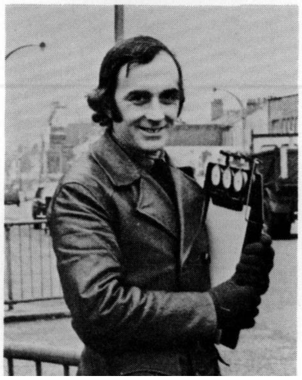
A program for simulating the dispersion of platoons of road traffic



by

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PHILIP A. SEDDON was graduated from the University of Manchester Institute of Science and Technology with an honours degree in Municipal Engineering. After military service with the Corps of Royal Engineers, he spent several years gaining practical experience in highway and traffic engineering with a number of local government authorities. This period saw his election to the Institutions of Civil Engineers and Municipal Engineers. In 1963 he returned to academic life with an appointment as lecturer at the University of Salford. He has been teaching mainly in the fields of highway and traffic engineering and related disciplines and doing research in the area of traffic operations and control.

His first use of the computer was for simple data processing, but this quickly grew with the development of a data-acquisition system in which the data is stored on punched paper tape. His PhD programme, successfully completed in 1971, took him one stage further — into the field of simulation of traffic for the most efficient linking of traffic signals, which he discusses in this paper.

For relaxation, he has a keen interest in social anthropology and, accompanied only by his wife, he has undertaken expeditions to the Middle East and North Africa. These journeys have given him a love of travel which he hopes to satisfy further in the near future by a visit to the United States. At home, his main hobby is the renovation of his 300-year old cottage on the edge of the Peak District National Park, and the weekends will find him busy with a trovel or saw.

SUMMARY

Digital simulation studies have been carried out on many traffic phenomena because, being stochastic, they are frequently too complex to be represented by a reasonable mathematical model. Furthermore, empirical laws are difficult to obtain because conditions on the road rarely remain stable for a sufficient time to obtain reliable data. Most simulations have been carried out to determine maximum flows, queue length, delays, etc. in terms of conflicting traffic flow, driver behaviour parameters, etc. A number of examples of this type of simulation are mentioned in the paper. The author's simulation program, however, was written to give information on vehicle behaviour within the platoon dispersion process. Having modelled starting conditions at the stopline and arrival patterns at points along the road sufficiently well, it was assumed that vehicle behaviour within the process was also being accurately modelled. The queues of vehicles at stopline are of random length with randomly selected vehicle type and random performance parameters. Leading vehicles in each lane accelerate according to an exponential law, and other vehicles are given accelerations according to one or other of the car-following laws. A novel technique allows driver reaction time to be taken into account. Vehicles may turn from the main road and overtake, the simulation program giving data on every vehicle's position, speed, and acceleration at each scan. The paper describes in detail the more important of the steps which make up the whole complex dispersion process and the various measures taken to verify the simulation.

INTRODUCTION

The development of software simulation techniques for the study of traffic phenomena has followed closely behind the development of electronic digital computers. As computers have become larger and faster, more complex traffic simulations have been made possible. Traffic flow is essentially a stochastic process, and consequently there are certain advantages in attempting to model the real-life situation on a computer provided that sufficiently accurate models of the various components in the process can be found. In the first place the complete process operating in a given situation is often too complex to be represented by a single mathematical model. Empirical laws can sometimes be obtained, but, in this case, the collection and analysis of sufficient data over a wide enough variety of conditions can be excessively laborious or expensive. Conditions on the site do not often remain steady enough for a sufficient length of time to allow reliable results to be obtained. The conditions found locally often do not cover a sufficient range for full analysis and are not under the control of the observer. Controller experiments on public highways are often impracticable or even impossible because of the large number of variables, and the results obtained on special research test tracks cannot necessarily be claimed to apply to public roads. Finally, empirical laws can only be obtained for conditions existing at the present time and cannot necessarily be applied to future or hypothetical situations.

Most simulations of traffic have been carried out (1) to determine maximum traffic flow, delays, queue lengths, etc. in terms of opposing traffic flows, driver and vehicular characteristics, etc. and (2) to assess various control strategies for traffic signals. A great deal of material has been published since 1955, a date which more or less signals the start of simulation of road traffic on digital computers. A number of examples can be used to illustrate the general trend. Gerlough[1] described a simulation of traffic flow on a multi-lane freeway. The technique allowed vehicles, represented as binary digits, to travel freely at a desired speed until they caught up a slower vehicle which they could then overtake or not, depending on certain criteria.

Goode *et al.*[2] discussed the merits of simulation as compared with analysis and trial. On the 5 criteria of cost, time, reproducibility, realism, and generality of results they considered that simulation lay midway between the two but, as situations became more complex, simulation became the only feasible method. They then described the simulation of a cross-block in which the distributions of vehicles in each of 20 possible lanes and movements were represented by a binary number held in a register. The presence of a figure 1 indicated the front of a vehicle and motion was obtained simply by binary addition. The model was used to determine delays for traffic-signal control and, although no validation with field data was given, the effect of varying certain parameters was clearly shown. In their conclusions, the authors pointed out that realism in simulation is not an end in itself, but rather a means to an end — that of understanding and accuracy.

Webster,[3] in his paper on the setting of fixed-time traffic signals for minimum delay, described how he obtained his delay formula by a simulation on one of the earliest British computers. His formula subsequently received extensive validation in the field and became the basis for British signal-design practice.

Wohl[4,5] discussed the general application of simulation techniques to traffic engineering problems. In the first paper he defined simulation, the major steps in the simulation process, and its application to traffic engineering. In the second, he described in detail the simulation of a freeway merging area.

Helly[6] simulated the effects of a bottleneck on traffic flowing in a single lane where lane changing was not allowed. Using a "follow the leader" philosophy for the individual driver, a computer model was constructed and its parameters fitted to observed data from the Holland Tunnel at New York.

1963 was a "vintage year" for reports of traffic simulation largely because of the second International Symposium on the Theory of Traffic Flow held in London. Gerlough and Wagner[7] described a simulation of a whole network of signal-controlled intersections in an attempt to speed up the evaluation of a series of alternate timing plans. The simulation was a macroscopic model rather than a microscopic one, i.e., it did not study the movement of individual vehicles. The simulation was tested against data from a network of 80 intersections and very good correlation was found.

Levy *et al.*[8] described the simulation of a general-purpose limited-access highway system which was designed to determine how complex models need to be to reproduce reality. The results showed, for example, that the variances of gap acceptance and car following distance are not important.

Francis and Lott[9] described a program which simulated traffic in a network of roads controlled by fixed-time signals. The program was used to study a series of nine linked traffic signals along a main traffic route in Central London. The results showed that by altering the offsets from their existing settings considerable reduction in delay could be achieved.

Young Rhee[10] described a program which simulated the movement of traffic on a network of streets controlled by traffic signals. The program had been applied to an actual network consisting of several streets and four traffic signals. Two control systems were compared: a real-time traffic adaptive system and the fixed-time system currently in use.

Lewis and Michael[11] described a simulation of a cross-roads in which the roadway system was represented by 3-dimensional arrays. The first dimension (being circular) corresponded to position on the road, the second gave information and characteristics of each vehicle, and the third identified the land occupied. All vehicles were identical, followed one another according to a safe-spacing law, and the system was scanned at one second intervals. The authors used the simulation to determine average wait for side-road traffic and average total delay, etc. for a two-way stop sign and semi-vehicle-actuated signal control. Finally, they combined the results to derive warrants for the installation of signals taking delays as the criterion.

Kell,[12] in a similar contribution compared stop sign and fixed-time signal control by means of a simulation taking total delay as the figure of merit. 50,000 hours of real time were simulated with a ratio to computer time of 900:1 for stop-sign control on an IBM 701 and 7000:1 for signal control on an IBM 7090 machine. Attempts to obtain equations for delay by multiple regression were not successful; so the results were shown in graphical and tabular form.

Finally, Wagner and Gerlough[13] in a more recent contribution described a microscopic simulation model of an isolated signal-controlled intersection, which enabled studies of control techniques to be made. They then described a macroscopic simulation model to extend the former model to a network of streets.

The reasons for attempting the simulation described below were somewhat different from those mentioned in the literature survey above. Rather than trying to forecast the end results of a traffic process, the object was to promote a better understanding of what vehicles were doing within the process. By ensuring that the starting conditions and the end results were sufficiently close to observed data it was then assumed that simulated vehicles were behaving in a manner similar to real vehicles. To provide background, a brief description of the problem will be given. For the successful coordination of traffic signals by the RRL Combination Method,[14] it is necessary to forecast the arrival rate, in time, of vehicles at a second traffic signal from a given flow pattern at the first signal, i.e., it is necessary to forecast the dispersion of the platoon of traffic. One method of making this forecast is that of Pacey[15] in which it is assumed that vehicles leave the first signal at constant velocities which belong to a normal distribution, overtaking one another at will. Although the method gives a good forecast, it was the unreality of the assumptions that caused the present author[16] to require, among other things, a closer examination of vehicle speed and behaviour during the dispersion process. The practical difficulty of obtaining data on the exact position, speed, and acceleration of every vehicle in a platoon for the whole of the time it is proceeding down the road from a traffic signal made the author turn to a microscopic simulation.

THE PROGRAM

The program at the present time is written in Algol for the English Electric KDF9 computer under the EGDON system. The broad outline can be followed in the simplified flow chart of Figure 1. Descriptions of the more important steps are given in the relevant sections below.

PROGRAM VALIDATION

When the complete program was working satisfactorily, an attempt was made to model two sites in the Manchester area. In choosing the sites the following requirements were taken into account.

1. They should represent quite different conditions, one where traffic flows freely with reasonable freedom for overtaking and another where overtaking is restricted.

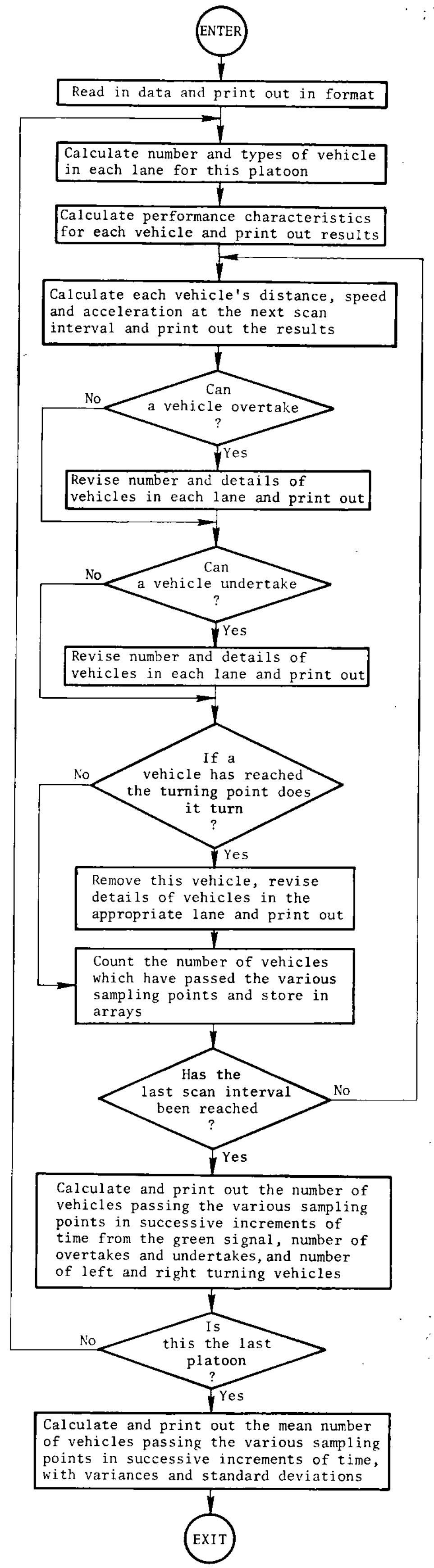

Figure 1 - Simplified flow diagram

2. There should be no delays or congestion at the intersection from vehicles making right turns (requiring them to cross lanes carrying approaching vehicles.)

3. There should be no major intersection, pedestrian crossing, or other interference with free flow for well over 300 m (1000 ft) from the stopline.

4. There should be no undue interference to flow from parked vehicles, bus stops, etc.

5. The road should be reasonably straight and level.

6. There should be reasonably heavy flows at peak hours.

Two sites were found which fulfilled most of these requirements, both on radial routes carrying heavy flows away from the city centre during the evening peak hours. Birchfields Road is a two-way road with a total width of 35 ft, it is marked down the centre, but traffic, being mainly cars in the peak hour, forms two lanes in each direction. The Crescent is a dual 3-lane road, each carriageway being 36 ft wide and carrying a higher proportion of trucks than Birchfields Road. Data on the number of vehicles in each lane at the stopline, turning flows, flow pattern over the stopline, overtaking manoeuvres, number of vehicles in each lane, and flow patterns at observation points along the road, etc., were collected at each site. These data were used to validate the assumptions made in writing the program and, after calibrating the various parameters, to ascertain that the final runs were modelling the traffic behaviour at the two sites in every possibly way. Seventeen platoons were simulated at each site, and the methods of comparing the simulation with the observed data are discussed in the appropriate sections below.

THE PSEUDO-RANDOM NUMBER GENERATOR

Random fractions are generated by the method of Behrenz,[17] which has been tested for randomness by many users. It is used in the program to generate values of various parameters belonging to rectangular, Poisson, and normal distributions, all of which were tested satisfactorily for significance.

THE VEHICLE ARRAYS

Information on each vehicle in a platoon is held in a 3-dimensional array of the form:

$$v(la,n,x)$$

where
la is the number of the lane counted from the near-side
n is the position of the vehicle in lane la counted from the front of the platoon
x is the location in the array which holds the various items of information about the vehicle.

These are the vehicle's length, desired speed, starting acceleration, driver's willingness to overtake, the vehicle's distance from the stopline, speed and acceleration after the last scan and for f previous scans (see Car Following, below).

THE RANDOM SELECTION OF QUEUE LENGTH IN EACH LANE

It is assumed that the number of vehicles in each lane of the approach, and hence the total number in the platoon, will be distributed according to a Poisson distribution. In the case of vehicle-actuated traffic signals, where the cycle time may not be constant, the Poisson distribution should not, strictly speaking, be applied as it requires an equal probability of events in equal intervals of time. It has been suggested that a negative binomial distribution provides a better fit than the Poisson for approach flows, but tests at the 5% level of significance (i.e., 5% probability of rejecting the hypothesis when, in fact, it is true) on observations at the two sites in Manchester showed the fitted Poisson distributions to be acceptable. As the number of platoons in any period of observation was, for consistency of flow, limited to about 20, use was made of the non-parametric Kolmogorov-Smirnov[18] test. It is also assumed that the proportion of vehicles in each lane is independent of the total number of vehicles in the platoon. This assumption was tested by calculating 95% confidence limits on the basis of a binomial distribution (a vehicle chooses a particular lane or not) and the majority of the observed data lay within those limits.

The average number of vehicles in the platoon is read in as data, and this figure is then divided into the appropriate average number for each lane according to the chosen proportions, again read in as data for the program. The actual number of vehicles in each lane is then chosen from a Poisson distribution with the given mean by the method of Gerlough.[19] With this method, the next random fraction is generated, then the program calculates successive probabilities $P(r)$ of the cumulative Poisson distribution. As soon as $P(r)$ equals or exceeds the fraction, r is taken as the number required. The number of vehicles in each lane for the final 17 runs at each site were compared with the Poisson distributions calculated from the means found from the observations. The Kolmogorov-Smirnov test at the 5% level showed the fit to be acceptable. The proportions of vehicles in each land were found for the final 17 simulated platoons at each site and, as the bulk of these lay within the 95% confidence limits calculated from the observed data, it was assumed that this aspect of the problem was being modelled satisfactorily.

THE RANDOM SELECTION OF VEHICLE TYPE

Vehicles are divided into two classes only, i.e., cars (including taxis, light vans, motor cycles, etc.) and heavy commercial vehicles, which include trucks and buses. For each lane at the stopline a constant proportion of trucks is chosen and as each vehicle is considered in turn, the next random fraction is generated and, if this is less than the proportion assigned to heavy vehicles, the vehicle is taken to be a truck. For the purpose of calculating the distance behind the stopline of each vehicle in the queues, all cars are assumed to have the same length and a similar assumption is made for trucks. The stationary spacing is taken as a constant, the values of these various dimensions being taken as the averages of measurements at the two Manchester sites. This part of the simulation program was verified by calculating 95% confidence limits for the proportion of trucks and buses in each lane from observed data. The majority of points from the observed and simulated platoons lay within these limits; so it was accepted that the assumption of a constant proportion was valid and that the simulation program was accurately modelling the real situation.

THE PERFORMANCE OF VEHICLES

The way in which a platoon of vehicles moves from the stopline is as follows:

1. The first vehicle in each lane accelerates freely up to its desired speed.

2. The second and subsequent vehicles in the platoon follow the vehicle in front according to one of the car-following laws (see below). As a fast vehicle may be followed by a slower one and the gap between them may become so large that the car-following conditions may not be applicable, this slower vehicle is permitted to accelerate freely to its own desired speed.

3. Vehicles are permitted to overtake, i.e., change one lane to the right (in UK), or "undertake", i.e., change one lane to the left, if certain conditions are satisfied (see below). This means that a vehicle other than the first vehicle in the queue may become a leading vehicle and therefore accelerate freely up to its desired speed.

Leading and other vehicles flowing freely are assumed to follow an exponential relationship for acceleration suggested by Pipes[20] of the form:

$$\ddot{x}(t) = cVe^{-ct} \qquad (1)$$

where

$\ddot{x}(t)$ is the acceleration at time

V is the final or desired speed, a constant for each vehicle

c is a constant having the dimensions of sec^{-1}

e is the base of Naperian logarithms

Integrating the expression for acceleration, the speed is given by

$$\dot{x}(t) = \int cVe^{-ct}dt$$

$$= V(1 - e^{-ct}) \qquad (2)$$

Integrating again, the distance travelled is given by

$$x(t) = \int V(1 - e^{-ct})dt$$

$$= V(ct + e^{-ct} - 1)/c \qquad (3)$$

The acceleration at time $t = 0$ is the starting acceleration A, a constant given by:

$$A = \ddot{x}(0) = cV.$$

Then $c = A/V$ and $\ddot{x}(t) = Ae^{-ct}$

If the equation for speed (2) is rewritten as

$$Ve^{-ct} = V - \dot{x}(t)/c$$

then $\ddot{x}(t) = cV - c\dot{x}(t)$

But $cV = A$ and $c = A/V$

therefore $\ddot{x}(t) = A[1 - \dot{x}(t)/V]$ **(4)**

which is a linear relationship in speed. This model was tested on data for cars from the motoring press and on data for commercial vehicles provided by the British Leyland and Ford motor companies. An appropriate choice of V and A produced a satisfactory fit.

If Equations 1 through 4 are used in the form shown, it is necessary to know the time t and consequently the time of start. This is acceptable if leading vehicles at the start remain in the lead, but if, through overtaking for example, another vehicle takes the lead, it becomes necessary to calculate a hypothetical time of start. The same is true for any vehicle which becomes free flowing due to the termination of car-following conditions for any reason. As this would be rather inefficient, the motion of all free flowing vehicles is calculated from an approximation to the exponential model:

$$x(t) = x(t-s) + \dot{x}(t-s)s + \tfrac{1}{2}\ddot{x}(t-s)s^2 \qquad (5)$$

$$\dot{x}(t) = \dot{x}(t-s) + \ddot{x}(t-s)s \qquad (6)$$

$$\ddot{x}(t) = A[1 - \dot{x}(t)V] \qquad (7)$$

where s is the scan interval. The approximation assumes that acceleration remains constant during a scan interval, which is not the case with the original models. However, for reasons of dynamic stability, explained later, the scan interval is kept quite small and so the errors involved are negligible.

It has thus been seen that each vehicle requires two performance characteristics, namely desired speed V and starting acceleration A. For each vehicle class, these parameters are selected from normal distributions whose means and standard deviations are read in as data. There is reasonable evidence that the speeds of vehicles for a given class under free flowing conditions belong to a normal distribution. There is, however, no evidence known to the author of distributions of starting acceleration and the choice of the normal is purely intuitive.

The method adopted for sampling a vehicle's performance characteristics from normal distributions is the widely used one which makes use of the Central Limit Theorem. These parameters are printed out for each vehicle at the start of a simulation, and the values from the 17 runs produced a satisfactory fit to the normal distribution according to the chi-square test at the 5% level of significance.

As a platoon moves along the road, the only vehicles which are clearly accelerating freely towards their desired speeds are the leading vehicles. The exponential model for performance was verified therefore by obtaining, at the two sites, the times of arrival after the green signal of leading vehicles at 5 stations down the road. The observed and simulated distance/time curves for the Birchfields Road site are shown in Figure 2. In this figure the arrival times for the mean, slowest, and fastest vehicles are shown. It would obviously have been better to show the 95 percentiles, but as there were only 20 platoons observed for each station, these would have little meaning. It will be seen that the correlation between simulated and observed mean leading vehicles is very good, and it was considered that this verified the exponential model and the sampling technique for the two performance parameters sufficiently well.

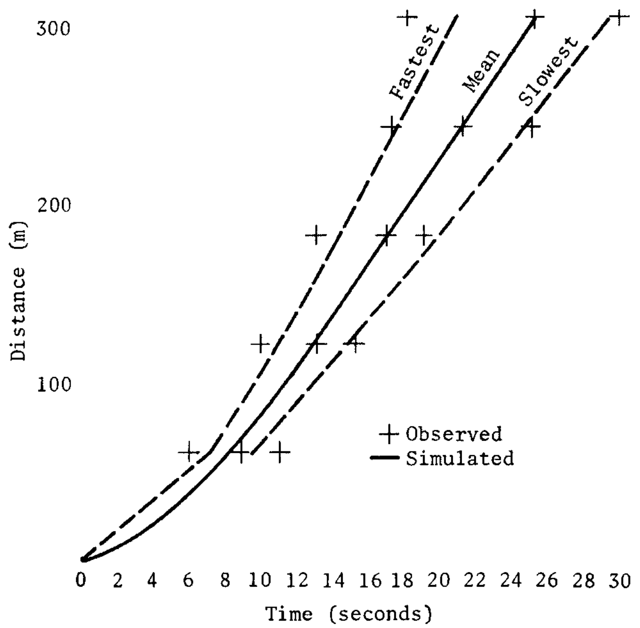

Figure 2 - Observed and simulated distance/time curves for leading vehicles at Birchfields Road, Manchester

CAR FOLLOWING

Considerable material has been published on the so-called car-following laws but the generalised form of Gazis, Herman and Rothery[21] will be used here:

$$\ddot{x}_{n+1}(t+T) = \frac{a\dot{x}^m_{n+1}(t+T)\,[\dot{x}_n(t) - \dot{x}_{n+1}(t)]}{[x_n(t) - x_{n+1}(t)]^{\ell}} \qquad (8)$$

where

$\ddot{x}_{n+1}(t+T)$ is the acceleration of the $(n+1)$th vehicle at time $(t+T)$

T is the time lag or reaction time

ℓ is an exponent taking the values 0 or 1

m is an exponent taking the values 0, 1, or 2

Other values of ℓ and m, including noninteger ones, have been considered by May and Keller.[22] This model means that the acceleration of a vehicle following another is some function of the relative velocity T seconds earlier. Values of the lag T between 0.6 and 1.6 sec have been suggested, but Constantine and Young[23] found a value of 1.0 sec in congested urban conditions.

There have been several attempts at the simulation of traffic flow using the car-following laws in which the scan interval has been taken as the reaction time T. With T of the order of 1 second, however, severe restraints have been needed to maintain stability. Restraints are required in digital simulation, but the extent to which they are called on, or rather the lack of this, can be taken as some measure of the success of the simulation and the accuracy of the model. Although the car-following law (8) above may describe the situation accurately in that a driver's acceleration or deceleration now is based on his relative velocity T seconds ago he will be continually changing it as conditions changed T seconds earlier. If, therefore, a digital simulation only scans the system every T seconds, it means that accelerations or decelerations are maintained for T seconds and this gives rise to instability. It also means that if the simulation attempts to start vehicles from a stationary queue, the vehicles will only begin to move every $2T$ seconds when, in fact, observations reveal that they start about every one second. The program is written, therefore, to scan the system at T/f seconds, f being an integer value read in as data, but at the same time basing individual vehicle's accelerations on relative velocities, etc. T seconds earlier. It is thus necessary to store the values of distance, speed, and acceleration for f scans. This is achieved by means of the vehicle array discussed earlier. During a scan each vehicle's distance, speed, and acceleration are calculated and stored in the array; then at the end of the scan each value is shifted 3 locations down the list, thus:

Distance now = $v(la,n,7)$

Velocity now = $v(la,n,8)$

Acceleration now = $v(la,n,9)$

become

Distance T/f sec ago = $v(la,n,10)$

Velocity T/f sec ago = $v(la,n,11)$

Acceleration T/f sec ago = $v(la,n,12)$

and so on until

Distance T sec ago = $v(la,n,7+3f)$

Velocity T sec ago = $v(la,n,8+3f)$

Acceleration T sec ago = $v(la,n,9+3f)$

If and when the 3 values have been used to calculate the latest accelerations, they are automatically replaced at the end of the scan by the 3 values further up the list. The value of f when T = 1.0 second (which just maintained stability) was found by trial and error to be 4.

A restraint applied to this system is that a vehicle's acceleration is never allowed to exceed that which is given by Equation 7 for the speed at which it is travelling at the present time. It was mentioned earlier that the car-following laws cease to apply when the headway gets too great. Constantine and Young[23] suggested that correlations were poor when the headway exceeded 200 feet, but in the program a critical time headway of about 2 seconds is used, the actual figure being read in as data.

No validation of this car-following model was made as it was information on the motion of vehicles within the platoon which was being sought by the simulation. Validation of the overall motion of the platoon is discussed in the section on sampling of arrival rates below.

OVERTAKING

Overtaking takes place as platoons move down the road. Provision is made for this in the simulation as it is essentially part of the mechanism whereby faster vehicles get to the front of a platoon and cause dispersion. As far as the simulation is concerned, overtaking is only permitted within the lanes available for the direction being considered, i.e., there is no conflict with the opposing traffic stream. Overtaking has two aspects:

1. *Overtaking.* This term is taken to mean the action of a vehicle moving into the lane to the right (in UK) in order to pass the vehicle in front in its present lane.

2. *Undertaking.* This term, for lack of a better word, is taken to mean the action of a vehicle moving into the lane to its left (in UK) after completing an overtaking manoeuvre and after having passed the vehicle formerly in front of it, or for any other reason.

The criteria which govern these two manoeuvres are different and are outlined below. (Note that *passing* another vehicle is not part of either *overtaking*; passing may occur before or after these manoeuvres.

(a) Overtaking manoeuvre

Criterion 1

Only a certain proportion of drivers (although it may be a high one) when presented with a situation which fulfills all other criteria, will actually overtake. After the vehicles in each lane have been allocated to a class and given the two performance parameters, they are selected as potential overtakers or not. The next pseudo-random fraction is compared with a preselected proportion of overtakers and, if it is less than or equal to this, a location in the vehicle array is given a value 1; otherwise it is given the value 0. It is quite likely that there is some correlation between drivers prepared to overtake and the values of the performance parameters. Presumably drivers using high values of these are more likely to overtake, but not necessarily so in every case. It is not considered necessary to link these two as other criteria involving performance characteristics have to be satisfied before an overtaking manoeuvre can take place.

Criterion 2

The overtaking vehicle must have better performance (a higher value of A) than the vehicle to be overtaken. Starting acceleration is used as, in urban conditions, there is not likely to be a wide variation in desired speed. Thus if the difference between the starting accelerations of the overtaking vehicle and the one in front is less than one standard deviation of starting acceleration, the manoeuvre is not permitted.

Criterion 3

The overtaking vehicle is sufficiently close to the vehicle in front. This spacing could be measured in terms of distance or time, but, as it is considered that driver's judgements of these matters are related to speed, the latter is used. Thus, if the distance between the front of the overtaking vehicle and the rear of the vehicle in front divided by the speed of the overtaking vehicle is greater than a critical value, the manoeuvre cannot take place.

Criterion 4

The next vehicle in the next lane to the right (in UK) is sufficiently far behind the overtaking vehicle. A critical headway (in seconds) is taken and, if the time between the rear of the overtaking vehicle and the front of the vehicle (in the lane to the right) which is to be preceded is less than this headway, the manoeuvre cannot take place. The time is determined in way similar to that used in Criterion 3.

Criterion 5

The next vehicle in front of the overtaking vehicle in the lane to the right is sufficiently far ahead of the overtaking vehicle. A critical headway is taken (less than that for Criterion 4) and if the time (determined as before) between the rear of the vehicle (in the lane to the right) to be followed and the front of the overtaking vehicle is less than this headway, the manoeuvre cannot take place.

After all the vehicles have been updated for distance, speed, and acceleration at a scan, the program works its way down the list of vehicles in all the lanes except the outside (fastest) lane and tests for the five criteria. If all are satisfied in a particular case, a printout states *vehicle number n in lane la becomes vehicle number d in lane (la + 1).* The overtaking vehicle is then assumed to move, immediately, into the next lane. The number of vehicles in lane la is decreased by one and the number in lane (la + 1) increased by one. The values held in the vehicle arrays are then reassigned into the locations appropriate for the revised positions of vehicles in the two lanes affected.

(b) Undertaking manoeuvre

Criterion 1

Only a certain proportion of drivers, when presented with a situation which fulfills all other criteria for undertaking will actually change lanes. This proportion will probably be less than the proportion prepared to overtake as criteria (2, 3, and 4 below) are less demanding than the corresponding criteria for overtaking. Furthermore, observations of driver behaviour in a competitive situation such as the one being simulated reveal a high proportion of vehicles remaining in an outer lane when there is ample opportunity to move to a nearer lane. Undertakers are randomly selected in the program in a way similar to the selection of overtakers. It is possible that there is some correlation between drivers prepared to overtake and those prepared to undertake and also with the performance characteristics of their vehicles. A driver using high starting acceleration and desirous of leading the platoon to the next traffic signal may be prepared to overtake and remain in an outer lane to prevent being overtaken. On the other hand, he may be prepared to undertake in order to pass a slower vehicle on its nearside. The complete picture is not clear, however, so no assumption of any correlation is made and undertakers are selected arbitrarily.

Criterion 2

The next vehicle behind the undertaking vehicle in the lane into which it is going to move is sufficiently far behind the undertaking vehicle. A procedure similar to Criterion 4 of the overtaking case is used.

Criterion 3

The next vehicle in front of the undertaking vehicle in the lane into which it is going to move is sufficiently far ahead of the undertaking vehicle. Again, a procedure similar to Criterion 4 of the overtaking case is used.

Criterion 4

The vehicle which the undertaking vehicle would be following after the manoeuvre must not have a performance much less than the undertaking vehicle. As with overtaking, starting acceleration is taken as the measure of performance. The procedure is similar to Criterion 2 of the overtaking case, but cars and trucks are treated differently.

The program tests for undertaking manoeuvres after the overtaking procedure and, if any are found, a printout message is given, and the vehicle array is amended in a way similar to that of the overtaking case. No accurate data were available on the critical headways used by drivers in the two manoeuvres. Observations were made of the headways by simply measuring distances by eye in terms of car length and roughly converting to time headway by a knowledge of average speed, but it is not claimed that these were accurate. Calibration of the model was carried out by varying the proportions of vehicles prepared to overtake and undertake so that the total number of each manoeuvre agreed with observations made at the two sites. Further verification was obtained by comparing the proportion of the platoon in each lane at a point 305 m (1000 ft) from the stopline with observed values at the two sites. As with the proportion in each lane at the stopline, 95% confidence limits were calculated for the observed data and the simulated proportions lay within the limits satisfactorily. With the simulations having satisfactorily reproduced lane occupancy at the stopline and at the end of the section considered and also having predicted the total number of overtaking and undertaking manoeuvres correctly, it was assumed that the simulation was modelling the overtaking process sufficiently well.

TURNING TRAFFIC

It is assumed that vehicles waiting in the queues at the stopline may turn left or right at the junction, but in doing so cause no delay to traffic proceeding straight on. There are obviously many intersections where problems do arise, particularly from vehicles waiting to turn right (in UK), but this is a large area of study in itself and could only be added to the present program at the expense of increased running time.

Only those vehicles in the nearside and outside lanes can make the turn and, as each vehicle reaches the turning point a chosen distance from the stopline, a decision is made on whether it turns or not. Chosen proportions of turning traffic are taken and, when a vehicle reaches the turning point, the next random fraction is generated and, if this is less than or equal to the chosen proportion, the vehicle is assumed to turn. The vehicle is then removed from the vehicle array, the number of vehicles in that lane is decreased by one, and the vehicle arrays are amended accordingly.

The turning process was validated by calculating 95% confidence limits of the proportions turning, assuming a binomial distribution, from observed data and checking that sufficient of the simulated proportions lay within these limits.

THE SAMPLING OF ARRIVAL RATES

The mean arrival rates in vehicles per 3-seconds interval from the green signal were obtained from observations at the two sites using a system devised by the author.[24] The system only allows one observation point to be occupied at a time, but can distinguish between vehicle types; so observations were made at the stopline and at five points down the road during the evening peak hours on different days. Statistical tests were carried out to ensure that the flow rates of cars and commercial vehicles were consistent. For each observation period the total number of vehicles passing was known. So the test hypothesis was made that the observed flows were from Poisson distributions with the same mean rate of flow. Estimated frequencies were obtained from the mean flow rate, and chi-square tests were successful at the 5% level for both sites. Similar tests were successful for the flow of trucks and buses in the observation periods. The results of 20 observations for Birchfields Road are shown as the dotted histograms of Figure 3.

The simulation program is written to sample the arrival distributions in the same way that the data acquisition system does, and the results for 17 platoons are shown in solid lines in Figure 3. The two main criteria for verifying the likeness of the simulation to the observed data were the average arrival time of the leading vehicle (Figure 2) and the "shape" of the flow patterns as seen in Figure 3.

It was found by trial and error that averages of two sets of 5 platoons with the same parameters differed only slightly from one another, while two sets of 10 platoons differed much less. Thus, in the calibration process, sets of 10 platoons were simulated with much of the printed output removed to save running time. The first step was to determine the particular values of average speed and acceleration and their standard deviations which gave a satisfactory fit to the arrival times of leading vehicles at the 5 observation points. Having found simulation parameters that produced runs that matched the above satisfactorily, the length and shape of the platoon, as measured by the average flows in each 3-second interval at the

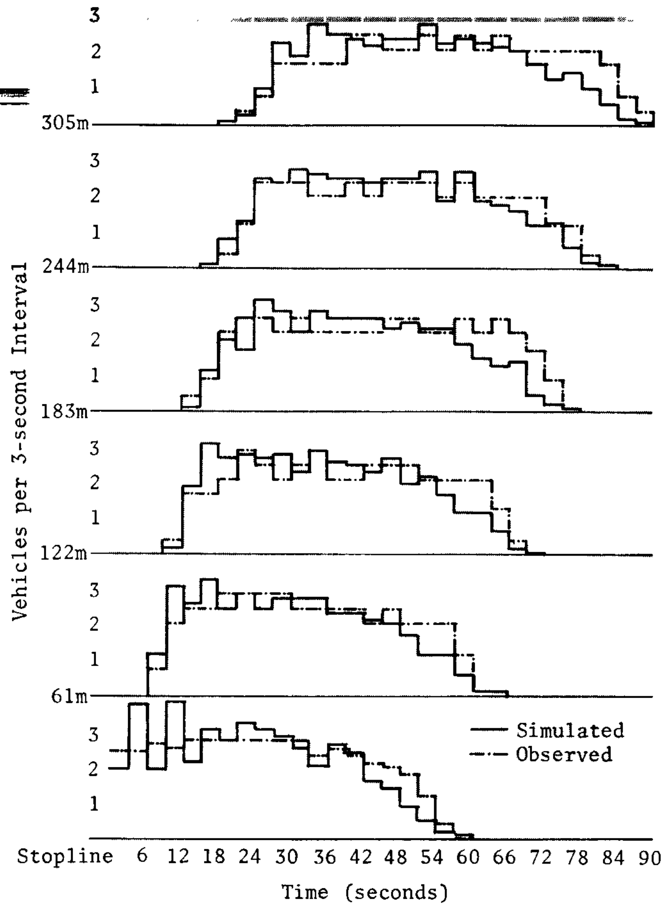

Figure 3 - Flow patterns in vehicles/3-second interval at five stations from the simulations and observations of Birchfields Road, Manchester

5 points, were checked. This shape was found to be affected primarily not only by the car-following model being used and its coefficient (α in Equation 8), but also by the standard deviation of speed and acceleration and the parameters controlling overtaking. Since many parameters were involved all of which influenced the overall results to some extent, a thorough optimisation process of varying one parameter at a time was not possible. This would have required excessive computer time; so the process used was largely one of trial and error in which more than one parameter was often varied at a time (based on experience gained from earlier runs). For the Birchfields Road site the car-following law which gave the best result was found to have $\ell = 1$ and $m = 0$, with the coefficient $\alpha = 10.0$. At the Crescent the best result was obtained when $\ell = 0$ and $m = 0$, with $\alpha = 0.45$. It will be seen in Figure 3 for Birchfields Road that correlation is quite good with, perhaps, the exception of the first few 3-second intervals at the stopline. The reason for this appears to be that there is a little more randomness in the starting behaviour of actual vehicles than of simulated vehicles. Further down the platoon, when the vehicles cross the stopline (enter the intersection) at higher speed, the simulation is better. As a further check on this starting behaviour, observations were made of the time elapsed from the moment the signal turns green until the vehicles cross the stopline. A linear regression produced for the observations at Birchfields Road the equation:

$$y = -0.857 + 2.156x, \quad (r^2 = 0.925) \qquad (10)$$

where

y is the time in seconds after the green signal

x is the position in the queue counted from the front

r is the sample correlation coefficient

A similar process carried out on the simulation of Birchfields Road produced the regression equation:

$$y = -1.047 + 2.270x, \quad (r^2 = 0.947) \qquad (11)$$

It was found that 95% confidence limits overlapped and a statistical test indicated that the two regression lines were coincident at the 5% level. With the similarity shown in Figure 3 and the above test for starting behaviour, it was considered that the simulation was reproducing the dispersion process sufficiently well.

CONCLUSIONS

Having satisfied all the various tests outlined above, it was considered that the simulation was reproducing vehicle behaviour accurately enough to allow use of the data on speed flow, concentration, etc. for examination of the Pacey and other models of forecasting platoon dispersion. In its present ALGOL form the program runs at about 5 times real time. This is obviously rather extravagant in computer time and could be reduced by cutting out some of the printed output. It is hoped to improve it shortly by translation into USERCODE. It would not be the intention to simplify the program in any of the main functions, as its prime function is to provide detailed information on vehicle behaviour. With its method of scanning at a fraction of reaction time, the program simulates car-following quite well and offers the opportunity of further studies in this area with perhaps an investigation of acceleration "noise." The overtaking manoeuvre offers the possibility of further studies with a view to defining some criteria. Any reader who feels that the program may be of help in his own studies is invited to get in touch with the author.

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