

REPRINT

Fuel efficiency and other objectives in traffic system management

R. AKÇELIK

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NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

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Fuel efficiency and other objectives in traffic system management

by R. Akçelik, Senior Research Scientist, Australian Road Research Board

INTRODUCTION

Traffic management is concerned with the control of the movement of road users in order to make the best use of existing road systems in the short term. In the '50s and '60s, traffic management was mainly concerned with vehicle traffic problems in local areas, and 'best use' usually meant improving safety and operational efficiency (more capacity, less delay, etc.). Traffic engineers tried to overcome the practical difficulties created by the conflicts among the individual objectives of safety and operational efficiency, as well as external objectives such as property access, by employing inadequate trade-off analysis methods.

The '70s introduced new dimensions to the problem, among which fuel consumption, air pollution and public transport priority are the important ones. The problems of road-user groups other than vehicles, i.e. pedestrians and cyclists, and the problem of traffic intrusion into residential streets, have also received increasing attention. The fact that there is now an increased number of often-conflicting objectives has important implications for traffic engineering solutions at both policy-related and technical levels¹⁻²⁰. The '70s also saw significant improvements in (urban) area traffic control systems which have enabled traffic engineers to implement flexible solutions to traffic problems in larger areas instead of fixed solutions to local problems^{16, 21-23}.

It is against this background that traditional traffic management is in the process of transforming into traffic system management. It is likely that this will continue to be related to the short-term solutions for a long time, and perhaps the term *transportation* system management is more appropriate in a context which includes long-term strategic solutions aiming to influence travel demand. However, the existence of conflicts among the short-term and long-term objectives has to be considered in the context of traffic system management because of their relevance to the use of techniques such as public transport priority which are expected to affect the flow pattern and demand levels in the network²⁴⁻²⁷.

This paper discusses the objective of

reducing vehicle fuel consumption in urban traffic conditions in relation to other traffic system management objectives. The discussion is centred around the tactical issues related to these objectives with a view to finding practical compromises which can be implemented. An elemental model of fuel consumption (pollutant emission, cost, etc.) is described in detail. The discussions of detailed matters are presented with the aid of examples of isolated and co-ordinated signal control. Similar considerations apply to the objective of reducing pollutant emissions, although there is an area of conflict between the fuel consumption and pollutant emission reduction objectives.

MODELS

A model is a quantitative description of the behaviour of a system to predict its performance over a relevant range of operational conditions. To be useful, a model should offer the ability to determine *in advance* the effects of new control policies (particularly useful when real-life testing is difficult or expensive) and should facilitate an understanding of the basic working of the system under study. The model should be kept as simple as possible, while providing an adequate level of accuracy for the purposes for which it is needed.

The fuel consumption problem must be considered in the context of overall traffic system management, and hence models of both fuel consumption and traffic operating characteristics (delay, number of stops, speed, etc.) are needed. The methodology for evaluating energy conservation policies related to traffic system management can be summarised as follows:

- (a) Define alternative traffic management measures, either individually or as packages.
- (b) Predict traffic operating characteristics under specified traffic management/control conditions (Traffic Model).
- (c) Predict fuel consumption from the calculated operating conditions, or directly (Fuel Consumption Model).
- (d) Establish traffic management measures which can reduce fuel consumption.

(e) Consider how the measures which can reduce fuel consumption affect other traffic system management objectives.

(f) Determine measures and policies considered to be appropriate in the context of all traffic system management objectives.

The fuel consumption models reported in the literature fall into one of the two broad categories:

- (i) analytical expressions which predict fuel consumption as a function of the basic traffic performance variables such as speed, delay and number of stops; and
- (ii) microscopic computer simulation methods which predict fuel consumption directly from individual vehicle trajectories (acceleration-deceleration profiles).

Similarly, the basic traffic performance variables can be calculated from analytical expressions or from computer simulation models of varying level of detail (microscopic or macroscopic; stochastic or deterministic).

The choice of model depends on the particular problem under study. Recent discussions and reviews of traffic models considered in the context of transport objectives and optimum control strategies are given by Allsop³, May¹¹, and Robertson¹⁶. An analytical expression for fuel consumption (pollutant emissions, cost, etc.), which will be referred to as the *elemental model*, is described in detail below. This model is preferred particularly because it has the advantages of simplicity, generality and conceptual clarity, and is well-related to the existing traffic modelling techniques. At the same time, it appears to provide a degree of accuracy which is considered to be sufficient for evaluating most traffic management/control measures (tactics).

An important point about fuel consumption modelling is that it is usually used for finding traffic management measures to reduce fuel consumption and the results are usually of a *marginal* nature (small amounts of reduction of the order of a few per cent). It is therefore essential that a good degree of accuracy is achieved in *relative* terms. Any model bias in this respect would give rise to misleading recommendations, in particular when location-specific results are generalised to express traffic management policies. The deficiency of a common model which appears to be simpler than the elemental model is discussed subsequently in this context.

It should be mentioned that the driving cycle methods which are geared to measuring individual vehicle fuel consumption rates under standardised conditions are not of particular use in the context of traffic management and control²⁸.

The elemental model

This model expresses fuel consumption as a function of three basic traffic performance variables: the amount of travel at the cruising speed; the delay time; and the number of stops. Appropriate fuel consumption rates are applied to these variables, which can also allow for the effects of different vehicle types, cruising speeds, grade, etc. The elemental model is equally applicable to pollutant emission, cost and other traffic

characteristics which can be expressed in terms of these three basic variables. This model is implied or its use in different form is reported by various authors in the literature^{15, 29, 36}.

The analytical formulation given below differs from the previous use of this model in certain aspects. The elemental model can be expressed as:

$$f = f_1 l + f_2 d_s + f_3 h \quad \text{.....(1)}$$

where

f = average fuel consumption per vehicle in L/veh

f_1 = fuel consumption rate while cruising in L/veh-km

f_2 = fuel consumption rate while idling in L/veh-h

f_3 = fuel consumption rate per complete stop in L/stop

l = cruising distance in km

d_s = average stopped delay (idling) time per vehicle in hours

h = stop rate (number of complete stops per vehicle)

(f , d , and h are average values for all vehicles, stopped and unstopped; the units can be generalised as 'unit time' and 'unit distance'.)

Figure 1 shows the time-distance trajectory of a vehicle which makes a complete stop by decelerating from a constant cruising speed to zero speed and accelerating back to the cruising speed, idling for a period of time between the deceleration and acceleration manoeuvres (the slope of time-distance trajectory is the speed of vehicle). The parameters shown in Fig 1 are:

v_c = cruising speed

l = cruising distance

$t_c = l/v_c$ = cruising time (uninterrupted travel time)

d = delay time

$t = t_c + d$ = travel time (interrupted)

t_a, t_b = deceleration and acceleration times

l_a, l_b = deceleration and acceleration distances

d_s = stopped delay (idling) time

d_h = deceleration-acceleration delay

Strictly speaking, the fuel consumption rate for cruising, f_1 , is relevant to the motion from 0 to A and from F to G. However, the first term of the elemental model is expressed in terms of the total distance, l , including the deceleration-acceleration distance, ($l_a + l_b$). This is corrected by using the consumption rate per stop, f_3 , as an excess consumption figure, i.e. the consumption during a deceleration from the cruising speed to zero speed and acceleration back to the cruising speed (a complete stop-and-go cycle with no idling time; A to C and D to F in Fig 1) less the consumption when the deceleration-acceleration distance is travelled at the cruising speed $f_1(l_a + l_b)$.

The fuel consumption rate for idling, f_2 , is relevant to stationary time (C to D). It is seen from Fig 1 that the delay experienced by a vehicle, i.e. the difference between the interrupted and uninterrupted travel times, can be measured at the stop-line by assuming infinite deceleration and acceleration rates. The existing analytical and most simulation

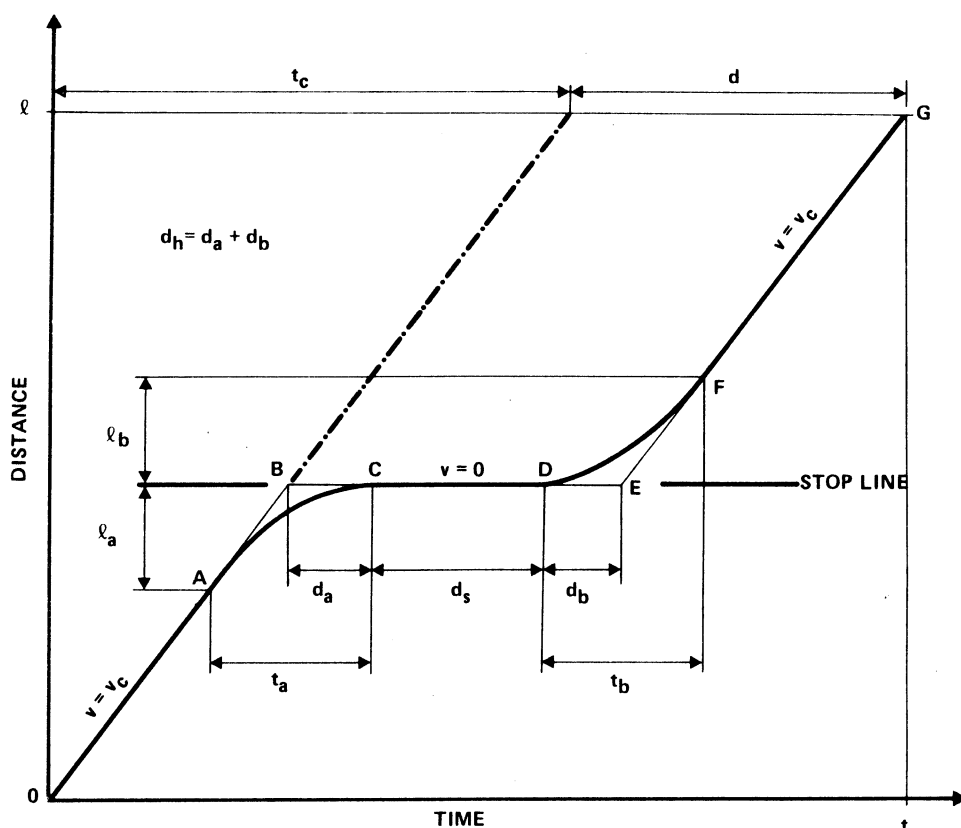


Fig 1. Time-distance trajectory of a vehicle which makes a complete stop with a stopped time delay.

models of traffic use this method of measurement (see Akçelik³⁸ for a discussion of signalised intersection delay models).

For an individual vehicle, the stopped delay time ($d_{si} = CD$) is the difference between the stop-line delay ($d_i = BE$) and the deceleration-acceleration delay (d_h) which is part of the total deceleration-acceleration time ($t_a + t_b$). The value of d_h can be estimated from $d_h = v_c/a$, where v_c is the cruising speed and a is the average deceleration-acceleration rate (see Akçelik³⁸).

Using the average delay and stop rate values, d and h , given by a traffic model, the average stopped delay time per vehicle, d_s , can be calculated from:

$$d_s = d - h d_h \quad \text{.....(2)}$$

It should be noted that, as in Equation (1), d_s , d and h are average values for all vehicles, stopped and unstopped, whereas d_h in Equation (2) applies to stopped vehicles only.

Therefore, using the stop-line delay given by an analytical or simulation model as a variable, the average fuel consumption per vehicle is:

$$f = f_1 l + f_2 d + f_3 h \quad \text{.....(3)}$$

where $f_3' = f_3 - f_2 d_h$ (the adjusted rate per complete stop).

The adjusted rate f_3' allows for the difference between the stopped time and the model delay. Most studies reported to date which used an elemental model of this type do not appear to allow for this effect and, hence, they are likely to have overestimated the effects of stops on fuel consumption, pollutant emissions, etc. Robertson *et al*³⁶ did allow for this adjustment in their fuel consumption prediction method.

The total fuel consumption for a flow of q vehicles per hour is:

$$F = f q = f_1 L + f_2 D + f_3' H \quad \text{.....(4)}$$

where

$L = l q$ = total amount of travel per hour (veh-km/h)

$D = d q$ = total delay per hour (veh-h/h)

$H = h q$ = total number of stops per hour

f_1, f_2, f_3' are as above, and F is in L/h. It should be noted that the elemental model can be expressed in terms of travel time rather than delay, as shown in the Appendix.

If desired, a fuel consumption rate defined as the consumption per vehicle-kilometre can be calculated from:

$$\bar{f} = \frac{f}{l} = \frac{F}{L} \quad \text{.....(5)}$$

where the parameters are as in Equations (1) to (4).

The following are other important points about the use of the elemental model:

(a) The rates f_1 and f_3 are dependent on the cruising speed.

(b) The rate f_1 is considered to include the effects of small variations in speed during cruising, as well as the effects of the road environment (road type, gradient, curvature, surface, adjacent land use, interference from standing vehicles, etc.) and the traffic volume. These factors also affect the average cruising speed.

(c) All rates are dependent on the particular traffic composition (allowing for different vehicle types).

(d) The stops in the above equations are considered to be complete stops. Partial stops (slowdowns) have smaller consumption rates. A feasible method of

allowing for this is to convert the partial stops to an equivalent number of complete stops so that the total calculated consumption is correct^{15,38}.

(e) The relative values of the rates for idling and stops, f_2 and f_3 , are related to the stop penalty concept used in traffic signal control^{36,39,41}. Using the rates f_2, f_3 in the same units as in Equations (1), (3) and (4), the stop penalty is given by $K = 3600 f_3/f_2$. Assuming the cruise component is unaffected by control conditions, a performance measure defined as $(D + KH)$, where D and H are total delay and stops, would be equivalent to a measure expressed by Equation (4).

(f) The rates f_1, f_2 and f_3 can be determined individually using a straightforward experimental design (see Claffey^{30,31}). This contrasts with the experimental methods which use regression analyses to determine the coefficients of a model (e.g. the simple time-dependent model described in detail later in this section). The advantage of determining the model parameters individually under controlled conditions is that the factors which affect fuel consumption are well distinguished.

(g) The data for the fuel consumption rates which will be used in the examples given in this paper are summarised in Table Ia. The data are given for light vehicles (cars, etc.), heavy vehicles (buses, trucks, etc.) and a composite vehicle (assuming 10 per cent heavy vehicles). The adjusted rate for stops, f'_3 , is calculated using $d_h = 12$ s. The data given in Table Ia are for a cruising speed of about 60 km/h, and represent the best guesses based on the data given in the literature. Table Ib summarises the rates specified by various authors. The reader is referred to the original publications to consider the bases (vehicle type, cruising speed and other conditions) of these figures. The stop penalty values using the adjusted rates, f'_3 , are also given in Tables Ia and Ib. As an example to the use of the data given in Table Ia, an average composite vehicle trip over a distance of 1 km, with 0.8 stop/km and 30 s stopped delay time would give a fuel consumption rate of

$$f = 0.012 + 2.230 \times (30/3600) + 0.044 \times 0.8$$

$$= 0.156 \text{ L/veh-km.}$$

(h) The fuel consumption calculations using the elemental model can be carried out on a link-by-link basis, i.e. for each traffic movement at an intersection or a network of intersections, using the correct set of flow and control parameters for each movement. The total fuel consumption in the system can then be calculated as a simple sum of link (movement) fuel consumptions.

(i) It should be noted that the method will give reliable estimates of fuel consumption, pollutant emissions, etc., only if the flow and control parameters, and hence the basic traffic variables (cruising speed, delay, number of stops),

Table Ia. Fuel consumption data used in the examples given in this paper

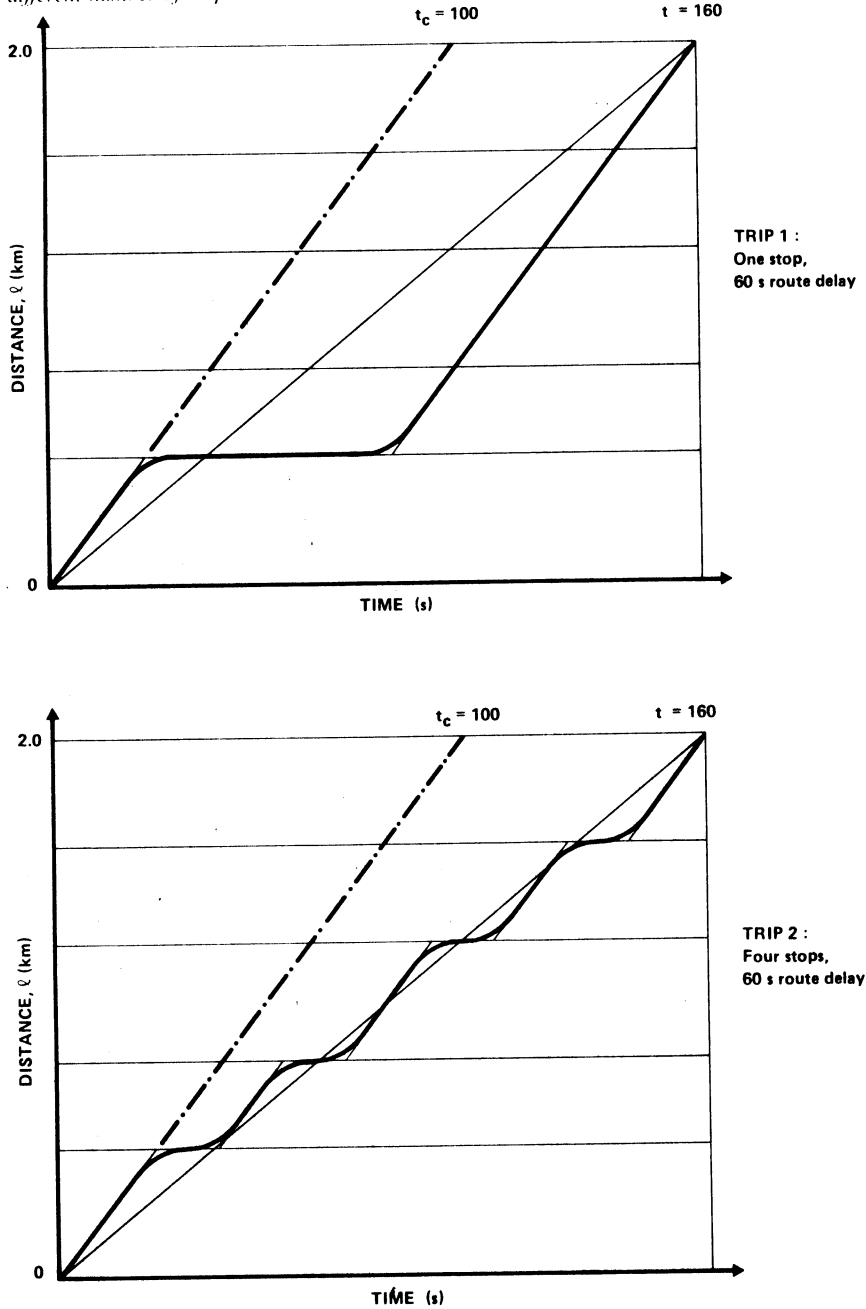
	Cruising f_1 (L/veh-km)	Idling f_2 (L/veh-h)	Stops f_3 (L/stop)	Adjusted f'_3 (L/stop)	Stop penalty K
Light vehicle	0.100	2.200	0.040	0.033	54
Heavy vehicle	0.120	2.500	0.080	0.072	104
Composite vehicle*	0.102	2.230	0.044	0.037	60

* 10 per cent heavy vehicles

Table Ib. Fuel consumption data used in the literature

	Cruising f_1 (L/veh-km)	Idling f_2 (L/veh-h)	Stops f_3 (L/stop)	Adjusted f'_3 (L/stop)	Stop penalty K
Claffey ^{30,31}	0.108	2.385	0.048	0.040	60
Bauer ²⁹	—	1.893	0.126	0.120	228
Courage and Parapar ³²	—	2.271	0.038	0.030	48
Dart and Mann ³³	0.112	2.366	0.025	0.017	26
Robertson, <i>et al</i> ³⁶	0.094	1.500	—	0.014	34

Fig 2. An example of two 'average' trips over the same distance with the same delay and average speed, but different number of stops.



are estimated with a reasonable accuracy. This should allow for both individual link characteristics and the interactions between links. For example, the backward spread of congestion from one link to another due to a lack of sufficient storage capacity could invalidate the assumptions about saturation flow of the upstream links.

A simpler model?

A simpler model based on a statistical approach has been used widely in the literature, which expresses the fuel consumption rate as a function of only the interrupted travel speed, \bar{v} , or the interrupted travel time per unit distance, \bar{t} ^{6,28,42-54}. The model is expressed as

$$\bar{f} = f_a + f_b \bar{t} \dots\dots(6)$$

where

\bar{f} = fuel consumption rate (L/veh-km)
 \bar{t} = average interrupted travel time per unit distance (h/km); with reference to Fig 1, $\bar{t} = t/l = 1/\bar{v}$.

The parameters f_a and f_b are jointly determined by linear regression to measured or simulated fuel consumption rates. For example, Evans and Herman⁴⁶ gave $f_a = 0.110$ L/veh-km, $f_b = 3.024$ L/veh-h for simulated data (for speeds less than 60 km/h), and Watson *et al*⁵⁴ gave $f_a = 0.094$ L/veh-km, $f_b = 2.457$ L/veh-h for peak hour driving conditions on arterial roads in Melbourne. In the literature, it has been stated that the parameters, f_a , f_b

represent consumption rates related respectively to the cruising distance and idling. However, these parameters should be expected to include the effects of speed changes (and, hence, stops) under the measured, or simulated, conditions, which are neglected in the regression analysis⁴⁹⁻⁵¹.

The main weakness of the simple model expressed by Equation (6) is that it cannot allow for the effects of stops explicitly. It has often been argued that the delay (and hence the travel time and speeds) and stops are correlated, and that therefore the simpler model is sufficient to allow for both effects. This is true only to the extent that each stop is associated with some delay and that there is a basic relationship between the delay, travel time and speed ($\bar{t} = t/l = (t_c + d)/l = 1/\bar{v}$). However, there is a range of conditions where the differential effects of stops and delays become important and the use of the above argument to justify the simpler model is not acceptable. This is almost always the case in the context of traffic management and control which deals with interrupted travel conditions in urban areas. Two important points relevant to this argument are illustrated in Figs 2 and 3.

Figure 2 shows that it is possible to travel the same distance with the same total delay time (hence travel time) but different number of stops. In this example, the travel time per unit distance is $\bar{t} = 80$ s/km for both trips ($\bar{v} = 45$ km/h), but TRIP 1 involves one stop with a delay of 60 s whereas TRIP 2 involves four stops with 15 s delay each. With the data given in Table 1a, the following fuel consumption rates are calculated using the elemental model:

TRIP 1:
$$\bar{f} = 0.102 + (2.23 \times 60/3600)/2$$
$$+ (0.037 \times 1)/2$$
$$= 0.138 \text{ L/veh-km}$$

TRIP 2:
$$\bar{f} = 0.102 + 4(2.23 \times 15/3600)/2$$
$$+ (0.037 \times 4)/2$$
$$= 0.195 \text{ L/veh-km}$$

The difference in relative terms (about 30 per cent) is too significant to be neglected. An inspection of the data reported in the literature indicates wider variation in fuel consumption rates for a given speed (e.g. see Watson²⁸, Fig 5.2, for $v = 45$ km/h). On the other hand, the simpler model predicts a single fuel consumption rate of

$$\bar{f} = 0.110 + (3.024 \times 80/3600)$$
$$= 0.177 \text{ L/veh-km}$$

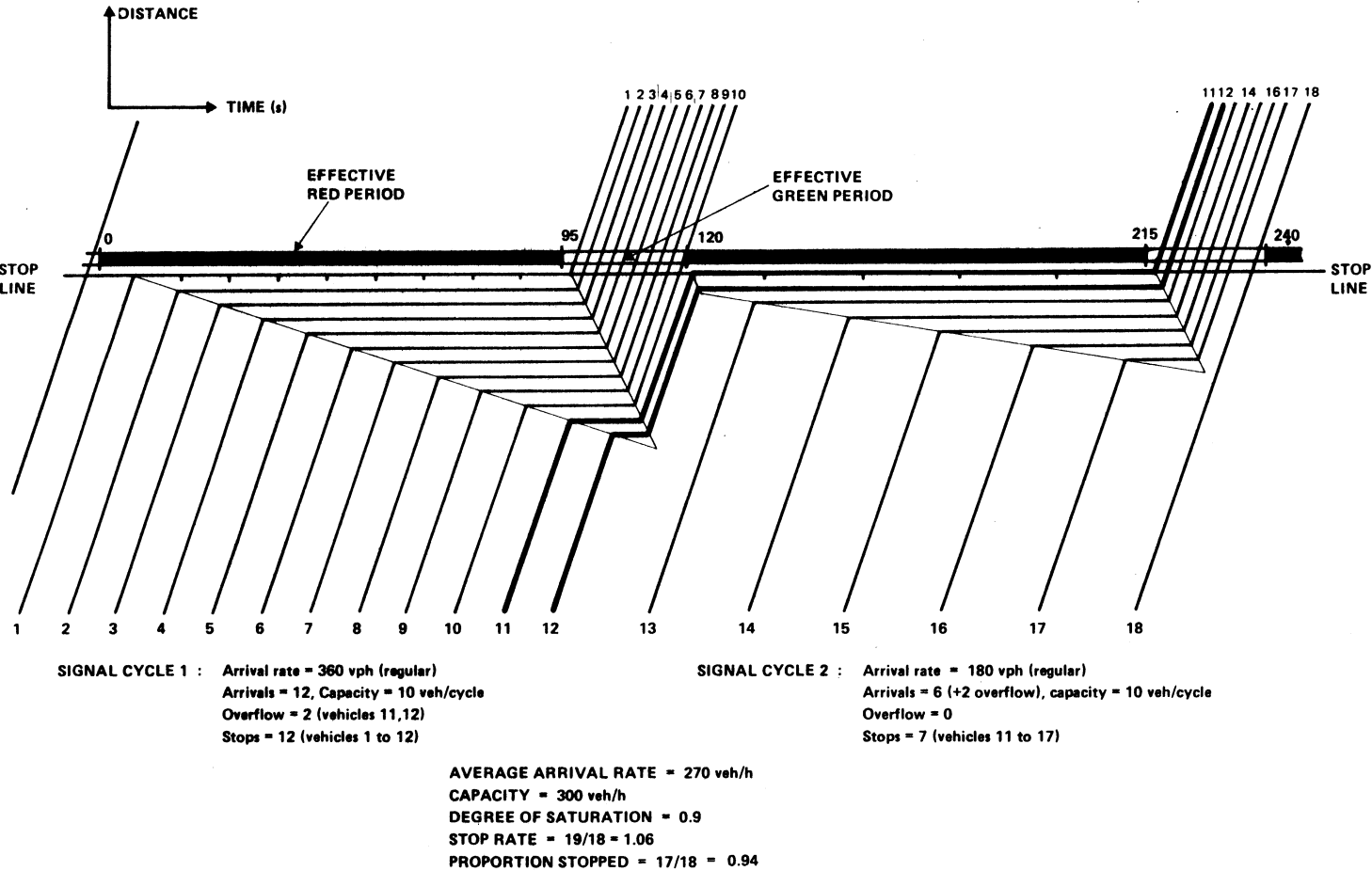
using the values of f_a and f_b given by Evans and Herman⁴⁶, or

$$\bar{f} = 0.094 + (2.457 \times 80/3600)$$
$$= 0.149 \text{ L/veh-km}$$

using the data given by Watson *et al*⁵⁴.

A possible source of error in the derivation of the simple model expressed by Equation (6) is related to the method of measuring stops. Most methods in use to date (analytical, simulation and field survey methods alike) measure the proportion of vehicles which stop, rather than the actual

Fig 3. An example for multiple stops.



number of stops made by vehicles. For example, in the field survey method described by Reilly *et al*⁵⁵, 'each vehicle is counted only *once* regardless of the number of stops it may have made'. This neglects *multiple stops* made by vehicles at traffic signals and other controlled conditions. A detailed discussion of this subject and a formula for predicting stops at isolated traffic signals allowing for multiple stops are given in Akcelik³⁸. Multiple stops may give rise to stop rates larger than one per vehicle, whereas the maximum value of the proportion of stopped vehicles is one. The effect of multiple stops becomes significant for degrees of saturation (volume/capacity ratios) greater than about 0.8. Since most signals operate near or at capacity conditions during peak periods, the methods which ignore multiple stops may significantly underestimate the number of stops and hence the fuel consumption and pollutant emissions rates, for the most relevant conditions of urban travel.

Figure 3 presents an example of the effect of multiple stops on the average number of stops per vehicle (stop rate) at isolated traffic signals. The first signal cycle is oversaturated (capacity exceeded) resulting in an overflow of two vehicles (vehicles 11 and 12). In the second signal cycle all new arrivals as well as the two vehicles left over from the first cycle are cleared. The last vehicle (vehicle 18) is unstopped. It is seen that vehicles 11 and 12 make two stops before they can clear the intersection and this results in a stop rate greater than one in spite of the undersaturated conditions on average. The effect of the random variations in arrival flow rates increases as average flow rates approach capacity resulting in larger overflow queues and greater number of multiple stops³⁸.

A related point of importance is that if both the multiple stops and the partial stops (slowdowns) are ignored, a bias will be introduced to fuel consumption (and similar) calculations. In contrast with the effect of multiple stops, the partial stops are significant under light traffic conditions. Therefore, the fuel consumption rates would be overestimated for light traffic conditions and underestimated for heavy traffic conditions. When alternative traffic management measures are considered, this could favour the measures which might lead to more congested conditions.

The errors in the prediction of stops will also affect the results from the elemental model, but this is related to the *use* of the model, rather than the model itself. In the case of models derived using statistical curve fitting methods, the measurement errors are built in as the model parameters (e.g. parameters f_a and f_b of Equation (6)).

Although the simple model expressed by Equation (6) has found some acceptance in literature because of its simplicity, its use in the context of traffic management and control is restricted because of the effects of stops. The sensitivity of fuel consumption to deceleration and acceleration (hence stops) and the deficiency of the simple speed (or time) dependent model have already been shown and emphasised by several authors^{49, 51, 53, 54, 56}. The importance of

stops in a wider context has been discussed by Huddart³⁹, May¹¹ and Robertson²². Work in the U.K. indicates that significant reductions can be obtained in fuel consumption without increasing travel times substantially when traffic control plans based on a minimum-delay strategy are replaced by optimum signal plans derived by weighting the number of stops against delay³⁶.

The following speed-dependent model has been proposed by Watson *et al*⁵⁴ to overcome the deficiency of the simple model expressed by Equation (6):

$$\bar{f} = k_1 + \frac{k_2}{\bar{v}} + k_3 \bar{v} + k_4 \text{PKE} \quad \text{.....(7)}$$

where

\bar{f} is the fuel consumption rate

\bar{v} is the average speed

PKE is the sum of 'positive acceleration kinetic energy changes'

Watson *et al*⁵³ describe the method of determining the PKE term, and give values for the coefficients k_1 to k_4 , which were determined by regression analysis using data from fuel consumption measurements in Melbourne. However, they do not specify how the model can be used to predict location-specific values of fuel consumption under particular traffic management/control conditions.

In conclusion, the elemental model described above is preferred because it can be used to determine, in advance, location-specific values of fuel consumption, pollutant emissions, cost, etc., and because it employs variables which can be predicted directly using existing traffic models. As such, it provides a satisfactory method of determining optimum traffic management/control tactics.

The elemental model has already been used in the computer programs SIDRA for

isolated signalised intersections and TRANSYT/6N for networks of co-ordinated signals (Akcelik²). The computations for the examples given later in this paper were carried out using these two programs. Before the examples are given to illustrate various specific points, a general discussion of the possible effects of alternative traffic management measures is given below.

TRAFFIC MANAGEMENT MEASURES FOR REDUCING FUEL CONSUMPTION

Detailed studies are required for the implementation of the methodology described above for establishing energy saving policies related to traffic system management. There are dangers in generalising location-specific results to define general policies without carrying out extensive studies. However, an attempt is made below to indicate the *expected* effects of various traffic system management measures (tactics) on fuel consumption and other objectives. Table II is presented for this purpose, and is based on research results reported in the literature^{33, 36, 47, 49, 53, 54, 56, 58}, and additional analysis by the author.

Each measure shown in Table II is first indicated with its expected effects on the basic traffic performance variables, namely: cruise (amount of travel related to uninterrupted conditions); delay (which also implies interrupted travel time and speed); and the number of stops. Expected effects on fuel consumption and safety are indicated by considering a combination of the impacts on the basic performance variables. The effects on pollutant emissions are expected to be similar to those on fuel consumption although they would have different optimum conditions in a marginal sense.

Some of the points indicated in Table II are shown in more specific terms in the examples given below. It should again be emphasised that the measures considered in

Fig 4. Fuel consumption as a function of the level of congestion.

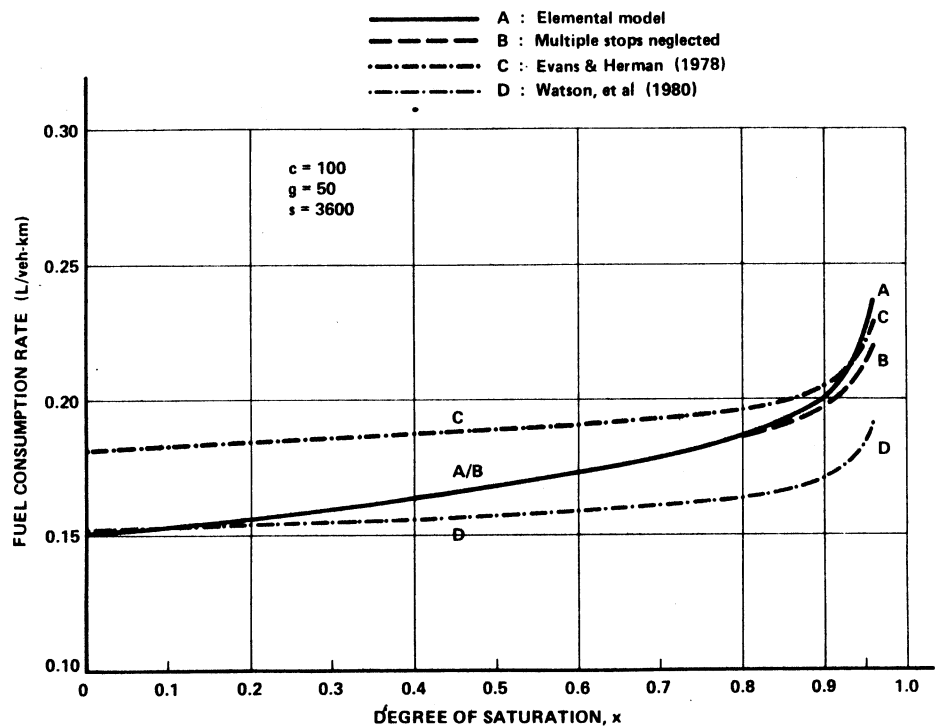


Table II. Expected effects of various traffic system management measures

Traffic system management measure	Traffic performance			Fuel consumption	Safety	Remarks
	Cruise	Delay	Stops			
Signal co-ordination and area traffic control	=	+	+	+	+	Important benefits from better signal preparation methods, dynamic controls, and on-line information gathering about traffic and control equipment conditions Possibility of attracting traffic from residential streets
Improved intersection geometry (e.g. additional turning lanes)	=	+	+	+	+	Important benefits from periodic checks on flow patterns
Better signal phasing	=	+	+	+	+	Good traffic engineering solutions using modern signal controllers will reduce the problems of flow pattern changes between peak and off-peak conditions
Optimising signal timings for fuel consumption rather than delay	=	—	+	+	?	Safety may be improved due to decreased stops provided delays are not increased to levels unacceptable by drivers Adverse effects on pedestrians and minor movements
Priority lanes and other public transport priority measures	?	—	—	—	?	Adverse effects in general unless designed carefully for net benefit or a reduction in car travel (long-term objective) Also adverse effects on property access
Pedestrian treatment at traffic signals	=	—	—	—	?	Safety and convenience for pedestrians may be improved
Right-turn prohibition at critical intersections	—	+	+	+	+	Net improvements possible provided losses due to increased travel are relatively small Possibility of diversion to residential streets and adverse effects on property access
One-way-street systems	—	+	+	+	+	As for right-turn prohibition
Tidal-flow arrangements (variable lane use)	=	+	+	+	?	
Clearways, parking restrictions	=	+	+	+	+	Travel distance may increase due to search for parking Adverse effects on property access
Better route (direction) signing and dynamic route control/advice systems	+	+	+	+	+	Excess travel and time losses due to wrong route choice will be reduced
Entry control (ramp metering or closure for freeways, gating for signalised arterials)	?	+	+	+	?	Travel distance may increase and losses may occur due to diversionary effects; performance of controlled traffic (ramps, side roads) must be considered with care
Reduce speed limits on uninterrupted road facilities	=	—	+	+	+	Safety and fuel benefits due to lower speeds and fewer speed changes

Key: + Improvement (gain) — Deterioration (loss) = No change ? Undetermined or highly varied

Table II and in the following sections of this paper are *short-term* measures which are relatively easy to implement. The longer-term management measures which aim for reducing the amount of traffic using the road system (e.g. parking restrictions in the city centre, improving the standard of public transport operations, etc.) are important, but outside the scope of this paper.

It should also be emphasised that the impacts indicated in Table II are by no means true in all cases, they are given only as the most likely impacts. Furthermore, some 'no change' effects are based on the assumption that flow levels remain unaffected by the measure in question.

TRAFFIC SIGNAL CONTROL

Some of the arguments put forward above will be discussed and illustrated below by means of examples of traffic signal control in

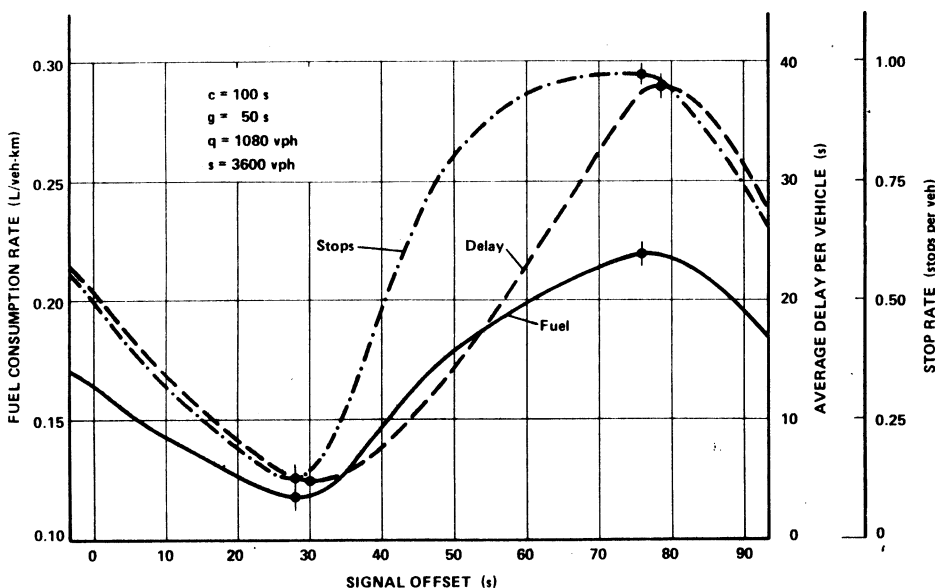
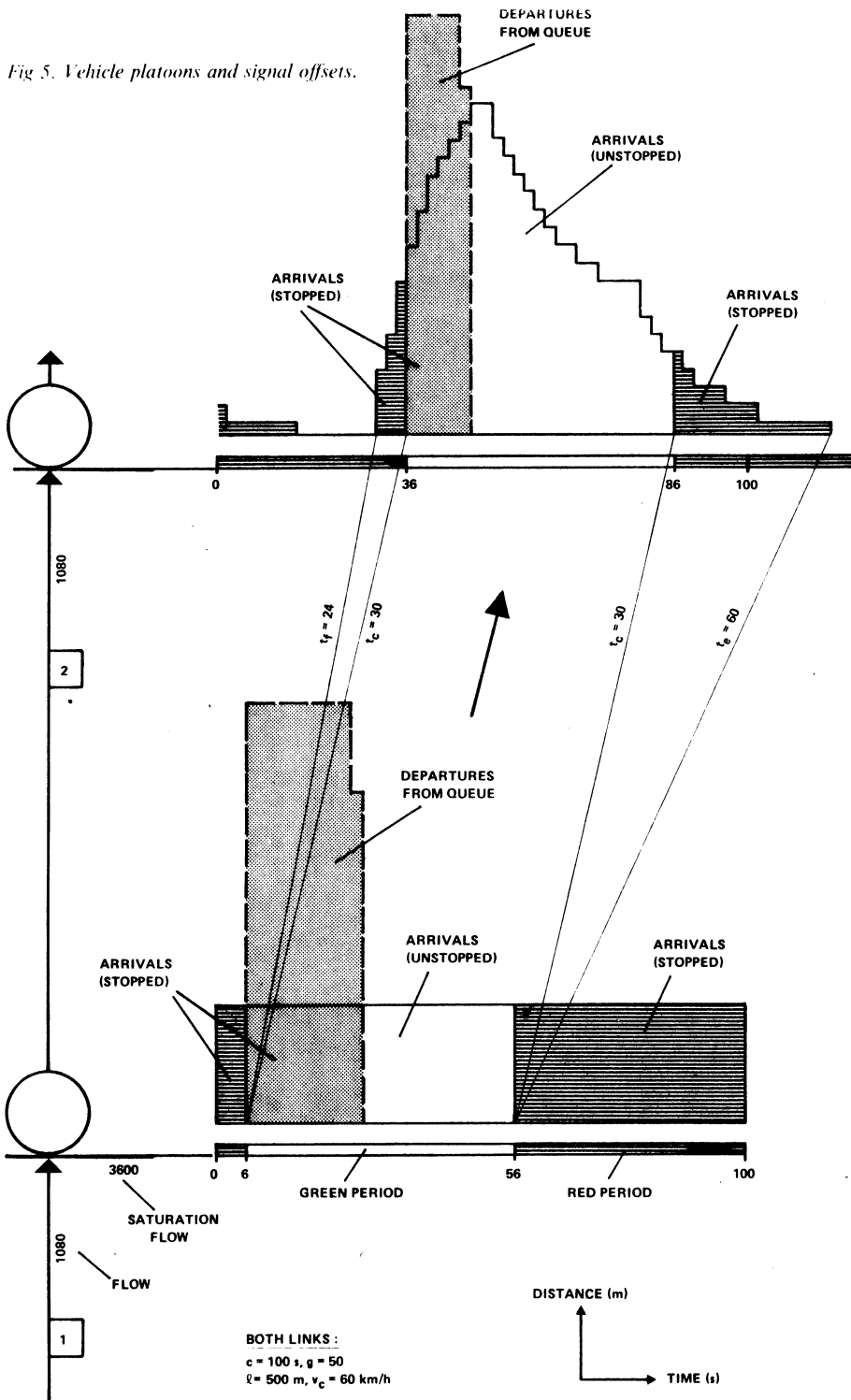
both isolated and co-ordinated signal cases, since this is the most relevant and positive area of urban traffic management. Before giving the examples to discuss specific issues, some basic aspects of isolated and co-ordinated signals will be explained.

The effect of the level of congestion (as described by the degree of saturation, i.e. the volume/capacity ratio) on the fuel consumption rate at an isolated (fixed-time) intersection is illustrated in Fig 4. The signal control parameters (signal cycle time, c , and effective green time, g) and the queue discharge characteristic (saturation flow, s) of, and hence the capacity, sg/c , for the movement under consideration is fixed. The arrival flow rate, q , and hence the degree of saturation, $x = qc/sg$, is varied. The delays and stops are calculated from the Miller formula⁵⁹ and a new formula by the author³⁸, respectively. Curve A represents

the fuel consumption rates calculated using the elemental model (Equations (1) to (5)) with the parameters shown in Table Ia. Curve B represents the fuel consumption rates when multiple stops are neglected. It is seen that this differs from Curve A for about $x > 0.8$ in this particular case and the difference becomes increasingly significant as x increases.

Curves C and D in Fig 4 represent the fuel consumption rates obtained from the simpler model (Equation (6)) using the parameters given by Evans and Herman⁴⁶ for Curve C and Watson *et al*⁵⁴ for Curve D, which are mentioned above. The interrupted travel times for Curves C and D are calculated using the delays as for Curve A and a cruising time of 60 s/km. Although the comparison of Curves C and D with Curve A is not quite meaningful (since Curves C and D are derived by curve fitting to measured or

Fig 5. Vehicle platoons and signal offsets.



simulated data points, whereas Curve A is derived by explicit calculation of delays and stops for a particular case), it is seen that Curve C overestimates fuel consumption rates for light traffic conditions and underestimates for heavy traffic conditions, whereas Curve D underestimates for all degrees of saturation in this particular case.

A simple case of a pair of links with the same arrival flow, saturation flow and signal timing parameters (hence the same degree of saturation) is shown in Fig 5. Link 1 represents a movement at an isolated intersection, and its parameters correspond to $x = 0.6$ in Fig 4. The arrival and departure patterns shown for this link assume regular arrivals and departures. However, the delays and stops are calculated assuming that the actual arrival rate changes randomly from cycle to cycle (see Akçelik³⁸). Link 2 represents an internal link in a system of co-ordinated signals. It is assumed that the only flow entering Link 2 is that which is discharged from Link 1 (external link). The arrival pattern at Link 2 is determined by the departure pattern of Link 1 modified according to a *platoon dispersion* process which allows for different vehicle speeds in the platoon. The pattern given in Fig 5 has been obtained using the TRANSYT computer program (Robertson and Gower⁴¹, Akçelik²) which simulates traffic in co-ordinated signal networks in this manner so as to predict delays and stops. The platoon arrival pattern of Link 2 shown in Fig 5 is of a cyclic character since it is generated from the regular arrival/departure pattern of Link 1. TRANSYT carries out a correction to delays to allow for randomness of platoons although it ignores this in the case of stops; in other words, it neglects the effects of multiple stops. However, this effect is negligible (i.e. the queues are always cleared) for the data used in Fig 5 because of the low degree of saturation.

An important aspect of the co-ordinated signal case is that the delays and stops are strongly dependent on the *signal offset* (the difference between the starting times of green periods). In Fig 6, the delay, stop rate and the fuel consumption rate as a function of the signal offset are shown for Link 2 of Fig 5. The fuel consumption rates are calculated from the elemental model using the values of delay and stop rate computed by the TRANSYT program and the parameter values given in Table Ia. It is seen that the offsets which minimise fuel consumption/stops and delay are quite close although the patterns of change are different.

Figure 6 illustrates the reason why signal co-ordination is one of the most effective ways of reducing fuel consumption, at the same time improving traffic performance and safety in urban areas. Assuming that the delays and stop rates in the case of unlinked but closely spaced signals can be approximated using the formulae for isolated signals, the fuel consumption for Link 2 would be the same as Link 1, i.e. $\bar{f} = 0.173 \text{ L/veh-km}$ ($x = 0.6$). The corresponding value in the co-ordinated case

Fig 6 (left). Delay, stops and fuel consumption as a function of the signal offset.

with an optimum offset of 28 s, is $f = 0.119 L/\text{veh-km}$, which implies a saving of the order of 30 per cent. However, a case as simple as that shown in Fig 5 can hardly be found in practice. Many conflicting objectives are presented at each intersection by various movements competing for a better proportion of the green time available and from intersection to intersection by various platoons of vehicles competing for a better offset. As a result, the savings which can be expected from signal co-ordination are reduced. This is illustrated below by means of two numerical examples.

It should be emphasised that the examples given below are still simple cases compared with what is commonly found in practice. They are presented here as simple examples to eliminate the effects of complicating factors such as signal phasing, saturation flow and lost time estimation, etc. Solutions for the two examples given below have been computed using the SIDRA (isolated signals) and TRANSYT/6N (co-ordinated signals) computer programs, and as such these examples illustrate some of the facilities of these two programs². Fuel consumption values have been calculated by these programs using the parameters given in Table Ia. The cycle time optimisation has been carried out with 5-s search increments.

EXAMPLE 1: AN ISOLATED INTERSECTION

This example is given to show the problems related to the consideration of various road-user groups, namely pedestrians, buses and other vehicles (mainly cars), and various optimisation objectives, namely delays, stops and fuel consumption. The intersection plan and the signal phasing system is shown in Fig 7 (a junction of two one-way roads, with rather heavy pedestrian flows, controlled by a simple two-phase signal system). The data are presented in Fig 7 and Table III. Two cases are considered:

- (1) All buses (36 per hour) and a vehicle flow of 300 veh/h (out of a total approach flow of 3 600) use the kerb lane. In other words, the kerb lane is under-utilised. The other lanes are assumed to be used equally.
- (2) Kerb lane is allocated to BUSES ONLY, thus shifting 300 veh/h to the other lanes.

In both cases, the pedestrian minimum green time requirements play an important role in the optimum solutions.

In Fig 8, the total person delay and the fuel consumption rate for the intersection are given as a function of the signal cycle time for Case (1). The total person delay is calculated using the occupancy data given in Table III and adding up the individual movement values. It is seen that the cycle times which minimise the total person delay and the total fuel consumption are 95 s and 165 s respectively, which indicates a substantial difference. If the 165-s cycle time is used the person time loss would be 23 per cent, whereas with the 95-s cycle time the fuel consumption loss would be 4 per cent. The person time measure corresponds to the objectives of bus and pedestrian treatment which are shown to be in conflict with the objective of reducing fuel consumption in this case. A trade-off solution could be to use

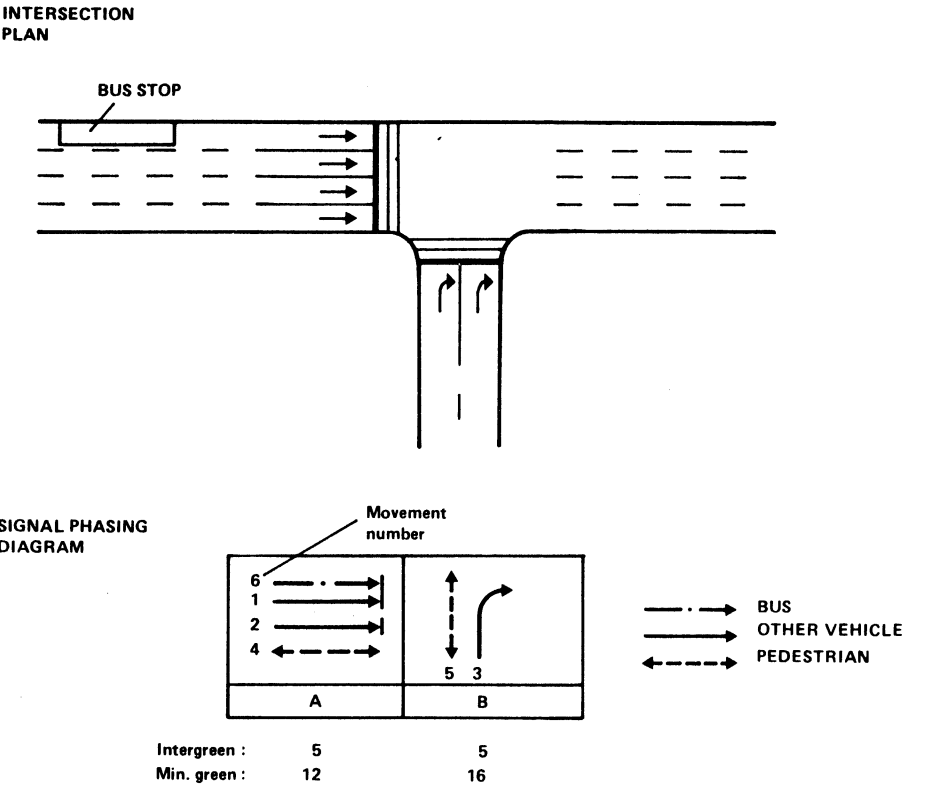


Fig 7. Data for Example 1.

Table III. Data for Example 1

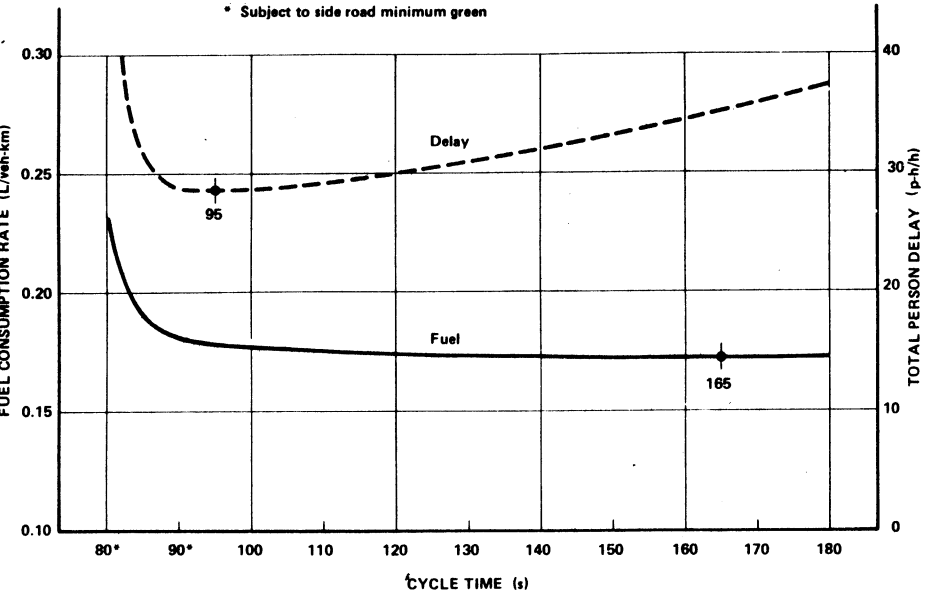
Movement number	Flow (veh/h)	Sat. flow (veh/h)	Speed (km/h)	Occupancy	Lost time (s)
1	300	1 350*	50	1.3	5*
2	3 300	5 000	60	1.3	5
3	240	1 600	50	1.3	5
4 Ped.	400	20 000	5	1.0	9
5 Ped.	400	20 000	5	1.0	13
6 Bus	36	*	50	40.0	*

* Movements 1 and 6 share the same stop-line (i.e. mixed traffic)

<i>With bus lane</i>					
1	Eliminated (kerb lane for buses only)				
2	3 600	5 000	60	1.3	5
6	36	750	50	40.0	5

N.B.: All link lengths = 500 m

Fig 8. Fuel consumption and person delay as a function of the signal cycle time (Example 1).



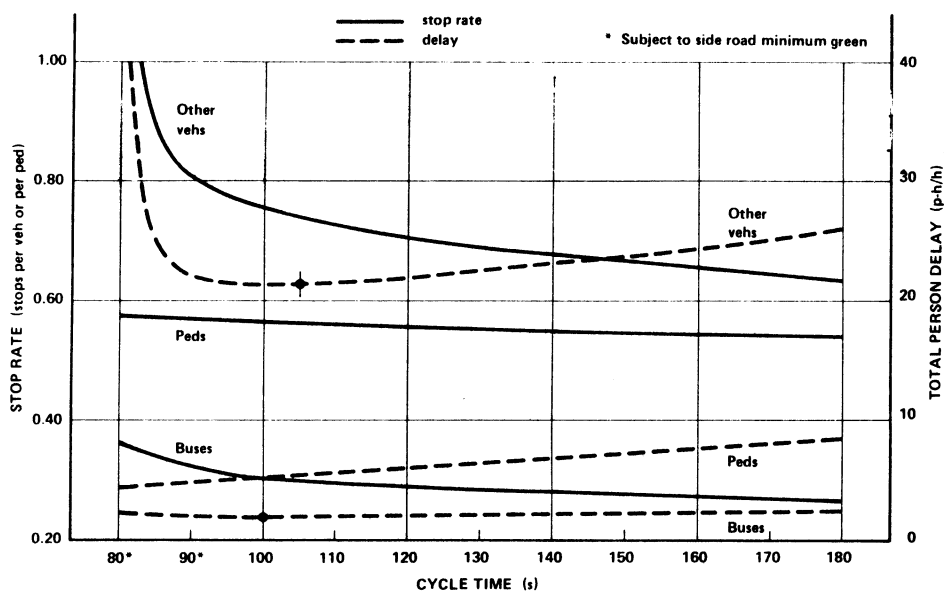


Fig 9. Pedestrian, bus and other vehicle delays and stops as a function of the signal cycle time (Example 1).

a cycle time of, say, 120 s, in which case a fuel consumption reduction of 3 per cent would be obtained at the expense of a 5 per cent increase in total person delay.

This example shows the dangers of adopting a narrow approach (considering only a single objective such as fuel consumption) and interpreting and implementing 'optimum' results too literally. It is seen that the gain, in this particular case, from using a substantially long cycle time is not that large. Furthermore, longer cycle times result in longer queues which may exceed storage capacities of the available road space, thus resulting in capacity losses and making the assumptions regarding the optimum solution not valid.

Effects of the signal cycle time on the performance of individual road user groups, i.e. pedestrians, buses and other vehicles, for this example (Case (1)) are illustrated in Fig 9. It is seen that stops are reduced for all groups by increasing the cycle time. The delays have optimum values for buses and other vehicles, but pedestrian delays decrease with decreasing cycle times. Again, Figs 8 and 9 show that a single objective of 'minimum pedestrian delay' might lead to the use of a small cycle time of, say, 80 s, which would result in a fuel consumption loss of 33 per cent (relative to the compromise solution of 120 s).

In Case (2) with the kerb lane for BUSES ONLY, the cycle time which optimises the total person delay is 138 s. The increase compared with the cycle time of 95 s without

the bus lane is due to shifting 300 veh/h from the kerb lane to the other lanes and hence an increased level of congestion. The benefits to bus passengers is 19 per cent in this case, but there is a net increase of 39 per cent in total person delay and 8 per cent in fuel consumption (relative to $c = 95$ s).

The results for Example 1 are summarised in Table IV indicating the solutions discussed above.

EXAMPLE 2:

A CO-ORDINATED SIGNAL SYSTEM

This example is given to discuss some aspects of finding 'optimum' solutions for co-ordinated signals. The considerations of various road-user groups and alternative optimisation objectives are ignored. Only vehicle fuel consumption is considered. A simple network of three intersections along an arterial road is considered. The data are given in Fig 10, which is presented in the form of a link-node diagram using the data preparation format of the TRANSYT program. The three groupings of links (movements) are also defined in Fig 10. All distances are 300 m except for the distance between intersections 2 and 3 which is 450 m. All cruising speeds are assumed to be 54 km/h. The following cases are considered:

- (1) Isolated signals: each intersection optimised individually.
- (2) Co-ordinated signals: optimised for the entire network (Groups 1, 2, 3), called Policy A.

(3) Co-ordinated signals: optimised for the major road (Groups 1, 2), neglecting side roads, called Policy B.

(4) Co-ordinated signals: optimised for the major road peak direction only (Group 1), neglecting side roads as well as major road opposite-peak direction traffic, called Policy C.

(5) Right-turn ban: co-ordinated signals optimised for the entire network (Policy A). In this case, Link 24 is eliminated and the phasing system of the critical intersection 2 is reduced to a simple two-phase system reducing its lost time from 15 s to 10 s. These vehicles are assumed to follow the path shown in Fig 10 and enter Link 23 increasing its flow rate to 600 veh/h. The saturation flows are assumed to remain unchanged.

The results are given in Table V indicating the optimum cycle time and the total fuel consumption under each policy. The benefits and disbenefits under Policies A, B and C (relative to the isolated conditions) and in the case of right-turn ban (relative to the co-ordinated, Policy A conditions) are given in Table VI. It should be noted that the side-road phases were subject to increased minimum green times of 15 s under policies B and C to represent constraints which define the extent to which this traffic can be neglected to practice.

It is seen that one could expect a reduction of 29 per cent by considering peak direction traffic only. This would be decreased to 26 per cent if the opposite-peak direction is taken into account also, and, more significantly, decreased to 13 per cent when side roads are considered also. In fact, these are the benefits to the peak direction traffic only; the total system experiences substantial disbenefits in the case of Policies B and C. It should be noted that these may not be deliberate policies, but they represent some current practices of field survey and signal plan preparation. It is seen that with the total system constraints at work, a fuel consumption reduction of 7 per cent is predicted. However, considering the fact that the real-life networks are more complicated than that used in this example, thus presenting a higher level of constraints, also allowing for the existence of other objectives such as bus priority and pedestrian treatment as in Example 1, the expected fuel consumption reduction would probably be less.

It is seen in Table VI that further fuel consumption reductions are possible by using measures like a right-turn ban at critical intersections (7 per cent for the network as a whole). However, this does not take into account the losses due to extra distance travelled by the diverted vehicles (360 veh/h). For example, let us assume that these vehicles are subject to an extra travel distance of 600 m, 0.8 stops and 20 s delay. This corresponds to an extra fuel consumption of 37 L/h (still neglecting the losses incurred by other traffic on the route to which these vehicles were diverted). Considering this loss, the system benefit from the right-turn ban is reduced to 3 per cent. It could be estimated that signal co-ordination and right-turn ban jointly might give rise to a fuel saving of 10 per cent.

Table IV. Results for Example 1

Cycle time (s)	Fuel cons. rate (L/veh-km)	Total person delay (p-h/h)	Person delays (p-h/h)		
			Pedestrians	Buses	Other veh.
80*	0.231	53.61	4.31	2.25	47.05
95	0.179	28.55 (min.)	4.99	2.04	21.52
120	0.174	29.84	5.99	2.13	21.74
165	0.172 (min)	35.04	7.83	2.33	24.88
138**	0.194	39.77 (min.)	6.78	1.66	31.33

* Side-road green at its minimum value ($G_m = 16$)

** Kerb lane for buses only

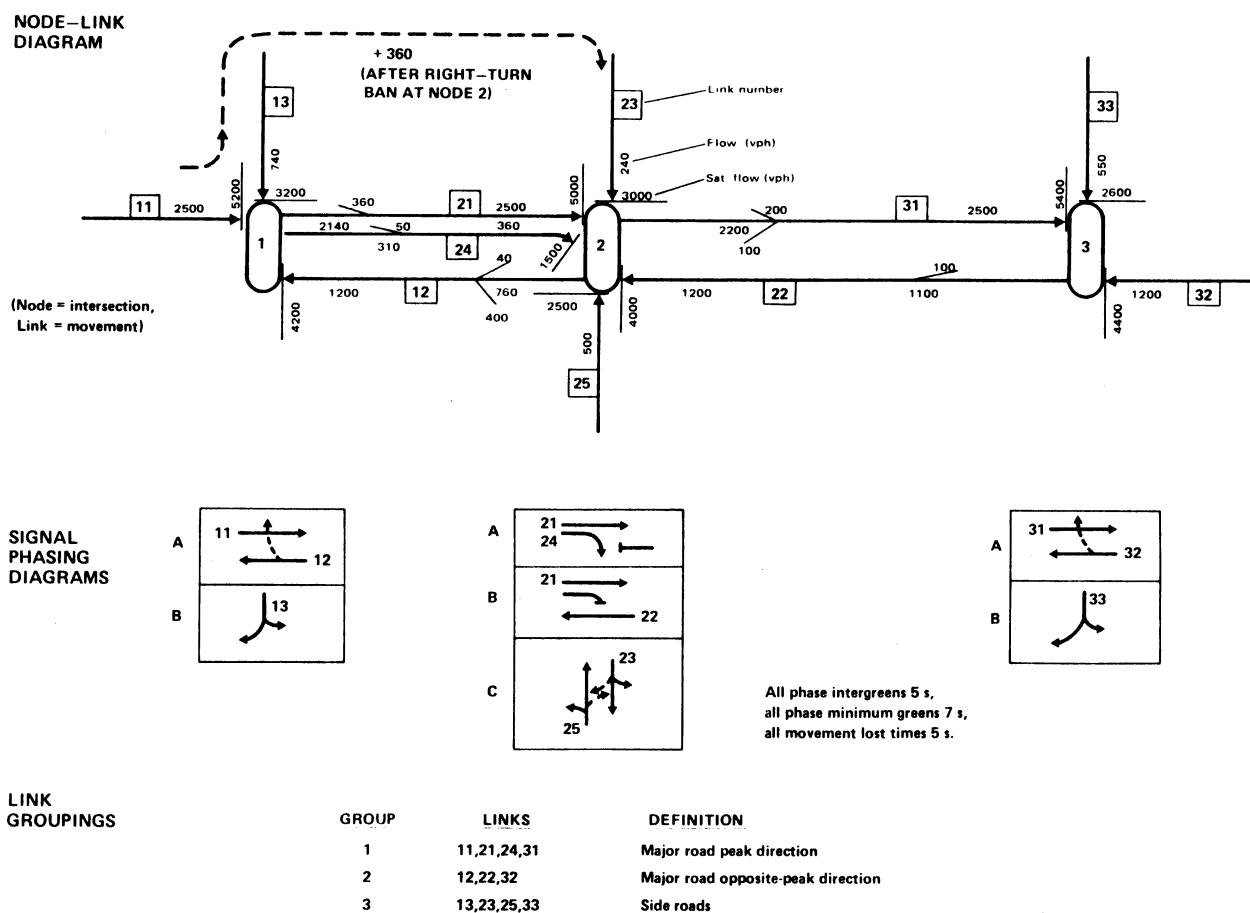


Fig 10. Data for Example 2.

It should be noted that the results given here are specific to this example (and involve some limitations of the stops model of the TRANSYT program), but the estimates of the level of reduction in fuel consumption are expected to be of the right order of magnitude in general terms. In specific cases, the improvement may be smaller or larger depending on the base and improved conditions. In the present example, the base case represents isolated signals with optimum conditions. In practice, there are many complicating factors such as flow variations between peak and off-peak periods, control equipment failures and long-term flow changes which result in non-optimum conditions of signal control. An area traffic control system which has on-line information gathering and signal plan updating facilities should therefore be expected to give greater benefits.

CONCLUSION

It has been emphasised in this paper that the fuel consumption problem must be considered in the context of an overall traffic system management approach. This should allow for the resolution of conflicts among various objectives (operational efficiency, fuel consumption, pollutant emissions, safety, etc.) and the needs of various road-user groups (pedestrians, buses, cars, major and minor-road traffic, etc.). Coupled with the fact that road traffic systems have location-specific and time-dependent characteristics, this leads to the conclusion that traffic system management is a continuous process which requires the use of

Table V. Results for Example 2

Conditions	Optimum cycle time	Total fuel consumption (L/h)		
		Groups 1, 2, 3	Groups 1, 2	Group 1
Isolated optimised individually	95, 115, 95	998	791	541
Co-ordinated: Policy A	110	925	724	473
Co-ordinated: Policy B	110	1 884	600	400
Co-ordinated: Policy C	110	3 569	2 173	382
Right-turn ban* Co-ordinated: Policy A	95	863	636	434

* The flow pattern is assumed to remain unchanged except in the case of right-turn ban; extra fuel consumed by the right-turners outside the system is not included in the values shown

Table VI. Benefits/disbenefits from various signal co-ordination policies (Example 2)

Policy	Benefits* to Groups		
	(1, 2, 3)	(1, 2)	(1 only)
A	7%	8%	13%
B	- 89%	24%	26%
C	- 258%	- 175%	29%
Right-turn ban	7%	12%	8%

* A negative number indicates a disbenefit

fine detailed analysis techniques and sophisticated implementation methods if significant levels of improvement are to be achieved and maintained. Emphasis should therefore be on good traffic engineering practice.

A detailed discussion of the selection of models for predicting fuel consumption by vehicles in urban traffic conditions has been given. An elemental model has been described in detail, and is preferred because of its conceptual clarity, simplicity and relevance to the existing traffic modelling techniques. In fact, it is recommended that the potential of the elemental model should be explored in the context of overall transport planning, route choice in particular, as a (perceived or actual) 'cost' function which includes the effects of stops in addition to the distance and time factors used traditionally.

Examples have been given to illustrate possible sources of error in the methods employed to date to evaluate fuel consumption effects of various traffic management measures. These errors include the use of models which do not predict the effects of stops explicitly, neglecting the effects of multiple stops and partial stops (slowdowns), the use of 'stop-line' delay instead of the actual stopped delay (idling) time, and considering the impacts on parts of the system only (particularly neglecting the effects on minor/side-road traffic).

The fundamental considerations and detailed examples of isolated and co-ordinated signal control given in this paper show the sensitivity of fuel consumption to traffic flow characteristics and signal control parameters. Based on the results of the examples given in this paper, as well as the results reported in the literature, it can be concluded that significant fuel consumption reductions of about 5 to 10 per cent could be expected from optimum traffic signal control with due consideration to other traffic system management objectives.

The discussion in this paper has concentrated on the tactical issues related to short-term traffic system management objectives. However, it is important that these objectives are considered in the context of a wider transportation system management approach which analyses relatively long-term impacts on route and mode choice, demand levels and vehicle occupancies, and tries to influence travel behaviour related to these factors. This is important because there are areas of conflict between short-term and long-term objectives. This would lead to the

considerations of political and institutional problems related to decision-making and implementation issues, which are as important as the technical problems considered in this paper.

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APPENDIX

The elemental model can be expressed in terms of travel time rather than delay. Since

$d = t - t_c = t - (l/v_c)$ as shown in Fig 1. Equation (3) can be re-written as:

$$f = f'_1 l + f_2 t + f'_3 h$$

where

l = cruising distance in km

t = average travel time (interrupted) in hours

h = stop rate (number of complete stops per vehicle)

f = average fuel consumption per vehicle in L/veh

$f'_1 = f_1 - (f_2/v_c)$ = adjusted fuel consumption rate for cruising in L/veh-km (v_c = cruising speed in km/h)

f_2 = fuel consumption rate for idling in L/veh-h

f'_3 = adjusted fuel consumption rate per complete stop as in Equation (3)

Similarly, Equation (4) can be re-written as:

$$F = fq = f'_1 L + f_2 T + f'_3 H$$

where

F = total fuel consumption (for a flow rate of q vehicles per hour) in L/h

L = total amount of travel in veh-km/h (= lq)

T = total travel time in veh-h/h (= tq)

H = total number of stops per hour (= hq)

The adjusted rate f'_1 can be easily calculated. For example, for the composite vehicle data given in Table Ia, for $v_c = 60$ km/h, $f'_1 = 0.102 - (2.23/60) = 0.065$ L/veh-km.

ABSTRACTS — RÉSUMÉ — RESÜMEE

FUEL EFFICIENCY AND OTHER OBJECTIVES IN TRAFFIC SYSTEM MANAGEMENT

R. Akcelik

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22 (2), February 1981, 54-65

This paper discusses the objective of reducing vehicle fuel consumption and pollutant emissions in urban traffic conditions in relation to other traffic system management objectives. The existence of conflicts among various objectives (safety, traffic performance, fuel consumption, pollutant emissions, property access, intrusion into residential areas) and the needs of various road user groups (pedestrians, buses, cars, major road traffic, side-road traffic) is emphasised. The discussion is centred around the tactical issues related to these objectives with a view to finding practical compromises which can be implemented. An elemental model of fuel consumption (pollutant emission, cost, etc.) is described in detail. The importance of the correct prediction of the number of vehicle stops is emphasised; possible sources of error are discussed. The expected impacts of various short-term traffic management measures on traffic performance, fuel consumption, safety and other objectives are summarised. The discussions of detailed matters are presented with the aid of examples of traffic signal control.

RENDEMENT ENERGETIQUE DES CARBURANTS ET AUTRES OBJECTIFS DE LA GESTION DES SYSTEMES DE CIRCULATION

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Cet exposé envisage les objectifs spécifiques de la réduction de la consommation des carburants et de la pollution des véhicules dans les conditions de circulation urbaine, cela par rapport aux autres objectifs de la gestion des systèmes de circulation. Sont notamment mis en valeur: l'existence de conflits entre objectifs (sécurité, rendement de la circulation, consommation de carburant, pollution, accès aux propriétés, intrusion dans les zones résidentielles), ainsi que les besoins des divers groupes d'utilisateurs des routes (piétons, autobus, voitures particulières, trafic des artères, trafic des voies secondaires). La discussion s'articule sur les questions tactiques ayant trait à ces objectifs, tout en se proposant de trouver les compromis pratiques qui seront susceptibles d'être mis en oeuvre. Un modèle élémentaire de la consommation de carburant (pollutions, coûts, etc.) fait notamment l'objet d'une description dans le détail. L'importance des pronostics justes quant au nombre d'arrêts de véhicules est appuyée. Les sources possibles d'erreurs sont envisagées. L'exposé résume les impacts attendus de diverses mesures de gestion de circulation à courte échéance sur les rendements de circulation, les consommations de carburant et la sécurité, entre autres objectifs. Les discussions dans le détail sont appuyées par des cas d'espèce de contrôle de la signalisation routière.

KRAFTSTOFF-WIRKUNGSGRAD UND ANDERE ZIELE DER VERKEHRSSYSTEMREGELUNG

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Dieser Artikel erörtert das Ziel einer Reduzierung des Kraftstoffverbrauchs und der Emission von luftverunreinigenden Stoffen in städtischen Verkehrsbedingungen in bezug auf andere Verkehrssystemregelungsziele. Es wird das Vorhandensein eines Konfliktes zwischen den verschiedenen Zielen (Sicherheit, Verkehrsleistung, Kraftstoffverbrauch, Emission von luftverunreinigenden Stoffen, Zugang zu Gebäuden, Eindringung in Wohngebiete) und den Anforderungen der verschiedenen Straßenbenutzergruppen (Fußgänger, Busse, Kraftfahrzeuge, Hauptstraßenverkehr, Nebenstraßenverkehr) betont. Die Diskussion konzentriert sich auf taktische Aspekte, die sich auf diese Zielsetzungen beziehen, um praktische Kompromisse herauszufinden, die durchgeführt werden können. Ein Elementarmodell des Kraftstoffverbrauchs (Emission von luftverunreinigenden Stoffen, Kosten usw.) wird ausführlich beschrieben. Besonders betont wird die Bedeutung einer korrekten Prognose der Anzahl von Fahrzeugstopps. Mögliche Fehlerquellen werden erörtert. Die zu erwartenden Auswirkungen verschiedener kurzfristiger Verkehrsregelungsmaßnahmen auf Verkehrsleistung, Kraftstoffverbrauch, Sicherheit und andere Ziele werden zusammengefaßt. Die Diskussionen detaillierter Angelegenheiten werden mit Hilfe von Beispielen einer Verkehrssignalsteuerung präsentiert.