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A MODEL FOR THE STRUCTURE OF LANE-CHANGING DECISIONS

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Abstract—A structure is proposed to connect the decisions which a driver has to make before changing lanes. The model is intended to cover the urban driving situation, where traffic signals, obstructions and heavy vehicles all exert an influence. The structure is designed to ensure that the vehicles in traffic simulations behave logically when confronted with situations commonly encountered in real traffic. The specific mathematical expression of the questions embedded in the decision process and employed in the present implementation of the model are not critical and can be replaced by alternatives, but the heirarchy of the decisions is crucial. On the basis of experience to date, the lane changing model produces a realistic simulation of driver behaviour and has proved very robust under a wide range of conditions.

INTRODUCTION

One of the major problems faced when proposing alterations to a road is to estimate in advance the likely effect of the alterations, and to determine possible side effects. If the traffic is so heavy that lane-changing is not possible or can only be performed by slow mergings at oversaturated bottlenecks, analytical methods of estimation can be devised. With lighter traffic the ability to change lanes, and the interaction between various features of the driving environment, make analytical techniques impossible in many urban situations. Factors such as turning movements, public transport and lane closures interact with each other and the general traffic, and the results of change are hard to predict. In these situations computer simulation represents a particularly straightforward approach to the problem.

At the level of the individual driver the effects of the various features of the road and traffic can produce reactions in two dimensions. The driver can accelerate or brake in an effort to maintain his desired speed without running into the vehicle ahead, or can change lanes. The model described in this paper deals with the second aspect—the ability and propensity of drivers to change lanes.

Modeling the behaviour of a vehicle within its present lane is relatively straightforward, as the only considerations of any importance are the speed and location of the preceding vehicle. Car-following models were developed to describe the manner in which drivers reacted to the vehicle ahead, and the literature contains many examples with diverse empirical and theoretical bases (Gazis, Herman and Rothery, 1961; Newell, 1961; Lee, 1966; and Lloyd and Gerlough, 1976).

Car-following models are relatively unaffected by what constitutes the previous vehicle; a fixed obstruction or a stop line at an intersection where the lights are red or amber constitute acceptable substitutes for a real vehicle. Nor do changes in desired speed, acceleration and braking with curves and gradients affect the models.

Lane changing, however, is more complex, because the decision to change lanes depends on a number of objectives, and at times these may conflict. For instance, a driver may be in the rightmost lane and wish to turn right within 50 metres but still have to change lanes to the left to avoid a breakdown. Or, a driver may be able to increase his speed in the short term by changing lanes, but in doing so become trapped behind a slow heavy vehicle and lose more than any temporary advantage he might gain. Thus, in coming to a decision concerning lane changing, a driver must be able to reconcile his short-term and long-term aims.

The subject of lane changing has received rather less attention than car following, and most of this has been directed towards lane changing on motorways. In this area the principal concern has been with forced lane changes due to termination of one lane, or lane changing to

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overtake slower vehicles. In both situations the decision to change is effectively assumed and it is the execution of the manouvre which is modeled or studied. Even the few models for lane changing on urban streets (Ikenouek, Saito and Hanado, 1973; Botma, 1978) concentrate on the mechanics of the manouvre rather than the decisions leading to the manouvre. This paper is consequently concerned with how the decision to change lanes is reached in the face of potentially conflicting goals, not the execution of the decision.

CONCERNING DRIVER BEHAVIOUR

A driver's decision to change lanes is the result of the answers to a number of composite questions, viz.

—Is it possible to change lanes?
—Is it necessary to change lanes?
—Is it desirable to change lanes?

In this paper a framework is proposed for asking the questions relevant to changing lanes and using the answers to arrive at a sensible decision. This framework is intended to cover the urban driving situation, where traffic signals, obstructions and heavy vehicles all exert an influence on the answers.

Before commencing to construct the model it is necessary to set out the assumptions and conjectures concerning driver behaviour on which the model is based.

First, it was assumed that each driver possesses his own personal goal of travelling from X to Y in safety and comfort within a given time. However, this very general goal is not amenable to mathematical modeling, and was therefore translated into a number of limited but specific objectives that would be simpler to handle.

It was supposed that, on any section of the road, the time and destination components of the goal could be reduced to the more concrete objectives of maintaining some desired speed and being in the correct lane to turn off the road at a particular intersection. Considerations of safety and comfort placed limits on the braking and acceleration employed by the driver. The effect of vehicle performance was thought to be minimal except for heavy vehicles.

Unfortunately, these objectives are not necessarily consistent with each other. A driver on the road encounters many conflicts. His desire to maintain a certain speed can conflict with his need to be in the correct lane for a particular manoeuvre. Other conflicts arise when certain lanes are reserved for buses and other specified classes of vehicles, generally multioccupancy cars or taxis. Such lanes tend to attract drivers because of their generally faster flow, but are not legally accessible to most vehicles except in special circumstances.

In view of these potential conflicts there needs to be a clear definition of the factors that influence drivers to change lanes. The following factors and their effects were considered to be most important for a general model.

(a) *Whether it is physically possible and safe to change lanes*

In general, a driver will not change lanes if there is an unacceptable risk of a collision. Before he attempts to change lanes, a driver verifies that he is level with a gap in the traffic in the target lane. Further, he checks the speeds of the vehicles at either end of the gap to ensure that he is not travelling too fast with respect to the leading vehicle, or too slowly with respect to the following vehicle. However, the size of the gap required and the level of safety demanded by the driver vary with the situation, and the close proximity of a fixed obstruction in his own lane may encourage a driver to accept a gap he would reject in other more favourable circumstances.

(b) *The location of permanent obstructions*

Drivers familiar with a road try to avoid being trapped behind known obstructions such as regular parking by selecting lanes that will give them free passage. They move out of blocked lanes as they approach obstructions and ignore temporary advantages offered by lanes containing an obstruction. This behaviour is modified by the distance separating the driver from the obstruction, so that the influence of an obstruction on the upstream traffic is greatest close to the obstruction and declines to negligible proportions further upstream.

(c) *The presence of transit lanes*

On some roads, certain lanes, known as transit lanes, are available for use by public transport and other designated high occupancy vehicles. These vehicles are not compelled to use the transit lanes, but tend to do so because of the lower flows and higher speeds. In general, vehicles entitled to use a transit lane move into other lanes only when necessary to pass obstructions or slow vehicles. Other vehicles are not permitted to enter transit lanes except in certain specified circumstances, such as when they wish to turn off the road or need to avoid a breakdown.

(d) *The driver's intended turning movement*

The readiness of a driver to change lanes is affected by the distance from his intended turn and the direction of that turn. Beyond a certain distance the intended turning movement has no effect on a driver's behaviour, but as he approaches the turn his willingness to change lanes in other than the desired direction declines. Closer still, the driver changes lanes in the desired direction at every opportunity, even matching speed with the traffic in the target lane to make this easier.

(e) *The presence of heavy vehicles*

Drivers try to avoid being trapped behind heavier vehicles because of their lower accelerations. This effect is most pronounced when the heavy vehicles are stationary and dies away almost completely at cruising speeds. As a corollary of their low acceleration, there is often a sizable gap in front of heavy vehicles, which offers other traffic a better than normal chance of changing lanes.

(f) *Speed*

The final factor affecting a driver's decision to change lanes is whether the traffic in the present lane or the target lane is more likely to limit his speed in the short term. One of the main purposes of changing lanes is to gain some speed advantage. The advantage required by a particular driver is likely to vary with the lane occupied by the vehicle and the lane to which a move is contemplated. It is possible for the advantage to be zero, when drivers are required to move toward the kerb after overtaking; or negative, because drivers frequently accept a speed penalty to avoid travelling in the outer lane on either side where the risks of delay from parked vehicles or turning traffic are high.

There is considerable interaction between all of these factors and their relative importance alters as a driver approaches his intended turn. Thus the decision process for a lane-changing model must be sensitive to the separation between the driver and his intended turn.

THE MODEL

The model was designed to describe the behaviour of cars and trucks entering, travelling along and turning off a section of road. From the moment they first appear in the simulation the drivers have a nominated junction and direction at which they are supposed to depart from the road. For a large proportion of the traffic the nominated junction is beyond the end of the section of roadway being simulated so they tend to behave as through traffic. The nomination of an intended turn when the vehicle is generated enables a consistent pattern of lane changing to be developed.

The driver's behaviour falls into one of three patterns, depending on the distance to his intended turn. While the turn is remote it has no effect on his lane-changing decisions and he concentrates on maintaining his desired speed. When the turn enters the zone the driver regards as middle distance he starts to ignore opportunities to improve his speed that involve changing lanes in the wrong direction. And once he has reached them the driver tends to remain in the pair of lanes most appropriate for his turn. So by the time the driver comes close to his intended turn he should be in the correct lane or the adjacent one. Finally, when he is close to his turn the driver is interested solely in reaching the correct lane and speed is unimportant.

The transition between these behaviour patterns is somewhat blurred and the model is not sensitive to the precise location of the boundaries.

The model of the lane-changing process described in this paper was designed to be used in conjunction with a car-following model (Gipps, 1981) that employs limits on a driver's braking rate, in order to calculate a safe speed with respect to the preceding vehicle:

$$v_n(t+T) = b_n T + [b_n^2 T^2 - b_n (2\{x_{n-1}(t) - s_{n-1} - x_n(t)\} - v_n(t) T - v_{n-1}(t)^2/\hat{b})]^{1/2} \quad (1)$$

where

- $v_n(t+T)$ is the maximum safe speed for vehicle n with respect to the preceding vehicle at time $(t+T)$,
- b_n (<0) is the most severe braking the driver is prepared to undertake,
- T is the time between consecutive calculations of speed and position,
- $x_n(t)$ is the location of the front of vehicle n at time t,
- s_{n-1} is the effective length of vehicle $n-1$, and
- $\hat{b}$ is an estimate of b_{n-1} employed by the driver of vehicle n.

For the purposes of the lane-changing model, this safe speed was limited above by the driver's desired speed, in order to prevent vehicles or obstructions too far ahead from influencing the driver's decision. With a braking limit of $-2\ \mathrm{ms}^{-2}$ this limits the influence of stationary objects to between 100 and 200 metres, depending on the desired speed of the driver.

The lane-changing model allows the driver to vary the severity of the braking he is prepared to undertake in response to the urgency of reaching a particular lane. If a driver is prepared to brake harder, the car-following model allows him to fit into a smaller gap.

Although the lane-changing model was designed for use with a specific car-following model, the only restrictions placed on the use of another model are that the function for the updated speed of the following vehicle should be bounded above, and that this bound is attained under appropriate conditions and not approached asymptotically.

The conditions producing the decision to change lanes left or right or remain in the present lane form three exhaustive and mutually exclusive regions in the multidimensional space describing traffic conditions around the subject vehicle. Because of the large number of factors involved, the boundaries between these regions are a pastiche of (curved) surfaces corresponding to different decision criteria. In theory, a look-up table with 2^n cells could be constructed to make the decision where the cells correspond to passing or failing n different criteria. In practice such a table would have well over a million cells, of which some could represent impossible combinations. An alternative approach, pursued in this paper, is to create a decision tree which minimizes the number of decisions that need to be made, by posing those questions of overriding importance first.

A simple summary of the decision process is shown in Fig. 1. The flowchart is intended to cover situations that might reasonably be expected to be encountered on an arterial road, and is not meant to handle pathological cases with peculiar layouts of obstructions and junctions. Any attempts to make the model more flexible in these unusual situations are liable to decrease the efficiency of the model in a more normal environment and make calibration more difficult.

The questions posed in the flowchart can be divided into two classes: objective and subjective. The objective questions such as: "Is the vehicle a transit vehicle?" are simple to answer and unlikely to be affected by regional differences. On the other hand, the subjective questions will probably require redefinition when applying the model in a new environment. In the general specification of the model, these questions were deliberately kept vague because they were considered most likely to display regional and temporal differences. However, when describing the model in detail, mathematical versions of these questions, which were employed in trials, will be given.

The main points that the model treats in arriving at a decision are discussed in detail below. The section numbers are reproduced on the flowchart in Fig. 1 at the places to which they refer.

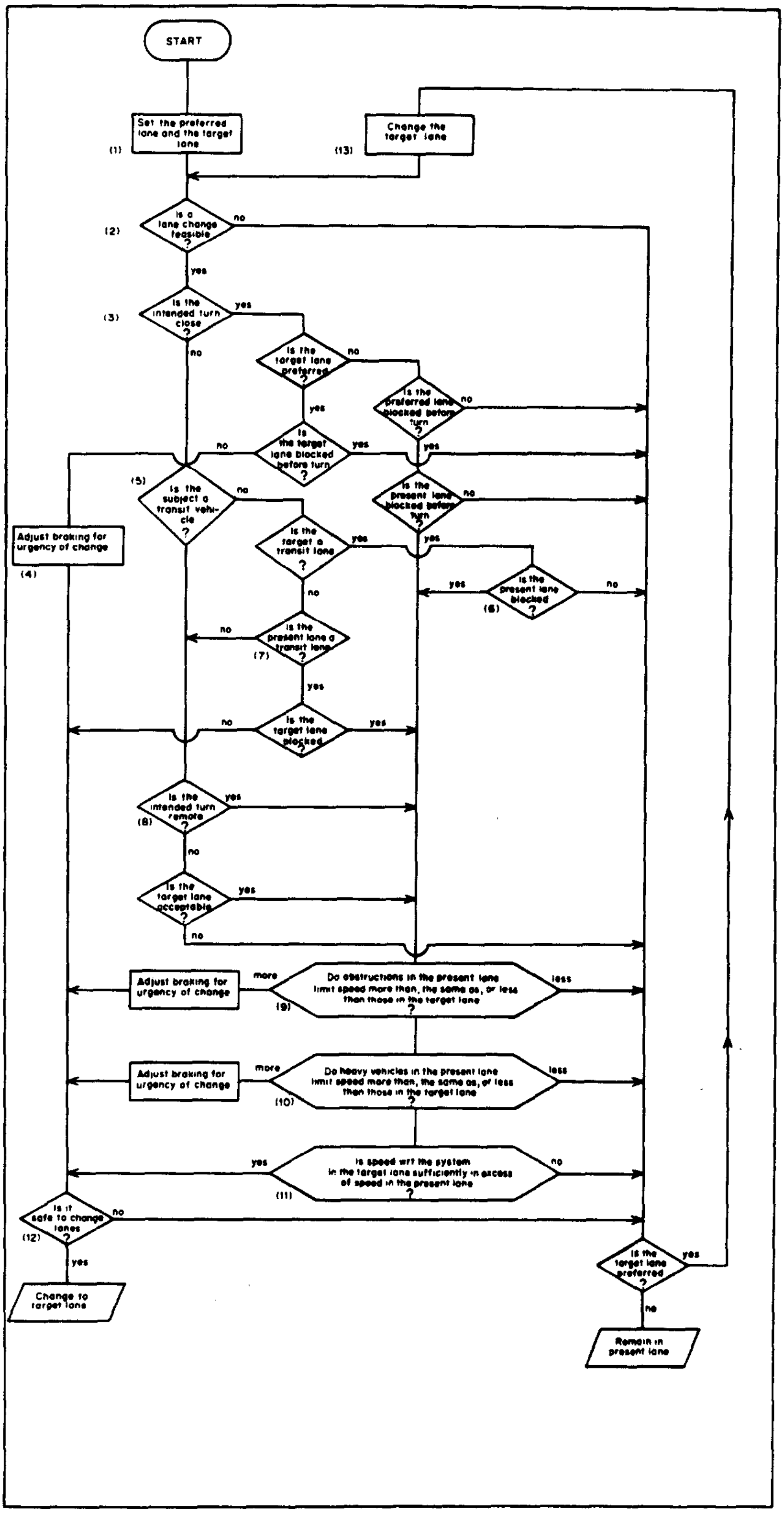

Fig. 1. Flowchart summarizing the decision process for changing lanes. The numbers in brackets are referred to in the text.

(1) *The selection of lanes*

The model is based on a divided road with N lanes available for traffic travelling in the direction of interest. These lanes are labelled 1, 2, . . ., N from the kerb to the median. For each driver the model defines his preferred lane l_p and his target lane l_t as a function of his present lane l_n.

The preferred lane lies adjacent to the present lane on the side toward which the driver wishes to turn eventually; thus

$$l_p = \begin{cases} l_n - 1 & \text{for drivers intending to turn toward the kerb,} \\ l_n + 1 & \text{for drivers intending to turn toward the median.} \end{cases}$$

The target lane is the lane into which the driver is contemplating a move. Initially, it is the same as the preferred lane, but should a lane change prove impossible or disadvantageous, the lane on the opposite side of the present lane is considered as a new target lane.

(2) *The feasibility of changing lanes*

The first question the simulated driver considers is whether it is possible to move into the target lane. This acts as a coarse filter and eliminates most situations where a change will not occur early in the decision processes. To obtain an affirmative answer to the question a number of conditions have to be satisfied.

First, the target lane must be one of the lanes available to the traffic, that is

$$1 \leqq l_t \leqq N.$$

Next, the section of target lane level with the subject must be devoid of physical obstructions and other vehicles.

In the implementation of the model demonstrated later, the subject vehicle was assigned a braking rate twice that which the driver would normally be prepared to use. Equation (1) was applied with the role of leading vehicle played by the preceding vehicle or blockage in the target lane and the role of following vehicle taken by the subject. If the required deceleration $(v_n(t+T) - v_n(t))/T$ was unacceptable to the subject the lane change was not feasible.

The subject's braking rate was then restored to normal and eqn (1) applied again with the subject as the leading vehicle, and the next vehicle in the target lane as the follower. In this instance, the follower was assumed to be willing to brake at -4 ms^2, and if the necessary deceleration was again acceptable the lane change was accepted as feasible.

(3) *Driver behaviour close to the intended turn*

Having ascertained that it is physically possible to change lanes, the model proceeds to ask whether the driver is close to his intended turn.

If the answer is yes the driver will always change into his preferred lane provided he can do so safely and it is not blocked before the turn. Only if his present lane and the preferred lane are both blocked before the junction will he consider moving into some other lane.

The definition of "close" is subjective and, in addition to regional differences, there are liable to be variations with traffic flows at a particular site. However, because the boundary between close and not close separates relatively minor variations in behaviour, the performance of the model is not critically dependent on the value. In trials it was found satisfactory to define close as being within 10 seconds' travel of the turn at the driver's desired speed.

(4) *Urgency of changing lanes*

As a driver not in the correct lane approaches his intended turn the urgency of changing lanes increases. This sense of urgency is reflected in the driver's willingness to brake harder and accept smaller gaps.

In the implementation the braking rate which a driver is prepared to accept doubles between first becoming close and reaching the intended turn. That is

$$b_n = [2 - (D_n - x_n(t))/10\, V_n]\, b_n^*,$$

where

D_n is the location of the intended turn,
V_n is the desired (or free) speed of the driver, and
b_n^* is the most severe braking the driver would otherwise be willing to undertake.

(5) *Transit lanes and vehicles*

On an increasing number of arterial roads, a lane is dedicated solely for the use of public transport and other high occupancy vehicles. In the terminology of the model these lanes are called transit lanes and the vehicles entitled to use them transit vehicles. Transit vehicles, however, are not restricted to transit lanes.

The level of occupancy of nonpublic transport vehicles before they can use the transit lane and the degree of observance of the law vary between regions. Therefore, in order to simplify the model, the term "transit vehicle" is taken to refer to any vehicle whose driver considers himself entitled to use the transit lane (legally or otherwise).

(6) *Entry of nontransit vehicles into transit lane*

Whilst ordinary vehicles are normally debarred from using a transit lane, the presence of a fixed obstruction in the present lane is considered sufficient justification for entering the transit lane.

In tests with the model, limiting the range at which a driver could detect a blockage to the distance that he could travel in 10 seconds at his desired speed was found to give satisfactory results.

(7) *Departure of nontransit vehicles from a transit lane*

Because the model allows nontransit vehicles to enter the transit lane to by pass an obstruction, it must also contain the logic to ensure that they leave the transit lane once the obstruction has been cleared. Accordingly, for nontransit vehicles in a transit lane, the model checks the target lane to see whether it is clear of obstructions. If the target lane is clear (i.e. not blocked) and it is safe to change lanes, the vehicle must depart from the transit lane. Because of its location in the decision process, this forced departure from the transit lane does not affect vehicles that are close to their intended turn.

(8) *Driver behaviour in the middle distance*

If a driver is "remote" from his intended turn, the direction in which he wishes to turn has no impact on his behaviour. But when the intended turn is neither remote nor close, the direction of the eventual turn is beginning to modify the driver's behaviour and not all lane changes will be acceptable.

The question of what distance may be classified as remote is of necessity rather vague. Tests with the model under Australian conditions obtained reasonable results by classifying those vehicles more than 50 seconds from their intended turn as being remote.

There is also a subjective judgment required in quantifying the tendency of a driver to move in the direction of his intended turn. A vehicle in the left lane and intending to turn left in 800 metres is likely to change lanes to the right to avoid a slow heavy vehicle. In this situation the second lane from the left would be considered as acceptable to the driver even if it is not the preferred lane. Thus, when the intended turn is in the middle distance, the model classifies the target lane as acceptable if it is the preferred lane, or if the present lane is either the kerb or median lane. That is, the target lane is acceptable if

$$(l_p - l_t)(l_n - l)(l_n - N) = 0.$$

(9) *Relative advantages of present and target lanes*

If none of the factors considered so far in the process have forced the simulated driver to make a firm decision on whether he should change lanes, he is free to look at the relative advantages of the present and target lanes. First the driver considers fixed obstructions in the present and target lanes and then selects the lane in which the next obstruction has least effect on his safe speed in accordance with eqn (1).

(10) *The effect of heavy vehicles*

Should the obstructions be level with each other or beyond the driver's horizon he defers the decision on changing lanes and looks ahead for heavy vehicles. The driver considers the next heavy vehicle in each lane ahead as though it were the leading vehicle in an ordinary car-following situation and selects the lane that would give him the higher speed. This method of calculating the effect of heavy vehicles reduces the influence of those travelling at the driver's cruising speed to negligible proportions while ensuring that he avoids ones which are slow or stationary.

(11) *The effect of the preceding vehicle*

If the absence of heavy vehicles within the driver's ambit still prevents a decision, the driver finally considers the speed possible in each lane and changes lanes if he gains a "sufficient" speed advantage. The sufficient advantage required may depend on the present lane, the target lane and the type of vehicle, and can be negative in certain circumstances. Selection of appropriate values can cause drivers to move back toward the kerb after overtaking, or avoid the extreme lanes on either side of the traffic flow.

In the implementation of the model a sufficient advantage for changing lanes toward the centre of the road was arbitrarily set at 1 ms^{-1} or 3.6 km/h. While to ensure vehicle moved back after overtaking, the sufficient advantage for changing lanes towards the kerb was set at -0.1 ms^{-1}.

(12) *Safety*

Once a driver has decided that he should change lanes, the only remaining question is whether he can do so safely. This question is left until last because the level of safety demanded by a driver is likely to vary with his reasons for changing lanes and the degree of urgency they impose. For instance, a driver who is close to his intended turn but has not reached his preferred lane will accept a smaller gap in the adjacent traffic than one who is changing for a minor speed advantage. Thus, if a safety factor is set at all points in the model that give direct access to this question, it is possible to adjust the level of safety to suit the circumstances.

(13) *Changing the target lane*

If a driver has rejected the notion of changing to the preferred lane, the model considers a lane change in the opposite direction and alters the target lane accordingly.

EXAMPLE

The decision structure for lane changing forms an integral part of the MULTSIM model (Gipps and Wilson, 1980) allowing a wide range of urban driving conditions to be simulated realistically. MULTSIM handles traffic travelling in one direction along a divided road and gives the user control over: length of road, duration of simulation, number of lanes, volume of traffic, number of intersections, and for each intersection location of "stop" line, width of intersection, volume of traffic making particular turns, if signalized, the signal timings including separate right turn phase, composition of traffic in terms of vehicle types, driver reaction time and distribution of desired speeds, location of bus stops and flow of passengers, location of tram stops and flow of passengers, obstructions to traffic such as kerb-side parking or breakdowns, turning lanes, bus bays, bus or transit lanes and the proportion of vehicles using them, and information to be collected.

Each vehicle to appear in the simulation is generated by a (user-supplied) subroutine which specifies the type of vehicle (this can range from motorcycles through various classes of cars and trucks to buses and trams); the length of the vehicle; the desired speed of the driver; and the maximum acceleration that the driver will employ. Use of a separate subroutine to generate vehicles allows the user to alter the composition of the traffic and control its characteristics. Other parameters which are set at this stage include the driver's intended turning movement, which enables a consistent pattern of lane changing to be modeled for individual vehicles.

The model is implemented as a FORTRAN program that with minor amendments runs on a wide spectrum of computers ranging from large main frames down to micros. The versions running on mainframe and microcomputers contrain facilities for producing time–distance diagrams of the traffic, while the microcomputer version incorporates interactive colour graphics with zoom and pan facilities so that the behaviour of vehicles can be monitored while the simulation is running.

In order to demonstrate the ability of the decision process to imitate the lane-changing behaviour of real drivers, an example was constructed involving many of the features considered in the model: turning movements, transit lanes, fixed obstructions and heavy vehicles. The section of road carried three lanes of traffic travelling in the same direction over a distance of 2000 metres (Fig. 2). The kerbside lane was designated as a transit lane and was available to only 18% of the non-bus traffic. The section of road contained four signalized intersections where traffic entered and departed, as well as five bus stops. A short obstruction was inserted in the second lane near the 700 metre mark to simulate a breakdown and another in the kerb lane near the 1700 metre mark to simulate an (illegally) parked car. The traffic comprised a mixture of vehicles of which 5% were classified as heavy. Figures 3, 4 and 5 show the time–distance trajectories produced by vehicles in the three lanes commencing some time after the

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                                                                MULTSIM 4.1     JUL 80
A    8. MINUTE SIMULATION OF 2000. METRES OF A 3 LANE ROAD

THE INITIAL FLOW IS 2100. CARS AND TRUCKS PER HOUR, OF WHICH 18. % ARE TRANSIT
VEHICLES WHICH CAN TRAVEL IN THE LEFT-MOST LANE(S) WITH BUSES.  OTHER VEHICLES
ONLY ENTER THE TRANSIT LANE IF THEY ARE GOING TO TURN LEFT WITHIN 200 METRES.

THE PERCENTAGES OF CAR AND TRUCK TYPES ARE:

MOTOR      SMALL      MEDIUM     LARGE      LIGHT      HEAVY      ARTICULATED
CYCLES     CARS       CARS       CARS       TRUCKS     TRUCKS     VEHICLES

  2.         20.        30.        30.        8.         5.         5.

THE DESIRED SPEEDS OF DRIVERS ARE DISTRIBUTED WITH MEAN  60. AND S.D. 11. KM/H
AND THEIR APPARENT REACTION TIME IS  .667 SECOND

THERE ARE 4 JUNCTIONS

JUNCTION                                  1        2        3        4

LOCATION OF STOP LINE       (METRES)    300.     800.    1300.    1800.
WIDTH OF JUNCTION              "         30.      30.      30.      30.

FLOW ENTERING FROM LEFT   (PER HOUR)     50.      50.      80.      50.
FLOW ENTERING FROM RIGHT       "        100.      40.     100.      40.
FLOW TURNING LEFT              "         50.      30.      70.      20.
FLOW TURNING RIGHT             "         50.      50.     100.      60.

DURATION OF GREEN          (SECONDS)     30.      30.      30.      30.
DURATION OF AMBER              "          5.       5.       5.       5.
DURATION OF RED                "         25.      25.      25.      25.
ABSOLUTE OFFSET                "          0.      35.      70.     105.
GREEN DELAY FOR RIGHT TURN     "          0.       0.       0.       0.
GREEN EXTENSION FOR RIGHT TURN "          0.       0.       0.       0.

THERE ARE   2 OBSTRUCTIONS TO TRAFFIC

OBSTRUCTION                               1        2

LANE CONTAINING OBSTRUCTION               1        2
START OF OBSTRUCTION        (METRES)   1700.     700.
FINISH OF OBSTRUCTION          "       1705.     705.

THERE ARE 5 BUS STOPS SERVED BY 30. BUSES PER HOUR

STOP                                      1        2        3        4        5

LOCATION OF STOP            (METRES)    280.     740.    1200.    1660.    1980.
FLOW OF PASSENGERS        (PER HOUR)     60.      73.      37.      50.      60.

THERE ARE   7 MONITORS LOCATED AT       (METRES)
                                         0.     200.     400.     700.     105.     120.
                                       999.

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Fig. 2. Complete description of the road being simulated.

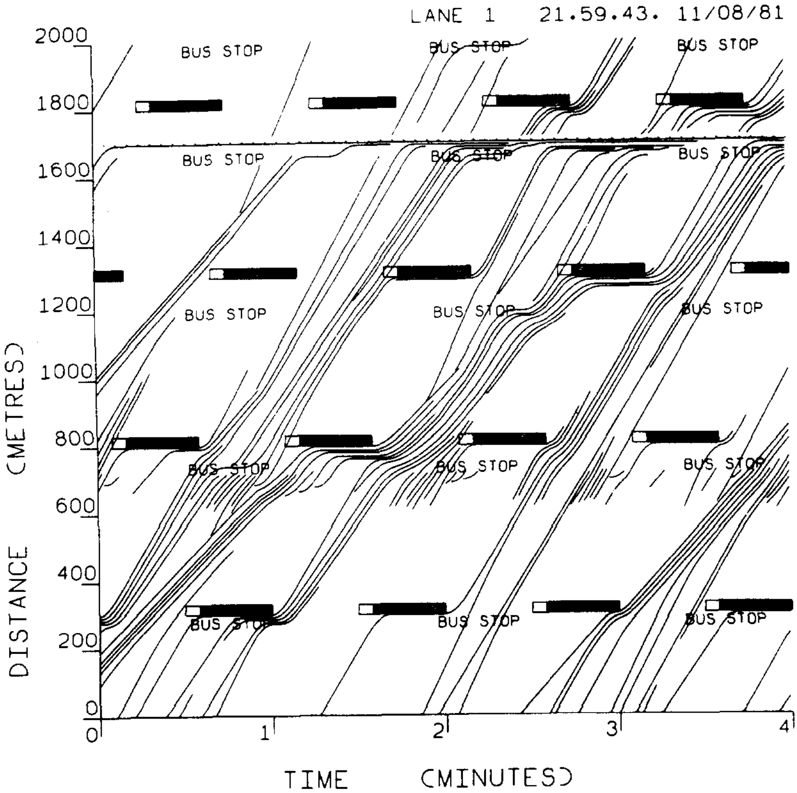

Fig. 3. Vehicle trajectories in the kerb (transit) lane showing bus stops, traffic signals and illegal parking.

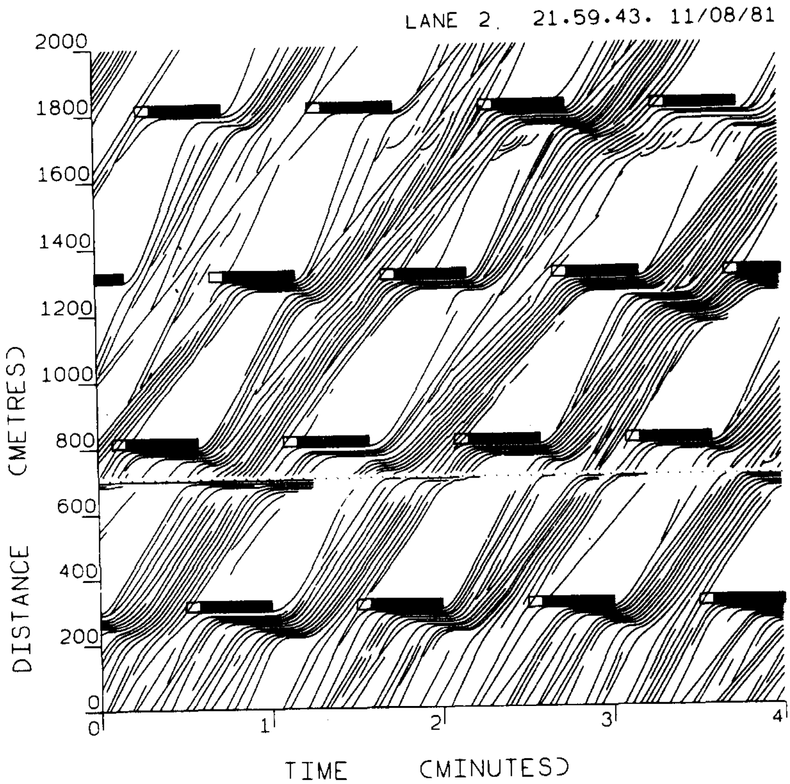

Fig. 4. Vehicle trajectories in the second lane.

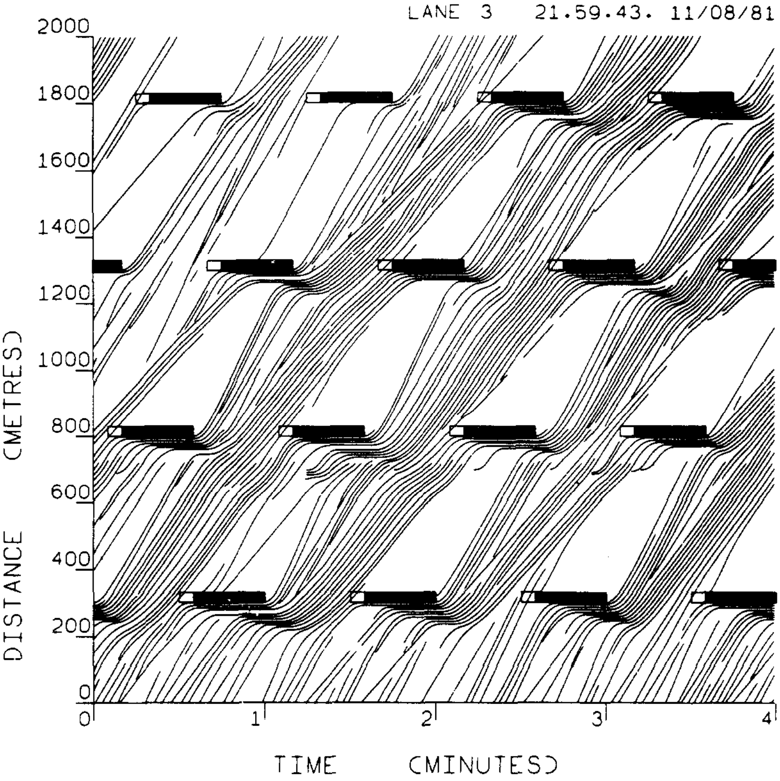

Fig. 5. Vehicle trajectories in the third lane.

start of the simulation. The sequences of gap, hollow rectangle and solid rectangle at 400 and 800 metres represent the green, amber and red phases, respectively, of the signals at the four intersections. A trajectory starting (or finishing) midblock represents a vehicle that has changed lanes and can be matched with a trajectory finishing (or starting) in one of the adjoining lanes. However, a trajectory starting (or finishing) at a junction is more likely to represent a vehicle that has turned onto (or off) the road, in which case the adjacent lane will not contain a matching trajectory. Trajectories of turning vehicles tend to be relatively flat in the region of the intersection.

The time–distance diagrams reveal the behaviour of the simulated vehicles to be consistent with that expected from real drivers in the same circumstances. The obstruction in lane 2 starts affecting the traffic nearly 100 metres before it is reached, as moving vehicles accept opportunities to change lanes. A few that are unable to find a suitable gap in the traffic come to a halt behind the obstruction to await a break in the other lanes. After the obstruction has been passed all the vehicles that moved into the transit lane make a reasonably prompt return to lane 2. But the movement of vehicles from lane 3 to lane 2 after the obstruction is not so well defined in time, distance and composition. Some of the vehicles that were in lane 2 originally change to lane 2 while others that were originally in lane 2, fail to return.

CLOSING REMARKS

The model described in this paper is essentially a structure connecting the decisions a driver has to make before changing lanes. The structure is designed to ensure that the simulated drivers behave logically when confronted with situations commonly encountered in real traffic. The specific mathematical expressions of the questions embedded in the decision process and employed in the present implementation of the model are not critical and can be replaced by alternatives, but the hierarchy of the decisions is important. The decision to change lanes depends on particular combinations of criteria being met. Some of these criteria are subordinate to others and are only considered in particular circumstances. The function of the hierarchy is to present the various criteria in an order which simplifies the decision process. If the structure is not correct and questions are presented in the wrong order the lane-changing behaviour of simulated vehicles departs markedly from that of real vehicles.

As with any reasonably complex model it is not possible to validate the model—it can only be invalidated. Finding a fault can invalidate the model; but, not finding a fault does not prove the model is correct—the fault may exist but be undetected. It is only extensive fault-free operation which can give the modeller confidence. Consequently, considerable effort was devoted in the course of developing this structure to testing it under complicated combinations of conditions and adjusting it when necessary.

By far the most powerful tool in this testing process has been the graphical facilities in the programs which highlighted logical flaws very clearly (Gipps, 1983). Successful use of the model as a test bed prior to conducting on road experiments with instrumented cars (Doughty and Trayford, 1982; Trayford, Doughty and Woolridge, 1984) has also contributed to confidence in the model.

On the basis of experience to date, the lane-changing model produces a realistic simulation of driver behaviour under Australian conditions. In other geographical areas, slight amendments to the basic flowchart may be required, but the decision process described has so far proved very robust under a wide range of conditions.

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