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CAR FUEL CONSUMPTION IN URBAN TRAFFIC. THE RESULTS OF A SURVEY IN LEEDS USING INSTRUMENTED VEHICLES.

by

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ABSTRACT

The work reported here was part of a research project sponsored by the Science and Engineering Research Council to investigate the impact of traffic management schemes on fuel consumption.

The report can be divided conveniently into two parts. In part I, the fuel consumed by a vehicle during each stage of an urban trip is analysed by drawing on the results of past studies as well as the results obtained by the author for a recent survey in Leeds using two instrumented cars supplied by the Transport and Road Research Laboratory. An equation is derived which relates the fuel consumed during a stop/start manoeuvre to the characteristics of that manoeuvre.

Part II deals with the development of two types of urban fuel consumption models, namely a simple fuel/speed relationship, and a more detailed expression for use with the traffic simulation/assignment model SATURN, which includes the number of stops and distinguishes between first time stops and those made as vehicles move up queues.

CONTENTS

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CAR FUEL CONSUMPTION IN URBAN TRAFFIC. THE RESULTS OF A SURVEY IN LEEDS USING INSTRUMENTED VEHICLES.

1. INTRODUCTION

This report deals with the development of urban fuel consumption estimation procedures to be used in conjunction with conventional traffic assignment models or more detailed models for traffic management evaluation. The work reported here was undertaken as part of a S.E.R.C. sponsored project dealing with the quantification of the fuel consumption impacts of urban transport management measures. The report can be conveniently divided into two parts.

Part I deals with the fuel consumed by cars for each element of an urban trip, and draws on the results of a recent survey conducted in Leeds with two instrumented vehicles supplied by the T.R.R.L. A description of the vehicles*, the test-runs undertaken, and the raw output data obtained, is given in Appendix A.

Part II deals with the derivation of two types of fuel consumption sub-model, namely, simple 'average speed' relationship and a more detailed function which takes into account the total delay and number of stops. At this stage, the fuel consumption sub-model incorporated into the SATURN traffic simulation and assignment model is also described.

PART I - URBAN TRIP FUEL CONSUMPTION

2. INTRODUCTION

The average engine capacity of the U.K. passenger car fleet is in the region of 1500 cc and in the fuel consumption analysis that follows such an engine size will be used, whenever possible, to estimate fuel consumption characteristics of the 'typical' vehicle.

... ...

* The vehicles are both Ford Cortina, 2.0 GL, 1982 models with automatic transmission and 1993 c.c. engine.

Section 3 deals with the fuel consumed when the vehicle is stationary and the engine is idling. In Section 4, the fuel consumption of a vehicle travelling at a constant speed is analysed, and Section 5 deals with the fuel consumed during a stop/start manoeuvre, i.e. when a vehicle decelerates from an initial steady speed to zero speed and then accelerates up to a final steady speed. When a trip starts with the engine cold, a fuel consumption penalty is incurred and the quantification of that excess fuel due to cold starts is the subject of Section 6 and a summary of the main results is given in Section 7.

3. IDLE FUEL FLOW RATE

Since the fuel consumed when the vehicle is idling is independent of road conditions and driving behaviour, the task of finding a representative value should be straightforward. However, even for the same vehicle there is considerable variation in idling fuel consumption depending on a number of vehicle related variables such as idling speed, combustion efficiency, ignition timing and engine temperature. The vehicle age will therefore affect its idling fuel flow rate and although no evidence has been obtained on this effect, it is reasonable to assume that such rates will increase with vehicle age.

The idling fuel consumed by the vehicles in the Leeds experiment was recorded for a total of 158 stops. As can be seen from Figure 1 this idling fuel flow rate was observed to vary considerably for stops of short duration. Such variation can be attributable to two main causes:

1) Measurement error associated with very short stops (i.e. the fuel consumed during a stop of only a few seconds may not be recorded accurately during that time period; some may be recorded just before and/or just after the stop duration); and
2) The fuel consumed by an engine idling for a short period will fluctuate until steady conditions are obtained.

Table 1 shows the mean and standard derivation of fuel flow rate for two sets of data, namely, all stops and stops of 20 seconds duration or more. In the latter case a mean fuel flow rate of 1.3 l/hr. was found.

FIGURE 1 INSTRUMENTED CARS - LEEDS RUNS

IDLE FUEL RATE

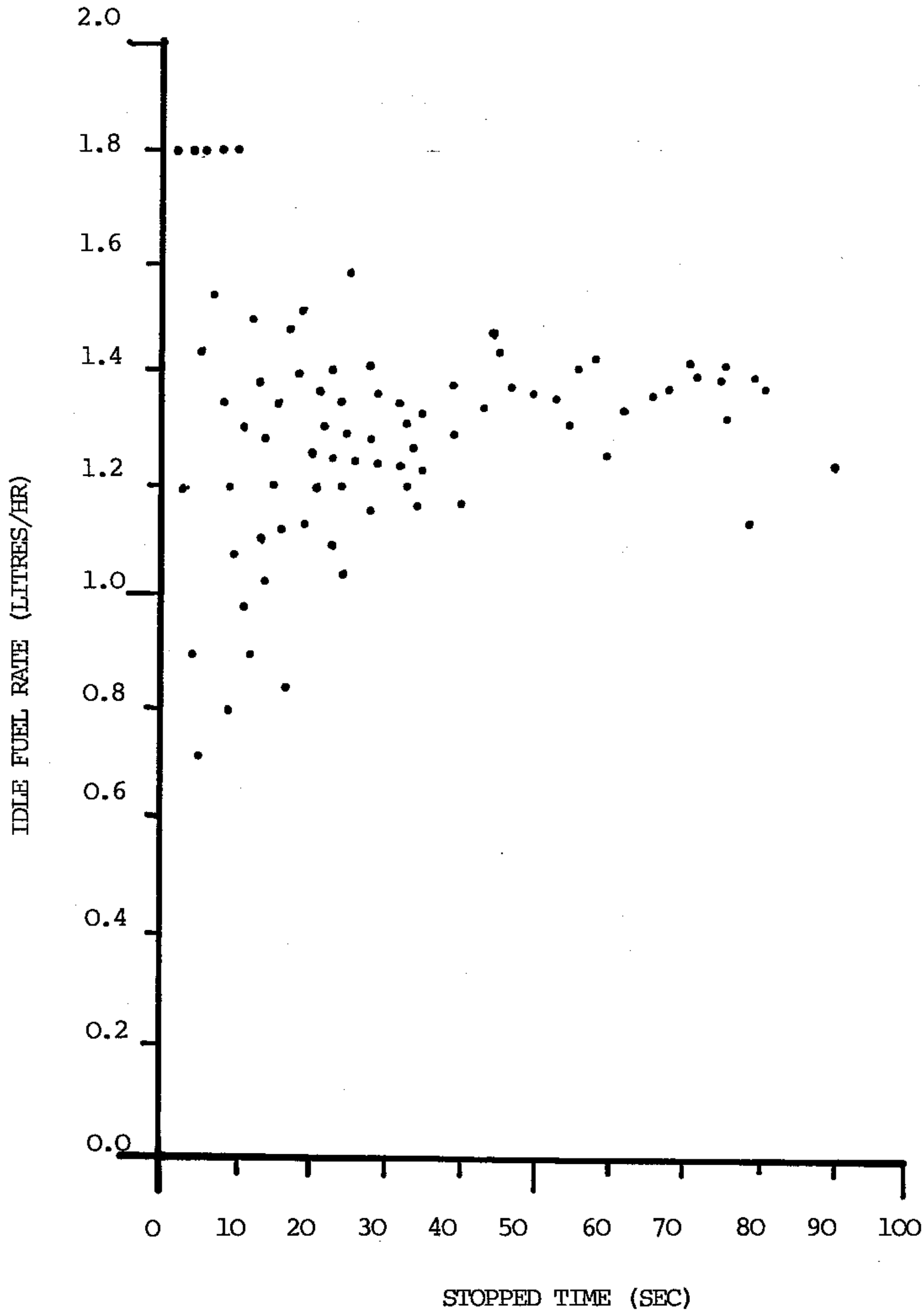


Table 1. Idle fuel flow rate - Leeds Experiment

Data set	Number of observations	Fuel flow rate (l/hr)	
		Mean	Standard deviation
All stops	158	1.24	2.17
Stops of 20 secs. or more	78	1.31	0.69

These results are compared with those obtained from other studies in Table 2 which relates idling fuel consumption rate to vehicle engine size.

Table 2. Idle fuel flow rate and engine size

1. Reference	2. Engine size (C) (c.c.)	3. Idle fuel flow (a_2) l/h	2/3. $C/a_2 \times 10^3$
Claffey (1971)	1180	1.14	1.0
Evans & Takasaki (1981)	1600	1.12	1.4
	2500	1.62	1.5
	2800	1.80	1.6
Robertson et al (1980)	2200	1.5	1.5
Leeds experiment	1993	1.3	1.5

It is apparent from this table that the ratio of engine size to the fuel flow rate does not remain constant over the range of vehicles considered. In effect, using those ratios to calculate the rate for a vehicle size of 1500 c.c. would result in a range of value from 0.94 to 1.5 l/h. It is interesting to note that this spread of values is not incompatible with that found for a single vehicle in tests undertaken by Robertson et al (1980) when the idling rate ranged from 1.0 to 1.5 l/h depending on tuning conditions.*

After considering the rates reported for vehicles whose engine size is similar to the average (Table 2), it was decided to use a central value of 1.2 l/h when building a fuel consumption sub-model to reflect average urban driving conditions.

... ...

* This refers to the Glasgow test reported in Robertson et al (1980) and was confirmed by Dr. D.I. Robertson in private communication.

4. FUEL CONSUMPTION AT CONSTANT SPEED

The fuel consumed by a vehicle at steady speeds will depend on that vehicle's characteristics and tuning conditions, on the cruising speed itself and on the manner in which it is being driven (e.g. the gearing being used). Several workers have put forward expressions for fuel consumption at constant speed obtained from experimental results, Watson (1980); Everall (1968); Akcelik (1982). Using regression analysis and several data sets of past studies, Akcelik (1982) found the following expression to be the most satisfactory:

$$F_c = a_o + \frac{a_1}{V_c} + a_2 V_c^2 \qquad (1)$$

where

F_c is the fuel consumption;

V_c the steady speed

and a_o to a_2 are constants.

In the present section we are interested in the fuel consumption of the average vehicle at a typical steady speed for urban driving conditions, and therefore a considerable amount of aggregation has to be present.

Following on from the arguments of the previous section, the average vehicle considered here has an engine size of 1500 c.c.. For a typical urban steady speed it is necessary to select that speed at which a vehicle would be able to travel if no delays took place. The most common speed limit in urban areas of 48 km/h is therefore used to estimate constant speed fuel consumption for urban trips. Table 3 shows some reported results of experimental tests carried out with a number of different vehicles at various cruising speeds. For the more recent vehicle models and cruising speeds close to 48 km/h, the fuel consumption rate varies from 9.4 to 5.2 l/100 km for vehicles of 2200 and 1100 c.c. engine sizes respectively.

Given the results of Table 3, it seems reasonable to assume a range of values of 6.0 to 7.0 l/100 km for this cruising speed. It was decided to use a value of 7.0 l/100 km as the more appropriate average for a 1500 c.c. vehicle, since it is in close agreement with the value obtained using the results of a very similar vehicle (i.e. the 1600 c.c. vehicle of Evans and Takasaki (1981)).

Table 3. Fuel consumption at various cruising speeds

Reference	Vehicle characteristics Engine Size (cc)	Fuel consumption (l/100 km)	Cruising speed (km/h)
Everall (1968)[1]	1050	6.0 - 6.5	70
Weeks (1981)	1100	5.2 5.5	50 65
Evans and Takasaki (1981)	1600	7.5 7.8	48 64
Everall (1968)[1]	1700	8.0 - 8.5	70
Pienaar (1981)	1900	7.7 6.6	40 50
Robertson et al (1980)	2200	9.7 9.4	41 52

Note: [1] Estimated from the graphs of motorway fuel consumption.

5. FUEL CONSUMPTION OF STOP/START MANOEUVRES - THE LEEDS SURVEY

This section deals with the characteristics of vehicle stops in urban traffic and with the fuel consumed during a stop/start manoeuvre. The excess fuel consumed during a stop/start manoeuvre is defined here as the difference between the total consumption during that manoeuvre and that fuel which would have been consumed if the same distance was travelled at a steady cruising speed. Since the speed limit in most urban areas is 48 km/h. this will be the cruising speed used to estimate the excess fuel due to stops.

The main objective is to obtain relationships which express that excess fuel in terms of the characteristics of the manoeuvre, to be used in fuel consumption sub-models which include the number and type of stop.

The section is organised as follows: In section 5.1 the notation used and the main characteristics of stops found in the Leeds experiment are given. Sections 5.2 and 5.3 deal with the fuel consumed during the deceleration and acceleration stages of each manoeuvre respectively. In section 5.4 the results of the two previous sections are used to derive expressions for the total and the excess fuel consumed. Finally, section 5.5 gives values for the excess fuel consumed for several cruising speeds and types of stops.

5.1 Characteristics of stops

One of the objectives of the experiment was to investigate the characteristics of vehicle stops in urban traffic. Before discussing the results obtained in this regard, it is useful to deal briefly with the various components of vehicle motion through a complete stop/start manoeuvre.

Referring to Figure 2, which shows a vehicle trajectory during such a manoeuvre, the following notation will be used:

V_i - Initial speed, i.e. that speed at which the deceleration stage starts.

V_f - Final speed, i.e. speed reached once the acceleration stage stops.

t_d - Time taken to decelerate from speed V_i to zero.

d - Deceleration rate

t_a - Time taken to accelerate from zero to speed V_f

a - Acceleration rate

t_s - Stopped time

F_d - Fuel consumed during the deceleration stage

F_a - Fuel consumed during the acceleration stage

F_t - Total fuel consumed during the complete stop/start manoeuvre that would have been

F_c - Fuel consumed if the same distance was travelled at a cruising speed V_c.

F_e - Excess fuel consumed due to stop/start manoeuvre, and given by: $F_e = F_t - F_c$.

The speeds (V_i and V_f) and the time elements (t_d, t_s and t_a) shown in Figure 2 were recorded from the output data as described in Appendix A. The fuel consumed at each of the three stages was also recorded for each complete stop. Data for a total of 428 stops is available although some fuel consumption components are missing due to fuel meter problems referred to in Appendix A. Missing values for V_i, t_d, V_f and t_a were also recorded whenever the deceleration or acceleration was not roughly constant. Clearly the choice of initial and final speeds is somewhat arbitrary given the speed fluctuations in urban traffic, particularly under congested peak conditions. In our case V_i was chosen at the point after which there was a steady decline in speed until the vehicle came to a standstill. Similarly V_f was taken to be that speed immediately after which there was no acceleration. Therefore neither V_i nor V_f is necessarily the highest speed reached over any one link.

Figures 3, 4 and 5 show the distribution of initial and final speeds observed in the case of runs on radial routes, Central Area runs, Off Peak and Evening Peak respectively. The corresponding means and standard deviations are given in Table 4. In the case of Central Area runs the distribution of initial and final speeds are of very similar shapes for both peak and off-peak conditions. From Table 4 the mean values which can be used to represent both initial and final speeds would be:

Radial routes (morning peak) - 30 km/h
Central area route (off peak) - 34 km/h
Central area route (evening peak) - 27 km/h

Table 4. Mean initial and final speeds

Routes	Speed type	Number of observations	Speed (km/h)	
			Mean	Standard deviation
All routes	Initial Final	428 403	30.9 28.8	12.7 11.4
Radial	Initial Final	158 138	34.9 31.1	13.7 11.6
Central area (off peak)	Initial Final	59 54	34.2 33.9	9.3 8.1
Central area (eve. peak)	Initial Final	211 211	26.9 25.9	11.5 11.2

5.2 Fuel consumed decelerating

As mentioned in the previous section, the initial speed and the time taken for the vehicle to come to a complete stop were used only when the rate of deceleration was roughly constant. In this way we can calculate the deceleration, d, as:

$$d = \frac{V_i}{t_d} \qquad (2)$$

where V_i and t_d are defined as before.

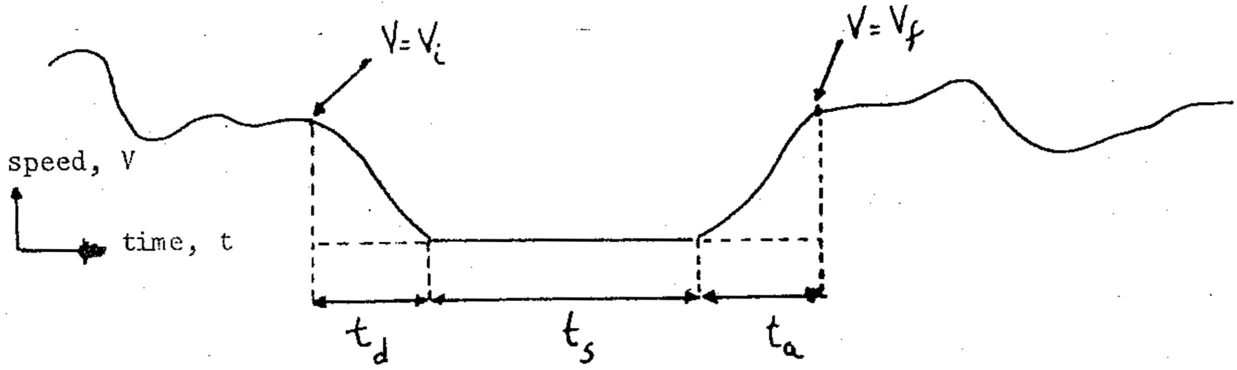
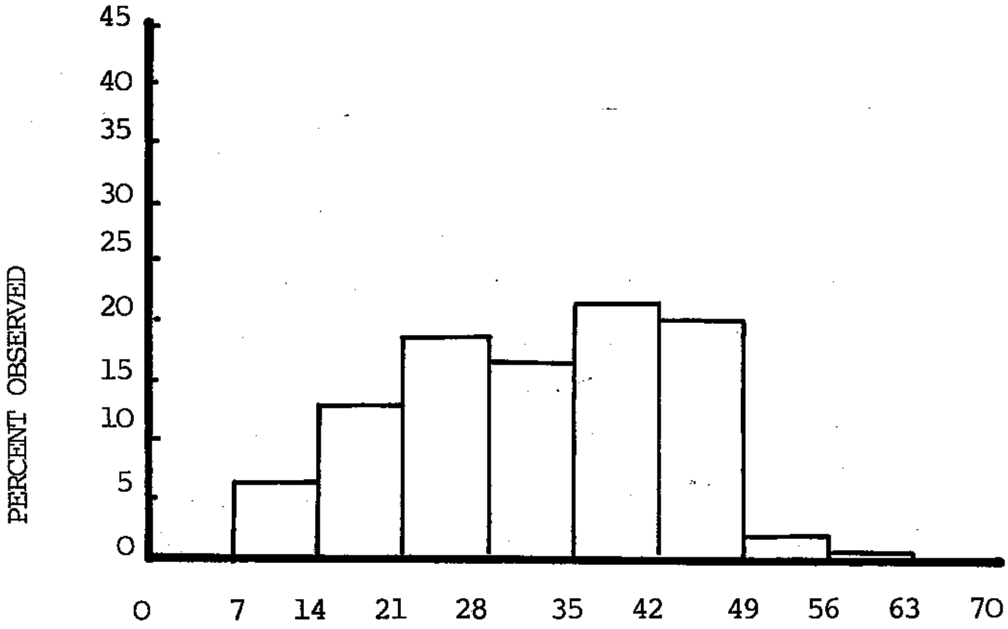


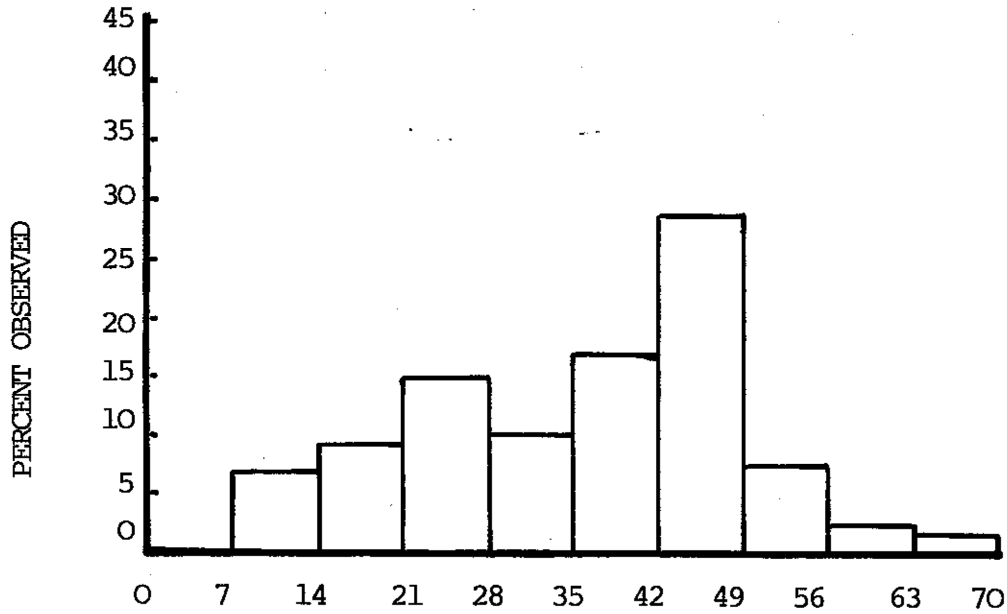
Figure 2 Vehicle trajectory during a complete stop

FIGURE 3

INSTRUMENTED CARS - LEEDS RUNS
SPEED FREQUENCY DISTRIBUTION
RADIAL ROUTES (M.PEAK)

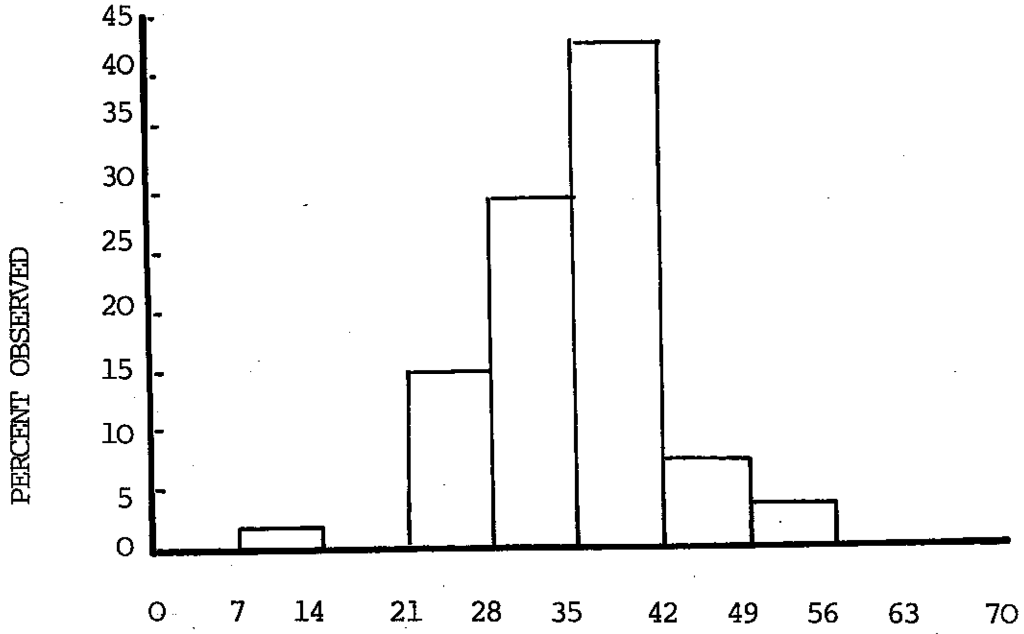


FINAL SPEED (KM/HR)

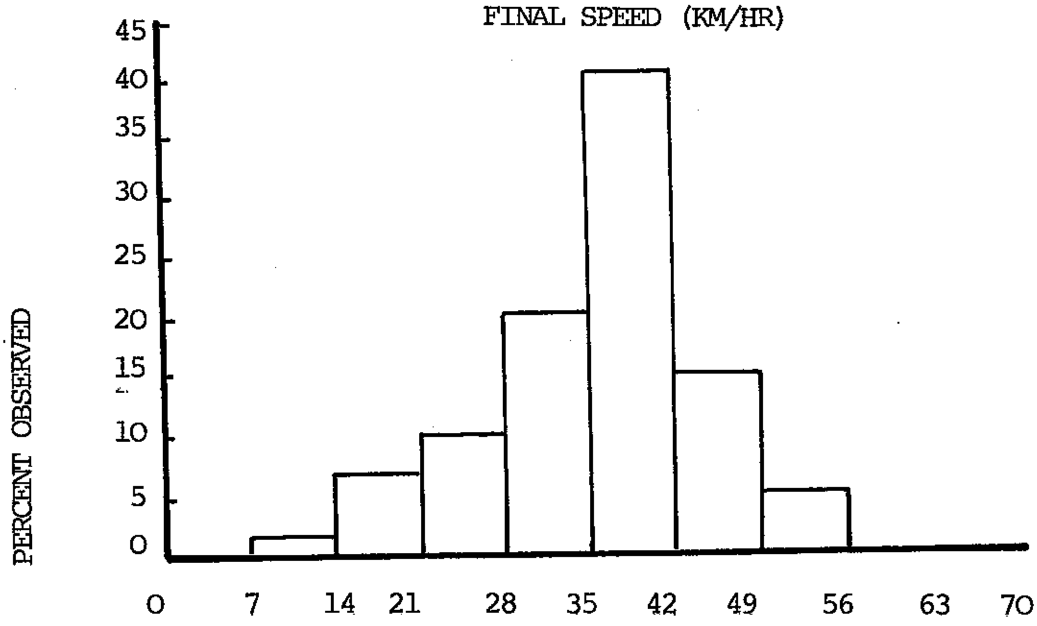


INITIAL SPEED (KM/HR)

FIGURE 4. INSTRUMENTED CARS - LEEDS RUNS
SPEED FREQUENCY DISTRIBUTIONS
CITY CENTRE ROUTE (OFF PEAK)

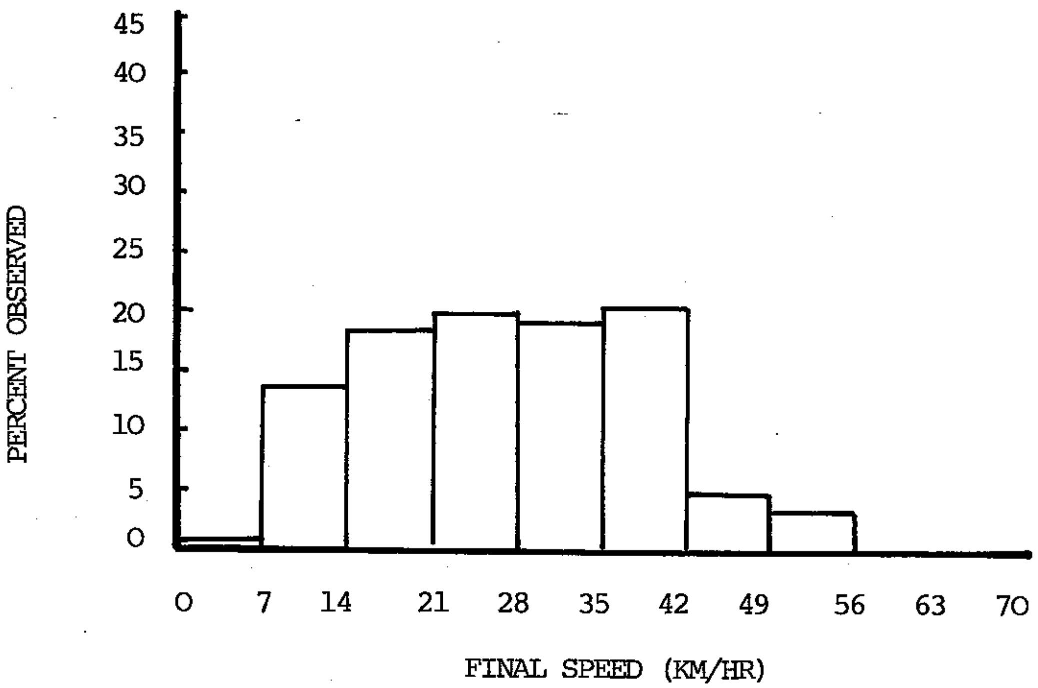


FINAL SPEED (KM/HR)



INITIAL SPEED (KM/HR)

FIGURE 5. INSTRUMENTED CARS - LEEDS RUNS
SPEED FREQUENCY DISTRIBUTIONS
CITY CENTRE ROUTE (EVENING PEAK)



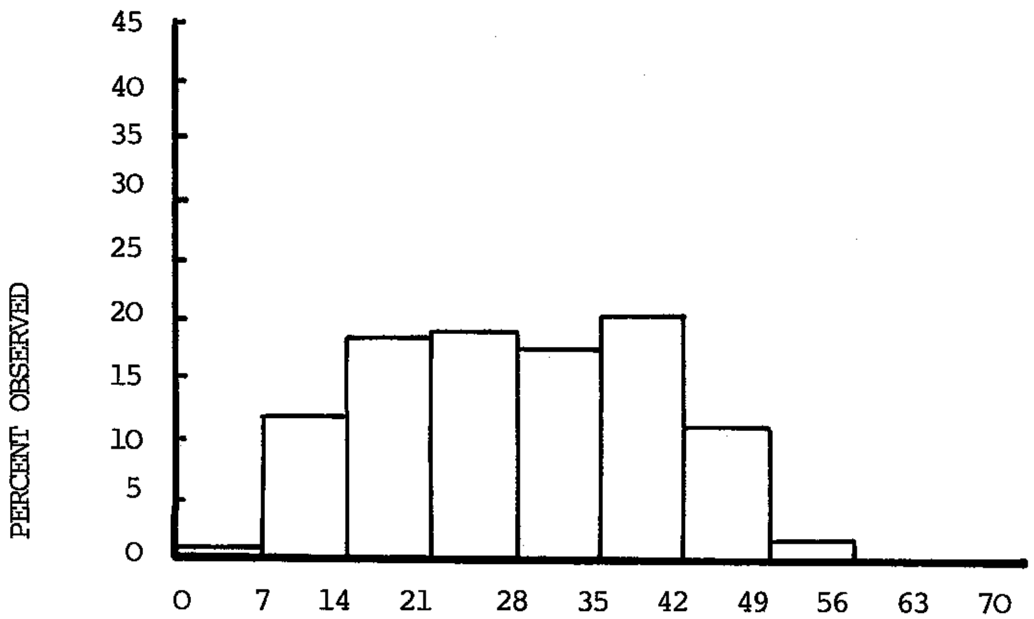


Table 5 shows the mean deceleration rates observed by route type.

Table 5. Mean deceleration rates

Route	Number of observations	Deceleration (m/s^2)	
		Mean	Standard deviation
All routes	428	0.82	0.36
Radials	158	0.83	0.31
Central area (Off peak)	59	1.01	0.36
Central area (eve. peak)	211	0.75	0.08

As can be seen from Figure 6 there is a wide range of deceleration rates (and therefore deceleration times) associated with each individual initial speed. The fuel consumed during the decelerating manoeuvre is plotted against initial speed in Figure 7.

Several regression equations were obtained using a total of 136 observations and expressing the fuel consumed during deceleration, F_d, as a function of the initial speed, V_i, and deceleration rate, d. The most satisfactory equations in terms of explanatory power has the form:

$$F_d = \underset{(0.0096)}{0.537}\left(\frac{V_i}{d}\right) \qquad (3)$$

where the value in brackets refers to the standard error of the co-efficient and F_d is in ml; V_i is in m/s and d in m/s^2.

Equation 6.4 has an R^2 of 0.96. Table 6 shows the values of F_d for a range of initial speeds, V_i, and deceleration rates, d, obtained using equation (3). These results will be discussed further when the excess fuel due to a stop is considered (Section 6.5.4).

FIGURE 6 INSTRUMENTED CARS - LEEDS RUNS

DECELERATION VS. INITIAL SPEED

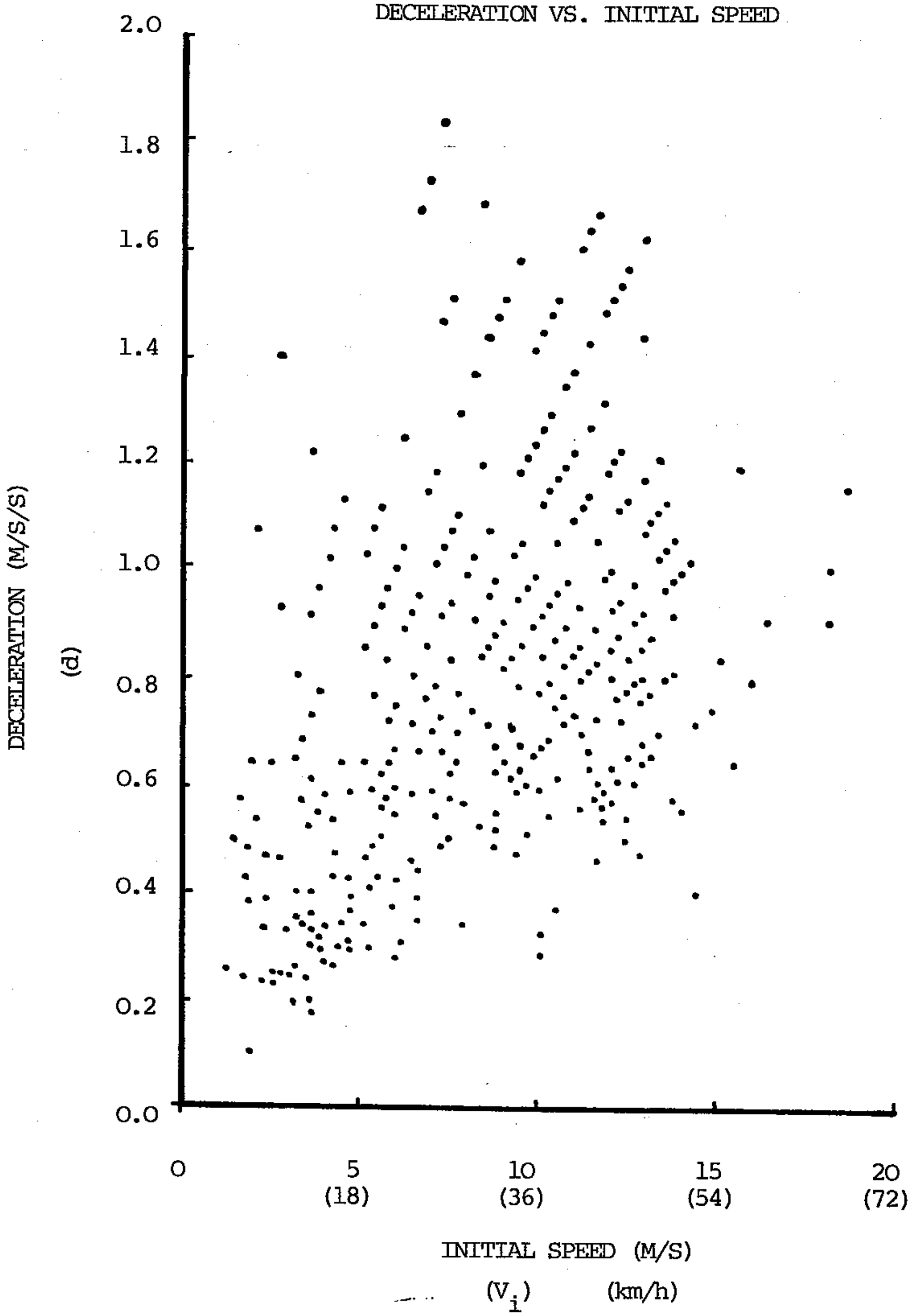


FIGURE 7 INSTRUMENTED CARS _ LEEDS RUNS
FUEL CONSUMED VS. INITIAL SPEED

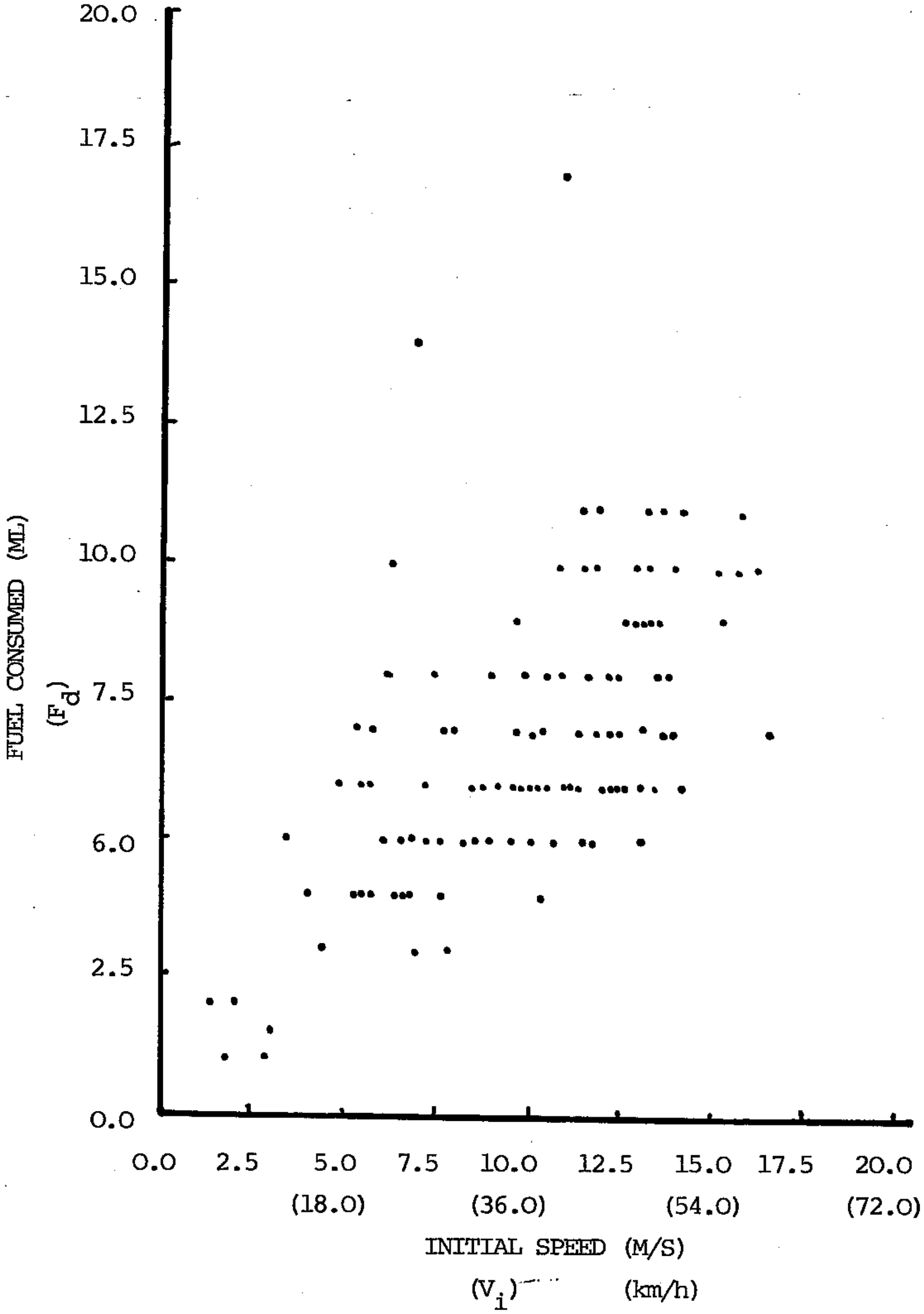


Table 6. Fuel consumption during deceleration - using equation (3)

Initial speed V_i (Km/h)	Fuel consumption during deceleration (ml)		
	Deceleration rate, d (m/s^2)		
	d = 0.6	d = 0.8	d = 1.0
10	2.5	1.9	1.5
20	5.0	3.7	3.0
30	7.5	5.6	4.5
40	9.9	7.5	6.0
50	12.4	9.3	7.5
60	14.9	11.2	8.9

5.3 Fuel consumed accelerating

The acceleration rates were obtained in the same way as the deceleration by assuming constant acceleration throughout the period from zero speed to the final speed, V_f. Table 7 gives the mean acceleration rates obtained by route type and Figure 8 shows the spread of those accelerations. Figure 9 shows the relationship between fuel consumption and final speed.

As shown in Figure 9 the fuel consumed for each period of acceleration and the corresponding final speed are much more correlated than was the case with the deceleration period. Following the notation used before, the following relationships were established following the work of Akcelik (1982):

R^2

$$F_a = \underset{(0.003)}{0.186}\, V_f^2 \qquad (4)\ 0.97$$

$$F_a = \underset{(0.007)}{0.130}\, V_f^2 + \underset{(0.051)}{0.420} \left(\frac{V_f}{a}\right) \qquad (5)\ 0.98$$

$$F_a = \underset{(0.017)}{0.239}\, V_f^2 - \underset{(0.0015)}{0.0046}\, V_f^3 \qquad (6)\ 0.97$$

where F_a is in ml, V_f in m/s and a in m/s^2.

FIGURE 8 INSTRUMENTED CARS - LEEDS RUNS
ACCELERATION VS. FINAL SPEED

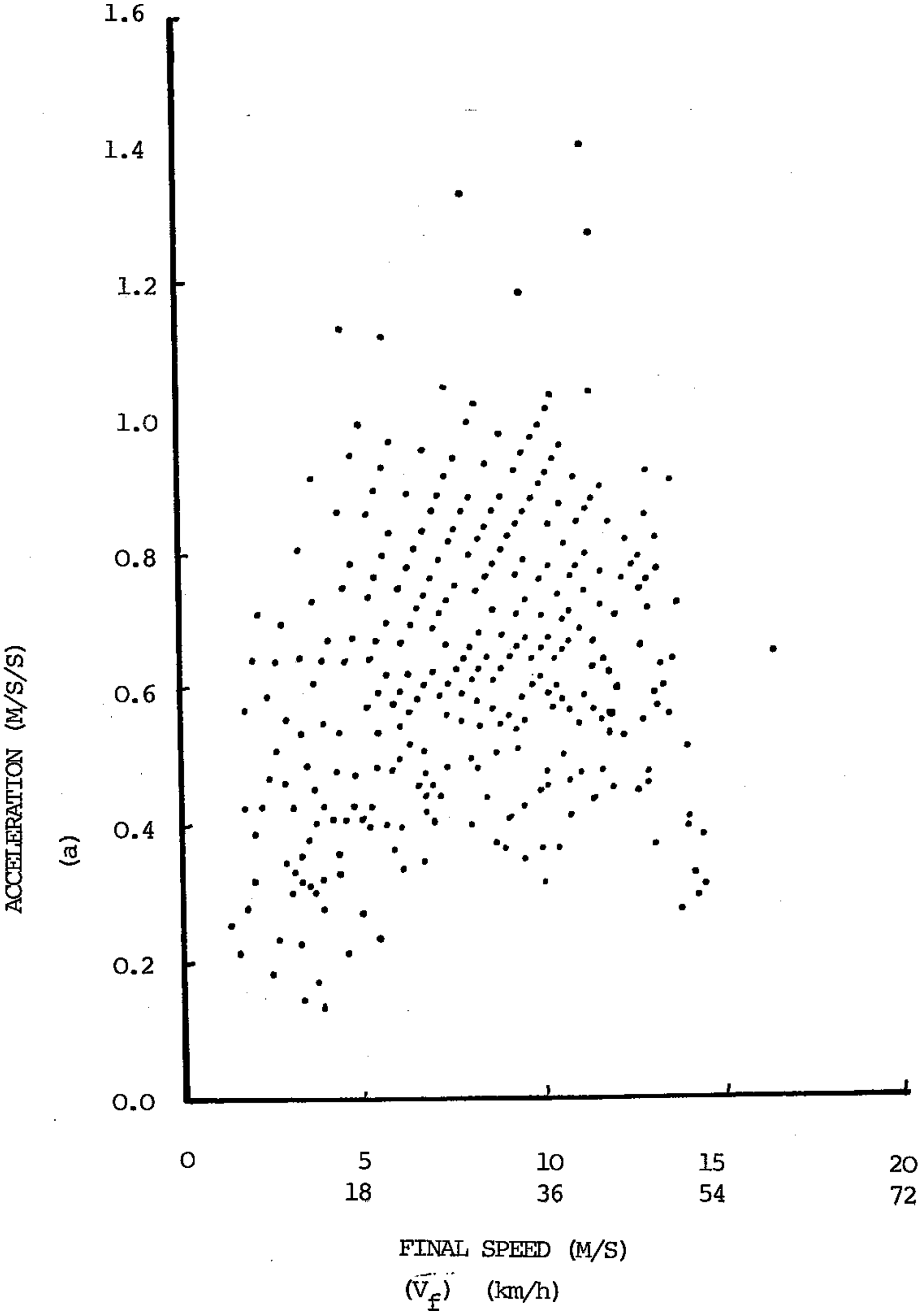


FIGURE 9 INSTRUMENTED CARS - LEEDS RUNS
FUEL CONSUMED VS. FINAL SPEED

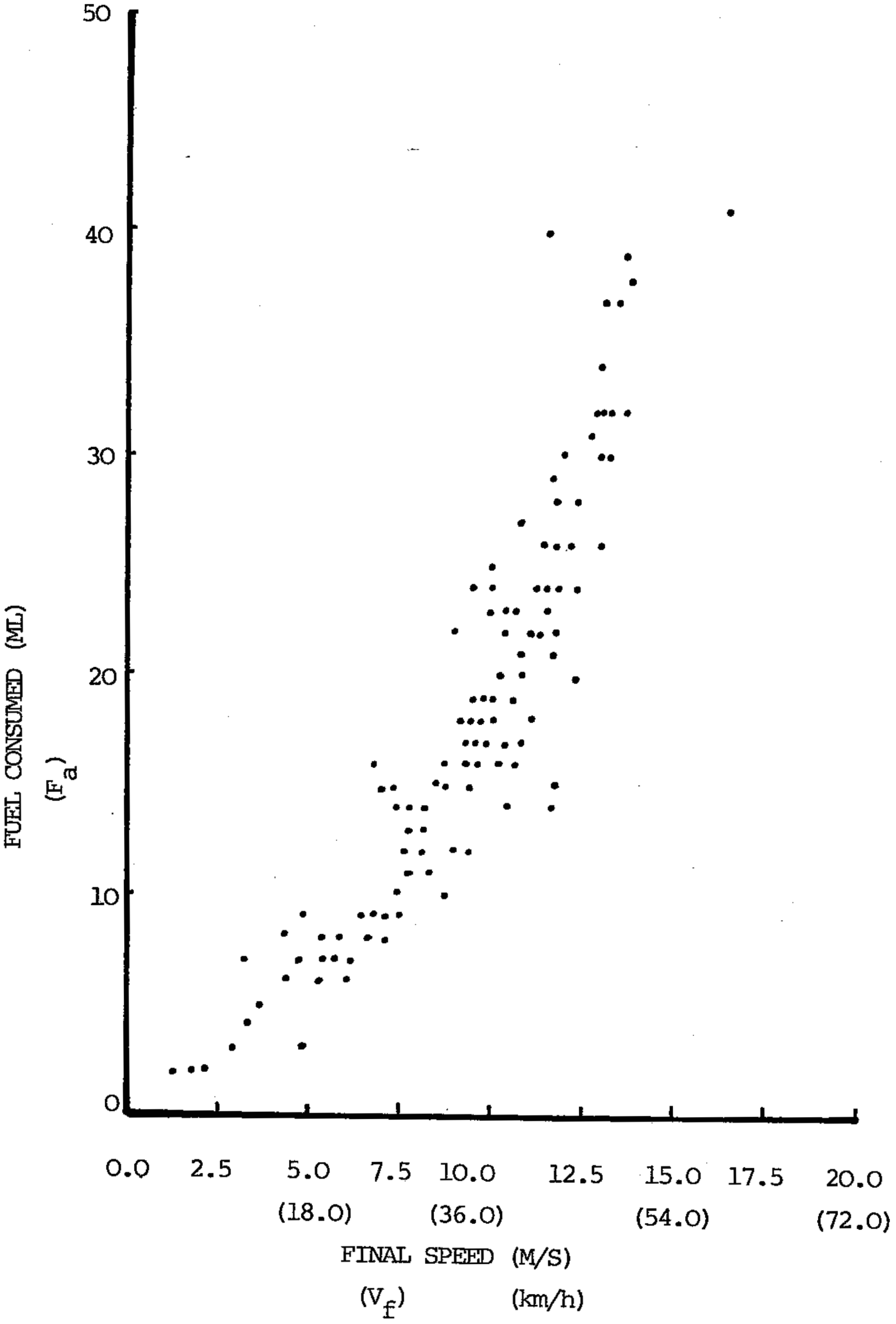


Table 7. Mean acceleration rates

Route	Number of observations	Accelerating rates (m/s^2)	
		Mean	Standard deviation
All routes	403	0.65	0.21
Radials (morn. peak)	138	0.66	0.18
Central area (off peak)	54	0.72	0.16
Central area (eve. peak)	24	0.63	0.23

Equation 5, which has the higher R^2 value, was used to calculate the fuel consumed during the acceleration stage of a stop/start manoeuvre for a range of acceleration rates and final speeds. The results which are shown in Table 8, illustrate the low sensitivity of fuel consumed with variations in the acceleration rate, a fact which was also noted by Richardson (1982), Akcelik (1982) and Evans and Takasaki (1981).

Table 8. Fuel consumption due to acceleration - using equation (5)

Final speed V_f (km/h)	Fuel consumed (ml)		
	Acceleration rate, a (m/s^2)		
	a = 0.6	a = 0.8	a = 1.0
10	2.9	2.5	2.2
20	7.9	6.9	6.3
30	14.9	13.4	12.5
40	23.8	21.9	20.7
50	34.8	32.4	30.9
60	47.8	44.9	43.1

5.4 Excess fuel due to complete stop/start manoeuvre

The equations derived in the previous sections from the Leeds experiment for the fuel consumed during the deceleration and acceleration stages of a complete manoeuvre are now used to obtain an expression for the total fuel consumption, F_t, during such manoeuvres. From equations (3) and (5) we have:

$$F_t = F_d + F_a = 0.537 \left(\frac{V_i}{d}\right) + 0.130 V_f^2 + 0.420 \left(\frac{V_F}{a}\right) \qquad (7)$$

Following the definition given in Section 5.1, the excess fuel consumed F_e, is given by:

$$F_e = F_t - F_c \qquad (8)$$

where F_c, the fuel consumed at constant cruising speed, V_c, can be expressed as:

$$F_c = f_c \frac{V_c^2}{2} \left(\frac{1}{d} + \frac{1}{a}\right) \qquad (9)$$

where f_c is the cruising speed fuel consumption per unit distance at the constant speed V_c;
and d and a are assumed constant.

It is now possible to estimate the excess fuel per stop for the Leeds experiment data using Tables 6 and 8, together with equation (9). Since it was not possible to obtain experimental values for f_c, the cruising speed fuel consumption rate, a value of 7.5 l/100 km is assumed for a value of V_c of 48 km/h. This assumption was based on the results shown in Table 3, after Evans and Takasaki (1981) and Pienaar (1981).

The excess fuel due to a stop/start manoeuvre was estimated for a range of final and initial speeds, and deceleration and acceleration rates. A summary of the results is shown in Table 9. In the case of the Leeds experiment when the final and initial speeds are both equal to the assumed cruising speed of 48 km/h, the excess fuel due to the complete stop/start manoeuvre is 22 ml.*

... ...

* Assuming constant deceleration and acceleration rates of 0.8 and 0.7 m/s^2 respectively, following the results of the Leeds experiment.

Experimental tests have been carried out by several researchers to determine the excess fuel due to a stop/start manoeuvre (e.g. Claffey (1971), (1976); Robertson et al (1980); Pienaar (1981); Evans and Takasaki (1981)). Although most of the vehicles used are not typical of the U.K. vehicle fleet, some of the results are relevant to this work and will now be compared with those observed from the Leeds experiment.

Table 9. Excess fuel due to stop/start manoeuvre

Initial/final speed (1) (km/h)	Excess fuel consumed (ml)		
	Deceleration/acceleration rate, k (2) (m/s^2)		
	k = 0.6	k = 0.8	k = 1.0
10	4.4	3.7	3.1
20	9.1	7.7	7.0
30	13.7	12.5	11.8
40	18.3	17.8	17.4
50	23.1	23.6	23.9
60	28.0	30.1	31.2

(1) Assumed equal

(2) Assuming equal deceleration and acceleration rates

From the results given by Evans and Takasaki (1981) using a vehicle with a 1600 c.c. engine, the excess fuel required to accelerate the vehicle to steady speeds of 48 and 64 km/h, was estimated to be 20 and 35 ml respectively. This does not include the deceleration stage of the manoeuvre and is therefore not directly comparable to the results of Table 9, whose corresponding values for the total excess fuel are in the region of 23 and 30 ml.

Vincent et al (1980) have put forward a relationship between F_e and the cruising speed, V_c of the form of:

$$F_e = 8.2 \times 10^{-6} V_c^2 \qquad (10)$$

where V_c is in km/h and F_e in litres of fuel.

Equation (10) was found to apply to data from experimental tests carried out by the TRRL with a vehicle with a 2200 c.c. engine.* For a cruising speed of 50 km/h, equation (10) gives a value of F_e of 20.5 ml. The corresponding value from Table 9 is in the region of 23 to 24 ml.

Pienaar (1981), using vehicles in the range of 1500 to 2000 c.c. engines and cruising speeds of 40 km/h, found a value of F_e of approximately 25 ml, whereas the corresponding value from Table 6.9 is approximately 18 ml.

It should be stressed that the values for excess fuel shown in Table 9 are all based on a cruising speed fo 48 km/h unlike those of past studies quoted above.

5.5 Excess fuel due to two types of stop/start manoeuvres

It is useful at this stage to distinguish between the stop/start manoeuvre described in Section 5.1 where a vehicle comes to rest from and accelerates to a steady speed, and a manoeuvre which can be described as 'queue crawling' where a vehicle accelerates from rest to a speed V_q and then decelerates back to rest. This latter manoeuvre is shown diagrammatically in Figure 10, for the case when the acceleration and deceleration rates are assumed constant and equal to k.

The excess fuel consumed during such a manoeuvre, which is a function of the cruising speed, V_c, and the final speed reached, V_q, can be obtained from equations (7) and (9) with $V_i = V_f = V_q$.

Table 10 shows the sensitivity of the excess fuel, F_e, to variations in the assumptions made about f_c, the cruising speed fuel consumption per unit of distance. It is clear from this Table that the excess fuel due to a 'queue crawling' manoeuvre is fairly insensitive to the assumption made about the cruising speed (i.e. the cruising speed fuel rate, f_c) for values of V_q, the maximum speed reached, lower than 25 km/h.

The results shown here for both the complete stop/start and the 'queue crawling' manoeuvres will be used in Part II to derive coefficients for fuel consumption sub-models appropriate to urban travel in the U.K.

... ...

* A value of 7.7×10^{-6} l/p.c.u. stop is given by Vincent et al (1980). This was converted to l/veh. Stop using a factor of 1.07 as recommended by those authors.

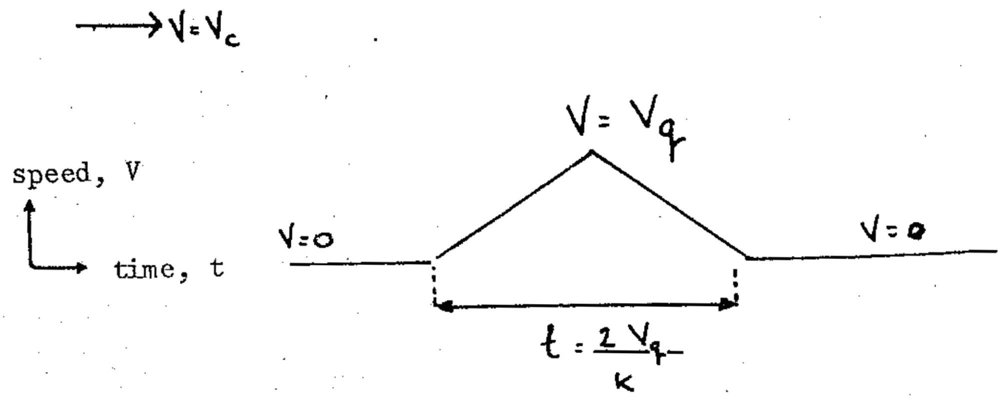


Figure 10 'Queue-crawling' manoeuvre

Table 10. Excess fuel consumption during 'queue crawling' manoeuvres

Maximum speed reached, V_q (km/h)	Excess fuel, F_e, (ml)[1]		
	Cruising speed fuel rate, f_c, (l/100 km)		
	7.0	7.5	8.0
30	13.1	12.6	12.2
25	10.6	10.3	9.9
20	8.2	8.0	7.8
15	5.9	5.8	5.7
10	3.8	3.8	3.7

(1) These results were calculated using the following:

- Equation (7) with $V_i = V_f = V_q$; and $a = 0.7\ m/s^2$ and $d = 0.8\ m/s^2$ following the results of the Leeds experiment.
- Equation (9) with a and d as above and the following V_c values: 40 km/h for f_c = 7.0 l/100 km; 48 km/h for f_c = 7.5 l/100 km and 30 km/h for f_c = 8.0 l/100 km. These values are based on the work by Akcelic (1982) showing the concave shape of the f_c vs. V_c curve (equation 1) and assumes that f_c increases at the lower cruising speed of 30 km/h.

6. THE EFFECT OF COLD STARTS

The additional fuel consumed during a trip where the vehicle has started with a cold engine, relative to the fuel consumed with the engine fully warm, has been investigated by several researchers (e.g. Everall and Northrop (1970); Waters and Laker (1980); Chang et al (1976); Pienaar and Jurgens (1980); and Frybourg (1979)). This section reviews some of the available evidence in this area.

Recent experimental tests undertaken by Pienaar and Jurgens (1980) with three passenger cars of 1600 c.c. engine capacity under urban driving conditions at average speeds of 42 km/h, are shown below.

Distance travelled (km)	Extra consumption due to cold start. As percentage of warmed-up consumption.
1.0	48
2.0	37
3.0	29
4.0	22
5.0	18
6.0	16

This compares with experiments in France which showed that the extra consumption due to cold starts over the first 2 km of a journey can be of the order of 30 percent of the warmed-up consumption in summer and 60 percent in winter.

In the U.K., Everall and Northrop (1970) carried out tests using a 1967 vehicle of 2000 c.c. engine on the TRRL test track. The relationship between the excess fuel consumed due to 'cold starts' and vehicle speeds, driving manner (i.e. gear changes), and the outside air temperature was investigated. Those authors found that when urban driving conditions were simulated, the distance necessary for the vehicle's engine to become fully warm was in the region of 9 km. At the national level, it was also estimated that if no account is taken of the effect of 'cold starts' the under-estimate of the fuel consumed when vehicles start from cold is in the region of 15 per cent of the actual fuel consumed.

Waters and Laker (1980), using a 1300 c.c. vehicle, at an ambient temperature of 6^{o}C, found that for a trip of approximately 3 km, the excess fuel consumed due to 'cold starts' was over 60 percent of the fully warmed-up amount.

It is difficult to compare the results of different tests due to the influence of driving techniques, average speeds and ambient temperature. However, there is a large measure of agreement that excluding the excess fuel due to 'cold starts' will lead to significant underestimates of fuel consumption for short journeys of less than around 6 kms. For a 3 km journey this extra fuel may range from 30 to 6o percent of the warmed-up consumption.

7. SUMMARY AND DISCUSSION

7.1 Idling fuel consumption

After comparing some available data on idling fuel flow rates of several vehicles with that obtained from the results of the Leeds Survey with two instrumented vehicles, it was decided to use a value of 1.2 litres/hour for the 'typical' U.K. vehicle with an engine size of 1500 c.c. There is considerable variation in idling rates even for the same vehicle and the value given above should be seen as the central value of a range which may be as high as $\pm$ 20 percent.

7.2 Constant-speed fuel consumption

For a vehicle of 1500 c.c. engine size the value of 7.0 l/100 km was adopted for a steady speed of 48 km/h. This value is very close to that found for similar vehicles and at similar steady speeds.

7.3 Fuel consumption of stop/start manoeuvres

The excess fuel consumed by a vehicle during such manoeuvres was investigated using the results of the Leeds experiment. Relationships between the fuel consumed during the deceleration and acceleration stages of a stop/start manoeuvre and the corresponding initial and final speeds, were found. Such relationships which apply only to the vehicles used in the experiment - 2000 c.c. engine, 1982 models - and to the actual driving conditions present, were derived using experimental data for each individual stop. Some errors are associated with obtaining the input data, particularly in the case of the fuel consumption data related to very short deceleration and acceleration stages.

The following is a summary of the results obtained:-

Average initial speed (V_i):	31 km/h
Average final speed (V_f):	29 km/h
Average deceleration rate (d):	0.82 m/s^2
Average acceleration rate (a):	0.65 m/s^2

Fuel consumption during deceleration stage, F_d (ml)

$$F_d = 0.537 \frac{V_i}{d} \qquad \text{with } R^2 = 0.96$$

Fuel consumption during acceleration stage, F_a (ml)

$$F_a = 0.130 V_f^2 + 0.420 \frac{V_f}{a} \qquad \text{with } R^2 = 0.98$$

The excess consumption due to a stop/start manoeuvre where V_i = V_f = 48 km/h. is of the order of 22 ml of fuel assuming average acceleration and deceleration rates as given above. Table 9 shows the excess fuel consumed for the stop/start manoeuvre for a range of acceleration and deceleration rates as well as final and initial speeds. Table 10 shows the excess fuel consumed during a 'queue crawling' manoeuvre for a range of maximum speeds reached under several cruising speed fuel rate assumptions. The excess fuel for 'queue crawling' manoeuvres where the maximum speeds reached are 30, 25 and 20 km/h, are estimated to be 13, 10 and 8 ml of fuel respectively.

Finally in Section 6 the effects of 'cold starts' on fuel consumption were discussed by reviewing the results of several experiments. It was concluded that for trips of less than 6 kms, significant under-estimation may occur if the fuel consumption estimation procedure ignores the effect of 'cold starts'. The degree of under-estimation depends on several factors including the ambient temperature, the driving behaviour and the traffic flow conditions.

PART II - URBAN FUEL CONSUMPTION SUB-MODELS

8. INTRODUCTION

Part II deals with the development of fuel consumption sub-models to be used in evaluating the impact of urban transport management (UTM) strategies on energy consumption. Such sub-models, which can be seen as additions to the analytical tools available to model urban transport demand, must satisfy two criteria:

1) They must be able to represent vehicle fuel consumption characteristics in urban driving conditions to a reasonable degree of accuracy, and
2) They should make use of the readily available outputs from the transport modelling process.

Fuel consumption sub-models appropriate to two specific levels of detail in measuring the responses to a range of UTM strategies are put forward:

1) A relationship between urban fuel consumption per vehicle km. and the inverse of average journey speed (total journey distance divided by total journey time), to be used with the results of the conventional four-step urban transport demand modelling process - trip generation, distribution, modal-split and assignment. Such a sub-model is best suited to quantify the fuel consumption impacts of UTM measures at an aggregate level of detail, and is therefore directed at the area-wide evaluation of those measures which influence total distance travelled and total time spent travelling by each mode. For example, changes in the relative travel costs of private and public transport (e.g. fuel pricing, parking charges, area licensing schemes and public transport fare subsidies) may result in modal-split changes which in turn may affect the level of congestion and therefore average journey speeds. By relating the likely impact of those travel cost changes on modal market shares one can estimate the corresponding effect on average speeds by loading the changed pattern of demand onto the road system using a conventional assignment model and use the above relationship to estimqte the fuel implications. The use of a simple relationship between average journey speed and fuel consumption to estimate the effects of UTM policies on total urban fuel consumption

is dealt with in the next section. The accuracy of such estimates will only enable broad conclusions to be drawn from the results. However the specification errors inherent in the over-simplification of such fuel consumption sub-models must be seen in the context of the predictive accuracy attached to the travel demand forecasting models. The latter, which will be used to predict average journey speed changes that result from the introduction of UTM measures, incorporate a number of simplifying assumptions about travel behaviour which lead to a large degree of uncertainty being attached to the outputs of such models.

2) A fuel consumption sub-model which has been incorporated in the SATURN traffic simulation and assignment model. That sub-model is able to use the results of more detailed analysis of traffic flow speed and delay in urban conditions and is therefore particularly suitable to quantify the effects of traffic management schemes which alter the supply of road space in medium sized towns or in the central areas of larger cities. As discussed in detail in Section 10, the sub-model expresses fuel consumption as a linear function of total distance travelled, total delayed time and the total number of vehicle stops. A distinction is made in SATURN between the first time a vehicle stops at an approach to a junction and any subsequent stops that vehicle may make at the same approach. The fuel consumption expression discussed above is therefore able to make use of that distinction when calculating the excess fuel consumed due to vehicle stops.

Even this second type of sub-model which relies solely on traffic flow effects to explain fuel consumption, does not take account of other factors which influence the fuel consumed by a vehicle. There are two other dimensions to be considered when estimating fuel consumption, namely the characteristics of the driver and of the vehicle itself. In addition, factors such as altitude and climatic conditions will also affect fuel consumption results and therefore data transferability in space must be conditioned by such factors.

The fuel consumption sub-models developed here are intended for use by traffic engineers and transport planners in U.K. urban area environments and must therefore incorproate a large degree of aggregation over vehicle and driver characteristics. That is, the fuel estimation procedures apply to the 'typical' vehicle and driver and the results are therefore subject to errors when they are compared with consumption levels of individual vehicles. However, the errors become less important when the fuel consumption sub-models are used as part of the local evaluation of a number of UTM measures. In this latter case the traffic engineer or transport planner is interested in the relative performance each measure or combination of measures.

9. THE 'AVERAGE SPEED' SUB-MODEL

9.1 Results from U.K. Studies

A number of research workers both in the U.K. and overseas have put forward a simple linear relationship between urban fuel consumption per unit distance (F) and the inverse of trip speed (V), the latter being calculated using total journey time taken to complete the trip. Such relationships have the form:

$$F = k_1 + \frac{k_2}{V} \tag{11}$$

where the constants k_1 and k_2 have been determined using simple linear regression analysis with observed data obtained by driving specially fitted test vehicles in urban areas.

Early work in Central London undertaken by Everall (1968) with two test cars - a Vauxhall Viva (1053 c.c.) and a Ford Zephyr (1703 c.c.) indicated a linear relationship between fuel consumption and the inverse of average speed (i.e. average journey time per unit distance). The relations obtained for Central London were:

a) 1053 c.c. car

$$F = 5.65 + \frac{115.9}{V} \tag{12}$$

and

b) 1073 c.c. car

$$F = 8.50 + \frac{191.3}{V} \tag{13}$$

where F = fuel consumption in 1/100 km

and V = average speed in km/h.

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

Some more recent experiments have been carried out by Weeks (1981) in London using a diesel and a petrol car. The petrol car used was a 1978 model VW Golf of 1100 c.c. engine capacity and the tests were carried out in two types of routes: one exclusively in Central London and another on a radial commuter route from Crowthorne to Central London. Although the experiments were designed to compare the fuel consumption of petrol and diesel vehicles of similar performance under urban congested conditions, the results obtained provide a basis to relate urban fuel consumption and observed speed.

Using the full data set, i.e. the results for all speeds and the two test routes, for the same vehicle and the same number of occupants, Weeks produced the following equation:

$$F = 11.48 + \frac{91.77}{V} - 0.16\ V + 0.0012\ V^2 \qquad (14)$$

where F and V are defined as before and the correlation coefficient, R^2 is 0.675.

By restricting the value of average speed to less than 60 km/h, the following equation is obtained:

$$F = 17.92 + \frac{54.42}{V} - 0.454\ V + 0.0045\ V^2 \qquad (15)$$

with $R^2 = 0.622$.

By assuming a simpler relationship of the form of equation (11), the following equations were obtained:

a) $V<60$ km/h

$$F = 6.61 + \frac{130.0}{V} \quad (R^2 = 0.60) \qquad (16)$$

and

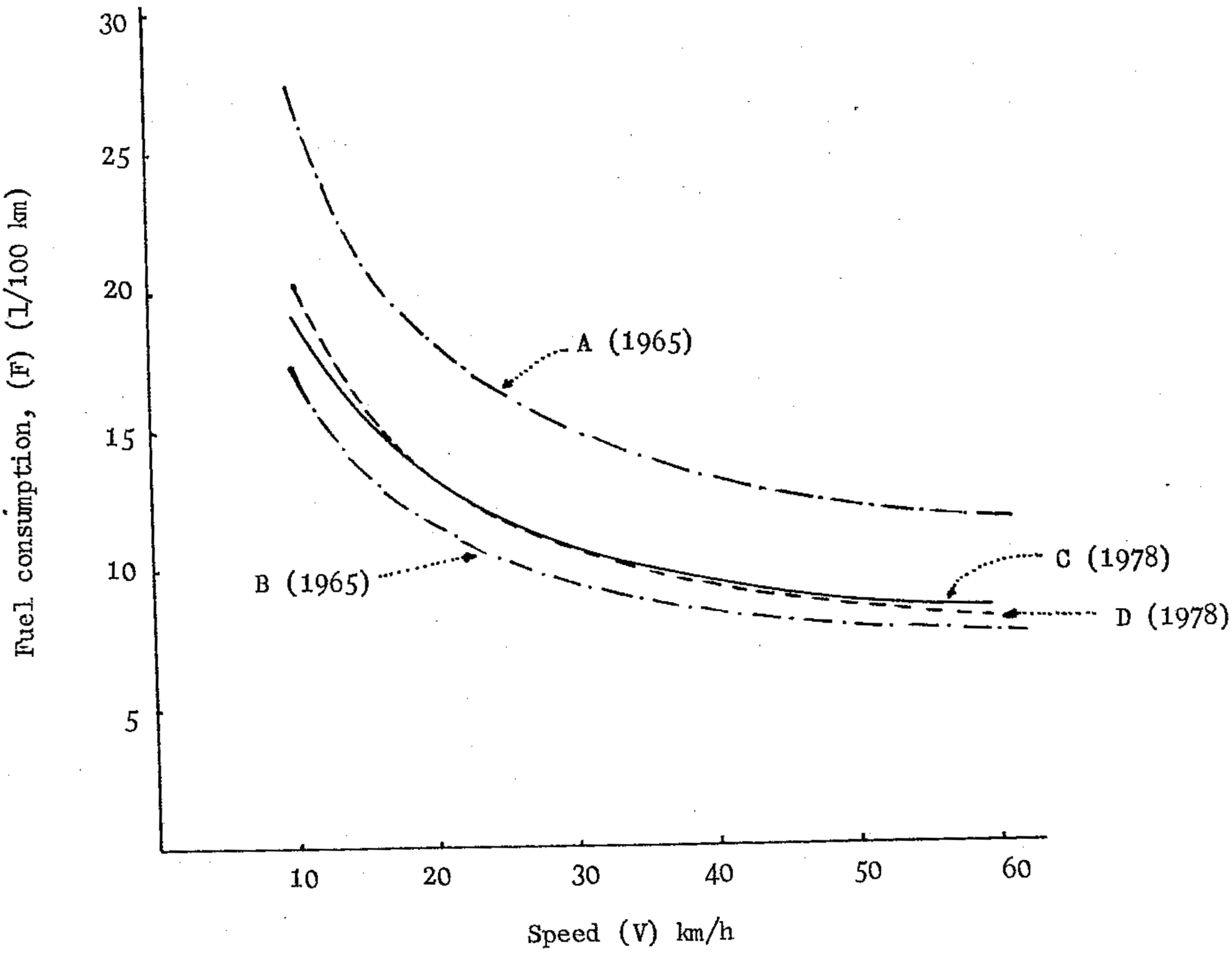
b) $10<V<60$ km/h

$$F = 5.80 + \frac{146.6}{V} \quad (R^2 = 0.58) \qquad (17)$$

This last equation was obtained using average speeds between 10 and 60 km/h, to enable a direct comparison to be made with the expressions developed by Everall for the same speed range. Figure 11 compares graphically equations (12), (13), (14) and (17).

Figure 11. Urban fuel consumption and speed (TRRL studies)

A (1965) - 1700 cc
B (1965) - 1000 cc
C (1978) - 1100 cc (Week's equation)
D (1978) - 1100 cc (Linear equation)



A number of points may be made from these results:

i) Whether a quadratic expression or the simple linear form is used the correlation coefficient is in the range 0.6 to 0.7 and therefore a considerable amount of variation in the data is not explained by any of the relationships developed. This is a problem which will be discussed further in Section 10.

ii) By choosing a simple linear relationship between fuel consumption and the inverse of average journey speed, in preference to expressions of the form of equations (14) and (15), not a great deal of explanatory power seems to be lost. For example, equations (15) and (16) which use the same average speed range and a quadratic and a linear relationship respectively, have corresponding correlation coefficients of 0.62 and 0.60.

Experimental work of this nature leading to the establishment of similar relationships between fuel consumption and journey speed has also been carried out in other countries. The next section deals with the results of work reported in the U.S., Australia and South Africa.

9.2 Overseas findings

The National Institute for Transport and Road Research (N.I.T.R.R.) in Pretoria undertook some experimental fuel consumption tests as part of a study to quantify the costs of travel in urban areas throughout South Africa, Pienaar (1981). Those tests, which covered routes in all the major urban areas of that country yielded the following equation:

$$F = 3.1 + \frac{244.8}{V} \qquad (18)$$

where F and V are expressed as before. The coefficient of determination is given as 0.94 and the expression is valid for speeds of less than 63 km/h.

Chang et al (1976), at General Motors in the U.S., have put forward a number of expressions relating fuel consumption to average journey speed using mainly American vehicles. The values found for k_1 and k_2 in euqation (11) are given in Table 11. The results of an earlier Australian study are also given in the same table.

It was not possible to establish the 'goodness-of-fit' of such equations from the information available in the reference cited above.

Table 11 Fuel consumption sub-models - coefficients k_1 and k_2 from U.S. and Australian studies

$(F = k_1 + \frac{k_2}{V})$ 1/100 km.

Reference	Vehicle	Year	k_1 (1/100 km)	k_2 (1/100 hrs)
Chang et al (1976)	Large-luxury American	1974	12.2	390.2
"	'Standard' American	1974	11.2	376.2
"	'Standard' American	1975	9.5	347.0
"	'Subcompact' station wagon - American	1975	7.2	212.4
Pelensky et al (1975)	Station-wagon American	1965	6.2	214.2

When making comparisons with the corresponding values for the coefficients k_1 and k_2 obtained in the U.K., it must be remembered that all the U.S. values given in Table 7.1 were obtained with vehicles which have automatic transmissions. The engine sizes are also considerably larger than in the U.K., although no detailed data on vehicle characteristics is available from the reference in question. For example, the 'standard' American vehicle of 1974 shown in the Table had an eight cylinder engine of 6600 cc capacity.

Although the American work is not directly transferable to European vehicle characteristics, the results are still very useful inasmuch as they provide further evidence that the inverse of average journey speed is the traffic flow variable which best helps to explain urban fuel consumtpion variations.

Chang et al (1976) have also advanced 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 consumed per unit distance to overcome mechanical losses. The relationship between k_1, k_2 and vehicle characteristics will be further discussed in Section 9.4.

9.3 Results from the Leeds Survey

The survey conducted in Leeds using two instrumented vehicles and described in Appendix A, provided link and route data which enabled the establishment of relationships of the type described in the previous sections - i.e. equation 11. The results obtained using link and route data will now be discussed in turn.

a) Link data

Data containing a complete set of link variables (described in Appendix A) was available for a total of 579 observations and all but 57 of these are associated with the same driver and vehicle. Figure 12 shows a plot of fuel consumption per unit distance against travel speed for each link. Table 12 gives the values of k_1, k_2 and their respective standard errors and the correlation coefficient for a number of equations which were obtained using different sub-sets of the data. The latter were used to determine the sensitivity of k_1 and k_2 to changes in:

a) link type (i.e. Radial/Central Area)
b) speed range
c) minimum link length.

The following comments are now made in relation to Table 12.

i) For a range of travel speeds not exceeding 60 km/h and excluding those links whose lengths are shorter than 50 m (to avoid atypical traffic conditions in very short sections of road), then equation 3 gives:

$$F = 5.41 + \frac{160.8}{V} \qquad (19)$$

where F is in l/100 km and V in km/h, and the R^2 value is 0.7.

There is relatively little change in the coefficients k_1 and k_2 where the minimum link lengths is 100 m when all links are included.

ii) By considering the Radial and Central Area link types separately two quite different results are obtained. The explanatory power of the equations obtained using Central Area data (R^2 = 0.46) is considerably lower than that of the corresponding equation for radial links (R^2 = 0.77). This can be partly explained by the fact that all

Table 12 Link fuel consumption and observed speed relationships – The Leeds experiment

$$\boxed{F = k_1 + \frac{k_2}{V}}$$

(where F is in 1/100 km and V is in km/h.)

(1) Figures in () are the standard errors of the corresponding coefficients.

Equation Number	Data Set	Number of Obs.	k_1	k_2 (1)	Coefficient of determination (R^2)	Speed (km/h)		Fuel Consumption (1/100 km)	
						Mean	St. Deviation	Mean	St. Deviation
1	All links	579	5.175	164.2 (4.5)	0.70	38.3	16.0	11.0	6.0
2	Links with: Dist > 50 m	575	5.153	163.8 (4.4)	0.70	38.4	16.0	11.0	5.9
3	Links with Dist > 50 m V < 60 km/h	527	5.410	160.8 (9.0)	0.70	35.9	14.4	11.4	6.0
4	As Eqn. 3 and also V > 10 km/h	510	5.359	162.8	0.43	36.9	13.6	10.7	4.4
5	As Eqn. 3 but Radial Routes only	343	4.620	166.3 (4.9)	0.77	39.9	14.2	10.2	6.4
6	As Eqn. 3 Central Area runs only	184	8.230	123.0 (9.8)	0.46	28.4	11.5	13.7	4.5

Central Area links used here are part of the same route, whereas the 343 radial observations cover five different routes and therefore have a larger degree of variation in traffic conditions. An equation using only one traffic parameter, i.e. average speed, will perform better with this larger spread of values.

iii) When the speed range is restricted to speeds between 10 and 60 km/h the correlation coefficient is again considerably lower (R^2 = 0.43).

Other forms of fuel consumption equations have been proposed (e.g. Watson et al (1982)) and some of these were investigated here. Two different formulations were used, namely:

$$F = a_o + \frac{a_1}{V} + a_2 V + a_3 V^2 \qquad (20)$$

and

$$F = a_o + \frac{a_1}{V} + a_2 V + a_4 KE \qquad (21)$$

where all variables are as before and KE is the loss of kinetic energy as calculated by the TRRL data analysis program. If the number of distance pulses recorded in three successive seconds are X_t; X_{t-1} and X_{t-2} such that $X_t < X_{t-1} < X_{t-2}$, then KE is given by*:

$$KE = \left(\frac{X_{t-2} + X_{t-2}}{2}\right)^2 - \left(\frac{X_{t-1} + X_t}{2}\right)^2 \qquad (22)$$

The sum of these losses of KE for each link is used in the regression analysis described here.

The values found for the coefficients of equations (20) and (21) are shown in Table 13. Unless stated otherwise in this table all coefficients were found to be statistically significant at the 99% level of confidence, although the explanatory power of the equations has not significantly improved with the addition of the extra terms of the two equations.

... ...

* Obtained from an internal report prepared by the Urban Networks Division of the TRRL.

Table 13 Fuel consumption average speed and kinetic energy - Leeds experiment

$$F = k_1 + \frac{k_2}{V} + k_3 V + k_4 V^2 + k_5 (KE)$$

Equation Number	Data Set	Number of Obs.	k_1	k_2	k_3	k_4	k_5	R^2
1	All links	579	3.692	163.8 (9.3)	0.135 (0.061)	-0.0021 (0.0007)	-	0.71
2	Links with Dist > 50 m V < 60 km/h	527	0.141*	178.6 (10.2)	0.318 (0.080)	-0.0046 (0.0019)	-	0.72
3	As in Equation 2.	527	8.470	143.1 (7.0)	-0.061 (0.015)	-	-0.0035 (0.001)	0.71

* Not significant at 95% Confidence level.

b) Route data

The data was aggregated for each run of each route so that the fuel consumption for each complete journey could be expressed in terms of journey speed. The mean speed of all runs was 37.6 km/h (standard deviation of 7.7 km/h) and the corresponding value for the Central Area route was 20.6 km/h (standard deviation of 4.7 km/h). The following relationship was obtained using data for 32 runs on the radial route and 6 runs on the Central Area route:

$$F = 2.24 + \frac{245.2}{V} \qquad (23)$$

where F and V are defined as before and a correlation coefficient, R^2, of 0.99 applies. The standard error for k_2 is 15.2.

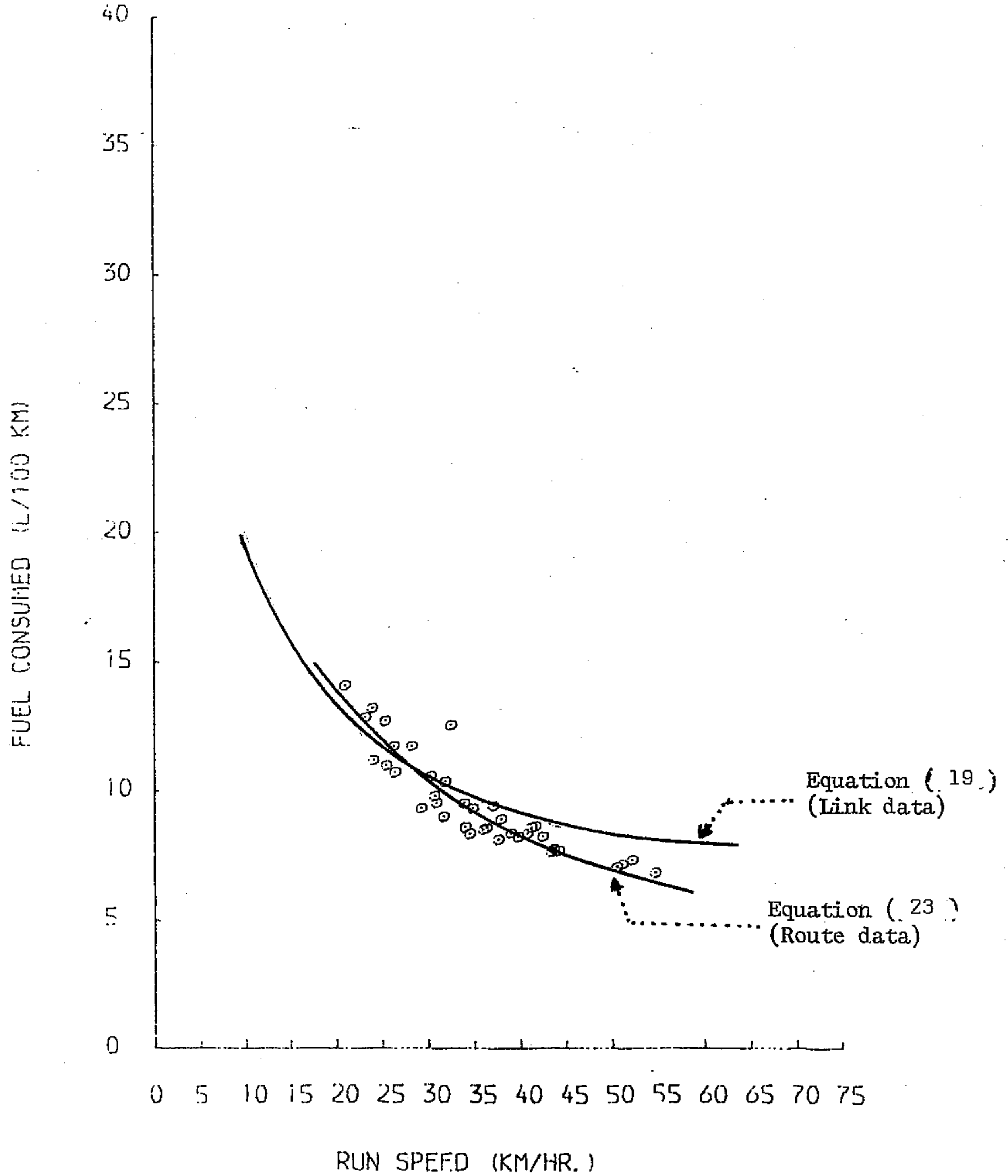
The data used to derive equation (23) is shown graphically in Figure 13. It is seen from this Figure that the average run speeds are all in the range 20 to 55 km/h. Since a great deal of the link data variation is no longer present here, the coefficients of equation (23) are considerably different from those obtained using data for the same runs disaggregated by link - equation (19). The two curves obtained from using these two equations are shown in Figure 13 from which it is seen that very similar results are obtained in the speed range of 20 to 30 km/h.

9.4 A fuel consumption sub-model for the U.K.

Using the results of the work reviewed so far in this Section an attempt is made now to develop a sub-model in which urban fuel consumption is expressed as a linear function of the inverse of average journey speed. Such an expression is to be used at the area-wide aggregate level of detail to quantify the impacts of several UTM measures on fuel consumption. The inputs required are total distance travelled and total time spent travelling i.e. overall journey speed.

It was decided to estimate typical values for the coefficients k_1 and k_2 on the basis of an average vehicle of 1500 cc engine size and a weight of 940 kg. The relationships put forward by Chang et al (1976) between k_1 and vehicle weight were investigated using available data from U.K. experience. The same authors also suggest that k_2 is approximately proportional to the idling fuel rate of the vehicle. This fuel rate may

Figure 13. INSTRUMENTED CARS - LEEDS RUNS
FUEL CONSUMED VS. RUN SPEED



vary even for the same vehicle as was illustrated in Section 3 . However the results presented then indicate that the ratio between engine size and idling fuel rate remains fairly constant. Therefore the coefficient k_2 was related to engine size for the U.K. data shown in the previous section.

Table 14 shows the ratios of vehicle weight (W), to k_1 and engine size (C), to k_2 for four U.K. equations using vehicles which range from a 1964 model - Everall (1968) to a 1982 model (Leeds survey). The same Table also gives the estimated coefficients k_1 and k_2, on the basis of each of the W/k_1 and C/k_2 ratios, for the typical vehicle. The main reasons for the large difference in those ratios are likely to be the different operating conditions of the experiments and the range of vehicles used. The equations derived by both Everall and Weeks were obtained using Central London runs with low average speeds whereas the Leeds data, which was obtained mainly from runs on radial routes outside the Central area, showed an average link speed of 36 km/h. If the earlier results of Everall (1968) are excluded since they were obtained with a 1965 vehicle (Equation (12)), and a 1964 vehicle (Equation (13)), the ranges of k_1 and k_2 for the typical vehicle are 8 and 4.9 and 179 and 121 respectively, using the same units as before. These values will be used here to represent a range of vehicle sizes and urban operating conditions. Clearly it is not possible to make firm conclusions about the most likely coefficients appropriate to U.K. urban conditions, on such evidence and central values for k_1 and k_2 and 165 will be used in the remainder of this work based on the assumption that the typical U.K. vehicle is more likely to be better represented by the results obtained by Weeks (1981) using a 1978 vehicle. Those results were therefore given a weight of 0.75 and rounded off when a weighted average was calculated using Leeds experiment and Weeks (1981) data. Clearly this is an arbitrary decision which has had to be made to arrive at single values for k_1 and k_2. The sensitivity of fuel consumption to changes in the coefficients is shown in Table 15 which shows that when speeds increase for 20 to 30 km/h the difference in the corresponding percentage decrease in fuel consumption is very small. (Either 17 or 18 percent depending on which of the three pairs of k_1 and k_2 values are used.)

The equation which will be used to represent typical U.K. conditions has the form:

$$F = 7 + \frac{165}{V} \qquad (24)$$

where F is in 1/100 km and V in km/h.

This equation can be rewritten in the form:

$$FC = 0.07D + 1.65T \qquad (25)$$

where FC is the total fuel consumed in a road network (in litres)
D is the total distance travelled (veh. km.)
and T is the total time taken (veh. hours).

Wagner (1980) in a recent study evaluating the impact of urban transport improvements on energy consumption in the U.S. used the following equation:

$$FC = 0.12D + 2.73T \qquad (26)$$

where FC, D and T are defined as in equation (25).

These coefficients which are said to apply to the 1976 U.S. vehicle fleet are 1.7 times the values for k_1 and k_2 given by the U.K. equation (25).

10. A MORE DETAILED FUEL CONSUMPTION SUB-MODEL

10.1 General

The type of fuel consumption sub-model described in the previous section is 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, and models which take direct account of the number of stops have been proposed, Messenger et al (1980), and Akcelik (1980). Such models usually take into account three separate elements of an urban trip, namely:

Table 14 Likely range of k_1 and k_2 for a typical vehicle

Reference (Equation Number in text)	Engine Size (cc)	W/k_1 (kg/l/100 km)	C/k_2 (cc/l/100 hr)	Estimated Coefficients for typical vehicle (1)	
				k_1 (l/100 km)	k_2 (l/100 hr)
	1	2	3	4	5
Everall (1968) (7.2)	1057	125.9	9.1	7.5	165
Everall (1968) (7.3)	1703	138.7	8.9	6.8	169
Weeks (1981) (7.6)	1093	116.8	8.4	8.0	179
Leeds experiment (7.10)	1993	193.0	12.4	4.9	121

(1) Assumed to have a weight of 940 kg and an engine capacity of 1500 cc. (from the results of Chapter 4).

Table 15. Fuel consumption sensitivity to changes in k_1 and k_2

Average speed (V) (km/h)	Fuel Consumption (F) (1/100 km)		
	$k_1 = 8$; $k_2 = 179$	$k_1 = 4.9$; $k_2 = 121$	$k_1 = 7$; $k_2 = 165$
10	25.9	17.0	23.5
20	17.0	11.0	15.3
30	14.0	8.9	12.5
40	12.5	7.9	11.1
50	11.6	7.3	10.3
60	11.0	6.9	9.8

1) Distance travelled at cruising speed (D)

2) The amount of stopped time (T_s)

3) The number of stops made (S)

Fuel consumption, FC is thus expressed as:-

$$FC = a_1 D + a_2 T_s + a_3 S \qquad (27)$$

where a_1 = fuel consumed at a steady cruising speed

a_2 = idle fuel flow rate

a_3 = excess fuel per complete stop.

Unlike the statistically determined coefficients of equation (11) values for a_1, a_2 and a_3 can be experimentaly obtained for any test vehicle. The coefficient a_3 represents the difference between the fuel consumed during a complete stop/start cycle and that fuel which would be consumed if the same distance was travelled at an assumed cruising speed as discussed in Part I. 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 estimate total delay experienced, Robertson (1969). 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 (27).

Figure 7.10 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:

$$T_s = T_{Del} - \frac{V}{2} \left(\frac{1}{d} + \frac{1}{a}\right) S \qquad (28)$$

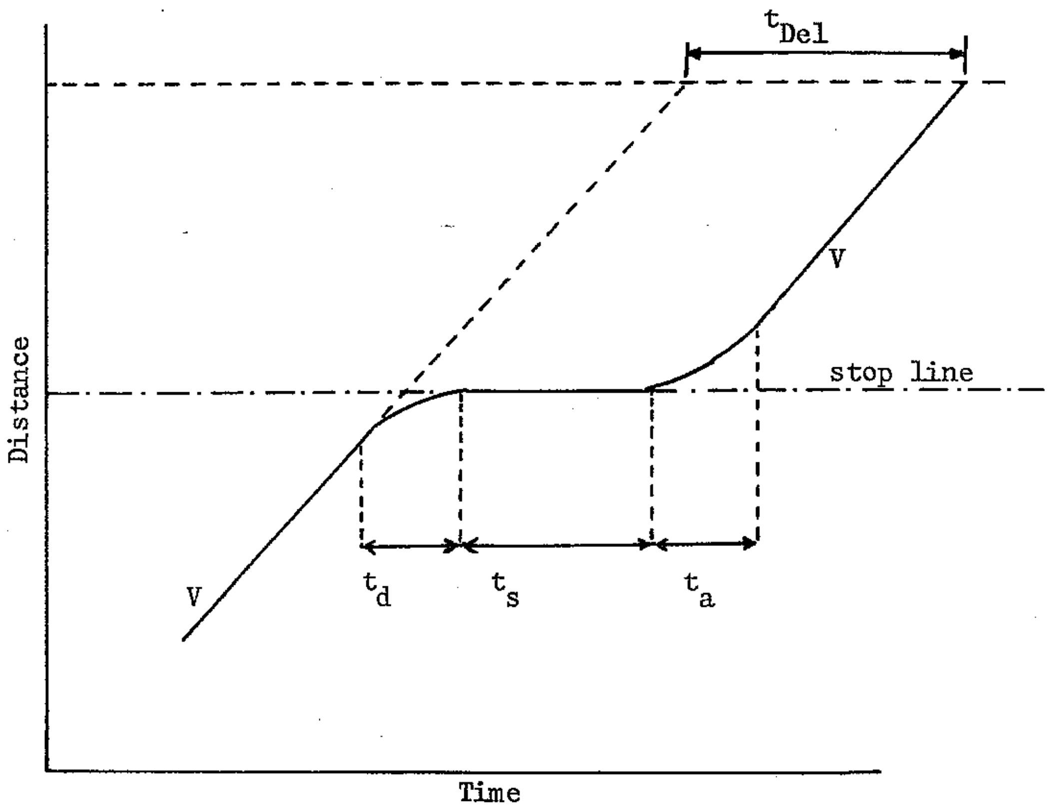
(Note: Capital T is used throughout to denote the summation, for the corresponding values of small t, over all vehicles.)

where S = the total number of stops made in the manner illustrated by Figure 14, i.e. from a cruising speed V to 0 and back to V.

and d and a are the deceleration and acceleration rates which are both assumed constant and positive.

If we make the further simplifying assumption that $d = a = k$ then equation (28) becomes:

Figure 14 Time vs. distance diagram: single stop



$$T_s = T_{Del} - \frac{V}{k} S \qquad (29)$$

From equations (27) and (29) we have:

$$FC = a_1 D + a_2 (T_{Del} - \frac{V}{k} S) + a_3 S \qquad (30)$$

or $$FC = a_1 D + a_2 T_{Del} + (a_3 - \frac{V}{k} a_2) S \qquad (31)$$

Akcelik (1980) has derived such an expression and used it in conjunction with fuel consumption estimates from TRANSYT results.

Before using the results of Part I to arrive at typical values for the coefficients a_1, a_2 and a_3, it is important to stress the difference between a_3, the excess fuel determined experimentally, and a 'correlated' coefficient, a_3', shown in equation (31) and given by

$$a_3' = a_3 - a_2 \frac{V}{k} \qquad (32)$$

where all symbols are as above.

Although a_3' does not represent any physical vehicle fuel consumption characteristic it enables the outputs of traffic flow models to be used directly in the estimation of fuel consumption. The adjustment factor $- a_2 \frac{V}{k}$ - to be applied to the coefficient a_3 is shown in Table 16 for a range of acceleration and deceleration rates and final and initial speeds. Those factors were calculated using the value of a_2 of 1.2 l/hr obtained in Section 3. Using equation (32) and the results shown in Part I, Table 9, for the excess fuel consumed at different speeds, a_3, it is possible to calculate the adjusted coefficient, a_3'. As an example, Figure 15 shows the way in which both a_3 and a_3' vary with initial and final speeds for the case of acceleration and deceleration rates remaining constant and equal to 0.8 m/s^2. It is important to note that all excess fuel calculations refer to that fuel which is consumed over and above that which would have been used to travel the same distance at a cruising speed of 48 km/h, irrespective of the actual initial and final speed been considered. The following values are obtained for a_3 and a_3', where the results described in Part I relating to the Leeds survey are used - i.e. using average acceleration and deceleration rates of 0.75 m/s^2, and assuming a cruising speed of 48 km/h.:

Initial and final speed (km/h)	a_3 (ml)	a'_3 (ml)
20	8	5
30	13	9
48	22	16

The following coefficients of equation (31) can now be put forward:

$$FC = 0.07\ D + 0.2\ T_{Del} + 0.009\ S \qquad (32)$$

where FC is in litres; D in veh-kms; T_{Del} in veh-hours and S is the number of complete stops.

Table 16 Adjustment factors for the coefficient a_3

Initial and final speed, V (km/h)	Adjustment factor (ml)[1] $(= a_2\frac{V}{2k})$ acceleration and deceleration rate, k, (m/s^2)		
	k = 0.6	k = 0.8	K = 1.0
10	1.5	1.2	0.9
20	3.1	2.3	1.8
30	4.6	3.5	2.8
40	6.2	4.6	3.7
50	7.7	5.8	4.6
60	9.2	6.9	5.6

(1) Assumes a_2 = 1.2 l/hr.

a_1 = 0.07 l/km following the constant speed fuel consumption analysis of Section 4, this vehicle assumes a cruising speed of 48 km/h and a vehicle of 1500 cc engine.

a_2 = 1.2 l/hr following the idling fuel consumption analysis of Section 3, assuming a vehicle of 1500 cc engine.

a_3' = 0.009 l/stop is the 'adjusted' excess fuel obtained above for an average initial and final speed of 30 km/h. This is approximately the average speed found from the Leeds experiment for initial and final speeds and is used here as typical of urban area driving conditions. It represents that average speed from which vehicles are likely to decelerate to a stop under a constant deceleration rate, and likewise during the acceleration from that stop. The excess fuel represents the difference between the fuel consumed during a stop/start manoeuvre from and to a speed of 30 km/h, and that fuel which would have been consumed if the same distance was travelled at the nominal cruising speed of 48 km/h. In a model which does not differentiate between types of stop/start manoeuvres the difference in assumed cruising and stop/start speeds represent the fact that at an intersection approach, subsequent stops after the first are made from and to very low speeds and it would be unrealistic to estimate the excess fuel assuming stop/start initial and final speeds equal to the assumed cruising speed. The alternative approach would be assume a cruising speed of 30 km/h when estimating both excess fuel and the travel distance coefficient (0.07 l/km). However such an assumption would imply an unrealistically low cruising speed. Although the average initial and final speed for a stop was found to be in the region of 30 km/h for the Leeds experiment, this does not mean that the vehicles were cruising at those speeds but rather that they started decelerating (and stopped accelerating) at a more or less constant rate.

The following regression equation was obtained using data from the Leeds survey for each complete run:

$$FC = \underset{(0.002)}{0.064}\, D + \underset{(0.41)}{1.99}\, Del + \underset{(0.004)}{0.005}\, S \quad (R^2 = 0.995) \qquad (34)$$

where the notation is as before and Del was defined as the difference between the actual run time and the time it would take to travel the same distance at a constant cruising speed of 48 km/h.

The coefficients a_1 and a_2 of equation (33) are representative of the average vehicle. The excess fuel coefficient is only given as an example of the specific conditions found during the Leeds survey since it applies to a vehicle which is both larger (in engine capacity terms) and much younger than the typical vehicle. Furthermore that coefficient was derived assuming that the average stop is made from a speed of 30 km/h. It therefore represents the difference between the actual fuel consumed by such a stop and that which would have been consumed if the same distance was travelled at the cruising speed of 48 km/h. By varying the assumption of average initial and final speeds for the average stop it is necessary to change a_3' accordingly. However, since the same cruising speed is assumed throughout, the distance coefficient, a_1, will remain unaltered.

The latest version of the TRANSYT program - TRANSYT 8 - uses a fuel consumption sub-model of the form of equation (33) with the following coefficients: $a_1 = 0.07$; $a_2 = 1.5$ and $a_3 = 0.008$ where the units are as given for that equation, Vincent et al (1980). The main difference is in the idle fuel rate, a_2, which in the case of TRANSYT was derived from experimental tests using a larger engine size vehicle (2200 cc).

10.2 The SATURN fuel consumption sub-model

The SATURN traffic simulation and assignment model combines a conventional equilibrium assignment model with a detailed traffic simulation model. The latter is based on the same principles and assumption which TRANSYT uses but deals with each turning movement in more detail.

The output available from SATURN is particularly suited for the estimation of fuel consumption as all traffic variables of the sub-model form given by equation (31) are present in SATURN.

A more detailed expression for the calculation of fuel consumption can be obtained by the inclusion of more than one type of stop made by a vehicle at a junction. One possible approach is to consider average values for the excess fuel consumed for two distinct types of stop:

(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_4 and represents the excess fuel consumed when a vehicle accelerates from a stop to a lower speed and decelerates back to a stop, i.e. the 'queue'crawling' manoeuvre analysed in Part I.

From the results given in the previous Section a fuel consumption expression can be put forward with the following coefficients:

$$FC = 0.07\,D + 1.2\,T_{Del} + 0.016\,S_1 + 0.005\,S_2 \qquad (35)$$

Where the coefficient of S_1 - 0.016 litres/stop - assumes that first time stops are made from an average speed of 48 km/h - the assumed cruising speed - and the coefficient of S_2 - 0.005 litres/stop - assumes that the average 'queue-crawling' stop reaches a speed of 20 km/h. Both coefficients, which are obtained from Section 10.1, were therefore derived through somewhat arbitrary average speed assumptions. Equation (35) shows the default coefficient values presently used in SATURN although it is possible to arrive at different values by using other assumptions more appropriate to local conditions and the methodology presented in Part I.

11. A COMPARISON OF SUB-MODELS USING SATURN OUTPUT DATA

The three types of fuel consumption sub-models put forward in the two previous sections - i.e. the simple 'average speed' expression (equation (25)), the more detailed sub-model with 3 variables (equation (33)) and the SATURN expression using four variables (equation (35)) - are now compared using the results from a run of SATURN with data from the Central area of Liverpool. The sensitivity of the final fuel consumption estimates to changes in the values of the coefficients of the sub-models is also investigated here.

The following set of SATURN outputs was used in this analysis:

Total number of vehicle trips	=	32982
Total distance travelled (D)	=	26840 pcu kms/hr
Total delayed time (T_{Del})	=	642 pcu hrs/hr

Total travel time (T) = 1306 pcu hrs/hr

Average speed = 20.5 kms/hr

Total number of first stops (S_1) = 84953

Total number of secondary stops (S_2) = 23910

These data refers to a run of SATURN using an evening peak origin-destination vehicle trip matrix and a network which represents the base year situation (1978) in the Central area of Liverpool.

Using the above data and equations (25), (33), and (35) the results shown in Table 17 were obtained. The simple 'average speed' sub-model gives an estimate of fuel consumption which is just over 2 percent lower than that given by the SATURN expression - equation (35). Using equation (33) the fuel consumption obtained is 12 percent lower than that given by the SATURN model. Considering the estimates given by equation (35), we have the following contributions of its constituent terms to the total of 4128 litres shown in Table 17:

(i) Distance term = 45 percent

(ii) Delay term = 19 "

(iii) First stop term = 33 "

(iv) Subsequent stops term = 3 "

Table 17 Comparing the results of three fuel consumption sub-models

Sub-model	Equation number in test	Total fuel consumed, FC (1)	Consumption rate (1/100 km)
$0.07\ D + 1.65\ T$	(25)	4034	15.0
$0.07\ D + 1.2\ T_{Del} + 0.009\ S$	(33)	3629	13.5
$0.0y\ D + 1.2\ T_{Del} + 0.016\ S_1 + 0.005\ S_2$	(35)	4128	15.4

(1) Where S is the total number of stops - (i.e. $S_1 + S_2$)

Therefore, for this example, changes in the coefficients representing excess fuel due to first time stops are over ten times more important as those in the coefficient representing the 'queue-crawling' manoeuvre.

Clearly these results are very sensitive to the specific case being considered.

12. SUMMARY AND DISCUSSION

Two types of urban fuel consumption estimation procedure were investigated in Part II. A brief summary of the results obtained for each will now be given in turn.

(i) A linear relationship between fuel consumed (FC), and total distance travelled, D, and total travel time, T, of the form:

$$FC = K_1 D + k_2 T$$

where k_1 and k_2 are constants found from empirical evidence and V is calculated using total travel time including all delay and stopped time. The evidence presented in Section 9 suggests that by using such an equation only some sixty to seventy percent of the variation in fuel consumption, from one road section to another, is explained.

In spite of this shortcoming such an expression is useful in that it can be used with the output of conventional transport demand modelling techniques. The traditional four-step process which begins with trip generation and ends with the loading of traffic onto a road network, i.e. traffic assignment, provides overall distance travelled and time spent on the network, thus enabling fuel consumption to be estimated directly.

The average vehicle for the U.K. passenger car fleet was taken to have an engine size of 1500 cc. Although this value is subjected to errors, the subsequent use to which it is put here means that the value is fairly insensitive to small changes in vehicle size. For such an average vehicle the values for K_1 and K_2 which were put forward are 0.07 l/km and 1.65 l/hr respectively.

(ii) More detailed expressions were also analysed in which fuel consumption (F) is given as a linear function of total distance travelled (D), total delay (T_{Del}), the total number of first time stops at an approach to an intersection (S_1)* and the total number of subsequent stops after the first (S_2)*. The following expressions were put forward:

$$FC = 0.07\ D + 1.2\ T_{Del} + 0.016\ S_1 + 0.005\ S_2$$

and $$FC = 0.07\ D + 1.2\ T_{Del} + 0.009\ S$$

where $S = S_1 + S_2$.

The following assumptions were made when estimating the above coefficients:

a) The average cruising speed coefficient, 0.07 l/km, assumes an average cruising speed of 48 km/h (i.e. the speed limit on most urban roads).

b) The excess fuel coefficient related to the total number of stops, S, assumes that the average stop is made from a speed of 30 km/h.

c) The excess fuel coefficient related to the number of first time stops (S_1) is based on an average initial and final speed for such stops of 48 km/h, i.e. the same as the assumed cruising speeds.

d) The excess fuel related to the number of subsequent stops after the first, i.e. the 'queue-crawling' manoeuvre, assumes average initial and final speeds for such stops of 20 km/h. Although such an assumption is somewhat arbitrary - the analysis of stops in the Leeds experiment was not disaggregated in this way - it is felt that this is a reasonable assumption, given the overall distribution of final and initial speeds in the Leeds case.

A comparison of the results of using the three fuel consumption

... ...

* S_1 and S_2 represent respectively the values of first time and subsequent stops summed over all approaches and over all intersections.

expressions described under (i) and (ii) above was undertaken using the SATURN traffic simulation/assignment model with data from the Central Area of Liverpool. Using the 'typical' values given above for the coefficients of both equations, the final fuel consumption totals were found to be within 12 percent of each other. The overall vehicle consumption rate of 13.5 to 15.4 litres per 100 km for the average 1500 cc engine vehicle found from these results should be compared with the 14.3 litres per km found by Weeks (1981) using an instrumented vehicle of 1100 cc in Central London. The average journey speeds for both cases are very similar (i.e. for the Central Area of Liverpool, as given in Section 11, the average journey speed was 20.5 km/h and speeds in Central London are close to this*).

The case for using a particular method of fuel consumption estimation depends on the use to which the results will be put, i.e. the reasons for the estimation in the first instance, as well as on the level of detail of the available input data. The more detailed expression, which includes the two types of stops as described in Section 10.2 is to be preferred for an evaluation of a number of different traffic management schemes for an urban area where the degree of congestion is high and the main objective is to alleviate that congestion. This is the case of such traffic management measures as improvements to junction control (either individually or as part of an area traffic control system), vehicle restraint measures or the introduction of environmental areas.

As was discussed in Section 6, the coefficients given above do not include the effect of starting with a cold engine which, as was seen, can be considerable in the case of very short trips. If the average journey length and the proportion of trips which start from cold are known, it is possible to adjust the equations by adding an additional term which would be a constant - i.e. the excess fuel due to a 'cold' start per trip - times the number of trips affected.

Other factors not accounted for directly by any of the sub-models ... ...

* The average speeds for the Central Area of London in 1980 were 19.4 km/h and 18.6 km/h in the peak and off-peak respectively, (GLC Traffic Monitoring Review, 1981).

proposed here include the effect of slowdowns and other speed fluctuations, as well as the effect of different gradients. This latter factor may be important when transferring the results in space or when quantifying the effects of UTM measures which are likely to cause rerouting to or from links of considerably different gradients.

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APPENDIX A

THE LEEDS FUEL CONSUMPTION SURVEY USING INSTRUMENTED VEHICLES

A1 INTRODUCTION

This Appendix describes an experiment conducted in May 1982 with two instrumented cars provided by the Transport and Road Research Laboratory (TRRL). The original aims of the experiment were to test the automatic recording of journey times as part of a research project currently under-way at the ITS, University of Leeds, concerned with the monitoring of urban congestion. It was decided to extend the scope of the experiment by adding an additional route covering the Central Area of Leeds to the five radial routes originally planned. The Central Area route and the off-peak time period were included for fuel consumption purposes only.

The next section describes the vehicles used and gives details of the routes covered. The data obtained for the instrumentation on board the vehicles is also described at this stage.

A2 THE VEHICLES

The two vehicles used have identical design characteristics which are shown in Table A1. Both cars were acquired new by the TRRL early in 1982 and will be referred to as car W (white) and car B (blue).

Table A1 The instrumented vehicles

Make:	Ford Cortina
Model:	2.0 GL
Year of Manufacture:	1982
Engine size:	1993 cc
Transmission:	Automatic
Unladen weight:	1042 kg

The cars were fitted with instrumentation which enabled the fuel consumption and distance travelled to be recorded for each one second of vehicle operation. The fuel meters installed in the two vehicles are of the positive displacement type and are considerably more accurate than those installed in past TRRL vehicles, Robertson et al (1980). The fuel meter resolution is 1 ml and the distance can be recorded in units of one quarter of a metre.

A3 THE ROUTES

The vehicles were driven in Leeds from Monday to Friday in the week beginning on the 24th May 1982. Six different routes were covered and these are shown in Figure A1. Each route was subdivided into sections, called links, the end points of which were chosen mainly where delay was expected to occur (e.g. traffic signals, zebra crossings and other restrictions). In a few cases long sections of a route were sub-divided at appropriate landmarks to obtain more disaggregate data. The vehicle instrumentation enabled summary data to be obtained for each link and for the whole route separately.

Tables A2 and A3 show the characteristics of each route and give details of the runs made by each vehicle. Two drivers were used throughout the experiment with driver 1 being allocated to the white car, and driver 2 to the blue car. Only in the case of a small number of runs on the Central Area route did this schedule have to change due to instrumentation problems associated with one of the vehicles. An observer was always present to monitor the instrumentation and identify the passing of the timing point at the end of each link on a route. The observer was required to check a log-sheet listing the timing points.

Table A4 gives details of junction types for each of the routes covered.

A4 THE OUTPUT DATA

Information from each run was stored on a magnetic tape which was then used as input to a program developed by the Urban Networks Division of TRRL. This program outputs two types of data:

(i) Summary data for each link of the route. An example of such data is shown in Table A5. For each link the following information is available: distance; travel time; stopped time; petrol consumed and the loss of kinetic energy experienced by the vehicle over the link. The cumulative data for distance travelled, petrol consumed and kinetic losses since the start of the run, are also output at this stage

and

(ii) The vehicle speed profile as shown in Figure A2. The distance travelled and the fuel consumed for each second are shown here. (Each distance pulse is equivalent to 0.21068 metres, and each fuel consumption pulse represents 1 ml of petrol.) The summary information mentioned in (i) is also given here as shown in Figure A2.

The output data for all runs enabled three sets of data to be coded and stored on the Leeds University computer as three separate data files, namely:

1) Data on vehicle stops
2) Link data
and 3) Route data.

A brief description of the data will now be given.

1) Data on vehicle stops

The information contained in the speed profile output was used to obtain this data set. The following variables were stored for each stop/start manoeuvre:

1) Route number
2) Run number;
3) Driver;
4) Time period;
5) Junction type;
6) Stopped time;
7) Fuel consumed whilst idling;
8) Speed at which deceleration starts (V_i);
9) Time taken to decelerate from speed V_i to zero (t_d);
10) Fuel consumed during time t_d;
11) Final speed reached after acceleration (V_f);
12) Time taken to accelerate from speed zero to V_f (t_a);
13) Fuel consumed during time t_a.

2) Link data

The total number of runs made over all routes generated information for a total of 946 observations with a mean link length of 302 metres (standard deviation of 227 metres). The link length frequency distribution is shown in Figure A3. For each link the following data was stored*. Identification of route; driver; run; time period; and link as well as the following traffic parameters:

1) Travel distance;
2) Travel time;
3) Stopped time;
4) Petrol consumed and kinetic energy loss.

3) Route data

A third data set was built up using aggregate information for each run. Only runs for which there was complete information were used and the following data was stored:

1) Run distance;
2) Journey time;
3) Stopped time;
4) Number of stops;
5) Fuel consumed;
6) Delay assuming a free flow speed of 60 km/h; and
7) Delay assuming 48 km/h as the free flow speed.

This data was obtained by manipulation of the link data file described earlier and by adding the number of complete stops obtained from the speed profile output. Due to difficulties with vaporisation in the fuel pipes only data for 38 runs was included in this analysis. A description of the runs is given in Table A6.

... ...

* Due to technical difficulties with one of the fuel meters most of the fuel consumption data for Central Area links was lost. A number of runs on other routes were also not available when the analysis was undertaken due to problems in reading the magnetic tapes.

Table A2 The routes surveyed

Route Number	Route Name	Route Distance (km)	Number of Links	Day of Survey	Time[1] Period	Number of runs	
						Blue Car	White Car
1	York Rd/ Selby Rd	5.9	14	Monday	M. Peak	5	5
2	Hunslet Rd	3.1	10	Tuesday	M. Peak	9	9
3	Kirkstall Rd	7.6	15	Wednesday	M. Peak	5	6
4	Otley Rd	4.6	12	Thursday	M. Peak	7	7
5	Roundhay Rd	5.7	12	Friday	M. Peak	6	6
6	Central Area	6.3	30	Monday to Thursday	Off Peak Ev. Peak	See Table A3.3	

(1) M. Peak period: 0700h - 0930h

Off Peak period: 1400h - 1600h

Ev. Peak period: 1700h - 1800h

Table A3 Runs on Central Area route

Day of Week	Time Period	Runs made (Vehicle/driver) (1)	
Monday	Off Peak	3 (W/1)	
	Ev. Peak	-	
Tuesday	Off Peak	2 (B/1)	
	Ev. Peak	3 (W/1)	3 (B/2)
Wednesday	Off Peak	3 (W/1)	
	Ev. Peak	3 (W/1)	3 (B/2)
Thursday	Off Peak	3 (W/2)	
	Ev. Peak	1 (W/1)	1 (B/2)

(1) W/1 ⟶ White car, driver 1
B/2 ⟶ Blue car, driver 2

Table A4 Junction type by route

Route Number	Number of Junctions (1)				
	TS	PJ	R	P	Z
1	4	-	1	4	2
2	6	-	-	2	2
3	4	-	-	6	4
4	6	-	-	4	1
5	5	-	1	2	3
6	21	2	-	3	2

(1) TS - Traffic signal; PJ - Priority junction; R - Roundabout
P - Pelican crossing; Z - Zebra.

Table A5 Output link data

Time of Day

RUN NUMBER 41 TAPE RUN NO 41 DATE ON TAPE 20 3 7 30 30

RUN NUMBER 41 TAPE RUN NO 41 DATE ON TAPE 20 3 7 30 30

TP	DIST	CUDIS	JT	ST	PET	CUPET	KE	CUKE
1	211	211	17	0	25	25	7	7
2	424	635	30	0	28	53	19	26
3	337	972	22	0	22	75	12	38
4	612	1584	35	0	21	96	28	66
5	1144	2728	66	0	85	181	291	357
6	526	3254	31	0	36	217	48	405
7	788	4042	48	0	50	267	119	524
8	145	4187	15	0	8	275	168	692
9	1014	5201	72	0	79	354	45	737
10	361	5562	24	0	27	381	78	815
11	223	5785	15	0	16	397	43	858
12	479	6264	35	0	32	429	154	1012
13	242	6506	21	0	19	448	54	1066
14	335	6841	32	0	27	475	28	1094
15	704	7545	74	16	58	533	253	1347

RUN NUMBER 42 TAPE RUN NO 42 DATE ON TAPE 20 3 7 49 18

RUN NUMBER 42 TAPE RUN NO 42 DATE ON TAPE 20 3 7 49 18

TP	DIST	CUDIS	JT	ST	PET	CUPET	KE	CUKE
1	216	216	18	0	28	28	4	4
2	426	642	29	0	25	53	42	46
3	337	979	23	0	20	73	61	107
4	599	1578	38	0	18	91	26	133
5	1169	2747	67	0	80	171	92	225
6	513	3260	31	0	28	199	94	319
7	790	4050	86	24	71	270	370	689
8	147	4197	11	0	21	291	0	689
9	1015	5212	62	0	69	360	35	724
10	358	5570	22	0	21	381	47	771
11	232	5802	15	0	15	396	25	796
12	471	6273	52	1	47	443	257	1053
13	240	6513	22	0	20	463	135	1188
14	323	6836	67	13	52	515	119	1307
15	726	7562	71	10	65	580	296	1602

TP - Timing point (i.e. end of a link)

DIST - Distance travelled from previous to present TP (m)

CUDIS - Total distance travelled on this run so far (m)

JT - Total travel time from previous to present TP (sec.)

ST - Stopped time from previous to present TP (sec.)

PET - Petrol consumed from previous to present TP (ml)

CUPET - Total petrol consumed on this run so far (ml)

KE - Kinetic energy loss from previous to present TP

CUKE - Total kinetic energy losses on this run so far.

Table A6 The 38 complete runs

Route Number	Driver	Number of Runs	Total Distance (km)
1	1	5	29.5
2	1	9	27.9
3	1	6	45.6
4	1	7	32.2
5	1	5	28.5
6	1	4	37.8
	2	2	
	TOTAL	38	201.5

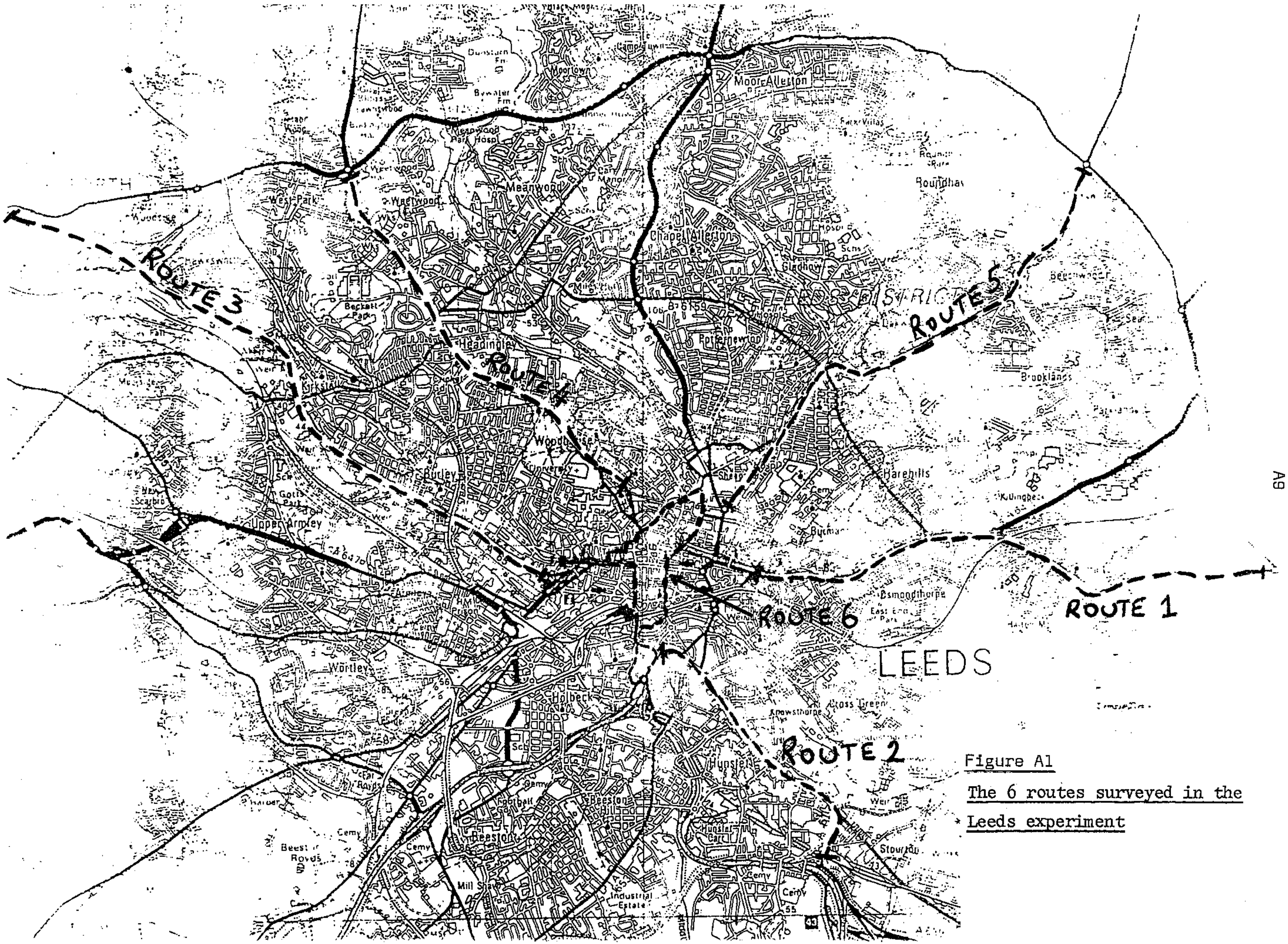

Figure A1

The 6 routes surveyed in the Leeds experiment

A9

Figure A2 Example of speed profile output

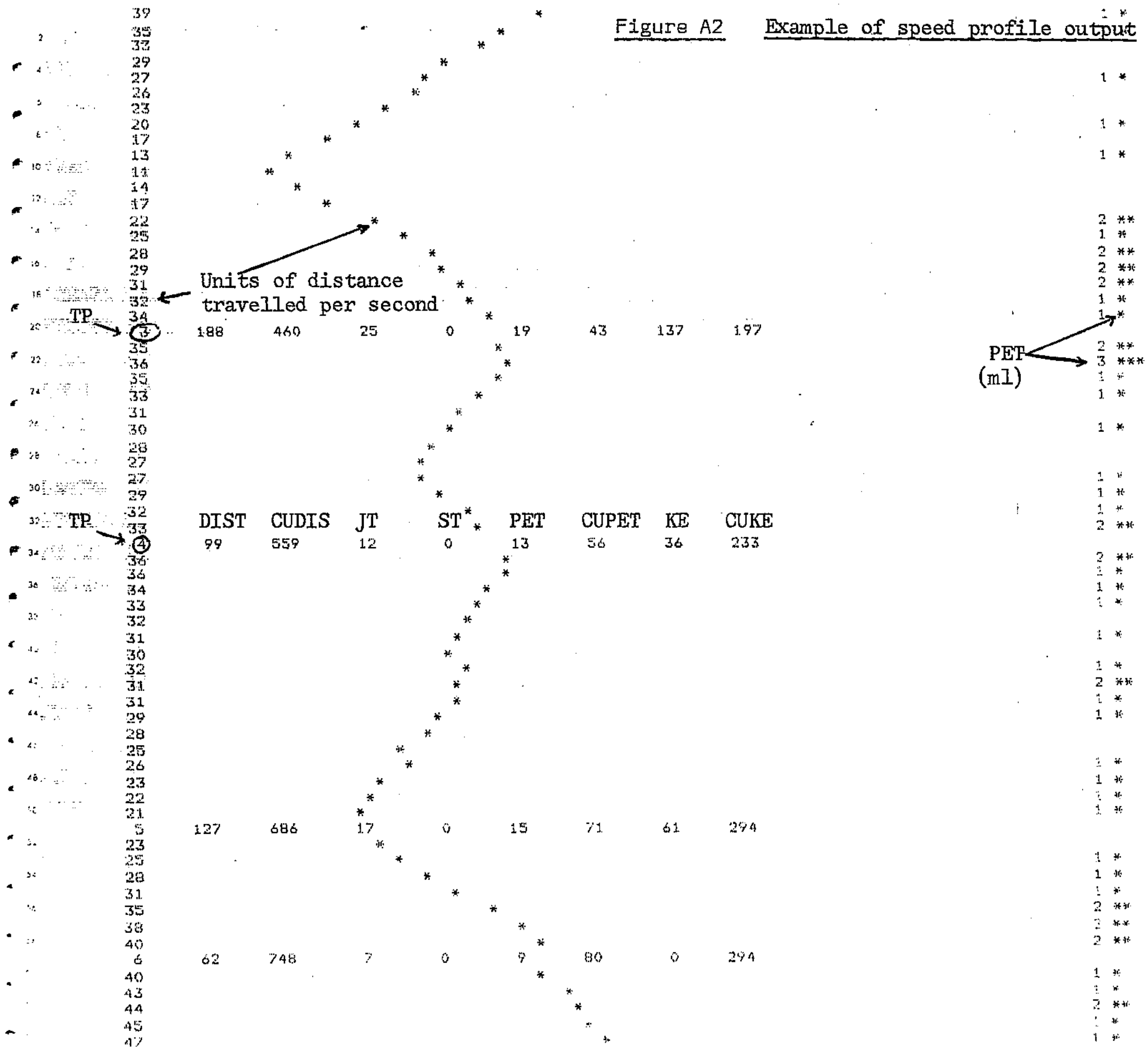

Figure A3 INSTRUMENTED CARS - LEEDS RUNS
FREQ. DISTRIBUTION - LINK DISTANCE