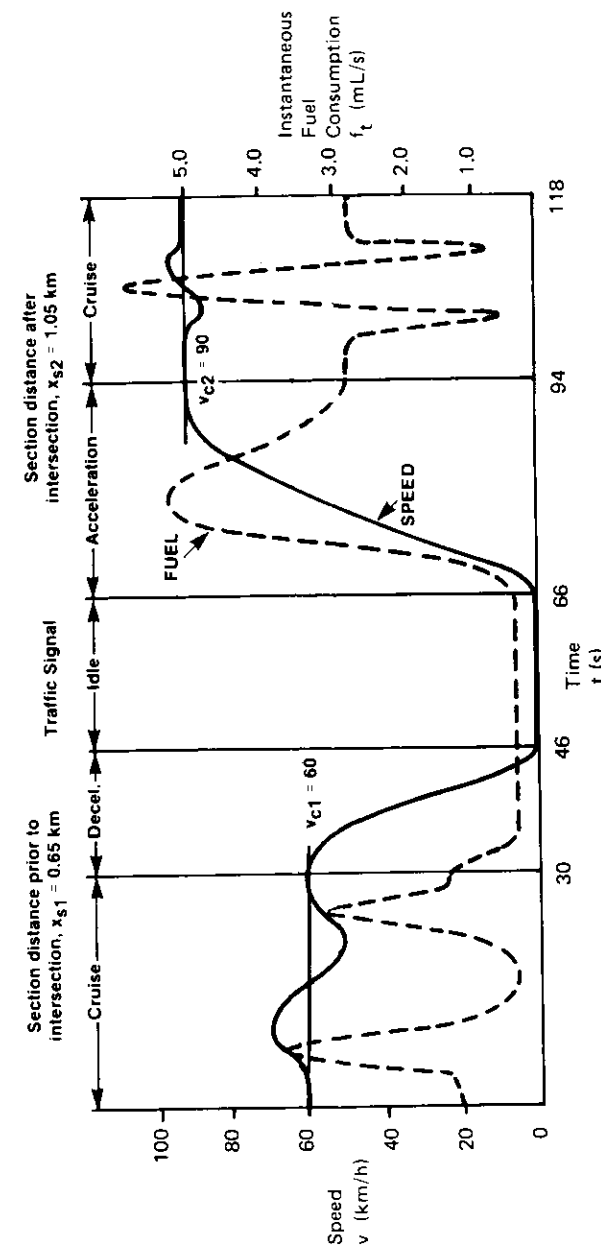


Fig. 1 — Speed-time trace and estimated instantaneous fuel consumption

A.2.2 An Elemental Model of Fuel Consumption

Areas of use As for the instantaneous model, but where only cruise speeds, or initial and final speeds in each driving mode (i.e. cruise, idle, deceleration and acceleration), are available.

Data required Average cruise speed, v_c , stopped time, t_i , section distance, x_s , and average grade for each intersection or road section in the traffic system. More accurate estimates will be obtained if initial and final speeds in each acceleration and deceleration are known. The differences in estimation accuracy are discussed in Section B.4.3.

Model Total fuel consumption (mL) over a cruise-deceleration-idle-acceleration-cruise cycle (as, for example, in Fig. 1) is estimated for the default car by summing the fuel consumed during each driving mode:

$$F_s = f_{c1}(x_{s1} - x_d) + F_d + 0.444 t_i + F_a + f_{c2}(x_{s2} - x_a)$$

where

f_{c1} , f_{c2} are the cruise fuel consumption rates for the initial and final cruise speeds, v_{c1} and v_{c2} respectively, and can be found from Fig. 2, and

F_a , F_d , x_a and x_d can be found from Figs 3, 4 and 5 for given initial deceleration and final acceleration speeds and zero grade.

The section distance prior to stop, x_{s1} (km), and after stop, x_{s2} (km) and the stopped time t_i are known. The excess fuel consumed during a deceleration and an acceleration from speed v_c to zero and back to v_c compared to cruising the same distance at v_c is shown in Fig. 6. The procedure for calculating the excess fuel from the elemental model is given in Section B.4.3.5.

Example

Estimate the total fuel consumed by a car over sections of road, x_{s1} and x_{s2} , prior to and after a traffic signal. The vehicle follows the speed-time trace given in Fig. 1.

From Fig. 1 initial and final speeds in each drive mode are: $v_{c1} = 60$ and $v_{c2} = 90$ for the two cruise modes, $v_i = 60$ and $v_i = 0$ for deceleration, and $v_i = 0$ and $v_i = 90$ for acceleration. Section distances are $x_{s1} = 0.65$ km and $x_{s2} = 1.05$ km. Total fuel consumption is calculated

as follows:

$$F_s = 92 (0.65 - 0.16) + 10 + 0.444 \times 20 \\ + 96 + 113 (1.05 - 0.44) = 229 \text{ mL}$$

This compares with 231 mL calculated using the instantaneous model. More generally, estimates based on the elemental model have been found to be within 10 per cent of the instantaneous model values in 85 per cent of cases. On average, the elemental model estimated section fuel consumption with errors of less than 2 per cent.

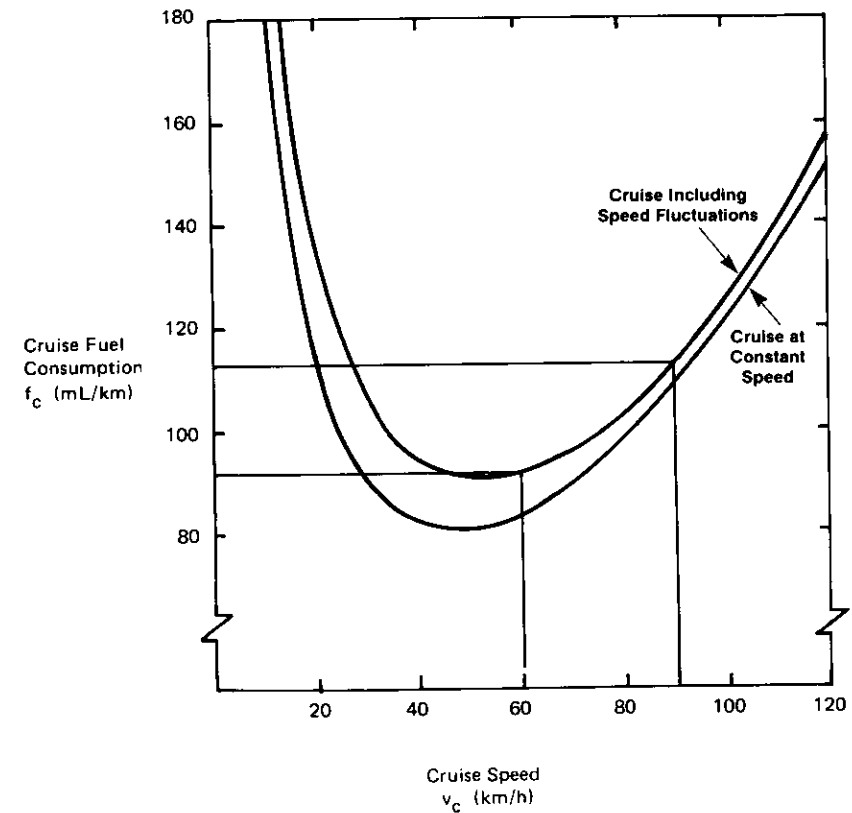


Fig. 2 — Cruise fuel consumption rate as a function of average cruise speed

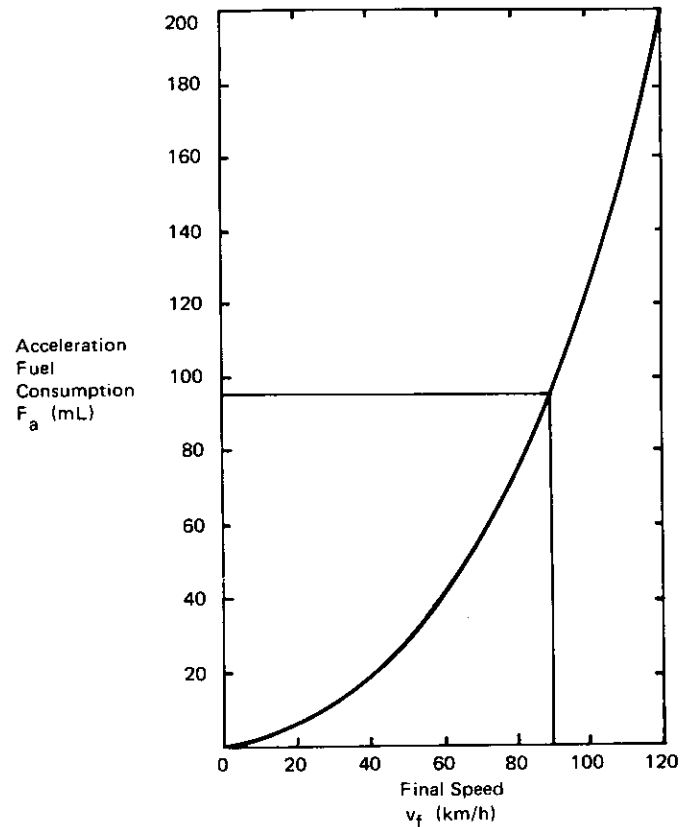


Fig. 3 — Acceleration fuel consumption as a function of final speed

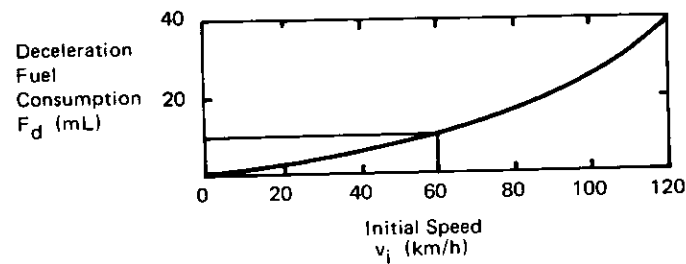


Fig. 4 — Deceleration fuel consumption as a function of initial speed

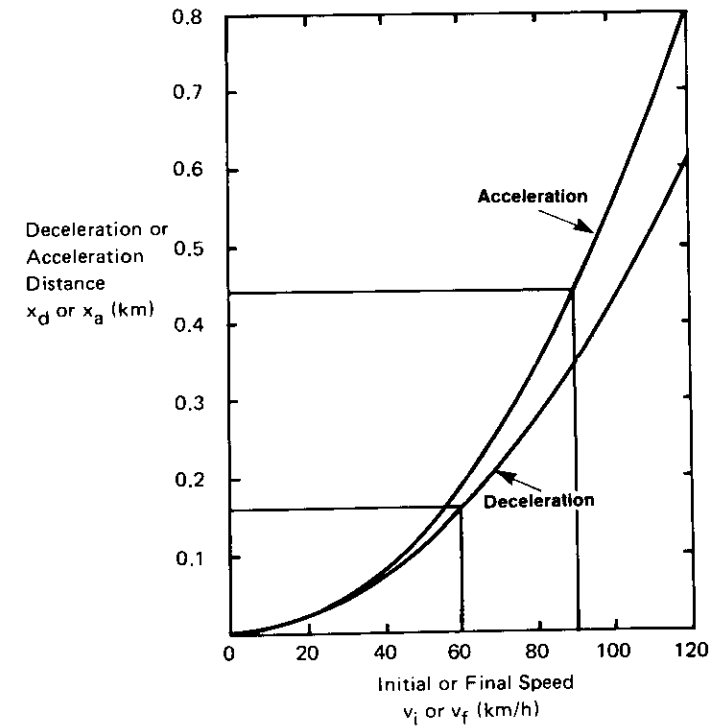


Fig. 5 — Deceleration and acceleration distances as a function of initial and final speeds

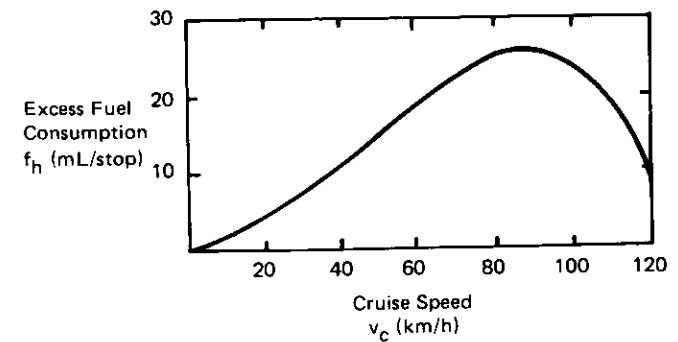


Fig. 6 — Excess deceleration-acceleration fuel consumption as a function of cruise speed

A.2.3 A Running Speed Model of Fuel Consumption

Areas of use For estimation of total fuel consumption for a trip, but not for the design of traffic management schemes and where running speed and stopped time data are available. A trip will be typically longer than 1 km.

Data required Travel time, t_s , distance, x_s , and stopped time, t_i , over the total trip. Actual values of positive kinetic energy changes can be used if initial and final speeds in each acceleration are known. The resulting accuracy increase is considered in Section B.4.4.

Model Total fuel consumption for the default car over a section of length, x_s , is estimated by

$$F_s = x_s f_r + 0.444 t_i \text{ (mL)}$$

where

f_r is the fuel consumption per unit distance, excluding stopped time effects, and can be found from Fig. 7 for a given running speed, v_r :

$$v_r = 3600 x_s / (t_s - t_i)$$

The values of x_s (km) and stopped time, t_i (s), are known.

Running speed and idle time can be expressed as functions of the average travel speed (eqns(43) and (44)). Thus, the running speed model can be applied at a trip or network level where only average travel speed, v_s , is known. Fig. 8 shows the relationship between the fuel consumption rate per unit distance, f_x , and v_s , using the running speed model. Total fuel consumption is then estimated by $F_s = x_s f_x$.

Example

Estimate the total fuel consumed for the micro-trip depicted in Fig. 1 using the running speed model.

From Fig. 1, $x_s = 0.65 + 1.05 = 1.7$ km, $t_s = 118$ s and $t_i = 66 - 46 = 20$ s. The average running speed is therefore,

$$v_r = 3600 \times 1.7 / (118 - 20) = 62.4 \text{ km/h}$$

and total section fuel consumption is:

$$F_s = 1.7 \times 106 + 0.444 \times 20 = 189 \text{ mL}$$

In this example the running speed model underestimates total fuel consumption considerably (189 compared to 231 mL for the instantaneous model). This is due, in part, to the default estimates of the total positive kinetic energy change as discussed in Section B.4.4. Generally the model is better suited to estimating fuel consumption over trips, rather than short road sections as in this example.

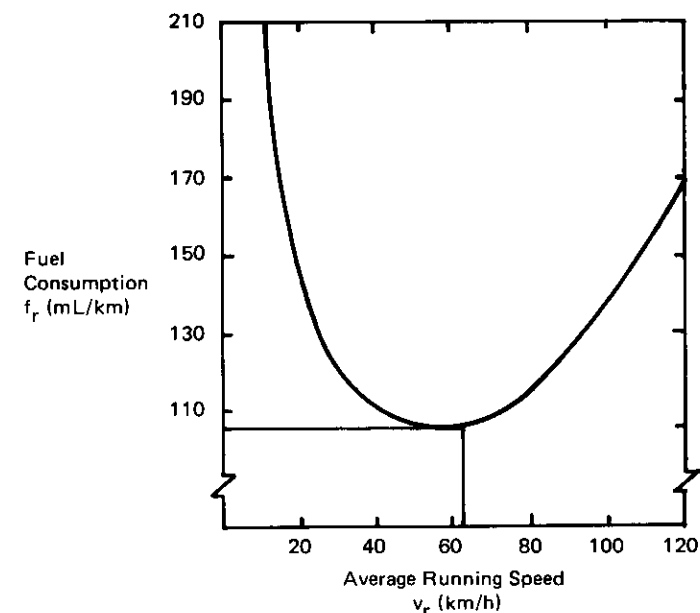


Fig. 7 — Fuel consumption per unit distance, f_r , as a function of average running speed

A.2.4 An Average Travel Speed Model of Fuel Consumption

Areas of use For estimation of total fuel consumption in large urban traffic systems and for assessing the impacts of *transport* management schemes which are likely to impact on average speeds and the level of travel demand. This model is accurate only for average travel speeds less than 50 km/h.

Data required Vehicle travel distance, x_s , and average travel speed, v_s , or travel time, t_s .

Model Total travel fuel consumption for the default car is estimated by

$$F_s = x_s f_x \text{ (mL)}$$

where

f_x can be found from Figs 8 or 9 for a given average travel speed ($v_s = 3600x_s/t_s$), and x_s (km) is known.

The dependence of the estimation function, f_x , on driving environment is shown in Fig. 8. When average travel speeds are greater than 50 km/h, the running speed model, with running speed and idle time estimated from average travel speed, should be used. This fuel consumption rate is also included in Fig. 8. The fuel consumption rate, f_x , is also dependent on car size as shown in Fig. 9. The method for adjusting the fuel consumption models to suit different vehicle types is given in Chapter B.4.

Example

Estimate the total fuel consumption for the micro-trip shown in Fig. 1 using the average travel speed model.

Applying the average travel speed model to the micro-trip given in Fig. 1, fuel consumption is estimated using the 'other urban' driving environment in Fig. 8 by:

$$F_s = 1.7 \times 105 = 179 \text{ mL}$$

However, as the average travel speed is greater than 50 km/h, the running speed model based on the average travel speed should be used and fuel consumption is estimated from Fig. 8 to be:

$$F_s = 1.7 \times 110 = 187 \text{ mL}$$

These estimates are significantly less than the instantaneous estimate (231 mL) and in general, models using average travel speed are too coarse to give accurate estimates of fuel consumption in this micro-trip context. Higher accuracy is usually obtained for estimates of total fuel consumption over long trips or traffic networks.

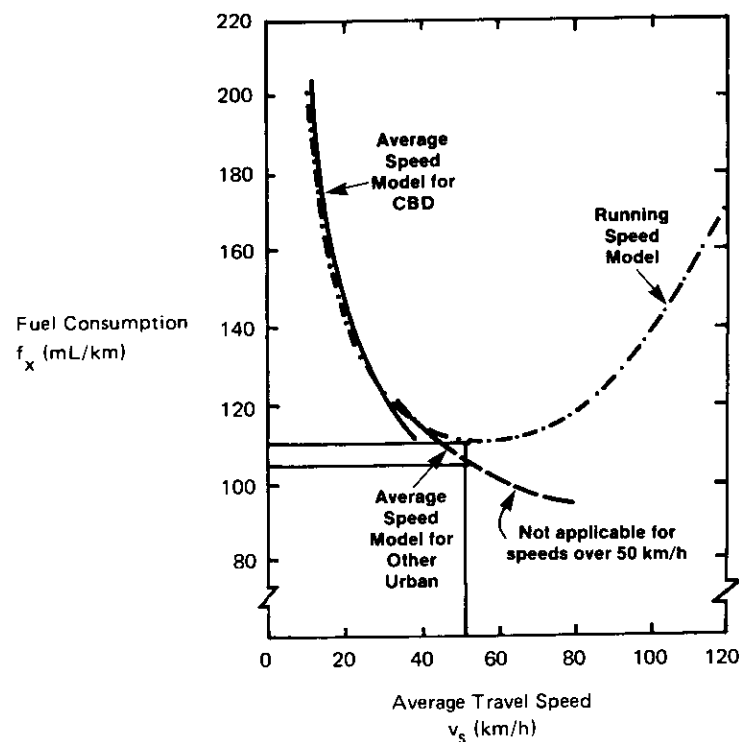


Fig. 8 — Fuel consumption per unit distance as a function of average travel speed

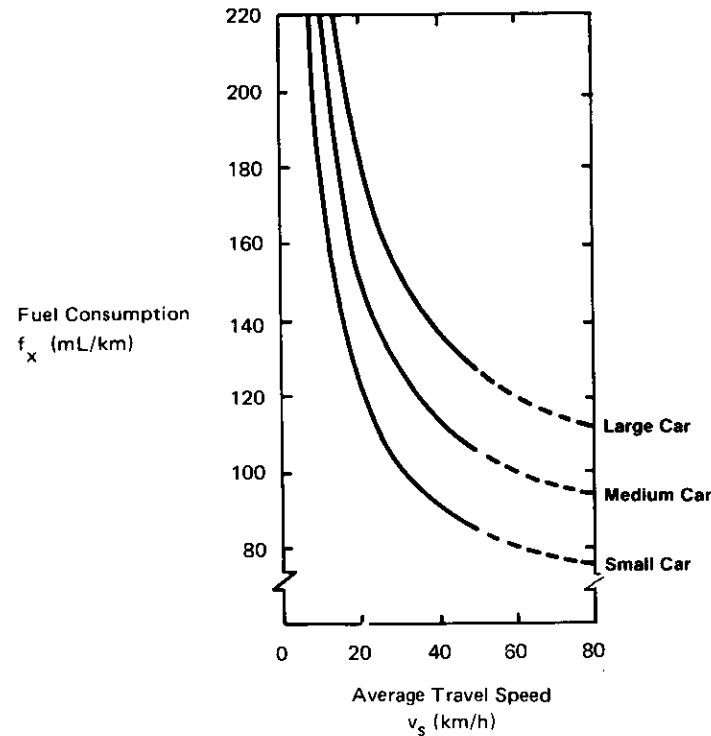


Fig. 9 — Fuel consumption per unit distance as a function of average travel speed for a small, medium and large car in general urban driving

A.3. LINKS BETWEEN TRAFFIC SYSTEMS, TRAFFIC MODELS AND FUEL CONSUMPTION MODELS

Traffic models are a primary means of estimating traffic variables and, thus, total fuel consumption in a traffic system. There is a wide range of both traffic systems and forms of traffic management techniques to be considered in traffic management practice. Thus the choices of the traffic model and the form of fuel consumption module within the traffic model are important for their effective use in a particular management situation.

A number of factors must be addressed when choosing the traffic model and ensuring that the fuel consumption module is correctly specified. These factors are discussed in Chapter B.3, and their relevance for particular design situations demonstrated through the case studies in Chapter B.5.

Tables I and II provide a summary of the information which is relevant to traffic management practice, at least in Australian urban contexts. Several points should be stressed. Firstly, an hierarchy of models exists and each traffic model is appropriate to a particular scale of traffic system. Models are not sufficiently accurate if used below their indicated level and would be unnecessarily costly if used above their level. The second point is that the fuel consumption module should contain the most appropriate model and calculate fuel at the appropriate level. For example, the SATURN traffic model is appropriate for the analysis of macro-meso scale systems, i.e. 'small' area analyses. The structure of SATURN is such that traffic variables are calculated for individual road sections. An elemental model of fuel consumption is therefore suitable for use with SATURN.

TABLE I

TRAFFIC VARIABLES REQUIRED FOR EACH FUEL CONSUMPTION MODEL

Fuel Consumption Model	Required Traffic Variables*
Average Speed	x_s, t_s for each trip or network
Running Speed	
Option a.	x_s, t_s for each trip or road section
Option b.	t_s, t_i, x_s for each trip or road section
Option c.	t_s, t_i, x_s, E_{k+} for each trip or road section
Elemental	
Option a.	x_s, t_i, v_c , number of stops for each road section
Option b.	x_s, t_i and v_i, v_f for each acceleration/deceleration, for each road section
Instantaneous	v, G for each second over a road section

* Variables defined in Notations and Definitions section at start of report.

TABLE II

TRAFFIC MODELS AND FUEL CONSUMPTION MODULES
APPROPRIATE TO LEVELS OF TRAFFIC SYSTEM SCALE

<i>Traffic System Scale</i>	<i>Traffic Model†</i>	<i>Fuel Consumption Module Specification*</i>
Macro	UTPS	(a) No freeways: use average speed model, calculated at the total network level. (b) With freeways: use running speed model (option a) for freeways, calculated at the trip level.
	LATM	Running speed model (option b), calculated at road section level.
Macro/Meso	SATURN	Elemental model (option a) calculated at road section level.
	TRANSYT	Elemental model (option a) calculated at the link level.
Meso/Micro	SCATSIM	Elemental model (option b)
	SIDRA	Elemental model (option b) calculated at the lane level.
Micro	MULTSIM	Instantaneous model, calculated at 1 second intervals.
	INSECT	Instantaneous model, calculated at 1 second intervals.

* The options for fuel consumption models are given in *Table I*.

† References which give details of traffic models are given in footnotes to *Table III*, Chapter B.3.

PART B

COMPREHENSIVE GUIDE TO FUEL
CONSUMPTION ANALYSIS



B.1. INTRODUCTION

This part of the report is intended to provide a comprehensive guide for the use of techniques for fuel consumption analyses in urban traffic systems. It should assist traffic engineers and managers in detailed assessment of fuel consumption changes associated with particular forms of traffic management. A secondary aim is to serve as a teaching aid, particularly in tertiary level studies.

There exists a large body of analytical aids to fuel consumption analyses. Recent research, particularly that reported by Bowyer *et al.* (1984), has revealed the need for careful selection of fuel-related analytical aids for particular management tasks to ensure cost-effective use of these aids. Thus, this part of the report addresses three primary questions:

- (a) how do fuel consumption considerations vary with the management task?;
- (b) what are appropriate models and analytical procedures for each task, particularly the scheme design task?; and
- (c) how can these be cost-effectively employed in the design task?

The report is structured as follows.

Chapter B.2. The primary objectives involved in traffic management and the forms of fuel consumption information required for each task are briefly discussed. This provides a basis for the detailed consideration (in Chapters B.3, B.4 and B.5) of analytical techniques appropriate to the *scheme design* task.

Chapter B.3. The notion of a traffic analysis hierarchy is introduced and traffic analysis models appropriate to each level of the hierarchy and to particular forms of traffic management are briefly described.

Chapter B.4. Four car fuel consumption models are described, in increasing order of aggregation. Simple worked-examples are given to demonstrate the calculation procedure with each model.

Chapter B.5. Several case studies are presented. These relate to the design of particular management schemes and are intended to demonstrate the choice and use of the models described in Chapters B.3 and B.4 in the scheme design task.

B.2. CONSIDERING FUEL CONSUMPTION IN TRAFFIC MANAGEMENT

B.2.1 TRAFFIC MANAGEMENT OBJECTIVES

A number of objectives are commonly pursued through traffic management. In designing a management scheme, the traffic manager may be required to consider objectives relating to safety, air pollution, traffic performance (e.g. delays), energy consumption, property access and traffic intrusion into residential areas.

In some traffic contexts, the minimisation of delays might be consistent with, and more important than, the reduction of fuel consumption. In these contexts fuel analyses could be of minor value in traffic management decisions. On the other hand, some of these objectives, such as minimising intrusion and minimising fuel consumption, can be in conflict, particularly in management at the local traffic system level. In these contexts, management decisions might be sensitive to the estimation of fuel consumption. Therefore, important initial considerations in planning a management action in a particular situation are the enunciation of objectives and determination of relevant constraints and performance criteria. These considerations bear directly on the need for, and desirable form of, fuel consumption analysis.

Two energy-related objectives are the conservation of scarce resources and the maximisation of system efficiency. The importance of energy conservation will vary with the perceived or actual availability of energy resources, particularly oil-based fuels. System efficiency is, however, a continuing concern in traffic and transport management. Fuel is one element of system cost and, perhaps, the most quantifiable. Thus fuel savings are likely to continue to be an important consideration in many urban traffic management schemes.

B.2.2 INFORMATION FORMS FOR MANAGEMENT TASKS

Published guides to fuel consumption estimation in traffic management place a strong emphasis on ease of use of techniques. They typically provide graphs of fuel consumption rates as the basis for estimating fuel consumption, with the forms of graphs and estimation processes varying in complexity between the guides. Extracts from several published guides are given in Appendix A.

A major limitation with all of the existing guides is that they do not explicitly recognise the variation in required information forms and levels of accuracy across the various traffic and transport management tasks. It is necessary to consider the differing information forms and accuracy as a basis for presenting a guide which will encourage cost-effective fuel consumption analyses in traffic management practice. The information forms

and accuracy can be conveniently considered with regard to diagnosis and design, and implementation and evaluation. These are considered below.

B.2.2.1 Diagnosis and Design

Traffic management actions are commonly a response to the detection of congestion. As will be seen later (Section B.5.1) management of non-congested situations is also important from energy conservation and efficiency perspectives.

Two related tasks follow the detection of congestion. These might be described as diagnosis of the problem and determination of the most appropriate management scheme design.

Problem Diagnosis

Diagnosis is an important task which should provide an understanding of the nature of the traffic problem. It is fundamental to determining the general form of an appropriate management scheme and to the choice of appropriate analysis techniques for use in detailed design of the scheme.

An important element in understanding the traffic problem is information to aid identification of causal factors. Congestion might be caused by local inefficiencies in management of the traffic or by wider system factors (e.g. residential and employment distributions) causing excess load on the local network. A knowledge of the influence of these factors could provide some feel for the travel or traffic characteristics which are likely to be open to change. This, in turn, could indicate the form(s) of management and analysis techniques most appropriate to scheme design in the particular situation.

Consider the case of congestion being detected on the 'minor' arm of a 'T' intersection which is operating under priority control. A possible management treatment would be to signalise and some form of isolated signal model might be sought to aid design of a signal scheme. However, improved operation on the minor arm could cause redistribution of traffic in the local network and shift the demand on each arm to a comparable level. If this likelihood was identified in the diagnostic phase, then it would suggest that a roundabout should also be considered as a management solution. A different traffic model would then be required in the design phase to estimate the order of likely traffic redistribution and to enable comparative assessments of signal and roundabout solutions. Estimates of fuel consumption changes are not likely to be required in this stage, but an indication as to their importance in assessing alternative schemes could aid model choice in the design stage.

Scheme Design

Having determined from a diagnostic analysis that improved performance is likely to result from particular forms of traffic management, it is then necessary to design the most appropriate scheme. Three primary evaluation considerations in the design phase can be described as:

- (a) specifying *criteria* appropriate to the management objectives;
- (b) determining the *scope* of analyses; in particular, whether the change in each performance criterion is adequate or whether a comprehensive, weighted indicator of performance is required; and,
- (c) determining *analysis procedures* which provide information with accuracy appropriate to (a) and (b) and which are cost-effective in themselves.

An important analytical consideration is the form of evaluation required for determining the most appropriate scheme. The simplest form of evaluation would be to rank the management alternatives according to selected criteria and to choose the best alternative. A more rigorous evaluation of alternatives could involve estimation of the marginal user benefits and resource costs for each alternative, relative to the existing control system.

The following hypothetical example, based on the real network shown in Fig. 10, demonstrates the possible influence of alternative forms of evaluation on the choice of the most appropriate management scheme. An area traffic control experiment conducted in this network was reported by Luk, Sims and Lowrie (1983). Most of the intersections are signalised and there are a number of possible alternative signal control modes. These include isolated vehicle-actuated mode, linked vehicle-actuated mode, fixed-time (TRANSYT-based) mode and dynamic (SCATS-based) mode.

The on-road experiment indicated that, if the existing system was operating in isolated signal mode, all three alternative signal modes would significantly improve total travel time in the network. The reductions for fixed-time and dynamic modes are of a similar order (Fig. 11) and it can be assumed for demonstration here that the reductions are statistically comparable. If the design decision was based on travel time only, then the linked vehicle-actuated, dynamic and fixed-time schemes would be equally acceptable. However, the dynamic and linked vehicle-actuated modes reduce stops, and probably fuel consumption, more than the fixed-time mode (Fig. 12).

An evaluation interest might then be the marginal cost-effectiveness of dynamic signal control over a fixed-time coordination scheme. To investigate this, a clear indication is required as to the relevant traffic management and, perhaps, transport investment objectives. If 'reduction in direct user costs' is a primary management objective, then an estimate of the reduction in stops and fuel consumption under each control mode is required. On the estimates given in Fig. 12, the marginal value of dynamic control over fixed-time control in fuel consumption terms is only of the order of \$22/h (i.e. $2800 \text{ stops} \times 0.016 \text{ L/stop} \times \$0.48/\text{L}$). Thus the pay-back period from dynamic control in this particular location could be very long. This could imply that investment might be better directed towards dynamic control in other parts of the urban road system, or towards other forms of management in this location.

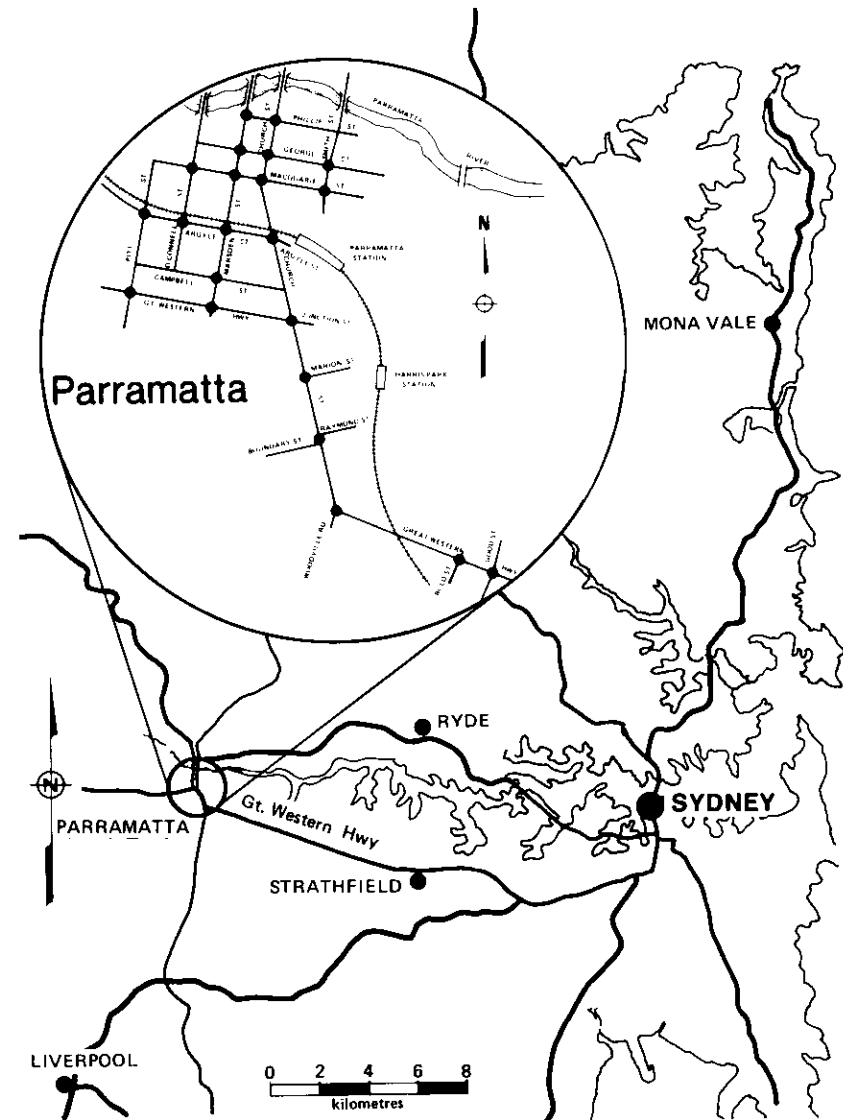


Fig. 10 — Location of Parramatta Network
Source: Luk, Sims and Lowrie (1983)

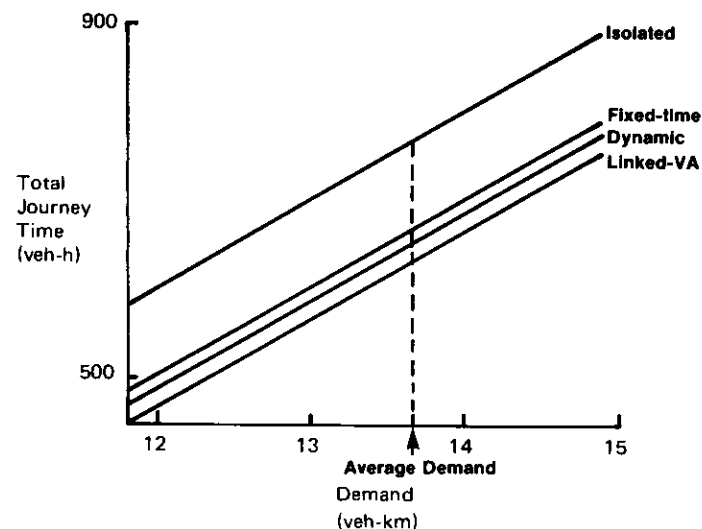


Fig. 11 — Estimated journey time under four signal modes
Source: Luk, Sims and Lowrie (1983)

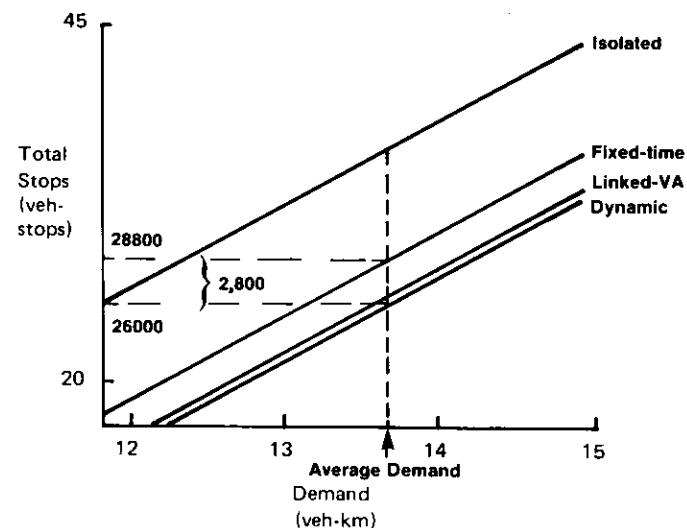


Fig. 12 — Estimated number of stops under four signal modes
Source: Luk, Sims and Lowrie (1983)

B.2.2.2 Implementation and Evaluation

In traffic management practice it is desirable to systematically conduct post-assessment of schemes and to 'tune' them to suit on-road conditions. This need stems from the fact that on-road measurements show both high variance in performance (e.g. speed) for a particular traffic demand and a wide range of demand over periods within the day and days of the week. See, for example, *Fig. 13*. In traffic management practice, it is common that only small samples of traffic variables are taken. This will limit the accuracy of model-based fuel consumption estimates. A further important possibility is that impacts might occur which are not reflected by a model. It is desirable, therefore, to encourage a process of design-implementation-evaluation, to avoid both analytical overkill in the design phase and ineffective implementation of schemes.

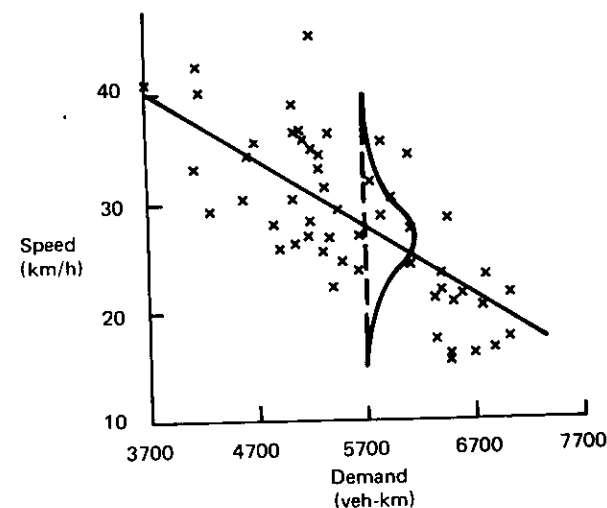


Fig. 13 — Measured speeds on Great Western Highway under isolated-VA control
Source: Luk, Sims and Lowrie (1983)

Implementation

The implementation task calls for an iterative procedure of estimating the change in performance resulting from implementation then adjusting the scheme to seek better performance. An important element in guiding this adjustment (tuning) procedure is the demand-performance function for the particular traffic system. This function might shift in the way depicted in *Fig. 14* as a result of implementing a management scheme. The *actual* user benefits will depend on whether there is a change in travel demand in the traffic system, as indicated in *Fig. 14*.

Consider fuel consumption as the performance variable and reduction in fuel consumption as the user benefit. There are two primary means of

estimating this user benefit: *direct* on-road measurement of fuel consumption or, modelled estimates of fuel consumption using fuel consumption models and, possibly, traffic models. Direct on-road measurement of fuel consumption removes problems associated with traffic modelling, but raises other difficulties. High variance in both traffic demand and performance variables is common. This necessitates well planned on-road surveys (see, for example, Luk *et al.* 1983) and care in analyses to estimate performance changes. A general analysis procedure for fixed demand conditions has been proposed by Bowyer (1984). If demand changes (through re-assignment or generation of trips), the on-road measurement procedures will need to ensure that adequate samples of demand and fuel consumption data are taken to enable estimation of user benefits.

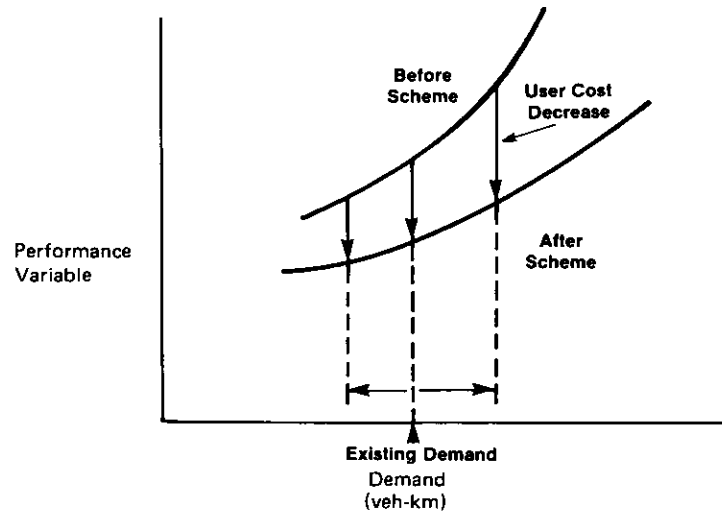


Fig. 14 — Shift in performance-demand function resulting from traffic management scheme

If appropriate traffic and fuel models are available and used in the design phase, it might be more cost-effective to estimate actual performance changes through these models.

Evaluation

The final task in the process for a particular traffic management scheme is to estimate the actual, resultant performance changes. This should provide both a post-assessment of the particular scheme and information to aid the design and implementation of future traffic management schemes. The performance estimates for conditions prior to implementation and at the final step of the implementation stage should enable estimation of user benefits. On the cost side, resources used in each of the management phases (diagnosis, design, implementation) should be accounted for.

B.3. TRAFFIC ANALYSIS HIERARCHY

It is evident from the discussion in Chapter B.2 that, in each of the management tasks, the manager might be confronted with a diverse scale of traffic systems (e.g. isolated intersection, sub-area networks) and a wide range of change in traffic variables (e.g. vehicle-travel demand, speeds, stops). It is appropriate, therefore, to think in terms of an 'analysis hierarchy'. If fuel analyses are to be cost-effective, one must be able to select the analytical tools and procedures which are appropriate to the particular level of the hierarchy (Akcelik *et al.* 1983).

There are two primary means of obtaining estimates of fuel consumption for use in urban traffic management. These are through on-road measurement procedures or traffic models. With on-road procedures, fuel consumption estimates can be derived through either *direct* measurement of fuel consumption or measurement of traffic system variables. If traffic variables are measured, fuel consumption can then be estimated by the appropriate fuel consumption model. As noted in Section B.2.2.2, on-road measurement procedures could be appropriate to aid implementation of a management scheme. There are, however, a number of issues associated with these procedures and the reader is referred to other sources (for example, Luk *et al.* 1983) for detailed consideration of these.

In this section, some of the traffic models which relate to particular levels of the traffic analysis hierarchy are discussed. The primary emphasis is on models which are relevant to the scheme design stage of the traffic management process. As noted in Chapter B.2 these might also assist in the other stages of the process, particularly the implementation stage. Fuel consumption models which are appropriate to these traffic models are discussed in Section B.4.

A large number of traffic models have been developed and employed to estimate the traffic system changes resulting from traffic management. Most of these models now have incorporated into them a module for estimating fuel consumption.

Choosing a Traffic Model

There are several factors to consider in the choice of a traffic model for fuel analyses in a particular situation. From a fuel consumption perspective, the primary function of a traffic analysis model is to provide estimates of traffic variables for input to the relevant fuel consumption function. For cost-effective use these estimates should be of sufficient accuracy to reflect the actual fuel changes relevant to the required decisions, be obtained at reasonable cost and be unbiased or at least internally consistent. These requirements will only be met if the models reflect the supply and demand elements relevant to the particular traffic management context.

It is appropriate, then, to consider traffic models in terms of the traffic-transport system context to which they relate and the traffic variables which are estimated and can be input to fuel consumption models. This can be

conveniently viewed as a model hierarchy, as depicted in *Table III*. The models selected for inclusion in the Table are those which are likely to be relevant in Australian urban contexts and are sufficiently developed to warrant their consideration in practice. The fuel consumption models appropriate to each traffic model considered here are summarised in *Table II*, Part A.

Descriptions and, in most cases, documentation of these models are provided in existing publications. Several useful comparisons have also been made in previous studies (see, for example, Luk *et al.* (1983); Luk and Akcelik (1984)). In the following sections, the models of each level of the hierarchy will only briefly be described and compared, with emphasis on the aspects relevant to fuel consumption analyses. References to primary sources will be given where appropriate.

B.3.1 MICRO TRAFFIC MODELS

The base level of analysis can be considered as the detailed assessment of traffic operations in an individual intersection or road section. This is indicated as the bottom of the system scale in *Table III*. Typically traffic volumes on each lane or movement are taken as fixed (i.e. demand is constant).

Two models relevant to this level are SIDRA-2 (Akcelik and Besley (1984) and INSECT (Nairn and Partners 1983a). SIDRA-2 is intended to aid signal design at isolated intersections while INSECT is currently structured for analyses of intersections under priority control (give-way or stops) or with roundabouts. The two models reflect two fundamentally different approaches to traffic modelling, that is, analytic functions and time simulation. INSECT simulates the movement of *individual vehicles* in the traffic system and provides estimates of the 'state' of each vehicle at successive time points. This can include the speed at, say, 1 second intervals. Thus this model can provide inputs to an instantaneous fuel consumption function or, to more aggregate functions such as elemental forms of drive-mode models. SIDRA-2 utilises analytic functions to estimate the delay and number of stops experienced by vehicles on *individual movements* without simulating the movement of individual vehicles. With delays and number of stops as the estimated traffic system variables, a higher level form of fuel function is necessary. This is the four-mode elemental model described in Section B.4.3 (i.e. cruise, deceleration, idle and acceleration are considered separately).

B.3.2 MICRO-MESO TRAFFIC MODELS

Increasing attention is being given to the assessment of traffic operations in small, sub-area networks which involve a number of intersections under some form of control. At this level of analysis demand is assumed constant. Traffic operations might be considered at one of several levels of detail, including the micro-assessment of individual intersections or road sections. The top end of the scale is, however, much finer than the coarse

TABLE III
SELECTED TRAFFIC MODELS APPROPRIATE TO PARTICULAR
TRAFFIC-TRANSPORT SYSTEM CONTEXTS

Traffic — Transport System Context			Selected Traffic Models		
System Scale	Travel Demand Variables	System Supply Description	Name	Estimated Traffic Variables	Model Features
Macro	Destinations modes, routes	Travel costs specified for travel links	UTPS ⁽¹⁾	Link volumes and travel costs	Travel analyses and system evaluation
Macro/Meso	Routes	Travel time specified for traffic links	LATM ⁽²⁾	Traffic demand, delay and queues on traffic links	Dynamic trip assignment and intersection delay estimation
			SATURN ⁽³⁾	Traffic demand, delay, queue time, stops, on traffic movements	Trip assignment, interfaced to a detailed traffic model (TRANSYT-like)
Micro/Meso	Constant Demand	Explicit description of intersections and their interactions	TRANSYT ⁽⁴⁾	Travel time, delay, stops on traffic movements	Analytic estimation of delays, stops and queue lengths in a network
		Explicit description of vehicle movements	SCATSIM ⁽⁵⁾	Instantaneous velocity of individual vehicles	Event simulation in a signal network
Micro	Constant Demand	Detailed description of individual intersection and movement interactions	SIDRA ⁽⁶⁾	Delay, stops, queue lengths, travel time on traffic movements	Analytic estimation of capacity and traffic performance for movements at a single intersection
		Explicit description of vehicle movements	MULTSIM ⁽⁷⁾ INSECT ⁽⁸⁾	Instantaneous velocity of individual vehicles	event simulation; event simulation; priority control intersections only

References:

- (1) UMTA (1977)
- (2) Taylor (1980)
- (3) Bolland, Hall and van Vliet (1979)
- (4) Vincent, Mitchell and Robertson (1980)
- (5) Negus and Fehon (1982)
- (6) Akcelik and Besley (1984)
- (7) Gipps and Wilson (1980)
- (8) Nairn and Partners (1983a)

link-level analyses in macro-transport systems. The term micro-meso is thus appropriate to denote this traffic context.

Two models developed to address this traffic context are TRANSYT/8 (Vincent, Mitchell and Robertson 1980) and SCATSIM (Negus and Fehon 1982). SCATSIM considers only signalised intersections while TRANSYT/8 can also model give-way controls.

A major difference in modelling philosophy exists between these models, similar to that between SIDRA-2 and INSECT at the micro level. TRANSYT/8 performs a steady-state simulation of traffic flow through a signalised network. It uses analytic methods to estimate delays, number of stops and queue length. A form of elemental model is used in TRANSYT/8. With this modelling approach it is possible only to assess various *fixed-time* signal plans. SCATSIM, like INSECT, attempts a dynamic simulation of individual vehicle movements (i.e. time simulation) in the system. It thus provides estimates of instantaneous vehicle speeds, which could be used as inputs to either an instantaneous fuel consumption model or a detailed form of the elemental model (see *Table II*). A feature of the dynamic simulation which will be vital in some contexts is that it enables assessment of traffic operation under several forms of signal control, including isolated-VA, linked-VA and dynamic coordination.

B.3.3 MESO-MACRO TRAFFIC MODELS

A traffic management scheme might induce travel behaviour changes within or beyond the sub-area in which it is introduced. In contexts where behavioural variation is possible, a comprehensive assessment of alternative schemes will require use of travel analysis techniques.

There are a number of degrees of freedom in travel systems, but a short-run change which is likely with traffic management in sub-areas is in driver route choice. Thus route choice analysis techniques are required as an element in the total traffic model, together with a traffic operations model. At this meso-macro level in the traffic system hierarchy one must trade-off between comprehensiveness (in demand-supply interactions) and simulation detail (particularly in traffic operations).

The models LATM (Taylor 1980) and SATURN (Bolland, Hall and Van Vliet 1979) represent two different approaches to this trade-off. Both are essentially enhanced traffic assignment models in that a primary aspect of each is the attempt to explicitly incorporate intersection delay elements into the flow-delay functions which are used to assign vehicles to movements. However, the process for estimating delays and queues (in over-saturated conditions) differs markedly. LATM generates steady-state estimates of delay from a set of typical analytic functions (one for each intersection type) but then attempts to simulate the dynamics of queue formation-dissipation and route choice over small time increments (typically 15 min). SATURN is also a steady-state estimation process but employs a detailed traffic model (essentially TRANSYT-like) to estimate delays and stops and also remaining queues when oversaturation occurs.

In principle queue dynamics could be modelled in a similar way to that with LATM. However, considerable resources would be required to do this. The consequences of not doing so for fuel analysis are considered in Section B.5.3.

B.3.4 MACRO TRAFFIC MODELS

In broader transport system contexts, estimates of aggregate system performance and, possibly, link traffic volumes are appropriate for decision purposes. Travel demand variations are of greater importance than at the meso-macro level and analytical tractability dictates that simple flow-delay functions be used to reflect traffic conditions on network links. Thus comprehensiveness is maintained, but simulation emphasis is now on travel behaviour rather than traffic operations as is the case at lower levels.

Models such as UTPS are appropriate to this level (SATURN, in 'buffer' mode, is also). The primary traffic variables relevant to fuel analyses are volumes, distances and average speeds on travel links.

B.4. CAR FUEL CONSUMPTION MODELS

B.4.1 GENERAL

Fuel consumption models of four levels of detail will be described. These are, in increasing order of aggregation:

- (a) an energy-related instantaneous fuel consumption model,
- (b) a four-mode elemental model of fuel consumption,
- (c) a running speed model of fuel consumption, and
- (d) an average travel speed model of fuel consumption.

Although different versions of each of these models are found in the literature, the models presented here are improved and better calibrated than earlier models of the same category. In particular, the instantaneous model is an extension of the power model reported by Kent, Tomlin and Post (1982), the elemental model is a refinement of the form reported by Akcelik (1983), and the running speed model is similar to the positive kinetic energy models developed by Watson (1981). Most importantly, all four models are inter-related and form part of the same modelling framework. A simpler model is derived from a more detailed model, e.g. the

elemental model from the instantaneous model, keeping the vehicle characteristics such as mass, drag function and energy efficiency as explicit parameters at all model levels. This integrated framework of fuel consumption models should lead to an improved understanding of the aggregate models used in the literature.

Each model will be described below by presenting 'default' model parameters for a car which is a fairly representative one. The models are set in such a way that the users of this guide can easily employ their own vehicle parameters which may correspond to a 'representative car', a 'fleet-average car', etc. in their application. Vehicle characteristics are likely to change over time, and from country to country, and therefore this is a particularly useful property of the models. It should be noted that, although the models presented here should also be applicable to heavy vehicles (i.e. trucks), accurate parameters (in particular the energy efficiency parameters) are not yet available. However, the drag and mass parameters can be adjusted to represent a chosen heavy vehicle fairly well, thus allowing for approximate calculations (see, for example *Table XXI*).

The models given here have been calibrated using data from special on-road experiments in Melbourne (Biggs and Akcelik 1983) and extensive on-road driving data collected in Sydney (Tomlin *et al.* 1983). The calibration of vehicle and model parameters is summarised in Appendix B and discussed in detail in Biggs and Akcelik (1985). The likely ranges of these parameters are also included in Appendix B. Some of the results have been checked against available dynamometer data. Emphasis in this work has been on the use of on-road data since the dynamometer data (mostly based on specified drive cycles) have been found to be limited in the ranges of speed and acceleration employed. The estimation accuracies of the four models are discussed in Appendix C.

The 'default' parameters which are applicable to all models are given in *Table IV*. The default values do not correspond to a particular car. They are based on limited information available at the time of the analysis. The comparative parameter values for particular cars are shown in *Table XXI* (Appendix B). Notations, definitions and units are summarised at the start of this publication. Numerical examples are given to explain each model of fuel consumption, and all examples are solved using the 'default' parameters given in *Table IV*.

B.4.2 AN ENERGY-RELATED INSTANTANEOUS FUEL CONSUMPTION MODEL

The instantaneous fuel consumption model described below estimates fuel consumption from second-by-second speed-time and grade information. This is the most fundamental and accurate fuel consumption model for traffic analyses since there is no aggregation involved in terms of driving information, i.e. such variables as average speed, number of stops, etc. are not used.

TABLE IV
DEFAULT VEHICLE PARAMETERS APPLICABLE TO ALL MODELS

Parameter	Default Value	Description
α	0.444	Idle fuel rate in mL/s
I_i	1600	As α but in mL/h
M	1200	Mass in kg
β_1	0.090	Energy efficiency parameter in mL/kJ
β_2	0.045	Energy-acceleration efficiency parameter in mL/(kJ.m/s ²)
b_1	0.333	Drag force parameter in kN, mainly related to rolling resistance*
b_2	0.00108	Drag force parameter in kN/(m/s) ² , mainly related to aerodynamic resistance*
$c_1 = \beta_1 b_1$	0.030	Drag fuel consumption component in mL/m, mainly due to rolling resistance
$c_2 = \beta_1 b_2$	9.72×10^{-5}	Drag fuel consumption component in (mL/m)/(m/s) ² mainly due to aerodynamic resistance
$A = 10^3 c_1$	30.0	As c_1 but in mL/km
$B = c_2/0.01296$	0.00750	As c_2 but in (mL/km)/(km/h) ²

* b_1 and b_2 are also related to the component of drag associated with the engine.

Basically, the model presented here relates fuel consumption during a small time increment, dt , to:

- the fuel to maintain engine operation,
- the energy consumed (work done) by the vehicle engine while travelling an increment of distance, dx , during this time period, and
- the product of energy and acceleration during periods of positive acceleration.

Part (c) allows for the inefficient use of fuel during periods of high acceleration. Since energy is $dE = R_T dx$, where R_T is the total tractive force required to drive the vehicle along distance dx , the fundamental relation which expresses fuel consumption is:

$$\begin{aligned} dF &= \alpha dt + \beta_1 R_T dx + [\beta_2 a R_T dx]_{a>0} & \text{for } R_T > 0 \\ &= \alpha dt & \text{for } R_T \leq 0 \end{aligned} \quad (1)$$

where dF = increment of fuel consumed (mL) during travel along distance dx (m) and in time dt (s),

α = constant idle fuel rate (mL/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation),

β_1 = the efficiency parameter which relates fuel consumed to the energy provided by the engine, i.e. fuel consumption per unit of energy (mL/kJ),

β_2 = the efficiency parameter which relates fuel consumed during positive acceleration to the product of inertia energy and acceleration, i.e. fuel consumption per unit of energy-acceleration (mL/(kJ.m/s²)),

a = instantaneous acceleration (dv/dt) in m/s², which has a negative value for slowing down, and

R_T = total 'tractive' force required to drive the vehicle, which is the sum of drag force (R_D), inertia force (R_I) and grade force (R_G) in kN (kilonewtons):

$$R_T = R_D + R_I + R_G \quad (2)$$

The resistive forces can be expressed as:

$$R_D = b_1 + b_2 v^2 \quad (3)$$

$$R_I = Ma/1000 \quad (4)$$

$$R_G = 9.81 M(G/100)/1000 \quad (5)$$

where v = speed (dx/dt) in m/s,

G = per cent grade which has a negative value for downhill grade,

M = vehicle mass in kg, including occupants and any other load, and

b_1, b_2 = drag force parameters related mainly to rolling and aerodynamic resistance, respectively. Parameter b_1 is roughly proportional to vehicle mass and parameter b_2 is approximately proportional to the frontal area of the vehicle. Parameters b_1 and b_2 also reflect some component of drag associated with the engine.

Fuel consumption per unit time (mL/s) can be expressed as:

$$\begin{aligned} f_t = dF/dt &= \alpha + \beta_1 R_T v + [\beta_2 Ma^2 v/1000]_{a>0} & \text{for } R_T > 0 \\ &= \alpha & \text{for } R_T \leq 0 \end{aligned} \quad (6)$$

where the total tractive force required is

$$R_T = b_1 + b_2 v^2 + Ma/1000 + 9.81 \times 10^{-5} MG \quad (7)$$

Note that $R_T v = P_T$ is the total tractive power (kW) and $Ma^2 v/1000 = aP_i$, where P_i is the inertial power (kW).

Fuel consumption per unit distance (mL/m) is similarly expressed as:

$$\begin{aligned} f_x = dF/dx &= f_t/v = \alpha/v + \beta_1 R_T + [\beta_2 Ma^2/1000]_{a>0} & \text{for } R_T > 0 \\ &= \alpha/v & \text{for } R_T \leq 0 \end{aligned} \quad (8)$$

Fuel consumption per unit time for constant speed travel along a level road ($a = 0, G = 0$) is obtained from the above equations as:

$$f'_{c,t} = \alpha + \beta_1 (b_1 + b_2 v^2) v = \alpha + c_1 v + c_2 v^3 \quad (9)$$

Using the default variables given in Table IV, the instantaneous fuel consumption model can be written as follows:

$$\begin{aligned} f_t &= 0.444 + 0.090 R_T v + [0.054 a^2 v]_{a>0} & \text{for } R_T > 0 \\ &= 0.444 & \text{for } R_T \leq 0 \end{aligned} \quad (10)$$

$$R_T = 0.333 + 0.00108 v^2 + 1.20 a + 0.1177 G \quad (11)$$

and

$$f'_{c,t} = 0.444 + 0.030 v + 9.72 \times 10^{-5} v^3 \quad (12)$$

The constant speed fuel consumption function for level road and in units of mL/km using cruise speed, v_c , in km/h is:

$$f'_{c,x} = f_t/v_c + A + B v_c^2 \quad (13)$$

where $f'_{c,x}$ = constant speed fuel consumption per unit distance in mL/km;

f_t = idle fuel flow rate in mL/h ($= 3600\alpha$);

A, B = function parameters corresponding to c_1 and c_2 in eqn (9), whose default values are given in Table IV.

This functional form is used in fuel consumption models of more aggregate levels as described in the following sections.

Example 1 Acceleration (instantaneous)

A vehicle is accelerating from rest to 90 km/h. What is the instantaneous fuel consumption rate in mL/s at the point when its speed is 40 km/h and acceleration rate is 5.9 km/h/s:

- (a) on a level road,
- (b) on an uphill grade of 5 per cent, and
- (c) on a downhill grade of 5 per cent?

Answer:

The speed and acceleration rate in SI units are:
 $v = 40/3.6 = 11.11 \text{ m/s}$ and $a = 5.9/3.6 = 1.639 \text{ m/s}^2$

- (a) Level road, $G = 0$:
 From eqn (11), the total tractive force required is:
 $R_T = 0.333 + 0.00108 \times 11.11 \times 11.11 + 1.20 \times 1.639 = 2.433 \text{ kN}$
 From eqn (10), fuel consumption rate is:
 $f_t = 0.444 + 0.090 \times 2.433 \times 11.11 + 0.054 \times 1.639 \times 1.639 \times 11.11$
 $= 0.444 + 4.044 = 4.49 \text{ mL/s}$
- (b) Uphill grade, $G = 5$:
 From eqn (11):
 $R_T = 2.433 + 0.1177 \times 5 = 3.022 \text{ kN}$
 From eqn (10):
 $f_t = 0.444 + 0.090 \times 3.022 \times 11.11 + 0.054 \times 1.639 \times 1.639 \times 11.11$
 $= 0.444 + 4.633 = 5.08 \text{ mL/s}$
- (c) Downhill grade, $G = -5$:
 Similarly:
 $R_T = 2.433 + 0.1177 \times (-5) = 1.8445 \text{ kN}$, and
 $f_t = 0.444 + 0.090 \times 1.8445 \times 11.11 + 0.054 \times 1.639 \times 1.639 \times 11.11$
 $= 0.444 + 3.455 = 3.90 \text{ mL/s}$

Example 2 Deceleration (instantaneous)

A vehicle is decelerating from 60 km/h to rest. What is the instantaneous fuel consumption rate in mL/s at the point when its speed is 54 km/h and deceleration rate is 3.1 km/h/s:

- (a) on a level road,
- (b) on an uphill grade of 5 per cent, and
- (c) on a downhill grade of 5 per cent?

Answer:

The speed and acceleration rate in SI units are:
 $v = 54/3.6 = 15.0 \text{ m/s}$ and $a = -3.1/3.6 = -0.861 \text{ m/s}^2$
 The problem is solved in a similar way to Example 1.

- (a) Level road, $G = 0$:
 $R_T = 0.333 + 0.00108 \times 15.0 \times 15.0 + 1.20 \times (-0.861) = -0.457 \text{ kN}$
 Since $R_T < 0$, $f_t = 0.444 \text{ mL/s}$ (idle rate)
- (b) Uphill grade, $G = 5$:
 $R_T = -0.457 + 0.1177 \times 5 = 0.132 \text{ kN}$
 $f_t = 0.444 + 0.090 \times 0.132 \times 15.0 = 0.622 \text{ mL/s}$
- (c) Downhill grade, $G = -5$:
 $R_T = -0.758 - 0.1177 \times 5 < 0$, hence $f_t = 0.444 \text{ mL/s}$ (idle rate)

Example 3 Constant Speed Cruise

What is the fuel consumption rate in mL/km of a vehicle travelling at a constant speed of 60 km/h on a level road?

Answer:

With default vehicle parameters from Table IV, eqn (13) becomes

$$f'_{c,x} = 1600/v_c + 30 + 0.0075 v_c^2.$$

Putting $v_c = 60$, $f'_{c,x} = 1600/60 + 30 + 0.0075 \times 60 \times 60 = 83.7 \text{ mL/km}$ is found.

Example 4 Acceleration (total)

What is the total fuel consumed during acceleration from 60 km/h to 70 km/h by a vehicle on a level road, assuming a constant acceleration rate of 2.0 km/h/s throughout acceleration?

Answer:

The acceleration time is $t_a = (v_f - v_i)/a = (70 - 60)/2.0 = 5.0 \text{ s}$.

The speed at each point during acceleration can be calculated from $v = v_i + at$. In SI units, $v = 16.67 + 0.556 t$. The speed from this equation, tractive force from eqn (11) and fuel consumption rate from eqn (10) at each point during acceleration are given in Table V, with the total fuel consumed being 14.70 mL.

TABLE V

Time Interval (s)	Time, t (s)	Speed, v (m/s)	Tractive Force, R_T (kN)	Fuel Consumption (mL/s)
0-1	0.5	16.94	1.310	2.72
1-2	1.5	17.50	1.330	2.83
2-3	2.5	18.06	1.352	2.94
3-4	3.5	18.61	1.373	3.05
4-5	4.5	19.17	1.396	3.17
Total fuel consumed =				14.70 mL

Example 5 Cruise-Deceleration-Idle-Acceleration-Cruise Cycle

What is the fuel consumption of the vehicle whose distance-time, speed-time and acceleration-time traces are shown in Fig. 15? This represents a cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle. The road section has a constant grade of

- (a) zero (i.e., level road),
- (b) 5 per cent uphill, and
- (c) 5 per cent downhill.

Answer:

The problem is solved using a computer routine which calculates fuel consumption rate for each point of speed trace using eqns (10) and (11). The process is similar to the solution given for Example 4. The instantaneous and cumulative fuel consumption results are shown in Fig. 16 and the sums for each drive mode and overall total are given in Table VI.

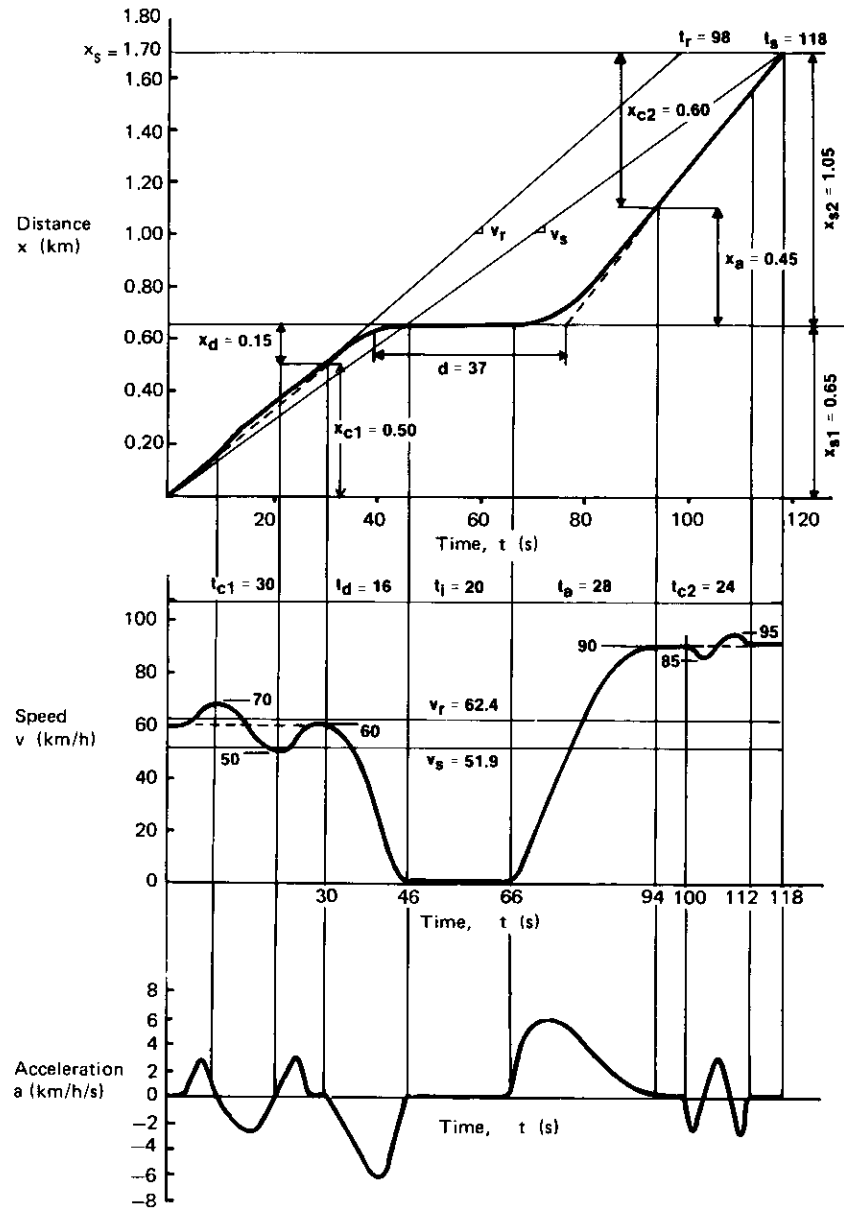


Fig. 15 — Distance, speed and acceleration-time traces over cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle

TABLE VI

Grade	Fuel Consumed (mL)					Total
	Initial Cruise ($v_c = 60$)	Deceleration ($v_i = 60$, $v_f = 0$)	Idle ($v = 0$)	Acceleration ($v_i = 0$, $v_f = 90$)	Final Cruise ($v_c = 90$)	
0	47.2	8.5	8.9	99.1	67.2	231
+5	71.9	11.8	8.9	123.0	98.9	315
-5	27.9	7.1	8.9	75.3	37.8	157

Using the total section distance of 1.7 km, the fuel consumption rates are:

- (a) $G = 0$: $f_x = 231/1.7 = 136$ mL/km,
 (b) $G = +5$: $f_x = 315/1.7 = 185$ mL/km, and
 (c) $G = -5$: $f_x = 157/1.7 = 92$ mL/km

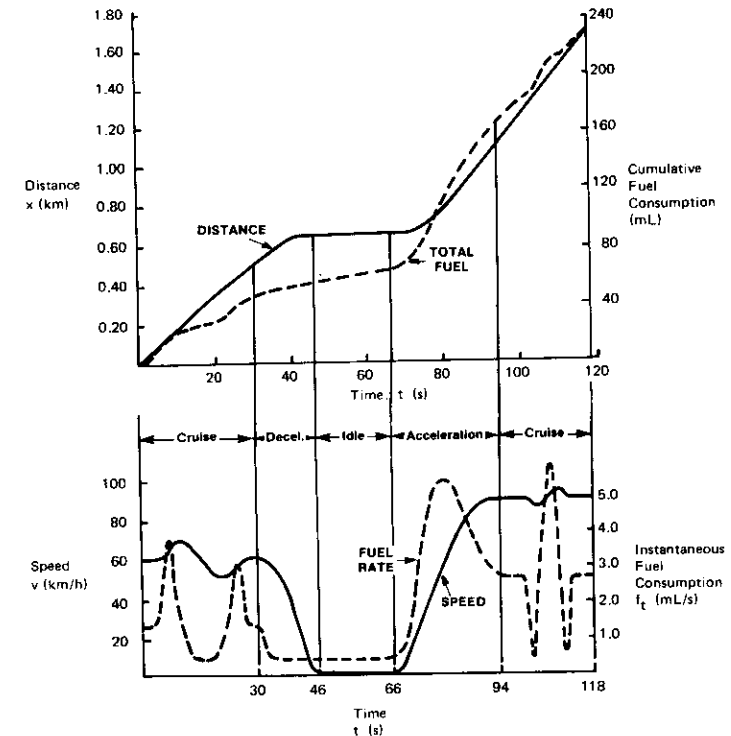


Fig. 16 — Distance, cumulative fuel consumption, speed and instantaneous fuel consumption over a cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle

B.4.3 A FOUR MODE ELEMENTAL MODEL OF FUEL CONSUMPTION

The elemental model of fuel consumption described here consists of a set of functions to estimate fuel consumption for each of four modes of driving, namely idle, cruise, acceleration and deceleration. These functions are derived from the instantaneous fuel consumption model given in the previous section. Thus, the same vehicle related parameters apply. However, integration coefficients are introduced due to aggregation of second-by-second speed-time information into drive mode information. This method of aggregation allows for minimum loss of driving information, hence minimum loss of accuracy in fuel consumption estimates. The model is useful for estimation of fuel consumption at a short road short section (or micro-trip) level. At this level, it is appropriate to use average grade along the road section at the expense of some loss of accuracy.

The calculation procedures and accuracy of fuel consumption estimates will depend on the available traffic data. The minimum items required for application of the elemental model are total section distance, cruise speed, stopped time and average grade. More accurate estimates will be obtained if initial and final speeds in each acceleration and deceleration are known. If acceleration and/or deceleration times and/or distances are known, these, rather than the estimated values, can be used.

The functions given estimate actual acceleration and deceleration fuel consumption rather than the excess fuel consumption (the latter is the actual fuel consumption less the fuel consumed while cruising the equivalent distance). The recommended method for estimating cruise distance is to calculate, where necessary, the distances covered during the acceleration and deceleration manoeuvres and subtract these from the total section distance. In some situations negative cruise distance estimates may result. This can be avoided by adjusting the initial estimates of acceleration and deceleration times and distances to obtain zero cruise distance and/or by modifying the cruise speeds.

It is common for many traffic models to predict the number of stops rather than accelerations and decelerations. In this case, each stop can be modelled as a deceleration-acceleration pair. However, the model should distinguish between different types of stops such as an initial stop from the cruise and a stop in the queue. The definition of a stop is also very important. A definition such as 'a stop is counted whenever the speed falls below 5 km/h' may result in underestimation of fuel consumption. In this case, a higher value of the minimum speed, e.g. 20 km/h, could be used in order to include major slow-downs such as from 80 km/h. This limit can be made dependent on the cruise speed. For stops in the queue, only the acceleration to a speed above the specified minimum speed should be counted. For traffic models which require excess fuel consumption per stop, the method given in Section B.4.3.5 can be used.

B.4.3.1 Acceleration Fuel Consumption

The following function can be used to estimate fuel consumed during an acceleration from an initial speed of v_i to a final speed of v_f ($v_f > v_i$):

$$F_a = \alpha t_a + [A + k_1 B (v_i^2 + v_f^2) + \beta_1 M E_k + k_2 \beta_2 M E_k^2 + 0.0981 \beta_1 M G] x_a \quad (14)$$

or αt_a , whichever is larger

where F_a = total fuel consumption during acceleration (mL);

t_a = acceleration time (s),

x_a = acceleration distance (km),

E_k = the change (increase) in kinetic energy per unit mass per unit distance during acceleration from v_i to v_f (J/kg.m) and is given by:

$$E_k = 0.3858 \times 10^{-4} (v_f^2 - v_i^2) / x_a \quad (15)$$

$\alpha, A, B, M, \beta_1, \beta_2$ = vehicle related parameters as in eqns (1) and (13) whose default values are given in Table IV, and

k_1, k_2 = integration coefficients given by:

$$k_1 = 0.616 + 0.000544 v_f - 0.0171 \sqrt{v_f} \quad (16a)$$

$$k_2 = 1.376 + 0.00205 v_f - 0.00538 v_i \quad (16b)$$

G = per cent grade (e.g. $G = 3$ means a grade of 0.03), using a negative value for downhill grade,

Using the default parameters given in Table IV, eqn (14) becomes:

$$F_a = 0.444 t_a + [30 + 0.0075 k_1 (v_i^2 + v_f^2) + 108 E_k + 54 k_2 E_k^2 + 10.6 G] x_a \quad (17)$$

or $0.444 t_a$, whichever is larger

When the acceleration distance and time, x_a and t_a , are not known, they can be estimated from the following equations:

$$x_a = m_a (v_i + v_f) t_a / 3600 \quad (18a)$$

$$m_a = 0.467 + 0.00200 v_f - 0.00210 v_i \quad (18b)$$

$$t_a = (v_f - v_i) / (2.08 + 0.127 \sqrt{v_f - v_i} - 0.0182 v_i) \quad (19)$$

The results from eqn (19) can be considered to correspond to medium acceleration rates. For slow acceleration rates, $1.2 t_a$, and for hard acceleration rates, $0.8 t_a$ can be used where necessary.

Example 6 Acceleration

What is the fuel consumed during an acceleration from rest to a final speed of 90 km/h

- (a) on a level road,
- (b) on an uphill grade of 5 per cent, and
- (c) on a downhill grade of 5 per cent?

Answer

From eqns (15) to (19), general parameters for $v_i = 0$, $v_f = 90$ km/h are

$$\begin{aligned} t_a &= 90 / (2.08 + 0.127 \sqrt{90}) = 27.4 \text{ s} \\ m_a &= 0.467 + 0.00200 \times 90 = 0.647 \\ x_a &= 0.647 \times 90 \times 27.4 / 3600 = 0.443 \text{ km} \\ E_k &= 0.3858 \times (0.90 \times 0.90 - 0) / 0.443 = 0.7054 \text{ J/kg.m} \\ k_1 &= 0.616 + 0.000544 \times 90 = 0.6646 \\ k_2 &= 1.376 + 0.00205 \times 90 = 1.5605 \end{aligned}$$

From eqn (17), the acceleration fuel consumption values are as follows:

$$\begin{aligned} \text{(a)} \quad G &= 0: \\ F_a &= 0.444 \times 27.4 + (30 + 0.0075 \times 0.6646 \times 90 \times 90 + 108 \times 0.7054 \\ &\quad + 54 \times 1.5605 \times 0.7054 \times 0.7054) 0.443 \\ &= 12.17 + 188.48 \times 0.443 = 95.7 \text{ mL} \\ \text{(b)} \quad G &= +5: \\ F_a &= 95.7 + 10.6 \times 5 \times 0.443 = 119.2 \text{ mL} \\ \text{(c)} \quad G &= -5: \\ F_a &= 95.7 - 10.6 \times 5 \times 0.443 = 72.2 \text{ mL} \end{aligned}$$

B.4.3.2 Deceleration Fuel Consumption

The expression for deceleration fuel consumption is similar to that for acceleration fuel consumption, eqn (14). However, total tractive force is not greater than zero during the whole deceleration due to the negative inertia force. For this reason, three further parameters are introduced to account for the fact that all energy related terms contribute only for the part of the deceleration when the total tractive force is positive. Also the acceleration-energy term ($\beta_2 M E_k^2$) of eqn (14) does not apply in this case. Deceleration fuel consumption is estimated by:

$$F_d = \alpha t_d + [k_x A + k_y k_1 B (v_i^2 + v_f^2) + k_a \beta_1 M E_k + 0.0981 k_x \beta_1 M G] x_d \quad (20)$$

or αt_d , whichever is larger

where F_d = total fuel consumption during deceleration (mL),
 t_d, x_d = deceleration time (s) and distance (km), respectively,
 and

k_x, k_y, k_a = the energy-related parameters.

Other parameters and variables are as defined in eqn (14), with the value of E_k calculated from eqn (15) using x_d instead of x_a . Note that eqn (15) will give a negative value of E_k since v_i is less than v_f , which means that E_k is the decrease in kinetic energy per unit mass per unit distance during the deceleration manoeuvre.

The three energy related parameters are estimated from:

$$k_x = 0.046 + 100/M + 0.00421 v_i + 0.00260 v_f + 0.0544 G \quad (21a)$$

or 0 if the above value is less than 0,
 or 1.0 if the above value is greater than 1.

$$k_y = k_x^{0.75} \quad (21b)$$

$$k_a = k_x^{3.81} (2 - k_x^{3.81}) \quad (21c)$$

and the integration coefficient is given by

$$k_1 = 0.621 + 0.000777 v_i - 0.0189 \sqrt{v_i} \quad (21d)$$

Using the default parameters given in Table IV, eqn (20) becomes

$$F_d = 0.444 t_d + [30 k_x + 0.0075 k_y k_1 (v_i^2 + v_f^2) + 108 k_a E_k + 10.6 k_x G] x_d \quad (22)$$

or 0.444 t_d , whichever is larger

The following equations can be used to estimate deceleration distance and time where necessary:

$$x_d = m_d (v_i + v_f) t_d / 3600 \quad (23a)$$

$$m_d = 0.473 + 0.00155 v_i - 0.00137 v_f \quad (23b)$$

$$t_d = (v_i - v_f) / (1.71 + 0.238 \sqrt{v_i - v_f} - 0.0090 v_i) \quad (24)$$

As in the case of positive accelerations, 1.2 t_d and 0.8 t_d can be used for slow and hard decelerations, respectively.

Example 7 Deceleration

What is the fuel consumed during a deceleration (slowing down) from an initial speed of 60 km/h to rest:

- on a level road
- on an uphill grade of 5 per cent, and
- on a downhill grade of 5 per cent?

Answer:

From eqns (15) and (21) to (24),

$$\begin{aligned} t_d &= 60 / (1.71 + 0.238 \sqrt{60}) = 16.9 \text{ s} \\ m_d &= 0.473 + 0.00155 \times 60 = 0.566 \\ x_d &= 0.566 \times 60 \times 16.9 / 3600 = 0.159 \text{ km} \\ E_k &= 0.3858 \times (0 - 0.60 \times 0.60) / 0.159 = -0.8735 \text{ J/kg.m} \\ k_1 &= 0.621 + 0.000777 \times 60 = 0.6676 \end{aligned}$$

From eqns (21) and (22), the deceleration fuel consumption values are as follows:

$$\begin{aligned} \text{(a)} \quad G &= 0: \\ k_x &= 0.046 + 100/1200 + 0.00421 \times 60 = 0.3819 \\ k_y &= 0.4858 \\ k_a &= 0.0504 \\ F_d &= 0.444 \times 16.9 + (30 \times 0.3819 + 0.0075 \times 0.4858 \times 0.6676 \times 60 \times 60 \\ &\quad + 108 \times 0.0504 \times (-0.8735)) 0.159 \\ &= 7.50 + 15.46 \times 0.159 = 10.0 \text{ mL} \end{aligned}$$

$$\begin{aligned}
 \text{(b)} \quad G &= +5; \\
 k_x &= 0.3819 + 0.0544 \times 5 = 0.6539 \\
 k_y &= 0.7272 \\
 k_a &= 0.3571 \\
 F_d &= 7.50 + (30 \times 0.6539 + 0.0075 \times 0.7272 \times 0.6676 \times 60 \times 60 + 108 \\
 &\quad \times 0.3571 \times (-0.8735) + 10.6 \times 0.6539 \times 5) \times 0.159 \\
 &= 7.50 + 33.69 \times 0.159 = 12.9 \text{ mL} \\
 \text{(c)} \quad G &= -5; \\
 k_x &= 0.3819 - 0.0544 \times 5 = 0.1099 \\
 k_y &= 0.1909 \\
 k_a &= 0.0004 \\
 F_d &= 7.50 + (30 \times 0.1099 + 0.0075 \times 0.1909 \times 0.6676 \times 60 \times 60 + 108 \\
 &\quad \times 0.0004 \times (-0.8735) + 10.6 \times 0.1099 \times (-5)) \times 0.159 \\
 &= 7.50 + 0.88 \times 0.159 = 7.6 \text{ mL}
 \end{aligned}$$

B.4.3.3 Cruise Fuel Consumption

Cruise mode is defined as travel from the end of an acceleration which originated from a 'stop' to the start of the next deceleration which finishes at a 'stop' (in our calibration of the cruise fuel consumption function, a 'stop' was identified when speed went below 20 km/h). The following function, which is an extension of eqn (13) for constant-speed cruise, can be used to estimate fuel consumption by a vehicle during cruise allowing for speed fluctuations:

$$f_c = f_i/v_c + A + Bv_c^2 + k_{E1} \beta_1 ME_{k+} + k_{E2} \beta_2 ME_{k+}^2 + 0.0981 k_G \beta_1 MG$$

or f_i/v_c , whichever is larger (25)

where f_c = cruise fuel consumption per unit distance (mL/km),

v_c = average cruise speed (km/h) allowing for speed fluctuations; strictly speaking this is the average 'running' speed which includes acceleration and deceleration delays while cruising,

E_{k+} = sum of positive kinetic energy changes per unit mass per unit distance during cruise (J/kg.m) given by:

$$E_{k+} = 0.3858 \times 10^{-4} [\Sigma(v_f^2 - v_i^2)]/x_c \quad (26)$$

where v_f, v_i = final and initial speeds (km/h) during each positive acceleration during cruise ($v_f > v_i$),

x_c = cruise distance (km),

G = average per cent grade (negative for downhill grade),

k_{E1}, k_{E2}, k_G = calibration parameters estimated from:

$$k_{E1} = 12.5/v_c + 0.000013 v_c^2 \quad (27a)$$

or 0.63, whichever is smallest

$$k_{E2} = 3.17 \quad (27b)$$

$$k_G = 1 - 2.1 E_{k+} \quad \text{for } G < 0 \quad (27c)$$

$$1 - 0.3 E_{k+} \quad \text{for } G > 0$$

The cruise fuel consumption function has been calibrated (as described in Appendix B) so that the marginal fuel consumption due to speed fluctuations is the sum of E_{k+} and E_{k+}^2 terms while the marginal fuel consumption due to grade is the last term of eqn (25).

Generally, the value of E_{k+} may not be known, and therefore can be estimated from

$$E_{k+} = 0.258 - 0.0018 v_c \quad (28)$$

or 0.10, whichever is larger

Using the default parameters given in Table IV, eqn (25) can be written as:

$$f_c = 1600/v_c + 30 + 0.0075 v_c^2 + 108 k_{E1} E_{k+} + 171.2 E_{k+}^2 + 10.6 k_G G \quad (29)$$

Using the results from the above equation, total fuel consumed while cruising, F_c in mL, can be calculated from

$$F_c = f_c x_c \quad (30)$$

where x_c is the cruise distance in km.

Example 8 Cruise

What are the fuel consumption values of a vehicle which travels along a 0.5 km section of road at an average cruise speed of 60 km/h and a 0.6 km section of road at an average cruise speed of 90 km/h on a:

- level road,
- 5 per cent uphill grade, and
- 5 per cent downhill grade?

Answer

For the first section ($x_{c1} = 0.5$ km, $v_{c1} = 60$ km/h), the estimate of E_{k+} from eqn (28) is:

$$E_{k+} = 0.258 - 0.0018 \times 60 = 0.150 \text{ J/kg.m}$$

The value of E_{k+} calculated from speed fluctuations via eqn (26) is 0.185. The estimated value of 0.150 is used below.

From eqn (27),

$$k_{E1} = 12.5/60 + 0.000013 \times 60 \times 60 = 0.255$$

Fuel consumption values are found from eqns (29) and (30) as follows:

$$\begin{aligned}
 \text{(a)} \quad G &= 0: \\
 f_{c1} &= (1600/60 + 30 + 0.0075 \times 60 \times 60) + (108 \times 0.255 \times 0.150 + 171.2 \\
 &\quad \times 0.150 \times 0.150) = 83.67 + 7.98 = 91.65 \text{ mL/km} \\
 F_{c1} &= 91.65 \times 0.5 = 45.8 \text{ mL}
 \end{aligned}$$

- (b) $G = 5$:
 $k_G = 1 - 0.3 \times 0.150 = 0.955$
 $f_{c1} = 91.65 + 10.6 \times 0.955 \times 5 = 91.65 + 50.61 = 142.27 \text{ mL/km}$
 $F_{c1} = 142.27 \times 0.5 = 71.1 \text{ mL}$
- (c) $G = -5$:
 $k_G = 1 - 2.1 \times 0.150 = 0.685$
 $f_{c1} = 91.65 + 10.6 \times 0.685 \times (-5) = 91.65 - 36.31 = 55.34 \text{ mL/km}$
 $F_{c1} = 55.34 \times 0.5 = 27.7 \text{ mL}$

For the second section ($x_{c2} = 0.6 \text{ km}$, $v_{c2} = 90 \text{ km/h}$), similarly:

$E_{k+} = 0.10 \text{ J/kg.m}$ and $k_{E1} = 0.244$ are found. The calculated value of E_{k+} via eqn (26) is 0.116 J/kg.m , but again, the estimated value is used.

- (a) $G = 0$:
 $f_{c2} = (1600/90 + 30 + 0.0075 \times 90 \times 90) + 108 \times 0.244 \times 0.10 + 171.2 \times 0.10 \times 0.10$
 $= 108.53 + 4.35 = 112.88 \text{ mL/km}$
 $F_{c2} = 112.88 \times 0.6 = 67.7 \text{ mL}$
- (b) $G = 5$:
 $k_G = 1 - 0.3 \times 0.1 = 0.97$
 $f_{c2} = 112.88 + 10.6 \times 0.97 \times 5 = 164.29 \text{ mL/km}$
 $F_{c2} = 164.29 \times 0.6 = 98.6 \text{ mL}$
- (c) $G = -5$:
 $k_G = 1 - 2.1 \times 0.1 = 0.79$
 $f_{c2} = 112.88 + 10.6 \times 0.79 \times (-5) = 71.01 \text{ mL/km}$
 $F_{c2} = 71.01 \times 0.6 = 42.6 \text{ mL}$

Note that the marginal fuel consumption due to the uphill grade on the first section is 50.6 mL/km , while on the downhill grade the marginal effect is 36.3 mL/km . The marginal fuel consumption rate due to speed fluctuations on the first section is small (8.0 mL/km) due to small E_{k+} , and the same trip at a constant speed on a level road would have a fuel consumption rate of 83.7 mL/km .

B.4.3.4 Fuel Consumption While Stopped

Total fuel consumed while the vehicle is stopped, F_i in mL, can be calculated from:

$$F_i = \alpha t_i \quad (31)$$

where t_i = stopped time (s), and

α = idle fuel rate (mL/s) whose default value is 0.444 mL/s .

For practical purposes, the vehicle may be considered to be stopped where speed is below 5 km/h . Some traffic models predict delay including acceleration and deceleration delays. The relation between this type of delay and the stopped time is as follows:

$$t_i = d - (1 - m_a) t_a - (1 - m_d) t_d \quad (32)$$

where d = delay including time lost due to acceleration and deceleration (s),

t_a, t_d = acceleration and deceleration time (s), use eqns (19) and (24) for estimating these variables,

m_a, m_d = coefficients to predict acceleration and deceleration distances (see eqns (18b) and (23b)).

Example 9 Idle

A traffic model predicts a delay of 37s including acceleration and deceleration delays for a vehicle which decelerates from 60 km/h to rest and then accelerates to a final speed of 90 km/h . What is the stopped time and the corresponding fuel consumption?

Answer:

From eqns (18b) and (23b),

$$m_a = 0.467 + 0.00200 \times 90 = 0.647$$

$$m_d = 0.473 + 0.00155 \times 60 = 0.566$$

From eqns (19) and (24),

$$t_a = 90 / (2.08 + 0.127 \sqrt{90}) = 27.4 \text{ s}$$

$$t_d = 60 / (1.71 + 0.238 \sqrt{60}) = 16.9 \text{ s}$$

The stopped time from eqn (32) is,

$$t_i = 37.0 - (1 - 0.647) \times 27.4 - (1 - 0.566) \times 16.9 = 37.0 - 17.0 = 20.0 \text{ s}$$

From eqn (31),

$$F_i = 0.444 \times 20.0 = 8.9 \text{ mL}$$

B.4.3.5 Excess Fuel Consumption per Stop (or Slow-down)

The excess fuel consumption associated with a stop-start (or deceleration-acceleration) manoeuvre, i.e. a deceleration from an initial cruise speed of v_{c1} to a final speed of v_f and an acceleration from an initial speed of v_f to a final cruise speed of v_{c2} , can be calculated from

$$f_h = F_a + F_d - (f_{c1} x_d + f_{c2} x_a + \Delta F) \quad (33a)$$

where F_a = acceleration fuel consumption in mL given by eqn (14),

F_d = deceleration fuel consumption in mL given by eqn (20),

f_{c1}, f_{c2} = cruise fuel consumption in mL given by eqn (25) using speeds of v_{c1} and v_{c2} , respectively,

x_a = acceleration distance in km (estimated using eqn (18) if unknown),

x_d = deceleration distance in km (estimated by eqn (23) if unknown), and

ΔF = is the extra excess fuel when $v_{c1} \neq v_{c2}$ and is estimated by:

$$\begin{aligned} \Delta F &= F'_a - f_{c2} x'_a & \text{for } v_{c1} < v_{c2} \\ &= F'_d - f_{c1} x'_d & \text{for } v_{c1} > v_{c2} \end{aligned} \quad (33b)$$

- where F'_a = is the fuel consumption to accelerate from v_{c1} to v_{c2} ($v_{c1} < v_{c2}$) in mL given by eqn (14),
- F'_d = is the fuel consumption to decelerate from v_{c1} to v_{c2} ($v_{c1} > v_{c2}$) in mL given by eqn (20),
- x'_a = is the distance travelled accelerating from v_{c1} to v_{c2} ($v_{c1} < v_{c2}$) in km estimated using eqn (18), and
- x'_d = is the distance travelled decelerating from v_{c1} to v_{c2} ($v_{c1} > v_{c2}$) in km estimated using eqn (23).

Eqn (33) is derived by subtracting from the deceleration-acceleration fuel consumption the fuel that would have been consumed had the vehicle cruised the equivalent distance. However, if $v_{c1} \neq v_{c2}$, some acceleration or deceleration will be necessary and it is assumed that the vehicle crosses the stop (or minimum speed) position of the deceleration-acceleration cycle at the lower of the two cruise speeds. Note that the excess fuel consumption, eqn (33) includes the components due to deceleration and acceleration delays (i.e. d in Section B.4.3.4).

Example 10 Excess Fuel Consumption (full stop)

What is the excess fuel consumption per stop for a vehicle which decelerates from 60 km/h to rest and accelerates back to 90 km/h:

- on a level road,
- on an uphill grade of 5 per cent,
- on a downhill grade of 5 per cent?

Answer:

Firstly calculate F'_a , the fuel to accelerate from 60 to 90 km/h.

From eqns (15) to (19), general parameters for acceleration are,

$$\begin{aligned} t'_a &= (90 - 60)/(2.08 + 0.127 \sqrt{90 - 60} - 0.0182 \times 60) = 17.8 \text{ s} \\ m'_a &= 0.467 + 0.00200 \times 90 - 0.00210 \times 60 = 0.521 \\ x'_a &= 0.521 (60 + 90) 14.5/3600 = 0.386 \text{ km} \\ E'_k &= 0.3858 \times 10^{-4} (90 \times 90 - 60 \times 60)/0.386 = 0.450 \text{ J/kg.m} \\ k'_1 &= 0.616 + 0.000544 \times 90 - 0.0171 \times \sqrt{60} = 0.5325 \\ k'_2 &= 1.376 + 0.00205 \times 90 - 0.00538 \times 60 = 1.2377 \end{aligned}$$

$$\begin{aligned} \text{For } G = 0: F'_a &= 0.444 \times 17.8 - (30 + 0.0075 \times 0.5325 \times (60 \times 60 + 90 \times 90) \\ &\quad + 108 \times 0.450 + 54 \times 1.2377 \times 0.450 \times 0.450) 0.386 \\ &= 7.90 + 138.86 \times 0.386 = 61.5 \text{ mL} \end{aligned}$$

$$\text{For } G = +5: F'_a = 61.5 + 10.6 \times 5 \times 0.386 = 82.0 \text{ mL}$$

$$\text{For } G = -5: F'_a = 61.5 - 10.6 \times 5 \times 0.386 = 41.0 \text{ mL}$$

Now, using the results from Examples 6 to 8, the excess fuel consumption is calculated from eqn (33) as follows:

$$\begin{aligned} \text{(a) } G &= 0: \\ \Delta F &= 61.5 - 112.88 \times 0.386 = 17.9 \text{ mL} \\ f_h &= 95.7 + 10.0 - (91.65 \times 0.159 + 112.88 \times 0.443 + 17.9) \\ &= 105.7 - 82.5 = 23.2 \text{ mL/stop} \end{aligned}$$

$$\begin{aligned} \text{(b) } G &= 5: \\ \Delta F &= 82.0 - 164.29 \times 0.386 = 18.6 \text{ mL} \\ f_h &= 119.2 + 12.9 - (142.27 \times 0.159 + 164.29 \times 0.443 + 18.6) \\ &= 132.1 - 114.0 = 18.1 \text{ mL/stop} \\ \text{(c) } G &= -5: \\ \Delta F &= 41.0 - 71.01 \times 0.386 = 13.6 \text{ mL} \\ f_h &= 72.2 + 7.6 - (55.34 \times 0.159 + 71.01 \times 0.443 + 13.6) \\ &= 79.8 - 53.9 = 25.9 \text{ mL/stop} \end{aligned}$$

Example 11 Excess Fuel Consumption (slow down)

What are the results for Example 10(a) if the vehicle does not come to a rest, but slows down to 15 km/h?

Answer:

Firstly calculate fuel to decelerate from 60 to 15 km/h.

General parameters for deceleration are calculated from eqns (15), (21a) to (21c) and (23a) to (24):

$$\begin{aligned} t_d &= 14.2 \text{ s}, & m_d &= 0.5455, & x_d &= 0.161 \text{ km}, \\ k_x &= 0.4209, & k_y &= 0.5226, & k_a &= 0.726, \\ k_1 &= 0.5944 \text{ and } & E_k &= -0.8087 \text{ J/kg.m} \end{aligned}$$

From eqn (22), the deceleration fuel consumption for $G = 0$ is

$$\begin{aligned} F_d &= 0.444 \times 14.2 + (0.4209 \times 30 + 0.5226 \times 0.5944 \times 0.0075 (60 \times 60 \\ &\quad + 15 \times 15) + 0.0726 \times 108 \times (-0.8087)) 0.161 \\ &= 6.30 + 15.19 \times 0.161 = 8.7 \text{ mL} \end{aligned}$$

Now calculate fuel to accelerate from 15 to 90 km/h. From eqns (15) to (19),

$$\begin{aligned} t_a &= 25.8 \text{ s}, & m_a &= 0.6155, & x_a &= 0.463 \text{ km}, \\ E_k &= 0.6562 \text{ J/kg.m}, & k_1 &= 0.5987 \text{ and } & k_2 &= 1.4798 \end{aligned}$$

From eqn (17), the acceleration fuel consumption for $G = 0$ is

$$\begin{aligned} F_a &= 0.444 \times 25.8 + (30 + 0.0075 \times 0.5987 (15 \times 15 + 90 \times 90) + 108 \times 0.6562 \\ &\quad + 54 \times 1.4798 \times 0.6562 \times 0.6562) 0.463 \\ &= 11.45 + 172.6 \times 0.463 = 91.4 \text{ mL} \end{aligned}$$

From Example 8, the cruise fuel consumption rates at 60 and 90 km/h are 91.65 and 112.88 mL/km, respectively, and from Example 10(a), $\Delta F = 17.9$ mL. The excess fuel consumption for the slowdown is found from eqn (33) to be

$$\begin{aligned} f_h &= 91.4 + 8.7 - (91.65 \times 0.161 + 112.88 \times 0.463 + 17.9) \\ &= 100.1 - 84.9 = 15.2 \text{ mL/slowdown} \end{aligned}$$

B.4.3.6 Total Fuel Consumed During a 'CDIAC' Cycle

Total fuel consumption for a cruise-deceleration-idle-acceleration-cruise (CDIAC) cycle which is shown in Fig. 15 can be calculated from

$$F_s = F_{c1} + F_d + F_i + F_a + F_{c2} \quad (34)$$

where F_i = fuel consumed in mL while stopped from eqn (31),
 F_{c1}, F_{c2} = fuel consumed in mL while cruising on the approach section (speed v_{c1} , distance x_{c1}) and the exit section (speed v_{c2} , distance x_{c2}) calculated from eqns (25) and (30), and
 F_d, F_a = fuel consumed in mL during deceleration and acceleration from eqns (20) and (14), respectively.

It can be assumed that the information on average cruise speeds (v_{c1}, v_{c2}) and section distances (x_{s1}, x_{s2}) are available. Using the values of x_a and x_d calculated for use in the acceleration and deceleration fuel consumption functions, the cruise distances can be found from $x_{c1} = x_{s1} - x_d$ and $x_{c2} = x_{s2} - x_a$. Note that if the approach or departure sections are short it is possible that negative values of x_c will result. If any x_c value is found to be negative, it is necessary to adjust the x_a or x_d value to obtain $x_c = 0$, i.e. $x_d = x_{s1}$ or $x_a = x_{s2}$. This can be done by decreasing t_d or t_a , provided the result corresponds to an acceptable deceleration or acceleration rate. For example, if x_{c2} is found to be negative, set $x_a = x_{s2}$ and estimate acceleration time by:

$$t_a = 3600 x_a / m_a v_i$$

where m_a is given by eqn (18b).

Average acceleration, $\bar{a} = (v_i - v_f) / t_a$, should then be checked to be sure it is a reasonable value, say less than 5 km/h/s. Otherwise, it is necessary to adjust the cruise speed to a level which satisfies the non-negative cruise distance condition.

Using F_s in mL calculated from eqn (34), fuel consumption per unit distance in mL/km during the CDIA cycle can be estimated from

$$f_x = F_s / x_s \quad (35)$$

where $x_s = x_{s1} + x_{s2}$ is the total section distance in km.

Example 12 Cruise-Deceleration-Idle-Acceleration-Cruise Cycle

What is the total fuel consumption and the fuel consumption per unit distance for the cruise-deceleration-idle-acceleration-cruise (CDIA) cycle shown in Fig. 15? Section distances are $x_{s1} = 0.65$ km and $x_{s2} = 1.05$ km, average cruise speeds are $v_{c1} = 60$ km/h and $v_{c2} = 90$ km/h and stopped time is 20s. Find the results for:

- level road,
- uphill grade of 5 per cent, and
- downhill grade of 5 per cent.

Answer:

Using the deceleration and acceleration distances calculated in Examples 6 and 7, the cruise distances are found as:

$$\begin{aligned} x_{c1} &= 0.650 - 0.159 = 0.491 \text{ km, and} \\ x_{c2} &= 1.050 - 0.443 = 0.607 \text{ km.} \end{aligned}$$

Cruise fuel consumption values can be calculated using these distances and the fuel consumption rates found in Example 8. The idle fuel rate for all cases is:

$$F_i = 0.444 \times 20 = 8.9 \text{ mL.}$$

The acceleration and deceleration fuel consumption values are as found in Examples 6 and 7. The results are summarised in Table VII.

TABLE VII

Grade	Fuel Consumed (mL)					Total
	Initial Cruise ($v_c = 60$)	Deceleration ($v_i = 60$, $v_f = 0$)	Idle ($v = 0$)	Acceleration ($v_i = 0$, $v_f = 90$)	Final Cruise ($v_c = 90$)	
0	45.8	10.0	8.9	95.7	67.7	228
+5	71.1	12.9	8.9	119.2	98.6	311
-5	27.7	7.6	8.9	72.2	42.6	159

Since the total section distance is $x_s = 0.65 + 1.05 = 1.7$ km, the fuel consumption rates are:

- $G = 0$:
 $f_x = 228 / 1.7 = 134 \text{ mL/km,}$
- $G = 5$:
 $f_x = 311 / 1.7 = 183 \text{ mL/km, and}$
- $G = -5$:
 $f_x = 159 / 1.7 = 94 \text{ mL/km}$

Compared with the results from the instantaneous model given in Example 5, the elemental model is found to predict fuel consumption for this example with errors of the order of ± 1 per cent.

Note that in this example the final and initial speeds of all accelerations and decelerations (including those during cruise) are known. It is therefore possible to estimate the total fuel consumption by the sum of the fuel consumed during all accelerations and decelerations plus the steady-speed fuel consumption over each section of constant speed (found using eqn (13)). Using this approach for the zero grade case, the estimated cruise fuel consumption values, for the initial and final sections are 49.1 mL and 67.9 mL, respectively, and total fuel consumption is found to be 232 mL.

B.4.4 A RUNNING SPEED MODEL OF FUEL CONSUMPTION

A model which estimates fuel consumption separately during periods when the vehicle is stopped and running will be referred to as the running speed model. This is a more aggregate model than the elemental model considered in Section B.4.3 since the acceleration, deceleration and cruise phases are lumped together. In this model, the function for estimating the 'running' component of fuel consumption has the same form as the cruise fuel consumption function of the elemental model (eqn 25) except that:

- the cruise speed is replaced by the running speed which includes the effects of acceleration and deceleration delays due to stops or slowdowns along the section, but excludes the effect of stopped time; and

- (b) the coefficients for the energy and grade terms are different due to different conditions for calibration.

The model is given as:

$$F_s = \alpha t_i + f_r x_s \quad (36a)$$

or αt_s , whichever is larger

$$f_r = f_i/v_r + A + Bv_r^2 + k_{E1} \beta_1 ME_{k+} + k_{E2} \beta_2 ME_{k+}^2 + 0.0981 k_G \beta_1 MG \quad (36b)$$

where f_r = average section fuel consumption per unit distance excluding idle periods, in mL/km,

v_r = average running speed in km/h given by:

$$v_r = 3600 x_s / (t_s - t_i) \quad (37)$$

x_s = total section distance in km,

t_s = travel time along section in s,

t_i = idle (stopped) time in s,

E_{k+} = sum of positive kinetic energy changes per unit mass per unit distance along the section in J/kg.m = m/s² given by:

$$E_{k+} = 0.3858 \times 10^{-4} [\sum (v_f^2 - v_i^2)] / x_s \quad (38)$$

where v_f, v_i = final and initial speed (km/h) during each positive acceleration ($v_f > v_i$),

$f_i, \alpha, A, B, \beta_1, \beta_2, M$ = vehicle related parameters as in eqns (1) and (13); default values are given in Table IV,

k_{E1}, k_{E2}, k_G = calibration parameters estimated from:

$$k_{E1} = 0.675 - 1.22/v_r \quad (39a)$$

or 0.5, whichever is larger

$$k_{E2} = 2.78 + 0.0178 v_r \quad (39b)$$

$$k_G = \begin{matrix} 1 - 1.33 E_{k+} & \text{for } G < 0 \\ 0.9 & \text{for } G > 0 \end{matrix} \quad (39c)$$

If E_{k+} is not known, it can be estimated from:

$$E_{k+} = 0.35 - 0.0025 v_r \quad (40)$$

or 0.15, whichever is greater

The average section fuel consumption rate per unit distance can be expressed as

$$f_x = f_r + \alpha t_i / x_s \quad (41)$$

Using the default values of vehicle parameters given in Table IV, eqn (36b) becomes:

$$f_r = 1600/v_r + 30 + 0.0075 v_r^2 + 108 k_{E1} E_{k+} + 54 k_{E2} E_{k+}^2 + 10.6 k_G G \quad (42)$$

The running speed model can be used to estimate fuel consumption in a variety of traffic contexts, ranging from short sections to long trips. In cases where only the trip time and distance are known, average running speed and idle time can be estimated from:

$$v_r = 8.1 + 1.14 v_s - 0.00274 v_s^2 \quad (43)$$

or v_s , whichever is smaller

$$t_i = t_s - 3600 x_s / v_r \quad (44)$$

It should be noted that the grade term will only accurately reflect the fuel consumption due to grade over short sections where the average grade is a true measure of the changes in grade. Positive grades contribute fully to fuel consumption but, due to braking, negative grades sometimes do not contribute fully. Thus, over a long trip, the effect on fuel consumption of positive and negative grades may not cancel each other out and this can result in underestimation of fuel consumption. For Sydney on-road data, the maximum underestimate was found to be about four per cent.

Example 13 Running Speed Model

What is the total fuel consumption and the fuel consumption per unit distance for the CDIAC cycle shown in Fig. 15 using the running speed model? Find the results for

- level road,
- uphill grade of 5 per cent, and
- downhill grade of 5 per cent.

Answer:

From eqn (37), the average running speed for this example is:

$$v_r = 3600 \times 1.7 / (118 - 20) = 62.4 \text{ km/h}$$

From eqn (39),

$$k_{E1} = 0.675 - 1.22/62.4 = 0.655$$

$$k_{E2} = 2.78 + 0.0178 \times 62.4 = 3.891$$

The E_{k+} value can be calculated from eqn (38):

$$E_{k+} = 0.3858 \times (0.70^2 - 0.60^2 + 60^2 - 0.50^2 + 0.90^2 - 0 + 0.95^2 - 0.85^2) / 1.7$$

$$= 0.2791 \text{ J/kg.m}$$

The fuel consumption rates can be calculated from eqn (42) and total fuel consumption from eqn (36a) as follows:

- $G = 0$:

$$f_r = (1600/62.4 + 30 + 0.0075 \times 62.4 \times 62.4 + (108 \times 0.655 \times 0.2791 + 54 \times 3.891 \times 0.2791 \times 0.2791)) = 84.85 + 36.11$$

$$= 120.9 \text{ mL/km}$$

$$F_s = 120.9 \times 1.7 + 0.444 \times 20 = 214 \text{ mL}$$

Compared with $F_s = 231 \text{ mL}$ from the instantaneous model, this result corresponds to 8 per cent underestimation.

- $G = 5$:

From eqn (39c), $k_G = 0.9$

$$f_r = 120.9 + 10.6 \times 0.9 \times 5 = 168.6 \text{ mL/km}$$

$$F_s = 168.6 \times 1.7 + 0.444 \times 20 = 296 \text{ mL}$$

(6 per cent underestimated)

$$\begin{aligned}
 (c) \quad G &= -5: \\
 k_G &= 1 - 1.33 \times 0.2791 = 0.624 \\
 f_r &= 120.9 + 10.6 \times 0.629 \times (-5) = 87.6 \text{ mL/km} \\
 F_s &= 87.6 \times 1.7 + 0.444 \times 20 = 158 \text{ mL} \\
 &\text{(less than 1 per cent underestimated)}
 \end{aligned}$$

The predicted values are reasonably good. However, if the actual value of E_k is not known, it can be estimated from eqn (40):

$$E_{k+} = 0.349 - 0.00246 \times 62.4 = 0.1955 \text{ J/kg.m}$$

Using this estimated value of E_{k+} , section fuel consumption can be estimated by:

- (a) for $G = 0$, $F_s = 190 \text{ mL}$ (18% underestimated)
- (b) for $G = 5$, $F_s = 271 \text{ mL}$ (14% underestimated), and
- (c) for $G = -5$, $F_s = 124 \text{ mL}$ (22% underestimated).

B.4.5 AVERAGE TRAVEL SPEED MODEL OF FUEL CONSUMPTION

A simple, aggregate fuel consumption model which has been used widely is the one which relates fuel consumption per unit distance to average travel speed. It is appropriate to apply this model at a traffic network level rather than on short road sections. The model is:

$$f_x = a/v_s + b \quad (45)$$

where f_x = fuel consumption per unit distance in mL/km,

v_s = average travel speed in km/h (= $3600 x_s/t_s$, where x_s , t_s are total travel distance and travel time including any stopped time), and

a , b = regression coefficients.

The forms of the functions given in previous sections indicate that the coefficient for the speed term should be the idle fuel rate and on-road data confirm that there is almost no loss in accuracy by setting this parameter to the idle rate. The drag, inertia and grade components of fuel consumption are all accounted for by the constant term. The value of the constant, b , will therefore be influenced by the vehicle parameters M , β_1 , β_2 , etc. as well as the driving environment. The following expression can be used as an explicit form of the average travel speed model for estimation of urban fuel consumption:

$$F_s = f_x x_s \quad (46a)$$

$$f_x = f_i/v_s + cK \quad (46b)$$

where f_i = idle fuel consumption in mL/h,

x_s = total travel distance in km,

c = regression coefficient derived using the default parameters given in Table IV (page 29), and

K = adjustment factor to allow for varying vehicle parameters given by

$$\begin{aligned}
 K &= 1 - K_1 (1 - M/1200) - K_2 (1 - \beta_1/0.090) - K_3 (1 - \beta_2/0.045) \\
 &\quad - K_4 (1 - b_1/0.000278 M) - K_5 (1 - b_2/0.00108) \quad (47)
 \end{aligned}$$

From the analysis of Sydney on-road data, parameters c and K_1 to K_5 (hence K) have been found to depend on driving environment. The values of these parameters are summarised in Table VIII. Using the default parameters, given in Table IV, $K = 1$ is found, therefore

$$f_x = 1600/v_s + 73.8 \quad (48)$$

is obtained for the general urban environment. However, for a large car whose parameters are $f_i = 2400$, $M = 1700 \text{ kg}$, $\beta_1 = 0.100$, $\beta_2 = 0.050$, $b_1 = 0.405$, $b_2 = 0.00104$:

$$\begin{aligned}
 K &= 1 - 0.72(1 - 1700/1200) - 0.867(1 - 0.100/0.090) \\
 &\quad - 0.134(1 - 0.050/0.045) - 0.406(1 - 0.405/(0.000278 \times 1700)) \\
 &\quad - 0.280(1 - 0.00104/0.00108) \\
 &= 1 + 0.300 + 0.096 + 0.015 - 0.058 - 0.010 = 1.343 \\
 cK &= 73.8 \times 1.343 = 99.1
 \end{aligned}$$

Hence, the simple model for this large car in the general urban environment is

$$f_x = 2400/v_s + 99.1 \quad (49)$$

TABLE VIII

PARAMETERS FOR THE AVERAGE TRAVEL SPEED MODEL

Driving Environment	c	K_1	K_2	K_3	K_4	K_5
CBD	70.6	0.893	0.790	0.210	0.421	0.109
Other urban	74.2	0.701	0.875	0.125	0.404	0.299
Urban* (general)	73.8	0.720	0.867	0.134	0.406	0.280

* Average of CBD and other urban assuming 10 per cent of driving in CBD and 90 per cent in other urban areas.

The average travel speed model does not adequately reflect the increase in aerodynamic drag, and therefore fuel consumption, at high speeds. Thus the model is only applicable for urban driving where the average travel speed (over a trip or network) is below about 50 km/h. Where average travel speeds are over 50 km/h (e.g. in freeway sections of a traffic network), the running speed model eqn (36) with default estimates of v_r , t_r , and E_{k+} (eqns (43), (44) and (40), respectively) should be used.

Example 14 Average Travel Speed Model

What is the fuel consumption rate predicted using the average travel speed model for the example given in Fig. 15? Compare this estimate with those from the running speed model, with estimated v_r and t_r , and with the instantaneous model calculated in Example 5.

Answer:

The average section speed is $v_s = 3600 \times 1.7/118 = 51.9$ km/h.
From eqn (48) and (46a),

$$\begin{aligned} f_x &= 1600/51.9 + 73.8 = 104.6 \text{ mL/km} \\ F_s &= 104.6 \times 1.7 = 178 \text{ mL} \end{aligned}$$

Compared with the results from the instantaneous model (231, 315, 157 mL), the average trip model is found to underestimate fuel consumption by 23 per cent for zero grade, 43 per cent for uphill grade of 5 per cent and to overestimate by 13 per cent for downhill grade of 5 per cent.

However, as the average section speed is greater than 50 km/h, the running speed model, with v_r and t_r estimated from v_s , should be used. From eqns (43) and (44),

$$\begin{aligned} v_r &= 8.05 + 1.141 \times 51.9 - 0.00274 \times 51.9 \times 51.9 = 59.9 \text{ km/h} \\ t_r &= 118 - 3600 \times 1.7/59.9 = 15.8 \text{ s} \end{aligned}$$

With E_{k+} , k_{E1} , k_{E2} and k_G calculated using eqns (40) and (39a, b and c), respectively, the section fuel consumption was estimated from eqn (36) to be:

- (a) for $G = 0$, $F_s = 188$ mL (19% underestimated),
- (b) for $G = 5$, $F_s = 269$ mL (15% underestimated), and
- (c) for $G = -5$, $F_s = 128$ mL (12% underestimated).

Note that use of the running speed model in this situation has the advantage that grade can be allowed for, to some extent, in the estimation of fuel consumption.

B.5. SELECTED DESIGN CASE STUDIES

The primary consideration in this section will be the choice of both traffic and fuel consumption models to aid *design* of traffic management schemes in particular contexts. It is assumed in each of the cases that some diagnostic process has established that the particular forms of traffic management (i.e. priority control, signalisation) are appropriate. As discussed in Chapter B.3, there is a wide range of possible contexts which are likely to be experienced in practice. It is therefore not possible to indicate the appropriate choice in each specific situation. However, it is possible to demonstrate through several selected case studies, the factors to consider in choosing models, the information value that can result and the means of cost-effective use.

The models INSECT, SATURN and SIDRA-2 are used in the case studies. They reflect a range of models and are suitable for demonstrating the importance of particular model characteristics for fuel consumption analyses. It should be noted that the analyses reported here were completed in August, 1984, and reflect the status of the models at that time. Each of the models has been subsequently developed further and interested persons are referred to the relevant sources.

The cases to be discussed here will be conveniently based on one primary data set. This is the data compiled by Luk *et al.* (1983) and extended by Bowyer (1984), relating to the Parramatta area in Sydney (Fig. 10). This data set covers a number of traffic operating and control conditions (Fig. 17) and enables consideration of scheme design and fuel analyses at isolated unsignalised intersections (Section B.5.1), signalised intersections (Section B.5.2) and in small sub-areas within urban areas (Sections B.5.3, B.5.4). Finally, a brief consideration is given in Section B.5.5 to the cost-effectiveness of the fuel analyses in these selected cases.

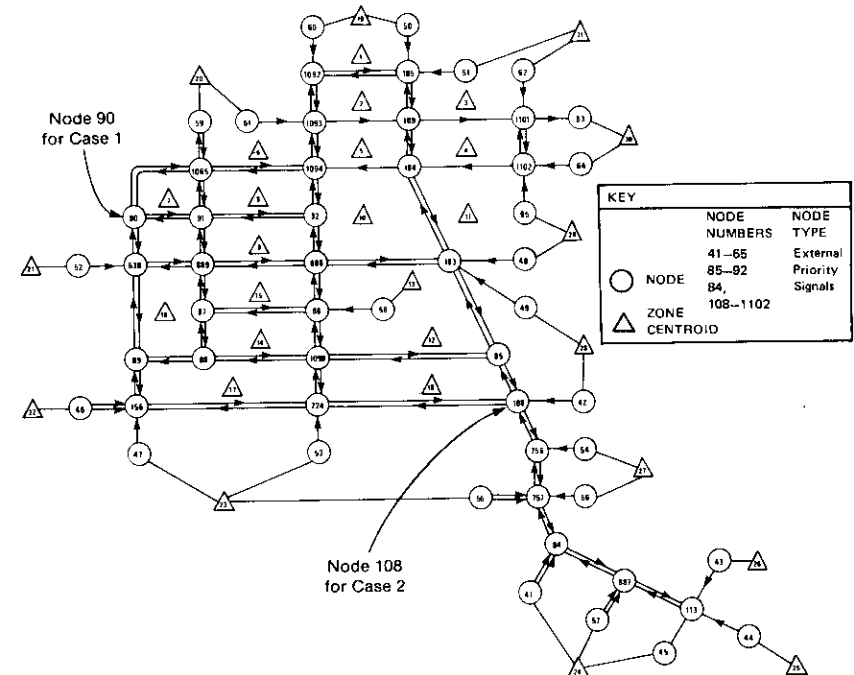


Fig. 17 — Parramatta network for design case studies

B.5.1 CASE 1: ISOLATED UNSIGNALISED INTERSECTIONS

A common and important consideration in Australian urban areas is the appropriate level of control at unsignalised intersections. The Australian standard for control devices (Standards Association of Australia 1978) encourages cost-benefit analyses to determine the appropriate control system for a particular intersection, but provides only broad volume and safety information to aid the traffic manager.

Decisions relating to the level of control might be aided by more detailed information on traffic performance under the alternative levels of

control. Here the use of traffic and fuel consumption models to estimate fuel consumption under stop and give-way control for the particular intersection represented by node 90 in Fig. 17 is considered. To represent the case of a simple 'T' intersection, node 90 will be coded with one-way flow on the major arm, as depicted in Fig. 18.

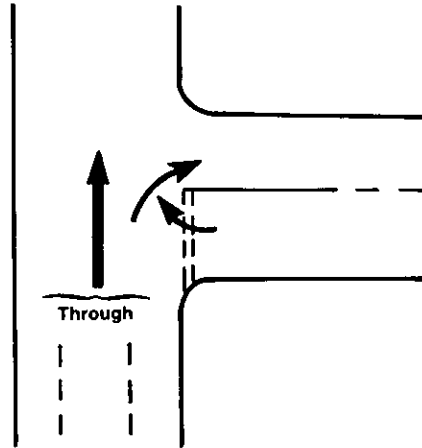


Fig. 18(a) — Description of Node 90, Fig. 17 (in one-way operation on the major arm) showing a single through movement

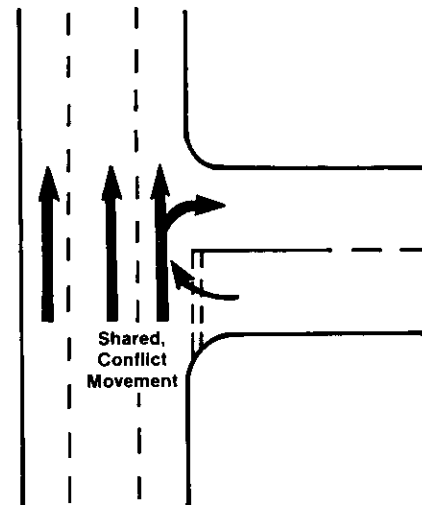


Fig. 18(b) — Description of Node 90, Fig. 17, showing the 'conflict' movement in shared lane

Choice of Traffic Model

There are a number of traffic models which can be used to analyse intersections under priority control. Two which are available in Australia are SATURN and INSECT. For this single intersection context, SATURN can be considered as a meso-traffic model, in that it attempts a steady-state simulation of the vehicle flow patterns into and out of the intersection. The set of feasible movements are user-specified and it is possible with SATURN to specify vehicle movements through the intersection at different levels of detail. Two options are depicted in Fig. 18a and 18b. For the cost-effective use of SATURN in small network analyses, a single 'through-movement' covering several vehicle lanes, as depicted in Fig. 18a, is commonly used. This coding was used for analyses in the total network (Fig. 17), from which results for node 90 were extracted. INSECT used the node description depicted in Fig. 18b.

Two important elements in SATURN relevant to this 'T' intersection context are the procedures for calculating capacity and number of stops on the side arm. The capacity is calculated as a function of the through volume on the major arm using a gap acceptance model. Estimates of delay and queueing on the side arm are based on this capacity and are calculated using average, analytic functions. A number of assumptions are made in estimating the number of stops. These include an assumption that all vehicles make one primary stop at a 'give-way' sign. INSECT attempts a micro-simulation of the traffic flow through the intersection. It is structured as a dynamic simulation system, which seeks to determine the movement of each vehicle in the system at successive time points. The transitions of each vehicle are governed by gap acceptance functions.

Estimated traffic variables for the intersection under 'priority' control are shown in Table IX. Several significant differences can be seen. Firstly, SATURN produces a much higher estimate of delay per vehicle on the minor arm than does INSECT for either control mode. The SATURN estimate is based on the total flow on the major arm while INSECT is based on the flow in the right (shared) lane. Both the delay estimates are highly sensitive to these volumes. The estimated primary stops reflects the fact that SATURN 'priority' control is essentially stop control. More significant still is the difference in estimated secondary stops. The primary reasons for this would appear to be the limitations of the analytic procedures employed in SATURN for reflecting gap acceptance behaviour and vehicle move-up/discharge behaviour at priority control intersections. These differences in traffic variable estimates would lead, logically, to a higher estimate of fuel consumption from SATURN.

This comparative analysis demonstrates the importance of careful choice of traffic model for investigations relating to isolated, unsignalised intersections. A micro-simulation tool would seem appropriate to assessing alternative levels of control. The specific results for SATURN also caution its use (in current form) for analysis in traffic networks which have predominantly 'give-way' control.

TABLE IX

ESTIMATES OF DELAY AND STOPS FOR THE MINOR ARM OF
NODE 90, Fig. 17

	SATURN Estimates*	INSECT Estimates	
		Give-Way Control	Stop Control
Delay (s/veh)	50	6	11
No. of stops — primary	135	35	152
— secondary†	230	6	15
— total	367	40	167
Veh. volume (veh/h)‡	135	151	151

* 'Priority Control' condition

† 'Move-ups' in INSECT, provides an upper-bound on secondary stops

‡ 'actual arrivals' simulated by INSECT for an expected arrival rate of 135 veh/h.

Choice of Fuel Consumption Model

INSECT estimates the speed of vehicles in the system at nominated time points, which can be specified down to intervals of one half of a second. Thus it can provide input to an instantaneous fuel consumption model of the form described in Chapter B.4. This model has been incorporated into INSECT. It is also possible to identify vehicle stops and to thus estimate the number of stops and the delay time in the system. These are primary traffic inputs to elemental forms of fuel consumption model, which estimate the fuel consumed in each drive mode. The form of drive-mode fuel consumption model currently in INSECT has been derived from Kent *et al.* (1982). It should be noted that this is a more aggregate specification of the elemental model than that described in Section B.4.3.

An important consideration is whether the choice of fuel consumption model would significantly influence the design decision. A comparative test of the two fuel consumption models can be conducted with the data for node 90. As shown in Table X, the INSECT elemental model estimate is significantly lower than the instantaneous model estimate for each of the two forms of control. The bottom line of the Table could have considerable importance for design decisions. This indicates the difference in fuel consumption for vehicles on the minor arm under stop or give-way control, estimated by the two fuel models. The INSECT elemental model estimate of -12 mL/veh represents a loss of at least \$14 per week in fuel costs. This suggests that the decision on level of priority control is important in fuel consumption terms and that fuel savings should be a factor in the decision. However, the instantaneous estimate of -3 mL/veh suggests that the difference in fuel consumption is not likely to be a significant factor in the control decision.

TABLE X

ESTIMATED FUEL CONSUMPTION FOR THE MINOR ARM OF
NODE 90, Fig. 17

Form of Control	Estimated Fuel Consumption* (mL/veh)		
	Elemental Model †	Instantaneous Model	Difference
Give-Way	30	44	-14
Stop	42	47	-5
Difference (mL/veh)	-12	-3	
(\$/week)‡	\$-14	\$-3	

* Results are for a 'medium' conflict level.

† An elemental form derived from Kent *et al.* (1982) as used in INSECT

‡ Basis is; 148 veh/h during peak period on the minor arm, loss occurs over 4h/day, 5 days a week, and fuel cost of 40¢/L.

Desirable Information Forms

The fuel consumption characteristics of the intersection under the two control alternatives of stop and give-way are depicted in Fig. 19. For design purposes the primary information is the estimated difference in fuel consumption between the two control modes. Intuitively this will vary with the conflicting volume on the major arm, but it might also vary with the volume on the minor arm, as depicted in Fig. 19. Thus, it is desirable to estimate the difference for the *likely* volume or for the range of possible volumes, if such traffic demand information is available. The results of such an analysis for a range of major road 'conflict' volumes in node 90 is shown in Fig. 20. It is evident that the fuel difference is more significant in low 'conflict' volume contexts.

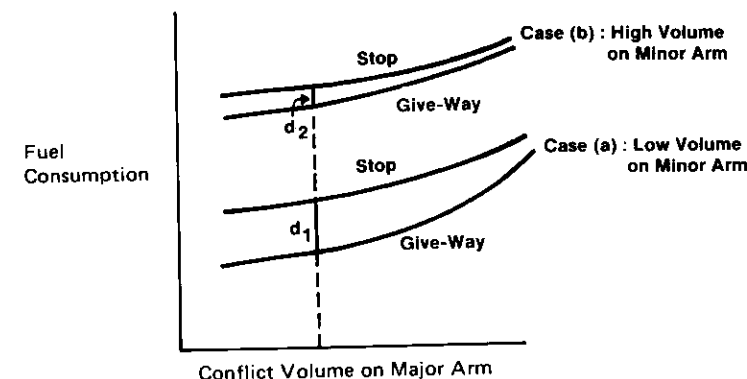


Fig. 19 — Fuel consumption rate for different traffic volumes and forms of control at an isolated intersection

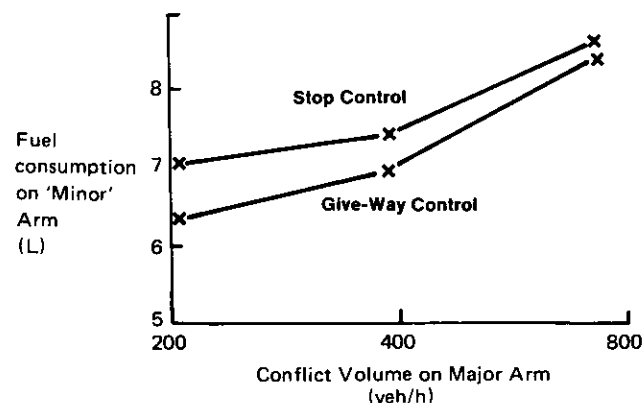


Fig. 20 — Estimated fuel consumption on the minor arm of Node 90, Fig. 17, under give-way and stop control

These findings carry two points of significance for the traffic manager. Firstly, fuel consumption could be a significant factor in the design of priority control at isolated intersections. Secondly, functions which reflect fuel differences in average traffic conditions (say, Case (a), Fig. 19) might not provide accurate estimates of fuel differences in other traffic conditions (say Case (b), Fig. 19).

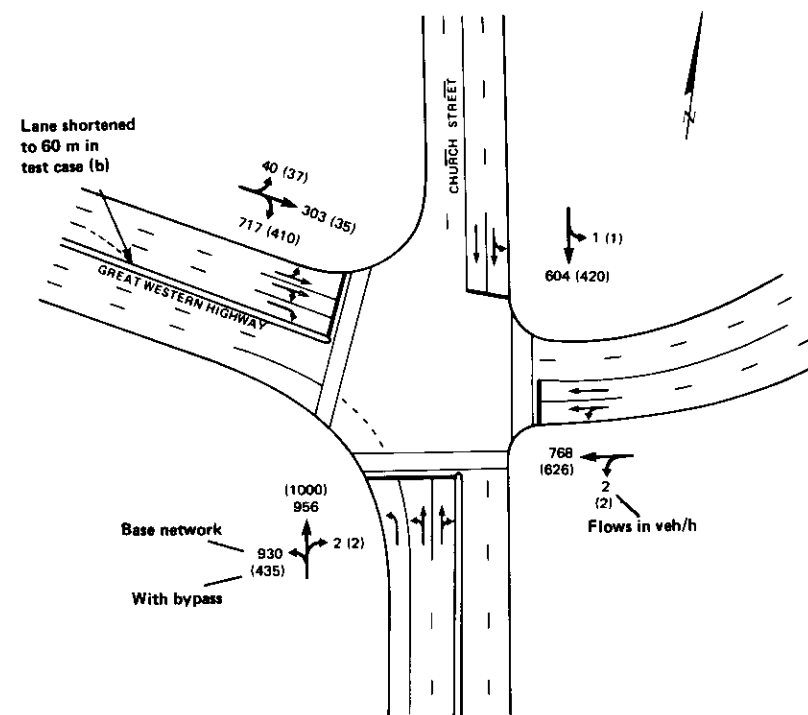
B.5.2 CASE 2: ISOLATED SIGNALISED INTERSECTIONS

There are many urban intersections in Australia which are operating under isolated signal control, that is, not coordinated with signals at adjacent intersections. A primary traffic management interest with these intersections is the detailed design of the geometric layout and signal settings for a particular intersection. It is instructive to consider several issues associated with the choice of traffic and fuel consumption models for estimating fuel consumption at a particular intersection of this type under alternative designs.

The intersection represented by node 108 in Fig. 17 can be considered as an isolated signalised intersection. The detailed layout of this intersection is shown in Fig. 21. The modelling of this intersection presents some difficulties due to lane interaction problems on the West and South approach roads. The purpose here is to compare traffic performance and fuel consumption estimates from two traffic models, SATURN and SIDRA-2.

Traffic and Fuel Consumption Model Characteristics

SATURN is a network program that accepts signal timings and saturation flows for each intersection as input, while SIDRA-2 is a more detailed program for a single intersection, which can estimate saturation flows and



Signal phasing

Movement numbers

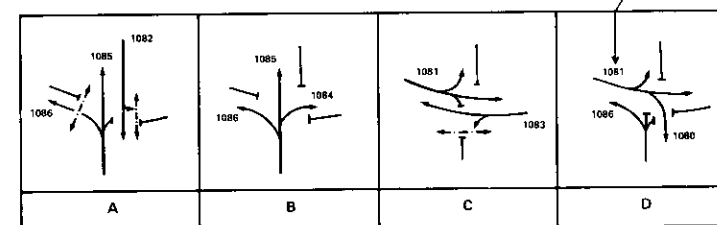


Fig. 21 — Intersection layout and flows for Node 108, Fig. 17 (used in Case Study 2)

compute signal timings. There are several important differences between the fuel consumption modules in the two traffic models. SIDRA-2 employs the four-mode elemental model of fuel consumption described in Section B.4.3 of this Guide. The model is applied to stopped and unstopped vehicles in each lane of each approach road separately. Stops in queue are accounted for separately from the major stops (first deceleration from the approach cruise speed and the final acceleration to the exit cruise speed). Fuel consumption estimates for SATURN are also found using an elemental form of fuel consumption model. However, the estimates are calculated by multiplying the summary statistics for the intersection as a whole by the appropriate fuel consumption rates (90 mL/km for cruise, 0.444 mL/s for delay and 15 mL for each stop). Differences in the fuel consumption estimates from SATURN and SIDRA-2 could be due to differences in both the fuel consumption modules and the traffic model estimates of traffic variables.

Traffic and Fuel Consumption Estimates

The importance of these model differences for estimation of traffic variables and fuel consumption can be seen by considering the following three cases for the intersection at node 108:

- the base network, with high flow conditions;
- as in (a) but with the right turn lane in the west approach road shortened to 60 m in length; and
- as in (a), but with medium flow conditions (caused by diversion to a bypass).

Condition (b) is included to indicate the sensitivity of results to a single design change, in this case, the effect of length of the turn lane on capacity and, thus, performance.

For cases (a) and (c), SATURN and SIDRA-2 were run with the same set of signal timings. In addition, SIDRA-2 was used to calculate practical signal timings for each flow condition. The traffic variable and fuel consumption estimates from these analyses are shown in *Table XI* and the following observations can be made.

- Under high flow conditions (case (a)) and SATURN timings, SIDRA-2 predicts much worse traffic performance and higher fuel consumption, e.g. average delay of 101 v. 51 seconds. The degree of saturation in this case is high (a maximum of 1.14) and SATURN underpredicts this because it neglects overflow queue effects near and above capacity.
- The procedure used to calculate fuel consumption in SATURN can also be used with the summary statistics produced by SIDRA-2. The fuel consumption rate for SIDRA-2 found in this way for condition (a) is 272 mL/km and compares with 205 mL/km found by SATURN and 245 mL/km found by the detailed elemental model in SIDRA-2. Thus the difference in traffic variables estimated by SATURN and SIDRA-2

TABLE XI

TRAFFIC PERFORMANCE AND FUEL CONSUMPTION ESTIMATES FOR CASE 2
(ISOLATED SIGNALISED INTERSECTION: NODE 108)

Traffic and Signal Timing Conditions	Total Arrival Flow (veh-h/h)	Total Distance Travelled (veh-km/h)	Average Speed (km/h)	Average Delay per Vehicle (s)	Total Number of Stops (veh/h)	Average Fuel Cons. Rate (mL/km)
HIGH FLOWS (Base Network Case)	4321	1298				
SATURN Results			14.0	51	4474	216
SIDRA-2 Results						
(a) SATURN Timings			8.5	101	5050	245
(b) SIDRA-2 Timings			17.1	37	3754	155
HIGH FLOWS (With a Short Lane)*	4321	1298				
SIDRA-2 Results						
(a) SATURN Timings			6.0	155	5704	318
(b) SIDRA-2 Timings			7.4	121	5797	270
MEDIUM FLOWS (Bypass Case)	2967	886				
SATURN			16.4	39	2670	193
SIDRA-2						
(a) SATURN Timings			17.2	35	2058	155
(b) SIDRA-2 Timings			20.0	27	2120	142

* 60 m short lane for right-turners from the West approach road (Great Western Highway)

SATURN Timings: Cycle time = 140, Phase change times = 0, 30, 74, 114 (same for all cases)

SIDRA-2 Timings: High Flows (Base Network Case) : Cycle time = 110, Phase change times = 0, 28, 52, 83

High Flows (With a Short Lane) : Cycle time = 110, Phase change times = 0, 28, 52, 90

Medium Flows (Bypass Case) : Cycle time = 100, Phase change times = 0, 28, 52, 78

produces a very different estimate of fuel consumption when the same fuel consumption model is used. The primary reason for this difference is the large difference in delay estimates. Also, the less detailed elemental model overestimates fuel consumption by 11 per cent in this example.

- (c) For high flow conditions, signal timings calculated by SIDRA-2 indicates a maximum degree of saturation of 0.88 (i.e. congestion not high), and much better performance results are therefore obtained, with fuel consumption reducing to 155 mL/km. This shows the importance of re-calculating signal timings for a given flow condition.
- (d) The case with a short lane instead of a lane of unlimited length shows how sensitive the results are to specific geometric design conditions. The overall fuel consumption rate is increased significantly by shortening the lane (74 per cent increase under re-calculated signal timings).
- (e) Under the medium flow conditions (case (c)), the predictions by SATURN and SIDRA-2 of delay and average speed are reasonably close although the number of stops differs significantly. In this case, the intersection is well below capacity (degree of saturation is 0.69) and the overflow terms have little contribution. Under SIDRA-2 timings (lower cycle time), the degree of saturation is increased to 0.79 which has the effect of decreasing the delay but increasing the number of stops, and the fuel consumption rate is decreased as a result.

These analyses show the importance of choosing a traffic model which is capable of estimating performance under alternative traffic flow and design conditions at a particular intersection. They also show the importance of choosing the exact form of fuel consumption model appropriate to the traffic model and traffic system being analysed.

The analyses for the medium flow conditions also have implications for using traffic models to estimate performance changes resulting from sub-area traffic management schemes. SIDRA-2 calculates an optimum cycle time of 100 seconds for medium flows, which is significantly lower than the 140 seconds set for the high flow conditions and input to SATURN. If a management scheme significantly changes flow patterns at a particular intersection, then the traffic model must be able to determine appropriate adjustments to signal timings, if performance changes are to be estimated accurately.

B.5.3 CASE 3: SUB-AREA CONTROL SYSTEMS

A common experience in Australian cities has been the significant fuel reductions which can be associated with improved signal control systems in urban sub-areas. A particular case is signal coordination along major arterial roads. These can be viewed as 'linear' sub-systems. These

experiences have led to strong confidence and interest in signal coordination systems along arterial roads, and in adjacent street networks. A particular thrust is towards dynamic systems such as SCATS.

Objectives and Design Criteria

The need for, and form of, fuel consumption analyses in the design of signal control systems for sub-areas will depend strongly on the management objectives and the related design criteria. It might be argued, for example, that the benefits of reduced 'down time' resulting from real-time detection of system faults is a primary justification for dynamic control systems. If reduced 'down time' is the main design criterion, then there is little need for detailed analyses of user benefits, including fuel savings, in particular situations. A general assessment of the signal system performance over time would be more appropriate (see, for example Nairn and Partners, 1983b).

It appears, however, that direct user benefits for control systems in particular sub-areas are a practical concern (Negus and Fehon 1982; Luk *et al.* 1983). Several recently reported studies indicate that user benefits will vary significantly with the traffic system context and that there are marginally decreasing returns from successively higher levels of control. The study by Luk *et al.*, for example, shows the marginal travel time and fuel savings to be of the form in Fig. 22, for the CBD sub-area, which can be defined as the network north of the GWH in Fig. 10. These savings are not, however, uniform across the study area. As indicated in Table XII, the impact of signal coordination on the CBD sub-system is significantly different from the impact on the more linear-arterial, GWH system.

It seems desirable, therefore, that consideration be given in the design phase to the marginal returns from the incremental forms of coordination, since full dynamic systems are more costly than, say, linked VA. From an analysis perspective estimation of delay and stops can demand considerable analytical effort and thus care is required to select the most appropriate modelling technique.

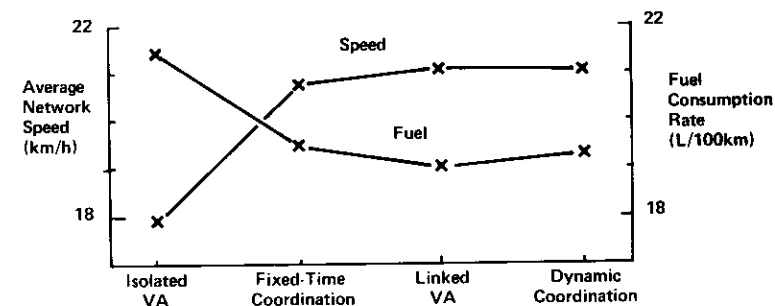


Fig. 22 — Speed and fuel consumption in the CBD sub-area under four signal control modes
Source: Estimates derived from on-road measurements reported by Luk, Sims and Lowrie (1983)

TABLE XII

PERFORMANCE DIFFERENCES BETWEEN CONTROL MODES
IN CBD AND GWH SYSTEMS*

Control Mode Change	System	Change in Traffic Variable (%)		
		Speed	Stops	Fuel
Isolated to Dynamic	CBD	0	-20	-3
	GWH	20	-48	-13
Fixed-time to Linked-VA	CBD	-2	6	5
	GWH	5	-18	-3
Fixed-time to Dynamic	CBD	-3	-5	2
	GWH	6	-25	-11

* The Central Business District (CBD) is the network above the Great Western Highway (GWH), shown in Fig. 10.

Choice of Traffic Model

Three primary factors will influence the choice of traffic model. These are the form of traffic control options being considered, the nature of traffic system impacts and the scale of the particular traffic system.

It is conceivable that in a particular sub-area, the base network could contain a mix of priority and signalised control modes for the intersections. Further, the set of traffic control options being considered in the design phase might require comparisons between levels of priority or signalised control modes. The full set of traffic control options which one might wish to simulate are shown in Table XIII. Also indicated in the Table is the suitability of available traffic models to simulate these options and it is evident that no one model spans the full set.

The nature of the impacts of control changes on travel demand and traffic operations in the sub-area could also influence the model choice. Demand changes of particular importance for fuel analyses are the possible impacts on driver route choice and the distribution of trips within the sub-area. Both LATM and SATURN can estimate route changes, but not trip changes. The latter requires the use of higher level transport analysis models. Traffic operational changes relevant to fuel analysis are the impacts on intersection delay and stops. All four models estimate delay and stops, but the accuracy of estimates could vary significantly across the models. It is important, therefore, to gauge the accuracy of the models in the particular context.

Assessments of SATURN's estimation of travel time, delays and stops have been made, using the Parramatta network (Luk and Stewart 1984; Bowyer 1984). Several findings from these assessments are relevant to this consideration of delays and stops.

TABLE XIII

SUITABILITY OF SELECTED TRAFFIC MODELS FOR
ANALYSIS RELATING TO PARTICULAR FORMS OF TRAFFIC
CONTROL IN SUB-AREAS

Traffic Control Option	Suitability of Traffic Model			
	TRANSYT	SCATSIM	SATURN	LATM
Priority:				
: Give-Way			*	*
: Stop	✓		✓	✓
: Roundabout			✓	✓
Signalised:				
: Isolated		✓††	✓†	
: Co-ordinated				
— Fixed	✓	✓	✓	✓
— LVA		✓		
— Dynamic		✓		

* Reflect delays at 'priority' control without distinguishing between give-way and stop control

† Fixed time

†† Vehicle actuated

For the total Parramatta network (Fig. 17), the estimate of vehicle travel time derived by SATURN is within the standard deviation of the on-road estimate, for fixed-time signal control in the system (Bowyer 1984). However, this accuracy is not maintained for estimates in sub-systems within this network.

Luk and Stewart (1984) found that SATURN underestimated delay by an average of 30 per cent for the set of intersections denoted by system A in Fig. 23. The number of stops was accurately estimated. An investigation of the slightly larger 'linear' system (systems A and B in Fig. 23) by Bowyer (1984) revealed oversaturation at several intersections and, as a consequence, queues remaining at the end of the SATURN simulation. The movement between nodes 724-108-756 is a particular case in the 'linear' system. A capacity of 599 veh/h was derived from on-road measurement. Successive iterations with SATURN show convergence toward a large remaining queue of 90 vehicles (Table XIV). While the movement is actually operating around capacity, it is unlikely to have a remaining queue of this magnitude at the end of the peak hour. One analytical option is to increase the capacity to approximate saturation. However, when this is done (to 689 veh/h) the assignment module in SATURN increased the movement volume. This converges to the order of 28 vehicles in the remaining queue (Table XIV).

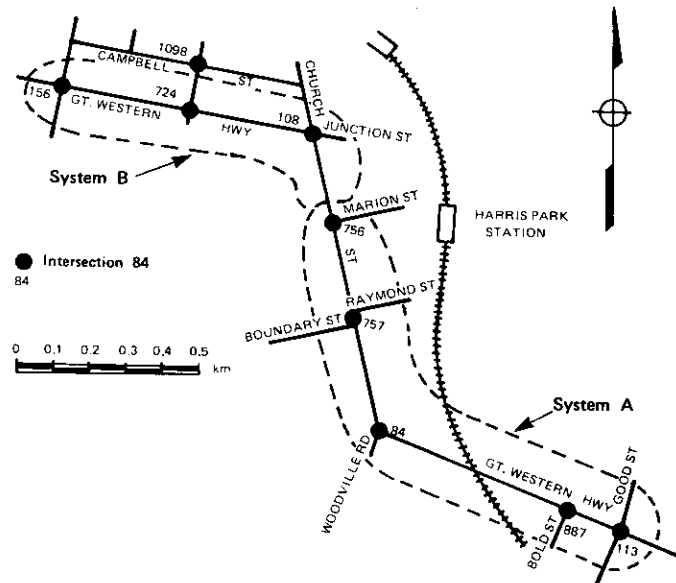


Fig. 23 — 'Linear' sub-systems along the GWH

TABLE XIV

OPERATING CHARACTERISTICS FOR MOVEMENT FROM
NODE 724 TO NODE 756 THROUGH NODE 108

Movement Capacity	Iteration	Assigned Vol.	V/C	Delay (s)		Remaining Queue
				Initial	Final	
599	1	658	110	57	408	59
	2	690	115	57	597	90
689	1	—	—	—	—	—
	2	704	102	54	131	15
	3	713	104	55	180	24
	4	718	104	56	202	28

Inspection of the flow-delay function for the movement 724-108-756 (Fig. 24) provides an understanding of the simulation process. The function is relatively 'flat' up to capacity, but rises steeply as the delay caused by remaining queues is added. The 'flat' characteristic reflects the fact that SATURN estimates only uniform delay for flows up to capacity. If a random delay function is superimposed it is seen that it is more continuous than the estimated SATURN function, but converges toward the latter. Three effects

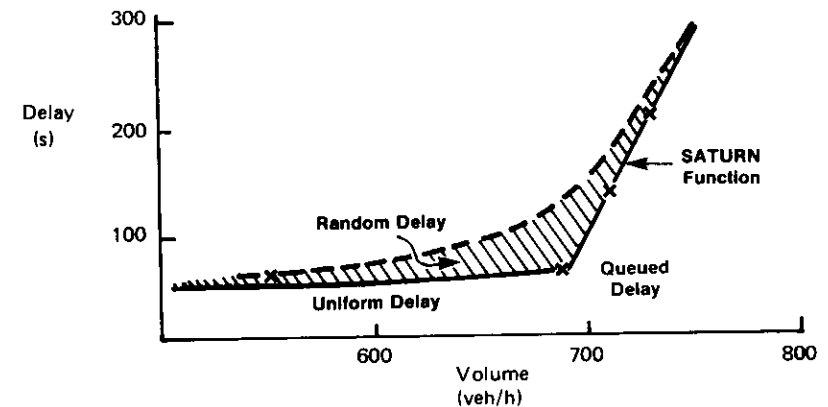


Fig. 24 — Flow-delay function for movement 724-108-756 in Fig. 17

are apparent. Firstly, the delay simulated by SATURN for this particular movement is relatively insensitive to volume increase. Thus the assignment process is relatively insensitive to volume increase, and thus delay, on this particular movement. Secondly, delay is consistently underestimated in the region of capacity (Fig. 24). If the random element was included in the flow-delay function then the assignment process might become more responsive. The third effect is that steady-state simulation over an hour causes a very small queue rate (28/30 vehicles per cycle) to accumulate to a substantial queue and associated delay. In this situation, division of the peak into shorter analysis intervals would be necessary to simulate queue dynamics (i.e., forming and dissipating). It would also substantially increase the analytical effort.

The effects of these errors on traffic variable estimates at the 'linear' system level are shown by the 'direct' estimates in Table XV. As would be expected, the average speed in the sub-area is overestimated (26 km/h) and the stop rate is underestimated. If it is assumed, based on the Luk and Stewart (1984) findings, that delay is underestimated by 30 per cent in the system, then the corrected estimate of speed is 23.1 km/h. As seen by Table XV, this is within the standard deviation of the on-road estimate. Thus the delay error is significant in this particular system.

Several important points of general relevance to traffic model choice can be drawn from this particular case. Firstly, the simultaneous simulation of traffic flow, queue dynamics and route choice involves complex model interactions. It is possible that estimation errors in traffic variables will occur, particularly in highly congested traffic contexts. Thus the use of a meso-level model in small sub-areas should include some validation of it in the particular system. The second general point is that effects of errors in traffic variables (particularly total vehicle travel time) is likely to reduce with increasing system scale. Exceptions could arise if a significant proportion of the system is operating near capacity.

TABLE XV

ESTIMATES OF PEAK PERIOD PERFORMANCE ON GWH
FROM SATURN AND ON-ROAD SURVEY

Variable	On-Road Estimate		SATURN Estimate	
	Average	Standard Deviation	Direct	Corrected
Stop Rate (no./veh-km)	2.1	±0.6	1.7	1.7
Average Speed (km/h)	18	±6	26	23*
Fuel Rate (L/100 km)	16.0	±1.0	12.3	15.1†

* System delay estimate increased by 30 per cent.

† Effect of:

- (a) delay increase,
- (b) fuel rate for stops increased from 0.0147 L/stop (for 44 km/h cruise speed conditions) to 0.028 L/stop (for 55 km/h cruise speed conditions). These values are derived from on-road measurement (Luk and Akcelik (1983)).

A final comment is appropriate regarding the influence of scale of the traffic system being investigated on the model choice. Detailed simulations with SCATSIM, for example, are likely to be unsuitable for networks of the scale and form of Fig. 17. For some sub-areas it might then be necessary to consider use of more than one traffic model to adequately accommodate the control options, anticipated impacts and scale of the system.

Choice of Fuel Model

This choice will obviously be strongly dependent on the choice of traffic model(s). The traffic variables which are estimated will determine the lowest level fuel model which can be employed. With SCATSIM, for example, this is the instantaneous fuel model.

There are, however, three other factors which might require consideration in particular contexts. These are the accuracy of the traffic variable estimates, the information required for design decisions and the scale of the sub-area.

As considered above, there are a number of strong assumptions and complex model interactions inherent in the estimates of instantaneous speeds and accelerations and of the delay and number of stops on a network link. Thus there might be bias or, at least, high variance in the traffic variable estimates. This will reflect directly in the fuel estimates. The fuel model choice should thus take into account the confidence which one has in the traffic variable estimates.

An interesting example of this is demonstrated by the errors in delay and stop estimates from SATURN when intersections are operating near capacity. The errors in delays and stops for the 'linear' system discussed

above lead one to expect errors in fuel consumption estimates. The 'direct' SATURN estimate is significantly lower than the on-road estimate (Table XV). The primary reasons for this can be seen by considering the elemental fuel consumption model which is used in SATURN. This takes as input variables the vehicle-distance, delay and stops and uses parameters for fuel consumption rates which are constant for the particular analysis. The delay component of fuel consumption accounts for 17 per cent of fuel consumption. Thus the delay underestimate will be a contributing factor to the fuel underestimate. The constant consumption rate parameter for the stops component also contributes to the underestimate. A parameter value of 0.0147 L/stop is appropriate as an average for the total Parramatta sub-area. However, link speeds on the Great Western Highway (GWH) are higher than the sub-area average and thus a parameter value of 0.028 L/stop is more appropriate. When corrections for delay underestimation and the consumption rate for stops are made, the resultant fuel estimate is within one standard deviation of the on-road estimate (Table XV).

SATURN has been shown to estimate travel time in the Parramatta area to acceptable accuracy (Bowyer 1984). Thus a possible practical consideration is whether fuel estimates which are more reliable and are also adequate for the consideration of control alternatives might be derived using a higher level fuel model. In Section B.4.5 it was shown that at a trip or network level, a function relating fuel consumption to the average travel speed could be estimated from data in particular operating environments. Applying this function to speeds estimated on-road under alternative forms of signal control in the Parramatta system, the fuel estimates in Table XVI are derived. It is apparent that the simple fuel function consistently underestimates both the on-road estimates, and the estimated changes in fuel consumption. This is particularly so for the transfer from isolated control to dynamic control in the GWH sub-area. The two sets of estimates do, however, provide a consistent ordering of the control alternatives, based on fuel savings. Speed estimates from a traffic model such as SATURN will, of course, depend on delay estimates. As shown in Table XV, SATURN is likely to be a reliable estimator of average speed in a sub-area if random delay estimation is included.

It can be deduced that in this context the higher level model might, at best, be adequate to identify the ranking of control options, but is inadequate for evaluation purposes. For rigorous evaluation of fuel savings in the design of control alternatives in sub-areas it appears that the most appropriate form of fuel consumption model is an elemental drive-mode model (functions to estimate consumption rates for each element are specified in Sections B.4.3.1 to B.4.3.6). These should be applied for each link in the network and summed to give total network fuel consumption.

B.5.4 CASE 4: TRAFFIC SYSTEM BOUNDARIES

The magnitude and per cent savings in fuel consumption is clearly related to the base systems. However, an assessment of selected fuel consumption studies has shown that there is often not a clear specification and

TABLE XVI

FUEL CONSUMPTION ESTIMATES FROM AVERAGE SPEED
MODEL AND ON-ROAD EXPERIMENT

Sub-Area	Form of Control	Fuel Consumption Estimates (L/100 km)	
		Average Speed Model	On-Road Experiment
GWH	Isolated-VA	11.6	13.8
	Dynamic	10.8	12.1
	Difference (%)	-7	-13
	Fixed-Time	11.0	13.9
	Linked-VA	10.8	12.1
	Difference (%)	-2	-3
CBD	Isolated-VA	19.7	24.5
	Dynamic	19.7	23.9
	Difference (%)	0	-3
	Fixed-Time	18.8	23.6
	Linked-VA	19.1	24.8
	Difference (%)	+2	+5

description of the traffic systems to which consumption changes relate (Bowyer 1984). Terms such as 'directly affected' traffic have come into use. The importance of clearly defining the system context, and several analytical issues in doing so, can be seen through the following case.

A one-way street system is to be introduced in the location shown in Fig. 25. The primary purpose is to facilitate circulation in this section of the Parramatta business district. In addition to traffic engineering changes on existing links, a new link and intersection (node 2291) are required.

This scheme is a sub-system in the network of Fig. 17, and the impacts on peak period fuel consumption can be estimated by SATURN. If an estimate of fuel changes for 'directly affected' traffic is required, then a primary consideration is the identification of the system which contains this traffic. A minimum system is the traffic on those links in the existing network which become part of the one-way street network (Fig. 26a). For this traffic the estimated consumption rate reduces by 4 per cent (Table XVII). The addition of node 2291, however, also impacts on traffic on the GWH and the two links marked in Fig. 26b should also be included. This results in the estimated fuel consumption levels given in Table XVII and indicates a significant increase in fuel consumption rate of 8 per cent.

A further observation on Table XVII is that the demand on the one-way links in the 'after' conditions (1468 veh-km) is significantly less than for the 'before' condition (1904 veh-km). This implies that the scheme has induced change in route choice and that the system boundary should be extended

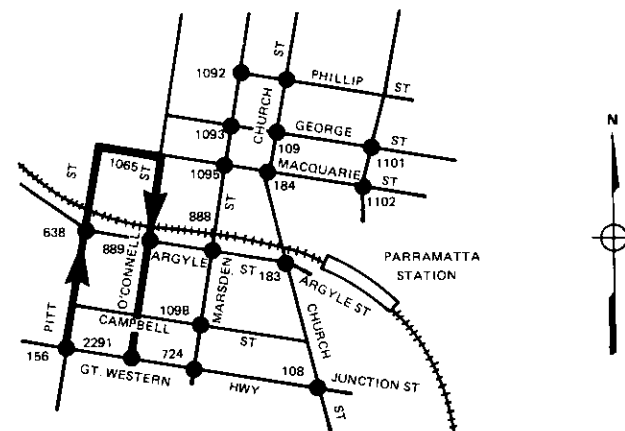


Fig. 25 — Location of the one-way street scheme

TABLE XVII

IMPACTS OF ONE-WAY STREET SYSTEM AT THREE LEVELS
OF SYSTEM SCALE

Performance Variables	Traffic System Defined by:					
	Links Changed to One-Way Movement		Directly Affected Links*		Links with Significant Volume Change	
	Before	After	Before	After	Before	After
Delay (veh-h/h) [†]	52	44	74	85	155	174
Queue Time (veh-h/h) [†]	21	—	21	—	26	8
Run Time (h/h) [†]	43	31	58	53	125	119
Travel Distance (km)	1904	1468	2602	2527	5497	5338
Average Speed (km/h)	16.5	19.6	17.2	18.4	17.9	17.8
Total Fuel (L)	308	233	407	431	869	913
Fuel Rate (L/100 km)	16.6	15.9	15.6	17.1	15.8	17.1
(difference)		(-0.7)		(1.5)		(1.3)

* The directly affected links are those on which traffic engineering or control changes are made as part of the one-way scheme.

† Variable definition as in SATURN (Bollen *et al.* 1979)

to encompass those links to which diversion has occurred. Inspection of assignments reveals the 'impacted' network to be that in *Fig. 26(c)*. Estimated fuel changes in this network indicate that the total effect of the one-way scheme is to increase fuel consumption by about eight per cent. This estimated increase is due mainly to the increased stops caused by the addition of node 2291 to the network.

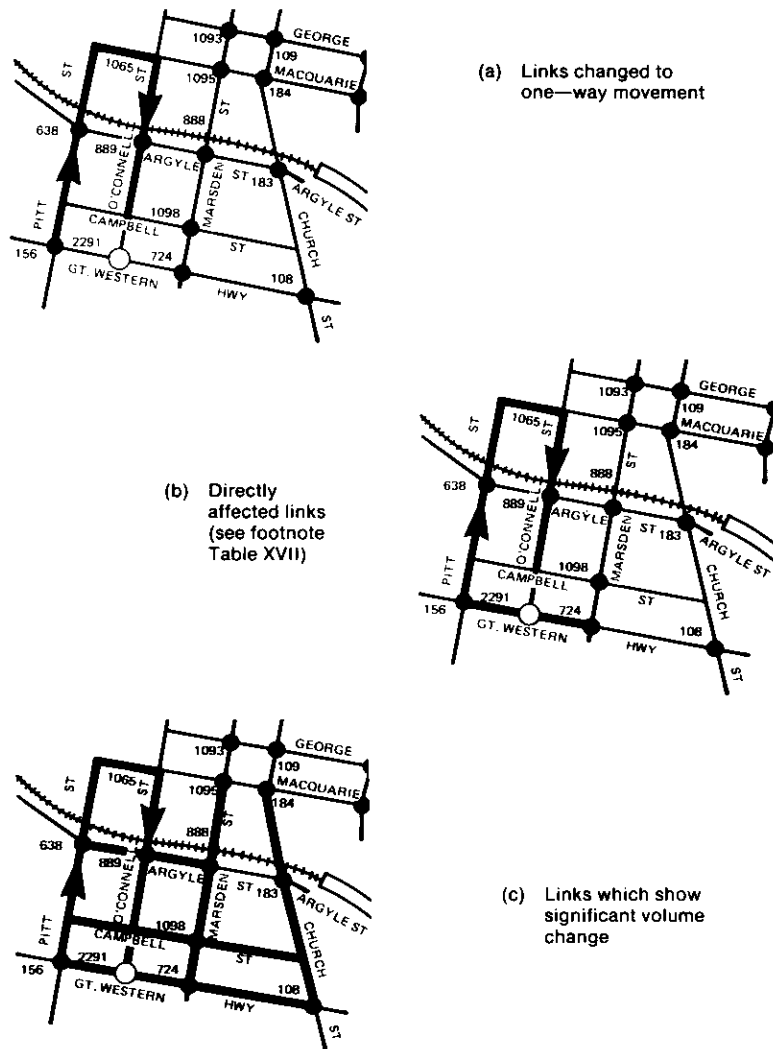


Fig. 26 — Impacts of one-way street system at three levels of system scale

B.5.5 COST-EFFECTIVENESS OF FUEL ANALYSES

It is evident from the selected cases considered in Sections B.5.1 to B.5.4 that the effective use of fuel analysis techniques calls for reasonable skill and care in selection and use of the models.

An appropriate final consideration is, therefore, the costs of generating fuel consumption estimates and the returns which might be realised from the use of the estimates in management scheme design. Two different traffic contexts are considered, intersection level and sub-area level.

Intersection Specific Analyses

In Section B.5.1 micro-simulation of the priority controlled intersection, node 90 in *Fig. 17*, identified significant differences in fuel consumption between stop and give-way control. It is conceivable that for this particular intersection there is no difference in safety between the two control forms. Also, the implementation costs are comparable. Thus the benefits from give-way control will be the savings in delay and fuel and the costs are those associated with the analyses. The user benefits estimated by INSECT are shown in *Table XVIII*.

TABLE XVIII
USER BENEFITS FROM GIVE-WAY CONTROL OVER STOP
CONTROL AT NODE 90, Fig. 17

	Form of Control		Difference	Benefit (\$/h)
	Stop	Give-Way		
Queue Time (veh-h/h)	0.096	0.028	0.068	0.28*
Fuel Consumption (L)	7.0	6.3	0.7	0.28†
				\$0.56/h

- Using a value of time of \$4/h

† Using a resource value of 0.40/L

Experience with INSECT in these and other analyses shows that, as a simulation model, it is best used in an 'experimental' manner, rather than as a single solution generating tool. A primary reason for this is that vehicles in the system are randomly generated and different generation patterns can result in significantly different conflict situations. Thus, typically a number of runs will be required for each set of traffic conditions using different random number seeds and, possibly, parameter values for gap acceptance, etc. This experimental approach to the analyses involved the estimated resources shown in *Table XIX*. Equating the costs and benefits gives an estimated return period of the order of 30 weeks, assuming benefits occur over 4 hours each work day.

This return period suggests that micro-analyses of individual inter-sections might be justified. However, it also encourages experimentation with techniques such as INSECT to establish whether performance graphs of the form in Fig. 20 can be applied to other locations.

Sub-Area Analyses

The scale and complexity of analyses in sub-area networks can vary widely. Also, the available traffic models vary in character and ease of use. Thus, the cost-effectiveness of using traffic models in scheme design at the sub-area level is likely to depend on the model and traffic context.

TABLE XIX

PRIMARY COSTS FOR ANALYSIS OF NODE 90 USING INSECT

Cost Item	Hours	Rate (\$/h)	Cost (\$)
Personnel*	8	30	240
Computing†	4	15	60
			300

* Data entry and processing requires minimal skill, but interpretation of results requires an experienced analyst.

† Running on a PDP/Spectrum micro-computer.

An indication of the possible pay-offs from using models at the sub-area level can be gained from the analyses of the one-way street scheme considered in Section B.5.4. This scheme induced significant re-assignment of traffic within the sub-area and information of importance in the scheme design stage should be the extent of re-assignment and the subsequent impact on traffic performance, particularly fuel consumption where *increases* are possible. SATURN is suitable for estimating such impacts. On links with significant volume change, the fuel consumption increase is estimated to be 5 per cent.

This percentage increase is quite significant in absolute terms. As shown in Table XX, it translates to a resource consumption value of \$350/week. Since there is no significant change in average speed on the impacted network, then this analysis would indicate that the one-way street scheme should not be introduced. The pay-offs from the analysis can then be considered to be the avoidance of a fuel consumption increase, valued at \$350/week. The estimated costs of using SATURN to analyse this scheme depend strongly on whether base network and travel files exist. If they do, then the analysis costs are \$5000 (Table XX), giving a return period of about fourteen weeks. If full set-up costs are included then the analysis cost increases to the order of \$20 000 and the return period to one year.

TABLE XX

ESTIMATED FUEL INCREASES AND ANALYSIS COSTS FOR SATURN ASSESSMENT OF ONE-WAY STREET SCHEME, Fig. 25

Peak Period Fuel Consumption

Fuel consumption increase*	44 L/h
Assume loss over 4 hrs/day, 5 days/week	880 L/week
Resource value†	\$350/week

Analysis Costs

(a) Assuming network files exist:	
Person-time (2 weeks @ \$1500)	\$ 3000
Computing (commercial rates)	2000
	\$ 5000
(b) Complete study:	
Person-time for: traffic data	\$10000
network code	3000
demand code	2000
	\$15000
analysis	3000
Computing	2000
	\$20000

Return Periods

If costs (a)	14 weeks
If costs (b)	57 weeks

* Fuel consumption increased by 5 per cent (44 L/h) on links with significant volume change resulting from the one-way scheme.

† Using fuel costs of 40¢/L

B.6. CONCLUSIONS

The need for, and form of, fuel consumption analyses in traffic management is likely to vary significantly with the particular traffic management context and the management task being undertaken. A wide range of management contexts will exist in practice, these being defined primarily by the scale and nature of the traffic system and the forms of management objectives and schemes. The major management tasks can be conveniently considered as problem diagnosis, scheme design, implementation and evaluation. Scheme design is a critical task and model-based analysis procedures are the only practical means of generating the required information on fuel consumption, and other performance criteria.

Fuel consumption models have been specified and each has been shown to be appropriate to estimating fuel consumption in a particular scale of traffic system. The models are all inter-related and form part of the

same modelling framework. Vehicle parameters are explicit parameters at all model levels, thus allowing the user to choose vehicle parameters for a particular application and to allow for changing vehicle characteristics over time, and from country to country.

A number of existing traffic models are suitable for practical use in Australia and the traffic system context to which each is appropriate has been shown in this report. Also, the general form of fuel consumption module has been specified for each traffic model.

The case studies have shown that the choice of traffic and fuel consumption model is important for fuel analyses to be effective aids to scheme design. As might be expected, the ease and cost-effectiveness of use of the models will depend on the scale of traffic system and form of management schemes being assessed. It is likely that analyses relating to the design of control schemes for isolated intersections will require small resources and be cost-effective. Techniques to aid design of management schemes in sub-areas will require increased effort and the cost-effectiveness will depend on a number of factors, including the availability of suitable traffic and travel demand data.

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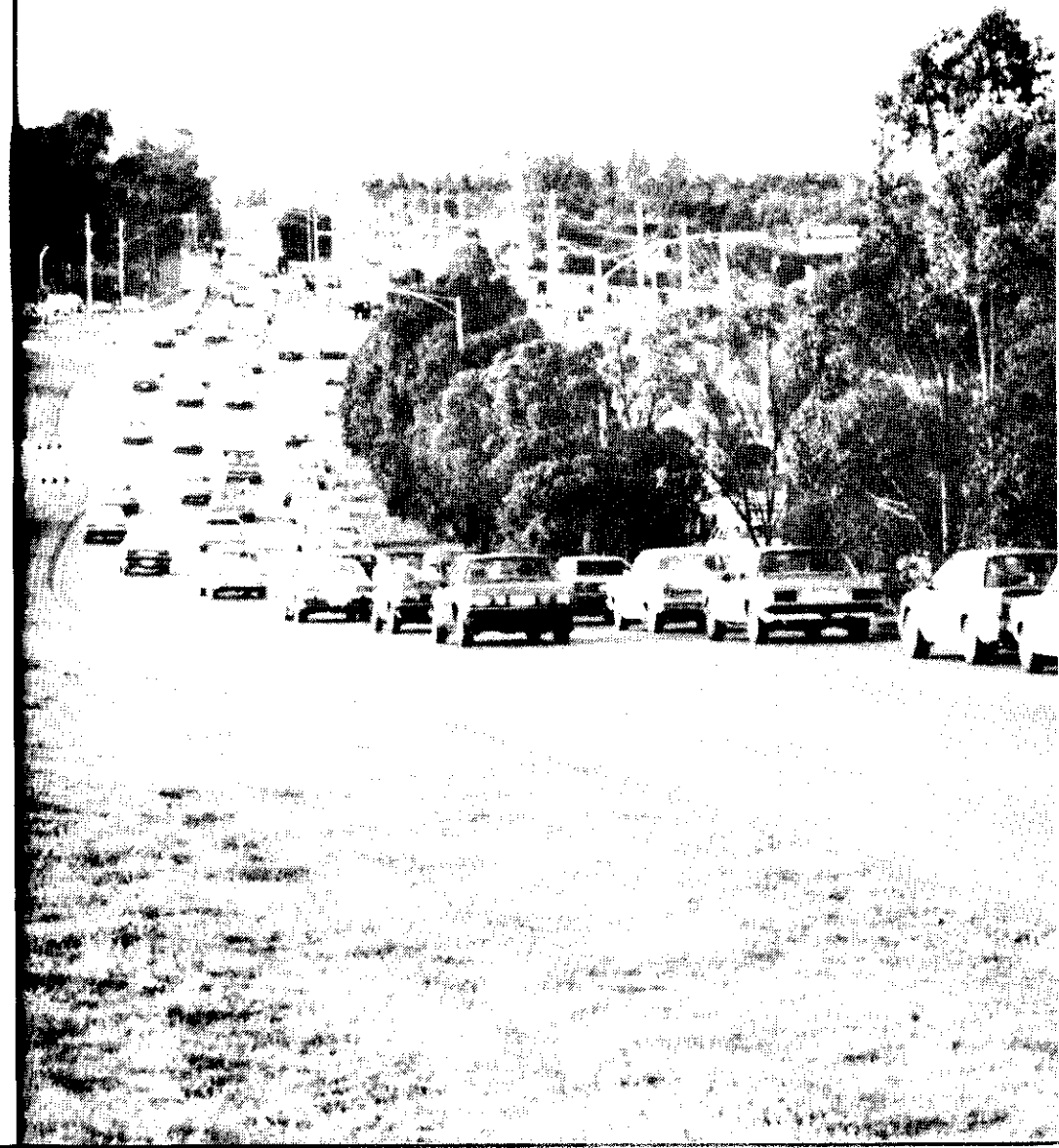
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APPENDICES



APPENDIX A**EXTRACTS FROM PUBLISHED GUIDES**

Published guides to fuel consumption estimation in traffic management place a strong emphasis on ease of use of techniques. Thus they typically provide graphs of fuel consumption rates as the basis for estimating fuel consumption, with the forms of graphs and estimation processes varying in complexity between the guides.

The simplest guides contain graphs of consumption rates derived by correlating fuel consumption and average speed, using data sampled on-road in a particular traffic system (see for example Federal Highway Administration (FHWA 1981); *Fig. 27*). Such functions are relatively low cost

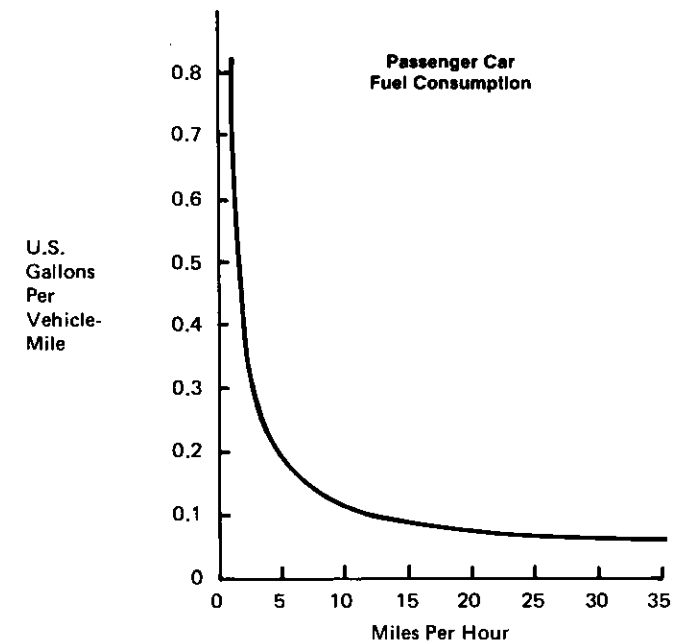


Fig. 27 — Fuel consumption related to average speed, defined as 'speed over a distance'
Source: FHWA (1981)

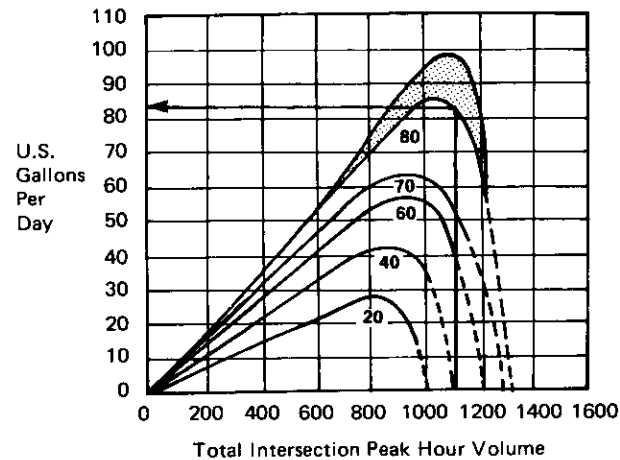


Fig. 28 — Fuel reduction from replacing a four-way stop sign with two-way stop sign
Source: U.S. DoT (1981)

to generate and to apply, but, of course, are a simplified, aggregate representation of a complex process. It is not clear from Fig. 27 precisely which traffic system contexts it is appropriate to, although the FHWA (1981) guide recognises that such aggregate, regression-based functions might be unreliable beyond the traffic system from which they were derived. A more refined approach is reported in U.S. Department of Transport (1981). This guide provides fuel consumption graphs reflecting the impact of particular forms of traffic management (e.g. signal coordination) in *typical* traffic conditions (e.g. road geometry, traffic conditions). An example is shown as Fig. 28. The accuracy of this procedure for design of specific signal control systems is limited. An extension and generalisation of this approach is taken in the guide by New York State Department of Transportation (1981) (Fig. 29). This guide provides a worksheet for each form of traffic management, as a guide to the *process* to follow in fuel estimation.

More recently, an NCHRP (1983) guide noted that there are a number of major assumptions underlying these simple estimation guides. These assumptions relate to traffic composition, physical environment, etc., and it is difficult to determine the accuracy and suitability of these guides in contexts other than those on which they are based.

TSM ENERGY ANALYSIS WORKSHEET					
TRAFFIC OPERATIONS : INTERSECTION ANALYSIS					
A. BASE DATA					
APPROACH VOLUME	%	TOTAL STOPPING	AVG. DELAY (SEC)	3600	TOTAL DELAY (HR)
A <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	= <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	=	<input style="width: 50px;" type="text"/>
T <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	= <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	=	<input style="width: 50px;" type="text"/>
APPROACH SPEED (MPH)					
A <input style="width: 50px;" type="text"/>	T <input style="width: 50px;" type="text"/>				
B. FUEL CONSUMPTION					
TOTAL DELAY	FCR	FUEL ECONOMY ADJ	FUEL CONSUMPTION (GAL)		
A <input style="width: 50px;" type="text"/>	X .58	X <input style="width: 50px;" type="text"/>	= <input style="width: 50px;" type="text"/>		
T <input style="width: 50px;" type="text"/>	X .61		= <input style="width: 50px;" type="text"/>		
TOTAL STOPPING					
A <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>	= <input style="width: 50px;" type="text"/>		
T <input style="width: 50px;" type="text"/>	X <input style="width: 50px;" type="text"/>		= <input style="width: 50px;" type="text"/>		
			SUBTOTAL	<input style="width: 50px;" type="text"/>	DAILY FUEL CONSUMPTION
			X 250	WORKDAYS PER YEAR	
			TOTAL	<input style="width: 50px;" type="text"/>	ANNUAL FUEL CONSUMPTION

A = AUTO
 T = TRUCK
 FCR = FUEL CONSUMPTION RATE
 (GALLONS PER VEHICLE HOUR)

Fig. 29 — Sample of energy analysis worksheet
Source: New York State DoT (1981)

APPENDIX B

CALIBRATION OF VEHICLE AND FUEL CONSUMPTION MODEL PARAMETERS

The suggested procedures for estimating vehicle parameters and the methods used to calibrate fuel consumption model parameters are outlined below. Full details are given in Biggs and Akcelik (1985). *Table XXI* gives vehicle parameters for particular vehicles and the approximate range of vehicle parameters for cars on the road in Australia. *Figs 30* and *31* show the relationships between idle fuel consumption and engine capacity and between engine capacity and vehicle mass, respectively. These can be used to estimate idle fuel consumption and vehicle mass if only engine capacity is known. *Table XXII* gives the range of model parameters calculated using Sydney on-road data (described in Section B2).

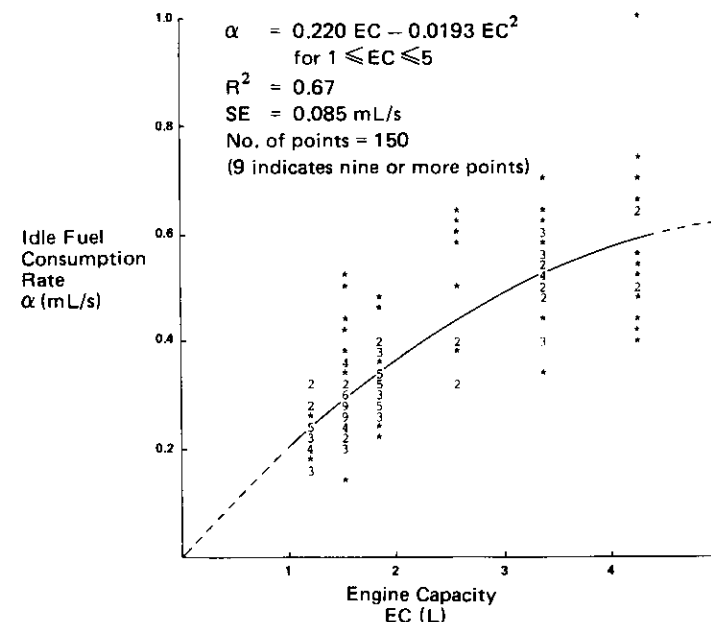


Fig. 30 — Idle fuel consumption rate as a function of engine capacity
(Data source: Post et al. 1981)

TABLE XXI APPROXIMATE RANGE OF VEHICLE PARAMETERS AND PARAMETER VALUES OBSERVED FOR VARIOUS VEHICLES

Range/Vehicle	M (kg)	α (mL/s)	β_1 (mL/kJ)	β_2 (mL/(kJ.m/s ²))	b ₁ (kJ)	b ₂ (kJ/(m/s ²))
(Min., Max.) — Car	(600, 2000)	(0.1, 1.0)	(0.05, 0.16)	(0.01, 0.06)	(0.10, 0.70)	(0.0003, 0.0015)
95% within interval — Car	(800, 1700)	(0.15, 0.70)	(0.06, 0.13)	(0.01, 0.05)	(0.15, 0.60)	(0.0004, 0.0012)
Default*	1200	0.444	0.090	0.045	0.333	0.00108
GMH Kingswood† (1976, 4.2 L, auto.)	1640	0.51	0.099	0.020	0.41	0.00102
Ford Cortina‡ (1977, 4.1 L, auto.)	1690	0.67	0.072	0.034	0.53	0.00095
Ford Cortina†† (1977, 4.1 L, auto.)	1535	0.72	0.078	0.019	0.41	0.00121
GMH Commodore (1984, 3.3 L, auto.)	1433	0.57	0.110	0.026	0.22	0.00093
GMH Commodore† (1983, 3.3 L, auto.)	1380	0.72	0.080	0.027	0.41	0.00084
Honda Civic† (1981, 1.3 L, manual)	850	0.20	0.083	0.021	0.43	0.00038
Daihatsu Charade† (1.0 L, 5-sp. manual)	813	0.16	0.083	0.021	0.34	0.00057
Nissan Bluebird† (2.0 L, 3-sp. auto.)	1150	0.42	0.076	0.039	0.35	0.00092
Toyota Corona† (2.0 L, 4-sp. manual)	1190	0.46	0.074	0.014	0.18	0.00089
Nissan Prairie† (1.5 L, 5-sp. manual)	1247	0.34	0.070	0.033	0.15	0.00095
Ford Falcon XE† (4.1 L, 3-sp. auto.)	1465	0.62	0.078	0.017	0.11	0.00118
GMH Kingswood† (3.3 L, 3-sp. auto.)	1500	0.61	0.094	0.033	0.41	0.00070
Mitsb. Canter Truck#	3040	0.27	0.094	0.026	0.47	0.00317
(Diesel 3.3 L, 5-sp. manual)	4390	0.27	0.094	0.026	0.75	0.00317
Toyota Dyna Tip Truck#	3350	0.27	0.082	0.016	0.62	0.00256
(Diesel 4.0 L, 5-sp. manual)	6580	0.27	0.080	0.015	0.92	0.00252
GMH Isuzu Tray Truck#	3800	0.31	0.084	0.009	0.58	0.00219
(Diesel 5.8 L, 5-sp. manual)	7780	0.31	0.077	0.013	0.83	0.00218
Ford F350 Truck† (5.9 L, 5-sp. manual)	4460	0.83	0.088	0.019	0.50	0.00324

* Default values were chosen using limited information available at the time of the analysis. From the above observed parameter values, better default values of β_1 and β_2 might be; $\beta_1 = 0.03$ and $\beta_2 = 0.0008$

† Parameter values calculated from dynamometer data by University of Melbourne, Mechanical Engineering Department.

†† Parameter values for the same Cortina test vehicle derived using data collected 1½ years apart.

Parameter values calculated by Murdoch University, School of Environmental and Life Sciences.

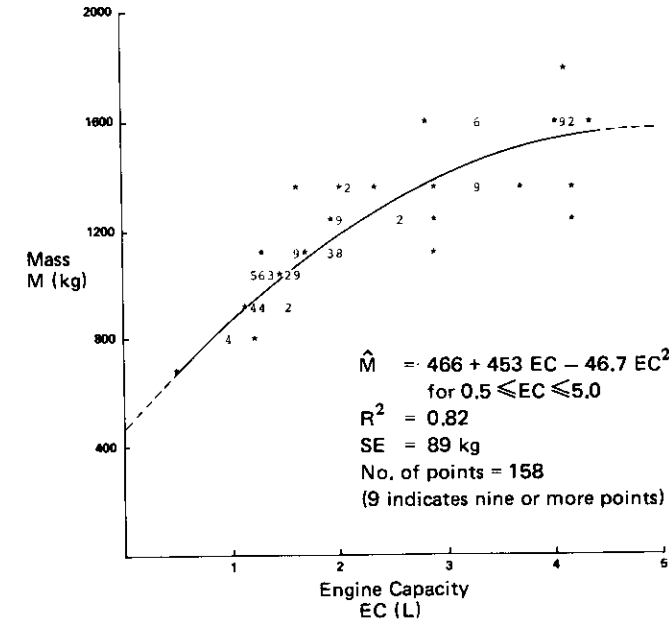


Fig. 31 — Relationship between engine capacity and vehicle mass (mass includes two occupants) (Data source: Post et al. 1981)

TABLE XXII
MEAN, STANDARD DEVIATION AND RANGE OF MODEL
PARAMETERS CALCULATED USING OBSERVED PROFILES IN
SYDNEY DATA

Model	Parameter	Mean	S.D.	(Min., Max.)	95% in Interval
Elemental- Acceleration	k ₁	0.61	0.07	(0.31, 0.81)	(0.47, 0.75)
	k ₂	1.42	0.31	(0.53, 3.45)	(1.0, 2.1)
	m _a	0.55	0.07	(0.24, 0.75)	(0.40, 0.68)
	a ⁺	2.72	1.00	(0.50, 10)	(1.1, 4.9)
	k ₁	0.63	0.06	(0.28, 0.83)	(0.52, 0.77)
Deceleration	m _d	0.54	0.07	(0.27, 0.78)	(0.40, 0.68)
	-a ⁻	3.15	1.25	(0.60, 15)	(1.5, 5.9)
	k _x	0.40	0.27	(0, 1)	(0, 0.93)
	k _y	0.49	0.30	(0, 1)	(0, 0.93)
	k _a	0.12	0.15	(0, 0.96)	(0, 0.55)
Cruise	k _{E1}	0.30	0.28	(-1.7, 1.5)	(-0.2, 0.75)
	k _{E2}	3.17	0.85	(0, 7.7)	(1.9, 4.8)
	k _G G < 0	0.65	0.2	(0, 1)	(0, 1)
	G > 0	0.95	0.08	(0.5, 1)	(0.5, 1)
	E _{k+}	1.64	0.07	(0.01, 0.79)	(0.05, 0.32)
Running Speed	k _{E1}	0.64	0.11	(0.27, 1.11)	(0.42, 0.87)
	k _{E2}	3.45	0.76	(1.46, 7.0)	(2.3, 5.2)
	k _G G < 0	0.6	0.2	(0, 1)	(0, 1)
	G > 0	0.9	0.2	(0.3, 1)	(0.3, 1)
	E _{k+}	0.26	0.08	(0.06, 0.51)	(0.12, 0.46)

* Average accelerations are used to calculate t_a and t_d ($-(v_f - v_i)/\bar{a}$)

† Observed values of k_G became unstable with grades close to zero (but the grade term has little effect for small grades) and above values are based on k_G restricted to between 0 and 1.

B1 VEHICLE PARAMETERS

The vehicle parameters required for the instantaneous model are derived as follows:

- α Idle fuel consumption rate of a warm engine, found by measuring total fuel consumption while idling for about 200 s. Repeat measurements several times during the day.
- A, B, c_1, c_2 Measure the fuel consumption rate at steady-speeds between 4 and 33 m/s (15 and 120 km/h) on a level road. When collecting this data, the gear used for a given speed should be similar for automatic and manual vehicles. This corresponds to the use of a higher gear (thus lower engine revolutions) for constant speed driving compared with the gear used when the vehicle is accelerating at that speed. This is typical in traffic situations where vehicles must maintain a low steady-speed. The effect of the use of a lower gear during acceleration is accounted for in the β_2 term in the model. Determine the coefficients c_1 and c_2 by fitting the regression equation with the value of the constant fixed to α :

$$f'_{c,t} = \alpha + c_1 v + c_2 v^3 \quad (B1)$$

Then calculate $A = 1000 c_1$ and $B = 1000 c_2/12.96$.

- β_1, β_2 These parameters require instantaneous (typically second-by-second) speed, grade and fuel consumption values collected over at least 1000 s of driving. The range of speeds and accelerations should be similar to that observed on the road. If data are collected on-road, wind speed should be low (less than 1 m/s) and weather conditions dry. When data are collected on a dynamometer:

- the dynamometer must be carefully set to simulate all aspects of on-road driving, or
- the constant speed fuel consumption function, eqn (B1), must be derived using both on-road and dynamometer data. The function derived on the dynamometer should be used in the regression estimation of β_1 and β_2 (described below). The β_1 and β_2 derived in this way are transferable to on-road driving (provided the full range of accelerations are included in the dynamometer data). These and the drag parameters, c_1 and c_2 , (also A, B, b_1 and b_2) derived from on-road constant speed data, are the parameters required for estimation of on-road fuel consumption.

Fuel consumption cannot be measured accurately over small time intervals using a flow meter. The fuel flow recorded by the meter is the flow which goes into the carburettor, and there is a variable time lag between this and the fuel used by the engine

to provide tractive force. It is therefore necessary to aggregate the data into reasonably long time intervals. Similarly, on a dynamometer it is difficult to estimate exactly the time lag between when the fuel is burnt and when it is measured. An aggregation interval of between 10 and 20 seconds is recommended for a fuel flow meter and between 1 and 5 seconds for measurements on a dynamometer. To determine β_1 and β_2 with data divided into time intervals, each consisting of a certain number of data points, firstly calculate for each data point the inertial terms:

$$P_{IG} = (Mav + 9.81 Mv(G/100))/1000 \quad (B2)$$

$$aP_I = Ma^2v/1000 \quad (B3)$$

Then, aggregate each of these terms, as well as the inertial component of fuel consumption (difference between total and steady-speed fuel consumptions) into the time intervals as follows:

$$F_I^{(k)} = \sum (f_t - f'_{c,t}) \quad (B4)$$

$$P_{IG}^{(k)} = \sum P_{IG} \quad (B5)$$

$$P_T > 0$$

$$aP_I^{(k)} = \sum aP_I \quad (B6)$$

$$P_T > 0$$

$$a > 0$$

where the summations are over the points in time interval number k subject, in some cases, to additional restrictions on P_T and a ; and

$$P_T = P_{IG} + c_1 v / \beta_1^{(o)} + c_2 v^3 / \beta_1^{(o)} \quad (B7)$$

$\beta_1^{(o)}$ is a first guess of β_1 (could use default value of β_1)

The values of β_1 and β_2 are estimated jointly by regression of $P_{IG}^{(k)}$ and $aP_I^{(k)}$ on $F_I^{(k)}$ through the origin. Substitute new estimate of β_1 for $\beta_1^{(o)}$ in eqn (B7) and re-estimate β_1 and β_2 . Continue substituting new estimates of β_1 until its estimated value does not change. Note that negative values of β_2 should not be obtained and a likely cause of this error is that the time interval for aggregation is too small.

$$b_1, b_2 \quad \text{Found by: } b_1 = c_1 / \beta_1 \text{ and } b_2 = c_2 / \beta_1$$

B2 PARAMETERS FOR HIGHER LEVEL FUEL CONSUMPTION MODELS

The instantaneous model of fuel consumption uses instantaneous speed and grade values and only parameters relating to the vehicle are required. The more aggregate models are derived by integration of the instantaneous function and it is therefore necessary to introduce parameters which are

dependent on the speed-time profile over the integration interval. The parameter values have been related to initial and final or average speeds (and other relevant variables) for that interval using on-road data collected in urban driving. All terms included in the regression equations are significantly different from zero, despite some low R^2 (i.e. proportion of explained variation) values. In addition, the directional effect of each term has been checked to ensure it conforms with the expected effect of that term on the profile related parameter. Grade is assumed to be constant over the interval. This has the effect of underestimating the component of fuel consumption due to grade over long intervals where there are fluctuations in grade.

The data used for calibrating the models were collected in Sydney during 1981 using an instrumented 3.3 L automatic GMH Commodore sedan (Tomlin *et al.* 1983). The chase car technique was used so that the driving profiles would reflect the range of profiles observed on the road. The routes were chosen to cover the full range of driving conditions in Sydney but the sampling method was not truly random. The data covered 900 km of urban driving which included 68 km in the CBD, as well as 1300 km of non-urban driving.

The method used to calibrate the parameters for the acceleration, deceleration and cruise functions of the elemental model, and the parameters of the running speed and average travel speed models is given below.

Elemental Model : Acceleration Fuel Consumption Function

Given the speed-time trace during an acceleration, k_1 , k_2 and m_a can be calculated as follows:

$$k_1 = \int_0^{t_a} v^3 dt / [(v_f^2 + v_i^2) x_a] \quad (B8)$$

$$k_2 = 4 x_a \int_0^{t_a} a^2 v dt / [(v_f + v_i)^2 (v_f - v_i)^2] \quad (B9)$$

$$m_a = x_a / [(v_f + v_i) t_a] \quad (B10)$$

where v is in m/s, x is in m and t is in s.

The values of k_1 , k_2 and m_a were calculated for all accelerations identified in the Sydney data set, then equations were derived which related them to the initial and final speeds. In order to obtain the best estimates for accelerations from rest to cruise speed, the following method was used. Using only data where $v_i = 0$ and $v_f > 20$ km/h, the following regression equations were found for v_i in km/h.

$$k_1 = 0.616 + 0.000544 v_f \quad R^2 = 0.02, SE = 0.067 \quad (B11)$$

$$k_2 = 1.376 + 0.00205 v_f \quad R^2 = 0.01, SE = 0.307 \quad (B12)$$

$$m_a = 0.467 + 0.00200 v_f \quad R^2 = 0.21, SE = 0.066 \quad (B13)$$

$$\bar{a} = 2.08 + 0.127 \sqrt{v_f} \quad R^2 = 0.03, SE = 0.84 \quad (B14)$$

Then, using all the data with these coefficients fixed, v_f (km/h) was added to the equations:

$$k_1 = 0.616 + 0.000544 v_f - 0.0171 \sqrt{v_f} \quad R^2 = 0.26, SE = 0.064 \quad (B15)$$

$$k_2 = 1.376 + 0.00205 v_f - 0.00538 v_f \quad R^2 = 0.06, SE = 0.296 \quad (B16)$$

$$m_a = 0.467 + 0.00200 v_f - 0.00210 v_f \quad R^2 = 0.26, SE = 0.058 \quad (B17)$$

$$\bar{a} = 2.08 + 0.127 \sqrt{v_f - v_i} - 0.0182 v_f \quad R^2 = 0.12, SE = 0.93 \quad (B18)$$

Finally acceleration time was estimated by:

$$t_a = (v_f - v_i) / \bar{a} \quad R^2 = 0.48, SE = 5.46 \quad (B19)$$

Elemental Model : Deceleration Fuel Consumption Function

The parameters, k_1 and m_d , and the deceleration time were calibrated in a similar way to those in the acceleration fuel consumption function. k_1 and m_d can be calculated using eqns (B8) and (B10) given observed profiles. Using only data where $v_f = 0$ and $v_i > 20$ km/h, the following regressions were found:

$$k_1 = 0.621 + 0.000777 v_i \quad R^2 = 0.04, SE = 0.065 \quad (B20)$$

$$m_d = 0.473 + 0.00155 v_i \quad R^2 = 0.11, SE = 0.073 \quad (B21)$$

$$\bar{a} = -(1.71 + 0.238 \sqrt{v_i}) \quad R^2 = 0.07, SE = 1.04 \quad (B22)$$

Then, using all decelerations with these coefficients fixed, v_i was added to the equations:

$$k_1 = 0.621 + 0.000777 v_i - 0.0189 \sqrt{v_i} \quad R^2 = 0.29, SE = 0.065 \quad (B23)$$

$$m_d = 0.473 + 0.00155 v_i - 0.00137 v_i \quad R^2 = 0.13, SE = 0.065 \quad (B24)$$

$$\bar{a} = -(1.71 + 0.238 \sqrt{v_i - v_f} - 0.0090 v_i) \quad R^2 = 0.10, SE = 1.18 \quad (B25)$$

Deceleration time was estimated by:

$$t_d = (v_f - v_i) / \bar{a} \quad R^2 = 0.40, SE = 5.14 \quad (B26)$$

The parameters, k_x , k_y and k_a are related to the point at which the total tractive force, R_T , becomes zero during the deceleration (see Fig. 32). Letting t_o and x_o be the time and distance travelled to this point and v_o be the speed at this point, k_x , k_y and k_a can be calculated from an observed deceleration profile as follows:

$$k_x = x_o / x_d \quad (B27)$$

$$k_y = \int_0^{t_o} v^3 dt / \int_0^{t_d} v^3 dt \quad (B28)$$

$$k_a = 1 - (v_o / v_i)^2 \quad (B29)$$

The point of zero tractive force was found to be related to v_i , v_f , grade and mass of vehicle. Firstly, k_x was related to mass by calculating observed k_x values for all deceleration in Sydney data with grade set to zero using vehicles of mass 900, 1250 and 1600 kg. The coefficient of $1/M$ was estimated by regression to be 100.

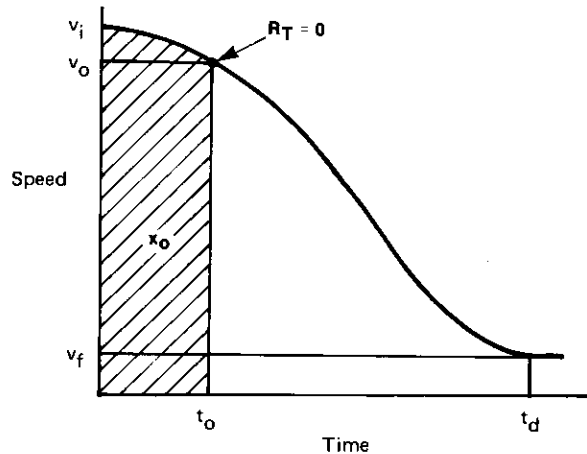


Fig. 32 — Deceleration profile showing the speed, time and distance at the point where total tractive force becomes zero

Using data for the three vehicle masses, selecting decelerations where $v_f = 0$ and $v_i > 20$ km/h and fixing the mass coefficient, the following regression equation was found using observed k_x found with grade set to zero:

$$k_x = 0.046 + 100/M + 0.00421 v_i \quad R^2 = 0.13, SE = 0.182 \quad (B30)$$

With these coefficients fixed, the coefficient of v_f was determined using all decelerations (grade still set to zero). Finally, the observed values of k_x were re-calculated with grade included and the coefficient of grade was estimated by regression with the other coefficients fixed:

$$k_x = 0.046 + 100/M + 0.00421 v_i + 0.00260 v_f + 0.0544 G \quad R^2 = 0.44, SE = 0.191 \quad (B31)$$

Since k_x is the proportion of the deceleration distance travelled with total tractive force greater than zero, the estimated k_x must be restricted to lying between zero and one. The parameters k_v and k_a are very strongly related to k_x and were therefore estimated as functions of k_x rather than v_i , v_f , mass and grade. A power function was found to best describe the relationship between k_x and k_v and v_o/v_i . Summing the logarithms of observed k_x , k_v and $(1 - v_o/v_i)$, the power coefficients were estimated by:

$$(a) \quad \text{Coefficient in } k_v: \quad \frac{\ln(k_v)}{\ln(k_x)} = \frac{-0.689}{-0.915} = 0.75$$

$$(b) \quad \text{Coefficient in } k_a: \quad \frac{\ln(1 - v_o/v_i)}{\ln(k_x)} = \frac{-3.49}{-0.915} = 3.81$$

Elemental Model : Cruise Fuel Consumption Function

Classification of the cruise sections of a trip is crucial to the estimation of default values of E_{k+} (positive kinetic energy) and important, to a lesser extent, in the calibration of k_{E1} , k_{E2} and k_G . The classification used in this report was chosen so that the cruise fuel consumption function would suit traffic models which can identify stops and slowdowns to low speeds but cannot identify speed fluctuations at the higher speeds. The cruise sections in the Sydney on-road data were identified in the following way (refer to Fig. 33):

- Major accelerations and decelerations were identified as those where speed increased above or dropped below 20 km/h, respectively.
- The end time and final speed, v_f , of an acceleration above 20 km/h and the start time and initial speed, v_i , of the next deceleration to below 20 km/h were found for each major acceleration and deceleration.
- So that the speed at the start and end of each cruise section are equal, the start and end points were chosen as follows:

If $v_f \geq v_i$, the point during acceleration when speed equalled v_i is start of cruise and start of deceleration is end of cruise

If $v_f < v_i$, the point during deceleration when speed equalled v_f is end of cruise and end of acceleration is start of cruise.

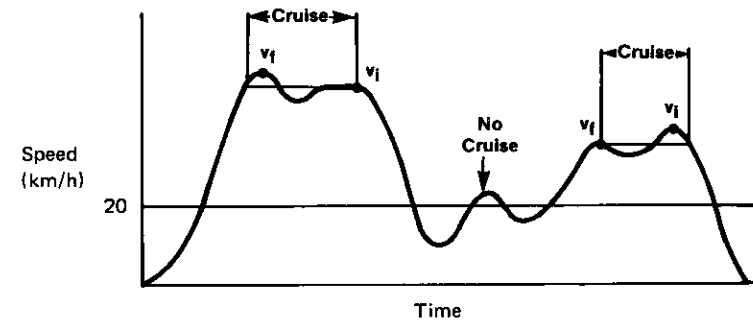


Fig. 33 — Speed-time profile showing the way cruise sections were identified

The cruise speed was taken to be the average speed between the start and end of cruise.

The coefficients k_{E1} , k_{E2} and k_G were estimated separately as follows:

- The $\beta_2 ME_{k+}^2$ term is related solely to be $[\beta_2 a R_i dx]_{a>0}$ term of the instantaneous model. Therefore, the sum, $\sum [\beta_2 a R_i dx]_{a>0}$, was found

for each cruise section and k_{E2} estimated by regression of the ratio, $\beta_2 ME_{k+}^2 / \sum [\beta_2 a R_i dx]_{a>0}$, on cruise speed. Cruise speed was not found to be significant ($R^2 < 0.01$) and the equation for estimating k_{E2} , eqn (27b), is the mean of the above ratio.

- (b) Setting grade equal to zero, the cruise fuel consumption was estimated for each section using the instantaneous model. The constant speed and $\beta_2 ME_{k+}^2$ components of this fuel consumption, the latter being calculated exactly using instantaneous model, were subtracted, leaving the component due to the E_{k+} term, call it f_E . The equation for estimating k_{E1} , eqn (27a), was derived by regressing $f_E / \beta_1 ME_{k+}$ on the cruise speed ($R^2 = 0.03$, $SE = 0.45$). The maximum value for k_{E1} of 0.63 corresponds to a cruise speed of 20 km/h and this value, rather than one, was chosen because 20 km/h is the minimum cruise speeds with the classification of cruise sections used in this analysis.
- (c) Finally, cruise fuel consumption over each section was re-estimated with grade included and that part due to grade, say f_G , was found by subtracting the non-grade components, with k_{E1} found above and $\beta_2 ME_{k+}^2$ component calculated exactly using instantaneous model. Eqn (27c) for estimating k_G was found by regression of the ratio, $f_G / \beta_1 MG$, on E_{k+} , grade and cruise speed for positive and negative grades separately. The latter two were found to be insignificant.

The equation for the default estimation of E_{k+} , eqn (28), was derived by regressing observed values of E_{k+} over the cruise sections against cruise speed ($R^2 = 0.13$, $SE = 0.068$). This form of equation provided a much better fit than one relating E_{k+} to $1/v_c$.

Running Speed Model

The procedure used to calibrate the running speed model was almost identical to that used for the cruise fuel consumption function. Positive speed sections were identified as those where speed was greater than 1 km/h. The calibration of k_{E1} , k_{E2} and k_G and the equation for the default estimation of E_{k+} were all derived in exactly the same way as described above but values were calculated over positive speed sections rather than cruise sections. The following R^2 and standard errors were obtained:

k_{E1} , eqn (39a) :	$R^2 = 0.02$	$SE = 0.11$
k_{E2} , eqn (39b) :	$R^2 = 0.12$	$SE = 0.72$
E_{k+} , eqn (40) :	$R^2 = 0.21$	$SE = 0.073$

The equation for estimating average running speed, v_r , from average travel speed, v_s , eqn (43), was found by regression of v_r on v_s ($R^2 = 0.98$, $SE = 2.14$) where both speeds were calculated on a total trip rather than section level. The function for estimating idle time, eqn(44), is found by rearranging eqn (37) with average speed given by eqn (43).

Average Travel Speed Model

The average travel speed model was not derived by integration of the instantaneous function and the vehicle parameters therefore do not occur explicitly in the model. However, two separate components of fuel consumption can be identified in the model; the fuel to maintain engine operation and the fuel to provide tractive force to the vehicle. The latter component is accounted for by the constant in the average travel speed model and can be related to the driving environment and the vehicle parameters. The model was calibrated for two driving environments, CBD and other urban. This was done by first estimating the constant, c of eqn (46b) in the two environments for the default car, then introducing correction factors to allow for different vehicle types.

Fuel consumption was estimated using the instantaneous model, with default car parameters, over each route in the Sydney data and the mean of the differences, $f_x - f/v_s$, over each environment was used to estimate c . The correction factor, K , was found by determining the contribution of the various power components to fuel consumption and from this determining the sensitivity of fuel consumption to changes in the vehicle parameters from the default values. Using the instantaneous model and the approach outlined in Biggs and Akcelik (1985) the contribution to fuel consumption of engine operation, rolling and aerodynamic drag, and inertia and grade forces was estimated. The results are given in Table XXIII. Both the contributions to overall fuel consumption and to non-idle fuel consumption are given but the constant, c , is related only to the non-idle component. The vehicle parameters which effect the contribution of each component are given at the bottom of the Table. The coefficients K_1 , K_2 , K_3 , K_4 and K_5 relate to M , β_1 , β_2 , b_1^* and b_2 , respectively (where $b_1^* = b_1/M$). Each is found by summing up the percentage contributions of the components which are affected by its related vehicle parameter. For example, the vehicle parameter related to K_5 is b_2 and only the aerodynamic drag component of fuel consumption is effected by b_2 . Thus K_5 equals the contribution of the aerodynamic drag component. The values of K_1 to K_5 for 'other urban' driving are found to be:

$$M : K_1 = 40.5 + 13.2 + 12.5 + 3.9 = 70.1\% = 0.701$$

$$\beta_1 : K_2 = 40.5 + 29.9 + 13.2 + 3.9 = 87.5\% = 0.875$$

$$\beta_2 : K_3 = 12.5\% = 0.125$$

$$b_1^* : K_4 = 40.5\% = 0.405$$

$$b_2 : K_5 = 29.9\% = 0.299$$

Since the contribution of the various components varies with driving environment, K_1 to K_5 must be calculated for both environments.

TABLE XXIII

THE CONTRIBUTION OF VARIOUS COMPONENTS TO FUEL CONSUMPTION AND THE VEHICLE PARAMETERS WHICH AFFECT THOSE COMPONENTS

Location	Base	Components of Fuel Consumption (%)					
		Engine Operation	Roll-drag [†]	Air-drag [†]	Inertia	aR_1	Grade
CBD	Overall	61.5	16.2	4.2	9.2	8.1	0.9
	Non-idle	—	42.1	10.9	23.9	21.0	2.3
Other Urban	Overall	40.9	23.9	17.7	7.8	7.4	2.3
	Non-idle	—	40.4	30.0	13.2	12.5	3.9
Vehicle Parameters		α	$Mb_1^*\beta_1$	$b_2\beta_1$	$M\beta_1$	$M\beta_2$	$M\beta_3$

* $b_1^* = b_1/M$

† These components also include the fuel to overcome engine drag.

APPENDIX C

ESTIMATION ACCURACY OF FUEL CONSUMPTION MODELS

Fuel consumption models are used to predict the fuel consumption of vehicles in traffic on the road. However, the fuel consumption rate of a vehicle on the road can vary greatly due to changing environmental factors (e.g. wind and precipitation) and vehicle factors (e.g. idle rate and engine temperature). Therefore, even instantaneous models do not predict on-road fuel consumption very accurately over short time intervals (of about 1 second). The accuracy of more aggregate models is also affected by the profiles during acceleration, cruise, etc. and these are dependent on both driver behaviour and traffic conditions.

Generally, fuel consumption models are used to estimate the fuel consumption of a vehicle over a number of trips, or of many vehicles. It is therefore of primary importance that the models be unbiased (i.e. the average error be zero) or at least internally consistent when comparing estimates of fuel consumption. The variation in prediction errors is of less importance since the error standard deviation per vehicle or trip decreases as the number of vehicles or, number or length of trips increases. For detailed assessment of the impacts of traffic management schemes for intersections or in small sub-area networks, it is necessary that the model give unbiased estimates of fuel consumption for all modes of driving. Over larger networks, the condition of unbiased estimates of fuel consumption over a trip is adequate.

Firstly, fuel consumption predicted using the instantaneous model are compared with measured on-road fuel consumption. Then, estimates found using the aggregate models are compared with values calculated from the instantaneous model using speed-time data collected in traffic in Sydney. The accuracy of the fuel consumption models is discussed in detail in Biggs and Akcelik (1985).

INSTANTANEOUS MODEL

An indication of the possible errors in fuel consumption estimated using the instantaneous model is given in *Table XXIV* for the acceleration and cruise modes of driving and over acceleration-cruise-deceleration cycles.

Note that the instantaneous model does not predict cruise fuel consumption well at low speeds, although on average the errors are close to

zero. Acceleration fuel consumption is underestimated during very hard accelerations (average acceleration greater than 5 km/h/s), but few accelerations occur at these rates on the road. Percentage errors in deceleration fuel consumption are large (up to 30 per cent) but actual errors are small (less than 2 mL on average). The larger errors during deceleration are due to the large variation in observed deceleration fuel consumption (compared to actual fuel consumption) and to some lags in the use of fuel by the engine. Over acceleration-cruise-deceleration cycles, where any lag effects are minimised, the estimation accuracy is very good.

TABLE XXIV

ERRORS IN PREDICTED FUEL CONSUMPTION USING THE INSTANTANEOUS MODEL*

	Type of Driving	Mean Error (%)	Approximate Standard Deviation of Error (%) [†]
Cruise	10 to 25 km/h	-2	10
	25 to 65 km/h	0	4
	60 to 120 km/h	0	5
Acceleration	Slow	1	6
	Medium	-1	4
	Hard	-2	4
	Full Throttle	-9	5
Acceleration —	Slow Acceleration	1	3
Cruise —	Medium Acceleration	2	3
Deceleration Cycle	Hard Acceleration	-1	4

* Results based on tests using a 4.2 L Cortina station-wagon with automatic transmission.

† Errors expressed as a percentage of total fuel consumption.

AGGREGATE MODELS

The accuracy of the elemental, running speed and average travel speed models was investigated by comparing estimates of fuel consumption found using the three models with those calculated using the instantaneous model. Speed and grade data collected in Sydney by Tomlin *et al.* (1983) were used to make these comparisons. The elemental and running speed models were tested over idle-acceleration-cruise-deceleration cycles extracted from the data and the running-speed and average travel speed models were tested on a total trip level. Trip lengths ranged from 5 km for the low average travel speeds to hundreds of kilometers at the high speeds. Results are given in Table XXV.

TABLE XXV

APPROXIMATE ERRORS* IN PREDICTED FUEL CONSUMPTION OVER CYCLES AND TRIPS USING THE ELEMENTAL, RUNNING SPEED AND AVERAGE TRAVEL SPEED MODELS

Level of Data	Fuel Consumption Model	Optional Data Availability	Mean and SD of Error					Per cent of Cases Within x% of Actual F_s Value		
			Speeds v_c or v_s (km/h)					x = 5%	x = 10%	x = 20%
			10-30 (%)	30-50 (%)	50-90 (%)	90-120 (%)	120-160 (%)			
IACD Cycle [†]	Elemental	v_i, v_f known	1 (4)	1 (6)	2 (10)	69	97	69	97	99.2
	Running Speed	E_{k+} known	0 (3)	1 (4)	0 (7)	83	97	83	97	99.8
	Elemental	v_i, v_f unknown	3 (5)	-1 (10)	-2 (9)	56	85	56	85	98.5
Trip	Running Speed	E_{k+} unknown	4 (7)	2 (13)	4 (16)	40	67	40	67	93
	Running Speed	v_r, t_r, G known	-2 (4)	1 (3)	0 (3)	82	99	82	99	100
	Running Speed	Only v_s known	-3 (5)	-1 (4)	0 (3)	81	97	81	97	100
	Average Travel Speed		0 (5)	0 (4)	-15 (5)	72	87	72	87	100

* 'Observed' fuel consumption taken to be the fuel consumption estimated from the instantaneous model using observed speed and grade profile.

† Idle-acceleration-cruise-deceleration cycle.

Several interesting points can be seen in *Table XXV*.

- (a) When speed fluctuations during cruise (i.e. v_i , v_f and E_{k+}) are known, the elemental and running speed models predict fuel consumption very accurately, the elemental model being more suitable for short road sections and the running speed model more suitable for trips.
- (b) When speed fluctuations during cruise are unknown but cruise speeds are known, the accuracy of the elemental model over an idle-acceleration-cruise-deceleration (IACD) cycle is still very good.
- (c) The running speed model slightly underestimates fuel consumption over a trip. This error is primarily related to the grade term in the running speed model. Over a long trip average grade is not a good measure of the effect of grade on fuel consumption as positive and negative grades often cancel each other out. This leads to an underestimate of the grade component of trip fuel consumption.
- (d) The average travel speed model is adequate for estimation of fuel consumption provided average travel speeds are not high.

METRIC UNITS AND CONVERSION FACTORS

SI UNITS (BASE AND DERIVED)

Quantity	Unit	Symbol	Derivation
Length	metre	m	—
	kilometre	km	10^3 m
Time	second	s	—
	hour	h	3600 s
Mass	kilogram	kg	—
	gram	g	10^{-3} kg
Force	newton	N	kg.m/s^2
	kilonewton	kN	10^3 N
Energy, work	joule	J	N.m
	kilojoule	kJ	10^3 J
Power	watt	W	J/s
	kilowatt	kW	10^3 W

OTHER UNITS (METRIC)

Quantity	Unit	Symbol
Acceleration	metre per second squared	m/s^2
	kilometre per hour per second	km/h/s
Velocity (speed)	metre per second	m/s
	kilometre per hour	km/h
Fuel consumption		
volume per unit distance	litre per kilometre	L/km
volume per 100 kilometres	litre per 100 kilometres	L/100 km
volume per unit time	litre per hour	L/h

CONVERSION FACTORS

Quantity	Unit	In Metric Units
Length	foot	1 ft = 0.3048 m
	mile	1 mile = 1.609 km
Volume	litre	1 L = 10^{-3} m ³ = 10 ⁶ mm ³
	gallon (Imperial)	1 gal = 4.546 L
	gallon (U.S.)	1 U.S. gal = 3.785 L
Mass	tonne	1 t = 1000 kg
	ton (Imperial)	1 ton = 1.016 t
	ton (U.S.)	1 U.S. ton = 0.9072 t
	pound	1 lb = 0.4536 kg
Velocity (speed)	foot per second	1 ft/s = 0.3048 m/s
	mile per hour	1 mile/h = 0.4470 m/s = 1.609 km/h
	kilometre per hour	1 km/h = 0.2778 m/s
Acceleration	foot per second squared	1 ft/s ² = 0.3048 m/s ²
	gravity	32.17 ft/s ² = 9.807 m/s ²
	kilometre per hour per second	1 km/h/s = 0.2778 m/s ²
Force	pound-force	1 lbf = 4.448 N
	ton (Imperial) force	1 tonf = 9.964 kN
	kilogram-force	1 kgf = 9.807 N
Energy	foot pound-force	1 ft.lbf = 1.356 J
	kilogram-force metre	1 kgf.m = 9.807 J
	British thermal unit	1 Btu = 1.055 kJ
	calorie	1 cal = 4.187 J
Power	foot pound-force per second	1 ft.lbf/s = 1.356 W
	kilogram-force metre per second	1 kgf.m/s = 9.807 W
	British thermal unit per hour	1 Btu/h = 0.2931 W
	calorie per second	1 cal/s = 4.187 W
	horsepower	1 hp = 0.7457 kW
Fuel consumption	mile per gallon (Imperial)	1 mile/gal = 0.3540 km/L
	mile per gallon (U.S.)	1 mile/U.S. gal = 0.4251 km/L
	gallon (Imperial) per mile	1 gal/mile = 2.825 L/km
	gallon (U.S.) per mile	1 U.S. gal/mile = 2.352 L/km
	gallon (Imperial) per hour	1 gal/h = 1.263×10^{-3} L/s
	gallon (U.S.) per hour	1 U.S. gal/h = 1.051×10^{-3} L/s
	millilitre per kilometre	1 mL/km = 0.1 L/100 km
	millilitre per second	1 mL/s = 3.6 L/h

Notes:

1. This publication uses upper case 'L' for litre since the standard symbol, lower case 'l', may be confused with number one in printed text.
2. Units such as millilitre per kilometre and kilometres per hour per second are not standard. They are used in this publication because they provide values of a convenient magnitude and are commonly used in the area of application of this work.
3. It is suggested that, when applying and calibrating the fuel consumption models of this guide, the user should convert any non-metric variables (speed, acceleration, mass, idle fuel rate) to metric units and use the converted variables. Resulting estimates of fuel consumption can then be converted to non-metric units.