A TRANSPORTATION NETWORK EVACUATION MODEL[†]

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(Received 8 July 1980; in revised form 28 September 1981)

Abstract—This paper describes NETVACI, a model for simulating the traffic pattern during an emergency evacuation. The development of the model has been motivated by the need to estimate network clearance time for areas surrounding nuclear power plant sites, and the model has been applied in this context. NETVACI is a macro traffic simulation model sensitive to network topology, intersection design and control, and a wide array of evacuation management strategies. The model can handle large networks at modest computational costs and includes many reporting options. The paper includes a review of other approaches used to model evacuations and estimate network clearance times, a description of the structure and logic of the model and some computational experience.

INTRODUCTION

Most of the literature on traffic assignment models deals with the steady state problem of finding link flows from an origin-destination trip matrix. Time-dependent traffic assignment on a transportation network has not been widely studied in the transportation literature.[‡] Briefly stated, the problem is to find the traffic flow, density, speed and queues on each of the network links, as a function of time, given the rates of generated traffic (as a function of time), the desired destinations and the physical characteristics of the transportation network (roadways and the capacity and controls at each intersection).

This problem has been studied by the authors in the context of estimating network clearance times during emergency evacuations. This paper describes a computer model, NETVACI, for the analysis of traffic patterns and traffic clearance times on a road network. The development of the model was originally motivated by the need for such analyses for communities surrounding

Note that the initial warning time may cease to be an issue with the completion of the installation of new warning systems (sirens) in many sites and that the verification time may be considered as exogenous to the problem. The preparation time is an experimental question that should be handled by a reasonable worst-case assumption; in most cases, however, one can argue that it will not dictate the total evacuation time since it will be lower than the time required to load the network (which is capacity constrained). Note also that importance methological issues regarding the estimation and specification of the input trip rates (the loading profile) are also outside the scope of this paper. nuclear power plants,§ but the approach is applicable to the analysis of other mass evacuation situations. In this paper we explain the methodology utilized and describe its application to the estimation of emergency clearance times.

The model has been applied to several nuclear plant sites around the country where an emergency evacuation has been simulated. These applications are mentioned in the last section of this paper.

The paper is organized as follows: The first section presents a review and critique of existing techniques for estimating emergency evacuation times. Section 2 describes the general structure of the model and some of its key features, while Section 3 outlines the logic of the simulation program itself. Section 4 tests and depicts some of the model features using data from an actual nuclear plant site. Section 5 briefly describes the inputs, outputs and major options available to the model user and concludes the paper with an account of some computational experience and a brief description of on-going research.

1. EXISTING PRACTICE

The total evacuation time for nuclear power plant (and other) sites includes four (partially overlapping) components: initial warning time, individuals' preparation time, network clearance time and evacuation verification time. The focus of this paper is on the network clearance time, i.e. given the spatial and temporal profile of the network loading pattern the figure of merit is the time needed for the evacuating volume to clear the network.

This section consists of a critical review of existing methods used to describe travel patterns and estimate clearance times during an emergency evacutation. We include here three techniques which have been actually used in practice: the dissipation rate model, manual capacity analysis and micro traffic simulation.

(a) Dissipation rate model

A simple aggregate formula for estimating evacuation

[†]The development of NETVACl was funded, in part, by HMM Associates of Lexington, MA 02145, U.S.A.

[‡]Early contributions in this area include the pioneering work of Yagar (1971, 1976a) on numerical techniques for the dynamic traffic assignment problem and later, the equivalent mathematical programming formulation offered by Merchant and Nemhauser (1978a, 1978b).

[§]In a 29 November 1979 letter, the Emergency Preparedness Task Group of the Nuclear Regulatory Commission (NRC) issued a request for information regarding evacuation times for various areas around nuclear power reactors.

time is described by Houston (1975) in an NRC working paper. Using data from actual evacuation events compiled by Hans and Sell (1974), Houston correlated the evacuation area size and the population density with the evacuation time. The model assumed a negative exponential functional form of areawide delay and a constant flow rate of 10,000 people per egress route. The model includes two parameters, the first of which is inversely proportional to the population size and the second is statistically calibrated based on the reported evacuation times.

Houston's model is the simplest and easiest to use among all the methods reviewed in this section. However, the approach is grossly aggregate and does not account for location specific variables such as network topology, spatial distribution of population and activities, intersection capacity and control, etc. It should also be noted that the model has been calibrated on a data set which includes evacuations in areas with poor communication and warning systems. Furthermore, the statistical fit of the model is not very satisfactory, a problem which is compounded by the high sensitivity of the model to the values of the estimated parameters. Naturally, such a model is not intended for detailed analysis or planning, the need for which motivated utilities and government agencies to look for more detailed analysis methods.

(b) Manual capacity analysis

It is difficult to describe the manual approach in detail since we actually refer here to a loosely defined set of techniques used by various analysts at different times. As such, no reference provides a systematic description of this approach. Examples of such analyses can be found in the Wilbur-Smith (1975) study of the sector evacuation of the Seabrook, New Hampshire area, in the Stone and Webster (1980) study of the Zion plant in Illinois, and in two (unpublished) HMM studies of midwestern plants.[†]

In these studies, the consultant calculated the capacity of each of the roads in the area using standard traffic engineering procedures in accordance with the Highway Capacity Manual (HCM) published by the Highway Research Board (1965). Next, several possible evacuation routes were identified for each evacuated sector and the population of each sector was allocated to these routes. Clearance times were then obtained by dividing the total number of vehicles assumed to participate in the evacuation process by the capacity of the evacuation routes.

Such procedures obviously rely to a large extent on arbitrary judgment which varies with the analyst performing the calculations. In addition they are weak in capturing network effects, i.e. the interelationships between the evacuation routes. In other words, such an analysis would not be able to capture the effect of intersection delays and spill-backs on the throughput of other intersections and on route choice decisions, thereby affecting the entire traffic pattern during an evacuation. Another factor limiting the validity of the manual approach is that it ignores congestion which is one of the more serious problems that may arise during an evacuation. Once the process starts one can expect extremely high flows through roadways and intersections which were never designed to operate under such conditions, causing average speeds to fall substantially below normal operating speeds, long queues and substantial delays.

(c) Traffic simulation models

In order to improve on this situation, there have been several attempts to use existing large scale micro-traffic simulation models for studying the evacuation process. For example, HMM used the well-known NETSIM model (see for example Peat, Marwick, Mitchell and Co. (1973)), in their study of the evacuation pattern in the area surrounding two nuclear plants in the northeastern part of the United States and two plants in the south.

The NETSIM network simulation model was developed for the purpose of analyzing traffic control strategies for small urban street networks. Thus it requires a high level of detail in the representation of roadways, intersections and controls. The model keeps track of every individual vehicle in the system, including an array of characteristics relating to the vehicle type and the behavior of its driver under various traffic situations.

The main advantage of using NETSIM is that it is a computerized procedure and thus consistent in repeated applications as well as amenable to rigorous sensitivity analysis. The model has also been validated in a few studies where the model output has shown a reasonable agreement with observed traffic parameters. These validations, however, were conducted in small urban network under normal operating conditions which are probably not very indicative of an emergency evacuation in rural setting.

The main drawback of NETSIM is its limited capacity; the computational resources required for a realistic size problem exceed by far those of the largest available computers.[‡] Even for very small problems, just within the standard capacity of the model, its use would involve tens of thousands of dollars in computational costs. Furthermore, NETSIM requires the analyst to specify the turning movement at every intersection *a priori*, not allowing for a dynamic route selection model (accounting for drivers' response to changing traffic conditions).

It should be noted that NETSIM is not the only traffic simulation model available. A good review of existing models is given by Gibson and Ross (1977). However, we are not aware of the use of any other traffic simulation model for evacuation analysis.

This state of the art has motivated the development of NETVACL, which is specifically designed to model evacu-

[†]In this paper we refer several times to evacuation studies performed by HMM for several utilities in the United States. Due to the sensitive nature of the subject we are not at liberty to offer an exact reference to specific power plants.

[‡]For example, in its standard format NETSIM can handle up to 99 nodes, 160 links and a maximum network occupancy of 1600 vehicles. These numbers are more than an order of magnitude smaller than some of the problems which had to be analyzed.

ation traffic patterns including queue formation processes, dynamic route selection and a wide variety of options designed to simulate alternative evacuation scenarios (in terms of weather, intersection controls, lane management strategies. etc.). The model costs approximately two orders of magnitude less than NETSIM in terms of core requirements and CPU time and, therefore, can be used in a planning mode as well as in an analysis mode. The next section decribes the logic of the model.

2. MODEL STRUCTURE AND BASIC FEATURES

NETVACI is a fixed time macro-traffic simulation model, using established traffic flow models and relationships to simulate the flow of vehicles through a network. It uses a graph representation of the transportation network. i.e. a set of nodes and arcs represent, in general, intersections and roadways. The model does not keep track of individual vehicles (like NETSIM and other micro simulation models) but rather uses mathematical relationships between flows, speeds, densities, queue length, spill-backs and other relevant traffic variables in order to simulate the evacuation process. Due to the heavy flows expected during an evacuation the deterministic flow models utilized in NETVACI can be expected to be relatively accurate. In other words, random phenomena which characterized light traffic flows are not expected to play a major role in determining the traffic stream characteristics during an evacuation.

Given a description of the transportation network and the location and rates of originating traffic, NETVACI provides a detailed account of the traffic conditions on the entire network throughout the simulation process. A brief description of the input, output, options and parameters is included in Section 5 of this paper. In this section we describe the general structure of the model and three of its basic features: the dynamic route selection, the priority treatment of flow at unsignalized intersections and the capacity calculations.

(a) General structure

NETVACI is organized in four basic units (procedures): the main program, the data procedure, the preprocessor and the simulator. The main program manages the entire execution by controlling the calls to the other procedures, the simulation itself and the reporting of network conditions at specified intervals. This program also controls the length of the simulation by terminating the program once the network is empty (or after a specified elapsed time).

The data procedure reads in the network, the parameters and the options to be used in the run. This subroutine uses a special list processing technique to store the network; the link list is stored with both forward and backward pointers, allowing all the links pointing into and out of any given node to be easily identified at any moment during the simulation. This list processing technique is one of the keys to the model's high computational efficiency. The preprocessor procedure converts the physical description of each link into measures of capacity, speed and density. For each specified type of link the preprocessor computes two types of capacity:

Section capacity: which is the capacity along the link regardless of downstream intersection restrictions.

Approach capacity: which is the capacity of the link to handle vehicles going into the downstream intersection.

Note that in standard traffic engineering studies, section capacities are associated with highways whereas the traffic flow through signalized networks is controlled by the approach capacity. NETVACI computes both capacities since they serve different purposes. The section capacity serves as an upper bound on the flow that can move along a link, restricting the number of vehicles that will reach the intersection during a simulation interval. The approach capacity, on the other hand, limits the number of vehicles than can actually move through the intersection. Vehicles that reach the intersection but cannot move through it are assigned to a queue.

The NETVACl simulator includes two separate logical units, the link pass and the node pass. The link pass handles the flow on the links while the node pass handles the transfer of flow from link to link. Section 3 is devoted to the simulator and thus it is not described further here.

(b) Dynamic route selection

NETVACI does not use a pre-specified set of turning movements at each intersection; instead, the turning movements are determined at each simulation interval as a function of the changing traffic conditions and the directionality of the links. Drivers approaching an intersection are assumed to make a choice of outbound (away from the intersection) link based on how fast this outbound link can get them to safety. This, in turn, is a function of the direction of the outbound links (away from the nuclear plant) and the traffic conditions on these links.

NETVACI thus assumes that driver's choice is based on two considerations: first, a prior knowledge of the network in terms of directionality and the normal characteristics of the links; and second, a "myopic" view of the traffic conditions directly ahead. The first of these criteria is reflected through a user-supplied "preference factor" which is specifed for each link while the second is captured by the speeds on each of the alternative outbound links. In order to facilitate the explanation of the route choice mechanism let PF_j denote the preference factor for the *j*th outbound link at a given intersection. In other words, the relative *a priori* preference

of link j is $PF_{j} \sum_{k} PF_{k}$ where the sum goes over all the

links emanating out of the node under consideration (including j)[†]. The choice probability, or the probability of a random driver choosing an outbound link j out of a given intersection at (simulated) time t, $P_j(t)$, is determined as a function of the preference factors and the

[†]The preference factors are user-supplied inputs to the model.

speeds on all the outbound links as:

$$P_{j}(t) = \frac{PF_{j} \cdot U_{j}(t)}{\sum_{k} PF_{k} \cdot U_{k}(t)},$$
(1)

where $U_j(t)$ is the speed on link j at time t. Equation (1) reflects the hypothesis that the likelihood of choosing a given outbound link increases when the speed on this link increases (in other words, when congestion there decreases). Note that the $P_j(t)$'s are computed for each incoming link separately due to turning prohibitions from some links into some other links (a reference to the incoming link was omitted from the notation of the choice probability for clarity of exposition).

(c) The priority treatment

The treatment of intersection controls in the context of an emergency evacuation raises a number of questions pertaining to the extent of driver compliance and the alternative facilities utilization pattern resulting from non-compliance. In order to allow the analyst the flexibility of making different assumptions about the degree of compliance on an intersection specific basis, several traffic control levels can be specified at the downstream end of each link. These include signal control, priority control and no control.

Under signal control the given timing pattern is assumed to be followed by the evacuating motorists. This is likely to take place during an orderly evacuation (when the danger is remote), or when an outside agent is effectively maintaining order.

Unsignalized intersections usually operate according to some priority scheme. Even under evacuation conditions traffic on some intersection approaches might effectively take precedence over other approaches. This behavior may be, again, due to compliance with current stop/yield control in the case of orderly evacuation or due to differences in geometric features (e.g. visibility restrictions, turning movements, etc.), or flow levels between the approaches. Under evacuation conditions it is not evident that such priority would correspond to the existing controls and thus NETVACI accepts a userspecified priority parameter indicating if an approach has a primary or secondary priority.

The model gives first priority approaches equal opportunity in the competition for the common conflict area (subject to the capacity constraints explained in the next section). Flow through second priority approaches is directly dependent on the existence of interruptions in the higher priority traffic stream. It is well known that the capacity of a secondary (or minor) approach is a function of the gap acceptance behavior of motorists in the minor approach and the headways (gaps) distribution in the major stream. Analytical expressions for this capacity have been derived under certain idealized conditions (see for example Herman and Weiss (1961), and Miller (1972)) which are not likely to prevail during an evacuation.

NETVACI casts this issue as a capacity allocation problem, assigning first a certain volume of vehicles (at every simulation interval at each intersection) from the primary priority to the outbound links.

The secondary priority approaches emit traffic only under one of the following conditions: first, if there is residual intersection capacity from the primary priority traffic, flow can be emitted into the intersection from the secondary priority road subject to the residual capacity constraint. Second, if the residual capacity is zero, NETVACI provides some small capacity for the lower priority approaches to allow for "sneak-in" effects. Note that Yagar (1976b) argues that this effect may be substantial even in everyday congested rush hour situations (in the particular context of a freeway operation).

It is thus left for the analyst to decide on the particular control for each intersection, based on the assumption regarding driver behavior and existing or planned control.

(d) Capacity calculations

The capacity of a transportation facility is the maximum flow that can go through the facility. NETVACI determines capacity in two stages: first, the preprocessor assigns a section capacity and an approach capacity to each link in the network, as mentioned in section (a) above. Second, approach capacities are updated continuously, throughout the simulation as changing turning movements affect the maximum throughput of each link into its downstream intersection.

The capacity calculations are based on the Highway Research Board's (1965) Highway Capacity Manual (HCM) and the recent Transportation Research Board (1980) Interim Material on Highway Capacity which are the accepted practice in the field. Following these references the section capacity is calculated in the preprocessor for links with and without physical separation between opposing directions while the approach capacity is calculated as a function of the physical conditions (width, parking, turning pockets, etc.), environmental conditions (area type, peak hour and load factors[†]), traffic characteristics (traffic mix and percentage of turning movements[‡]), and approach type.

As mentioned before, the approach capacities calculated in the preprocessor are not the actual bounds on the flow. NETVACI adjusts the approach capacity continuously in order to reflect the changing turning percentage resulting from the dynamic route selection.

The capacity of the *i*th approach coming into an intersection at simulation interval t. $C_i(t)$ is given by:

$$C_i(t) = C_i \cdot AL(t) \cdot AR(t)$$
(2)

where C_i is the standard capacity of link *i* as calculated by the preprocessor and AL(t) and AR(t) are the correction factors for left and right turning movements, respectively. These correction factors are a function of

[†]Both peak hour factors and load factors, which have to be specified according to the HCM, are assumed to be 1.0 to reflect the continuously heavy load likely to develop in the case of an emergency evacuation.

[‡]Traffic mix is assumed constant throughout the simulation at the HCM standard of 5% heavy vehicles, an assumption which is likely to yield conservative capacity estimates.

the percent of turning traffic, the approach width, and parking allowance, as suggested by the HCM. These factors do not apply, of course, in case the turning traffic is using special turning lanes or turning pockets.

3. THE SIMULATOR

The simulator is the core of the model. This part of the program executes a given number of procedures at every simulation interval, the length of which is user-controlled.

The simulator includes two major logical units: the link pass and the node pass. The links and nodes are the components of the transportation network as it is represented in the computer. NETVACI uses a directed graph representation of the network and thus links represent one-way roads (two-way roads are represented by two links) and nodes represent intersections of links.[†]

The link pass calculates the number of vehicles that would reach the upstream node or join the queue there in a given simulation interval. The node pass calculates how many vehicles should be moved from each of the links entering a particular intersection (inbound links) to each of the links leaving that intersection (outbound links). The node pass scans all the nodes and the link pass scans all the links at every simulation interval. Figure 1 gives a schematic view of the functions of each of these procedures, which are explained below in greater detail.

The link pass determines the volume traversing each link during a simulation interval. At each interval the model computes the current density of moving vehicles



Fig. 1. Input/output flow chart of the simulator.

⁺The nodes are also used to identify each link in the network; in order to indicate the directionality of the links we refer to upstream (tail) node and downstream (head) node for each link. Nodes also represent sources and sinks, i.e. points where traffic enter and leave the network.

per lane on each link by dividing the number (per lane) of vehicles moving on the link at time t (termed VM(t)) by the difference between the link length (LD) and the length occupied by the queue at the head of the link (LQ(t)). Given this density, K(t), the average (space mean) speed, U(t), over the moving part of the link is computed by using a given speed-density relationship. In its current version, NETVACI uses the linear model for this purpose[†] and thus the speed is given by:

$$U(t) = UF \cdot \left(1 - \frac{K(t)}{KJ}\right),\tag{3}$$

where UF, the free flow speed, and KJ, the jam density (per lane), are known.[‡] The link flow at time t, F(t), can now be easily computed from the fundamental relationship of traffic flow as:

$$F(t) = K(t) \cdot U(t) \cdot NL, \qquad (4)$$

where NL is the number of lanes. The number of vehicles to reach the downstream node of the link (or the rear of the queue if there is one), VR(t), is now given by:

$$VR(t) = F(t) \cdot T \tag{5}$$

where T is the length of the simulation interval in appropriate units. If VR(t) > VM(t) the procedure sets VR(t) = VM(t) to insure that the number of vehicles reaching the downstream node is no greater than the number of moving vehicles on the link. Also [VM(t) - VR(t)] is recorded for the next simulation interval (where VM(t+T) will be given by the sum of this recorded quantity and the volume added to the link§).

Finally, the excess vehicular capacity available on each link for the next iteration, VE(t), is computed (i.e. VE(t) is the maximum number of vehicles that can be added to the link at the next simulation interval) as:

$$VE(t) = [LD - LQ(t)] \cdot [KJ - K(t)] \cdot NL, \qquad (6)$$

where all quantities are expressed in comparable units.

The number of vehicles arriving at the downstream end of the link during a simulation interval, VR(t), is added to the queue (if any) and this sum comprises the total number of vehicles which desire to leave the link. We now turn to discuss the logic of this transfer which is calculated at the node pass.

(b) The node pass

The node pass is somewhat more intricate than the link

pass. It determines the number of vehicles that are traversing each intersection in the network at each simulation interval as well as the number of vehicles entering and exiting the network. The output of the node pass includes the number of vehicles that remain in queue and the number added to and subtracted from each link at every simulation interval.

At each interval (in other words, at simulated time t) the node pass is executed for every node in the network, following the execution of the link pass. At first, only primary priority inbound links are considered while secondary priority links are ignored.

The procedure starts by calculating the traffic volume VW(t) on every incoming (primary priority) link that would be in a position to use the intersection in the simulation interval under consideration. This volume is given by VW(t) = VQ(t) + VR(t), where YQ(t) is the number of vehicles in the queue and VR(t) is the number arriving at the intersection during the interval under consideration, as mentioned above.

The fraction of time that traffic from an inbound link can move through a signalized intersection is determined by the green split, GS, (the fraction of time that the signal face is green) of each incoming direction. For unsignalized intersections, NETVAC1 computes an "equivalent green split" GE(t), which for the *i*th incoming link is given by:

$$GE_i(t) = \frac{VW_i(t)/NL_i}{\sum VW_k(t)/NL_k},$$
(7)

where NL_i is the number of lanes in the *i*th link approach and the sum includes all primary priority links.

Using eqn (1), the share of straight $P_s(t)$, diagonal $P_d(t)$, left $P_i(t)$, and right $P_r(t)$, movements are calculated for each approach. These shares used to calculate an updated capacity for the approach under consideration using the capacity updating mechanism explained in part (d) of Section 2. The updated capacity (see eqn (2)) is given per hour of green; thus, to get the upper bound on the flow of cars out of a given link the approach capacity of the *i*th approach, $CA_i(t)$ is calculated as:

$$CA_i(t) = G_i \cdot C_i(t), \tag{8}$$

where $G_i = GS_i$ for signalized approaches and $G_i = GE_i(t)$ for unsignalized approaches.

The volume of cars that can potentially be moved out of inbound link *i* into link *j* is given by the product of $VW_i(t)$ and the share of drivers coming from link *i* who choose to continue the evacuation over link *j*, $P_{ij}(t)$ (see eqn (1)). Let $M_{ij}(t)$ denote the volume that is actually transferred from inbound link *i* to outbound link *j* at time *t*. $M_{ij}(t)$ is subject to two sets of constraints: the first one on the total flow that can be moved out of link *j* and the second one on the total flow that can be moved into link *j*.

The first set of constraints states only that the total volume moved from i (to all outbound links) is subject to

⁺NETVACI can be modified to include any other speed density model. The specific model used, however, is not going to affect substantially the results since all traffic flow models exhibit similar behavior for very heavy traffic and the linear model is the simplest to use.

 $[\]pm$ Both UF and KJ can be input to the model or computed from link description using standard traffic engineering relationships.

^{\$}Note that the simulation interval should always be less than the smallest link traversing time (i.e. the minimum of UFILD over all the network links). NETVACI reports this minimum in a pre-processing stage.

the approach capacity of link *i*. Let $VI_i(t)$ denote this volume when (only) the first set of constraints has been satisfied, i.e.

$$Vl_i(t) = \min \{T \cdot C_i(t); VW_i(t)\}.$$
 (9)

where $T \cdot C_i(t)$ is the total volume that can move through the approach in one simulation interval. The second set of constraints bounds the total volume that can be processed by the receiving link. It includes a constraint due to the section capacity of link j and a constraint due to the physical capacity of the outbound link given by $VE_j(t)$. The total potential flow into link jafter the first set of constraints has been applied is $\sum_i VI_i(t) \cdot P_{ij}(t)$, where the sum includes all (primary) inbound links *i* from which a turn to *j* is specified. This volume is then scaled down due to the constraints in the second set, using the mechanism explained below.

Let the section capacity of link *j* be denoted by CS_j . The total volume received by link *j*, $VO_j(t)$, is given by:

$$VO_j(t) = \min\left\{\sum_i VI_i(t) \cdot P_{ij}(t); \quad T \cdot CS_j; \quad VE_j(t)\right\}.$$
(10)

in accordance with the second set of constraints. All the movements from i to j are now scaled down appropriately to obtain $M_{ij}(t)$, the volume transferred from link i to link j at time t, i.e.

$$M_{ij}(t) = VI_i(t) \cdot P_{ij}(t) \cdot \frac{VO_j(t)}{\sum_i VI_i(t) \cdot P_{ij}(t)}.$$
 (11)

With this, the assignment at a given node is completed with respect to the primary priority links. In order to perform the assignment from the low priority links the remaining capacity on each outbound link, $VL_j(t)$, is calculated for every outbound link:

$$VL_{j}(t) = \min \{T \cdot CS_{j}; VE_{j}(t)\} - \sum_{i} M_{ij}(t),$$
 (12)

where $VL_j(t) = 0$ if min $\{T \cdot CS_j; VE_j(t)\} \le \sum_i M_{ij}(t)$. The

assignment from the secondary priority links follows the same steps as the assignment from the primary priority links described in this section. The only difference is that the upper bound on the volume that can be received by outbound link j is now constrained by $VL_i(t)$ reflecting the reduced capacity on the outbound links, and the sum in $\sum_i VI_i(t) \cdot P_{ij}(t)$ and in eqn (7) includes only the capacity on proceed links.

secondary approach links.

The volume of cars remaining on any incoming links after the volume transfer is designated as the queue for the next simulation interval. The volume added to the outbound links is used in the next link pass to compute the density of the moving vehicles.

The next section investigates some of the features of the model using an actual case study.

4. SOME NUMERICAL EXPERIMENTS

This section describes some experiments conducted with NETVACI in order to better understand the model's features and the nature of evacuation processes. The numerical tests reported here were carried out using the actual network of the 10 mile emergency planning zone surrounding a nuclear plant in the southern part of the United States. The original data set includes 368 links, 147 nodes and a total of approximately 10.000 evacuating vehicles.

The two types of tests described in this section are aimed at determining the model's sensitivity to the length of the simulation interval and to the modelling of the route choice process.

The first type of experiments consisted of two sets of runs. In the first set the simulation interval was varied between 0.2 and 2.0 min. After each run both the network clearance time and the computational cost of the run (in terms of CPU time) were recorded. This set of runs was then repeated with an artificially higher demand level which was double the original one.

It should be noted that these simulation intervals are all higher than the maximum allowable interval which in this case was 0.1 min. The maximum allowable interval is determined by the link with the minimum traversing time (under free flow conditions). If, however, one can use larger simulation intervals the computational cost savings may be very significant.

The CPU time for a fixed simulation length is proportional to the ratio between the clearance time (the simulation length) and the simulation interval. Thus one would expect a hyperbolic decrease in the CPU requirements as the simulation interval increases.

The simulated clearance time can be expected to increase as the simulation interval increases, a phenomenon that is best explained by an example. Consider a short link that has a capacity of holding at most 10 cars, and assume a simulation interval of 1 hr is being used. The program then cannot move more than 10 cars per hr from the link, implying a maximum departure rate of 10 cars per hr even if the capacity is, say, 1500 cars per hr. Thus excessively long simulation intervals produce an artificial bottleneck for the simple reason that flow cannot enter a link at a rate that it may leave it. Just the same, it may be possible to obtain accurate results with simulation intervals that exceed the minimum if the constraining links do not carry a lot of flow.

Figure 2 demonstrates the magnitude of the above mentioned effects. The dashed curves in the figure are the computational cost (CPU time) curves for the high and low volumes. As expected, these curves are hyperbolic with a significant reduction in the CPU time for simulation intervals between 0.1 and 0.5 min. Also, as expected, the clearance time curve depicts the expected increase in the clearance time as the simulation interval increases.

It is interesting to note, though, that the clearance time estimate remains reasonably accurate even for simulation intervals that are five to ten times larger than the maximum allowable interval. The computational costs though are almost an order of magnitude lower



with the larger interval. This suggests that when the model is used repetitively (say, in an interactive evacuation planning mode) one can try and use large intervals in order to save on costs. This conclusion is, of course, not generalizeable to all networks and its applicability should be tested on a case-by-case basis.

The reason for the slow increase in the evacuation time with increasing simulation interval is that over a limited range, when the network becomes congested, the allowable interval is, in fact, longer than the aforementioned bound. As the speed over the network drops the links' traversing time drops and the length of the maximum allowable simulation interval increases. This suggests, naturally, that significant economies may be achieved with a variable simulation interval; a topic which is beyond the scope of this paper.

The second numerical experiment conducted with the same network data is motivated by the manual capacity analysis mentioned in Section 1 of this paper. This method calls for pre-specified evacuation routes to be analyzed in isolation of each other.

In order to model such an evacuation NETVACl was constrained to use only one outbound link at every intersection (the link with the highest preference factor). The same data used in the previous experiments were utilized in this run and the clearance times generated by both models were compared.

The result of this test was that the choice-constrained model gave a clearance time which was 25% lower than the unconstrained case. This result may appear counterintuitive in light of the fact that the constrained model causes traffic to be routed along fewer links (in effect "shutting off" some links to traffic). The higher flow level on the remaining links creates congestion and slow down along them, a phenomenon which should have increased the evacuation times. This phenomenon, however, is more than offset by the increased intersection capacities which result from the new restricted flow. As indicated by eqn (2) the capacity of intersections is reduced in the presence of turning movements, a reduction which more than offsets the increased congestion over the links. This is obvious from general "traffic engineering wisdom" (and everyday experience) which argues that delays occur mainly at intersections and not along links.

This phenomenon suggests, however, a very important conclusion with regard to evacuation planning: by controlling the flow at intersections and channelizing it along specific routes one may be able to reduce the network clearance time significantly. The comparison of constrained and unconstrained movements also suggests that models which do not include route choice effects err in their clearance time estimate and this error is nonconservative.

The next section briefly describes some of the userside options and parameters of NETVACl and concludes the paper.

5. USER CONSIDERATIONS AND FURTHER DEVELOPMENT

This section describes three aspects of evacuation planning with NETVACI. These include the usage aspects in terms of input needed and output provided,[†] some computational experience acquired to date, and some possible extensions of the current effort including a mention of on-going developments.

NETVACI requires the following three types of input information:

(a) Network Description, including its connectivity, preference factors and the physical and operational characteristics of the links.

(b) Spatial and temporal loading pattern, specified for any node.

(c) Control parameters specifying the options exercised during a particular run.

The output information includes an extensive account of the flows, queues, speeds and other measures of level of service and flow pattern throughout the evacuation process. This information is given for each link at each (specified) reporting interval, generating a profile of each link's condition. The evacuation is completed when the network is empty (or when the number of vehicles on the network reaches a pre-specified level).

NETVACI offers an array of options that can be called upon in order to simulate alternative evacuation scenarios. These include non compliance with intersection controls, evacuation under adverse weather conditions, lane overcrowding and various others. For example, the "ADVERSE" parameter multiplies all the network capacities by a constant. The effect of various values of ADVERSE is demonstrated in Fig. 3 for the same data used in the previous sections, where as expected, reduced capacity is associated with longer clearance times.

Computational experience with the model has been

⁺The model's features are described in great detail in the model user's manual prepared by Sheffi *et al.* (1980).





acquired through the use of the model to estimate evacuation times (by sector and totals) in over a dozen nuclear plant sites.⁺ These applications include relatively large networks; the network around the Midland Power Plant, for example, included over 1200 links, several hundred nodes (approximately 100 of them signalized) and over 80,000 evacuating vehicles. (This site has been analyzed by HMM (1980)).

Using a sample of these model applications one can estimate the computational requirements of the model in terms of CPU seconds, NT, with the following relationships:'

$$NT = \alpha \cdot NA \cdot (1 + \beta \cdot NI) \tag{13}$$

where NA is the number of links in the network, NI is the number of simulation intervals and α and β are computer-specific constants. For the IBM 370/3033 used in these applications, $\alpha \approx .11$ and $\beta \approx 11 \times 10^{-2}$.

In its current format, the model is constrained to process up to 1500 links and modes with no bound on the number of vehicles that can be evacuated. This number can be easily increased as much as needed (subject only to computer capacity) by re-dimensioning a few link arrays in the program. Model applications usually include many runs corresponding to several different scenarios. These scenarios differ mainly in the population to be evacuated which may include only a sector of the area surrounding the plant, a certain radius, or certain population units (e.g. towns, industrial parks, etc.). Evacuations are also simulated under various weather conditions and under various demographic assumptions on the population's distribution (e.g. the density of transient population in resort areas). When the model is applied in a planning and design mode, one would naturally simulate a large set of traffic control and other evacuation management options.

At this point, it should be mentioned that in an evacuation study, the traffic simulation model is only a part of the picture and obviously reliable estimates of evacuation times depend on reliable input to the model. This input includes the population distribution and, indirectly, the assumptions of the rate at which evacuees would get on the network, the car occupancy factors and a whole set of similar assumptions.

In most cases the assumptions built into NETVACI and evacuation studies in general are quite conservative. For example, the analysis conducted in the abovementioned cases assumed that all the vehicles are emitted onto the network at the same time, immediately at the beginning of the evacuation. This loading pattern naturally causes congestion, queues and spillbacks which may be exaggerated due to this assumption. Other conservative assumptions are imbedded in the inputs, i.e. the use of peak population figures and low auto occupancy factors.

It is envisioned that in the future this modelling approach will be increasingly used in a design and planning mode rather than in a descriptive mode. As an evacuation planning tool, the model can be used to prepare evacuation plans and to test traffic management schemes for evacuation purposes. This application is not limited, of course, to the areas surrounding nuclear power plants, but can be used to simulate, as well as prepare, evacuation plans for areas surrounding rail lines and highways carrying hazardous traffic and to model the evacuations due to hurricanes, floods, earthquakes, or any other emergency.

The model can also be used as part of a design study or a regulatory and licensing process. The applications here include site selection by chemical, nuclear or other potentially hazardous plants, or granting authority to haul hazardous material over certain routes and tracks.

Taking an even more general view, this modelling approach may be used, with minor modifications, to model any transportation phenomena where the transient effects are more pronounced than the stochastic effects. Examples include traffic patterns following special events, peak hour loading on transit lines and cyclic demand patterns over freight terminals.

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[†]These include work performed by HMM Associates for Boston Edison Company, Consumers Power Company, Florida Power and Light Company, Public Service Company of New Hampshire, Virginia Electric Power Company, Yankee Atomic Electric Company, Tennessee Valley Authority, Mississippi Power and Light Company, Alabama Power Company, as well as work performed by the Stone and Webster Engineering Corporation for Baltimore Gas and Electric Company and other utilities.

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