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ENERGY EFFICIENCY OF AUTOMOBILES

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ABSTRACT: *A computer model has been developed to predict the fuel consumption of an automobile in response to changes in vehicle design and traffic characteristics. The structure of the model allows for data relating to car body (drag coefficient, vehicle mass etc.), engine (capacity, no. of cylinders etc.), gear box (gear ratio, final drive ratio, etc.), load factor, and traffic characteristic (average speed, number of stops per km., etc.) to be input to the model. This enables the effect of variation of input parameters on the energy efficiency to be assessed. The model produces a variety of output in graphical as well as tabular form. The output, it is hoped, will provide guidelines for policy-making by identifying areas in which efforts should be concentrated.*

Among the range of operational and design options evaluated in this study, increasing load factor offers the greatest reduction of about 60 percent. Other options such as reduction in vehicle weight, the addition of a fifth gear, improvements in drag coefficient and higher tyre inflation result in savings of between 2 to 15 percent. Smaller cars (in terms of engine capacity) and improved traffic management offer significantly higher fuel saving potential of between 35-40 percent.

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INTRODUCTION

A computer model of automobile fuel consumption has been developed to predict the fuel consumption of an automobile in response to changes in vehicle design and traffic characteristics. The structure of the model allows data relating to car body (drag coefficient, vehicle mass, etc.), engine (capacity, number of cylinders, etc.), gear box (gear ratio, final drive ratio, etc.), load factor, and traffic characteristics (in the form of a driving cycle) to be input to the model. This enables the effect of variations of input parameters on the energy efficiency to be assessed.

This facility is believed to be useful in the process of setting priorities in fuel conservation program for automobiles and can be used to predict the automobile fuel demand in the future based on the estimates of various technological and regulatory parameters.

STRUCTURE OF THE FUEL CONSUMPTION MODEL

The basic approach to modelling fuel consumption in automobiles is based on Watson, Milkins and Marshall (1979). The acceleration of a vehicle is considered to be constrained by the torque available at the driving wheels, T_w, given by

$$T_w = r_w \left[I_v \frac{dV}{dt} + a\, C_d A_v V^2 + \left(\left(b + \frac{c}{P_t} + e\,\frac{V^2}{P_t} + g \sin\alpha\right) M\right)\right] \quad \ldots(1)$$

where a, b, c and e are constants

r_w = wheel rolling radius, m
I_v = vehicle inertia, kg
C_d = drag coefficient
A_v = frontal area of the vehicle, m^2
P_t = tyre pressure, kPa
M = vehicle mass, kg
α = road gradient, radians
g = gravitational acceleration m/s^2
V = instantaneous vehicle speed, m/s

The wheel torque, T_w, is related to the engine torque, T_e, by Equation 2 while the engine speed, N, is given by Equation 3.

$$T_e = \frac{1}{R_f} \cdot \frac{1}{R_g} \cdot T_w \cdot \frac{1}{\eta_f} \cdot \frac{1}{\eta_g} + I_e \frac{dN}{dt} + T_p \quad \ldots(2)$$

and

$$N = \frac{V}{r_w} \cdot R_f \cdot R_g \quad \ldots(3)$$

where R_f = final drive ratio
R_g = gear ratio
η_f = final drive efficiency
η_g = transmission efficiency
I_e = engine inertia, kg m^2
T_p = parasitic torque, N·m

The fuel flow rate is a function of the engine torque, engine speed and other engine characteristics which determine its thermal efficiency at that torque and speed. The fuel flow rate is easily converted to the fuel consumed per unit distance. By determining the fuel consumed for each segment of a driving cycle (where a segment represents a constant acceleration section of the cycle), the fuel consumption can be determined.

$$m_f = o \cdot T_e + n \cdot N + m_{idle} \quad \text{....(4)}$$

and $$FC = \frac{m_f}{V \cdot \rho} \quad \text{....(5)}$$

where m_f = fuel flow rate, kg/s
m_{idle} = idle fuel flow rate, kg/s
FC = fuel consumption, m^3/m
ρ = density of the fuel (kg/m^3)
o and n are functions of the engine.

The fuel consumption can be easily converted to ℓ/100 km or miles per gallon.

DETAILED MODEL DESCRIPTION

The detailed structure of the fuel consumption model is described below and shown in Figure 1.

Vehicle Characteristics Inputs

Vehicle specifications are input in five separate data files. These are

BODY·DAT This file inputs general information about the vehicle and contains

- drag coefficient
- vehicle height, m
- ground clearance, m
- maximum vehicle width, m
- passenger capacity, number
- kerbside weight, kg
- fuel tank capacity, m^3
- wheel rolling diameter, m
- tyre pressure, kPa

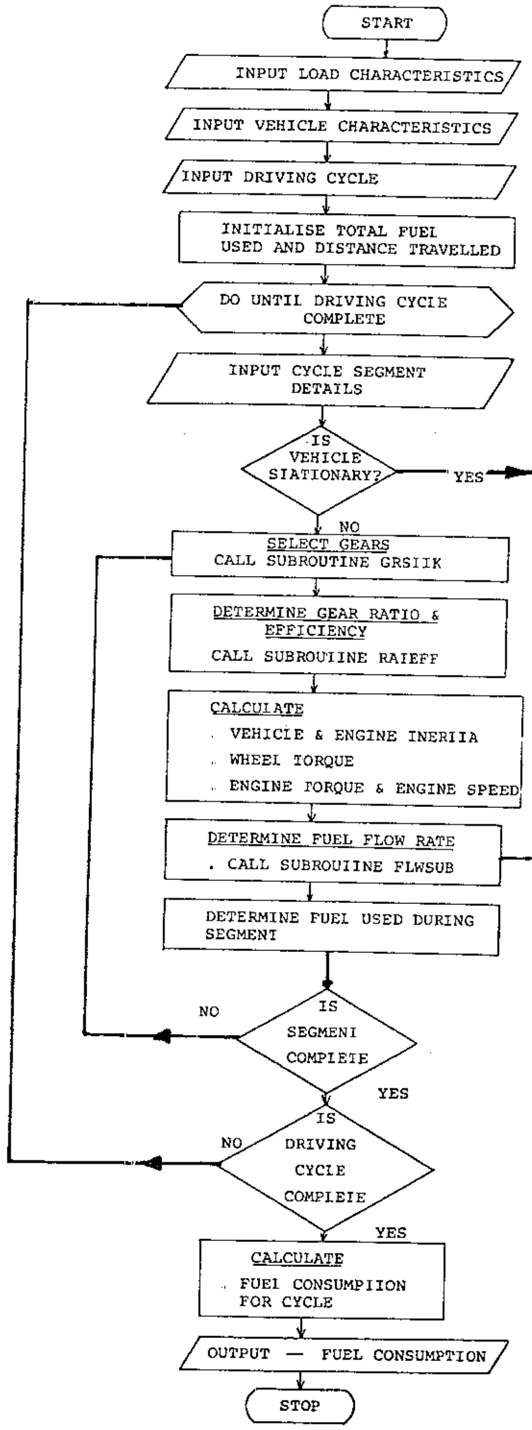


Figure 1. Structure of the Fuel Consumption Model

ENGINE·DAT This file inputs the engine specifications

- engine capacity, m^3
- maximum engine torque, Nm

GEAR·DAT This file inputs gearbox details and contain

- gear ratios
- final drive ratio

CLUTCH·DAT This file inputs the velocities at which gears should be changed, as recommended by the manufacturer.

FCMTRX·DAT This file contains the fuel flow rates for combinations of engine speed and engine torque for a particular engine.

Vehicle characteristics, independent of the vehicle speed, are calculated in the model. These include

Frontal area The model currently uses a simplified formula in the determination of frontal area, based on the height, width and ground clearance. However, actual frontal area of a particular vehicle can be given as an explicit input

Effective vehicle mass The vehicle mass effective on the tyres consists of the kerbside weight, the passenger weight and the fuel weight. In the calculation of passenger weight, an average value of 70 kg/person is assumed. For calculating the fuel weight, it is assumed that the fuel tank is three-quarters full.

Idle fuel flow rate The speed-torque-efficiency contours used for calculating fuel flow are not sufficiently accurate to determine the fuel flow rate at idle. Watson, Milkins and Marshall (1979) produced experimental results suggesting the following linear relationship between idle fuel flow rate and engine capacity

$$m_{idle} = 0.000183 \cdot EC \cdot \rho \qquad \ldots (6)$$

where EC = engine capacity, m^3

ρ = density of the fuel, kg/m^3

In addition, the ratio of passenger occupancy to vehicle capacity (defined as load factor) is input by the data file, ALPHA·DAT.

Travel Characteristics Inputs

To compare vehicle performance, a need was seen for a standard set of driving conditions and the concept of the driving cycle was evolved. The United States pioneered the concept by developing U.S. 72FTP (urban driving) and the U.S. Highway (non-urban driving) cycles. The Standards Association of Australia (1979) adopted these cycles for Australian tests. Rule, Allen and Kent (1976) developed the Sydney driving cycle. In this study, the Highway cycle and the Sydney cycle are taken as representative of the Australian conditions for non-urban and urban driving conditions, respectively. The driving cycles specify an explicit velocity-time history to which vehicles are expected to conform during the fuel consumption test. For each second of the cycle, the vehicle speed is specified to an accuracy of 0.1 km/hour. The velocity-time profiles of the cycles used in this study are shown in Figure 2.

To present the cycles for input to the program, the velocity-time curve is divided into segments of constant slope (or acceleration). There are four possible types of constant acceleration segments - positive acceleration, negative acceleration, zero acceleration (cruise) and zero acceleration (idle). These are shown in Figure 3.

Four pieces of information are required for each constant acceleration segment. These are vehicle speeds at the beginning and end of the segment, the time taken and the grade of the road. To keep computer time within reasonable limits, minor speed fluctuations are ignored when segmenting the velocity-time curve.

Major Subroutines Used in the Model

Gearshifting - GRSTIK The logic used in this subroutine is shown as a decision tree in Figure 4. The basic assumption in the operation of the gearbox is that the vehicle will change gears at specified speeds. If the vehicle has positive acceleration, the routine determines whether the segment can be completed without changing up a gear. If not, the segment is split into subsegments and the fuel consumption is calculated for each gear used. If the vehicle has constant non-zero speed for the segment, no gear change is required. If it is decelerating due to traffic conditions, again no gear change is made. However, if the deceleration is because of a positive gradient, a gear change may be necessary.

Gear ratio and gear efficiency - RATEFF This subroutine determines the gear ratio and gear efficiency corresponding to the gear selected by GRSTIK. Gear ratio and gearbox efficiencies are those used by Watson and Goldsworthy (1978).

Fuel flow rate - FLWSUB The thermal efficiency of an engine at a particular value of engine torque and engine speed depends on parameters such as engine capacity and configuration, compression ratio and carburretion. The common method of expressing the efficiency of an engine is by a plotting contours of efficiency on engine torque - engine speed axes. To input this information into the model requires some simplification.

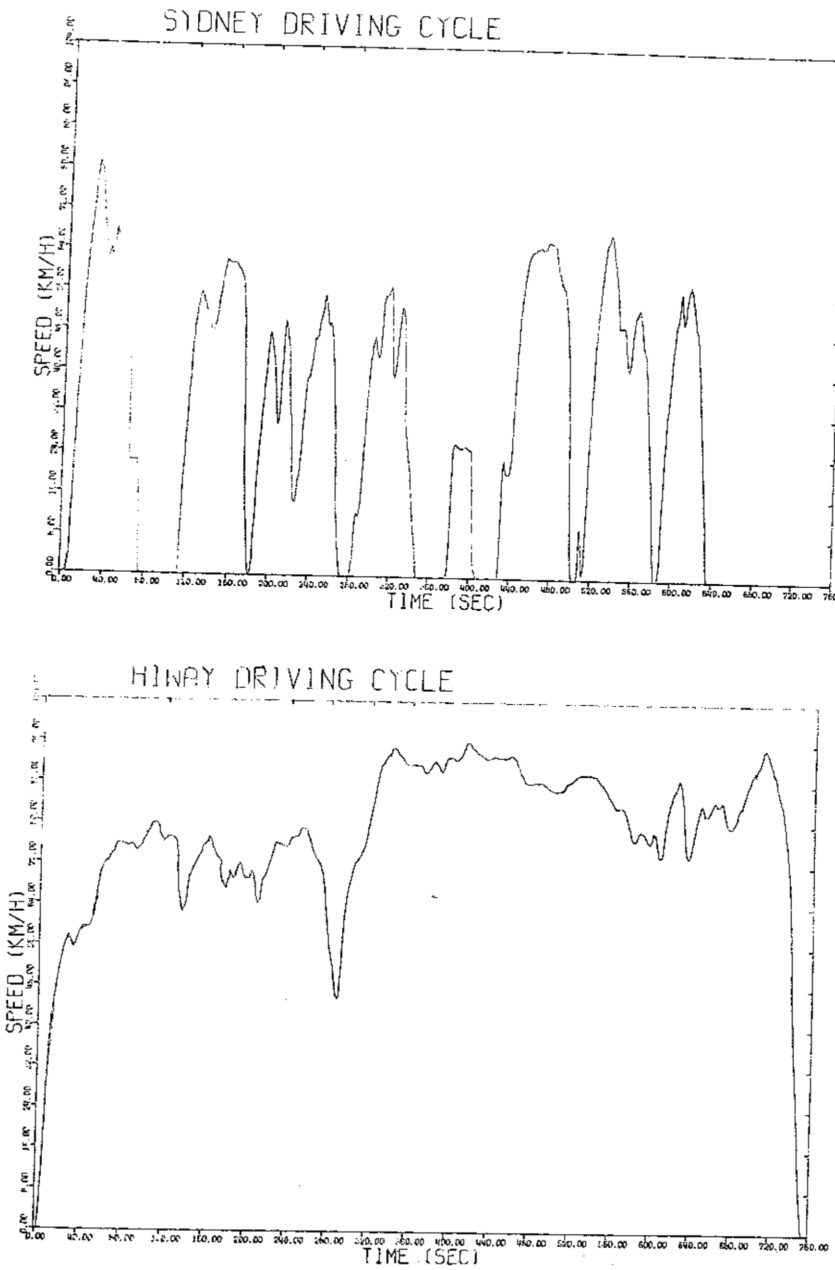


Figure 2. Sydney and Highway Driving Cycles.

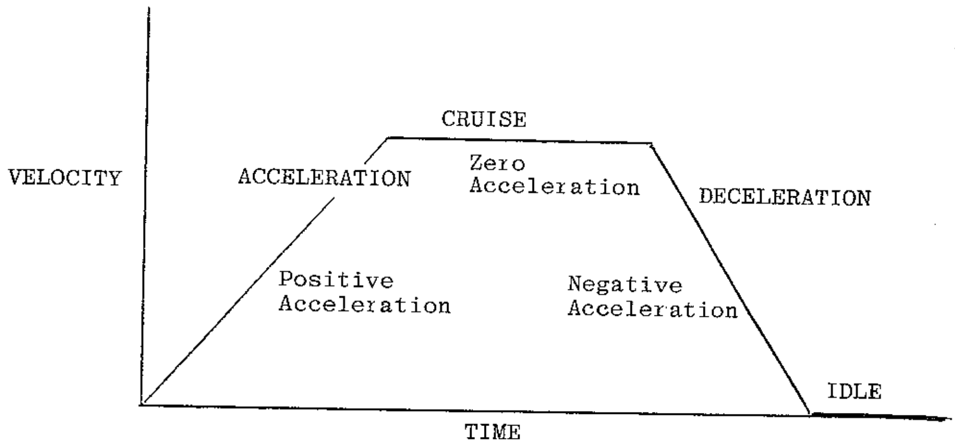


Figure 3. Constant Acceleration Segments

The method adopted was to place a grid over the contours, and at each intersection on the grid, the fuel flow rate was determined. Hence for a range of torque-speed combinations, fuel flow rates are known. Unfortunately a torque-speed-efficiency plot can only be obtained from a dynamometer test, the equipment for which was not available for this study. Only two examples were found, one for a 1272 cm^3 engine, and the other for a 4100 cm^3 engine. Therefore the model at present has information for only two sizes of engines. It is recognised that the gathering of further information in this area would vastly improve the model's effectiveness

Steps in Calculating Fuel Consumption

Vehicle and engine inertia Although vehicle inertia is more accurately given by Lamb (1914) as

$$I_v = M + n \cdot m \left(1 + \frac{K^2}{r_w^2}\right) \qquad \ldots (7)$$

where M = mass of car minus wheels, kg

n = number of wheels

m = mass of each wheel, kg

K = radius of gyration of the wheels, m

r_w = radius of the wheel, m

the model assumes that the vehicle inertia is equal to the vehicle mass because of the relatively minor difference between the two. Similarly, the engine inertia is assumed to have a small, non-varying value

Wheel torque The wheel torque is obtained as the product of the wheel radius and the sum of the four forces acting on the vehicle. These are the inertia force, aerodynamic drag, tyre drag and the gradient force. This leads to Equation (1).

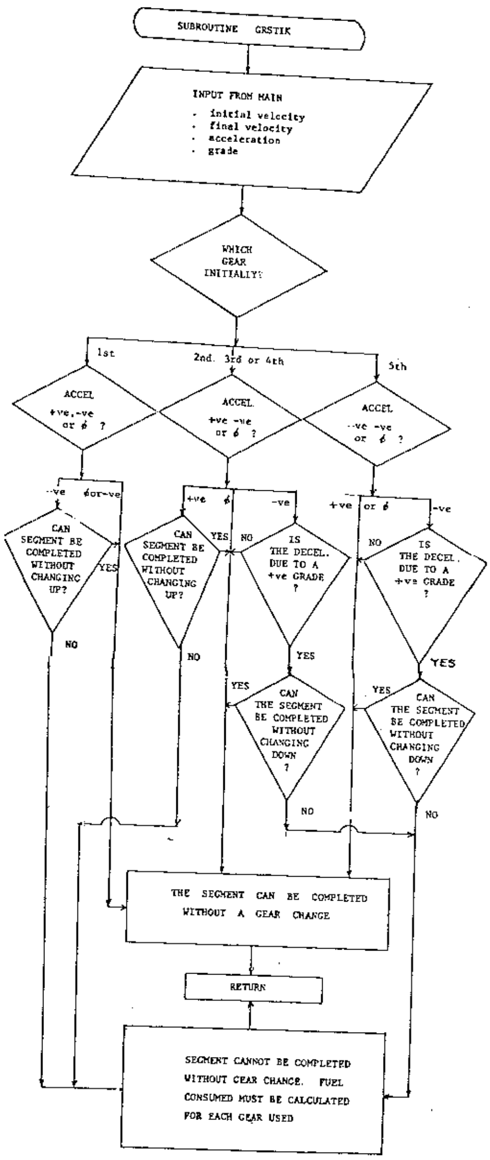


Figure 4. Structure of Gear Shifting Routine

<u>Engine torque and engine speed</u> These are calculated by using Equation 2 and 3. The final drive efficiency is given by Watson (1981) as

$$\eta_f = \frac{T_w}{T_{w(max)}} \cdot 0.089 + 0.871 \qquad \ldots(8)$$

The transmission efficiency is given by Watson and Goldsworthy (1978) as

$$\eta_g = \eta_f \cdot \eta_{gb} \qquad \ldots(9)$$

where η_{gb} = gearbox efficiency

The parasitic torque is calculated by adding the torque due to various accessories. This is given in Equation (10) which is due to Kent et. al. (1981)

$$T_p = T_{fp} + T_{alt} + T_{ps} + T_f \qquad \ldots(10)$$

where $T_{fp} = 1.8 + 200\ EC$

$T_{alt} + 2$ to 4

$T_{ps} = 1.5 + 0.0013\ M$

$T_f = 0.002\ N$

<u>Fuel consumption</u> The fuel flow for each segment of the driving cycle is obtained by using the subroutine FLWSUB, which is converted to fuel consumption by using Equation (5). These are added up to give the fuel consumption for the whole cycle.

<u>Output</u>

The fuel consumption is calculated in three different units: ℓ/100 km, miles per gallon, and ℓ/100 pass. km. Both tabular and graphical output is available as will be shown in the next section.

MODEL SIMULATIONS

The usefulness of a simulation model is the ability to conduct experiments with a view to evaluating the effect of a designated policy by simply varying any number of input parameters. This facility is used in this study to evaluate the following options related to vehicle and traffic improvement. The vehicle parameter values used as datums in the simulation run are given in Table 1.

TABLE 1

Datum values used in model simulations

Parameter	Value
drag coefficient	0.45
frontal area	2.16 m^2
kerbside weight	1200 kg
fuel tank capacity	50ℓ
tyre pressure	150 kPa
passenger capacity	5 people
wheel diameter	0.6 m
engine capacity	4100 cm^3
maximum engine torque	175 N.m
1st gear ratio	3.181
2nd gear ratio	1.823
3rd gear ratio	1.300
4th gear ratio	1.000
5th gear ratio	1.000
final drive ratio	4 384
load factor	0.2

Aerodynamic Drag

Streamlining the vehicle shape has been seen as one method of reducing fuel consumption in automobiles. The vehicle parameters which influence aerodynamic drag are the drag coefficient and the frontal area Because of the interpendency of these factors, the effect of changes in the product of drag coefficient (C_d) and the frontal area (A_v) has been examined. The average value of this product for European cars is 0.855 m^2 but a figure as low as 0 6 m^2 has been attained on a Mercedes-Benz test car. The fuel consumption for both the Highway cycle and Sydney cycle with variations in aerodynamic drag are given in Table 2.

TABLE 2

Effect of Aerodynamic Drag on Fuel Consumption

$C_d\ A_v$ (m^2)	Fuel Consumption ℓ/100 km	
	Sydney Cycle	Highway Cycle
0.6	13.92	8.95
0.7	14.18	9.00
0.8	14.21	9.19
0.9	14.36	9.28
1.0	14.46	9.65

The results show that the effect of reduction in aerodynamic drag is more significant in non-urban driving conditions. The improvement in fuel consumption is about 7.5 percent for a decrease in $C_d \cdot A_v$ from 1.0 m^2 to 0.6 m^2 for the Highway cycle. The corresponding saving for the Sydney cycle is less than 4 percent. This is not unexpected since the effect of aerodynamic drag is proportional to the square of vehicle speed.

Vehicle Weight

Reduction in vehicle weight can reduce fuel consumption appreciably. This effect is analysed by using the fuel consumption model. Vehicle weight is varied between 800 and 1500 kg and fuel consumption was determined for both the urban and highway driving conditions. The results are given in Table 3.

TABLE 3

Effect of Vehicle Weight on Fuel Consumption

Kerbside Weight (kg)	Fuel Consumption (ℓ/100 km)	
	Sydney Cycle	Highway Cycle
800	12.92	8.80
900	13.49	9.03
1000	13.80	9.09
1100	14.02	9.31
1200	14.46	9.64
1300	14.66	9.75
1400	15.01	9.83
1500	15.18	9.88

The results show that if the kerbside weight was reduced from 1500 kg to 800 kg, improvement of 15 percent on the Sydney cycle and 11 percent on the Highway cycle can be obtained. In urban driving, the improvement results from a reduction in vehicle inertia as there is a large percentage of time spent in accelerating and inertia forces are significant. The improvement in non-urban driving is due to a reduction in tyre drag which is a function of the vehicle weight and the square of the vehicle speed. It may be pointed out here that the urban driving cycle has a mean acceleration of 0.78 m/s^2 while the corresponding value for the highway cycle is 0.26 m/s^2. (Watson et. al., 1979) The engine size for both experiments is as given in Table 1.

Tyre Pressure

One of the factors in reducing fuel consumption in automobiles is correct inflation of tyres. The purpose is to reduce tyre drag which is inversely proportional to the tyre pressure. The effect of varying the tyre pressure from 100 kPa to 200 kPa is shown in Table 4.

TABLE 4

Effect of Tyre Pressure on Fuel Consumption

Tyre Pressure kPa	Fuel Consumption (ℓ/100 km)	
	Sydney Cycle	Highway Cycle
100	14.51	9.82
125	14.50	9.74
150	14.46	9.64
175	14.34	9.48
200	14.18	9.40

The reduction in fuel consumption over this range (100 kPa - 200 kPa) is 2 percent for the Sydney cycle and 5 percent for the Highway cycle. More significant improvement for the highway cycle is due to the fact that tyre drag is proportional to the square of the vehicle speed.

Load Factor

Work trips account for a large proportion of the total fuel bill. These trips are usually carried out during the morning and afternoon peak periods in congested traffic conditions and very low load factor. Improvements in work trip patterns can result in significant fuel savings. Car pooling is aimed at achieving this by increasing the load factor of work trips. The claimed benefits from increasing load factor are two-fold. Firstly it is obviously more efficient to carry four people in one car than in four separate cars. A secondary saving in fuel consumption results due to improvement in traffic flow and increase in average vehicle speed because of fewer vehicles on the road. The effect studied in this experiment is that of increasing the load factor (Table 5). The traffic improvement effects are examined separately.

TABLE 5

Effect of Load Factor on Fuel Consumption

Load Factor	Fuel Consumption (ℓ/100 pass. km)	
	Sydney Cycle	Highway Cycle
0.2	14.46	9.64
0.4	7.29	4.87
0.6	4.89	3.28
0.8	3.76	2.46
1.0	3.03	1.98

The figures shown in Table 5 have little relevance as far as the highway cycle is concerned. Firstly, for non-urban driving, the average load factor is already high. Secondly, the potential for increasing the load factor in this area is negligible. The model predicts a reduction in fuel usage of just under 80 percent for work-trips if full potential of car pooling could be realised.

Final Gear Ratio

Previously found only in high performance vehicles, a fifth or overdrive gear is now being incorporated in an increasing proportion of passenger vehicles. The fourth gear on most cars has a ratio of 1.0. The fifth gear ratio is approximately 0.7. It is usually not possible to use the fifth gear in normal urban driving. However, when vehicle speeds are high, the selection of the fifth gear reduces engine speed and hence fuel consumption. This is shown in Table 6. It is assumed that there are no losses due to the increased frequency of gear changing.

TABLE 6

Effect of Fifth Gear on Fuel Consumption

Final Gear Ratio	Fuel Consumption (ℓ/100 km)	
	Sydney Cycle	Highway Cycle
1.0	15.18	9.64
0.7	15.11	8.20

It is obvious that whereas a fuel saving of about 15 percent is achieved by using the fifth gear in highway driving, the savings in urban driving are negligible.

Engine Size

Motor vehicle registration figures produced by the Australian Bureau of Statistics show a trend towards smaller cars. This is in line with the increasing consciousness of the energy situation. The effect of engine size on fuel consumption has been simulated using the fuel consumption model and is summarized in Table 7.

TABLE 7

Effect of Engine Capacity on Fuel Consumption

Engine Size cm^3	Fuel Consumption, ℓ/100 km	
	Sydney Cycle	Highway Cycle
1272	8.6	6.1
4100	15.0	9.8

It can be seen that a smaller car with a 1272 cm^3 engine achieves a reduction in fuel consumption of about 40 percent compared to a car with a larger engine of 4100 cm^3. This improvement is slightly higher for the urban cycle than for the highway cycle. Vehicle weight for both experiments is as given in Table 1; therefore, the savings are conservative.

Traffic Conditions

By improving traffic flow in urban areas, traffic engineers can contribute to fuel conservation. The near free flow conditions on the highways and infrequent stops result in much lower fuel consumption for highway driving than for urban driving. This is shown in Table 8.

TABLE 8

Effect of Driving Conditions on Fuel Consumption

	Fuel Consumption, ℓ/100 km
Sydney cycle	15.0
Highway cycle	9.8

Thus, there could be a reduction of about 35 percent in fuel consumption if urban driving could be improved to correspond to the highway pattern.

A significant factor in achieving fuel economy on urban roads is to reduce the number of stops. Various traffic management policies can be devised to contribute to this objective A traffic simulation model has therefore been developed in a companion study to estimate the effect of designated traffic management policies on the average delay and the probability of stopping at a signalised intersection. This will be linked to the fuel consumption model described in this study to enable the energy saving potential of traffic management policies to be estimated This work is in progress.

The results of experiments described above are shown in Figure 5.

SUMMARY AND DISCUSSION

The model has been used to indicate the magnitude of fuel consumption changes which might result from changes in some vehicle design and traffic characteristics. A summary of the results obtained is given in Table 9.

TABLE 9

Summary of the Effects of Some Fuel Conservation Options

Parameter altered	Change			% Reduction in Fuel Consumption	
	Variable	From	To	Sydney Cycle	Highway Cycle
Aerodynamic drag	$C_d \cdot A_v$	1.0	0.6	4	7.5
Vehicle weight, kg	M	1500	800	15	11
Final gear ratio	R_g	1 0	0 7	-	15
Tyre inflation, kPa	P_t	100	200	2	5
Load factor	α	0.2	1	80	-
Engine size, cm^3	EC	4100	1272	43	38
Traffic condition	cycle	Sydney	Highway	-	35

The establishment of any fuel conservation policy requires expenditure of time, money, and energy. One must be sure, therefore, that the fuel savings exceed the implementation costs. The following paragraphs discuss the practicality of the various schemes.

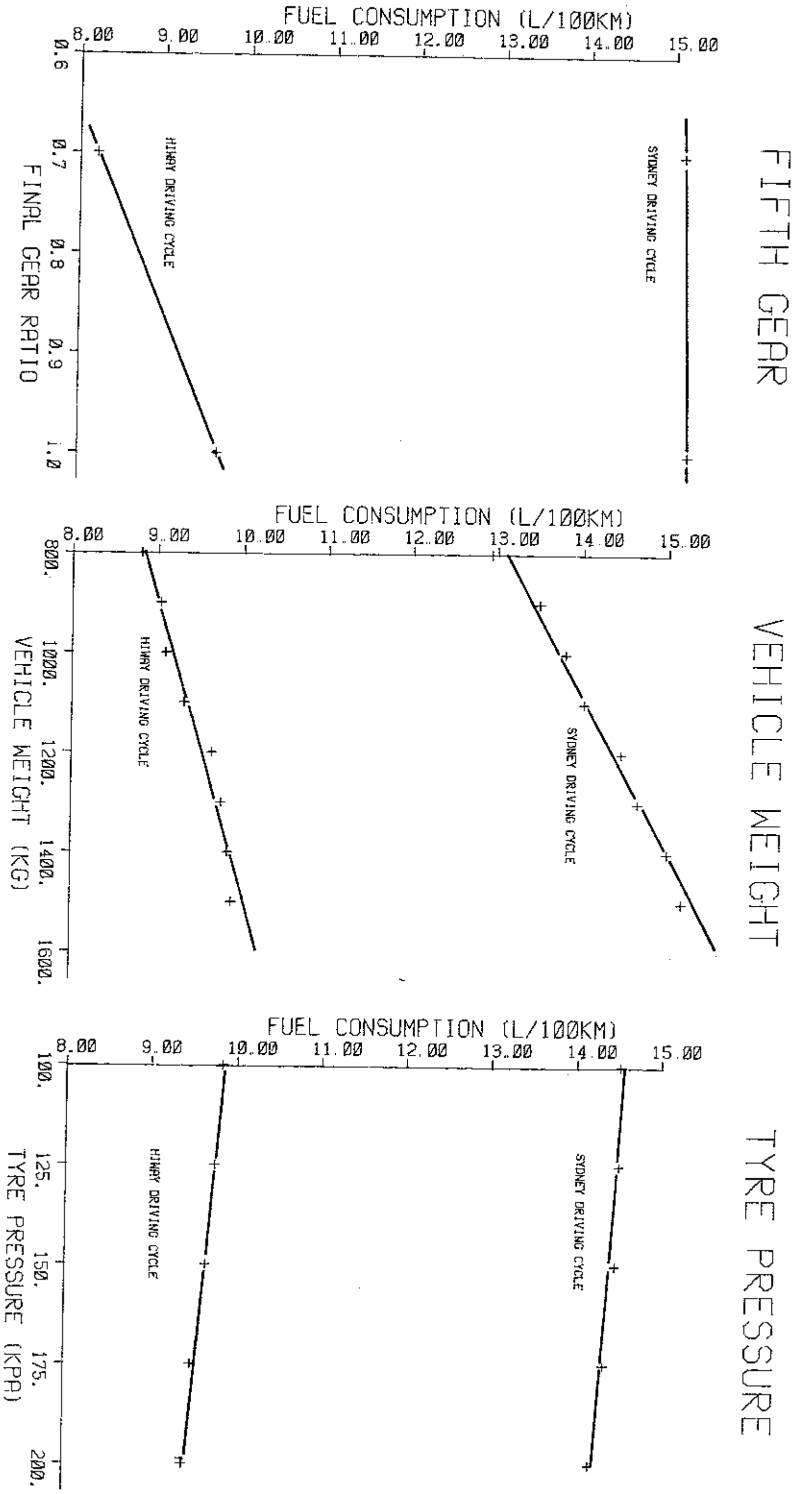
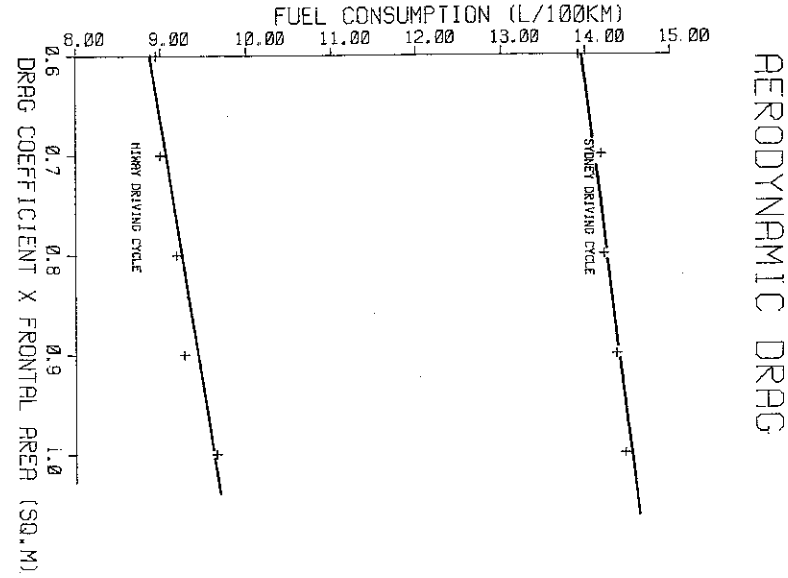


Figure 5. Results of Simulation Experiments



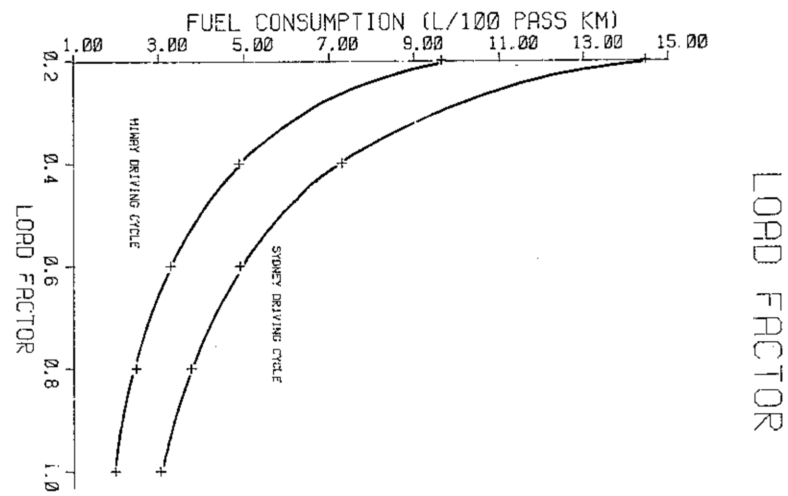


Figure 5 (cont)

Load Factor

Increasing load factor, obviously, offers the greatest potential as a fuel conservation measure. Savings of up to 80 percent are shown to be possible with full occupancy. This does not even consider the added advantage of less congested traffic flow. Unfortunately, of all the fuel conservation policies, it is perhaps the most difficult to achieve. Scheiner and Keiper (1976) found that of the various car pooling projects in the United States, 15 percent were very effective, 20 percent were moderately effective and 65 percent were not very effective at all. This happened in spite of the many incentives for car pooling and disincentives for solo drivers. In fact, a significant change in public attitudes is required before car pooling can be considered as viable.

Vehicle Size Reduction

Reduction in vehicle size is an option that the car buying public has already accepted. However, there always will be need for some large cars either for space or power requirements One alternative is to reduce vehicle weight without compromising size. This is beneficial since reducing weight results in more significant fuel savings in urban driving which is so energy inefficient. Moreover, it can be introduced subliminously since no attitudinal change is required for its acceptance The disadvantage of this policy is that the production of lighter materials is highly energy intensive. Christ (1980) has found that a vehicle has to be driven between 100 and 150 thousand kilometers before the increase in energy for lightweight material production will be balanced by the fuel savings gained by the reduced vehicle weight. He observed that while only 9 kW of energy is required to produce a kilogram of steel, 30-50 kW is required for a kilogram of aluminium and 80 kW for a kilogram of magnesium. A great deal of development is required but plastics offer the greatest potential for weight saving. It is recognised that the form of energy used in light weight production is electricity and not petroleum.

Aerodynamic Drag

Great efforts have been expended recently to reduce aerodynamic drag in passenger vehicles. According to the results obtained by using the fuel consumption model; however, the savings from this improvement appear to be limited especially for urban driving where most motor fuel is expended. A further disadvantage of reducing aerodynamic drag was noted by Christ (1980). He observed that improvements in drag coefficient generally led to reduced passenger safety. Visibility may be reduced through sloping windscreens and smaller exterior mirror. The vehicle handling may be compromised through a narrower track width.

Fifth Gear

The inclusion of the fifth gear in all passenger vehicle gearboxes would also appear to have limited potential. It is particularly effective in highway driving but offers virtually no savings in urban driving. For the high percentage of drivers, who spend most of their time in urban driving, the additional cost of the overdrive gear may be a dubious investment.

Tyre Pressure

Correct tyre inflation does reduce fuel consumption. Although savings of 10 percent or more have been suggested, the fuel consumption model shows the savings to be only about 5 percent. It is nonetheless a useful measure to reduce fuel consumption in view of no cost involvement.

Traffic Management

Improvement in urban traffic flow offers a significant potential for reducing fuel consumption. Although savings up to 35 percent are possible, specific effect of designated traffic improvement measures has not been investigated here. In a companion study, the effect of alternative traffic management policies on vehicle delay and the probability of stopping at a signalised intersection is being evaluated. This would be linked to the fuel consumption model discussed in this study to determine the fuel savings that are likely to result from specific policies

In summary, the usefulness of the fuel consumption model in evaluating the effect of the various fuel conservation options has been demonstrated. The model needs further refinement in certain areas, the most important being the calculation of fuel flow rate for any engine size and configuration for all values of engine torque and engine speed. Furthermore, the model needs to be linked to the traffic simulation model which is being developed in a parallel study. This will enable the evaluation of specific traffic improvement policies with the objective of fuel conservation in automobiles.

ACKNOWLEDGEMENTS

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