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ABSTRACT

The work described here was undertaken within the context of a research project whose main aim is the modelling of area-wide effects of traffic management measures through traffic flow simulation and assignment techniques. Given that fuel conservation is an objective of national importance, it was thought that a tool which is to be used in the evaluation of traffic management schemes should include fuel consumption as one of the performance measures.

Relationships between fuel consumption under urban driving conditions and the inverse of average travel speed have been inferred from experimental tests. These results, as well as those obtained from computer simulation of traffic flow and vehicle performance, are discussed and a relationship which gives urban fuel consumption as a function of journey distance, total delayed time and the number of stops is put forward for the 'average urban passenger car' in the U.K. Possible refinements to this formulation are discussed.

The role that traffic management measures can play in energy conservation is placed in perspective by looking briefly at the national and urban fuel consumption patterns. A review of reported potential fuel savings from traffic management measures is also undertaken. The fuel consumption consequences of changing the common cycle time for a co-ordinated system of signalised intersections are shown using data from Liverpool City Centre and the SATURN traffic simulation/assignment model.

CONTENTS

1. INTRODUCTION

It is often suggested that the use of the private motor car in urban areas at peak times is wasteful of scarce energy resources and should therefore be discouraged subject to economic and political constraints. To achieve energy savings in the transport sector a number of different strategies have been put forward. The main aims of such policies are to reduce (or modify) demand or to improve the efficiency of the supply - both the vehicles and the road system. It is important that we are able to predict the consequences of proposed energy conservation policies so as to assess their merits objectively and avoid making exaggerated claims.

The work described here is concerned with the development of a predictive model of car fuel consumption in urban areas. Section 3 reviews the work undertaken in this context both in the U.K. and abroad and puts forward some suggestions for improving on existing model formulations.

The likely impacts of energy saving policies are discussed in Sections 2 and 4. In the former an attempt is made to bring together a number of U.K. energy consumption statistics so that the urban component can be seen within an overall context. Section 4 deals more specifically with the fuel consumption consequences of traffic management policies by reviewing relevant literature on the subject. As an example, the effect of changing signal cycle times on fuel consumption is illustrated by means of the SATURN traffic simulation and assignment model.

2. FUEL CONSERVATION POLICIES

The reduction of fuel consumption in congested urban areas is often seen as an important contributor to lessening the national dependence on oil. This section reviews briefly some of the work done in the area of potential fuel savings in the transport sector. This is done in order that potential savings from urban traffic management policies can be placed in the national transport energy context.

2.1 National and urban consumption

In 1977, 25% of total oil consumed in the U.K. was attributable to the road transport sector.[1] Within the latter, passenger car consumption predominates as can be seen from the following vehicle type consumption percentages for 1977.

Passenger cars	63%
Light goods vehicles	11%
Heavy goods vehicles	20%
Other	6%

The amount of motor fuel consumed in Great Britain by passenger cars was estimated to be some 25,600 million litres in 1976[2]. Leach[3] puts the 1975 UK car consumption on urban roads at 54% of total as can be seen in Table 1.

Table 1. Vehicle kms and fuel consumption by road type* - 1975 (%)

	Motorways	Urban roads	Rural roads
Veh. km.	7.9	49.5	42.6
Fuel	7.8	54.2	38.0

* Source ref. 3, Table 6.15.

If we assume that consumption levels have not changed appreciably since the period 1975-1977, then the present fuel consumption of passenger cars in urban areas (roughly 13600 million litres of fuel) represents 34% of the total road transport consumption and 8.5% of the total U.K. oil consumption.

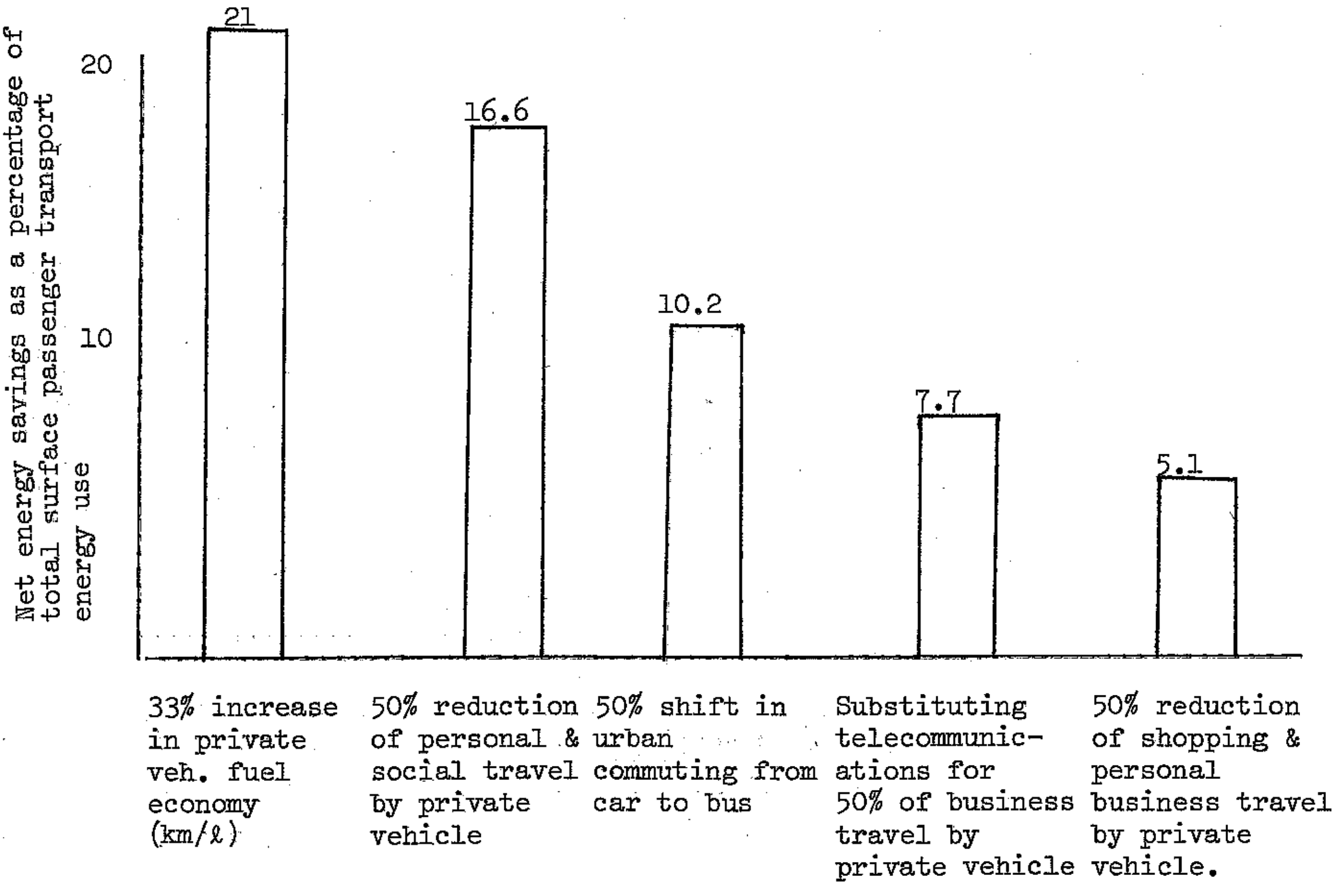
2.2 Possible saving areas

In a 1978 report on policy options for fuel conservation, Maltby et al[4] considered the impact of a wide range of fuel saving policies which included traffic restraint; higher fuel tax; restrictions on urban sprawl; development in telecommunications; curtailment of road investment; car engine size taxation; improvements to public transport service and changes to private vehicle technology. Amongst the criteria used to evaluate these options were the potential savings as well as the possible costs and related effects of each option. Figure 1 shows the net energy savings that would result from a number of different conservation strategies. These results refer to 1972, and are expressed as percentages of total surface passenger transport energy use.

The authors of that report concluded that traffic restraint measures did not appear 'on their own', to be justified if the only objective is to save fuel, since the number of trips affected would be small relative to the total amount of travel by private vehicle.

Still on the same theme, Leach[3] estimated that "if in 1976, bicycle and motorcycle traffic had trebled, and bus and rail passenger traffic doubled - all at the expense of the car - energy use for the U.K. passenger traffic would have been only 11% lower than it was".

Figure 1. Estimated net energy savings from conservation options (Based on 1972 data). Source: ref. 4.



Improvements in vehicle technology seem to offer the most promising prospects for fuel conservation. Not only are the potential savings high, but the financial incentives, in the form of increasing oil prices in real terms, should accelerate technological innovation. A concensus of opinion amongst 'experts' suggests a probable reduction of 40-50% for the average European car in the medium to long term.[3] Waters et al[1] suggest that the new 'average' car could have its fuel consumption in mixed urban and rural driving reduced to less than 60% of the present average. Whilst large achievable reductions have been suggested[5], a 'rough' cost benefit analysis of costs and benefits to users of increasing fuel economy from 30 to 50 m.p.g. was undertaken by Waters et al[1] who concluded that the initial extra cost per car would have to be less than £440 (1979 prices). Their calculations were based on the resource cost of fuel (excluding tax) and assumed a 10-year vehicle life and a 10% discount rate.

Driver education is another area of potential savings. Estimates of possible savings are 'difficult to quantify', although several guesses have been made[1,3]. National fuel savings of 10-15% is one 'informed guess'[1]. Section 3.3 will look in more detail at the relation between fuel consumption and driver behaviour. The potential of traffic management measures to improve urban traffic flow conditions and hence reduce energy consumption will be reviewed under Section 4.

3. ESTIMATING URBAN FUEL CONSUMPTION

The fuel consumption of private cars is obviously dependent on a large number of factors ranging from the vehicle itself to the driver and the specific traffic conditions encountered. For the same route, driver and car, the fuel consumed will be different on different occasions even if traffic conditions and ambient temperature were identical.

However, if an estimate is to be made of the impact of traffic management policies on energy usage, we need to be able to relate consumption to those traffic flow attributes which can be either measured or predicted. Several attempts at establishing such relationships are reviewed in this Section. A 'first stab' is also made at producing an equation which relates fuel consumption for the 'average urban car' to delays experienced and number of stops made during a journey.

3.1 Vehicle effects

Vehicle weight and engine size are the most important factors determining fuel consumption. Everall[6] found consumption to be related to engine size* by the equation:

$$F = 6.149 + 0.003011\,C \quad ..... \quad (1)$$

where

F = fuel consumption in rural and urban driving conditions in ℓ/100 km.

and

C = engine capacity in cubic centimetres (c.c.).

Table 2 illustrates the changes in engine size patterns that have taken place since 1966. Both the lower (< 1200 cc) and upper (> 2000 cc) have declined although it is the lower end which has experienced the major shift in favour of the medium-sized engines.

Table 2. Percentage cars licensed by engine size

	% licensed vehicles							
Engine capacity	1966		1970		1974		1976	
(c.c.)								
< 1000	29.9	55.2	25.0	50.9	17.8	39.2	15.8	34.9
1000 - 1200	25.3		25.9		21.4		19.1	
1200 - 1500	15.2	34.4	18.3	41.2	24.4	53.3	27.1	57.0
1500 - 2000	19.2		22.9		28.9		29.9	
2000 - 2500	3.9	10.4	2.2	7.8	2.7	7.4	2.9	7.3
> 2500	6.5		5.6		4.7		4.4	

Source: Transport Statistics Great Britain 1966-1976.

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* Engine size produced better results than either power or power/weight ratio.

Reductions in vehicle mass have been found in TRRL tests[1] to produce large savings in fuel consumption particularly in urban congested conditions. Under such conditions a 20% reduction in mass has produced a 6% saving in fuel. For steady speed rural driving the same saving in mass resulted in a 4% saving in fuel consumed.

There are other aspects of vehicle design which can influence fuel efficiency. Reference 3 discusses the potential fuel savings for passenger cars under several vehicle design headings. The following estimates are given.:

	% fuel saving
Aerodynamic drag	5 - 6
Tyre drag and inflation	2 - 2.5
Electronic controls	3 - 7
Engine design	20

3.2 Traffic flow effects

Several workers have reported on the effects of traffic flow characteristics, such as average speed, travel time, delay and number of stops, on fuel consumption. Essentially there seems to be two approaches to the estimation of fuel consumption, namely:-

(a) Fuel consumption per unit distance expressed as a linear function of total travel time. (References 6 to 17)

or

(b) the inclusion of delayed time and number of stops in the estimation of fuel consumption. (References 18 to 24).

These two approaches will now be reviewed in turn.

3.2.1 The simple approach

Early work in Central London undertaken by TRRL[6] with two test cars - a Vauxhall Viva (1057 cc) and a Ford Zephyr (1703 cc) indicated a linear relationship between fuel consumption and the inverse of average speed (i.e. average journey time per unit distance). The results are shown in Figure 2. The relations obtained for Central London were:

(a) 1053 cc car

$$F = 0.0565 + \frac{1.159}{V} \qquad (3)$$

and

(b) 1703 cc car

$$F = 0.0850 + \frac{1.913}{V} \qquad (4)$$

where F = fuel consumption in l/km
and V = average speed in km/h.

These relationships apply for average speeds in the range of 10 to 58 km/hr.

Interpolating from these two equations for the 'average urban car' - with an engine capacity of 1446 ccs (see Appendix A) we obtain the following equation:

$$F = 0.0723 + \frac{1.590}{V} \qquad (5)$$

where F and V are defined as before.

Fuel consumption tests were also carried out on other road types such as rural roads and motorways. The variation of fuel consumption of the average car* with speed is reproduced in Figure 2. The latter shows that fuel consumption is lowest when average speeds are in the range 50 - 70 km/h. For the same average speed 10 - 20% less fuel is used on motorways than on all purpose roads whilst in the latter, at average speeds around 100 km/h, cars consume 15% more fuel than at minimum consumption speeds. Another finding of this study is that gradients of up to 3% do not appear to significantly affect fuel consumption if averages are taken over both up and down gradients.

Some more recent work undertaken in the U.S.[7, 8, 9, 10, 11, 12, 13] and Australia[15, 16] has been reported in which fuel consumption, (F), has been expressed in terms of distance travelled, (D), and total time taken (T), (including stopped time). A relationship of the form:-

$$F = k_1 + k_2 \frac{T}{D} \qquad (6)$$

has been established using regression analysis with fuel consumption being either measured or simulated. Chang et al[7] have put forward a physical interpretation for the coefficients k_1 and k_2 by analysing data from several sources. The authors found k_1 to be approximately proportional to the mass of the vehicle and hence to rolling resistance. k_1 can therefore be said to represent the fuel consumed per unit distance to overcome rolling resistance. k_2 was found to be approximately proportional to the idle fuel flow rate and can be said to represent the fuel

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* In 1966 the average U.K registered car was estimated to have an engine capacity of 1346 ccs. The average of the two test cars lies close to this national average and was therefore taken to represent the average passenger car at that time.

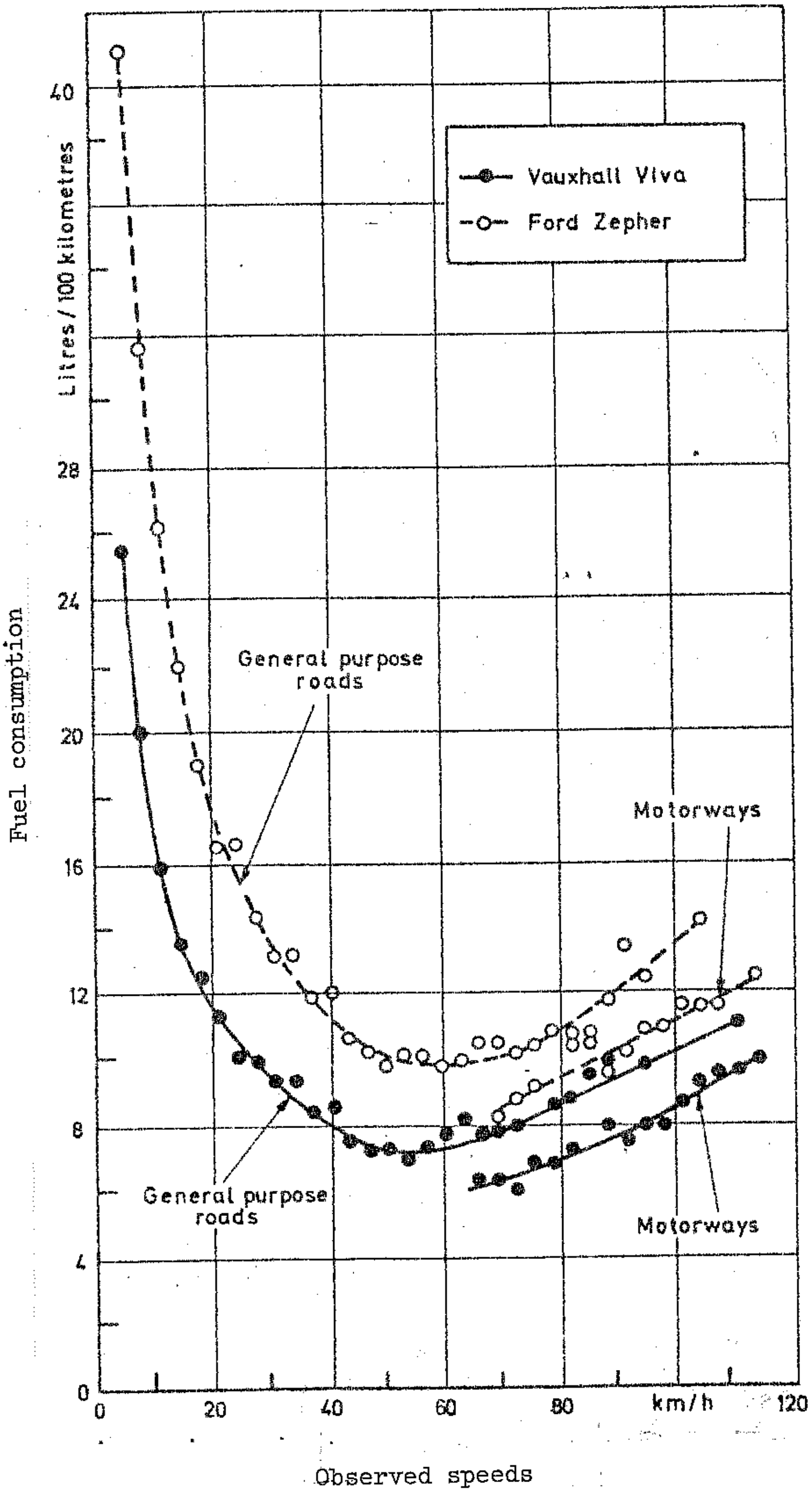
consumed per unit distance to overcome mechanical losses.

Table 3 below gives values of k_1 and k_2 reported in the literature. In general these results were found to hold for average trip speeds under 60 kph.

Table 3. Fuel consumption model coefficients (The simple approach)

Reference	Vehicle	Year	k_1 (ℓ/km)	k_2 (ℓ/hour)
6	Small British (1053 cc)	1965	0.0565	1.159
6	Medium British (1703 cc)	1964	0.0850	1.913
7	Standard-American (6600 cc)	1974	0.1116	3.762
7	Large-Luxury American	1974	0.1218	3.902
16	Australian		0.0940	2.457
17	Australian Station-wagon	1965	0.0621	2.142

Figure 2. The overall fuel consumption of cars



Source: Ref. 6.

3.2.2 An alternative model

The fuel consumption model described in the previous section is said to be deficient, in the context of urban traffic management evaluation, since it does not take explicit account of the effect of acceleration/deceleration cycles under congested driving conditions. We can have the situation where the same total travel time is taken to travel a given distance on two different runs although the number of stops made may be different. As far as fuel consumption is concerned it clearly matters whether one's time is spent idling in a queue or decelerating to and accelerating from a stopped position.

A number of researchers have highlighted this problem[14, 17, 18, 19] and models which take direct account of the number of stops have been proposed. Such models usually take into account three seperate elements of an urban trip, namely:-

(1) Distance travelled at cruising speed (D)
(2) The amount of stopped time (T_s)
(3) The number of stops made (S)

Fuel consumption, F, is thus expressed as:-

$$F = a_1 D + a_2 T_s + a_3 S \qquad (7)$$

where:- a_1 = fuel consumed at steady cruising speeds.
a_2 = Idle fuel flow rate
a_3 = Excess fuel per complete stop.

Unlike the statistically determined coefficients of equation (6), values for a_1, a_2 and a_3 can be experimentally obtained for any test vehicle. Values for a_3 have been obtained by Claffey [20, 21] for a number of different test vehicles. This coefficient represents the difference between the fuel consumed during a complete stop-go cycle and that fuel which would be consumed if the same distance was travelled at cruising speed. The time spent stopped is not included here since it is already allowed for under the second term of the equation.

The most commonly used traffic simulation models such as TRANSYT[25] estimate total delay experienced. This includes not only the stopped time but also the delays associated with each stop. Therefore, if the results of such models are to be used to estimate fuel consumption it is necessary to adjust equation (7).

Figure 3 shows as an example the time-distance diagram for a vehicle which stops once at a signalised junction. The total stopped time, T_s, in this case is given by:-

$$T_s = T_{Del} - \frac{V_c}{2} \left(\frac{1}{s_1} + \frac{1}{s_2}\right) S \qquad (8)$$

(Note: Capital T is used throughout to denote the summation, for the corresponding values of small t, over all vehicles.)

S = the total number of stops made in the manner illustrated by Fig 3, i.e. from a cruising speed $V = V_c$, to $V = 0$ and back to $V = V_c$.

V_c = cruising speed.

and s_1 and s_2 are the deceleration and acceleration rates which are both assumed constant and positive.

If we make the further simplifying assumption that $s_1 = s_2 = s$, then (8) becomes:-

$$T_s = T_{Del} - \frac{V_c}{s} S \qquad (9)$$

From equations (7) and (9) we have:

$$F = a_1 D + a_2 (T_{Del} - \frac{V_c}{s} S) + a_3 S \qquad (10)$$

or $$F = a_1 D + a_2 T_{Del} + (a_3 - \frac{V_c}{s} a_2) S \qquad (11)$$

Akcelik[18] has derived such an expression and used it in conjunction with fuel consumption estimates from TRANSYT[25] results. To the author's knowledge, the correction implied by equation (11) to take account of the difference between total and stopped delay has only been incorporated in the work reported in references 18 and 27.

Table 4 shows some of the results found in the literature for the coefficients of the type of model described earlier.

Table 4. Fuel consumption model coefficients - stops included

Reference	a_1 (ℓ/km)	a_2 (ℓ/hr)	a_3 (ℓ/stop)
18	0.10	2.200	0.040
19	-	2.270	0.038
20,21	0.110	2.385	0.048
22	-	1.893	0.126
26	0.112	2.366	0.025
27	0.100	1.500	0.008*

* This value for a_3 includes the adjustment for total delay discussed in this section.

Robertson et al[27] have recently put forward an expression for fuel consumption to be used with the TRANSYT signal optimisation program. This expression, whose coefficients are shown in Table 4, was obtained from experiments on a TRRL test track using a 2200 cc saloon car with automatic transmission. Reference 27 quotes values for the "adjusted' stops coefficient for three different cruising speeds. It was found that this coefficient is highly sensitive to cruising speed as the results below illustrate:-

Cruising speed (k/hr.)	Excess fuel, (a_3, adjusted for total delay) (ℓ/stop)
32.3	0,0063
41.4	0,0094
52.0	0,0141

3.2.3 SATURN fuel consumption estimation

A 'provisional' fuel consumption model has been incorporated in SATURN[30,31] - a traffic simulation and assignment model developed at the Institute for Transport Studies at Leeds University. At the present time this equation takes the form of equation (11):-

$$F = a_1D + a_2T_{Del} + K\,S_1 \qquad (12)$$

Where $K = a_3 - \frac{V_c}{s} a_2$

S_1 = number of first time stops at junctions[32] and other notation as before.

The coefficient for fuel consumption at cruising speed, a_1, was derived by interpolating between two values given by motor manufacturers for a small car (1059cc) and a medium sized car (1703 cc). The values given for fuel consumption at a steady speed of 60 km/hr are 6.0 ℓ/100 kms. and 8.4 ℓ/100 kms respectively. This represents a value of a_1 of 0.074 ℓ/km for the average urban car with an engine capacity of 1446 cc, (as estimated in Appendix A).

The idle fuel flow rate, a_2, was estimated to be 1.4 ℓ/hour of delay for the same engine size (1446 cc). This was inferred from the corresponding value of a smaller car (1180 cc) given by Claffey[20], and assumes that idle flow rate is directly proportional to engine capacity.

The excess fuel consumed per first time stop, a_3, was estimated again from Claffey's work in this area. The following data was obtained from reference 20.

Idle fuel flow rate (mℓ/sec)	a_3 (mℓ. of fuel/stop)
0,80	43.6
0,61	37.0

If we assume that the extra fuel consumed to accelerate from a stop is approximately proportional to engine size and idle fuel flow rate, we obtain a value for a_3 of 29 ml of fuel per stop.* If a cruising speed of 60km/hr and a constant acceleration rate of 1.1 m/s^2[18] are assumed, then equation (19) becomes:-

$$F = 0{,}074D + 1{,}4\ T_{Del} + 0{,}023\ S_1 \quad \ldots\ldots \qquad (13)$$

This is the equation presently used in SATURN to calculate fuel consumption. It is hoped to 'refine' the coefficients shown here and to include subsequent stops as discussed in Section 3.2.5.

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* Experiments reported in reference 24 indicate a value for a_3 of approximately 25 ml/stop. (40 km/hr cruising speed with vehicles in the 1500 cc to 2000 cc range).

3.2.4 Comparing the two models

The two approaches put forward for the estimation of fuel consumption were compared using the results from a run of SATURN with data from Liverpool City Centre, (where the model is currently being applied).

Equation (5), i.e. the 'simple approach', and equation (13) were used with the following data:-

Total number of vehicle trips = 14103
Total distance travelled (D) = 16355 veh. kms/hr
Total delayed time (T_{Del}) = 618.7 veh. hrs/hr
Total travel time (T) = 862.7 veh. hrs/hr
Average speed = 19 kms/hr
Average trip distance = 1.16 km
Total number of first stops = 35998
Total number of stops = 99623

The fuel consumption results are shown below:

	Fuel consumed ℓ/hr	Consumption rate ℓ/100km (mpg)
Simple approach (equation (5))	2551	15.6 (18.1)
Alternative model (equation (13))	2910	17.8 (15.9)

It should be stressed that the particular set of data on which this comparison was made does not reflect existing conditions in Liverpool City Centre completely satisfactorily. Final calibration of SATURN is still being carried out and the results shown above represent an intermediate stage of that calibration process. Nevertheless peak flow conditions illustrated above - 19 kph average speed, and 2.2 stops/veh.km seem to be fairly reasonable[33]. From the results shown above, the simple approach represented by equation (5) under-estimates the total fuel consumed by 12% relative to the alternative model which includes first stops. Since, as discussed in Section 3.2.5, this alternative formulation is itself deficient in its omission of partial and multiple stops, a simple expression such as equation (5) may misrepresent fuel consumption considerably.

3.2.5 Possible refinements to the SATURN expression

Most traffic simulation models and analytical expressions for the calculation of the number of stops do not deal with multiple stops at a junction[25, 28, 29]. These methods usually measure the proportion of stopped vehciles and the fact that some may stop more than once is ignored. This omission becomes important in peak time urban congested conditions where flows are at or near capacity.

An analytical expression to calculate the total number of stops at undersaturated intersections has been put forward which accounts for the random nature of arrivals at a junction[28]. The value of the average queue unable to clear at the end of the green period is used to calculate a random component of the stop rate (number of stops per vehicle). The estimation of the total number of stops as opposed to first time stops only, becomes important when we consider not only fuel consumption but also other vehicle operating costs, air pollution, safety and driver annoyance. A more accurate expression for the calculation of fuel consumption can be obtained by the inclusion of all stops made by a vehicle at a junction as illustrated in figure 4.

The coefficient a_3 in equation (7) - i.e. the excess fuel per complete stop - will vary with initial and final speeds, as well as deceleration and acceleration rates. That is, a_3 will be different for different kinds of stops. Whether the accuracy of inputs and the purpose to which the final fuel consumption estimates are put justify this disaggregations of stops by type, depends on the improvement that results from its inclusion.

One possible approach would be to consider average values of a_3 for two cases:

(1) The excess fuel consumed when a vehicle decelerates from an average cruising speed to a stop and accelerates back to the same average cruising speed (which will continue to be referred to as a_3).

and

(2) the excess fuel consumed by the average subsequent stop after the first. This will be referred to as a'_3 and represents the excess fuel consumed when a vehicle accelerates from a stop to a low speed and decelerates back to a stop.

Referring to Figure 4 we have:

$$t_s^1 + t_s^2 = t_{Del} - \tfrac{1}{2}\left[(t_d^1 + t_a^1) + (t_d^2 + t_a^2)\right] \qquad (14)$$

where all notation is as before.

Making the assumption of constant and equal average acceleration and deceleration rates, (if this proves in practice to be unjustified, individual average rates should be used), equation (11) can be written as:

$$F \;=\; a_1 D + a_2 T_{Del} + S_1(a_3 - T_1 a_2) + S_2(a_3' - T_2 a_2) \qquad (15)$$

where S_1 = total number of first time stops at a junction, summed over all junctions and all vehicles.

S_2 = total number of subsequent stops.

T_1 = average time taken to decelerate from a cruising speed to a stop and back to cruising speed (= $\frac{V_c}{s}$).

T_2 = average time taken to accelerate from a stopped position to a low average speed and decelerate back to a full stop.

The question that must be asked at this stage is what are the errors involved if multiple stops are not taken into account. Let us consider two cases:

(i) Only first time stops at a junction are included.

In this case the error, Δ_1, is given by the difference between equations (11) and (15) as:-

$$\Delta_1 \;=\; S_2(a_3' - T_2 a_2) \qquad (16)$$

Clearly this is significant under congested urban conditions (S_2 large) if a_3' is considerably larger than $T_2 a_2$. Consider as an example (which might not be very representative), the following values:

$a_2 \;=\; 1.4$ ℓ/hr.

$T_2 \;=\; \frac{T_1}{2} \;=\; 6$ sec.

$a_3 \;=\; 0{,}029$ ℓ/first stop

and $a_3' \;=\; \frac{a_3}{3}$

With such values an error of the order of 0,0073 litres per multiple stop omitted would apply. If we now take the same example as used in the previous section to compare the two models we have:-

$$S_2 = 63625 \text{ multiple stops/hr.}$$

and $\Delta_1 = 464.5$ litres.

This represents around 15% of the original value of total fuel consumed per hour.

(ii) All stops are included but treated equally (i.e. $a_3 = a_3'$). The error involved here Δ_2 is given by:-

$$\Delta_2 = S_2 \left[(a_3' - T_2 a_2) - (a_3 - T_1 a_2) \right]$$

$$\text{or} \quad \Delta_2 = S_2 = S_2 \left[a_2(T_1 - T_2) - (a_3 - a_3') \right] \qquad (17)$$

Using the values from the example given above we obtain an error (in this case an overestimate) of the order of 0,017 ℓ per multiple stop. Such an error could result in an overestimate of total fuel consumption of around 37% in the specific case illustrated in the previous section. It should be stressed that the values assumed here for the various variables may not be very typical of average conditions. These results should therefore be seen as illustrative of the type of sensitivity analysis that needs to be carried out.

So far the effect of slowdowns, as opposed to complete stops, has not been considered in the calculation of fuel consumption. Such effects cannot be ignored if congested conditions are being modelled. Figure 5 shows the distance vs. time diagrams for a vehicle which slows down just before a stop line.

$$F = a_1 D + a_2 T_{Del} + S_1(a_3 - T_1 a_2) + S_2(a_3' - T_2 a_2) + S_3 (a_3'' - T_3 a_2) \qquad (18)$$

where S_3 = total number of slowdowns

a_3'' = average excess fuel consumed due to a slowdown

T_3 = average delay experience as a result of a slowdown.

Figure 3. Time vs. distance diagram: single stop.

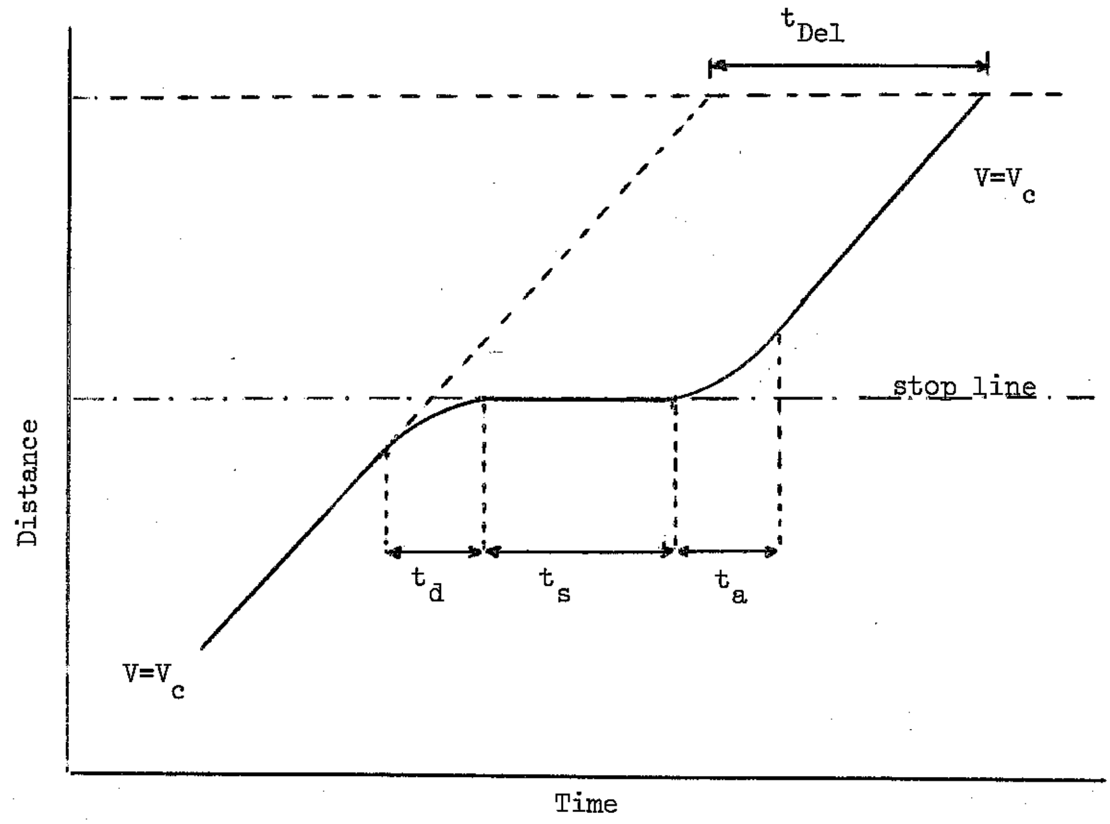
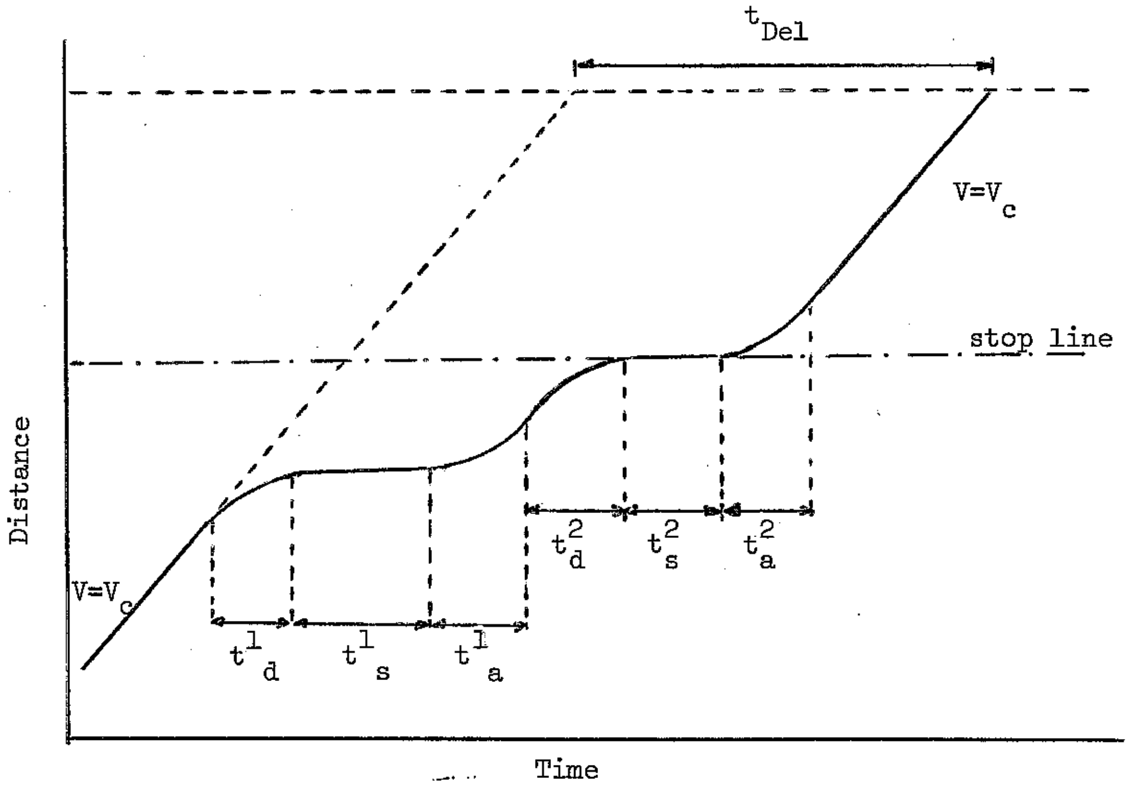


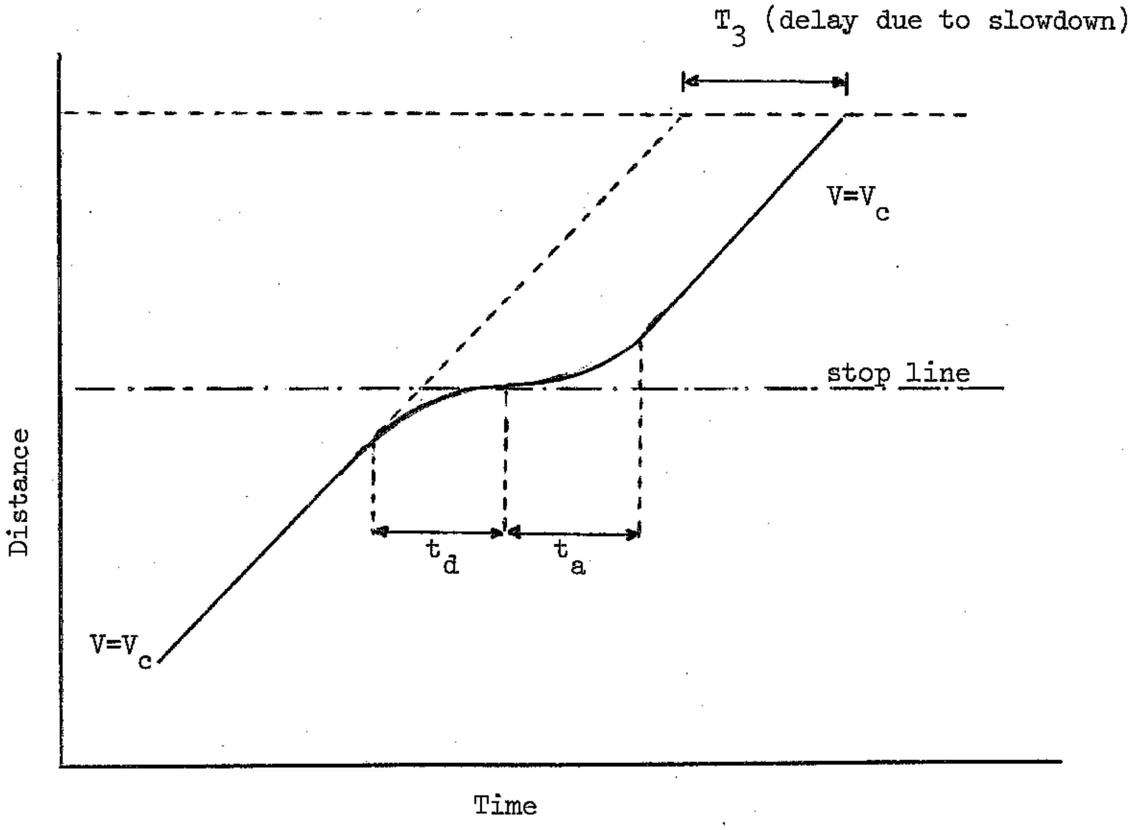
Figure 4. Time vs. distance diagram: multiple stops



The correction is necessary since T_3 is included as part of the total delay in the simulation of traffic flow.

The inclusion of multiple stops and slowdowns in fuel consumption modelling clearly calls for an experimental approach to find average values for the coefficients involved. It would appear worthwhile to conduct some sensitivity work to determine the importance of such variables since very little research has been reported.

Figure 5. Time - distance diagram: slowdown at a stop-line



3.3 Other effects

Clearly vehicle and traffic flow characteristics are not the only variables influencing fuel consumption. Not surprisingly, the behaviour of drivers has been found to affect consumption markedly. These effects and the influence of engine and ambient temperature are now reviewed.

3.3.1 Driver behaviour

The results of experimental tests undertaken to determine the effects of driver behaviour on fuel consumption have been reported by T.R.R.L.[1,6] and General Motors[34]. In each case several drivers were asked to drive the same test car, over the same route, under different sets of driving instructions. The latter included:- driving normally, driving as fast as possible; as cautiously as possible; minimising fuel consumption and using hard acceleration.

The results reported by T.R.R.L.[1] show the variation in fuel consumption between drivers and for the same driver over different test runs. Although these tests were undertaken under somewhat artificial traffic flow conditions - no other traffic was present in the 2,6 km test route - they point to large differences between the least and most economical driver when all nine drivers were asked to drive normally (with the least economical consuming 1.5 times the amount of the more fuel conscious). Individual drivers, when asked to drive ten times over the same route, showed quite large inconsistencies which ranged from ± 1.4% to ± 14% of their average fuel consumption.

The results from Everall[6] show fuel consumption to be approximately 12% greater than normal when driving fast and 2% less when driving economically. The same author also reports on the effects of 'hard' acceleration rates, i.e. 'heavy-footed' driving. It was calculated that 'gentle' acceleration and braking results in reductions in fuel consumption of one half of the 'hard'case, (with an associated increase in travel time of 57%). Similar results were reported by Evans[34] who had this advice to give to urban drivers:-

"1) Anticipate conditions ahead so that braking is minimized. Do not accelerate to a higher speed than required if you must later slow down or stop. Every time the brakes are applied, energy previously extracted from the fuel is unproductively dissipated.

2) Avoid stopped delays. Fuel used idling when the vehicle is stopped is of great importance in urban driving. Also, after the stop, the lost kinetic energy must be restored. It has been estimated that a driver who stops, idles for 30s. while waiting for a light to change, and accelerates to resume a speed of 60 km/h uses about 70 ml. more fuel than a driver who passes through the signal at a constant speed of 60 km/h.

3) Use low acceleration levels, unless a higher level will contribute to achieving actions 1 or 2, as in, for example, accelerating briskly up to the speed limit to make a traffic light."

Evans also reported on some interesting results as far as changes in urban fuel consumption with average speed are concerned. When the average speed of the traffic stream increases, the fuel consumption of those drivers who drive with the traffic decreases. However, if a driver increases his own average speed above that of the traffic stream, his fuel consumption will increase. These results were obtained for average speeds of 40 kph to 50 kph. For much lower speeds it becomes difficult (if not impossible) for drivers to change their behaviour.

The relationship between the behaviour of individual drivers and the total fuel consumed in an urban area has not been studied in great detail. What would happen to total fuel consumption if all drivers tried to minimise their own fuel consumption by following the kind of advice given above? In such a situation, the overall average speed might well decrease due to the 'gentle' acceleration rates of those drivers at the head of queues. This downward effect on average speeds would be opposed by other tendencies such as the avoidance of stops. At present little seems to be known about the system effects of individual actions in this respect.

Another aspect that needs to be considered is the implication of such energy saving actions by drivers on other planning objectives. The operational efficiency of the road system, for example, could be adversely affected if fuel economy were to be pursued at the expense of reductions in effective junction capacities in over-saturated conditions.

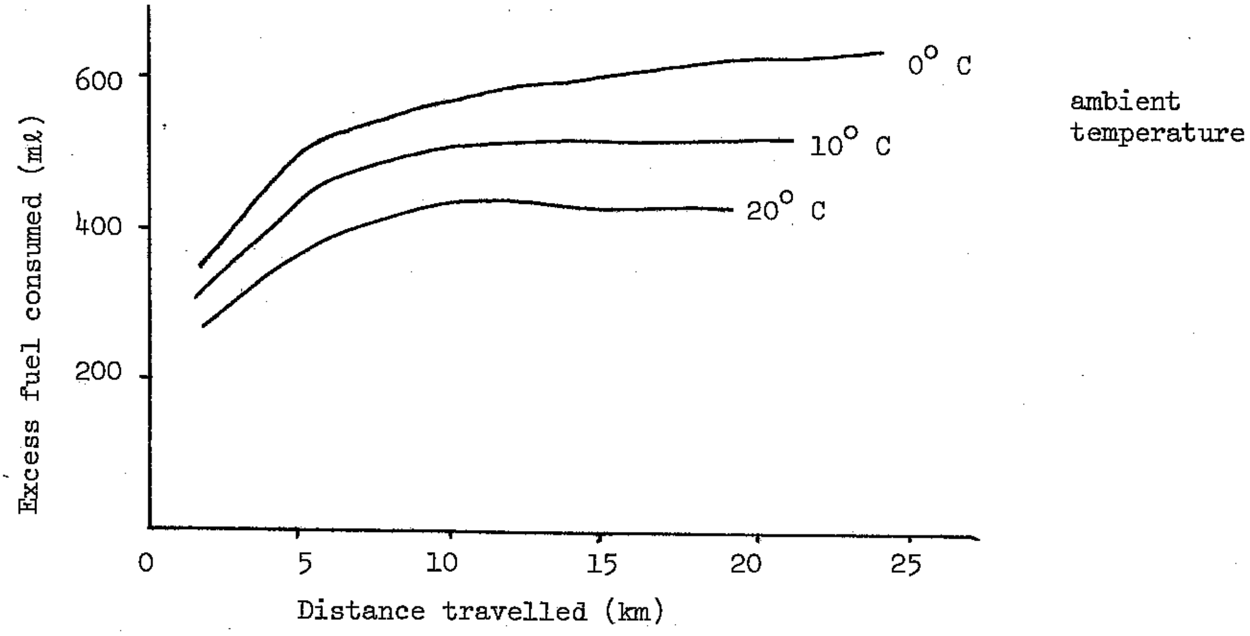
3.3.2 Engine temperature

Vehicle fuel consumption rates are usually quoted from the results of tests carried out with the engine fully warmed. The coefficients of equations (5) and (13), for example, do not take into account the fact that extra fuel is consumed if the engine is started from cold. This extra fuel is a function of ambient temperature as shown in Figure 6. The latter is reproduced here from the results reported by Chang et al[7].

Tests on the effects of cold starting have been undertaken by T.R.R.L. and are reported in References 1 and 35. The results indicate that the fuel economy obtained when starting from cold is only about half of the fully warmed up value for a one mile trip. For a two miles trip, 60% extra fuel is consumed under cold starting conditions. The test car used was a Ford Escort and the ambient temperature was approximately 21°C.

Figure 6. Excess fuel due to cold start vs distance travelled

Source: Ref. 7.



4. TRAFFIC MANAGEMENT AND FUEL SAVINGS

4.1 General

There are several ways in which traffic management measures can save fuel, although the likely impact of individual measures on fuel consumption is difficult to quantify at the aggregate national level. Some of the work reported at both local and aggregate level will now be reviewed.

Gross[36] has reported on the likely net savings in energy, (i.e energy savings subtracted from energy costs) from traffic management schemes undertaken in the State of New York. A total of 33 measures were identified and the energy savings and costs calculated. It was found that the following measures showed the largest likely net energy gains:

a) Traffic operational improvements
b) Carpooling activities
c) Amenities for public transport passengers
d) Area traffic control systems.

Amongst the net energy losers were:-

a) Bicycle facilities
b) Pedestrian facilities
c) Car restricted zones
d) Express bus services
e) Demand responsive public transport
f) Improved public transport monitoring.

Clearly the results of this study reflect the nature of local projects analysed and generalisations will certainly be dangerous. However some of the conclusions seemd to be borne out by other work in this field. In a U.S. study[37] of a 2km section of an urban arterial street, it was estimated that some 18% reduction in fuel consumption would result from the introduction of linked signal settings. (The section had 9 signal controlled intersections and 8 priority junctions).

A very detailed model of traffic flow and vehicle fuel consumption was used to evaluate the potential fuel savings from traffic signal optimisation techniques such as TRANSYT[25] and SIGOP[38], on a portion of Washington CBD[39]. The results showed an improvement of some 25% in fuel consumption. Another study which used traffic simulation techniques found that if the average traffic speed in the New York CBD could be increased, through traffic engineering measures, from the present 16 km/h to 20 km/h, fuel consumption would decrease by about 14%.

Messenger et al[14] have reported on the fuel consumption effects of implementing two different signal timing plans in a test route of 2.8 km of a Toronto suburban street. The route experiences little congestion throughout the day and the existing signal timing plan is derived from the SIGRID off-line optimisation program[40]. Against this base, a plan derived from TRANSYT[25] was tested. Fuel consumption calculations were undertaken using a vehicle simulator program[43] which calculates fuel consumption by means of velocity profiles and vehicle characteristics.[41] It was found that the TRANSYT plan performed better than the existing plan to the extent shown below:-

- delay	40.4%
- stops	34.5%
- total travel time	12.4%
- fuel consumption	2.2%

In the U.K., an authoritative source[27], has suggested a 'rule-of-thumb' for urban traffic management which equates a 10% reduction in journey times with a 6% to 8% saving in fuel consumed. However, reductions in total system delays do not necessarily mean less fuel consumed. Experiments conducted in Glasgow by the T.R.R.L, using the TRANSYT SIGNAL optimisation program, indicated that minimising stops as opposed to minimising total delay resulted in overall fuel savings of about 3% with no detectable difference in journey times[27]. As seen in the previous section, traffic flow 'smoothness', i.e. the absence of speed changes and large number of stops, significantly improves fuel consumption in urban traffic conditions. It has been estimated in the same Glasgow study that the test car engine was idling for 40% of the time consuming 18% of the total fuel in the process.

Bayliss and Wright[42] have evaluated the potential impact of several traffic management measures on energy conservation in the U.K. road transport sector. Table 5 gives a summary of the conclusions reported by those authors. The energy savings shown were calculated as percentages of the current road transport energy consumption.

The values shown in Table 5 'generally relate to Metropolitan areas but more specifically to London'. An account of the basic assumptions made is given in reference 42 and is essential to fully qualify the results.

Table 5. Energy savings from traffic management measures.
(Source: Reference 42.)

Measure	Traffic Effect leading to energy saving	Energy Saving	Comments
UTC	10-20% average speed increase	2-5%	easy to implement and cost effective
Traffic Signal Control		<1%	as above but limited in extent
Speed limited	Maximum speed 50 kmh	up to 8%	maximum saving requires very stringent control
Parking control	Traffic restraint and eased congestion	5%	base is uncontrolled situation
Area Licensing	Traffic restraint	2%	difficult to introduce
Car pooling	Reduced vehicle kms	½%	greater potential exists
Bus priorities	Transfer from private vehicle	2%	very variable
Pedestrian and cycle facilities	Transfer from private vehicle	3%	difficult to introduce and evaluate
Streetlighting			very variable

4.2 Signal cycle time and fuel consumption

The more specific relationship between the total fuel consumed and the area-wide signal cycle time will now be looked at. The evidence that has been put forward on this relationship will be compared with some preliminary results obtained when the fuel consumption equations developed in Section 3 were applied to data from a Liverpool City Centre Study.

According to the findings of Bauer[22] for an isolated intersection, the cycle length at which fuel consumption is minimised is longer than that which minimizes delay. Courage and Parapar[19] have also reported similar results on the effect of cycle time on delay and fuel consumption.

On the other hand, the work of Cohen and Euler[43] suggests that fuel consumption and delay are minimised at approximately the same cycle length. The results reported in reference 43 also indicates that the number of stops may increase with cycle length. This is in contrast with the expression for stops put forward by Webster[29] which predicts that the number of stops decreases with cycle length. These results were obtained using a microscopic network simulation model (NETSIM)[44], which takes into account the effect of a vehicle slowing down without coming to a complete stop as well as multiple stops. NETSIM also accounts for the fact that acceleration patterns will vary with a vehicle position in the queue. The discrepancies between these latter findings[43] and those of references 19 and 22 have been attributed to the very much more detailed nature of the models used by Cohen and Euler.

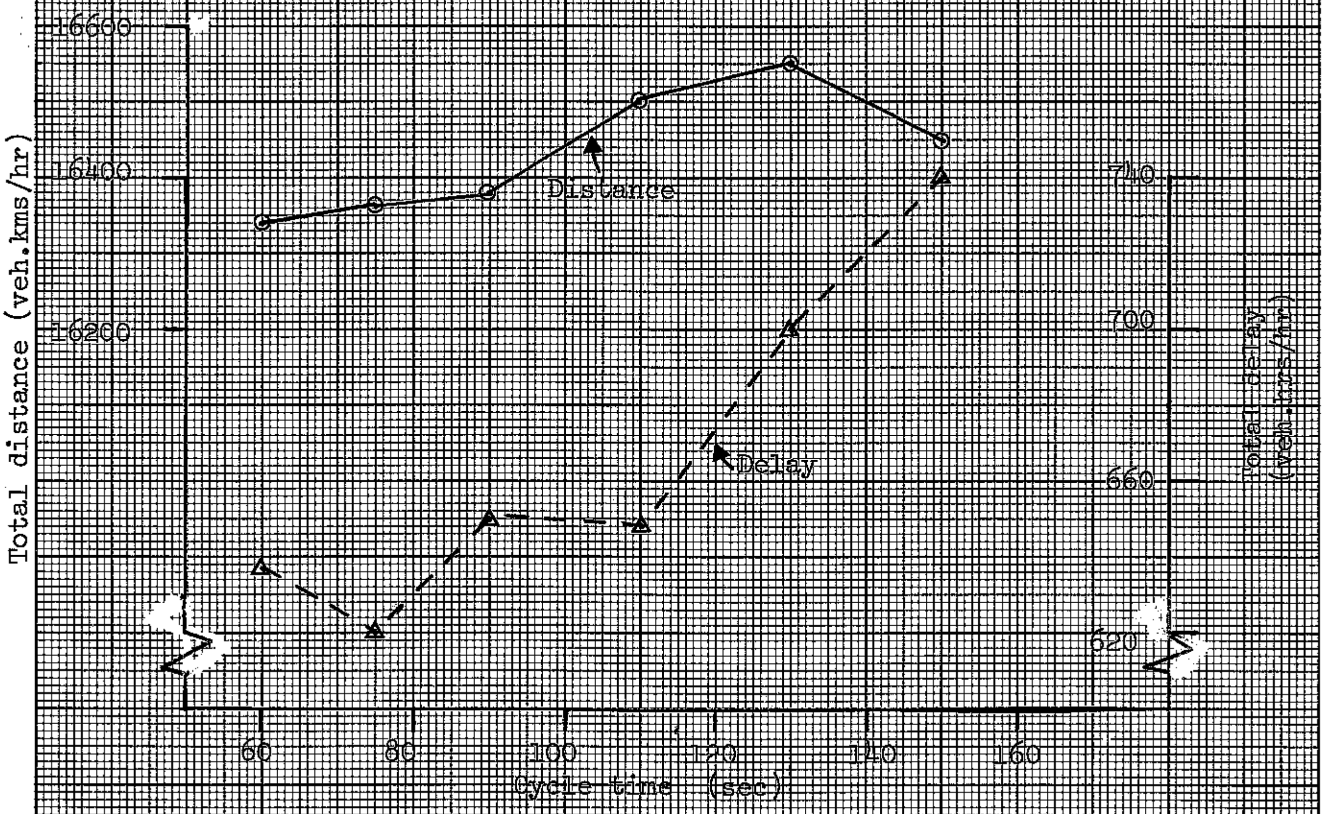
The sensitivity of several traffic flow parameters to signal cycle time changes has been investigated in connection with the application of SATURN to a study of traffic management options in Liverpool City Centre. This study is being undertaken jointly by Leeds University and Merseyside County Council. At the present time, the network being used comprises 57 intersections of which 26 are signalised and the remainder are priority type junctions. A co-ordinated plan with a 75 second cycle time is in operation throughout most of the 37 zone study area, for the time period of interest here - the one-hour evening peak. Calibration of the model, although not yet finalised, has reached a stage which has made feasible sensitivity testing of signal cycle timing strategies. Some of the results of such tests can be seen in Table 6 and Figure 7.

Table 6 Signal cycle time and fuel consumption - SATURN results using Liverpool data

Cycle time (sec.)	Total travel distance (veh. kms/hr)	Total travel time (veh. hrs/hr)	Total delayed time (veh. hrs/hr)	Total No. first stops	Fuel consumption	
					Equation(5) (Simple approach) (ℓ/hr)	Equation(13) (including stops) (ℓ/hr)
60	16339	881.0 (18.5)	637.5	35946	2582	2863
75	16355	862.7 (19.0)	618.7	35998	2554	2839
90	16384	897.0 (18.3)	652.3	35026	2611	2866
110	16499	894.5 (18.4)	647.3	35123	2615	2869
130	16545	953.3 (17.4)	705.0	35354	2712	2958
150	16437	988.0 (16.6)	741.9	36247	2759	3023

Figure 7 Signal cycle time sensitivity using SATURN (Liverpool City Centre data)

a) Cycle time vs. total distance travelled and total delay



b) Cycle time vs fuel consumption and stops

As cycle time increases the model predicts increases in total delay. Average trip distances also increase up to a cycle time of 130 seconds as a result of rerouteing by drivers attempting to avoid the more congested junctions. The relationship between the number of first stops at junctions and cycle time follows the delay curve closely, i.e. after an initial decline, (60 sec to 90 sec cycle time range), a steady rise is predicted as shown in Figure 7b. Two sets of fuel consumption estimates are given, based on the two approaches described in Section 3. The simple method, which does not include stops - equation (5) - gives fuel consumption estimates which are 8% to 10% lower than the alternative model represented by equation (20). It is interesting to note that both models predict an increase in total fuel consumed as the cycle time increases.

It should be stressed at this point that only one time period, namely the one-hour evening peak has been considered throughout this analysis.

5. CONCLUSIONS

The contribution that urban traffic management can make to a national energy conservation programme is very limited when compared with other measures such as improvements in vehicle fuel economy. However, it is estimated here that passenger cars in urban areas consumed roughly 13600 million litres of fuel in 1977. This represents some 34% of total road transport consumption and 8.5% of the total U.K. oil consumption.

Therefore the part that traffic management can play in this area should not be too quickly dismissed as insignificant at the national level, although it is understandable if fuel conservation per se does not receive a high priority at the local planning level. Fortunately, important economic and environmental objectives tend to assis fuel conservation and major conflicts are unlikely to arise locally.

If traffic management has a part to play then we need to increase our knowledge of how specific measures affect fuel consumption. With this aim, a model for fuel consumption in U.K. urban conditions is put forward here. Fuel consumption is expressed in terms of distance travelled, delay experienced and the number of stops made. This model follows from a review of work undertaken both in this country and abroad and was developed for incorporation into SATURN, a traffic simulation and assignment model. It should not be seen as the final product but rather as the 'first stab' at a fuel consumption predictive model for U.K. conditions. Suggestions on possible improvements to include multiple stops and slowdowns are also given.

No academic work is complete without some reference to further research needed. Here are therefore, some related areas which, it is felt, are in need of attention:-

1. How does fuel consumption vary with vehicle type under urban congested conditions? Most of the experimental work undertaken has concentrated on passenger cars. Fuel consumption models for heavy commercial vehicles have not been dealt with here. One possible first step in the development of such models - short of conducting experimental test - is the use of data gathered by firms via the tachograph.
2. What are the system-side effects of driver education policies designed to minimise fuel consumption for individual vehicles?
3. If changes in price and/or availablility of fuel altered the political and economic climate, what energy savings could be achieved at national level, in the short term, by means of urban transport management? (Without jeopardising the economic viability of urban areas.)
4. Questions such as those just posed can only be satisfactorily answered if we have confidence in the predictive ability of the fuel consumption expressions used. This in turn leads to three questions (at least!):
    a) To what extent can we believe the output of traffic simulation and assignment models which provide the inputs?
    b) How good are the fuel consumption expressions themselves given such factors as the variability of driver behaviour?
    c) Is it cost effective to develop more sophisticated fuel consumption expressions in terms of the number of explanatory variables given the problems in estimating the latter?

If there is a case for developing more precise fuel consumption expressions, it would seem advisable to undertake experimental tests under urban congested conditions. The co-operation of motor manufacturers should be sought for a supply of both vehicles and expertise.

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APPENDIX A Calculating the engine capacity of the 'average urban car'

The engine capacity of the average car travelling on urban roads is calculated here for 1975 using two sets of data:-

1) The percentage of vehicle-kms and fuel used in urban areas by engine size category. This is shown in Table A1 which also shows the weight given to each engine size category according to its usage of fuel in urban areas.

Table A1. Car traffic and fuel consumption in urban roads 1975

Engine size (cc)	% urban road usage		weight by fuel
	veh. km.	fuel consumed	
< 1000	8	6.6	.162
1000 - 1500	22.3	23.0	.451
1500 - 2000	15.0	17.7	.303
2000 - 3000	2.8	4.2	.057
> 3000	1.4	2.7	.028
	Σ 49.5	Σ 54.2	Σ 1.00

2) The percentage of licensed private cars and vans by engine size for the same year (1975), given by Transport Statistics Great Britain, 1966-1976. This enabled the rather large engine size categories to be further split as shown in Table A2.

Table A2. Private cars and vans by engine size - 1975

Engine size (cc)	% vehicles registered in each sub-category
1000 - 1200	43.9
1200 - 1500	56.1
1000 - 1500	Σ 100.0
1500 - 1800	75.4
1800 - 2000	24.6
1500 - 2000	Σ 100.0
2000 - 2500	57.0
2500 - 3000	43.0
2000 - 3000	Σ 100.0

It is therefore possible to estimate the engine capacity of the 'average car' using urban roads in 1975. This is given by:

$$\overline{C} = 850 \times .162 + \{\, 0.459 \mid 1100 \times .439 + 1350 \times .561 \mid \} +$$

$$+ \{\, 0.303 \mid 1650 \times .754 + 1900 \times .246 \mid \} +$$

$$+ \{\, 0.057 \mid 2225 \times .57 + 2750 \times .43 \mid \} + 3225 \times 0.028$$

$$\text{or } \overline{C} = 1445.6 \text{ cc.}$$