COORDINATING TRAFFIC SIGNALS TO REDUCE FUEL CONSUMPTION

by

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COORDINATING TRAFFIC SIGNALS TO REDUCE FUEL CONSUMPTION

ABSTRACT

The delay suffered by traffic in an urban area can be reduced by coordinating adjacent signals on fixed time plans. Plans that minimise delay may be derived by an offline optimisation method such as TRANSYT. This method can be extended to predict the fuel consumed within a network of signals as a function of the distance travelled, the total delay time and the number of stops. The calibration and use of TRANSYT to minimise fuel consumption is described.

TRANSYT predicts that, in central urban areas, a saving in delay that reduces journey times by, say, 10 per cent is likely to save from 6 to 8 per cent of the fuel consumed. TRANSYT has also been used to derive fixed time plans that minimise fuel consumption rather than delay. When tested in Glasgow, an additional fuel saving of about 3 per cent was both measured and predicted. This fuel saving is estimated to be worth £75,000 per annum within the network of 91 signals in central Glasgow.

The results in Glasgow may not be typical of other cities but the TRANSYT method can be used elsewhere to estimate the benefits on fuel consumption of signal coordination.

1. INTRODUCTION

The delay suffered by traffic in an urban area can be reduced by coordinating adjacent signals on fixed time plans. The signals are operated on a common cycle time and their relative stage change times are set so that, as far as possible, vehicles encounter green indications as they travel through the urban area. TRRL have conducted experiments\(^1\) that demonstrate that fixed time plans, calculated off-line by a computer based method such as TRANSYT\(^2\), provide a simple yet efficient form of control. Plans are calculated for the average traffic flows expected during the working day – typically, separate plans are calculated for the morning peak, for the between peak period and for the evening peak. Other plans may be provided to deal with special events such as a football match and public holidays.

It is common practice for traffic engineers to calculate fixed time plans that minimise vehicle delay and hence average journey times. Plans that minimise journey times are, in general, also likely to reduce the total fuel consumed and to achieve safety and environmental benefits compared with methods of control that cause more delay. However there is the possibility of deriving fixed time plans that explicitly seek to minimise fuel consumption even though one consequence may be some increase in delay. The purpose of this report is to describe some theoretical studies of the relationship between vehicle delay and fuel consumption and to present the results of an experiment which was conducted to test the validity of the theory.

Section 2 describes measurements of fuel consumption that were made under controlled conditions on the test track at TRRL. Section 3 describes how these measurements are used with the TRANSYT...
traffic model to predict the consumption of fuel as a function of the total distance travelled, the delay and the number of stops. In Section 4, the TRANSYT signal optimiser is used to investigate the relationship between vehicle delay, stops and fuel consumed within a test network of 21 signalled junctions. Section 5 describes how the results from earlier sections were used to derive two sets of fixed time plans to control traffic in central Glasgow. The first set of plans was designed to minimise journey time whilst the second set of plans was intended to minimise fuel consumption. Section 5 includes the predictions made by TRANSYT for the effects of these signal timing plans on journey times, vehicle stops and fuel consumption in Glasgow. Section 6 describes a traffic survey in Glasgow during which the above two sets of fixed time signal plans were used and their effects on traffic measured by the floating car technique. Section 7 discusses various aspects of the work and the conclusions are given in Section 8.

The joint importance of delay and stops to fuel consumption, and the relevance of TRANSYT, have been recognised by others. For example May has produced an extended version of TRANSYT called 6C that estimates fuel consumption using similar principles to those described in this report. A slightly simpler procedure is adopted by Akcelik in his version '6N' of TRANSYT. Courage has used TRANSYT to estimate the effects of signal coordination on fuel consumption. The model of fuel consumption described in this report has been incorporated by TRRL into version 8 of TRANSYT.

2. MEASUREMENTS OF FUEL CONSUMPTION

Figure 1 shows the movement of three vehicles as trajectories in time and space. The vehicles are assumed to be travelling within an urban area through a series of signal controlled road junctions. The purpose of the diagram is to illustrate the alternative ways in which vehicles may be affected by traffic signals and by the queue that the signals cause.

Vehicle A is fortunate and travels at a steady cruising speed through all the signals without delay. The slope of the trajectory corresponds to the cruising speed of the vehicle which is assumed to be dictated by conditions along the street, eg speed limits, parking, pedestrians and road width. Vehicle B has to stop at several signals but in each case the delay is short. The total delay suffered by B is defined as the additional journey time over that required to travel the same distance at cruising speed. Vehicle C experiences only one stop but the delay is somewhat longer than for B. The diagram illustrates that, in general, there need be no fixed relationship between the distance travelled, the time spent delayed and the number of stops. Since appreciable quantities of fuel may be consumed during each of these three vehicular states, it is reasonable to expect the total fuel consumed in an urban area to be some function of these three variables. A simple relationship that satisfies this requirement is:

\[ F = aL + bS + cD \]  \hspace{1cm} (1)

where, in a specified period of time:

- \( F \) is the total fuel consumed in litres
- \( L \) is the total distance travelled in vehicle-kilometres
- \( S \) is the total number of vehicle stops, and
- \( D \) is the total delay in vehicle hours.
The coefficients a, b and c convert the measures of traffic behaviour into the quantity of fuel used. The values of these coefficients will depend upon such characteristics of the urban area as the traffic composition (e.g., proportion of goods vehicles), cruising speeds, road gradients and so on. Whilst some information is available that suggests average values for these coefficients, it was decided to conduct fuel flow measurements to determine values a, b and c for the type of survey car to be used in the subsequent traffic experiment in Glasgow. This procedure has the merit that, if equation 1 is valid, there should then be close agreement between the theoretical and actual fuel consumptions of the survey cars. On the other hand, the procedure has the limitation that no direct information is gained on the fuel consumed by other types of vehicles. However, Section 2.2 presents evidence to show that the results in this report are consistent with measurements on traffic of mixed composition.

Use of equation 1 is proposed for situations where the traffic engineer is concerned with the effect of signal timings on fuel consumption. Where other traffic management actions are contemplated, for example 'no parking' restrictions, then the effects on fuel consumption will be indirect through changes in the average cruising speeds and hence in the values of a, b and c. This report does not investigate such effects.

2.1 Fuel consumed during speed change cycles

A series of measurements of fuel consumption were made under controlled conditions on the test track at TRRL. The purpose was to determine values for the coefficients a, b and c in equation 1.

The measurements were made with one of five similar cars that have been used by TRRL for some years for journey time measurements. The car is a medium sized family saloon with an unladen weight of 1204 kilogrammes. The engine is of 2.2 litre capacity with 6 cylinders and develops 110 BHP at 5250 rpm. The car is fitted with automatic transmission and power steering to reduce fatigue and to help drivers to perform in a consistent manner throughout long periods of measurements. It had covered about 45,000 km at the time of the test.

Prior to and during the tests, the ignition and carburettor settings of the engine were checked using modern test equipment. Fuel consumption was recorded by a Floscan 624E meter, the calibration of which was checked prior to the tests. Some tests were repeated with direct measurements of the total volumes of fuel drawn from an auxiliary tank. The distance travelled each second was recorded on magnetic tape cassettes by special equipment that is installed in these TRRL cars.

The tests were conducted within TRRL on a circular track 1.48 km long. Seven 'stoplines' were marked at positions around the track. Ten drivers were each asked to perform three pairs of runs. A 'pair' of runs consisted first of driving around the track for seven circuits at a constant cruising speed. The second run of the pair consisted of a further seven circuits during which the driver stopped at each of the seven stoplines and immediately restarted. Hence, the second run included a total of 49 speed change cycles from which the excess fuel used per stop could be estimated. The three pairs of runs for each driver differed in that drivers were asked to maintain a steady cruising speed of, respectively, about 30, 40 and 50 km/h at all times other than during the stop/start speed change cycles. These speeds were chosen to span the range of cruising speeds likely to be used in urban areas. Measurements were also made of the fuel consumed whilst the engine was idling.

The ten drivers were selected from TRRL scientific staff; none were professional drivers but most had experiences of traffic surveys in urban areas. These drivers were instructed to decelerate and accelerate...
as they would during ‘normal’ urban driving. However, it is possible that the absence of interference from other vehicles and the usual physical features of urban streets may have had some effect on driver behaviour and hence fuel consumption. It is unlikely that the errors in fuel consumption that can be attributed to the artificial nature of these tests are important but it is desirable that the measurements should be confirmed under more realistic traffic conditions. In urban areas there is a complex interaction between the traffic situation and driver behaviour that makes it difficult to attribute correctly fuel use to speed change cycles from and to specific cruising speeds — this subject requires further study.

The results of the above series of tests are summarised in Table 1.

<table>
<thead>
<tr>
<th>Measured cruising speed — km/h</th>
<th>32.3</th>
<th>41.4</th>
<th>52.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel used in litres:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) to cover 10 km at cruising speed</td>
<td>1.07</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>b) excess fuel for 100 stop/starts</td>
<td>0.63</td>
<td>0.94</td>
<td>1.41</td>
</tr>
<tr>
<td>c) per hour during idling</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
</tbody>
</table>

* unladen weight of 1204 kg; 6 cylinder engine of 2.2 litre capacity; automatic transmission and power steering.

The table shows that the fuel consumed at a steady speed is not greatly affected by cruising speeds within the range 30 to 50 km/hr. The fuel consumed whilst the car was stationary is, of course, the same regardless of the initial cruising speed. However, Table 1 shows that, as expected, the fuel consumed during a stop/start cycle depends strongly upon the initial cruising speed. Simple theory suggests that the quantity of fuel used would be proportional to the kinetic energy lost during braking and hence to the square of the speed. The values in Table 1 are reasonably consistent with this relationship but there is insufficient data to establish a more accurate relationship.

Throughout the delay time it is assumed that fuel is used at ‘idling’ rate even though part of the delay accrues whilst vehicles are accelerating or decelerating, as can be seen from Figure 1. It should be noted that line ‘b’ of Table 1 gives the excess fuel required to stop and restart compared to the fuel required to idle for the same delay time. Thus, line ‘b’ was calculated by first subtracting the fuel used in steady cruising from the fuel used in stop/start circuits and then subtracting the fuel that would be used at idling rate during a period equal to the excess journey time. This procedure has no direct physical interpretation but has the advantage that the coefficients in Table 1 can be applied directly to the TRANSYT predictions of delay and stops. Further, in practice the time spent ‘idling’ depends on the extent to which drivers ‘crawl’ at slow speeds and the minimum distance — time increment that is assumed to indicate zero speed; for example, is a vehicle stopped if it covers less than 1 metre in 5 seconds? The procedure adopted in this report has the merit that it is insensitive to these aspects of traffic behaviour.

To clarify the method of estimating fuel consumption, assume that the survey car stops and restarts once whilst travelling 100 metres. No time is spent idling but the delay time is 10 seconds. If the cruising speed is a nominal 40 km/hr then, from Table 1:
(a) fuel used to cover 100 metres at cruising speed = 9.7 cc's
(b) fuel used by 1 stop/start = 9.4 cc's
(c) fuel used at idling rate during 10 seconds delay = 4.2 cc's

Total = 23.3 cc's

Table 1 gives the average values of the fuel consumption coefficients as determined by tests involving ten drivers. The variation between individual drivers and due to measurement errors, caused a standard deviation of about 3 per cent in the fuel consumed at 'constant' speed. The standard deviation on the measurement of the excess fuel per 100 stop/start is about 11 per cent. Rather surprisingly, considerable variation was measured in the fuel consumption whilst idling. A series of 30 minute measurements on the test car yielded a standard deviation of about 13 per cent due, it is thought, to small changes in the engine speed and temperature. When the engine was carefully adjusted to a very slow idle speed, the consumption was reduced to below one litre per hour; the importance of this measurement is discussed in Section 7.4.

2.2 Comparisons with other measurements of fuel consumption

Everall\(^7\) studied the fuel consumption of several types of vehicle as a function of their average journey speed under a variety of conditions in England including travel in urban areas. He concluded that the fuel used per vehicle in a traffic stream of average compositions is given by the relationship

\[
C = 6.11 + \frac{209}{V} + 0.0004V^2
\]

where

- \(C\) is the consumption in litres per 100 km
- \(V\) is the average journey speed in km/hr

This relationship is widely used and is plotted in Figure 2. It is seen that the average fuel consumption is minimised for journey speeds of about one minute per kilometre and increases at lower and higher journey speeds. No attempt was made in reference 7 to determine the separate components of fuel consumption that could be attributed to cruise time, delay and stops.

The fuel consumption model that is assumed in equation \(1\) implies that the fuel consumed is a linear function of the average journey time provided that the number of stops is directly related to the total delay. Later sections of this report show that the relationship between stops and delay can vary but that a typical value in the conditions studied is 40 seconds of delay for each stop. With this value, the fuel usage implied by the coefficients in Table 1 is shown on Figure 2 as a linear function of journey time for each of the three cruising speeds. It can be seen that these linear functions are reasonably consistent, for the longer journey times typical of urban areas, with the measurements made by Everall.

Chang et al\(^8\) have studied the fuel consumed by nine American vehicles ranging in size from a sub-compact car to a large luxury car. They conclude that, in an urban area where the average speeds are less than 60 km/hr, the fuel consumed may be represented by the linear relationship shown on Figure 2. It is seen that, for the same journey time, the fuel consumed by the average American car is considerably higher than that used by the TRRL survey car and the average values reported by Everall. This result is as expected because American cars are relatively heavy and have large engines that are usually fitted with automatic transmissions.
The slope of the 'curves' on Figure 2 suggest that, at journey times typical of central urban areas, action that reduces journey times by 10 per cent, but without affecting the cruise speed, will save approximately 6 to 8 per cent of the fuel consumption. This appears to be a useful general relationship and is further discussed in later sections of this report.

3. PREDICTIONS OF FUEL CONSUMPTION IN AN URBAN AREA

It is relatively easy for a traffic engineer to adjust signal timings and hence affect delay and stops. The likely consequences of such actions on fuel consumption can be predicted by the TRANSYT method of modelling the timings of a network of coordinated signals.

3.1 The TRANSYT model of traffic

TRANSYT is a method of modelling and optimising the operation of fixed time signal plans. The method is implemented by a Fortran IV computer program that is readily available from TRRL. The program is widely used and there is evidence that the predictions of the traffic model accord reasonably well with reality. The importance of TRANSYT in the present context is that the traffic model predicts the total distance travelled, the total delay and the total number of vehicle stops for any signal network of known configuration and average traffic flows. These are the three traffic variables from which, it is argued above, fuel consumption can be predicted. The equation used in this report is:

\[ F = 0.1L + 1.5D + 0.008S \]  

where, in a specified period of time:

- \( F \) is the total fuel consumed in litres
- \( L \) is the total distance travelled in vehicle-kilometres
- \( D \) is the total delay in vehicle hours, and
- \( S \) is the total number of stop/starts

The coefficients in the equation were derived from the series of measurements that were described in Section 2.1 and correspond to an average cruising speed of about 37 km/hr. In other applications where the cruising speeds vary considerably from street to street, equation 3 must be modified in accordance with the fuel coefficients given in Table 1. The next three sections describe how the traffic variables \( L \), \( D \) and \( S \) are estimated.

3.2 Distance travelled

The total distance travelled (\( L \)) is estimated by TRANSYT as the flow weighted sum of the distance along individual links in the network. In TRANSYT the routes chosen by drivers are assumed to be unaffected by the timings of the traffic signals and hence the total distance travelled in a specified period of time is also independent of the signal timings. An exception to this rule occurs where the traffic demand exceeds capacity for extended periods of time and thus the hourly rates of flow along some streets may be lower than expected due to the 'metering' action of one or more upstream junctions that are congested. Whilst the 'metering' action of signals is modelled in TRANSYT, no provision is made to calculate the effects of the resulting queues on traffic conditions at later times. If such traffic situations are of primary interest, they must be studied by means of a method, such as CONTRAM\(^9\), that is designed to model time-varying demands in congested networks.
3.3 Delay

The total delay (D) is the sum of the delay suffered by individual vehicles in a specified period of time and usually has units of 'vehicle-hours per hour' or simply 'vehicles'. Total delay corresponds to the average queue throughout the period of time and is estimated in TRANSYT as the sum of what is called the 'uniform' delay and the 'random' delay. The uniform delay is calculated as described in reference 2. TRANSYT predicts the traffic flow that arrives at each stopline as a histogram of the average flows in successive short intervals (typically 1 or 2 seconds) throughout one cycle time of the signals. These histograms describe the 'platoons' of vehicles that are formed by the operation of the upstream signals. The uniform delay is estimated from these histograms of flows and the red-green periods of the signal.

Additional 'random' delay is caused by cycle-to-cycle fluctuations in traffic behaviour. In the more recent versions of TRANSYT, the original equation used to estimate random delay (reference 2, appendix 2) has been modified. The modification was introduced by Mr P D Whiting so that a more realistic estimate could be made of delay where demand exceeds capacity for a specified period of time as, for example, during a peak period. A simplified form of the equation now used is:

\[ D_r = \frac{t}{4} \left[ (q-Q) + \sqrt{(q-Q)^2 + \frac{2q}{t}} \right] \]  

where

- \( D_r \) is the total delay, in vehicle-hours per hour, due to random effects
- \( q \) is the average vehicular demand flow rate per hour
- \( Q \) is the maximum discharge capacity, in vehicles per hour, across a signal stopline, and
- \( t \) is the time period in hours, that the flow conditions persist.

Equation 4 was derived by an axis transformation on the original random delay term so that the infinity asymptote corresponds to the average value of the queue that would be expected to grow linearly when demand greatly exceeds capacity for time period \( t \). The effect of this modification is illustrated in Figure 3. The theory of time-varying queues is further developed in reference 10.

3.4 Stops

Version 6 of the TRANSYT program\(^{11}\) was developed to support the work described in this report. The main change from earlier versions is that an improved estimate is made of the number of vehicle stops. In previous versions of TRANSYT it was assumed that any vehicle that suffered delay, however brief, experienced one stop. In reality a small delay of, say, three seconds would cause a vehicle to slow down and then speed up without fully stopping. Hence, in this respect early versions of TRANSYT tend to overestimate the number of stops. This simplification is thought to be undesirable where vehicle stops are to be used to estimate fuel consumption. Version 6 of the program has a facility whereby the user of the program can specify the relationship between the time a vehicle is delayed and the proportion of a full stop that is incurred. Reference 11 describes this facility and recommends a set of values that were derived mainly by theoretical calculations based on assumptions about driver behaviour and vehicle performance.

The relationship between delay time and vehicle stops has been further investigated as part of the series of tests that were described in Section 2.1 of this report. Figure 4 shows the average distance travelled in successive one second periods of time during a speed change cycle. The average is for eight drivers each of whom
performed 49 stop/start speed change cycles from and to a nominal speed of 40 km/hr. Figure 4 shows their average deceleration and average acceleration behaviour as two histograms that overlap. The shaded area above and between the histograms corresponds to the distance that a vehicle undergoing a partial speed change cycle would fall behind a second vehicle that maintained the original steady cruising speed. The delay time as defined above is calculated from this distance divided by the cruising speed. A relationship between delay time and the minimum speed during a speed change cycle can be derived by varying the extent to which the two histograms in Figure 4 are overlapped. The results of such a calculation are shown as a graph at the top of Figure 5. In this calculation, it is also assumed that drivers take 1 second to change from deceleration to acceleration. This is primarily to allow time for the driver to transfer his foot from the brake to the accelerator.

Next, the relative importance of a partial stop is defined as the ratio of the fuel consumed by a partial stop compared to that needed for a full stop. Section 2.1 presents some evidence that the fuel used depends on the kinetic energy loss and hence on the difference between the square of the cruise and minimum vehicle speeds. This relationship has been used to transform the graph at the top of Figure 5 into the lower graph. The lower graph relates the vehicle delay time to the resulting per cent loss of kinetic energy and is of the form required for input to the TRANSYT program.

On the basis of the above measurements and calculations, it is recommended that the following revised values be used with the TRANSYT program versions 6 and 7:

<table>
<thead>
<tr>
<th>Delay time (seconds)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial stop (per cent)</td>
<td>42</td>
<td>64</td>
<td>78</td>
<td>88</td>
<td>94</td>
<td>98</td>
<td>99</td>
<td>100</td>
</tr>
</tbody>
</table>

The lower graph on Figure 5 shows how this relationship differs from that previously recommended. It should be remembered that the new relationship was derived from measurements on one car driven in an artificial situation that did not involve partial stops. Simple theory suggests that this relationship should be sensitive to the initial cruise speed and to the way drivers anticipate delay and minimise their speed loss. It is desirable that further tests be conducted under more realistic conditions with direct measurement of the fuel consumed during partial stops from a range of cruise speeds. Nevertheless it has been found that the TRANSYT predictions of total stops are relatively insensitive to small changes in the relationship between delay and partial stops. The predictions of fuel consumption in subsequent sections are made using the TRANSYT 6 'delay-partial stop' relationship. Use of the revised relationship is likely to increase the predictions of total stops between 1 and 2 per cent but to have negligible effect on the signal optimisation procedure.

One further reservation must be made about the accuracy of the number of stops predicted by TRANSYT. No allowance is made in this report, or in versions of TRANSYT prior to 8, for the additional stops caused by random variations in flow. The argument for such a correction is closely related to that in the previous section for random delay. However, it is necessary to study driver behaviour in congested conditions before reliable predictions of 'random' stops can be made. This is because drivers avoid repeated full speed change cycles where queues are long. An approximate correction for the effect of random stops suggests that the predicted overall fuel consumption should be increased by 1 or 2 per cent but that there will be very little effect on the comparisons in later sections of this report.
4. SIGNAL OPTIMISATION

As stated above, the TRANSYT traffic model predicts, amongst other things, the total vehicle delay and number of stops. These variables are combined together into what is called a Performance Index (PI) given by the equation:

\[ PI = D + K \cdot S \] ........................ (5)

where the delay is \( D \) vehicle-hours per hour and there are \( S \) vehicle stops per second. \( K \) is a constant that can be set to any non-negative value at the discretion of the user of the program. The performance index is a measure of the overall 'inefficiency' of traffic flow and the coefficient \( K \) permits the user of the program to balance the undesirability of delay against that of vehicle stops.

The TRANSYT program contains an optimisation procedure that searches for signal timings that minimise the PI. Hence, if \( K \) is set to zero, TRANSYT will calculate a fixed time plan that minimises delay without regard to the number of vehicle stops. Alternatively, if \( K \) is very large there will be a tendency to minimise stops at the expense of delay. Since delay and stops are to some extent independent of each other, but both affect fuel consumption, it is important to determine the effects of varying the coefficient \( K \). These relationships have been investigated using TRANSYT to predict traffic behaviour in a network of 21 signalled junctions.

The TRANSYT optimisation procedure searches for signal settings that minimise the PI but there is no guarantee that the global optimum will be found and small differences are likely to occur in the final values of delay and stops. This variability is of little concern in most practical situations but in the present context tends to obscure the effect of altering the coefficient \( K \) in the PI. Hence three runs of the TRANSYT program were performed from different initial signal timings for each condition to be studied. The result of each set of three runs is shown on Figure 6 as a triangle. After the signals have been optimised, the size of the triangle is a measure of the variability arising from the searching strategy used in TRANSYT to minimise the PI. Typically, the standard deviation of the variability is between 1 and 2 per cent of the PI.

Each set of three runs differ only in the initial offsets which constitute the starting values for optimisation of the signal timings. These initial offsets were randomised and, in effect, correspond to an uncoordinated network of signals in which the traffic platoons from one signal arrive at random times at the adjacent downstream signal. The delay and stops that correspond to these arbitrary signal offsets are shown by the two larger triangles at the top right of Figure 6. As expected these arbitrary signal timings are predicted to cause both more delay and stops than the optimised signal timings at the lower left of Figure 6.
The two sets of initial signal timings correspond to alternative assumptions about the cycle time of the signals. For one set of timings, all signals were assumed to operate on a fixed time cycle of 120 seconds; this is referred to as 'single cycling'. For the second set of timings, wherever possible junctions were operated on a 60 second cycle time provided that their maximum degree of saturation did not then exceed 90 per cent. Under the traffic conditions studied, it was possible to operate 15 out of the 21 junctions on a 60 second cycle with the remainder on 120 seconds. This mode of operation is referred to as 'double cycling'. Figure 6 shows that double cycling tends to reduce delay but to increase the number of stops. This is true for both the random initial offsets and for the optimised signal settings.

It is apparent from Figure 6 that substantial reductions in both delay and stops can be achieved by coordinating signals that previously operated in isolation from each other. In this example, coordination to minimise delay (double cycle with $K = 0$) achieves a reduction in delay of 31 per cent compared to uncoordinated operation of the signals on a common cycle time of 120 seconds. In addition, vehicle stops are reduced by about 4 per cent. Isolated operation on long fixed cycle times is a poor method of control; the reduction in delay of 31 per cent corresponds to a journey time reduction of about 22 per cent and it is unusual for signal coordination to achieve much larger benefits in journey time.

If the uncoordinated signals are assumed to be vehicle actuated, then the average cycle time of the less saturated signals will reduce and it is likely that the total delay and stops will be similar to those for the network with 'double cycling' and random offsets. If this is so, signal coordination to minimise delay achieves a more modest, but still substantial, delay reduction of 21 per cent, corresponding to a journey time saving of 14 per cent. However, the saving in stops improves to 11 per cent.

It is concluded from Figure 6 that delay is reduced by double cycling signals and setting $K = 0$ in the TRANSYT optimisation procedure. Journey time benefits of up to 20 per cent or more may be achieved by coordination depending on the prior standard of control that is assumed; there are also likely to be worthwhile reductions in the number of stops.

The effects of varying the coefficient $K$ is shown on Figure 6 for both the single and double cycled modes of signal operation. Three optimisation runs were made from random initial offsets for values of $K$ of 0, 2, 5, 10, 20, 50 and 100. It is seen that, as $K$ is increased the number of stops is reduced but there is some increase in delay. This is as expected and effects of similar magnitude occur in both the single and double cycled modes of operation. For example, if the signals are single cycled and $K$ is set to 20 then, compared with double cycling and $K = 0$, the number of stops can be reduced by about 21 per cent but at the expense of a 9 per cent increase in delay. These figures are based on the average of the three signal optimisation runs for each value of $K$. A 9 per cent increase in delay corresponds to a 5 per cent increase in journey time; in practice, such changes in journey time are difficult to measure reliably with 'floating car' survey methods.

Straight lines of constant fuel consumption are also plotted on Figure 6. These lines are derived from equation 3. The fuel used at cruising speed is predicted to be 291 litres per hour and is not affected by the values of delay and stops. Where the signals are coordinated to minimise delay, the extra fuel used in delay and stops is about 316 litres per hour to give a total of 607 litres per hour. This is 13 per cent less than the 701 litres per hour needed where the signals are uncoordinated and on a fixed time cycle of 120 seconds. The 13 per cent saving in fuel corresponds to a 22 per cent reduction in journey time. These relative savings are consistent with those deduced in Section 2.2 from Figure 2.
Table 1 indicates that, for a cruise speed of about 40 km/hr, one stop uses as much fuel as 22 seconds of delay. Hence, a 'K' value of about 20 makes the TRANSYT PI proportional to fuel consumption and signal settings that minimise this PI should therefore minimise fuel consumption. Figure 6 shows that the sensitivity of fuel consumption to the value of K is somewhat obscured by the small variations in the TRANSYT optimisation procedure. Nevertheless, there are indications that the signals should be single cycled to minimise fuel consumption and with K set to 20, it appears that a small but worthwhile additional saving in fuel of about 1 to 3 per cent can be achieved over signal settings that minimise delay (ie double cycle with K = 0). This topic is pursued in the next section.

5. PREDICTIONS FOR CENTRAL GLASGOW

On the basis of the above calculations of the benefits of signal coordination, it was decided to conduct a survey to compare the effects on traffic of signals coordinated to minimise delay (and hence average journey time) with signals coordinated to further reduce fuel consumption. The site chosen was Glasgow where TRRL cooperate with Strathclyde Regional Council to maintain an Urban Traffic Control facility that has been used for many experiments. Version 6 of the TRRL 'TRANSYT' program was used to calculate the two sets of signal coordination plans and to predict, as described above, the outcome of the experiment.

A total of 91 signalled junctions were coordinated together in Glasgow. Two sets of three fixed time plans were derived for the morning, evening and between peak traffic flow conditions. The two sets of plans are referred to subsequently as 'minimum delay' and 'minimum fuel' plans. With the 'minimum delay' plans, about one-third of the signals were double cycled and the weighting on stops in TRANSYT was set to zero. With the 'minimum fuel' plans, all signals were single cycled and the stop weighting in TRANSYT was set to a value of 20. Table 2 summarises the predictions that were derived from TRANSYT.

### TABLE 2

Summary of TRANSYT predictions for the centre of Glasgow

<table>
<thead>
<tr>
<th>Average journey speed (km/hr)</th>
<th>am peak</th>
<th>Period of the day between peaks</th>
<th>pm peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>min-delay plan</td>
<td>min-fuel plan</td>
<td>min-delay plan</td>
<td>min-fuel plan</td>
</tr>
<tr>
<td>13.7</td>
<td>13.8</td>
<td>15.2</td>
<td>14.9</td>
</tr>
<tr>
<td>Total distance travelled (veh-km/hr)</td>
<td>30,752</td>
<td>30,752</td>
<td>30,362</td>
</tr>
<tr>
<td>Total delay (veh-hrs/hr)</td>
<td>1,418</td>
<td>1,407</td>
<td>1,191</td>
</tr>
<tr>
<td>Total stops per hr</td>
<td>117,828</td>
<td>95,832</td>
<td>122,184</td>
</tr>
<tr>
<td>Fuel used (litres per hr):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at cruise</td>
<td>3,075</td>
<td>3,075</td>
<td>3,036</td>
</tr>
<tr>
<td>during delay time</td>
<td>2,127</td>
<td>2,111</td>
<td>1,787</td>
</tr>
<tr>
<td>by stops/starts</td>
<td>943</td>
<td>767</td>
<td>977</td>
</tr>
<tr>
<td>Totals</td>
<td>6,145</td>
<td>5,953</td>
<td>5,800</td>
</tr>
</tbody>
</table>
Table 2 shows that the 'minimum fuel' plans are predicted to reduce fuel consumption by between 2 and 3 per cent and the number of stops by about 18 per cent. In two of the three periods of the day, the 'minimum fuel' plan is expected to increase the time spent travelling by 1 to 2 per cent. However, in one period, the morning peak, there is a reduction of ¾ per cent in the predicted time spent travelling. This is contrary to expectations and was found, after the experiment had been conducted, to be caused by one junction which TRANSYT predicted would become near saturation when double-cycled. This was an error in the preparation of the signal plans but it illustrates a point of real world importance, namely that signals that are double-cycled have less spare capacity to deal with unexpected increases in traffic flows.

Table 2 shows that considerable quantities of fuel may be attributed to all three traffic states of cruise, delay and stops; the proportions are roughly 3:2:1. The effect of delay and stops is, in this network, predicted to approximately double the fuel required to travel the same distance at a steady cruising speed. Note also that the total distances travelled in the am peak and between peak periods in Glasgow are similar but the distribution of flows differs considerably. The heaviest flows occur during the pm peak period.

6. THE TRAFFIC SURVEY IN GLASGOW

The survey followed the practice established by TRRL during previous experiments in Glasgow. Five identical specially equipped cars were used to record journey times, number of stops and fuel consumptions along 15 fixed routes in central Glasgow. Each route took about 20 to 25 minutes to cover and was started at scheduled times. The routes were selected to follow most of the major traffic movements in Glasgow and almost every arm of each signalled junction and all major turning movements were covered at least once.

The working day was divided into four periods: am peak, am off peak, pm off peak and pm peak. All fifteen routes were covered once in each period. A total of 10 working days of measurements were recorded with the 'minimum delay' signal plans in operation and a further 10 days with the 'minimum fuel' timings. The measurements were recorded in the cars on paper tape and subsequently analysed by computer.

The overall average journey speed in each period was estimated as the flow weighted sum of the journey times along individual streets in the network. Average flows on individual streets were recorded in 15 minute periods by the central computer. The total number of stops was estimated as the flow weighted sum of the stops of the survey cars. The equipment in the cars records one stop wherever the distance travelled is less than 2.8 metres (9.2 ft) in one second provided a greater distance was travelled in the previous second.

The resolution in the operation of the fuel consumption meters was such that fuel usage could not accurately be attributed to individual streets. Hence, the fuel consumptions in each period were summed for all the survey routes and converted to an estimate for the area by multiplying by the ratio of the total distance travelled divided by the length of the survey car routes. The total distance travelled was estimated as the flow weighted sum of the distances along individual streets.

The traffic flows vary from day to day and affect congestion and hence journey times, numbers of stops and fuel consumption. The analysis of covariance was used to correct for such effects and the results of the analysis are presented in Table 3. The table compares the estimates derived from the survey car measurements with the predictions described in Section 5. These comparisons are discussed in Section 7.
TABLE 3
Results of the traffic survey in Glasgow

<table>
<thead>
<tr>
<th>Period of the day</th>
<th>am peak</th>
<th>between peak</th>
<th>pm peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured</td>
<td>predicted</td>
<td>measured</td>
</tr>
<tr>
<td>Average journey speeds (km/hr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>min delay</td>
<td>16.5</td>
<td>13.7</td>
<td>15.5</td>
</tr>
<tr>
<td>min fuel</td>
<td>16.7</td>
<td>13.8</td>
<td>16.2</td>
</tr>
<tr>
<td>% change</td>
<td>+1.9</td>
<td>+0.7</td>
<td>+4.1*</td>
</tr>
<tr>
<td>Stops per km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>min delay</td>
<td>6.90</td>
<td>3.83</td>
<td>8.00</td>
</tr>
<tr>
<td>min fuel</td>
<td>6.35</td>
<td>3.12</td>
<td>6.97</td>
</tr>
<tr>
<td>% change</td>
<td>-8.0</td>
<td>-18.7</td>
<td>-12.9*</td>
</tr>
<tr>
<td>Fuel used in litres per 100 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>min delay</td>
<td>19.3</td>
<td>20.0</td>
<td>19.8</td>
</tr>
<tr>
<td>min fuel</td>
<td>18.8</td>
<td>19.4</td>
<td>19.2</td>
</tr>
<tr>
<td>% change</td>
<td>-2.8*</td>
<td>-3.1</td>
<td>-3.0*</td>
</tr>
</tbody>
</table>

* The change is statistically significant at the 5 per cent level.

7. DISCUSSION

7.1 Results of the survey

Table 3 shows that the 'minimum fuel' signal timing plans succeeded in reducing the fuel consumption by about 3 per cent throughout the working day. This result is statistically significant in all periods. There is good agreement between theory and practice in both relative and absolute terms.

The table shows that, in spite of the good results on fuel consumption, there are major discrepancies between the measured and predicted number of stops per kilometre. The measured stops are, on average, twice as numerous as predicted. The most probable explanation lies in the definition of a 'stop' as measured by the survey cars. Each time the speed drops to below 2.8 metres a second, one stop is recorded. Hence, any speed change cycles at slow speeds could result in numerous 'stops'. Conversely, partial stops are not recorded. The magnitude of these effects is not known and further research is required to explain the discrepancies in Table 3. However, the results in Table 3 suggest that the 'minimum fuel' plans succeeded in reducing the number of stops by a substantial amount and the changes are statistically significant, with the exception of the morning peak period, throughout the working day. The procedure used by TRRL to measure stops will be revised in future 'floating car' surveys.

The absolute values of the predicted journey speeds average 10 per cent less than the measured journey speeds; this is probably due to an overestimate of the degree of saturation at some junctions. In all periods of the day, the 'minimum fuel' plan achieves slightly higher measured journey speeds than the 'minimum delay' plan. The changes are contrary to expectations but are statistically significant only in the off peak period. It is possible that some junctions that are double cycled under the 'minimum delay' timings became sufficiently overloaded as to negate the predicted advantages of their shorter cycle time. Earlier experiments in Glasgow indicated that, as predicted by theory, the use of double-cycling could reduce journey times but these latest results suggest that the effect is complex and rather sensitive to data errors. The choice of signal cycle time is a current topic of research at TRRL.
7.2 Other measurements in Glasgow

TRRL have developed a specially instrumented car\textsuperscript{12} that was used, in addition to the five cars already described, to measure fuel consumption and other vehicle parameters during the traffic survey described in Section 6. The car was a Ford Escort 1300 saloon and was equipped to compute vehicle speed, accumulated distance, acceleration, propeller shaft torque, engine power output, fuel flow rate, throttle opening, engine efficiency, locomotive efficiency, fuel consumption and the number of stops. The Escort was driven along two routes selected from the fifteen routes covered by the other five survey cars. The purpose was to assess the above parameters of vehicle operation in urban conditions and to determine whether the two types of survey vehicles recorded consistent information concerning the effects of signal timings on fuel consumption.

It was found that, compared to the 'minimum-delay' signal plans, the 'minimum fuel' plans reduced the average consumption of the Escort by 5.8 per cent while the average journey time increased by 0.3 per cent. These results are in reasonably good agreement with those of the other five survey cars. The overall average fuel saving for the other five survey cars was about 3 per cent but varied considerably between the individual survey routes; the higher saving achieved by the Escort appears to be largely explained by the characteristics of the two routes that were selected from the fifteen covered by the other cars.

The average journey speed of the Escort was 14.8 km/hr and the car was stationary for about 40 per cent of the journey time. The overall consumption was 14 litres per 100 kilometres. These values are consistent with the survey results given in Section 6.

7.3 The costs of delay and stops

The reduction in fuel consumption of about 3 per cent that was obtained by the minimum fuel signal plans is relatively modest but can be implemented at very little cost by a minor alteration to the method of using TRANSYT. In central Glasgow there are approximately 80 million vehicle-kilometres travelled each year through the 91 signals that are under computer control. Fuel is used at about 1 litre per 5 kilometres and hence a 3 per cent saving reduces the fuel consumed by \( \frac{1}{2} \) million litres. The untaxed cost of fuel in late 1979 is about 15p per litre, hence the annual saving is £75,000. This saving in a real resource is achieved without requiring conscious action by drivers, modifications to vehicles or special equipment. Further, the reduction in fuel consumption is likely to reduce the total exhaust emissions and will therefore probably be of some small extra benefit to the environment.

The above saving of 3 per cent is in addition to that achieved where previously isolated signals are coordinated to minimise journey times. The savings achieved in urban areas by coordination will depend strongly on the spacing between signals, the levels of traffic flow and the prior method of control. On the evidence in this report, the savings in fuel consumption may be up to 15 per cent and hence be worth up to £4000 per signalled junction per annum where conditions are similar to Glasgow. TRANSYT can be used as described in this report to predict, in particular traffic situations, the benefits of coordinating adjacent signals.

Table 1 shows that, at a typical urban cruising speed of about 40 km/hr, 1 stop will consume as much fuel as 22 seconds of delay. It was this argument that lead to the use in Section 4 of \( K = 20 \) in the TRANSYT Performance Index; the cost of the delay to occupants in the vehicles was ignored. If the commuting time of a person is valued at 35p per hour and there are, on average, 1.4 persons per vehicle, then 1 second of delay costs 0.014p whereas the untaxed fuel cost per second is only 0.0006p (at 15p per litre). Thus, the
total cost of delay tends to be dominated by the valuation on people's time, even where only commuting time is considered. Since the fuel costs of 1 stop from 40 km/hr are about 0.14p, it follows that a stop weighting of $K = 7$ should be used where a person's time is valued at 35p per hour. Higher valuations of time may justify further reductions in the value of $K$.

It is plausible to argue that accident rates are likely to be more highly correlated with the number of vehicle stops than with the general level of traffic flow delay. If accident rates could be shown to be directly proportional to the number of stops, then the cost of accidents would justify a high value for the stop weighting $K$. For example, the above calculations suggest that there are about 3 million vehicle stops per annum at each signalled junction in central Glasgow. If there are 4 personal injury accidents per annum per signalled junction at a cost to the community of £5000 each, then each stop costs about 0.7p. This cost is about five times as large as the fuel costs of a stop. However, accidents have many causes and there appears to be no evidence to support the assumption that the number of stops and accident rates are directly correlated. It seems to be difficult to devise an experiment which would determine the degree of correlation, if any, between stops and accidents.

Other considerations are relevant to the value chosen for the stop weighting $K$. Stops cause mechanical wear on the vehicle, noise pollution and are a nuisance to the driver and passengers; such considerations favour higher values for $K$. Version 6c3 of TRANSYT includes a prediction, for conditions in the USA, of the rates of vehicle emissions of carbon monoxide, hydrocarbons and nitrous oxides. At present, it is not clear what value of $K$ minimises the harmful effects on the community of air pollution from vehicle exhausts.

Summarising, the factors that can be quantified, primarily waste of fuel and time, jointly suggest a stop weighting of from 5 to 10. Other arguments about accidents and nuisance mostly favour a higher value. Giving some weight to these latter arguments suggests use of $K = 20$ which has the particular merit of minimising fuel use.

7.4 Fuel used at idle rate

Table 2 makes it clear that large quantities of fuel are wasted by delay and stops. The time spent idling is less than that delayed because some delay time is incurred during deceleration and acceleration. Figure 5 shows that a delay of longer than 8 seconds is necessary before a vehicle has stopped. Therefore an average of 110,000 stops per hour in Glasgow incurs about 250 vehicle-hours per hour of delay. The additional delay in Glasgow of over 1000 veh-hours per hour occurs at idling. Hence, about 80 per cent of the fuel wasted by delay is consumed at idling rate. Since about one-third of the total fuel consumed is due to delay, it follows that one-quarter of the total fuel is used whilst vehicles are stationary.

It was noted in Section 2.1 that, on average, 1.5 litres of fuel per hour were consumed at idling rate but that rates of less than 1 litre per hour could be achieved with the engine of the TRRL survey car adjusted to run at a very slow 'tickover'. If this saving of one-third could be generally realised then the fuel consumed in urban areas would be reduced by about 8 per cent. This calculation is made to quantify one aspect of the potential benefits from adjustments to the engine; further consideration of such benefits is beyond the scope of this report.
8. CONCLUSIONS

In this report, the TRANSYT computer program is used to predict the fuel consumed within a network of traffic signals. Fuel consumption is predicted as a function of the distance travelled at cruising speed, the total time delayed and the number of stops and starts. With suitable coefficients that relate these traffic measures to the fuel used, there is good agreement between the predicted and observed fuel consumptions of the survey cars in Glasgow. Further, the predictions are consistent with earlier work on various types of vehicles in which no separate account was taken of vehicle delay and stops. The observations in Glasgow will not necessarily be typical of most urban areas but TRANSYT can be used in other areas to predict the effects of signal coordination on the fuel consumed.

The fuel consumed in central urban areas similar to Glasgow is about twice that needed to cover the same distance at a steady cruising speed. In such conditions a 10 per cent saving in journey times will reduce the fuel consumption by from 6 to 8 per cent. Signals that are coordinated to minimise total delay can reduce journey times by up to about 20 per cent depending primarily on the prior standard of control but also on the traffic flow levels and the layout of the streets. The highest savings are more likely to be achieved where the distances between signals are short, traffic flows heavy and the signals were previously operated in isolation from each other on fixed cycle times of long duration.

Even where signals have been recently coordinated to minimise delay, the traffic survey in Glasgow demonstrated that an additional saving of about 3 per cent in the overall fuel consumption may be achieved by altering the signal coordination to reduce the number of stops and starts. This saving in fuel is estimated to be worth £75,000 per annum within the network of 91 signals in central Glasgow. It was predicted that some small increase of 1 or 2 per cent in the journey time would occur but the floating car survey could not detect changes of this magnitude. There is some evidence that the total number of vehicle stops was reduced, with the 'minimum fuel' plan, by from 8 to 14 per cent but improvements must be made in the procedure for measuring stops before these results can be quoted with confidence.

The coefficients used to relate the TRANSYT predictions of the distance travelled at cruise speed, the delay time and the number of stops to the total fuel consumption were derived from a series of measurements involving speed change cycles from and to a range of steady cruise speeds. It was found that, where cruising speeds are about 40 km/hr (25 mph), one stop/start speed change cycle uses as much fuel as 20 to 25 seconds of delay. Thus, 'minimum fuel' signal timing plans may be derived from TRANSYT by optimising a weighted sum of delay and stops where the weighting, K, on stops is set to a value of about 20. The studies with TRANSYT suggest that, in general, fuel consumption is also reduced by operating all signals within an area on a common cycle time even where some signals have sufficient spare capacity to be 'double cycled'. Conversely, delay, and hence journey time, is generally reduced by the use of short cycle times with signals double cycled wherever practical. These guidelines do not always apply and the use of TRANSYT is recommended to evaluate the options in specific situations.

Although there is, as yet, no supporting evidence, it is plausible to suppose that some accidents might be avoided by reducing the total number of vehicle stops and starts. If this can be shown to be true, then the case for coordinating signals to reduce the number of stops is considerably strengthened. Conversely, if a high valuation is placed on the waste of people's time then the relative importance of vehicle stops is substantially reduced. A reasonable compromise, in the absence of further evidence, is to set the value of K in the TRANSYT PI to about 20.
Further research is required to understand driver behaviour better during speed change cycles in central urban areas, particularly where junctions are heavily congested. It is desirable that the measurements of fuel consumption during cruise time, delay time and speed change cycles be extended to other vehicle types so that the effects of the composition of traffic streams can be calculated.

9. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Urban Networks Division (Division Head: Mr D I Robertson) of the Traffic Engineering Department of TRRL. The work on the development and use of the instrumented car described in Section 7.2 was carried out by members of the Assessment Division of the Transport Systems Department of TRRL.

10. REFERENCES


3. MAY, A D and T J CLAUSEN. The analysis and evaluation of selected impacts of traffic management strategies on surface streets. Institute of Transportation Studies, University of California, Berkeley, October, 1976.


Fig. 1 THREE EXAMPLES THAT SHOW HOW THE SIGNAL TIMINGS MAY AFFECT VEHICLE DELAY AND THE NUMBER OF STOPS
Average for 9 American cars (Ref. 8)

Average for traffic of typical composition in England (Ref. 7)

Fuel consumption predicted from equation 1 and table 1 for 3 cruising speeds (km/h)

52.0 41.4 32.3

Fuel consumption (litre/10 km)

Journey time (min/km)

Fig. 2 FUEL CONSUMPTION AS A FUNCTION OF AVERAGE JOURNEY TIME
Maximum stopline capacity
= 1600 vehicle/h

Equation used in later versions of TRANSYT

Equation used in TRANSYT version 1

Stopline data
Saturation flow = 3600 vehicle/h
Cycle time = 90s
Red time = 50s
Duration of flow = 0.5h

Fig. 3 VEHICLE DELAY AT A SIGNAL STOPLINE
Cruising speed
= 11.4 m/s
= 41 km/h

Shaded area = loss of distance caused by a speed change cycle

Distance travelled whilst decelerating

Distance travelled whilst accelerating

Minimum speed

Fig. 4 THE AVERAGE DISTANCE TRAVELLED DURING A SPEED CHANGE CYCLE
Fig. 5 THE EFFECT OF DELAY ON THE MINIMUM SPEED AND ENERGY LOST DURING A SPEED CHANGE CYCLE
Fig. 6 'TRANSYT' PREDICTIONS OF VEHICLE STOPS, DELAY AND FUEL CONSUMPTION WITHIN A NETWORK OF 21 SIGNALLLED JUNCTIONS
ABSTRACT

Coordinating traffic signals to reduce fuel consumption: D I ROBERTSON BSc CEng MIMechE, C F LUCAS CEng MIMechE and R T BAKER: Department of the Environment Department of Transport, TRRL Laboratory Report 934: Crowthorne, 1980 (Transport and Road Research Laboratory). The delay suffered by traffic in an urban area can be reduced by coordinating adjacent signals on fixed time plans. Plans that minimise delays may be derived by an offline optimisation method such as TRANSYT. This method can be extended to predict the fuel consumed within a network of signals as a function of the distance travelled, the total delay time and the number of stops. The calibration and use of TRANSYT to minimise fuel consumption is described.

TRANSYT predicts that, in central urban areas, a saving in delay that reduces journey times by, say, 10 per cent is likely to save from 6 to 8 per cent of the fuel consumed. TRANSYT has also been used to derive fixed time plans that minimise fuel consumption rather than delay. When tested in Glasgow, an additional fuel saving of about 3 per cent was both measured and predicted. This fuel saving is estimated to be worth £75,000 per annum within the network of 91 signals in central Glasgow.

The results in Glasgow may not be typical of other cities but the TRANSYT method can be used elsewhere to estimate the benefits on fuel consumption of signal coordination.

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