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DYNAMIC SIMULATION-ASSIGNMENT METHODOLOGY TO EVALUATE IN-VEHICLE INFORMATION STRATEGIES IN URBAN TRAFFIC NETWORKS

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ABSTRACT

A model combining traffic simulation and path assignment capabilities is presented to analyze the effectiveness of in-vehicle real time information on the performance of a congested traffic network. Drivers' route decisions in response to the information are modelled individually at each node. Results of a series of simulation experiments are discussed. Special coding considerations for efficient vector processing on supercomputers are also discussed.

1. INTRODUCTION

As traffic conditions continue to worsen at an alarming rate in many of the urban areas around the world, traffic engineers are becoming increasingly aware of the relatively limited impact of conventional and mostly local approaches to tackle the problem. Augmentation of network capacity via additional infrastructure is prohibitively expensive and is no longer considered a viable solution. With the availability and continued development of advanced communication technology, more and more efforts, around the world, are being directed towards utilizing the existing networks more efficiently by giving drivers real-time traffic information and distributing the traffic flow both spatially and temporally in more effective ways.

In addition to the development of and experimentation with hardware for traffic guidance and route control, it is important to look deeper into the dynamics of traffic under information, especially the implications of driver behavior. These dynamics are not all intuitively predictable, and it seems essential that frameworks for modelling and analyzing traffic networks under real-time information are developed, so that expensive and possibly counterproductive real-world experimentation can be avoided. It is also important to understand what happens to the utility that the drivers derive after the traffic system stabilizes into an equilibrium, if it ever does, under information so that the effectiveness of information strategies can be evaluated more objectively.

In this paper we report on our research effort that integrates the main components of a traffic network under real-time information, namely, 1) the traffic flow, 2) the driver behavior and 3) the network information dissemination, into a single modelling framework which is then used to study the underlying dynamics and evaluate alternative designs of such traffic systems. We also report on the use of the framework for a study of the system dynamics and equilibration characteristics and give some results for illustrative purposes.

1.1 Objectives and Scope

The main objective of our research was to formulate the modelling framework, and then to carry out experimentation with a representative traffic network to evaluate its performance under different informational and behavioral scenarios. The main parameters representing the level of information in the network would be the fraction of drivers who have access to information and the frequency of updating of the information on network conditions. On the driver behavioral side, the main factor would be their propensity to accept the information and change their routes, which could be captured using models based on bounded rationality, namely the driver indifference to minimal advantages from route switching.

The objective was also to keep the behavioral and informational details to simple and tractable basics, while ensuring that they are significant enough to capture the essential aspects of the traffic system dynamics. This is necessitated by the unavailability of calibrated models of sufficient sophistication and also the lack of real-world data for calibrating such models. This also means that the simulation studies had to be carried out with alternative scenarios to gain insights into the system performance under such conditions. An implicit objective of the research effort was to develop the modelling framework in such a way that it is flexible enough for incorporating more detailed behavioral and informational models which may become available in the future. Even though this will not affect the conclusions from the research it is important from the point of view of future research in the same area.

In this paper, we also discuss the necessary modifications that are attempted for more detailed general network simulations, specifically on the path processing component, and comment on the computational aspects of the reported simulations with certain pointers to future requirements. We also present some simple coding considerations to effect vector processing on a supercomputer, that results in significant simulation time savings.

2. BACKGROUND REVIEW

Most of the existing literature in the topic of traffic networks under information are on the relatively limited experience to-date from the one and two-way communication systems being experimented with around the world. Probably the first of such studies was sponsored by Federal Highway Administration in the early 70's [Rosen et al. 1970]. After that research effort was abandoned, the CACS (Comprehensive Automobile Traffic Control System) was undertaken in Japan in the mid 70's [Fuji 1986]. CACS proved to be the forerunner of current implementation studies in Japan, RACS [Shibano et al. 1989], and AMTICS [Okamoto 1989]. The ALI-SCOUT in Germany [Von Tomkewitsch 1987] and AUTOGUIDE in England [Jeffery et al. 1987; Belcher and Catling 1987, 1989] are two of the recent systems in Europe, the success of which has resulted in two new joint efforts, PROMETHEUS and DRIVE, by the European community. Such global interest in this topic is accompanied by some renewed efforts in the U.S. too. The PATHFINDER project being initiated and field-tested by Federal Highway Administration with General Motors and California Department of Transportation is the main U.S. effort to date. Preparations are, however, underway for several more or less ambitious demonstrations in a few states. Research has been initiated on the ergonomical aspects of in-vehicle navigation equipment also [Dingus et al. 1989]. Jovanis and Kitamura [1988] examined certain safety implications of such systems.

To evaluate the effectiveness of in-vehicle information systems, Tsuji et al. [1983, 1985] formulated a model based on the stochastic nature of the travel times, and tested the model using the CACS pilot study data from Tokyo. But this model cannot evaluate non-prescriptive guidance of vehicles, when the drivers themselves make route decisions based on the real-time information. A simplified model of static equilibrium under information for idealized systems with one or two routes was developed by Arnott et al. [1990], but that model was more for gaining some basic insights than to evaluate alternative information strategies. Koutsopoulos and Lotan [1989] developed a Stochastic User Equilibrium assignment model, but the link-performance functions used in that work do not seem to be adequate to capture real-time dynamics and congestion and there was no attempt to capture the non-equilibrium conditions with drivers making route decisions.

Simulation models may be the only practical approach to evaluate traffic networks under real-time information, and there have been some early efforts at developing such models at the University of Texas [Mahmassani and Jayakrishnan 1990] and at Queen's University [van Aerde and Yagar 1988a,b; Blum and van Aerde 1989]. The simulation models developed at Queen's University do not have a meaningful model of the driver behavior, even though the network traffic is simulated sufficiently effectively. This paper describes a modelling system that incorporates the driver behavior also in a simple and meaningful manner.

The key element in a general large network simulation, with route switching under information, is modelling the generation and updating of the shortest paths between nodes in the network performed by the traffic control center or, alternatively, the on-board computers. Depending on how mandatory the system is, the drivers could be utilizing the information to form their own choice sets of routes to select from or switch to, resulting in routes that are not always the shortest paths. If routing or assignment to the best path only is simulated, then only simple shortest path trees need to be built, as in the case of the traffic assignment program CONTRAM developed in Britain [Leonard et al. 1989], and the routing program used by ALI-SCOUT [Haeussermann 1984]. The approach of van Aerde and Yagar [1988a, b] also models routing to the shortest path only, disregarding the driver decisions. From a network traffic control standpoint, assignment to one's current shortest path is likely to be effective only at low levels of market penetration, when only a small fraction of users have access to real-time information. The current study proposes a model with flexibility to have more than one path in the driver's route choice set. Thus k-shortest path routines are necessary. This is useful also for the purpose of infrequent updating of the paths.

3. MODELLING FRAMEWORK

3.1 Modelling Approach

Different modelling approaches to evaluate traffic systems under in-vehicle information are: 1) analytical methods, 2) assignment-based methods and 3) simulation-based methods. The analytical methods are available to model only the different components of such a system. For instance, the traffic can be modelled with differential equations which can be solved with numerical methods or finite element methods, which are practical only for simplified corridors, or multiple-bottleneck problems. Mathematical models for the behavior of the drivers are available, but they are microscopic in nature. No models of aggregate driver behavior under information are available, and traffic flow models which incorporate such behavior are bound to be intractable, when expanded to real networks. Other analytical models include the stochastic models of the effectiveness of route guidance, as well as economic models of information dissipation, which were mentioned earlier. These are not detailed enough to capture the traffic and behavioral dynamics, and furthermore, they are not flexible enough to evaluate alternative system configurations.

The second approach is based on assignment, which models the traffic system in the equilibrium state. As of now, there are no insights into whether a traffic system reaches an equilibrium under information or not. Dynamic equilibrium models of traffic systems are available [Merchant and Nemhauser 1978; Mahmassani and Herman 1984; Carey 1987], and could have been used for the current problem under the assumption that there are equilibria under information, but these models are currently solvable only in simplified linear cases, and again may not be immediately extended to the case at hand. One main drawback of assignment based models is the use of link performance functions to represent traffic performance, which are not sufficient to capture the dynamics of congestion development and dissipation. Besides, it is not clear how applicable the usual user equilibrium conditions would be under information.

The approach adopted in this research integrates traffic flow models, behavioral models and information supply strategies into a single simulation model, which has the time-dependent travel demand between Origin-Destination pairs as input. Such a model can also be used to study the system-equilibration by iterative simulation and consequently be used to obtain a dynamic equilibrium traffic flow pattern. The essential components of the framework are shown in Figure 1. The components are explained in detail next.

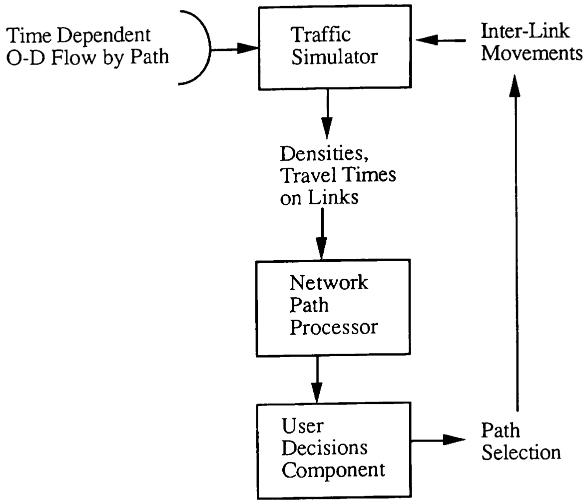


Figure 1. The Overall Framework

3.2 Traffic Simulation

The traffic simulation model is an extension of the macroparticle simulation model (MPSM) [Chang et al. 1985], a special-purpose code developed for the experimental study of commuter dynamics in congested traffic corridors. The logic of the simulation is adapted from the magnetohydrodynamic particle code developed for applications in plasma physics [Leboeuf et al. 1979]. The vehicles are moved in bunches, called macroparticles, at prevailing local speeds derived from density-speed relations within discretized segments of highways. See Figure 2 for an example of a discretized segment. The traffic follows a flow-concentration relationship, which is equivalent to a fluid conservation equation,

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = g(x,t)$$

where,

q = Flow
k = Concentration
g = Net generation at source/sink

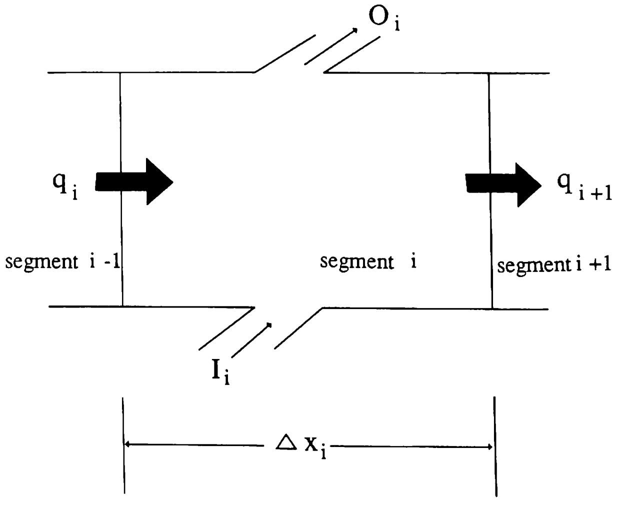


Figure 2. Example of a Discretized Segment

The finite difference form of this equation is used for simulating traffic. That is,

$$k_i^{t+1} = k_i^t + \frac{\Delta t}{\Delta x_i}\left[q_i^t - q_{i+1}^t + \frac{I_i^t}{\Delta t} - \frac{O_i^t}{\Delta t}\right]$$

where, at time t

Δt = Time increment

Δx_i = Length of segment i

q_i^t = Flow into segment i

k_i^t = Concentration in segment i

I_i^t = Ramp entry rate into segment i

O_i^t = Ramp exit rate from segment 1

Thus the concentration at the end of a time step in a segment depends on the concentration in the previous time-step and the net flux. The link-to-link flux depends on the current step's speeds, and the driver decisions for route choice. Using this concentration, the link-speeds for the next time step are calculated according to the following speed-density relationship.

$$v_i^t = (v_f - v_0)\left(1 - k_i^t/k_0\right)^{\alpha} + v_0$$

where,

v_i^t = mean speed in section i during the t-th time step.

v_f, v_0 = mean free speed and the minimum speed, assumed.

k_0 = maximum or jam concentration

α = a parameter

Other functional forms are possible for this relationship. The higher order continuum models [Payne 1971, 1979; Phillips 1979] used by Michalopoulos and Beskos [1984] in simulations is an example. These models are not necessary to capture the essential features of the traffic under information and the congestion dynamics, and so the simpler model shown above was selected.

The macroparticle size can be fixed at any number, but our experience shows that simulation with single-vehicle particles is very much possible as supercomputer resources were available. Such individual vehicle simulations are necessary because the behavioral models are applied at the individual driver level.

3.3 Queue Delay Modelling

Single queues are modelled at the end of each link. These queues form when there is demand for movement into the downstream links (based on driver route-decisions) and there is insufficient available capacity in one or more of the downstream links. Such queues are modelled deterministically, with a variable service rate that is determined on a time-dependent basis according to prevailing conditions, subject to certain physical capacity limitations. Potential conflict at the entry of links with multiple incident links is handled through priority allocation rules. Queue delay modelling is an essential feature for realistic representation of incident conditions and traffic disruptions.

3.4 Network Modelling

Two different kinds of simulation models are being developed. The multiple parallel corridor model, which is fast and efficient due to the simplified path processing utilizing specific network topology, and the general network model, which can perform generalized path processing for trips from any node to any other in any kind of network.

3.4.1 Corridor Model

This model has a network simulation component which is general as far as traffic simulation is concerned, but is limited in its route choice and path processing related aspects. It does not allow composite routes with multiple switches to be in the drivers' choice sets and the switching decisions are made based on the corridor trip times only. But drivers may travel in such routes as a result of subsequent switch-decisions [Mahmassani and Jayakrishnan 1990].

The program allows up to 10 parallel highways with up to 10 different cross over points on each highway where switching to another highway is allowed. These limits result from an efficient label-numbering scheme that is used to keep track of the highway that each link belongs to, thus resulting in a fast updating of route trip times used for information supply. See Figure 3, below, for the 3-corridor system for which the simulation results are reported in Section 4.

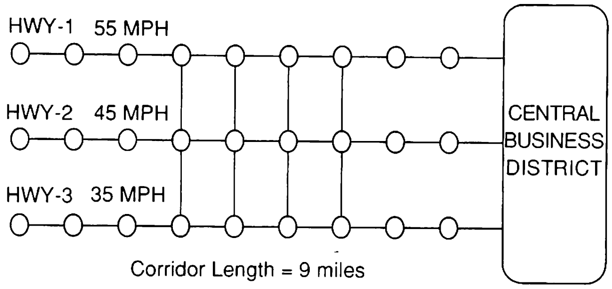


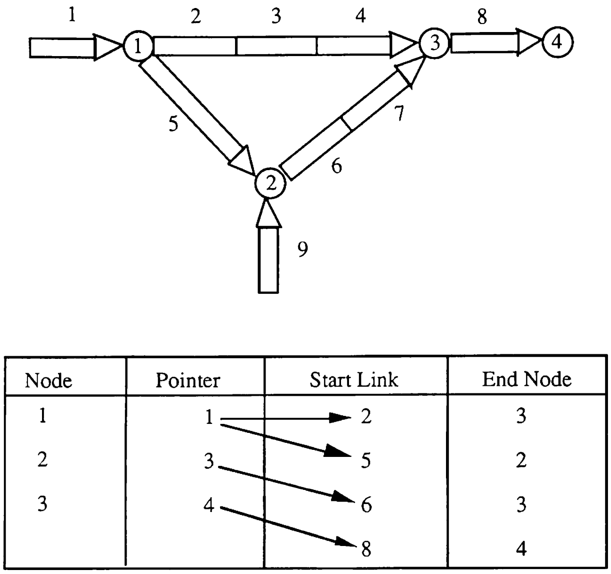
Figure 3. Three-Corridor Network Studied

Due to the efficient and fast way of handling multiple routes this model is of particular interest in doing studies related to the network equilibration and random utility-based dynamic equilibrium traffic patterns, where distinct and discrete route alternatives need to be simulated efficiently.

3.4.2 General Network Model

The general network model is capable of simulating networks with any kind of structure. This implies that the drivers' route choice sets consist of a large number of routes. This model considers many paths between all origin-destination pairs as well as the driver route choice from among all those routes or a subset thereof. The traffic simulation component that was used for the multiple-corridor case remains essentially unchanged, but trip-times over a much larger number of routes have to be calculated, to model the route choice under information. If only the best few routes between two nodes are considered, then simulating a relatively large (say, 2000 links) network is possible. For instance, if the best 5 paths between each O-D pair is assumed to enter the driver's decision to switch routes when given information, the storage requirement for routes between all node pairs in a 500 node network is 500x500x5 = 1.25 million words (1 word per path in predecessor node notation) and 1.25 million words for their trip times. This is within the capability of available computers.

The network model has numbered nodes and numbered links. Links are essentially discrete segments between nodes. The link to link connectivity is stored in a link-to-link incidence matrix, with up to 6 possible connected links at the downstream end of each link. The node-to-node connectivity is stored as a forward star, for shortest path calculations. The links with more than one downstream-links have a downstream node number stored. Similarly, corresponding to each forward star node of each node, the first link of the chain of links to that node is stored. One trip-time value will be stored every time step by summing the trip times over the chain of links between the nodes. See Figure 4 for an example of the numbering and storage structure.



Node	Pointer	Start Link	End Node
1	1	2	3
2	3	5	2
3	4	6	3
		8	4

Figure 4. Numbering and Data Structure for General Network

3.5 Route Trip Time Calculations

These are calculated by adding trip times on the links along the route. The trip time on a link consists of the time to cross the link and the queue waiting time. The queue waiting time in each link is calculated based on the rate of clearance of the queue for the previous five minutes (an assumption), or as long as the queue existed, if less than five minutes. Thus, for link i at time t

$$t_i = t_{iq} + t_{im}$$

$$= \frac{Q_t \cdot T}{N_T} + \frac{S_i}{v_i^t},$$

where,

t_{iq} = current queue wait time

t_{im} = current movement time

T = Min (5 min, length of time with queue)

N_T = number of vehicles cleared in time T

Q_t = current queue length in vehicles

S_i = length of link

v_i^t = current speed in the link.

An alternative assumption to estimate the queue waiting time is to use a standard service rate and the average queue length over the previous five minutes. This makes it less dependent on the current queue length. Simulations can be carried out with either assumption.

3.6 Driver Behavior Modelling

It is assumed that for different alternative designs of an information supply system, the basic information being provided to the drivers would be the travel times on alternate routes (the details of the on-board display are not of immediate concern here). The best route available also may be brought to the driver's attention. But the drivers may not always be required to follow the route that is suggested to them. Thus the behavioral rule has to capture this behavior as a driver route-choice decision, with the flexibility to model the case when the driver has to follow the guidance.

Experimental evidence presented by Mahmassani and Stephan [1988] suggests that commuter route choice behavior exhibits a boundedly-rational character, the kind of behavior proposed by Simon [1955] in business decisions. This means that drivers look for gains only outside a threshold, within which the results are satisfying and sufficing for them. This can be translated to the following model,

$$\delta_j(k) = \begin{cases} 1 \text{ if } TTC_j(k) - TTB_j(k) > \max(\eta_j \cdot TTC_j(k), \tau_j) \\ 0 \text{ otherwise} \end{cases}$$

where, for driver j,

$\delta_j(k)$ = 1, indicates a route switch; 0, no switch.

$TTC_j(k)$ = Trip time from node k to CBD on current path.

$TTB_j(k)$ = Trip time on the best alternate path.

η_j = Relative indifference threshold.

τ_j = Minimum improvement needed for a switch.

As this kind of a model has not yet been calibrated with real data, simulations will be carried out with different parameter values to understand the system performance under such scenarios. The indifference threshold fraction, η_j, can be assumed to be distributed over the driver population. Our simulations assumed that this had a triangular distribution with 50 % of the mean value as the range.

3.7 Key Outputs

The most important output from the simulations will be the average travel times per vehicle in the system, and the average travel times for each group of vehicles - with information and without. Many other outputs are available from the simulation including the averages and variances of trip times and schedule delays (based on assumed work start times), the number of route changes that each vehicle had, the link-end queuing statistics, the link-entry queuing statistics, density profiles of selected links, statistics on congested stretches that vehicles experience etc. While these may not be directly of use in evaluating the traffic systems under information, they are essential in understanding the microscopic details of traffic and also in explaining some of the overall system results that are obtained. When more elaborate frameworks become available in the future to evaluate system performance based on more descriptors than just travel time, these outputs may become even more significant.

4. SIMULATION EXPERIMENTS

4.1 Information Supply Strategy

The kind of information supply strategies that are intended to be evaluated by this model are largely descriptive in nature. This means that non-compulsory vehicle routing strategies can be studied. Prescriptive routing can also be simulated by the model, by suitably adjusting the driver behavioral mechanism to accept the best alternative provided to them. Then the case of compulsory guidance can be simulated by providing the appropriate route as the best route to the route-choice routine. Thus, due to the modularity of the program a wide variety of information supply strategies can be modelled with fairly easy code modifications. The experiments conducted are all for the case of giving route trip time information on alternate routes to the drivers. The case of zero trip-time threshold for switching does simulate the case of compulsory routing to the best route, though.

4.2 Experiments with Real-Time Information

Due to the lack of empirical data on the exact nature of driver behavior, the assumed models are tested for different information scenarios and different network conditions. Hence, different behavioral parameter values and information levels are tested with different traffic conditions resulting from different driver departure patterns. All the following simulations were done on one network over a two hour period.

4.2.1 Network Studied

The three-facility corridor network shown in Figure 3 is studied. It is nine miles long with vehicles entering it from the farthest six sectors of one mile each and travelling to the CBD. There are four cross-over points where drivers can switch from any corridor to any other. The free-flow speed of the highways were different as shown. The minimum (jam) speed was 10 mph on all three.

4.2.2 Behavioral Model Parameters

The behavioral model parameter that was changed for different simulations was the mean of the relative indifference threshold that was explained earlier. Five different values were simulated - 0, 0.1, 0.2, 0.3 and 0.5. A value of zero would mean a very high propensity to switch routes, because the drivers switch whenever there is some route with better trip time. A value of 0.5 would mean a very low propensity to switch. Values above 0.5 do not seem to be realistic. The value of zero would also be equivalent to a case of compulsory guidance to the best route. The lower limit on this switching threshold was assumed to be 1 minute, other than in the case of the 0 indifference threshold (in which case no such lower limit was imposed).

4.2.3 Level of Information

The level of information is captured by the fraction of vehicles that are equipped with information capability. This also varies between 0 and 100 %. Values of 0, 10, 25, 50, 75 and 100 percent were simulated. Whenever a vehicle is generated into the traffic system, it is randomly assigned to the group of drivers with information or the other group, such that the above fractions are attained.

4.2.4 Vehicle Loading Pattern

The departure pattern assumed in the simulations reported here is as follows. The six sectors of each highway that are farthest from the CBD get about 530 vehicles each, over a 20-minute period at a uniform rate. This causes some kind of an impact loading and consequent congestion. Simulations have also been carried out with a dynamic user equilibrium departure pattern derived from iterative simulations with a utility function, the details of which appear elsewhere [Mahmassani and Jayakrishnan 1990].

4.2.5 Results

Figures 5 to 7 show the results of the above simulation experiments. All the average trip time values are shown as percentages of the case when there is no information supply. The curves are for different values of the indifference threshold which was mentioned earlier.

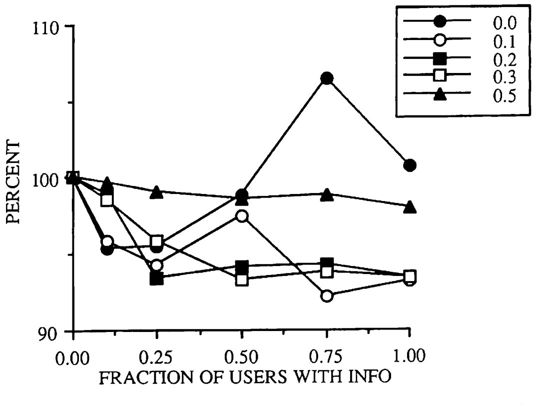


Figure 5. Variation of Total Travel Time, as a Percent of No Information Case, with Fraction of Users with Information, for Each Mean Relative Indifference Band

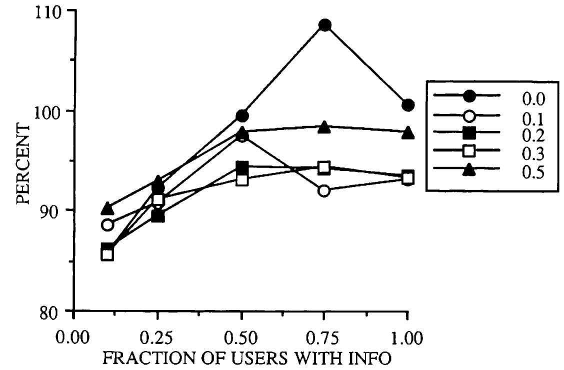


Figure 6. Average Trip Time for Users with Information, as Percent of Value for No Info Base Case

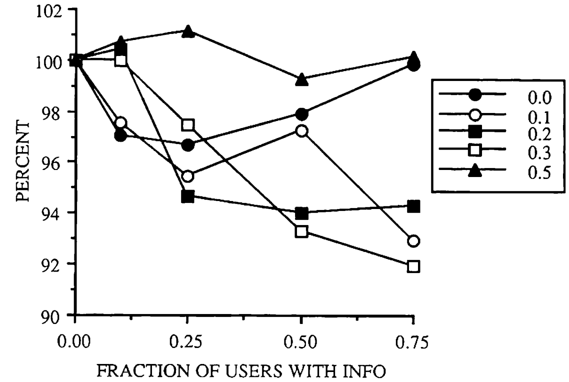


Figure 7. Average Trip Time for Users with No Information, as Percent of Value for No Info Base Case

The main intent of these results is to illustrate the simulation procedure. However, highlighting some of the substantive conclusions is in order. We see that the marginal advantages from information supply decrease as more and more vehicles are equipped with information. The group without information gain more and more advantages as more vehicles get equipped, while the group with information get less and less advantages. Another noticeable result is that when drivers switch routes very easily (i.e., IB = 0) and when they switch very rarely (i.e., IB = 0.5) we get worse results. An indifference threshold of about 0.2 to 0.3 seems to give good results. Note, though, that this is a behavioral parameter which may not be under the direct control of the traffic engineer.

4.3 Computational Experiments

A few simulation runs were made for determining the computational aspects of the simulation model. We report some of those results here.

4.3.1 Network Size

Three different parallel corridor networks were simulated, corresponding to three, five, and seven highway facilities, respectively. Table 1 summarizes the corresponding computational performance.

We can see that the computational requirement linearly increases with the link number, and is not much dependent on the number of vehicles.

Table 1. Computational Requirements for Different Networks (2 hr traffic simulation, timestep = 0.1 minute)

Network	No. of Links	No. of Vehicles	CPU Time (sec.)
3-Highway	51	9600	54.3
5-Highway	125	16000	131.55
7-Highway	231	22400	243.51

4.3.2 Vector Processing

As the simulations were performed on the CRAY X-MP/24 supercomputer, the vectorization capabilities of the compiler were utilized. This was accomplished by writing DO loops in such a way that arrays can be loaded and operated on, rather than sequentially processing array elements [Zenios et al. 1986].

The code in the earlier version of the simulation program [Chang et al. 1985], to rearrange vehicle numbers within a link after every time step is as follows. Here I denotes the links, LIST the array of vehicle numbers, and KJ the position within the link at the beginning of time step. A zero at a location means that the vehicle has left the link. This code moves all the vehicles forward in the vehicle list.

```
      DO 1 I=1,N
      LJ=0
      DO 1 KJ=1,400
      IF(LIST(I,KJ).EQ.0) GO TO 1
      LJ=LJ+1
      IF(KJ.EQ.LJ) GO TO 1
      LIST(I,LJ)=LIST(I,KJ)
      LIST(I,KJ)=0
 1    CONTINUE
```

The array LIST above will not be loaded for vector processing by the compiler because it detects possible dependency between successive DO index values due to the IF (KJ •EQ•LJ) statement. The code is rearranged as follows by breaking it down to four DO loops, all of which are vector-processed.

```
      DO 1 I=1,N
      LJ=0
C
      DO 2 KJ=1,400
      IF(LIST(I,KJ).EQ.0) GO TO 2
      LJ=LJ+1
2     L1(LJ)=KJ
C
      DO 3 KJ=1,LJ
3     L2(KJ)=LIST(I,L1(KJ))
C
      DO 4 KJ=1,LJ
4     LIST(I,KJ)=L2(KJ)
C
      DO 5 KJ=LJ+1,400
5     LIST(I,KJ)=0
C
1     CONTINUE
```

This portion of the code which takes up 40 to 50% of the total simulation time, ran in about 10% of the total simulation time, thus reducing the simulation time by 35 to 45 percent. This shows the substantial amount of savings that can be obtained from vectorizing the code, an area that does not seem to be addressed enough by researchers.

5. SUMMARY & CONCLUSIONS

The modelling framework suggested here and its application to simulation experiments are very useful in providing many insights into the effect of certain types of in-vehicle real-time information systems to improve conditions in congested networks. The model allows the identification of the key underlying parameters and the exploration of their effect. The simulations are largely illustrative in nature, serving to highlight the key insights and demonstrate the flexibility of the framework in the application to general city networks.

The simulation code is efficiently written to utilize the vector processing capabilities of supercomputers, rather substantial processing time being saved with the use of simple code modifications. The simulation framework is also capable of handling incidents in the traffic network.

The simulations bring out the subtlety and complexity of the effect of information, thereby precluding general conclusions and clarifying possible misconceptions that guidance information will automatically improve the traffic conditions. The results from a simple corridor network suggest that information availability to a rather small percentage of the driver population (about 20 to 30 percent) may be sufficient to attain most of the advantages. Beyond this level of market penetration, more elaborate coordinated control schemes are necessary to achieve meaningful improvements in traffic conditions. Further simulations are intended to see if this is true for larger general networks.

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REFERENCES

Arnott, R., A. de Palma, and R. Lindsey (1990), "Does Providing Information to Drivers Reduce Traffic Congestion?," presented at the 69th annual meeting of the Transportation Research Board, Washington DC.

Belcher, P. and I. Catling (1987), "Electronic Route Guidance by Autoguide: The London Demonstration," *Traffic Engineering and Control 28*, 11.

Belcher, P. and I. Catling (1989), "AUTOGUIDE - Electronic Route Guidance for London and the U.K.," Second IEE International Conference on Road Traffic Monitoring, London, UK.

Blum, Y. and M. van Aerde (1989), "A Comprehensive Approach to In-Vehicle Route Guidance Using Q-Route," presented at the 68th Annual Meeting of the Transportation Research Board, Washington, DC.

Carey, M. (1987), "Optimal Time-Varying Flows in Congested Networks," *Operations Research 35*, 1.

Chang, G.L., H.S. Mahmassani, and R. Herman (1985), "A Macroparticle Traffic Simulation Model to Investigate Peak-Period Commuter Decision Dynamics," *Transportation Research Record 1005*, 107-120, Washington, DC.

Dewar, R.E. (1988), "In-Vehicle Information and Driver Overload," *International Journal of Vehicle Design 9*, 4/5, 557-564.

Dingus, T.A., J.F. Antin, M.C. Hulse, and W.W. Wierwille (1989), "Attentional Requirements of an Automobile Moving-Map Navigation System," *Transportation Research 23A*, 4, 301-315.

Fuji, H. (1986), "The CACS Project," presented at the 65th Annual Meeting of the Transportation Research Board, Washington, DC.

Haeussermann, P. (1984), "On-Board Computer System for Navigation, Orientation, and Route Optimization," Technical Paper Series 840485, Society of Automotive Engineers.

Jeffery, D.J., K. Russam, and D.I. Robertson (1987), "Electronic Route Guidance by AUTOGUIDE: Research Background," *Traffic Engineering and Control 28*, 10.

Jovanis, P.P. and R. Kitamura (1988), "User Perceptions and Safety Implications of In-Vehicle Navigation Systems," presented at the VNIS International Conference, Toronto, Canada.

Koutsopoulos, H.N. and T. Lotan (1989), "Motorist Information Systems and Recurrent Traffic Congestion: A Sensitivity Analysis of Expected Benefits," presented at the VNIS Conference, Toronto, Canada.

Leboeuf, J.N., T. Tajima, and J.M. Dawson (1979), "A Magnetohydrodynamic Particle Code for Fluid Simulation of Plasmas," *Journal of Comparative Physics* 31, 3, 379-408.

Leonard, D.R., P. Gower, and N.B. Taylor (1989), "CONTRAM: Structure of the Model," Research Report 178, Transport and Road Research Laboratory, Crowthorne, UK.

Mahmassani, H.S. and R. Herman, (1984), "Dynamic User Equilibrium, Departure Times and Route Choice in Idealized Traffic Arterials," *Transportation Science 18*, 362-384.

Mahmassani, H.S. and R. Jayakrishnan (1990), "System Performance and User Response under Real-Time Information in a Congested Traffic Corridor," forthcoming in the *Journal of Transportation Research.*

Mahmassani, H.S. and D.G. Stephan (1988), "Experimental Investigation of Route and Departure Time Dynamics of Urban Commuters," *Transportation Research Record 1203*, 69-84, Washington, D.C.

Merchant, D.K. and G.L. Nemhauser (1978), "A Model and an Algorithm for the Dynamic Traffic Assignment Problem," *Transportation Science 12*, 183-199.

Michalopoulos, P.G. and D.E. Beskos (1984), "Improved Continuum Models of Freeway Flow," In *Proceedings of the 9th International Symposium on Transportation and Traffic Theory*, VNU Press, 89-111.

Payne, H.J. (1971), "Models of Freeway Traffic and Control," In *International Proceedings on Mathematics of Public Systems*, Simulation Council, Vol. 1, 51-61.

Payne, H.J. (1979), "FREFLO: A Macroscopic Simulation Model for Freeway Traffic," *Transportation Research Record 722*, 68-77, Washington, DC.

Phillips, W.F. (1979), "A New Continuum Model of Traffic Flow," Report DOT-RC-82018, Utah State University, Logan, UT.

Rosen, D.A., F.J. Mammano, and R. Favort (1970), "An Electronic Route Guidance System for Highway Vehicles," *IEEE Transactions on Vehicular Technology VT-19*.

Shibano, Y., T. Norikane, T. Iwai, and M. Yamada (1989), "Development of Mobile Communication System for RACS," In *Proceeding of Vehicle Navigation and Communication Systems Conference*, Toronto, Canada.

Simon, H. "A Behavioral model of Rational Choice," *Quarterly Journal of Economics 69*, 99-118.

Tsuji, H. and H. Kawashima (1983), "Stochastic Models for Estimating the Effectiveness of a Route Guidance System," In *Control in Transportation Systems, Proceedings of the IFAC/IFIP/IFORS Conference*, Baden-Baden, Federal Republic of Germany.

Tsuji, H., R. Takahashi, H. Kawashima, and Y. Yamamoto (1985), "A Stochastic Approach for Estimating the Effectiveness of a Route Guidance System and its Related Parameters," *Transportation Science 19*, 4, 333-351.

van Aerde, M. and S. Yagar (1988a), "Dynamic Integrated Freeway/Traffic Signal Networks: Problems and Proposed Solutions," *Transportation Research, 22A*, 6, 435-443.

van Aerde, M. and S. Yagar (1988b), "Dynamic Integrated Freeway/Traffic Signal Networks: A Routing-based Modelling Approach," *Transportation Research 22A*, 6, 445-453.

Von Tomkewitsch, R. (1987), "ALI-SCOUT: A Universal Guidance and Information System for Road Traffic," 6th IEEE International Conference on Automotive Electronics, London, U.K.