SIMULATION MODELS OF TRAFFIC FLOW

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Abstract

This paper reviews the range of traffic models, with particular attention to microsimulation. Although there are major types, there are so many hybrids that it is difficult to classify them all. The standard way of assigning traffic to a network is to find a static equilibrium from which no driver would be able to find a quicker route. This gives fairly good predictions of the link flows resulting from driver choices. Traffic is loaded on to shortest routes, times are modified by a speed-flow function, leading to reassignment to more routes, and the solution is iterated until all used routes between each origin-destination pair take equal time.

An alternative is stochastic user equilibrium, taking explicit account of the variability of choice. Each route between an O-D pair that does not backtrack is given an initial share by logit distribution. Again, travel times are modified to take account of congestion, and there is a somewhat messy iterative process to reach equilibrium. Curiously, stochastic user equilibrium is as deterministic as 'deterministic user equilibrium'. A criticism of equilibrium models is that the process of adjustment after a change to the network may be of more interest than the apparently stable outcome.

Microsimulation has been used for small components of the network but recent models at the single vehicle level can simulate whole urban networks, using a great deal of computer power. One uses cellular automata, such that each cell in a spatial lattice is updated according to its own state and the states of its nearby neighbours at the previous time step. More conventional microsimulations use simple rule based behaviour. Simulations are designed not only to show the emergent order but also the impact of incidents which generate spreading instabilities. Microsimulation is also used to capture the expected effects of route information, as well as indicating control and routing strategies.

1 Introduction

Representation of traffic flows is an essential adjunct to both urban and non-urban planning. Being important working tools for governments and consultants, traffic models have received a great deal of attention from academic and other analysts. Urban traffic models have been of greatest interest, because congestion adds to the complexity, but traffic modelling is also essential for non-urban road planning and investment. Traffic flow may be treated as a fluid, without considering the individual elements, or individual vehicles may be modelled. The term 'simulation' is taken broadly to mean

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any model which attempts to represent or mirror actual traffic behaviour and includes equilibrium models. A common convention is to call simulation of the individual vehicles in a traffic stream 'microsimulation' but the terms are used loosely in this paper. To some extent, models reflect stages in the development of the field but the differences are mainly attributable to differing needs and applications.

1.1 The Nature of the Traffic Assignment Problem

The first task in modelling traffic on a network is to identify the reasonable routes, which do not backtrack, between each origin and destination and to identify the shortest (in terms of travel time). Then there are two main possibilities: assign all of the traffic to the shortest route between each O-D pair or distribute it approximately normally across all reasonable routes between each pair. The latter is usual for non-urban routes where congestion is not significant. Where congestion is significant, it has been more usual to initially assign to shortest routes. Figure 1 shows traffic assigned to the shortest (quickest) paths from A to B and so on. After the traffic between only four O-D pairs has been assigned, the links in the K-J corridor are becoming congested. In real life, motorists would start to seek alternative routes, and the modeller must mimic this behaviour. In other words, the modelling process is based on people pursuing their own objectives. Generally, the aggregate equilibrium found is not a utility maximum for the population.

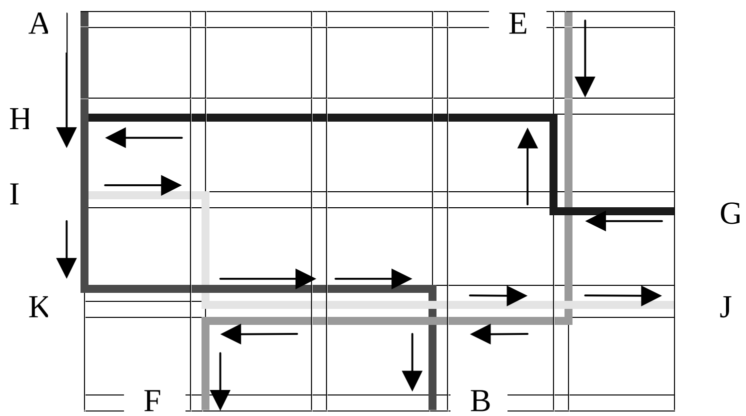

Figure 1. Initial assignments of origin-destination traffic to shortest routes

2 Modelling Alternatives

The various ways of handling the traffic simulation problem are indicated in Figure 2, which starts with the two basic inputs, the network and the demands, and maps out the alternative modelling paths that may be followed. Although it takes the form of a flow chart with decision points, the chain of reasoning would be followed implicitly, at best. In fact, there is a tendency to cling to familiar models, which is reinforced by the ownership and licensing of proprietary packages. It is also the case that a standard static model is often adequate to represent the effects of additions or modifications to the road system for planning purposes. However, none of these models is simple to apply to an urban network. Some of the major models are discussed in the following brief review.

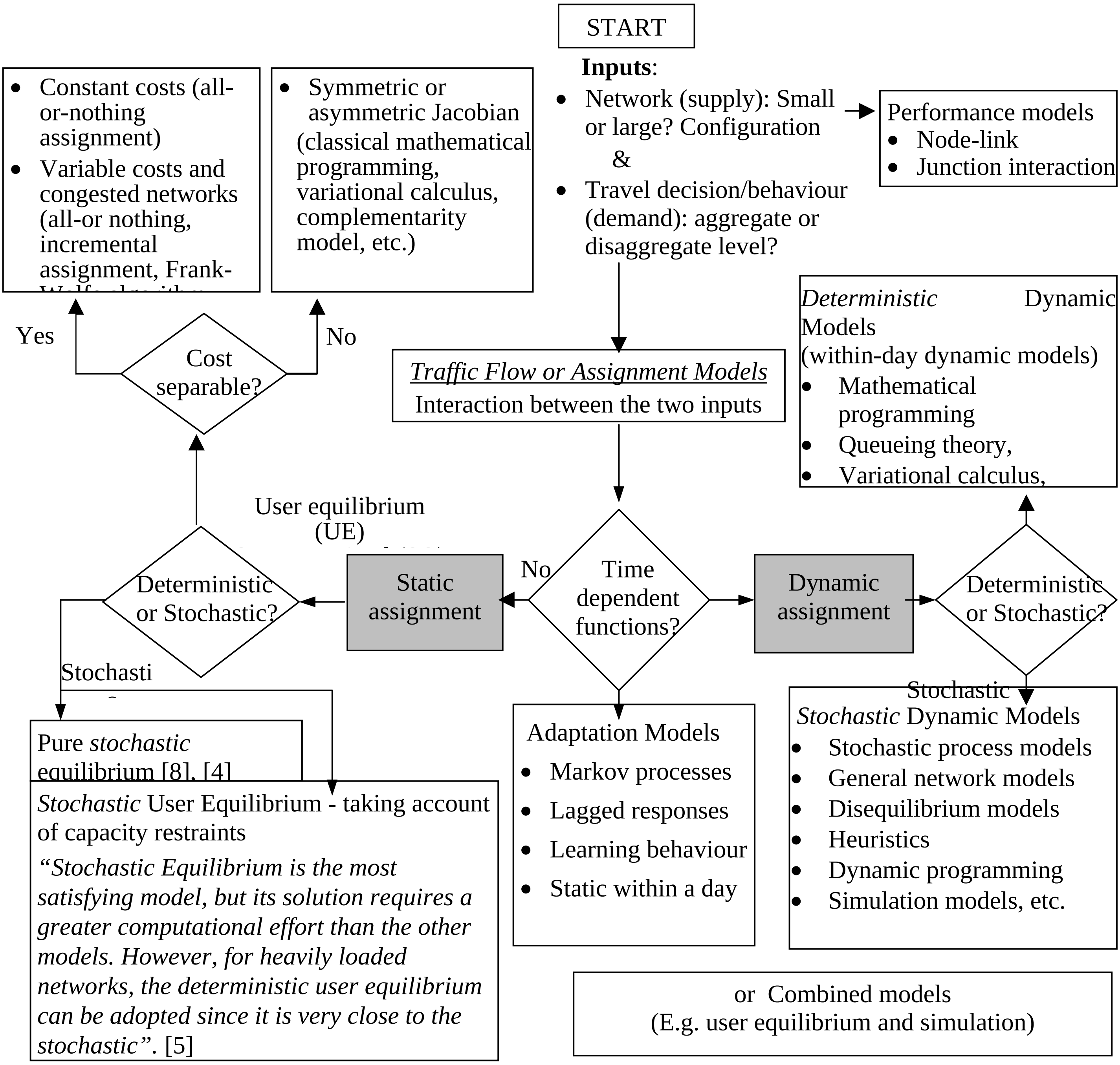

Figure 2. Traffic modelling alternatives

2.1 Performance Models

Performance models stand outside the general modelling structure because they represent small area or intersection configurations to be tested under arbitrarily specified loads. A good example is SIDRA, an intersection model developed at ARRB Transport Research.

3 Static Models

The first major split shown in Figure 2 is with respect to time. Whereas models on the right explicitly deal with change through time, either continuously or in increments, those on the left are static in the sense that the final result represents a steady state after road users have finished making their adjustments or the marginal shifts have settled down to a condition in which they roughly compensate for each other. Almost all methods start by finding the shortest path between each origin and destination, which is a time consuming operation [21].

3.1 Deterministic User Equilibrium (DUE)

The top left box in Figure 2 shows deterministic models with separable costs, meaning that a driver takes into account only the directly experienced costs, being time mainly. Only the second case in the box is significant for modelling. In a congested network, drivers seek routes which minimise their individual travel times, providing the basis for Wardrop's [28] first principle that the journey times on all routes actually used between any OD pair are equal and less than what would be experienced by a single vehicle on any of the unused routes. This leads to an adequate representation of what happens in a congested urban network and results in realistic approximations.

User-optimised traffic flows [19] are estimated by solving the following problem [2]:

$$\text{Minimise } \sum_a \int_0^{f_a} c_a(x)dx$$

$$\text{Subject to } \sum_{r \in R_{ij}} h_r = T_{ij} \forall i, j$$

$$h_r \geq 0 \forall r \in R$$

$$f_a = \sum_{r \in R} \delta_{ar} h_r \forall a \in L$$

The objective is replaced by: Minimise $\sum_a f_a c_a(f_a)$

f_a the hourly flow of vehicles on link a; c_a travel cost on link a;
T_{ij} hourly trips origin i to destination j; h_r the flow on route r;
R_{ij} all routes from origins to destinations; δ_{ar} is 1 if link a is on route r, 0 otherwise;
L all links on the routes from origins to destinations.

Traffic is loaded on to the least cost routes, the effects of congestion on travel times are calculated and traffic is re-assigned. If it were simply assigned to the new least cost routes there would be cycling and the process would be unlikely to converge [17]. One solution is incremental loading of the traffic but this may lead to some initial assignments which exceed the optimum.

The preferred solution uses the Frank-Wolfe algorithm [10],[17]. Using optimal re-assignments, the algorithm reaches the user equilibrium solution, as in Wardrop's second principle. Convergence generally takes a small number of iterations, even for a large urban network. The method has been a fairly good predictor of what will happen after a network is modified, as drivers do some experimenting and settle down to the new 'equilibrium'. Thus, it has been a useful planning tool but analysts have tended to worry about the lack of dynamic content and the gap between this method and individual behaviour.

3.2 Stochastic User Equilibrium (SUE)

The bottom left boxes in Figure 2 show stochastic but static models which take account of the fact that not all drivers choose quickest routes. Variability of choice is represented in SUE models [20], each reasonable route having a non-zero probability of being used and longer routes having lower probability. For ease of computation, the logistic function is commonly used to distribute the traffic. Pure stochastic equilibrium models are used for non-urban travel, where there is little congestion and it would be unreasonable to assign all traffic to shortest paths [26]. In the urban case, the SUE solution includes some routes which would be excluded by Wardrop's second principle from the DUE solution. Standard solution methods for SUE [22],[6] involve iterative approximations.

4 Adaptation Models

Adaptation models are time dependent but changes are from day to day. They involve markovian transitions which represent learning and modification of choices [11].

5 Dynamic Models

A notoriously intractable class of dynamic problem is to construct models which not only assign traffic between routes but also between time periods. In an age of flexible working hours, it is important to be able to represent shifts of work trips to less congested times, in response to peak congestion, as well as shifts between routes. The behavioural responses can be assessed by discrete choice studies of revealed and stated preferences [12] but modelling such behaviour between arbitrarily delimited time periods is difficult. Such work is being actively pursued by the methods indicated in Figure 2. New approaches include disequilibrium models which maximise some measure of welfare but recognise that traffic in a network is not necessarily in equilibrium and that capacity changes induce transient phenomena.

This paper focuses on microsimulation as an emerging and potentially dominant form of dynamic modelling.

6 Microsimulation

At the most detailed level, a microsimulation takes a vehicle from its network entry point to its final exit [13]. Interactions between vehicles at intersections may be represented, and boarding and alighting at public transport stations or stops may be modelled in detail. At a less detailed level, simulation may refer to platoons, user groups [14], lanes, competition among operators or parts of the transport network [1]. At the microsimulation level, the purpose of modelling every vehicle in the network is to reproduce traffic conditions as realistically as possible.

> "Here, behind the apparent randomness of road traffic, lies a complex order based on simple rules of car following, gap acceptance and vehicle kinematics. These can produce complex behaviour over a wide area when traffic densities are high. One reason for this complexity is that high density traffic is prone to chaotic processes which are sensitive to small disturbances." [9].

There has recently been a proliferation of both commercially available software and software developed by research institutions for microsimulation of traffic flows. The high cost of simulating traffic as discrete entities is justified when it picks up system effects which might otherwise be missed, such as propagation of waves after an incident. In general, the more detailed the model the better it represents reality but more elements make the problem more intricate and require more resources. Choice of model involves tradeoffs between speed, realism and cost. An important question is whether a model produces realistic results under varying conditions. Generally, average time estimates and predictions of delays are better assessed by macro models of flows because there is some danger of microsimulation underestimating the global outcomes [25],[16]. Nevertheless, it has been suggested that the choice between microscopic and macroscopic models is more a philosophical than a technical issue [20].

6.1 Simple Rule Based Behaviour

Simulation may use simple rules based on driver behaviour. In a car following model, drivers accelerate or decelerate in reaction to the vehicles ahead or drivers may try to maintain a minimum desired speed (hence, lane changing). Various behavioural characteristics of drivers may be modelled and the origin and destination of each driver is commonly specified.

An alternative method is to distribute vehicles randomly in the network and assign random turning choices at intersections, using turning percentages. A table for each direction of each intersection dictates which fraction of vehicles would go left, straight, right, etc. This method has been criticised by Nagel because collecting all of the necessary data is difficult and the method "…is only useful for representing the status quo, but useless if one wants to study changes in the transportation system, because the turning percentages change immediately. The only way out seems to be to give individual drivers intentions, i.e., an idea of where they want to go" [15].

Nagel's approach means giving users individual origins and destinations, with route plans (paths) so that they know on which intersections they have to make turns in order to reach their destinations. Travellers are initially given the 10 shortest paths as choices and the one which performed best in the past is then given a high probability of being used, but there is a small probability of choosing another option at random. An interesting result is that after the users of the network have settled down to their choices of path, the overall network throughput is lower than when the shortest path is used [15]. This is a variant of Braess's Paradox that a new or improved link may have a negative effect on aggregate utility [3].

6.2 Cellular Automata (CA)

Another alternative is to use cellular automata in a discrete dynamic system. Space, time, and the states of the system are discrete. Each point in a regular spatial lattice, called a cell, can have any one of a finite number of states. The states of the cells in the lattice are updated according to a local rule. That is, the state of a cell at a given time depends only on its own state one time step previously, and the states of its nearby neighbours at the previous time step. All cells in the lattice are updated together, so that the state of the entire lattice advances in discrete time steps. The transportation simulation group at Los Alamos National Lab have developed the Transportation Analysis Simulation System (TRANSIMS) [24] are co-operating with The Centre for Parallel Computing at University of Cologne in using cellular automata for the microsimulation of traffic flow. Details of the system, including lane changing, complex turns and intersection configurations, are fully represented and each driver is given a destination and a preferred path.

6.3 Simulating the Effects of Traffic Controls and Information

Simulation is a convenient way to study signal cycle times, ramp metering, route diversion, speed limits and other measures within the traffic network context. It is also used to model the effects of advanced traveller information systems (ATIS) and route guidance on individual travel decisions [14],[1]. Thus, it can model the responses of users to both controls and real-time traffic information, as well as the interactions between them, and is used for testing, verifying and improving traffic management policies [30],[29]. Although simulation models may obscure their assumptions, compound their errors and yield results that are difficult to interpret, they are increasingly favoured as decision support tools and for the study of integrated traffic control, route selection logic, individual behaviour and interaction between individuals, as well as traffic flow characteristics [23].

There has been some debate on the use of advanced traveller information systems (ATIS) for alleviating traffic congestion. The dynamics of rerouting, the operation of adjacent traffic signals at different cycle times, effects of queuing on capacity, and the various forms of real-time intersection control are a challenge for microsimulation. During the development of an integrated traffic simulation program that performs all phases of linked trip decision making, pre-trip planning, en-route travel and post-trip evaluation, Chen and Mahmassani [7] found that when all users were given access to real-time information severe congestion resulted. On the other hand, information accessible to only a fraction of users resulted in benefits to these individuals, and possibly to others as well.

6.4 Model Calibration

In order to mimic real-world decisions, models must be calibrated so that they are applicable in a variety of contexts. Decision rules are based on estimates made with discrete choice models or on heuristic and algorithmic procedures derived from behavioural research. Polak and Axhausen [18] identify three types of behavioural research needed to develop models: in-vehicle behaviour in response to systems design, driving behaviour (overtaking, gap acceptance, manoeuvre, signal behaviour etc.) and travel behaviour, including route choice, compliance with ATIS advice and responses to information from other sources. All three types of research try to find how various factors contribute to choices, in order to simulate a stochastic network system based on each driver determining his or her route.

7 Combined Models

The best known example of a combined model is SATURN [27]. Each time interval is treated as a steady-state assignment problem, vehicles are in platoons and the model takes full account of interaction between different flows in roundabouts and in signal-controlled and priority junctions. Because the model needs information about link flows, queues and delays, an assignment model is used to load a trip matrix on to the network and obtain an estimate of the flows. The relationship between the simulation and the assignment is depicted in Figure 3.

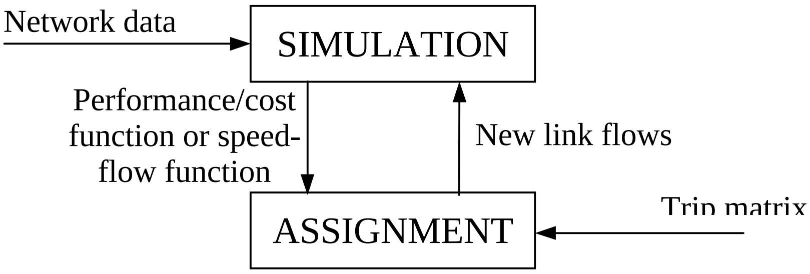

Figure 3 Simulation assignment cycle in SATURN

To achieve a synthesis of simulation with the conventional mathematical models of equilibrium and assignment, Ben Akiva [1] has proposed a unified evaluation and design framework, bringing together traffic control and routing strategies with driver behaviour and network performance models (Figure 4). By calculating performance measures, the laboratory provides an integrated device for off-line evaluation and benefit assessment of advanced traffic management and user information systems.

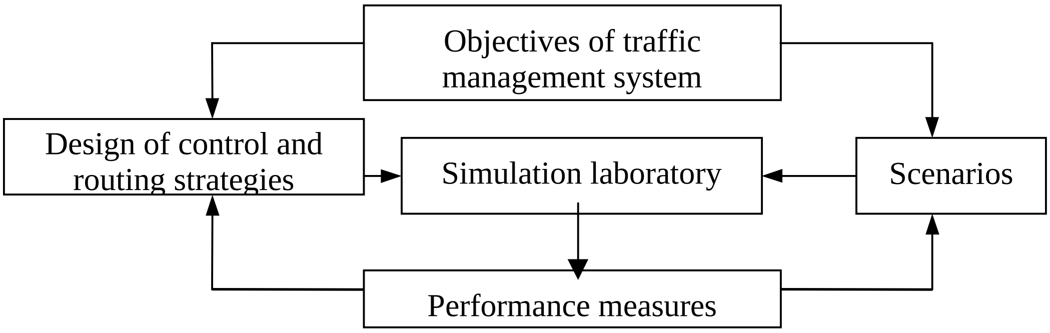

Figure 4 Simulation laboratory structure (as in [1])

8 Conclusion

The main conclusion is that a great variety of applicable models have been developed to simulate traffic. Some of these are listed in Table 1 (after References). It is an active field, with vigorous development in several directions, but there are strong indications that microsimulation will come to dominate traffic modelling as the use of parallel computing becomes widespread.

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Table 1 Some of the models used to simulate traffic flows

MODEL	**YEAR**	**APPROACH**	**IMPLEMENTATION**
FRESIM	1999	Stochastic microsimulation of traffic on freeways	Assess the influence of traffic, design and vehicle characteristics
TRANSIMS [24]	1998	Microsimulation of metropolitan networks; uses cellular automata	Gives position and status of vehicles, time, speed, stops
SCATSIM [16] (based on TRANSYT)	1997	Simulates traffic under various conditions (microscopic)	Flow, stops, total and terminal delay, travel and idle time, speed, fuel consumption, emissions
NETSIM [25]	1997	Interval-based microsimulation; events are updated every second	To describe traffic operations and effect of variable control devices
PARAMICS [9]	1996	Microsim: vehicle following, gap acceptance and lane changing	Large cities, using parallel computing where needed
DRACULA [13]	1996	Driver responses assessed against normal experience	Study congestion pricing, signal control, dynamic route guidance
SMARTPATH	1995	Microsimulation	For automated highway systems
AIMSUN2	1995	Combined discrete-continuous simulation of the traffic network	Applied to urban networks
FREFLO	1994	Event-based microsimulation moving each vehicle intermittently	Applied to urban networks
DYNASMART	1994	Simulation of network dynamics, varying information systems	Study information strategies and information control systems
TRAF-NETSIM	1994	Event driven network simulation	Study effects of intersection control devices
MITRAM	1993	Real time or batch mode	For traffic control and forecasting

		simulation; fuzzy vehicle modules	flows
FASTCARS	1993	Simulation of driver responses to traffic information	Calibrate predictive models of driver behaviour with information
THOREAU	1992	Macrosimulation of speed-flow relations	Study aggregate traffic flows
NEMIS	1991	Simulate route guidance strategies	Assess regulations, traffic light control, network improvements
INTEGRATION [20]	1988	Integrated simulation and traffic assignment model	To evaluate freeway and traffic signal network controls
KRONOS	1985	Finite difference methods to solve system of partial differential equns	Simulation for urban areas
SATURN [27]	1982	Combined detrministic user equilibrium and simulation; dynamic; vehicles in platoons;	Interactions between flows in roundabouts, signal-controlled and priority junctions
CONTRAM	1982	Assigns single vehicles or small groups; releases them sequentially	Applied to urban networks
TRANSYT	1980	An off-line deterministic user equilibrium model	Simulates network traffic; effects of platoon dispersion; fixed signal settings
INFRAS-FRESIM	1980	Stochastic model	Predict freeway traffic, detection and control of incidents