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IMPLEMENTATION OF AN ADVISORY SPEED ALGORITHM IN TRANSYT

J. VAN LEERSUM
Division of Energy Technology, Commonwealth Scientific and Industrial Research Organization, Highett, Victoria, Australia

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Abstract—Dynamic advisory speed signs which display speeds at which motorists can travel smoothly through downstream signalized intersections appear to offer benefits to both the national economy and the driver. Modifications to the traffic simulation program TRANSYT have enabled some of these benefits to be quantified on a typical urban road network. Provided that the greater proportion of motorists obey the signs it is shown that fuel consumption can be reduced by as much as 13% and the total number of stops by up to 38%.

1. INTRODUCTION

Amongst the many traffic management schemes designed to reduce motor vehicle fuel consumption, a recent study by Doughty and Trayford (1982) has shown that the use of dynamic advisory speed signs may well lead to significant savings. These signs are stationed, at least one per link, throughout a traffic network, and are linked with the nearest downstream traffic signal. The signals feed the signs, dynamically changing speeds, which, when displayed to the motorist willing to adhere to them, enable him to progress through the next set of traffic lights without stopping and with minimum change in speed. Because there is no need for feedback from the sign to the signal, these systems can be added to existing traffic control systems without imposing additional loads on signal controllers or computers controlling them. All that is required is an outlet port in existing signals which could convey information about the current signal cycle to the advisory speed signs.

Of four networks in which dynamic advisory speed signs have been implemented and assessed in the scientific literature, only one is still operational. The scant information on a system installed in Detroit, Michigan, during the 1960s suggests that it improved the quality of traffic flow, but fell into a state of disrepair due to lack of maintenance (Morrison *et al.*, 1962). Another system was really only a short term (days) experiment by the Transport and Road Research Laboratory in the U.K. (Ellson, 1964). It was set up to discover whether a network implemented with advisory speed signs could handle a higher traffic flow than normal, but the effects on fuel consumption, stops, and delays do not appear to have been considered. Related work on traffic flow in a tunnel in New York, U.S.A. suggested that if drivers comply with an advisory speed sign placed some distance before the tunnel, bottleneck conditions can be decreased significantly and traffic can flow more smoothly (Foote, 1968). The latter conclusion was also reached by Trayford (1982) after driving through a traffic network in Dusseldorf, Germany, where advisory speed signs are presently operational (von Stein, 1978).

Unfortunately, the above systems appear to have been designed by trial and error and no analysis of, or data on, their performance could be found. For a fourth system implemented in Sweden, Hammarström (1981) reports fuel savings between 8 and 11%, reduction in the number of stops ranging from 25 to 50%, and a drop of between 2.1 and 4.3 km/h in the mean speed of progression through the system.

With the availability of traffic simulation programs like TRANSYT (Vincent *et al.*, 1980) and MULTSIM (Gipps and Wilson, 1980), feasibility studies of such systems can be carried out after the programs have been modified to include the advisory speed management strategy.

MULTSIM is a micro-simulation traffic flow model which follows individual cars through a traffic network. Although very detailed and accurate (Anderson, 1981), it is expensive to run for large networks and hence its use is generally restricted to paths consisting of one-way links joined by intersections, or two-way links with almost zero coupling between the flows in both directions (e.g. divided roads), thus allowing traffic simulation in each direction separately. Results from a modified version of MULTSIM indicate that for such simple paths, fuel savings of up to 15% can occur when advisory speed signs are introduced. Because MULTSIM is not an ideal tool to use on a network, TRANSYT (Vincent *et al.*, 1980) was modified to include the advisory speed sign traffic management strategy. The following sections describe the necessary modifications, together with some trends established from initial simulations and results.

2. OPERATION OF TRANSYT AT INTERSECTIONS

During the simulation of a traffic network, TRANSYT computes, for each stopline at each signalized road junction, the variation of traffic flow with time for the following three conditions.

(1) The IN pattern, which is the way vehicles arrive at the intersection.

(2) The OUT pattern, which is the way vehicles leave the intersection.

(3) The GO pattern, which is the vehicle outflow pattern adopted under maximum possible discharge rates at

the intersection. These occur for fully saturated IN patterns.

Steady-state traffic flow is assumed and therefore the IN, OUT, and GO patterns are cyclic, with a period equal to the signal cycle time, t_c, which, in TRANSYT, is constant for all intersections except for those that are double cycled. This limits the usefulness of TRANSYT to traffic situations where steady state is actually obtained, hence results obtained simulating, for example, traffic in peak periods where the traffic characteristics change continuously should be examined with caution.

Referring to Fig. 1, the OUT pattern from signal I is modified by a dispersion relationship and shifted by a time corresponding to the specified travel time down the link I–$I + 1$ to provide the IN pattern at signal $I + 1$. The signal cycle is split into time steps and one calculation for the flow relevant to each time step is performed. If the dispersion and time shift operations move positions of the flow to times greater than t_c, the times are simply transferred modulo t_c so that they lie in the interval $[0, t_c]$. Once the IN pattern is determined, the interaction between it and the GO pattern is simulated with a discrete queuing model to produce the OUT pattern from signal $I + 1$. In this way, parameters such as average queue length, number of stops per vehicle, and delay are determined.

3. IMPLEMENTATION OF THE ADVISORY SPEED FACILITY ALGORITHM

The traffic flow on each link is split into two groups—one consisting of drivers who obey the advisory speeds and the other consisting of those who do not. In practice, the fraction, x, of drivers who comply with the advised speeds will be a complicated function of a number of human factors, as well as the traffic flow configuration. The functional form of this relationship is not yet determined, so it has been assumed in the following that x is an input, constant throughout the entire network. Simulation results have been given over a range of x to demonstrate system sensitivity to it.

The only other additional inputs to TRANSYT 8 required by the advisory speed algorithm are the limits (v_a, v_b) between which advisory speeds are displayed. The choice of these limits depends on the blanket speed limits, human factors, and traffic authority policy. Because the interaction of these effects has not been studied, $v_a = 20$ km h^{-1} and $v_b = 80$ km h^{-1} have been used below. This choice was made after a consideration of experimental results which showed that there were speeds under which and speeds over which the majority of drivers would not drive, even when advised to do so (Trayford, 1983).

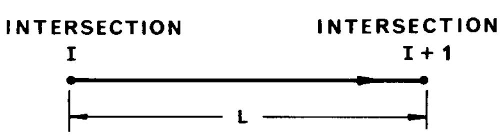

Fig. 1. Two linked intersections.

3.1. *Calculation of advisory speeds*

Before each flow profile computation in the modified version of TRANSYT 8, it is necessary to determine an advisory speed for each network link, and then test whether the advised speed concept is "reasonable" for the particular flow configuration on the link. The concept is considered "unreasonable," that is, the algorithm is bypassed on all links where:

(a) The link is a network entry or exit link (e.g. links 10, 11, 12, 3, 24, 25, 72, 113 in the TRANSYT 8 user manual example (Vincent, 1980), a schematic of which is reproduced in Fig. 2);

(b) the link terminates at a priority (unsignalized) intersection (e.g. links 1 and 2, in the TRANSYT 8 user manual example, Fig. 2);

(c) the computed advisory speed lies outside the limits (v_a, v_b).

Considering the simplest case of a link joining two signalized intersections, each with one green phase per cycle, the flow geometry may be represented by Fig. 3. The basic advisory speed algorithm for TRANSYT 8 assumes any complying driver passing through the green phase of intersection I will be given an advisory speed which should allow him to pass through the green phase of intersection $I + 1$, at a time comparable with that at which he passed through the intersection I green phase, relative to the start of the green phases (Fig. 3). That is

$$t_I/t_{g_I} = t_{I+1}/t_{g_{I+1}}. \quad (1)$$

The flow pattern of complying traffic leaving intersection I must therefore be mapped into the green phase of intersection $I + 1$. Vehicles which obey the advisory signs are likely to bunch up into fairly compact platoons which will "fit" the downstream intersection's green phase. It is therefore assumed that complying vehicles form sharp-edged platoons which just fit into the downstream intersection's green phase for the relevant stopline. Any other assumption could result in undesirable and unnecessary bunching in the add-on system proposed by Doughty and Trayford (1982).

The speed corresponding to this assumption is termed the advisory speed for the link and this is the "mean free speed" assigned by the algorithm to all complying vehicles, as distinct from the user-supplied "mean free speed" assigned to the noncomplying vehicles. It is this speed which is used to check whether the advisory speed concept is "reasonable" for the link in question, and also to calculate speed dependent components of the TRANSYT 8 performance index and fuel consumption for the complying vehicles.

TRANSYT 8 can cope with only one characteristic advisory speed for complying vehicles. Figure 3 shows that there is an infinite number of such speeds within specified limits which could be given to complying vehicles if $t_{g_I} \neq t_{g_{I+1}}$. These are

$$v_c = 3.6L/(t_o + nt_c) \quad (2)$$

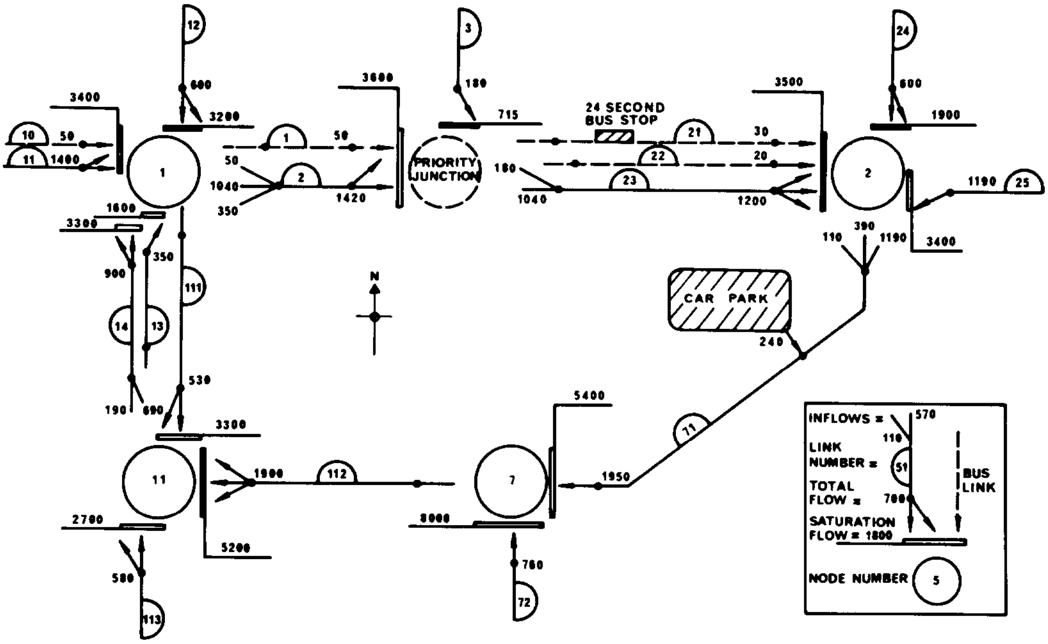

Fig. 2. Link diagram for TRANSYT 8 example (reproduced from Vincent *et al.*, 1980).

where t_o will vary during the green period if eqn (1) is to be satisfied. It is assumed that the value of t_o used to define a unique and reasonable value of v_c corresponds to a vehicle starting midway through the green period of intersection I and arriving midway through the corresponding green period at intersection $I + 1$. Therefore, v_c is a function of offsets and green times. Since the objective is to minimise fuel consumption, n is chosen so that v_c is as close as possible to the minimum fuel consumption speed (46 km/h if the default fuel consumption coefficients in the TRANSYT 8 model are used).

If intersection I is a bottleneck link, then the GO pattern will generally spread over the whole cycle length, hence t_c is taken as the green time at intersection I.

Since up to two green periods per stopline per signal cycle are allowed to occur at each intersection in the TRANSYT model (Vincent *et al.*, 1980), it is possible for two distinct advisory speeds to be calculated. In this case, the advised speed for the link is assumed to be a

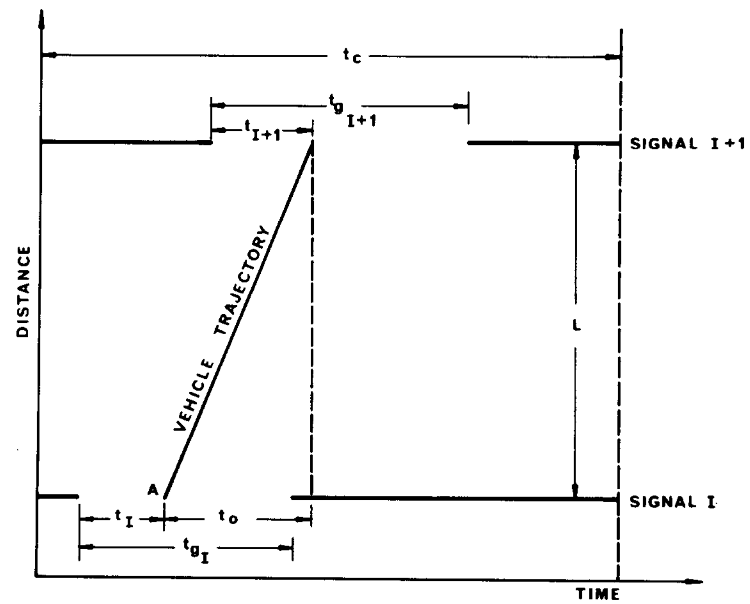

Fig. 3. Time–distance diagram for a complying vehicle.

green time averaged mean of the two speeds, since only one advisory speed and one mean free speed per link are allowed in the developed algorithm. The logic in the algorithm caters for all possibilities and produces a single value of v_c for each link. This value is checked with the allowed range (v_a, v_b) and a decision made as to whether vehicles can comply on the link. If so, the advisory speed algorithm is entered. If not, the standard TRANSYT 8 logic is followed. However, this calculation is only for the purpose of determining a single advised speed, and the advisory speed algorithm is applied to each combination separately, as described in Section 3.2.

For calculating journey time and fuel consumption on each link, both of which are dependent on the "mean free speed" down the link, separate calculations are made for the complying vehicles travelling at the advisory speed and the noncomplying vehicles, travelling at the link speeds inferred from the data input. A final value for each parameter is obtained by weighting the complying components with the compliance, x and the noncomplying components with $(1 - x)$ and summing.

3.2. *The advisory speed algorithm*

Consider firstly two single cycled intersections I and $I + 1$. Suppose, as in Fig. 3, that some traffic will comply during the journey between these intersections. It is assumed that all complying vehicles are directed at the green phase of intersection $I + 1$. The advisory speed algorithm splits the OUT pattern from intersection I into complying and noncomplying parts, then ensures that the IN pattern at intersection $I + 1$ contains all complying vehicles positioned uniformly between the green phase limits of intersection $I + 1$. To achieve this, the complete OUT pattern at intersection I is shifted and dispersed to form an IN pattern at intersection $I + 1$ using the standard TRANSYT algorithm. Figure 4(a) represents a typical IN pattern thus formed. The ordinates of the IN pattern are multiplied by $(1 - x)$ to produce the non-complying portion of the IN pattern. The total number of complying vehicles is then

$$N = \int_o^{t_c} xQ(t)\,\mathrm{d}t \tag{3}$$

and the quantity

$$A_x = \frac{N}{t_{g_{I+1}}} \tag{4}$$

where $t_{g_{I+1}}$ is the length of the green phase for intersection $I + 1$, and A_x represents the constant flow amplitude of an undispersed complying platoon, uniformly distributed over the green phase of intersection $I + 1$ [Fig. 4(b)]. This is assumed to be the IN pattern of the complying

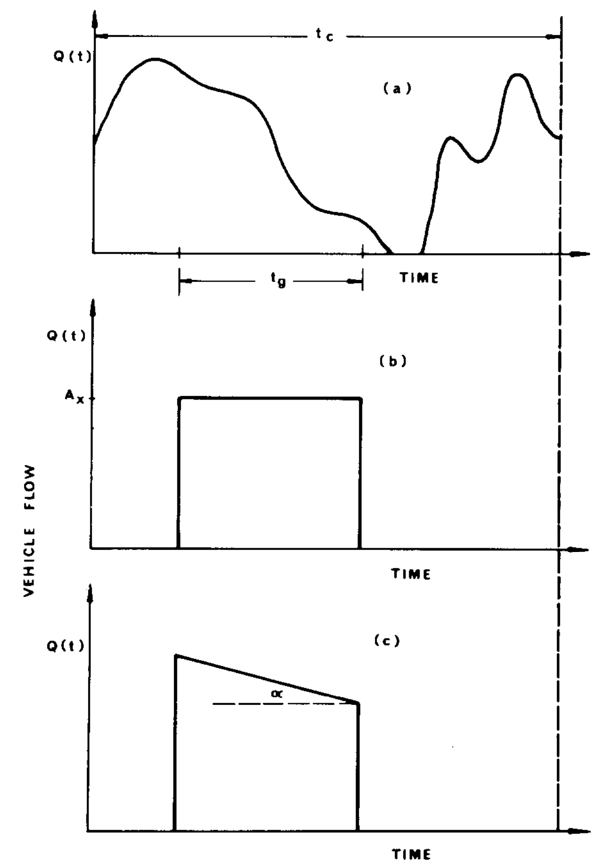

Fig. 4. (a) IN pattern as calculated by unmodified TRANSYT if no compliance. (b) Assumed flow vs. time relationship for complying vehicle. (c) Possible variation of (b) allowed for by TRANSYT modification.

traffic. The assumption of a square-edged, uniformly distributed complying platoon has only been justified in part using the microsimulation model MULTSIM (Doughty and Trayford, 1982). It suggests that the platoon shape should look more like that in Fig. 4(c), so it would be a simple matter to modify the algorithms to include this feature if necessary. Insufficient information is available to determine a suitable value of a with any degree of confidence, so all of the following results were produced using the shape of the platoons in Fig. 4(b). The final IN pattern submitted to the discrete queuing model at intersection $I + 1$ is the sum of a pattern like that in Fig. 4(b) and $(1 - x)$ times a pattern like that in Fig. 4(a). This ensures that a given percentage of traffic will deliberately obey all signs and present itself uniformly to the green phase of signal $I + 1$. The fortuitous arrival at this green "gate" of noncomplying traffic occurs in reality and the compliance, x, is not modified to account for it.

The algorithm attempts to ensure that if all vehicles complied with the advised speeds, they would arrive at intersection $I + 1$ during its green phase, and clear the intersection before the end of this phase, provided it is not saturated. That is, the uniform delay should be close to zero. As fewer vehicles comply, delays occur and queues build up. These are reflected in the IN patterns of the noncomplying portions of the flows. By adding the relevant complying portions of the IN pattern to the noncomplying portions, any uniform delays caused by queues are passed onto the complying vehicles via the discrete queue simulation routine in TRANSYT 8. To some extent, therefore, the algorithm is self-reinforcing in that increasing compliance implies less noncomplying vehicles, hence smaller queues, hence less delay for complying vehicles. It should be emphasized that the calculated advisory speed is the assumed "mean free speed" of an *undelayed* complying vehicle moving down the link, and just like the user-defined "mean free speed" of the noncomplying vehicles, has no interaction with the TRANSYT 8 queueing algorithm. It was introduced only to be consistent with the TRANSYT 8 model. The worth of the advisory speed algorithm is in directing a sharp-edged platoon of complying vehicles at the green phase of intersection $I + 1$. The standard TRANSYT 8 queuing model then determines the consequences. Section 4 shows that even though some complying vehicles are delayed, there are overall benefits to be gained by implementing the algorithm.

It is possible that an algorithm resulting in increased benefits to the network could be derived, by taking into account queue formation at intersection $I + 1$ and deliberately packing the complying vehicles into sections of the green phase where queues are small or nonexistent. In a real system, production of such an algorithm relies on prior information about queue formation which may not be available because of an absence in the system of vehicle detectors. The option was therefore not considered, the aim being to demonstrate the benefits of the simplest system. However, Trayford *et al.* (1984) have used queue information in the design of an algorithm used during on road experiments in an instrumented car.

For double cycled intersections, three different situations can arise.

(i) A double-cycled intersection feeds a single-cycled intersection.

(ii) A single-cycled intersection feeds a double-cycled intersection.

(iii) A double-cycled intersection feeds a double-cycled intersection. In this case, it is assumed in the advisory speed algorithm that for the complying traffic, the jth cycle in time of intersection I feeds the jth cycle of intersection $I + 1$ for $j = 1, 2$. This assumption tends to promote the smoothest flow by comparison with other combinations, which would sometimes cause large speed differentials between vehicles in different complying streams.

Initially, the course taken by the modified version of TRANSYT is the same as that taken for single cycled intersections, but once the total flow of complying vehicles has been determined, this subflow is further split in the ratio of the green times for intersection $I + 1$ in cases (ii) and (iii), but kept intact for case (i). The sharp-fronted platoons are then formed to match the green phases to which they are targeted, and the resulting IN patterns added at the appropriate green phase times to the non-complying vehicle IN patterns. Thus, although the calculated "advisory speed" (Section 3.1) is an average of two advisory speeds, which itself could possibly target the vehicles out of a green phase, the platoons of complying traffic are aimed at green phases. The "advisory speed" is only used to calculate undelayed travel time, and the cruise component of fuel consumption, so little error is introduced in assuming it to be a linear combination of two true advisory speeds.

It should be noted that the algorithms are add-on facilities which do not affect other parts of TRANSYT 8 except for the minor modifications described below. The optimization facility works in conjunction with them, varying signal offsets in an attempt to minimize a user specified performance index. The set of offsets corresponding to the minimum performance index will henceforth be referred to as optimum offsets. It has been shown that in the case of the user manual example (Vincent *et al.*, 1980), the output supplied by TRRL agrees with the modified version's output for zero compliance.

3.3. *Necessary modifications for calculating travel time on links*

In standard TRANSYT, link travel times are obtained from input data and are invariant during all calculations by the program. As explained previously, advisory speeds are dependent on traffic signal offsets, which are varied as the TRANSYT optimizer seeks to minimize its performance index (PI). The link travel times for complying traffic therefore vary with every change in offset, hence the mean link travel time for both complying and noncomplying traffic will also vary with offsets. An additional subroutine calculates the mean link travel times every time offsets are changed.

3.4. *Modifications to the performance index (PI) in TRANSYT*

The purpose of studying advisory speed signs was to examine whether their adoption in a traffic system would decrease total fuel consumption. Fuel consumption is dependent, in part, on the mean free traffic speed down the links, which has been noted in the above section as varying with signal offsets for non-zero compliances. Whereas in standard TRANSYT, the coefficients of stops and delays in the PI could be specified so that PI was a measure of fuel consumption (Vincent *et al.*, 1980), this is no longer the case in the modified version because the component of fuel consumption due to cruising on each link (Vincent *et al.*, 1980) changes as offsets are varied by the optimizer, and the advisory speeds change. The additional subroutine mentioned in the previous section allows calculation of the fuel consumption cruise component, and the whole expression for fuel consumption has been added into the PI, in front of a user-specified constant, thereby allowing PI to be an explicit function of fuel consumption. In all following simulations, constants and penalties in the modified PI have been chosen so that it is equivalent to fuel consumption and hence "optimized conditions" imply minimum fuel consumption.

The fuel consumption model used is that included in the standard version of TRANSYT, the constants being the default values supplied with the program.

4. EFFECT OF ADVISORY SPEED SIGNS ON A TRAFFIC NETWORK

The TRANSYT user manual example (Vincent *et al.*, 1980) was used to demonstrate the effects of the modifications made to the program. A set of runs was made to determine the variation of fuel consumption with driver compliances of 0, 25, 50, 75 and 100%. The initial offsets used were those calculated as optimal at 100% compliance for a previous run of TRANSYT with the performance index as specified in the user manual example, and starting from zero offsets. This enabled a comparison of fuel consumptions at close to optimum offsets for 100% compliance with that at other compliances and the same offsets.

The program seeks minimum total fuel consumption for the network, hence the fuel consumption on individual links will not necessarily be minimum. Because situations (a) and/or (b) (Section 3) occur on some of the network links, only links 21, 22, 23, 71, 112, 13, 14 and 111 in Fig. 2 can contain complying drivers. The given offsets determine advisory speeds and since these must be between two limits (20 and 80 km/h in these simulations), there will be circumstances where traffic cannot comply on some of these links [situation (c), Section 3].

4.1. *Overall results for the network*

Fuel consumption in l/(100 km) and stops/km/pcu were calculated from the TRANSYT output and graphed as functions of compliance. The overall results for the network are shown in Fig. 5. The proximity of the fuel consumption on the "initial" and "optimized" offsets curves at 100% compliance reflect the independence of the optimization algorithm on starting offsets, since, as explained above, the "initial offsets" are the optimized offsets at 100% compliance, starting from zero offsets. It is also clear that the offsets for minimum fuel consumption are strong functions of compliance.

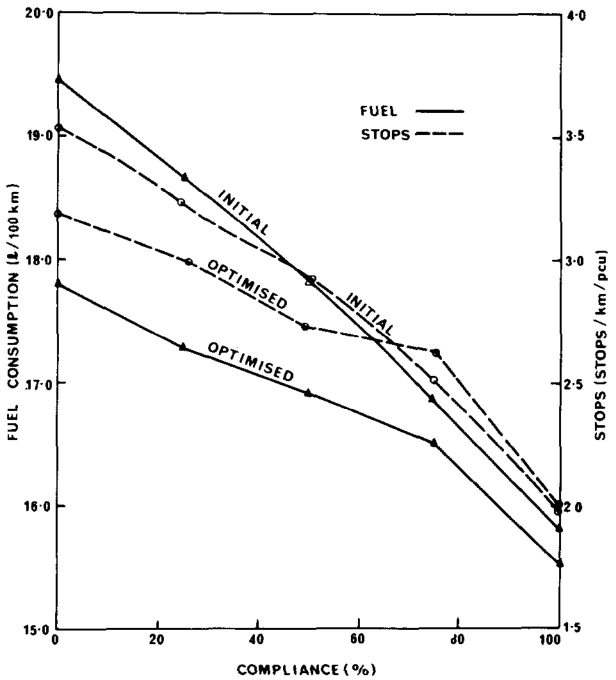

Fig. 5. TRANSYT user manual example (overall).

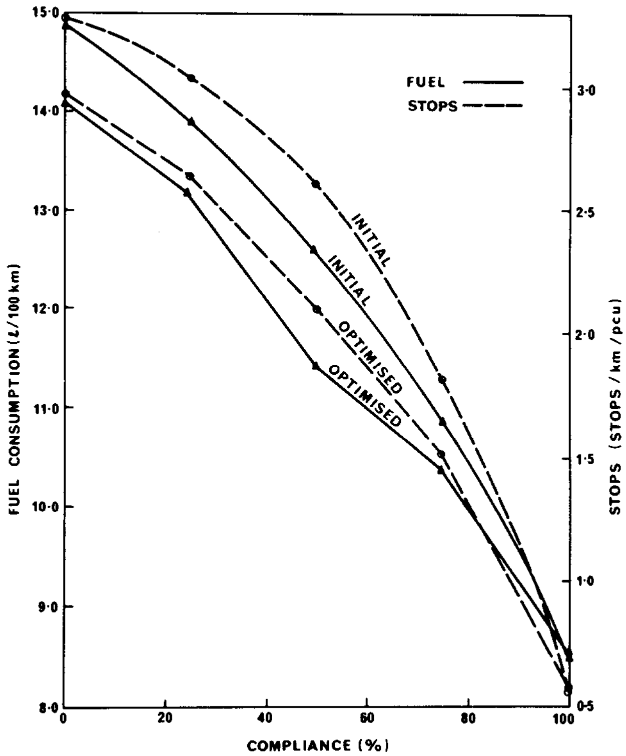

Fig. 6. TRANSYT user manual example (link 23).

The graphs in Fig. 5 show that the difference between fuel consumption when 100% of drivers comply, from that when none comply in the network, is 18.7% for the initial offsets chosen. This difference is still significant (12.8%) if optimized offsets for the 0 and 100% compliance are compared. In practice, savings would lie somewhere between 12.8 and 18.7% as the number of drivers obeying the advisory signs is never likely to be known with sufficient accuracy to enable truly optimum offsets to be chosen.

The number of stops is shown in Fig. 5 to decrease markedly as compliance rises. Since fuel consumption is the performance index, there is no guarantee that the optimizer also produces minimum stops, since the two are not synonymous. The dramatic decrease in number of stops with increasing compliance should provide a perceived reinforcement for drivers to obey the advised speeds.

The fuel consumption curve drawn from the initial offsets is smooth, and decreases monotonically, whilst that resulting from the optimized offsets contains irregular bumps. This appears to be because the optimization routine in TRANSYT does not always calculate global optima, hence some of the points on this curve may be local optima. As well as this, eqn (2) shows the optimization problem to be of mixed integer character, by virtue of the variable n, resulting in the possibility of some points on the optimized curves corresponding to completely different offsets than their neighbours. To indicate this, the relevant points are joined by straight lines for all such cases in Figs. 5–8. Studies (Lines, 1983) have shown that any local optimum to which the TRANSYT optimizer converges is supposed to be within 5% of the global optimum, hence it is, to all intents and purposes, a global optimum. Figure 5 shows that all points on the "optimum" fuel consumption curve are lower than their counterparts on the "initial" offset curve, and there is a steady decrease in fuel consumption with increasing compliance. Such is not the case for the curves showing stops vs compliance. It can be seen that for a range of compliances, the number of stops for the "optimized" offsets exceeds those for the "initial" offsets. Since "number of stops" is not the performance index, this does not violate any principle.

For all compliances except zero, advisory speeds for both initial and optimized offsets were such that the given fraction of drivers was able to comply on links 21, 22, 23, 71, and 112. In addition, the advisory speeds for the initial offsets and the optimized offsets for 100% compliance were such that drivers were able to comply on links 13 and 14. Advisory speeds on link 111 were considerably less than 20 km/h except for the optimized offsets at 50% compliance, when the advised speed was 21 km/h, thus allowing use of the advisory speed algorithm in this case. Under no conditions was it possible to obtain simultaneous two-way driver compliance on the only links in the network affording this geometry—links 111 and 14 or 13. However, the cases where all links but 111 allowed driver compliance represent a one-way clockwise loop in the network, broken only by the links entering the priority junction which, by definition [situation (b), Section 3], cannot have advisory speed signs installed. It should be emphasized that components of the performance index due to the contributions of

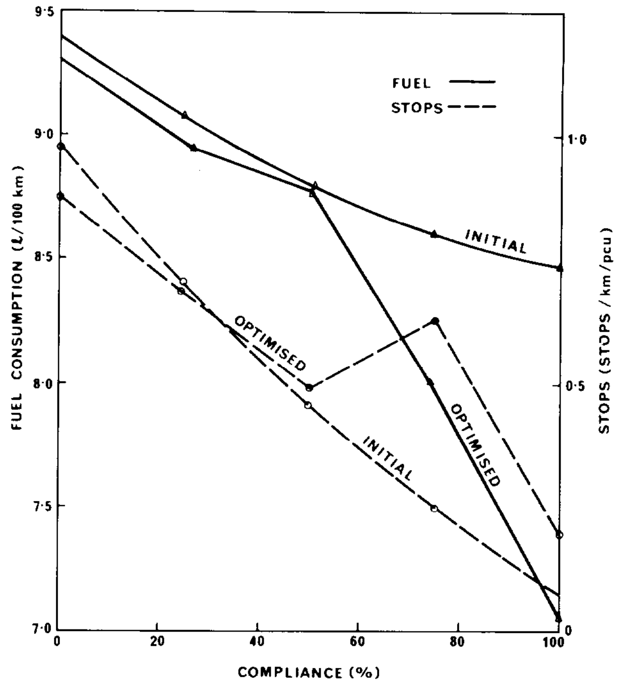

Fig. 7. TRANSYT user manual example (link 71).

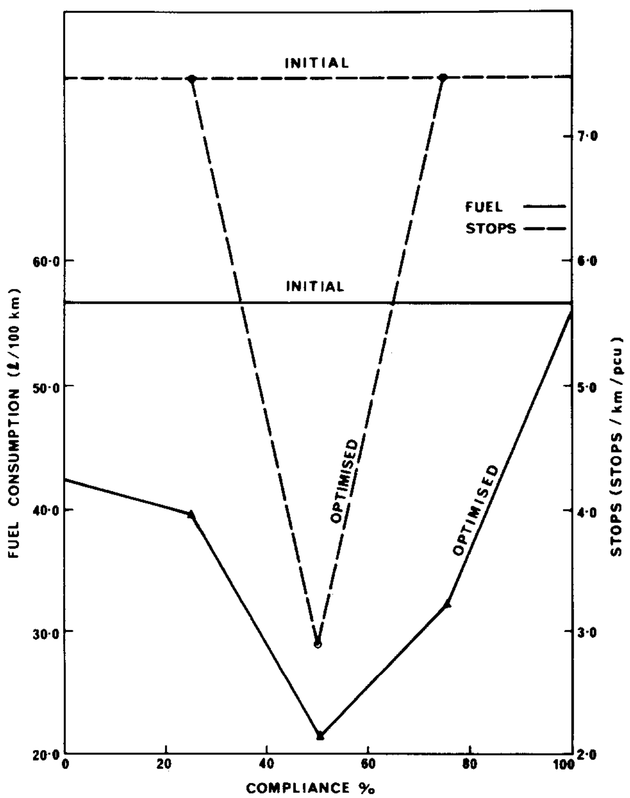

Fig. 8. TRANSYT user manual example (link 111).

network entry links and links terminating at priority junctions are taken into account when calculating the overall performance index for the network. The reason for this is that all "advised" networks must have "nonadvised" entry links and/or some "nonadvised" internal links, and the network behaviour clearly affects traffic flow on the nonadvised links. It is therefore conceivable that the portion of a network which can accept advisory speed signs could operate quite efficiently whilst its entry links and nonadvised internal links were choked, leading to a total system which operates poorly. Whilst such situations have not been encountered, it is necessary not to preclude their occurrence. Nevertheless, for the example given, the significant benefits to the whole network (including entry and nonadvised links) when drivers on only 7 links out of 18 are able to comply with advisory speeds made the concept of such systems well worth further research. Realization that in most real networks there appears to be a potential for about 2/3 of the links to contain advised traffic reinforces this conclusion. Further benefits were obtained when the advisory speed limits $[v_a, v_b]$ were expanded. However, because it has been observed that most drivers will not travel at less than 20 km/h (Trayford, 1983), the effect of expanded limits was not explored further.

Table 1 indicates mean speeds of progression through the network as functions of compliance for both initial and optimized offsets. These were taken directly from the corresponding TRANSYT outputs. Time savings of about 12% are possible at the initial offsets but these are halved when comparing with the results for the optimized offsets. The main point to be noted is that travel time through the system decreases as compliance increases. This is not a general conclusion, as when low advisory speeds are involved, some increase in travel time through the system often occurs (Doughty and Trayford, 1982). In all cases studied so far, the increase/decrease is not large and is considered only as a secondary effect to the main aim of this study, which is to save fuel.

4.2. *Results for individual links in the network*

Figures 6 and 7 show the effect of compliance on fuel consumption and stops for links 23 and 71, respectively. These are links on which drivers are able to comply for both initial and all optimized offsets. The curves in Figs. 6 and 7 are similar in character to Fig. 5 with the results for optimized offsets containing bumps for the reasons given in Section 4.1. Although fuel consumption decreases monotonically with increasing compliance, the number of stops on link 71 is seen to increase between compliances of 50 and 70%. This is because the advisory speed for the initial offsets is 28 km/h, whilst that for the optimized offsets is 47 km/h. Since the minimum fuel consumption speed in the TRANSYT model is 46 km/h, the lower fuel consumption at the optimum offsets is understandable. However, because of the way in which TRANSYT treats partial stops (Vincent *et al.*, 1980) as being proportional to the kinetic energy of the moving vehicle, all other factors being equal, the number of stops at 47 km/h cruising speed will be much higher than the number of 28 km/h for the 75% of traffic complying. Further, it should be noted that the caption "optimized" on the curves in Figs. 6–8 refer to a network optimization, not a link optimization. It can be seen that fuel savings on individual links on which traffic can comply are generally greater than for the whole network on a percentage basis.

Mean speeds at which individual links are traversed show considerably more variation than for the whole network (Table 1). Table 2 shows results for comparison.

Both of these links contain complying drivers. For initial offsets, the variation of V_{L_i} with compliance is strongly dependent on the fixed mean free speed of noncomplying drivers and the advisory speed, determined by the offsets. The relative magnitude of these quantities can establish a monotonic increasing or decreasing relationship because

$$t_{L_c} = 3.6\left(x\frac{L}{v_c} + \frac{(1-x)L}{v_L}\right) \tag{3}$$

(definition of mean run time on link).

Adding the total delay time to the run time gives the mean residence time of a vehicle on the link

$$\begin{aligned} t_L &= t_{L_c} + t_D \\ &= 3.6\left(x\left(\frac{L}{v_c} - \frac{L}{v_L}\right) + \frac{L}{v_L}\right) + t_D. \end{aligned} \tag{4}$$

Hence the perceived mean link travel speed is

$$V_L = \frac{3.6L}{t_L} = \frac{1}{x\left(\dfrac{1}{v_c} - \dfrac{1}{v_L}\right) + \dfrac{t_D}{3.6L} + \dfrac{1}{v_L}} \tag{5}$$

where: t_D is the delay on the link; t_L the total time spent on link, including cruise time; and v_L the speed of noncomplying traffic on link, specified by user.

The only variables in the expression for V_L are t_D and x when the offsets are constant. Normally, the delay on a link should decrease as the compliance increases, so if this is the dominant term in the denominator, V_L will increase as x increases. However, if delay is small, and

Table 1. Variation of mean speed of progression through network with compliance

Compliance (%)	0	25	50	75	100
V_{N_i} (km/h)	11.7	12.1	12.5	12.9	13.3
V_{N_o} (km/h)	12.9	13.3	13.3	13.6	13.8

Table 2. Variation of mean speed of progression down individual links with compliance

Compliance (%)	0	25	50	75	100	0	25	50	75	100
V_{L_1} (km/h)	19.7	21.8	24.4	27.6	30.7	28.4	28.4	27.5	27.5	26.7
V_{L_0} (km/h)	20.7	22.4	26.7	27.6	30.7	27.5	28.4	28.4	37.4	40.7
	2(a) Link 23					2(b) Link 71				

the first term is dominant, then the variation of V_L with x will be either monotonic increasing or decreasing, depending on the sign of $(1/v_c) - (1/v_L)$. The magnitude of the changes in V_L will be a strong function of the difference between v_c and v_L. Table 2 for the initial offsets illustrates these points. In Table 2(a) the values of v_c and v_L are very different, whilst in Table 2(b) they are similar for initial offsets. If both denominator terms in the expression for V_L are of comparable magnitude, then monotonic relationships may not occur.

When similar relationships for the optimized offsets are considered, v_c varies with the offsets, which in turn vary with the compliance, so it is then difficult to forecast the form of the relationship between compliance and speed of progression down the link. Although Table 2 shows monotonic relationships for optimized offsets in the given network, other networks can produce quite different behaviour.

Figure 8 shows results for link 111. In contrast to the other figures, fuel consumption and stops are very high, the only exception being at the optimum offsets for 50% compliance, where advisory speeds were between v_a and v_b and could therefore be obeyed by complying vehicles.

Table 3 shows, for the optimized offsets, the expected delay, cruise time, advisory speed and mean speed of progression down link 111 as functions of compliance.

Because the modifications to TRANSYT force a reversion to the standard program operation if the advisory speed is less than 20 km/h, the cruise time for all compliances other than 50% corresponds to the user supplied mean free speed down the link (32 km/h in this case). This is a consequence of traffic on link 111 being able to comply for optimum offsets at only 50% compliance. For the noncomplying cases, the expected delay time is well in excess of the cruise time, resulting in very low mean speeds of progression down the link. In the case of 50% compliance, the mean speed of progression down the link is still only 8.5 km/h, but the delay is considerably less than for three of the other four cases.

5. CONCLUSIONS

There are benefits in fuel consumption and number of stops if traffic complies with advisory speed signs. For given offsets, network fuel consumption decreases monotonically as compliance rises from 0 to 100%, there being a saving of 18.8% between the two extremes for the network example quoted. The corresponding decrease in number of stops was 44.1%. Fuel consumption and number of stops decreased by 12.8 and 38.1%, respectively, between the two extreme compliances when the offsets used were those corresponding to minimum fuel consumption at each compliance. Particular fuel consumptions for these offsets were less than corresponding ones for the initial offsets.

Mean travel speeds through the network do not vary considerably, suggesting that introduction of the signs may not alter the assumed traffic flow patterns significantly. However, it is desirable in future work to check this conclusion by adding a sound assignment algorithm to TRANSYT.

It should be noted that TRANSYT is a steady state traffic model, hence all of the results presented imply the traffic having been able to achieve this condition. Since, for these results, the degree of saturation on each link was no higher than when the unmodified version of TRANSYT was used, interpretation of these results in the context of steady state behaviour appears to be justified. Further, no attempt has been made to check the sensitivity of the results to the coefficients used by TRANSYT to determine fuel consumption. This should be done, but is unlikely to change the general trend indicated by the present results, unless the TRANSYT fuel consumption model is changed.

Because the results show a strong reduction in fuel consumption with increasing compliance, and even further benefits when the fuel consumption is optimized, the compliance is a critical variable in the advisory speed concept. For example, a traffic authority wanting to achieve

Table 3. Performance of link 111 as a function of compliance at optimum offsets

Compliance (%)	0	25	50	75	100
Delay (sec/pcu)	54.0	50.0	25.0	33.0	89.0
Cruise (sec/pcu)	10.0	10.0	13.0	10.0	10.0
Advisory speed (km/h)(v_c)	7.0	8.0	21.0	14.0	4.0
Mean speed (km/h) (V_L)	5.1	5.4	8.5	7.5	3.3

maximum benefits would need to know the likely compliance, in order that it could choose the network offsets corresponding to minimum fuel consumption at this compliance. Hence, there is a need for research into human factors to determine:

(a) how to ensure maximum compliance;

(b) under what conditions, and with what parameters compliance varies;

(c) likely values of compliance together with confidence limits.

Such research is planned for a later phase of the project now that the potential benefits of the system have been established.

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NOMENCLATURE

A_x mean flow rate of complying vehicles during green phase (pcu/h)
L link length (m)
n integer part of the link cruise time expressed as the number of signal cycles (cycles)
N number of complying vehicles per cycle (pcu)
pcu passenger car unit
$Q(t)$ variation in time of traffic flow at a stopline (pcu/h)
t time (s)
t_c cycle time common to all signalized intersections in the network (s)
t_D total vehicle delay on a link (s)
t_{gI} green time on link I (s)
t_I time after start of green at signal I (s)
t_L travel time on a link, including cruise and delay components (s)
t_{L_c} mean cruise travel time on a link, excluding delay (s)
t_o time for complying vehicle to traverse link I, modulo t_c [see Fig. 3] (s)
v_a minimum speed at which a complying vehicle will travel (km/h)
v_b maximum speed at which a complying vehicle will travel (km/h)
v_c advisory speed (km/h)
v_L mean free link speed (km/h)
V_L $3.6L/t_L$ mean speed of progression down link for complying and noncomplying vehicles, (km/h)
V_N mean speed of progression through network for all vehicles (km/h)
x fraction of vehicles on all links where compliance is possible, who do comply with the advisory speeds
α see Fig. 4(c).

Subscripts

i with initial offsets
o with optimized offsets.

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