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Regional Evacuation Modeling: A State-of-the-Art Review

F. Southworth

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Frank Southworth

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Center for Transportation Analysis
OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, TN 37831, U.S.A.
managed by
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ABSTRACT

Regional evacuation modeling is treated as a five step process: involving vehicle trip generation, trip departure time, trip destination, and trip route selection modeling, supplemented by plan set-up and analysis procedures. Progress under each of these headings is reviewed and gaps in the process identified. The potential for emergency planners to make use of real time traffic data, resulting from the recent technical and economic revolutions in telecommunications and infrared traffic sensing, is identified as the single greatest opportunity for the near future; and some beginnings in the development of real time dynamic traffic modeling specifically geared to evacuation planning are highlighted. Significant data problems associated with the time of day location of large urban populations represent a second area requiring extensive research. A third area requiring much additional effort is the translation of the considerable knowledge we have on evacuee behavior in times of crisis into reliable quantitative measures of the timing of evacuee mobilization, notably by distance from the source of the hazard. Specific evacuation models are referenced and categorized by method. Incorporation of evacuation model findings into the definition of emergency planning zone boundaries is also discussed.

1. INTRODUCTION

Few things as complex and involving as many different actors as a mass evacuation go off "as planned." Prior knowledge of how people will respond to both publicly sanctioned and spontaneously generated forms of information can improve not only the way we develop evacuation plans but also the process by which we apply such plans during the course of an emergency. Reasons for developing regional evacuation plans over the past twenty years include safety from man-made problems such as nuclear reactor failures (Golding and Kasperson, 1988), chemical releases (Sorensen, 1986), and dam-failure related flooding (Southworth and Chin, 1987); as well as safety from natural disasters (Perry, 1980) brought on by hurricanes (Sorensen, Mileti and Vogt, 1988), volcanic eruptions (Perry and Greene, 1983), tsunamis and earthquakes. In addition to the much publicized events surrounding Three Mile Island, Mount St. Helens, Chernobyl, Hurricane Hugo and the Mexico City earthquake, numerous localized evacuations occur every year in response to chemical spills, flash flooding, and other severe weather conditions.

In many of these situations an en mass population evacuation may offer the best or only means of ensuring a population's safety. With this growing interest in evacuation plans has come a similar interest in quantitative methods for projecting the time it takes to "clear" an at risk region by means of an evacuation. Clearing the region in this case means reaching a safe haven beyond the extent of the hazard. For urban systems of any size it may also mean serious traffic congestion and hence delay in the flight to safety. In some instances such delay could lead to loss of life. In others it could indicate that a better chance of survival rests with in situ protective actions, such as sheltering.

Our developing ability to carry out realistic simulations of many interacting traffic streams, and the steadily falling computational expense of doing so, have led to relatively simple evacuation models being replaced by increasingly complex ones. These network-based evacuation and traffic simulation models are the focus of this review. However, the review is not limited to the case of selecting evacuation routes. This step is just one in a series of steps required of the evacuation scenarios building process. The goal of such scenario building exercises is effective pre-event planning for public protection and safety. The challenge is one of realistic replication of a likely evacuation event. The proof of the value of such pre-planning rests in its ability to provide emergency decisionmakers with valid information at the time of crisis. The review emphasizes large scale regional population evacuations, involving one or more urban areas, and emphasizing massive private and public vehicle fleet mobilizations. The review makes no effort to recommend specific software packages. Under the current state of the art this decision will often be determined by the experience of the analyst and by the budget available to do the work.

The review proceeds as follows. Section 2 defines evacuation modeling as a five step process. Sections 3 through 7 describe progress to date under each of these five steps. The major modeling options employed by past regional evacuation studies are listed and described, with frequent reference to specific software packages, as well as to articles and reports found in the open literature. Topics not well covered by past efforts are identified as areas for future research. This is the major purpose of the review: to reveal those areas most in need of development. A number of significant gaps in our knowledge and weaknesses in existing technique are highlighted. The notion of using the results of evacuation modeling studies to contribute significantly to the designation of evacuation planning zone boundaries is put forward in section 7.2 as an area for further exploration. Section 8 considers recent developments in real time traffic monitoring and control and their implications for real time evacuation planning. This recent and ongoing revolution in the technology and economics of communication holds tremendous opportunities for the emergency manager. The transition from models used to predict evacuee response on the basis of limited and difficult to elicit data, to planning models based upon real time monitoring of evacuations as they occur is seen as the single most significant near-to-mid term opportunity for more effective evacuation planning. To be able to control such evacuations, this impending wealth of real time information must be complimented with a better understanding of the behavioral responses of evacuees under a variety of different threat situations. The first developments in real time evacuation monitoring are reported.

Some of these opportunities, if grasped, will remove a good deal of the current skepticism over the validity and appropriateness of network evacuation models. In particular, recent developments in the area of dynamic traffic route assignment, discussed in section 6 of this review, suggest that we might revolutionize the current state-of-the-art in evacuation planning over the course of the coming decade. Section 9 summarizes the review's major conclusions.

2. EVACUATION MODELING AS A FIVE STEP PROCESS

To simulate realistically a major population evacuation, the following information is required:

a. an accurate description of the transportation infrastructure, most notably the highway network.

b. an accurate description of the spatial distribution of population, by time of day and type of activity.

c. an accurate representation of vehicle utilization during an emergency of the type under consideration.

d. an accurate representation of the timing of people's response to the emergency, and how this timing varies by a person's location and current activity at the time he/she finds out about the threat.

e. an accurate representation of evacuee route and destination selection behavior.

f. an accurate representation of any traffic management controls that may be incorporated within the evacuation plan.

g. an accurate representation of any non-evacuation based protective actions (e.g., in situ sheltering) taken by significant population sub-groups within the at risk area.

Today's network evacuation models allow the planner to experiment with a selection of alternative evacuation routes, destinations and evacuee response rates as a means of determining effective evacuation strategies. This process of generating evacuation plans and expected network clearance (evacuation) times currently requires a five step process, involving the creation and calibration of:

- a traffic generation sub-model;
- a traffic departure time (often termed a traffic loading rate or traffic mobilization) sub-model;
- a destination selection sub-model;

- a traffic route selection (often termed a traffic route assignment) sub-model; and

- a user specified plan set-up, analysis and revision procedure.

The traffic generation sub-model addresses requirements a through c as well as requirement g above. The traffic time departure sub-model addresses requirement d. The destination (i.e., shelter) and route selection sub-models, which may be either separate or combined into a single modeling step, address requirement e; and the plan set-up, analysis and revision process addresses the emergency manager's need to experiment with any traffic management controls (e.g., signal timings, route closures) he or she may have access to in a given situation. Each of these modeling steps is now reviewed.

3. TRAFFIC GENERATION: EVACUEE POPULATION ESTIMATES AND OTHER DATA PROBLEMS

Terming the traffic generation step a modeling exercise in evacuation planning is, strictly speaking, incorrect at the present time. In practice, given the importance of the purpose, the number of vehicles to be loaded onto the highway network is derived from a sometimes wide range of survey data. The only modeling typically involved is the translation of number of people into number of vehicles evacuating: a procedure required because data on vehicle availability and use during crises is limited at best.

It is with the different time of day scenarios that data collection becomes a major task. Recent articles by Glickman (1986) and Stern (1990) point out both the considerable discrepancies possible between daytime and nighttime population distributions, and the considerable difficulty involved in obtaining such information. In practice, we have very poor data on the geographic distribution of people during different times of the day: nor has the situation received much in the way of modeling to date.

3.1 DERIVING DAYTIME POPULATION ESTIMATES: AN EXPENSIVE OCCUPATION

The most expensive and time consuming part of an evacuation plan building exercise is often the creation of the daytime vehicle loading rates. For nighttime evacuation planning, Census information on the number of residents by small area (in the United States, by Enumeration District or Census Block, or, for small urban centers by Census Place) can reasonably be used to distribute the vast majority of evacuees across a network's set of traffic origination nodes. In contrast, daytime evacuations require considerably more data collection effort.

Data collection methods involve driving an areas' roads complete with odometer and tape recorder, the latter used to note the location of potentially high traffic generator facilities; use of published data sources, and many telephone calls. Good, up to date maps of an area at risk are especially important. They are often surprisingly hard to come by, and more than one map source is usually required. Nevertheless, maps such as the recent ADC series in the United States for selected, rapidly growing urban areas do provide excellent locational information related to many of the above defined special facilities, as well as good highway network information (ADC Inc., 1989). A recent study by Southworth et al (1990), involving a regional population at risk of more than 350,000 people, lists more than 20 different data sources, and three different map series: including census of population data and projections; state, county and local chamber of commerce estimates of numbers of people employed; school board and archdiocese estimates of both public and private school populations; shopping mall information (typically number of employees and number of parking spaces is all that can be obtained, as retail center management agencies are loath to release their daily traffic counts, if they exist); and regional transportation planning agency population and employment projections.

Because of their different situations and travel needs, notably vehicle availability and subsequent vehicle utilization rates, location specific populations are often further differentiated for both estimation and planning purposes by the following categories:

- at home populations
- at work populations
- at school (including day care) populations
- special facility populations, notably:
    - hospitals, nursing homes and health care centers
    - large institutions of higher education: universities and colleges
    - correctional facilities: prisons
    - large retail centers: shopping malls
    - large transient population centers: hotels
    - parks and recreational centers.

There are two reasons to include a special facility population in the database. First, we might expect a significant number of people to be present during a typical day (workday or weekend). Good examples of this sort of facility are large shopping malls, significant concentrations of hotels, and centers of higher education. Such activity centers may experience severe traffic congestion, even on a typical weekday: and in the case of shopping centers may be prone to long traffic delays during weekends. A second reason for inclusion may be unique problems associated with a rapid evacuation. Hospitals and nursing homes for the sick and elderly may have problems associated with patient movement and vehicle availability; prisons are another example where special attention to vehicle availability and inmate control is required. A recent review of special facility evacuation planning by Vogt (1990) points out the largely anecdotal nature of the information available on how such facilities evacuate, or plan to do so.

Once an estimate of the number of people at work, school, shopping or elsewhere has been obtained, we are then faced with the task of estimating the number of people who remain at home during the daytime. The study by Southworth et al (1990) represents, to the author's knowledge, the first time such a computation has been reported in detail. A procedure for "backing out" the at home daytime population is described. That is, for a given residential population estimate of N_i, assigned to traffic generating node i, we need to compute the average number of people assigned to that node during the daytime, D_i:

$$D_i = H_i + W_i + P_i + S_i \tag{1}$$

where W_i = the number of workers at i, P_i = the number of schoolchildren at i; S_i = the number of people located at special purpose facilities assigned to node i, and where H_i = the number of people at home and assigned to traffic loading node i. H_i is estimated as:

$$H_i = [N_i - (W_i + P_i)] * (1 - s_i) \tag{2}$$

where s_i refers to the probability of non-working adults and infants not in daycare being out of the home and engaged in a special purpose activity such as shopping, personal business, recreational or social pursuits. Working through an example based upon national rates and averages, and combining nationally based data sources found in Davis et al (1989) and the U.S. Bureau of Census, Current Population Reports Series P-25, N0. 1018, we might expect approximately:

46.2% of the population to be at work
18.2% of the population to be at school or day care
35.6% of the population to be at home

during the typical workday, and where the 35.6% representing the potentially "<u>at home</u>" population is further broken down (approximately) as follows:

12.7% = under 5 years old (7.4%) or over 75 years old (5.3%)
22.9% = between 5 and 75 years old

Of these latter, at home driving age adults, some 90% in the United States can be expected to possess a driver's license. This gives 22.9% * 90% = 20.6% (rounded up) of the household population, on average, as neither at work or school, and likely to be able to drive during the day. The above assumptions and values imply (20.6/35.6)= 0.58 drivers per home based evacuee. Now with 2.62

people per U.S. household, on average, we have (2.62*0.356) = 0.93 persons per household at home, on the average, so we get:

(0.93*0.58) = 0.54 licensed drivers at home per household in the daytime, on average.

Obtaining a reasonable value for s_i in equation (2), for a specific study area, is more problematic. Glickman (1986) offers a beginning in this area. Using travel survey data collected by the Metropolitan Washington Council of Governments, Glickman grouped selected census tracts according to whether they were largely (a) commercial (b) residential (c) shopping/entertainment or (d) mixed use. Grouping data into 96 15-minute intervals over the course of a day, the number of people in each of a number of representative census tracts is computed as the number at the start of the day (taken as 4 a.m. to ensure a steady state beginning point) plus the number entering minus the number leaving an area by the end of each time interval. While a full description of the database used was not provided, the results nonetheless provide food for thought. Commercial tracts, as expected, display highly variable population profiles, increasing as workers move from home to office, and falling off as commuters leave at the end of the work day. Residential tracts mirror to a large extent the commercial tract profile, losing workers during the morning and getting them back during the late afternoon/early evening hours. The shopping/entertainment and mixed use tracts reported, notably the former, also show significant variations over the course of a weekday: with a daytime peak of over 50% higher than the census population number for the shopping/entertainment tract.

Glickman demonstrates the potential errors involved in ignoring such wide variations in population presence, and in accepting published census or regional planning agency totals as a realistic representation of the population on hand at the time of a crisis/incident. He employs some basic notions in consequence analysis to demonstrate this point. If a risk profile f(x) represents the probability that the magnitude of the consequence of an event of interest is greater than x (Glickman refers to accidents but we can extend his notion easily to evacuation warnings), then we can say that:

$$f(x) = \sum_t p_t * P(n_t) * \sum_{y>x} P(y/n_t) \tag{3}$$

where p_t is the probability that an accident occurs in time interval t; $P(n_t)$ is the probability distribution of the population n_t in the vicinity (in our case, associated with a specific traffic origination node); and $P(y/n_t)$ is the conditional probability that the consequence has magnitude y, given that the population in the vicinity is n_t. Within the context of an emergency evacuation such a consequence may be

defined as the delay in clearing the vicinity as a result of traffic build-up. This suggests that we will need to run a full evacuation model to compute this value: and to do so for a suitable range of population sizes in order to assess the delay associated with the evacuation event initiated at a specific time of day.
An assumption implicit in practically all past evacuation studies (to have been reported in the open literature) is that the evacuation warning is equally likely to occur in the mid-morning or mid-afternoon, during the lunch period, or during the early evening hours. This seems a reasonable assumption for most evacuation events, and allows us to set $p_t = p$. For a range of empirically derived values of population presence during time period t, $n_i(t)$, $i=1,2,...k$, with relative frequencies given by q_i (and assuming that each of these $n_i(t)$ values is a separate estimate of $E(n_t)$, the expected value of n_t), Glickman suggests replacing (3) above for practical purposes with the formula:

$$f(x) = p * \sum_i q_i * [\sum_{y>x} P(y/n_t)] \tag{4}$$

To be useful, such ideas need to be backed up with reliable data sources. Work is also required to quantify the differences, some of which are clearly significant, between weekday and weekend daily activity profiles as well as between seasonal activity patterns. A good deal of research over the past decade has improved our knowledge of daily activity travel, and as a direct result our knowledge of destination activity patterns and durations (see Jones et al, 1983; Kitamura, 1988). The orientation of this body or work to date has been towards understanding travel patterns and associated constraints on personal mobility. It would be worth trying to translate the empirical information contained is in such work into useful measures of daytime population presence.

A special population sub-category is nighttime workers. While these are generally too few to affect the clearance time estimates generated for large urban or regional evacuations, an important exception may be the presence of a large employer with day-round operations requiring significant numbers of shift workers. Failure to recognize the presence of multiple shifts, such as three shifts per day in a large steel plant, can also lead to significant misrepresentation of daytime worst case scenarios (the worst case coming at shift change time).

Complicating further this problem of estimating population presence in built-up areas is the presence of significant numbers of persons already travelling on the highways during the daytime. Indeed, traffic congestion in most large U.S. cities has begun to spread from clearly defined morning and evening peaks to a much broader daily problem. These on the road volumes may prove important in the case of a rapidly developing emergency, such as a local chemical release. For example, if one out of every three non-working, non-pupil household members happen to be shopping at a large regional mall during the development of a mid-day crisis, the potential is significant for misrepresenting the nature of traffic build-up around homes and retail locations in the area by using the "typical mid-day" situation. If a significant percentage of the population happen to be on the highway at the time of the warning, and if such a warning reaches them via car radio, this may either speed up an evacuation, or slow it down if many of these drivers attempt to return home or elsewhere to collect family members.

Data on the typical daily traffic volumes of most major roads can be obtained in the United States from state or locally collected traffic counts. This allows us to approximate the initial on-the-road conditions under which a particular evacuation might be initiated. It helps us only a little in the distribution of the daytime population. Where these travellers come from and are going presents a more difficult question to answer: especially if a significant percentage are from outside the study area, or are simply passing through it. The best we can currently do with this information is to estimate the implied proportion of the area's at large population to be on the highway during a particular hour of the day, and perhaps assign some percentage of these travellers to non-workers and workers engaged in travel as part of their business day. The most widely available form of this information is the Average Annual Daily Traffic (AADT) count: the average number of vehicles passing a count site over a 24 hour period. Regional transportation planning agencies often also collect and publish data on the temporal peaking of this daily traffic movement, often broken down by highway class and location. It is then a fuzzy process to translate such information into the area's mid-morning, mid-day or early evening population.

Given such uncertainty in the daytime whereabouts of people, three conclusions may be drawn. First, we need to put much more effort into collecting data on the range of urban population distributions between the hours of 6 a.m. and 10 p.m. Second, realizing that such data collection efforts are expensive, we need to develop cost effective modeling procedures to alleviate this burden somewhat from subsequent studies. For better or worse, large shopping centers, health care complexes and recreational centers across the country display very similar built environments and as a result similar traffic attraction/generation characteristics. We ought to be able to make something of these similarities once an appropriate modeling approach has been developed. Third, we must realize that the population distribution at the time of crisis will be one from a potentially wide range of daytime scenarios. This means recognizing and generating a representative range of conditions during the development of regional evacuation plans. The usual approach to date has been to generate "worst case" and "average" scenarios: based on nighttime or rather vaguely defined daytime conditions; upon good versus bad weather conditions (notably by adapting the speed-flow relationships on the network database links to reflect slower moving traffic); and upon different rates of evacuee response and vehicle utilization. The greatest weakness in this approach to date is the quality of information on location specific daytime population presence.

3.2. ESTIMATING VEHICLE OCCUPANCIES/VEHICLE UTILIZATION RATES

The number of evacuees needs to be translated into the numbers of evacuating vehicles for the purposes of estimating area clearance rates and assessing the potential for traffic delays. There is very little published literature on the derivation of vehicle utilization rates during emergency evacuations: or for that matter during many of the daily activities we undertake, other than commuting and vacation travel. In particular, data is limited for non-working and at-home daytime residents. We are currently therefore left to rely on one of three, none of them entirely satisfactory, approaches:

- the results of post-evacuation surveys;
- the results of evacuee intent surveys (i.e., people are asked what they think they would do under a set of hypothetical circumstances);
- judgement, based upon information on commute vehicle occupancies, household size and vehicle ownership data, and upon calculations of feasible upper bounds on vehicle utilization.

Only a handful of past papers report the results of post-evacuation surveys covering only a small range of possible emergency situations and geographic locations. Baker (1979, 1987) reports 75% vehicle utilization rates from a series of post hurricane evacuation surveys, while a 52% vehicle utilization rate was reported in post evacuation surveys associated with the Mount St. Helens eruptions (Perry and Greene, 1983). This latter case represents 1.3 used vehicles per household, among a population where over 80% of households apparently had two vehicles available.

The different rates of vehicle utilization we can expect from nighttime versus daytime evacuations is not currently well understood, except that we should typically expect higher use rates during the workday for multi-car urban families separated at the time of the event. Rogers et al (1990, Chapter 5) report the use of values in the range 2.0 to 2.5 persons per vehicle in past evacuation studies, based primarily on estimates derived from evacuation intent surveys. They note however, that "very limited behavioral data exists to support this assumption."

Given this lack of direct information, Southworth et al (1990) adopt the third approach listed above. For nighttime evacuations, a lower bound on vehicle use is to assume one vehicle per household. At approximately 2.62 persons per household on average (in the United States), this equals 0.38 vehicles per evacuee. For commuters involved in daytime evacuations, a good approximation, this time an upper bound, can usually be obtained from the county or regional transportation planning agency. Typical commute vehicle occupancies in the United States fall within the quite narrow range of 1.2 to 1.3 persons per vehicle where public transit is largely absent.

The biggest challenge is to approximate the number of vehicles in use by daytime residents. Noting that there are two possible constraints on the number of home based vehicles used during an evacuation: the number of vehicles left at home, and the number of licensed drivers among the non-work, non-school population, Southworth et al (1990) make use of generally available planning data to carry out computations of the following kind:

Let V_{ih} = the total available personal vehicle fleet at (residence) node i minus any vehicles used in the commute. This is approximated as:

$$V_{ih} = V_i - V_{iw} \tag{5}$$

where V_i = total vehicles available at i; and V_{iw} = vehicles available at i, and used in the commute. To obtain V_{ih} estimates, it was necessary to break down the elements in (5) as follows:

$$V_{ih} = (H_i * v_H) - (N_{iw} / v_W) \tag{6}$$

where H_i = the number of households attached to trip origination node i; v_H = the average number of vehicles per household in the region; N_{iw} = the average number of workers per household at node i multiplied by N_i, the resident population at node i; and v_W = the average commute vehicle occupancy rate. Noting that there are, on average, 1.03 vehicles per licensed driver in the United States, that the average household contains 1.25 workers and owns 1.87 private use vehicles (see Davis et al, 1989), and assuming 1.25 commuters per vehicle, gives approximately 1 vehicle per household used in the work trip (i.e., 1.25 workers per household/1.25 workers per commute vehicle): leaving approximately 0.87 vehicles available, on average, to non-working household members. Ignoring vehicles used by older school age students as being typically a very small percentage of the total fleet, making more use of the data on the distribution of vehicle ownership rates among U.S. households (i.e., the percentage owning 0,1, 2, or 3+ vehicles) and again using nationally averaged values, Southworth et al (1990) bring this upper bound down to 0.79 vehicles available per household during the daytime.

Recalling the procedure described in section 3.1 above for estimating the number of available, at home licensed drivers (approximately 0.54 per household), driver availability is, in the U.S. as a whole, still slightly more constraining than vehicle availability. Of course, this result may reverse itself within a specific location. Such calculations do however suggest a reasonable lower bound on the average home based vehicle occupancy rate of close to (1/0.54) = 1.85 daytime evacuees per vehicle. Recognizing that such calculations do not take into account a number of important factors, such as the true cross-product effects of the distribution of vehicle ownership by household size, the spatial separation of driver and vehicle at the time of the event (especially if a rapidly developing one), or an unknown percentage of vehicles currently out of order, suggests an "average worst case" (lower bound) at home based vehicle occupancy rate of 1.8 persons per daytime evacuating vehicle.

Unfortunately, none of the above methods or past empirical evidence help us to deal with significant differences in vehicle ownership levels which may exist across urban locations (see Sinuany-Stern and Stern, 1989). The same is true for significant amounts of public transit use: creating a potentially very difficult situation for downtown commuters, while freeing up more vehicles for use in residential evacuation zones. Such instances need to be identified and dealt with on a case by case basis. The same is unfortunately true of vehicle utilization by special purpose activity centers: such as hospitals, schools, universities, prisons, and (on weekends) churches. The evacuation modeler must often rely on assumptions that vehicle fleets assigned to these institutions (e.g., school buses, ambulances) will be used. This presupposes that staff at such institutions, as well as parents and other relatives, follow a pre-specified and sensible evacuation process. To date, the literature on this subject is largely anecdotal.

In an initial effort to rectify this situation, Vogt (1990) engaged recently in an extensive data collection exercise based around (i) articles describing evacuations, (ii) supporting community information data and (iii) follow on telephone interviews of staff in selected hospitals, nursing homes, educational institutions and correctional facilities. Building on a conceptual framework developed by Quarantelli (1980), Vogt calibrates a multiple regression model against 40 observations, obtaining a statistical relationship between time required to evacuate a nursing home and whether the threat was weather related or not, the number of external sources of help available (off-duty staff, volunteers, local and non-local emergency services), and the population density in the vicinity of the facility. The results were, however, somewhat unusual (as the author points out), if noteworthy for the first attempt to quantify what remains a little evaluated process.

While such research is geared towards single facility evacuations, regional evacuations from one perspective are built up from the evacuation of large numbers of not only residences but from many large as well as small workplaces and a wide range of special facilities. Under marginally acceptable network clearance times caused by high levels of traffic congestion, concentrations of special facilities may determine the acceptability of an evacuation plan.

To summarize, proper understanding of vehicle utilization, in particular utilization during the daytime hours, requires much better data than we currently possess, or innovative methods to make use of the diverse sources of information available. A household based model of daytime activity profiles would be a most welcome addition to the literature, as would further empirical evidence on such activity patterns and associated vehicle utilization rates.

4. EVACUEE MOBILIZATION RATES: MODELING THE TIMING OF TRIP DEPARTURES

The timing of evacuee response to a crisis can have a significant effect on the level of traffic congestion experienced during the flight to safety. In practice, we can expect that some people will leave an area when asked to do so, others will delay their decision until they gain more confidence in the official instructions, and others are likely to remain behind either as a residual at risk population, or until forced to move.

Four different approaches currently exist for approximating what has been variously called the traffic loading curve or evacuee mobilization time curve:

- Approximations based upon past empirical evidence (i.e., post evacuation surveys), for similar types of evacuation;
- Approximations based upon surveys of the stated intentions of potential evacuees;
- Approximations based upon planner judgement and conceptualizations of human response to an emergency;
- Approximations based upon simulation of the diffusion of emergency warning system messages (sirens, loud speakers, television and radio) and the subsequent spread of information (by word of mouth, telephone) within the community at risk.

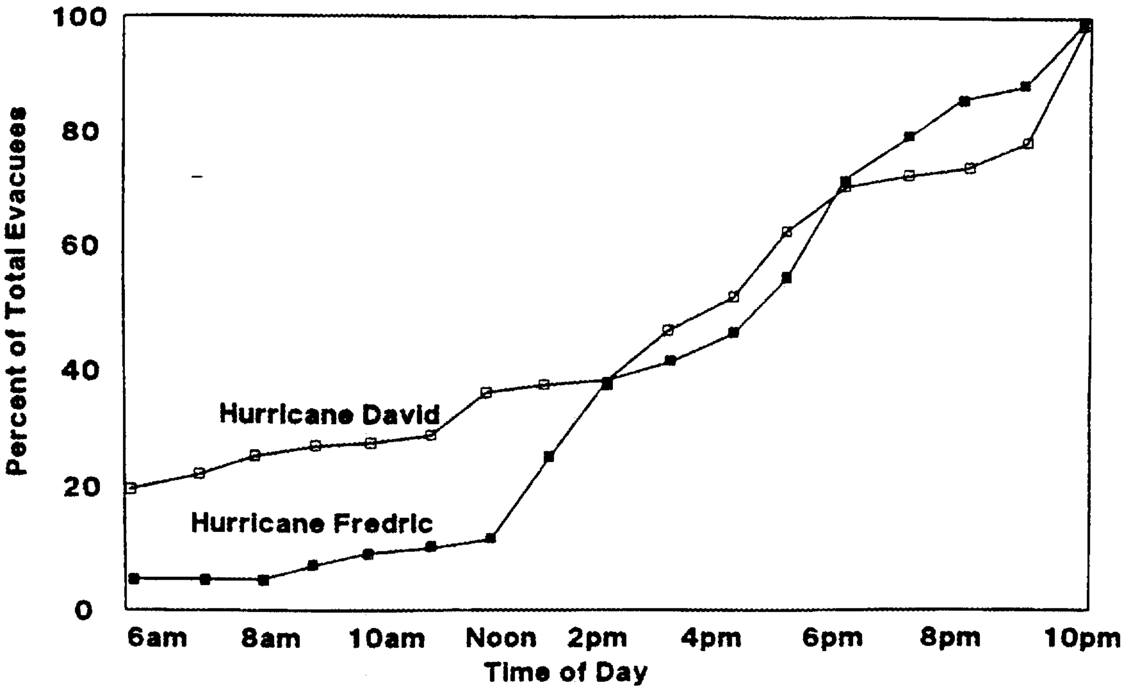
The empirical study of public evacuation and response to emergency warning has an extensive literature, now spanning several decades (see Sorensen, Vogt and Mileti, 1987; and the annotated guide to research produced by Vogt and Sorensen, 1987). However, until quite recently, as Sorensen and Mileti (1988) point out, relatively few of these studies have provided concrete evidence on just when, where, and in total how many people will choose to evacuate during a particular type of crisis.

Although evidence from a number of chemical accident, flood and hurricane related evacuations have been published (see Baker, 1979; Sorensen and Mileti, 1988; Rogers and Sorensen, 1989; Rogers et al, 1990), such data was either not originally collected or reported with an eye to its subsequent use within detailed network routing and destination planning models: or the information was simply not available in any statistically reliable form at the level of spatial resolution required. Figure 1 shows a selection of traffic mobilization curves, based upon post evacuee survey data. In general, current information is sparse, limited in sample size and covers only a limited range of emergency types and situations. In particular, the spatial representation of such response rates, when translated into numbers of evacuating vehicles loading onto a highway network, is currently the weakest link within the evacuation modeling process.

Much of the mystery surrounding the effects of evacuee warning response rates, as they translate into traffic loading rates, could be removed by the presence of suitably located in-the-highway traffic counters, to track the temporal build-up of traffic on the system during an urban evacuation. Such information is certainly preferable (in this author's view) to that derived from (necessarily limited size) post evacuation surveys, or from surveys of evacuation intentions. The possibilities for collecting such data, and in real time, are discussed in section 8 of this review. However, even if or when such data becomes available, a sound behavioral basis for generating evacuee mobilization rates will still be required. Not all urban areas will have such counter systems in place, and in the right places, in the foreseeable future. Given the complexity of the process involved, sound behavioral models indicating the likely directions of divergence between a situation specific evacuee response and the past empirical evidence will still be required.

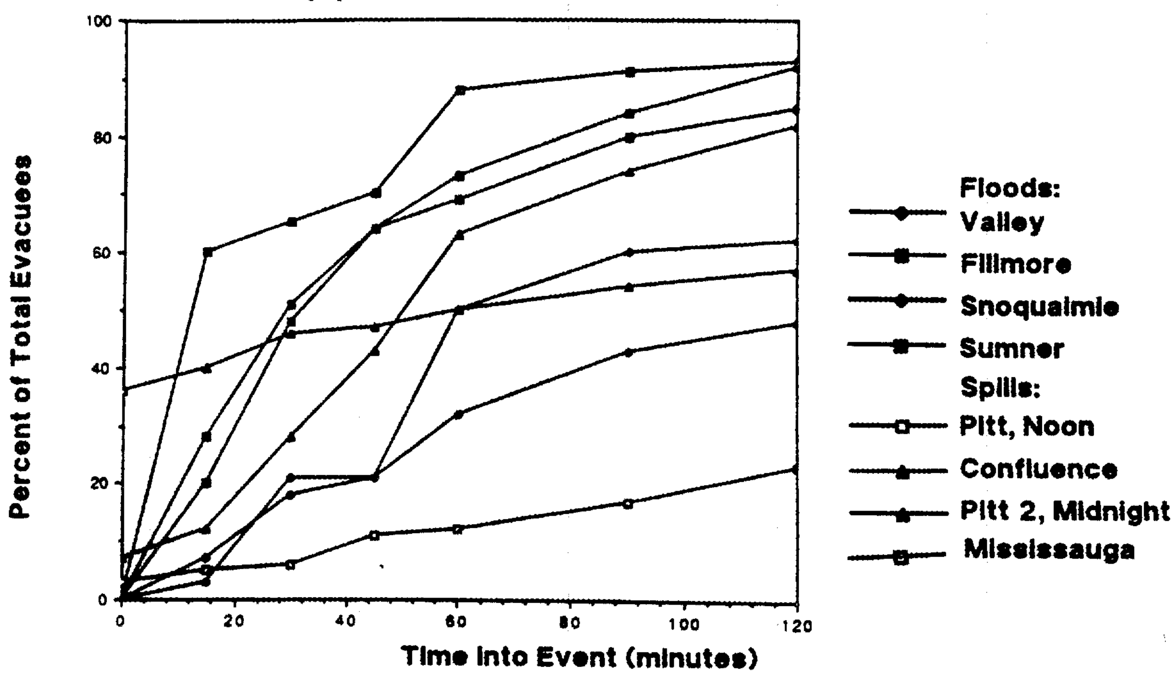
The second approach listed above, that of using the stated intentions of potential evacuees, has been of particular interest to analysts of radiological hazards (see Johnson, 1985; Johnson and Ziegler, 1986; Stern and Sinuany-Stern, 1989). Given the rarity of such events as the Three Mile Island scare and the Chernobyl incident, recourse to this approach is understandable. However, the approach suffers from the usual problems associated with discrepancies between what people say they will do during hypothetical situations and what in fact they actually do, when confronted with the reality of the situation.

Given the problems associated with using either existing empirical data or stated intentions, some evacuation studies have chosen to rely upon planner judgement. Just as a number of past studies have asked potential evacuees to describe how they believe they would respond to a particular type of emergency, so Sorensen et al (1988) asked emergency managers from communities around the United States to characterize the number of contacts they would make under certain emergency conditions. Tweedie et al (1986) used experts within the state Civil Defense Office to generate a mobilization curve based upon the Rayleigh probability distribution function, of the form:



Source: Leik, R.K. et al (1981) Community Repsonse to Natural Hazard Warnings: Final Report, University of Minnesota, Minneapolis, MN.

(a) Hurricane Mobilization Times.



Source: Rogers, G.O., et al. (1990). Evaluating Protective Actions for Chemical Agent Emergencies. ORNL-6615.

(b) Chemical Spill and Flash Flood Mobilization Times.

Figure 1. Mobilization Times in Selected Events.

$$F_t = 1 - \exp(-t^2/T) \tag{7}$$

where F_t is the percentage of the population mobilized by time t, and T is a parameter the analyst can adjust, to control both the slope of the traffic loading curve and also the maximum time at which all evacuees are assumed to have mobilized.

The most popular form of traffic loading curve has been the logistic. For example, Radwan et al (1986) incorporated the following within their MASSVAC code:

$$P_t = 1/[1 + \exp -a(t-b)] \tag{8}$$

where P_t = the cumulative percentage of total traffic volume to be evacuated at time t into the emergency (either for the region as a whole, or from a specific traffic generating node); *a, b* = model parameters to be calibrated: *a* gives the slope of the cumulative traffic loading curve, and *b* is a 'loading time factor' selected to locate the midpoint of the logistic curve. Rearranging (7) and setting $d = \exp(a.b)$ we have (Southworth and Chin, 1987):

$$P_t = 1/[1 + d(\exp(a.t))] \tag{9}$$

which at time t = 0 gives:

$$d = (1-P_0) \;/\; P_0 \tag{10}$$

which is the proportion of vehicles not yet loaded (mobilized) to those already on the network at the start of the evacuation. Taking this start time to be the time at which an official call goes out to mobilize, equation (10) provides an easy to compute expression for the number of "spontaneous" or unofficial evacuees, a number of considerable interest to evacuation planners where hazards such as hurricanes are concerned (see Southworth, Chin and Cheng, 1989, 1990, and the discussion in section 8 below).

In recent years the idea of simulating emergency warning and response as a diffusion process has received some attention. Proper application, however, requires the treatment of public warning and response as a potentially complex, multi-step process. Urbanik et al (1980) define "evacuation time" as the interval of time from the detection of an incident which ultimately requires evacuation to the end of the period required for individuals to physically move out of the area at risk. They separate evacuation time into four components: (i) decision time, defined as the time between incidence detection and an official decision to order an evacuation; (ii) notification time, defined as the time required to notify all individuals in the area at risk of such an evacuation order; (iii) preparation time, defined as the time required for individuals to prepare to evacuate the specified area; and (iv) response time, defined as the time required for individuals to physically travel to safety. The last component response time, is often also referred to as clearance time: the time taken by individuals to travel over the transportation network to a suitably safe location, usually outside an officially designated evacuation planning zone (see Section 7 below). The clearance time curves described later in this report refer to the cumulative percentage of evacuees passing across such a zonal boundary. Simulation of an evacuation event requires simulation of at least each of these four processes.

In a recent state-of-the-art review of public communication systems' use and response during emergencies, Mileti and Sorensen (1990) assess information gleaned from over 200 emergency events. They conclude that not only the method of transmittal but also the content of the message has a significant impact upon whether or not the public heeds the warning: and hence we can conclude that such communication is an important factor in subsequent mobilization response time. How quickly a public warning message is then passed on from evacuee to evacuee has also become an area of some concern. In countries where automobile ownership and hence availability are less than universal, and in areas where there are significant numbers of apartment as well as single home dwelling units, message diffusion might also be expected to differ noticeably. Stern and Sinuany-Stern (1989) propose modelling such characteristics through a form of decision tree analysis, using a household head's expected location, the presence of a TV/radio and whether on or not, and the type of dwelling unit to generate and cumulate a series of discrete response times at each stage in the tree-building process.

Rogers (1988) argues that this process of warning communication is further complicated by being not simply a sequential, but in practice a cyclical information acquisition, updating, transfer and response process. In the case of a rapidly changing threat or threat perception (as may occur during some hurricane warning periods), evacuees may go through more than one period of threat (re)-assessment. Indeed, in instances where significant uncertainty over the magnitude of an emergency exists (such as the repeated threat of landfall associated with Hurricane Elena in the Gulf of Mexico in August of 1985), more than a single evacuation event may take place. The spatial and temporal diffusion of information depends upon such factors as the perceived seriousness of and distance from the threat, the perceived danger of leaving the home or other current location, the time of day of the warning, the nature of the public warning systems used, and the family and socio-economic background of community members. In some cases noticeable levels of "spontaneous" evacuation may occur prior to official notification of the threat.

A topic much in need of further evaluation is the response of spatially separated family members: a highly probable situation should daytime evacuations be required at times when workers, non-workers and their school age children are each found at separate locations. Very little concrete evidence appears to be available on how people react in such situations. Stern (1989) offers some evidence on the intended behavior of parents under threat from a hypothetical radiological (nuclear generating facility) emergency. His results suggest that two-thirds of parents would choose to evacuate their children, either by taking them back home or out of the danger zone, rather than rely upon school authorities to do so. While unlikely to be generalizable to other emergency scenarios or events, this sort of result certainly points out the need to consider the impacts on traffic flow of such non-organized and possibly highly disruptive, non-channelized travel during an evacuation event.

Some theoretical support for application of a logistic, or at least for a general form of S-shaped traffic loading curve, in the absence of specifically applicable information, is provided by the work of Rogers and Nehnevajsa (1987). Pointing out that the diffusion of emergency warnings resembles diffusion of other types of information or communications, but within a shorter time period, they argue for an exponential form for the initial alerting process and a logistic form for the subsequent contagion or spread of the warning message through the population. The general mathematical form of the diffusion curve is:

$$dn/dt = k[a_1(N-n)] + (1-k)[a_2(N-n)] \tag{11}$$

where k is the proportion of the population alerted to the emergency via the broadcast process and who recognize the meaning of the signal, and (1-k) is the proportion of the population still to receive and recognize the nature of the warning at the t. The broadcast parameter, a_1, summarizes the efficiency of the warning process, while the parameter a_2 summarizes the efficiency of the subsequent information contagion process. N is the size of the population to be warned and n is the proportion of the population warned at the beginning of each time period (t_0, t_1,...t_i,..).

A search for appropriate values for the parameters k, a_1 and a_2 in equation (11) is reported by Rogers and Sorensen (1988). They use equation (11) and available empirical information to generate a series of warning diffusion curves by type of warning system (sirens and alarms; tone-alert radios; auto-dial telephones; use of the Emergency Broadcast System combined with media coverage; and selected combined systems). They also provide a discussion and preliminary estimates of population penetration levels by type of message transmittal system, adjusted to account for the location and activity of potential evacuees at the time the warning is transmitted. Each warning system is assigned a different penetration level according to five "fundamental locations/activities": home asleep; indoors at home or in the neighborhood; outdoors in the neighborhood; in transit (travelling between activities); and working or shopping. Figure 2, based on Rogers and Sorensen (1988), indicates the relative efficiencies expected from these different types of warning systems. Recent work at Oak Ridge National Laboratory has incorporated these findings within PAECE (Protective Action Evaluator for Chemical Emergencies: Rogers and Sharp, 1990), a package of PC-based computer programs developed to simulate an emergency response to airborne release of chemical agents under different warning systems and meteorological conditions.

These are very welcome and much needed developments. A much closer behavioral linkage between the timing of evacuee mobilization and the rest of the evacuation simulation exercise is certainly required. In sensitivity tests carried out by the author using each of the major types of traffic destination and route selection models reviewed in sections 5 and 6 below, and over a range of highway networks, the traffic loading rates and the spatial pattern of variability in such rates were found to be major determinants of the resulting network evacuation times. Nor is the situation always a straightforward one. In some instances, given sufficient traffic build-up and network complexity, traffic mobilization patterns based upon heavily weighing early response rates can generate traffic bottlenecks which more

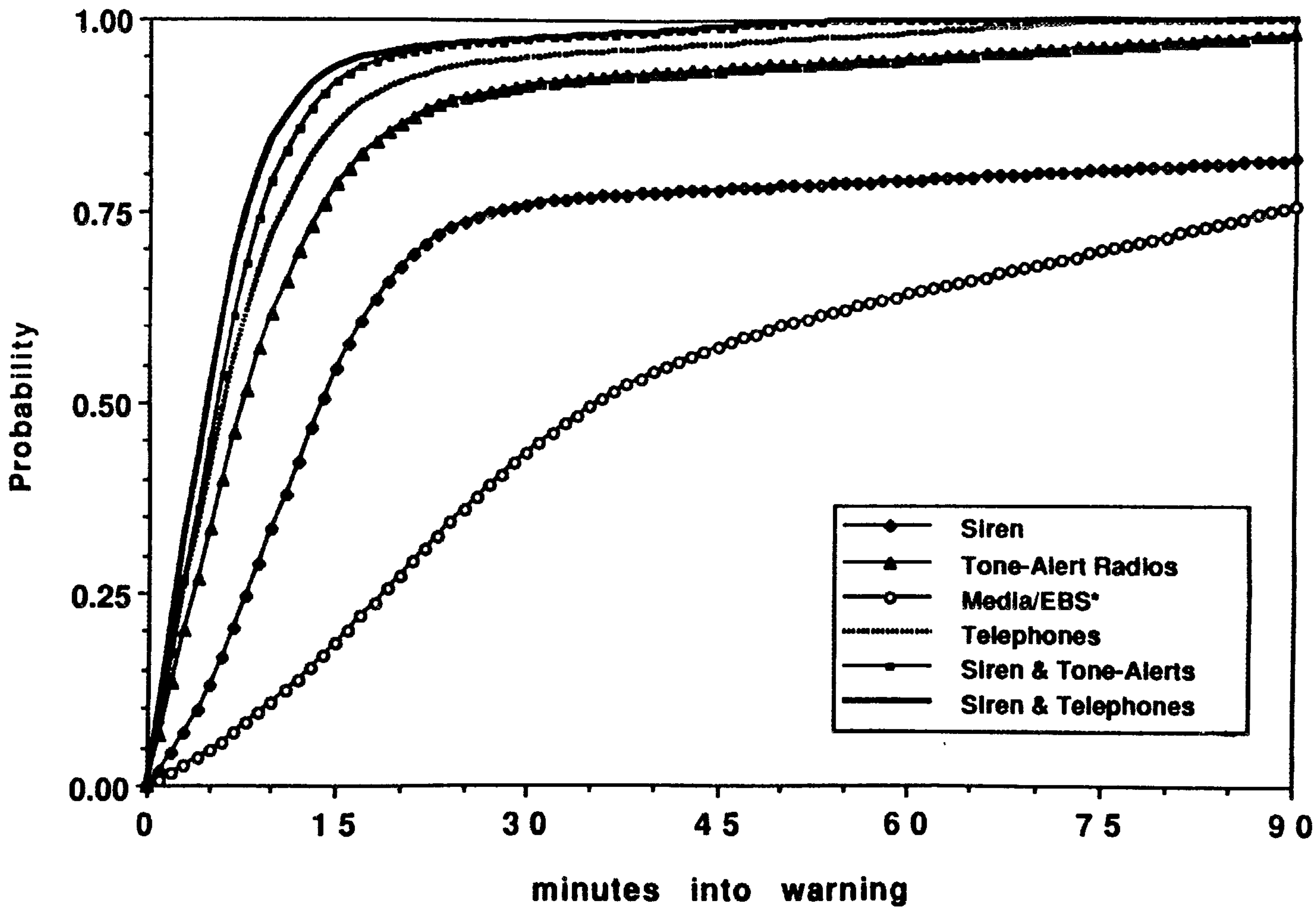


Figure 2. **Probability of receiving warning by warning system by time elapsed since warning decision.** *Source*: G. O. Rogers and J. H. Sorensen, "Diffusion of Emergency Warning," *The Environmental Professional*, Vol. 10, p. 281–94, 1988. *Emergency Broadcast System.

evenly loaded traffic flow conditions might be able to avoid. In other instances, as rapid a flight as possible may be the best answer for the at risk population as a whole.

Seen from the perspective of generating effective evacuation plans, the search for the optimal evacuee mobilization rate(s) for a given network of any size proves quite difficult. Indeed, the problem appears to be a spatially and temporally idiographic one. Failure to properly represent location specific evacuee mobilization rates could lead to potentially serious misrepresentation of subsequent traffic delays. The obvious first step towards this integration expresses itself within a number of the evacuation modeling codes referenced below through the inclusion of separate traffic mobilization curves according to the location of a specific (or specific sub-set of) trip origination nodes. That is, an operational linkage between temporally and spatially varying evacuee response rates and their subsequent use within destination and route selection models is relatively easy to implement. It is on the behavioral basis for adopting such mobilization rates, and on the effects such rates could have upon the development of effective evacuation route and destination planning that future research efforts need to be focussed.

5. DESTINATION SELECTION PROCEDURES

The choice of a destination to head for under threat to life or property tends to be modelled in one of four ways:

- evacuees are assumed to exit the at-risk area by heading for the closest destination (in terms of distance and/or expected travel time);
- evacuees will display some degree of dispersion in their selection of area exit points, depending upon such factors as the location of friends and relatives and the speed of the hazard on-set;
- evacuees will head for pre-specified destinations, according to an established evacuation plan;
- evacuees will exit the area on the basis of traffic conditions on the network at the time they try to leave the area.

In small urban system or rural evacuations, the first assumption may be a good one, although in general some spatial dispersion in destinations should be expected: in cases where the hazard is not approaching rapidly, and where evacuees may have relatives or simply better hopes of overnight shelter elsewhere. Option three is often used by the modeler to assess the system's response to an experimental traffic routing plan. Well publicized (if rarely practiced) evacuation routing plans now exist for a number of large cities within the United States. The Tampa Bay-St. Petersburg conurbation on Florida's Gulf Coast, for example, publishes a newspaper showing residents how to evacuate in case of hurricanes, on the basis of community location. Evacuees in clearly identified communities will be directed to a specific exit, or sub-set of exits from the area at risk. With a good plan in place supplemented by on-the-highway policing of traffic flow, this third option may provide the best method of evacuation. The fourth modeling option allows for the expression of myopic evacuee behavior. Since most traffic delay occurs at major intersections the channelization of flow is often the best evacuation option. It subsumes destination choice under evacuation route choice. The idea is that if evacuees see considerable traffic build-ups ahead of them, a significant proportion may detour, and end up exiting the area at a point other than their intended destination. This sort of assumption and the techniques required to represent it are discussed in section 6 below, under traffic route selection.

The most common and at the same time most readily adaptable expression of destination selection is some form of spatial interaction model. Such models have the general form:

$$T_{ij} = N_i * p_{ij} \tag{12}$$

where T_{ij} = the number of evacuees traveling from origination node i to shelter j; N_i = the number of evacuees located at i; and p_{ij} = the probability of travelling from i to j, given as:

$$p_{ij} = W_j * f(c_{ij}) \; / \; \sum_j W_j * f(c_{ij}) \tag{13}$$

for W_j = a measure of the attraction potential, or desirability of sheltering (or simply exiting the at risk area) at location j; and $f(c_{ij})$ = a function of the travel time associated with travelling from i to j.

Equations (12) and (13) represent a "production constrained" spatial interaction model (Wilson, 1970), in that all evacuees at each origination point i, N_i, are accounted for, while destinations receive trips in relation to their relative attractiveness to evacuees. The W_j terms may themselves represent composite indices of specific relevance to the type of evacuation taking place. Planning for overnight evacuations might include number of beds in such an index. Chemically related incidents might require number of medical staff on hand to be known. Sorensen and Mileti (1989) provide some much needed data, showing the percentages moving to relatives, friends and to official shelter by selected evacuations.

The most common functional form for $f(c_{ij})$ is the negative exponential, or $\exp(-a.c_{ij})$, for a suitably calibrated travel time-decay parameter, a. Two problems immediately present themselves, however. First, there is typically little or no evidence available upon which to base the value of a. Second, the values for c_{ij} are themselves a function of not only the destination chosen, but also of the routes selected: and these route specific travel times are in turn a function of the number of evacuees selecting specific destinations. Both of these problems have been well studied and reported on in the transportation planning and geography literature. They need to be solved each time a regional planning agency wishes to replicate its expected daily journey to work trip flows. For the case of rarely enacted regional evacuations, however, there is little behavioral evidence for selecting values of a, short of the general concept of Newtonian gravity (i.e. $f(c_{ij}) = c_{ij}^2$).

By setting the distance-decay parameter, a, to a very large value the spatial interactions implied by equations (12) and (13) will direct evacuees to the nearest destinations, by making trips extremely sensitive to extra travel. A useful procedure when applying the models is to begin with a high value for a, and reduce it to a "guesstimate" by varying it in conjunction with the calibration of other model parameters, notably those related to trip departure rates, in an effort to derive the most effective evacuation scenario. In such a procedure lies part of both the art and the danger associated with the derivation of network evacuation plans. Use of the process to generate most likely network clearance times remains suspect. When coupled with the procedures described above for allocating daytime populations over space and time, this model calibration process strongly determines the resulting network clearance times, and hence potentially the recommendations of whether or not to evacuate an area under certain hazardous situations.

6. EVACUATION ROUTE SELECTION PROCEDURES

6.1 INTRODUCTION

Route selection models are used to approximate the movement of evacuees over a transportation network, over time. They are also the basic tool around which to develop plans for the use of road space during an emergency. The objective is to get a good estimate of just how long it will take a population to clear an at risk area, and which highways and (where applicable) which rail or bus transit routes to use. Based on the time it takes to "clear" all of the population from an area, it may be considered prudent either to begin evacuation as early as possible, to stagger the timing of community mobilizations, or in cases where severe traffic congestion would prevent escape, to suggest other forms of protective action.

The theory and application of route choice models has been around now for four decades (see for example, Wardrop, 1952; Wachs 1967; Tagliacozzo and Frizio, 1973; Vaziri and Lam, 1983; Sheffi, 1984). With the advent of real time traffic data systems, route choice modeling has become an increasingly important aspect of the transportation planning process in most developing countries (Mahmassani, Chang and Herman, 1986; Shimazaki and Matsumoto, 1989; Tzeng, Shieh and Shiau, 1989; Stern and Bovy, 1989). With little reliable and (equally importantly) generalizable information available from actual evacuations, currently we are forced to rely upon this literature and upon the literature on evacuee intentions during crisis situations. While route selection is dependent upon a number of driver and situation specific characteristics, the most important question to be resolved by the modeler is the level of myopia versus pre-planning drivers put into their route selection process. In general, and taken over a significantly large driving population, we must assume that some combination of these two traits will manifest itself. We might expect a higher degree of myopic decision-making under rapidly developing and proximal hazards, versus a more considered assessment of where to head for as well as how to get there under less stressful conditions. Past and present evacuation route selection models have adopted a range of assumptions. These can be classified under the following four options:

- myopic route selection behavior, dictated by traffic conditions at each intersection;
- system optimal or user optimal route selection behavior;

- combined myopic plus user (typically, analyst imputed) route preference behavior;

- routing according to an established (and controllable) evacuation plan.

There is now a selection of public domain as well as commercially available network based evacuation models available to the emergency planner. Table 1 lists a number of the better known and documented network models currently available. The majority include recognition of mobilization time and destination selection as well as route choice, and each produces estimates of the time required to clear the area, as well as a geographic and temporal representation of traffic build-ups on specific highway sections and intersections. A number of the codes allow the analyst to experiment with a range of route selection behavior, from myopic to pre-selected. This can be done either by allowing the analyst to control route selections through detailed adjustments to the green time or turning movement options at highway intersections (for which DYNEV provides the most elaborate set options) or more directly, by using analyst generated route preference functions in combination with intersection control logic, as in NETVAC, MASSVAC, and EVACD.

While approaches have tended to merge somewhat over recent years, two different styles of route selection-cum-route planning model have led to the current set of available computer codes. The first style has evolved from the traffic engineering literature and is based upon detailed simulation, either of individual vehicle movements ("micro-simulation") or of the movements of limited numbers of vehicles forming part of a traffic stream or "platoon" ("meso-simulation"), coupled to relatively simple evacuee route selection logic. The second style of modeling, termed "dynamic traffic assignment," pays more attention to the route selection process. Also in the general sense a form of simulation, it relies upon a more aggregate representation of traffic as a series of flows, while attempting to match this demand for road space to the capacity of the highway system's links and intersections. This is termed "macro" simulation in Table 1.

Each approach requires some form of bookkeeping in order to track the transfer of vehicles from one time period to another throughout the network. Unlike traditional transportation planning applications, traffic loading and hence congestion must be modelled as a truly dynamic process where large urban evacuations are concerned.

6.2 MICRO- AND MESO-SCOPIC TRAFFIC SIMULATION MODELS

Evacuation models based upon detailed simulations of individual vehicle movements tend to focus their attention on the delays associated with highway intersections: whether signalized, lane controlled or otherwise. Most traffic congestion is initiated at such points of confluence. Route selection logic tends to be simple (see Table 1) in the sense that either (i) drivers are assumed to myopically occupy the least congested link beyond the current intersection; or (ii) restricted, as a result of planner judgement removing or controlling the flow through all but a limited number of routing options. Unless tied to more rigorous and general route selection logic, they are unlikely to be appropriate for larger urban systems applications. To date, they have been used in either geographically limited urban network studies, or in relatively small urban and urban-rural area studies.

Table 1. Characteristics of Selected Evacuation Models.

Model	Type of Traffic Stream Simulation:			Type of Traffic Route Assignment:		
	Micro	Meso	Macro	Simple	Static	Dynamic
CLEAR	X			X		
DYNEV		X			X	
DYMOD			X			X
EVACD			X			X
MASSVAC			X			X
NETVAC			X			X
NETSIM*	X			X		
SNEM	X			X		
TWEEDIE ET AL.	X			X		
UTPS-BASED**			X		X	

* NETSIM is a micro-traffic simulation program not a full evacuation model.
** UTPS is a transportation planning package, not an evacuation modeling package.

Among the earliest simulation models to be used for evacuation planning was the NETSIM model (for example, by Peat, Marwick, Mitchell and Company, 1973). NETSIM (see Rathi and Santiago, 1989, for latest developments) can be used to simulate in great detail and to keep a full account of the movement of individual vehicles within quite complex urban networks. Until the recent advances in microcomputer and workstation processing speeds, however, NETSIM was rather time consuming (and still is for networks with over 100 intersections). In part in response to this, and also because at very high traffic volumes (as well as at low ones) detailed traffic intersection logic may not offer any noticeable advantages over less elaborately devised network delay formulas, less elaborate simulation codes have been devised. These include the nuclear power plant evacuation model CLEAR (Moeller et al, 1981) and those developed more recently by Tweedie et al (1986), and SNEM (SLAM Network Evacuation Model) by Sinuany-Stern and Stern (1990). Each use a simple, "common sense" route selection process upon which to carry out their detailed micro-simulations, and each employs a number of simplifying assumptions to reduce the size of the network to be processed. They are applicable to relatively small scale evacuations only.

For example, Tweedie et al (1986) describe a probabilistic evacuation model for application to small scale (10 mile radius area, worst case 4510 vehicle) evacuations. The methodology was designed to follow U.S. Nuclear Regulatory Commission guidelines, and they describe its application to a licensing study for a proposed nuclear power plant at Black Fox Station, Oklahoma. The most likely sub-set of regional evacuation routes are pre-selected, further reducing the computational burden. Individual vehicles movements are modeled only on the primary road network. To reduce the burden of analyzing extensive local road patterns these travel times are estimated just once. Vehicles are arranged at local-to-primary road entry nodes in ascending order of their mobilization time plus local road travel time. Evacuation time is divided into three components: mobilization time (TM), travel time on local roads (TLT), and travel along the primary road network (TPT). The total evacuation time for a given vehicle is given as:

$$TTOT = TM + TLT + TPT \tag{14}$$

Detailed traffic flow is simulated only at the primary network level: a procedure often followed in practice even within the more elaborate modeling codes, in order to keep down the size of the networks to be analyzed.

Alternate traffic loading and traffic flowing computations take place, with vehicle loading onto the primary network taking place at discretized time intervals (results using one minute traffic loading intervals are described). Queues form at entry nodes if a primary link is already at capacity. These simplifications make the model not only easy to implement but also speed up its computations, allowing repeat d Monte Carlo simulations of the evacuation to be made from which average network clearance time estimates can be obtained. Twenty-five such simulations, or "trials," were considered sufficient to obtain an accurate picture of likely traffic flows by the authors.

The CLEAR model makes similar simplifying assumptions, dividing an at risk area up into a number of sectors which increase in number with distance form the point source (nuclear power station) hazard. Detailed traffic flow simulation is then limited to primary evacuation routes. SNET makes use of the SLAM II micro-simulation language (Prisker, 1984) and follows a similar approach to that employed in building evacuation modeling (see for example Talebi and MacGregor-Smith, 1984). Route selection is based upon the extremely myopic principle that drivers of evacuating vehicles will select their route on the basis of the distance to the vehicle ahead. That is, routes evolve as a function of the maximal distance to the last car ahead. Using survey collected data on the intentions of 9.8% of the households in a small Israeli town of 27,000, involving the evacuation of 2,231 vehicles and 4,450 pedestrians, they also provide one of the few studies to incorporate pedestrian evacuation behavior explicitly into the estimation of vehicle clearance times.

The most widely reported network evacuation model was developed for the Federal Emergency Management Agency (FEMA) by KLD Associates (FEMA, 1984; KLD, 1984) and is called DYNEV (Dynamic Evacuation). DYNEV is now also available as one component of FEMA's Integrated Emergency Management Information System (IEMIS: see Jaske, 1986; Bower, Millard, and Matsumoto, 1990), as well as in stand alone mode on a micro-computer, and termed PC-DYNEV (KLD, 1990). It combines a static, equilibrium assignment of traffic (see below) with what is termed in Table 1 a "meso-traffic simulation" based upon the well tested TRAFLO procedure developed for the Federal Highway Administration (Lieberman et al, 1983). This simulation is based not upon the movement of individual vehicles, but upon the interaction of different traffic streams, or "platoons" of vehicles. Such a platoon might be a series of vehicles assigned to a right turn or left turn lane at an downstream intersection. During this second phase of the DYNEV modeling process, detailed traffic simulations can be taken down to an interval of seconds, if desired.

Using a traffic route and destination assignment model as a prior step to detailed traffic flow simulations, DYNEV has been used to generate evacuation time estimates for a number of large urban populations. The user can experiment with a network's carrying capacity in a number of ways, including the adjustment of signal settings and individual lane controls through links and intersections. The approach has been subjected to a number of applications and sensitivity tests on a range of highway networks (see Urbanik, Moeller and Barnes, 1988, for example).

6.3 DYNAMIC TRAFFIC ASSIGNMENT MODELS

The alternative approach to traffic simulation is to use an analytic derivation of route selection based upon various well known mathematical programming models of traffic route assignment. This route selection process has received extensive research over the past 30 years, largely within the context of modeling the daily journeys to and from work. Most Metropolitan Planning Agencies and Regional Councils of Government in the United States today use a variation on the Urban Transportation Planning Process (UTPS) software, supplied by the U.S. Department of Transportation. This package includes a trip generation (i.e., how many trips), trip destination (where to) and travel mode (auto, rail, bus, rideshare) selection model linked to a static, user equilibrium route assignment model called UROAD. Such assignment models are termed "static" because they imply a steady state for traffic loading throughout the travel period. That is, if one hour traffic volumes are loaded onto the network, such a static assignment model assumes that such loadings represent conditions throughout the 15 minute period. For this assumed representative traffic loading, UROAD finds either the system or individual user (vehicle) optimal assignment of traffic flows to alternative routes, given the current network capacity, and taking all origin-to-destination flows into account at the same time. An optimal routing for evacuees with pre-specified origins and destinations is derived such that no vehicle can reach its destination by switching from the path assigned to it.

Such static traffic assignment models balance out demand for road space by ensuring the following Wardrop (1952) equilibrium conditions on route selection, for any origin i to destination j specific trip:

$$c_{rij} = c^*_{ij} \quad \text{if} \quad T^*_{rij} > 0 \qquad \text{for all } r, i, j \tag{15}$$

$$c_{rij} \geq c^*_{ij} \quad \text{if} \quad T^*_{rij} = 0 \qquad \text{for all } r, i, j \tag{16}$$

where c_{rij} = the travel impedance (travel time in evacuation studies) associated with trips from i to j using route r; c^*_{ij} = the at equilibrium travel time associated with an i to j trip; and T^*_{rij} = the number of vehicular i to j trips assigned by the model to route r at equilibrium. The equilibrium travel times, c^*_{ij}, refer to that set of route specific times which so distribute trips that no vehicle can reach j from i by a less time consuming route. Equation (15) says that all routes used between an i to j pair have the same travel time. Equation (16) says that routes with a longer travel time than c^*_{ij} will receive no trips. That is, travellers in aggregate are assumed to adapt to existing traffic conditions in a manner that minimizes congestion delay for each. Such a system recognizes therefore the effects of interacting origin to destination (i to j) traffic flows, as each of these flows may come into contact with each other on one or more specific highway links.

While such static assignment codes may have been used in the past to assess network clearance times (for example, see Tampa Bay Regional Planning Council, 1984), they are unrealistic for most large scale urban evacuations where the rate of traffic loading can vary significantly from one 5 minute interval to the next. In reality, traffic is far more dynamic and complex: and as conclusively demonstrated by Janson (1989, 1990a) such static assignments can noticeably underestimate the true levels of network congestion. To approximate this condition, the DYNEV evacuation modeling system has to be run for a series of different and successive traffic loading intervals, and the resulting and different traffic route assignments fed to a detailed simulation process that better reflects the dynamics associated with vehicle turning movements at various types of network intersections. This process of matching a series of static assignment results with the subsequent meso-traffic flow simulations within DYNEV is not entirely satisfactory, however, with no convergence between the two stage process guaranteed (or likely). Calibration for large, complex urban networks can become rather time consuming and hence expensive as a result: and requires a sound knowledge of traffic engineering principles and techniques.

The preferred traffic routing method for evacuations is dynamic traffic assignment. Until recently, the only practicable and generally available form for such assignment models was a version of stochastic route choice, as exemplified by the NETVAC1 (Sheffi, Mahmassani and Powell, 1982); EVACD (Stone et al, 1986), and MASSVAC (Radwan, Hobeika and Sivasailam, 1985; Hobeika and Jamei, 1985; Hobeika and Hwang, 1986) codes listed in Table 1. These models employ pre-set user route preference functions in conjunction with information on the relative volumes of traffic currently loaded onto links "downstream" of each traffic intersection, to stochastically assign evacuating traffic volumes at each intersection they meet.

NETVAC1 (Sheffi, Mahmassani and Powell, 1981, 1982) was developed for simulating nuclear power plant evacuations. Although NETVAC1 does simulate traffic interactions and updates them at a user specified time interval, it is not a simulation model in the sense of NETSIM or phase 2 of DYNEV. Instead of dealing with individual vehicles or platoons, it uses a series of computationally efficient mathematical relationships between traffic flows, speeds, densities, and queue lengths to simulate the evacuation process as a form of competition for road space. NETVAC combines the route selection procedure with the simulation of on-the-road traffic interactions into a single step. It does so and still manages to incorporate the effects of intersection as well as link traversal delays by computing both link and node (i.e., intersection) specific traffic volumes. A procedure termed the "link pass" gives the capacity along the link regardless of the downstream intersection restrictions. A node pass procedure then computes how many vehicles entering an intersection should be moved to each of the links exiting that intersection, and how many will need to be delayed until the next time interval before they can progress.

Route selection in NETVAC combines the assumption of prior driver knowledge of the best direction to take along a link (i.e., away from the hazard) with a myopic view of the traffic conditions the driver finds at the time of the evacuation. For any link j emanating from an intersection, the user of NETVAC can supply a "preference factor," denoted as PF_j, reflecting the driver's knowledge of which direction to take. If the travel speed on that link at time t is given as $U_j(t)$, then the probability of a random driver at time t selecting link j out of that intersection is given as:

$$P_j(t) = PF_j * U_j(t) / \sum_k PF_k * U_k(t) \tag{17}$$

where there are k = 1,2,..j..K ways out of the intersection, and with turning movement prohibitions requiring that such probabilities are calculated for each link coming into the intersection.

Intersections are processed by defining the volume that any link downstream of the intersection can receive. Such volumes are constrained to be the minimum from (i) the intersection handling capacity (ii) the link handling capacity and (iii) the volume assigned to the link by all relevant upstream links. Bookkeeping is required to ensure that traffic not cleared during a given time interval is added to any traffic loaded onto a link in successive intervals.

An updated version of the model, NETVAC2 is described briefly by McCandless (undated, mid-1980's). EVACD is based heavily on the NETVAC approach and will not be discussed further here. Stone et al (1986) provide a listing of the program's code.

MASSVAC offers yet another approach to evacuation routing. It is also a stochastic dynamic traffic assignment model, and is based upon similar bookkeeping principles to those of NETVAC, and of the DYMOD code discussed below. That is, traffic volumes are updated during each small interval of time (such as every 15 minutes) as new traffic loads onto the system. The assignment of traffic to routes is carried out in MASSVAC through a version of Dial's (1971) probabilistic multipath assignment procedure. Briefly here, let e refer to a specific link in the highway network, with origination node n and destination node s [that is e = (n,s)], and let R refer to a path through the network from origin point i to shelter j. According to Dial's approach, the probability of a particular path R being used by travellers is directly proportional to the product of the likelihood that each link in the path is used, i.e.:

$$P(R)=k*\Pi_{e\epsilon R}\ a(e) \tag{18}$$

where k is a constant of proportionality, and a(e) is this likelihood associated with selection of link e. To receive traffic volume, such a link must be on an "efficient" path. Such a path is defined as follows. Let p(n) refer to the shortest distance path between origin i and intersection node n, and let q(n) be the shortest path from n to destination j. Then for a link e of distance d(n,s), its likelihood of use is given as:

$$a(e) = \begin{cases} \exp[\theta[p(s)-p(n)-d(n,s)]] & if\ p(n)<p(s), q(s)<q(n) \\ 0 & otherwise \end{cases} \tag{19}$$

That is, if link e's end node s is not closer to the destination j than e's starting node n, and if point s is not farther away from i than is point n, link e is not considered to be on a reasonable path from i to j, and does not receive traffic. The probability of any such path R being used can be shown to be directly proportional to the value of $\exp[\theta(d^* - d(R))]$, where d^* is the shortest path distance from i to j, and d(R) is the path R distance (Dial, 1971). The relative extent to which alternative paths are used during the evacuation process can in practice be varied considerably by the user choosing different values of the path dispersion parameter θ in equation (19). Radwan, Hobeika and Sivasailam (1985) report obtaining similar traffic route loadings and area clearance times using MASSVAC and the detailed traffic simulator NETSIM on the same, reasonably small urban networks.

Recently, Janson (1989, 1990a) has developed the first published version of an optimization based dynamic traffic assignment (DTA) routine. Termed DYMOD, this algorithm loads traffic, as do MASSVAC, NETVAC and EVACD, at user specified loading intervals, such as every 10 minutes, and keeps track of where that traffic is within the system at the end of each time interval. New traffic loaded onto the network at subsequent time intervals is then allowed to interact with this already loaded traffic, should they meet at a particular intersection. Unlike these stochastic assignment models, however, DYMOD offers a deterministic but optimization-based approach for linking dynamically varying traffic volumes to route selection. It is based on a dynamic version of Wardrop's

(1952) principle of route selection, spreading a set of multiple origin to destination traffic volumes across a network's links by ensuring that all multi-link paths used by evacuees who mobilize at the same time and place, and who head for the same destination, will have equal path traversal times: and any unused paths will be unused because their use would increase someone's time to clear the network. This is a direct (if mathematically and computationally rather complex) extension of the previous static assignment method represented by UROAD to traffic flow dynamics (in fact, the static case is shown by Janson to be a special case of such a traffic dynamic). The dynamic version of conditions (15) and (16) as implemented in DYMOD may be stated as:

$$c_{rij}^{d} = c_{ij}^{d^*} \ \text{if} \ T_{rij}^{d^*} > 0 \quad \text{for all } r, i, j \tag{20}$$

$$c_{rij}^{d} > c_{ij}^{d^*} \ \text{if} \ T_{rij}^{d^*} = 0 \quad \text{for all } r, i, j \tag{21}$$

where the superscript d refers here to a specific trip departure time (or short time interval). That is, equations (20) and (21) indicate that travellers departing at time d from i will take $c^{d^*}_{ij}$ to reach j, no matter which route r they select: and that of all travellers departing i and bound for destination j at time d, $T^{d^*}_{rij}$ will select the series of links constituting route r. The computational procedure required to ensure conditions (20) and (21) is rather complex (see Janson, 1989), with great care required to avoid the creation of discontinuous flows across successive traffic loading intervals and at the same time maintain an equilibrium-based formulation.

The DYMOD routing procedure is presently being extended at Oak Ridge National Laboratory to handle multiple highway and traffic intersection types, and has already been embedded within a combined (and now dynamic) traffic route assignment-trip destination procedure analogous to that contained in DYNEV (Janson, 1990b). Recent theoretical and empirical work by Janson and Southworth (1989) and Janson (1990b) on the link between traffic dynamics and the selection of traveller departure times also offers the potential for DYMOD application in real time traffic information settings. The possibilities for real time network evacuation monitoring, and perhaps even control, look as a result to be much closer than they were only a handful of years ago.

Recently also, Anas and Kim (1990) have presented example experiments with an equilibrium based estimation procedure for stochastic route selection: comparing it favorably to the stochastic network loading procedures of the type used in NETVAC, EVACD and MASSVAC. While not applied to evacuation modeling directly, nor as yet tested on any large real world highway networks, the work is a further advance towards a fully specified route selection and, perhaps more significantly, route direction procedure for application to highly congested traffic conditions. This is perhaps the most interesting aspect of this and of the DYMOD work: the move towards a more complete understanding of just how much vehicular throughput we can actually get out of a complex urban network, and just how much congestion delay is inevitable under even the most effective traffic management schemes. Given the extremely large and abnormal vehicle volumes associated with large urban evacuations, we may one day have a need for, and be able to use effectively, such information.

6.4 OTHER WORK OF INTEREST

One further mass evacuation planning model worthy of note is the NESSY-IV (Network Structure Analyzing System IV) developed by Hiramatsu (1980, 1983). NESSY was built to help with the planning of busy downtown evacuations after an earthquake warning. Literature on the model makes it difficult to specify fully the level at which a simulation of traffic takes place, although it would appear to be a "macro-simulation" taken in the context of Table 1. The model is distinguished by its effort to simultaneously, and interactively, model the flows both of people and information (warning messages) throughout the system. It also distinguishes between four population segments: office workers, shoppers, people on the street and people in underground buildings at the time of the earthquake warning. As well as automobile, both walk and metropolitan rail travel modes are modeled. Quite detailed (500 node) networks can apparently be analyzed, and the approach is very much one of pure simulation, with user intervention as a means of assisting the FORTRAN routines to clear bottlenecks at one of a number of types of evacuee processor nodes.

Finally, in reviewing past literature on the topic, numerous papers were also found on the subject of building evacuation. In general, these studies use either simulation codes, such as Q-GERT models (Prisker, 1979), or stochastic programming methods, and usually the former, to address the problem. No new insights into the modeling of regional evacuations could be found in these papers. In general, the route selection processes used are similar, or simpler, than those associated with regional highway networks. Nevertheless, they shed some light on the process of replicating both individual and collective evacuee decisions. The reader is referred to the articles by Karbowicz and MacGregor Smith (1984), Talebi and MacGregor Smith (1984) and Watts (1987) for more on this.

7. PLAN SET-UP, ANALYSIS AND REVISION PROCEDURES

7.1 SET-UP AND ANALYSIS: COMPUTER GRAPHICS, ANIMATION AND EXPERT SYSTEMS

To assist the planner, today's network based evacuation planning packages compute a wide range of succinctly presented measures of network effectiveness (MOEs). For example, the DYNEV program generates the following MOEs:

- average delay per vehicle
- percentage of vehicle forced to stop en route during the evacuation process
- average space mean travel speed on the highway network
- average traffic queue content (number of vehicles)
- travel time per vehicle mile
- number of vehicles on the network at selected times into the evacuation (e.g. every 30 minutes).

Since delays tend, even within quite complex urban networks, to focus on a sub-set of highway intersections and routes, link and intersection specific indices, as well as areawide indices of vehicle occupancy and traffic speed, are also of considerable value. A significant aid to using these evacuation models to plan evacuations on complex urban networks can therefore be found in computer graphics. Useful graphical displays include:

- simulated origin to destination (i.e., shelter) traffic movements, by time period or in total.

- network displays of link and route specific traffic loadings, by time period.

- area or location specific traffic loading curves (for origins) and area clearance curves (for shelters), as well as summary curves for the full region.

Figures 3 and 4 provide examples of the last two types of display. Other examples can be found in the articles by Sheffi (1982), Hobeika and Kim (1991), and, showing the value of color, in Southworth and Chin (1987). The juxtaposition of traffic loading and clearance curves shown in Figure 4 is perhaps the best indicator of traffic delay caused by congestion: as evacuees are delayed en route, so the gap between these two curves increases. Useful for origin specific as well

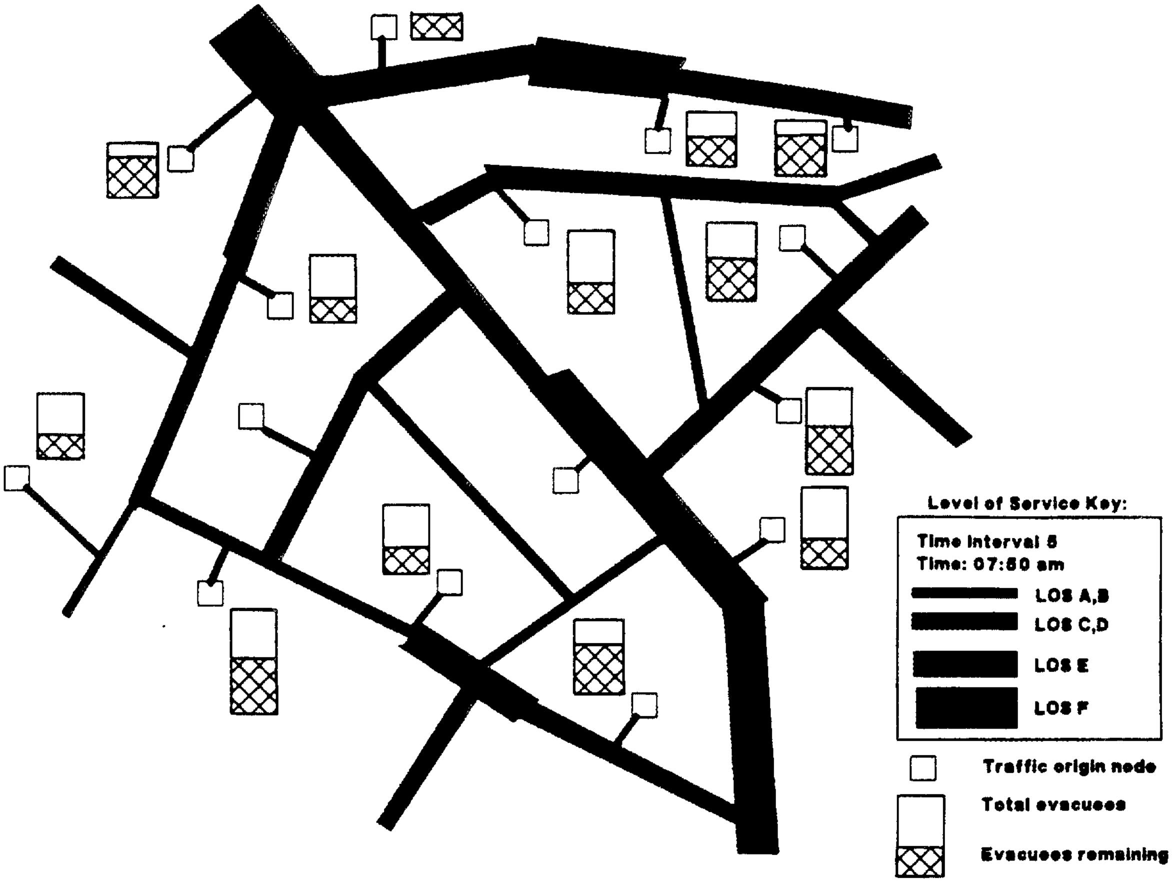


Figure 3. Display of Traffic Link Loadings And Associated Levels of Service For a Specific 10 Minute Time Interval

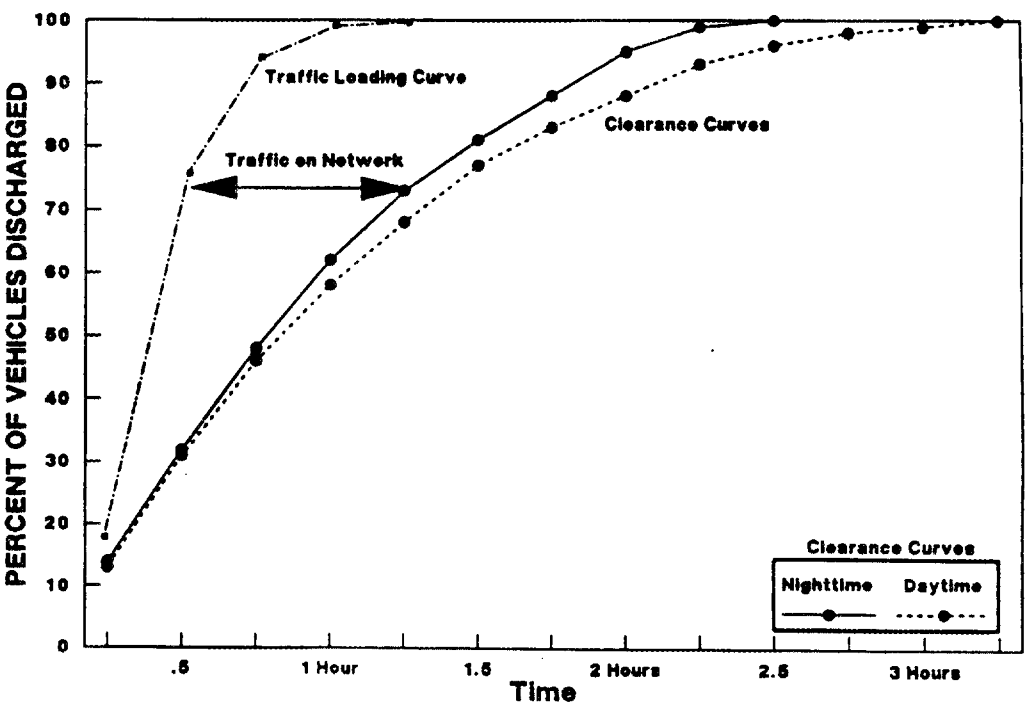


Figure 4. Example Network Loading and Associated Network Clearance Curves.

as areawide analyses, such curves have become the most common form of graphical results presentation.

A number of the network evacuation modeling codes listed in Table 1 are now linked up to similar graphics programs. These are not merely useful presentation tools. Interpreting the results from a DYNEV run for a large urban network is made much easier by the presence of the GDYNEV graphic post processor package (KLD, 1990), as is the interpretation of MASSVAC results using either the MVOPL post processing code (Southworth and Chin, 1987), or the Transportation Evacuation Decision Support System (Hobeika and Kim, 1991). Especially useful for bottleneck analysis is the ability to track a specific network link or intersection through successive time periods, in a rapid fashion.

A most promising and useful application of graphical animation is the process of overlaying the position of a moving hazard, such as a wind directed "plume" produced by a significant chemical spill. Similarly, the expected timing and inland penetration of a bad weather associated with hurricanes and tsunamis can be projected to the computer screen. By animating the predicted spread of a hazard and correlating its location and dosage with the presence of in situ or currently evacuating residents, prior assessment of the expected damage and threat to life may better be assessed. Under unstable meteorological conditions during which both the strength and direction of the hazard may change, a rapid re-assessment of evacuation plans may be possible with such tools, leading to better informed decisions about which evacuation routes to use or whether to evacuate specific communities within the larger at risk emergency planning zone. Figure 5 shows this concept in snap-short form. Workstation based animation and data handling software to do this can now be found in the marketplace. The recent emergence of commercially available geographic information systems (GIS) as important planning and analysis tools indicates that such software systems could be put together at reasonable cost. Emergency management offers a particularly important and challenging applications arena for such software development. When linked to real time information flows, such graphically based analysis tools may become an integral (and potentially indispensable) component of future emergency planning *and* decision-making systems.

While the author could find no published reference to the application of rule based expert system's analysis to network based evacuation modeling, there would appear to be room for experimentation here, especially in the context of high level plan analysis and control. As already noted, the calibration of current network evacuation modeling codes, when applied to large or dense urban networks, is rarely an easy task. Systems with the ability to store and learn from past attempts to direct traffic out of an area might save the analyst a good deal of experimentation. Data from past evacuations combined with the results of past modeling experiments might be combined to generate a better evacuation plan.

Genetic or other algorithms which rapidly search highly non-linear solution spaces may have application here. Certainly, the author's experiences with codes such as DYNEV and MASSVAC indicate that considerable time and effort could be saved in trying to calibrate the more sophisticated models, if expert systems logic could be brought to bear on the problem. Such models require considerable tampering with parameters associated with the timing, route and destination selection sub-models described above. A move to real time traffic analysis systems, as discussed below, may also require artificial intelligence help of this nature.

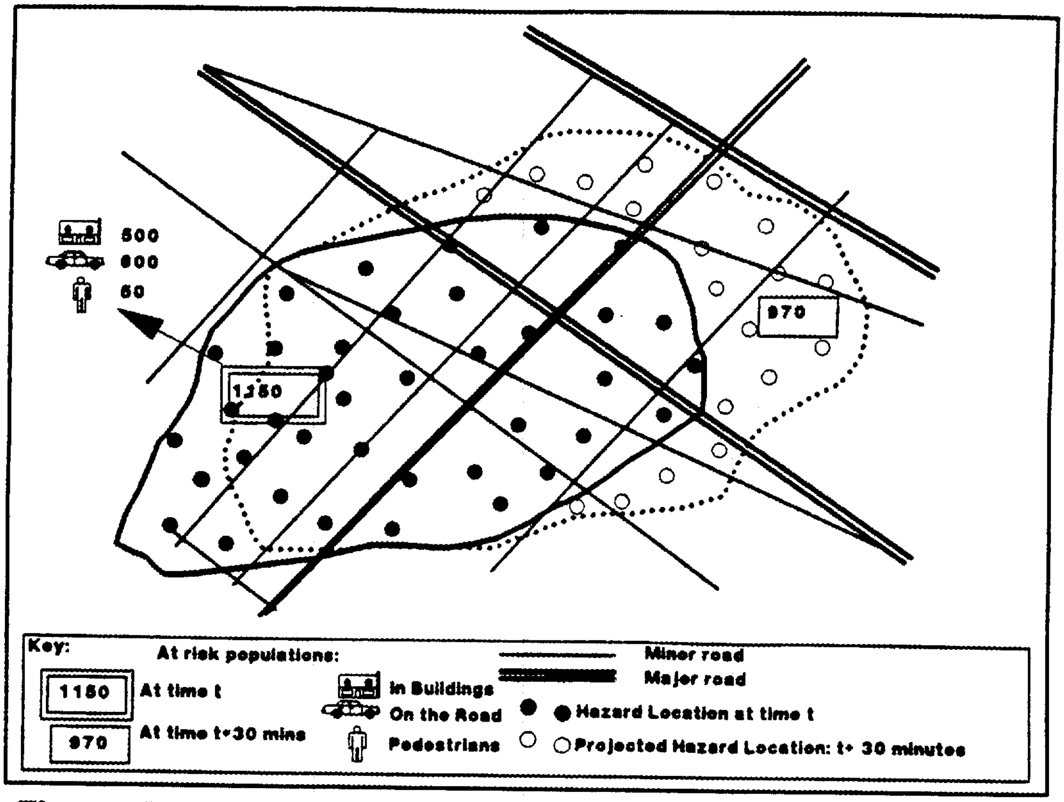


Figure 5. Displaying Population at Risk During an Evacuation

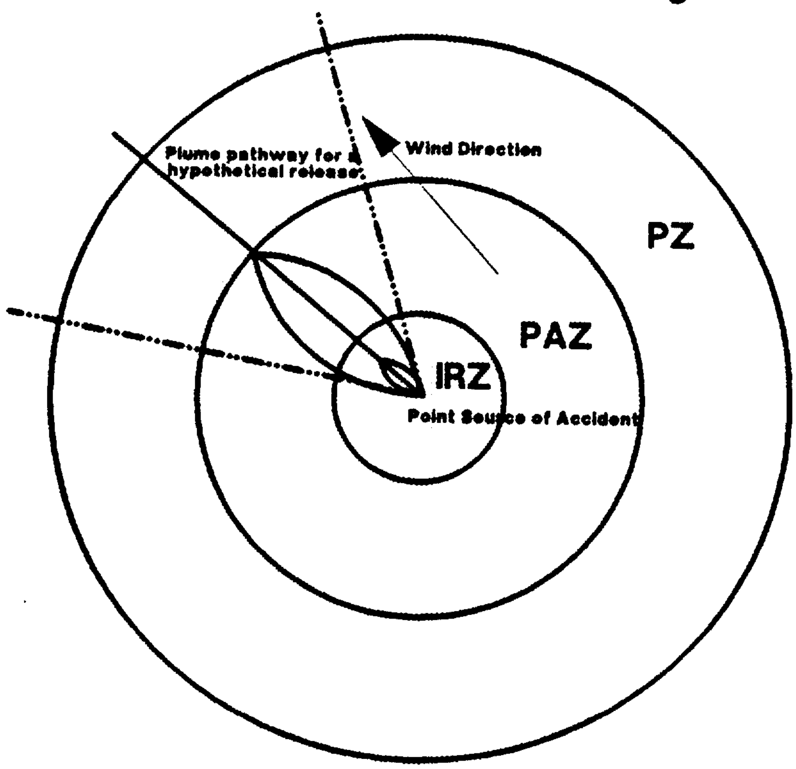


Figure 6. Spatial Relationship Between Chemical Agent Plume, Wind Direction, and Evacuation Zone Boundaries

7.2 PLAN REVISION: REFINING EVACUATION ZONE BOUNDARIES

In addition to this need to "play with" the evacuation modeling systems, there is often a need to update evacuation plans on the basis of new data: from data on the nature of a new hazard, to new information collected by the Census or other planning agency. A particularly interesting aspect of this procedure is the refinement of evacuation planning zones.

The usual method for applying one of the above evacuation planning models to a region is to begin with a given evacuation zone boundary. Selection of the zone indicates a belief that the hazard in question will not threaten anyone outside the zonal boundary. Sometimes there are a series of zones. For example, Carnes et al (1989) present a three zone concept for application to evacuations associated with the release of significant amounts of stockpiled chemical agent. The concept is displayed in Figure 6. Communities closest to the point source of a potential release fall within the Immediate Response Zone (or IRZ). Slightly farther away, but still under a potential threat depending upon meteorological conditions and size of an accident, are communities within the typically IRZ-surrounding Protective Action Zone (PAZ). The outermost zone, termed the Precautionary Zone (PZ) is larger still than the PAZ. Its outermost boundary represents the region beyond which no adverse human effects from a chemical release can be expected under the most extreme, worst case conditions. Evacuation plans are limited in such a case to IRZ only, PAZ only, and IRZ plus PAZ based populations, according to assumptions about size of release, and speed and direction at which a chemical cloud might disperse. For example, a very rapid spreading of gas coupled with low highway capacity might indicate in situ protective actions for IRZ residents, but evacuation for the rest of the PAZ. A small spill and low wind speeds might indicate an IRZ evacuation only.

An excellent historical review of the thinking and legislation associated with the designation of evacuation zones around nuclear power plants is provided by Golding and Kasperson (1988). The geography of evacuation zone boundaries, as well as of the powers of public agencies within them, is both a technically and politically sensitive issue. Little if anything in the literature on evacuation models reports the application of modeling results to the re-definition or refinement of such boundaries. While the extent of a zone is dependent foremost upon the anticipated maximum extent of a potential hazard (as in the case of radiological evacuations), the decisions about who to move, and when to notify communities within the zone should consider the effects of such actions upon the resulting traffic situation. Often the presence of administrative boundaries comes into play since the authority to warn and subsequently support a mass evacuation may lie with more than one local or regional authority. Where immediate response zones are concerned, and high traffic congestion is anticipated, staggered evacuations may be the best way to get everyone out in time. An effective evacuation model should be able to tell us when such a decision may be necessary: since the process of who takes charge among the various agencies involved needs to be resolved well before such an incident occurs.

8. REAL TIME EMERGENCY TRAFFIC MANAGEMENT: THE FUTURE FOR EVACUATION PLANNING

This review has been carried out at a particularly exciting time for traffic engineers and planners, because we are now entering the era of real time traffic information and, hopefully, control (see the collections of papers in Royal Institute of Electric Engineers, 1989; Institute for Electrical and Electronics Engineers, 1989; Mobility 2000, 1989). This emerging, and now in parts of Europe in place, traffic counting and in-vehicle surveillance technology has great potential for application to emergency management. Not only will we be able to monitor and record the magnitudes and directions of an evacuation as it occurs, but we should also be better able to control its progression. Real time measurement of traffic volumes can be done in two ways: from a fixed sensor such as induction loops embedded within the highway, or by collecting data from a vehicle moving within the traffic stream, the so-called floating vehicle method (Vargas Styer, 1990).

A first attempt to bring near real time traffic information to evacuation monitoring was reported recently by Southworth, Chin and Cheng (1989, 1990) and by Chin and Southworth (1990). Termed RTMAS (for Real-time Traffic Monitoring and Analysis System), this prototype traffic monitoring and analysis software has been under development at the Oak Ridge National Laboratory for the past two years. With sufficient numbers of well placed and telemetrically accessed loop traffic counters, the speed and directions of an evacuation can be recorded: either for subsequent analysis, or for on the spot decision-making with respect to which evacuation routes to encourage, deny or control entry to.

The concept for RTMAS came from the U.S. Federal Emergency Management Agency, who were interested in the ability to use telemetrically collected traffic information to monitor the "spontaneous" build-up of an evacuation over time. This interest in spontaneous evacuations stemmed in part from a retrospective look at the experience the city of London underwent during the build-up to World War II. Over a period of weeks a significant percentage of the population of the London region, in the face of the impending bombings, were some time later found to have evacuated the metropolis. Spread over a sufficiently protracted period, such an evacuation, even a very large one, becomes an almost invisible process. The result can be a relocation of population that may later place undue strain on regional resources: a strain the receiving regions' planners cannot anticipate. More common and less protracted forms of evacuation, such as those occasioned by impending hurricanes and floods, also frequently generate significant amounts of spontaneous evacuation. RTMAS is being developed to pick up this spontaneous portion of an evacuation, as well as to monitor the evacuation process to its conclusion. Extension of the system to include a dynamic traffic assignment model of the DYMOD type, linking evacuee routing analysis to real time vehicle counts is currently under consideration (Janson and Southworth, 1989; section 6.3 above). Inclusion of "floating vehicle" based speed information within such system is also not beyond the realm of possibility. An early RTMAS experiment with expert system software, as a means of generating rule based warning of spontaneous yet otherwise invisible traffic build-ups, is also discussed in Southworth, Chin and Cheng (1990).

Figure 7 shows the concept behind such a system's hardware: a workstation based user platform connected via normal telephone lines either directly to a series of sequentially polled loop counters, or in "one stop shopping" mode to a regional traffic data collection center, the preferred mode of operation. RTMAS software includes a data communications and retrieval program, a relational database, user friendly (including graphic and geographic) data retrieval and analysis screens, and automated Box-Jenkins time series modeling of the latest versus expected daily traffic volumes at selected locations along a city's major radial highways. At the present time RTMAS is still a prototype for what would need to be a more robust, higher capacity data handling system. Nor are telemetrically accessible urban or regional traffic counters systems currently widespread today, outside a small number of the world's largest cities (notably Los Angeles, Chicago, and Seattle within the United States).

If only in response to our growing urban traffic congestion problems, such real time traffic information systems are likely to spread. The Federal Highway Administration has recently put together a multi-million dollar program to advance this Intelligent Vehicle/Highway System (IV/HS) technology. Similar levels of effort and investment are underway within both the public and private sectors in western Europe and Japan. Complementing these real time traffic counting stations is the advent of infra-red traffic sensors linked to in-vehicle tracking and guidance information devices. Such a system (of some 250 sensors: Sparmann, 1989) was made operational in Berlin in June 1989, and a second is now under construction in the city of London (Catlin and Belcher, 1989). Microwave and optical sensor based systems are also being studied. A fourth emerging technology, not yet sufficiently accurate for urban street navigation, is the use of satellite communications to receive and transmit vehicle location information (Institute for Electrical and Electronics Engineers, 1989). As a result of these technologies, the first quarter of the next century could see a significant change in the way travelers, including evacuees, receive traffic directions. This information should also serve another purpose; it should help us to understand more about how drivers select routes in congested and crisis conditions. By combining this wealth of traffic information with suitable behaviorally based models of evacuee response, as reviewed in Section 4 of this report, even cities

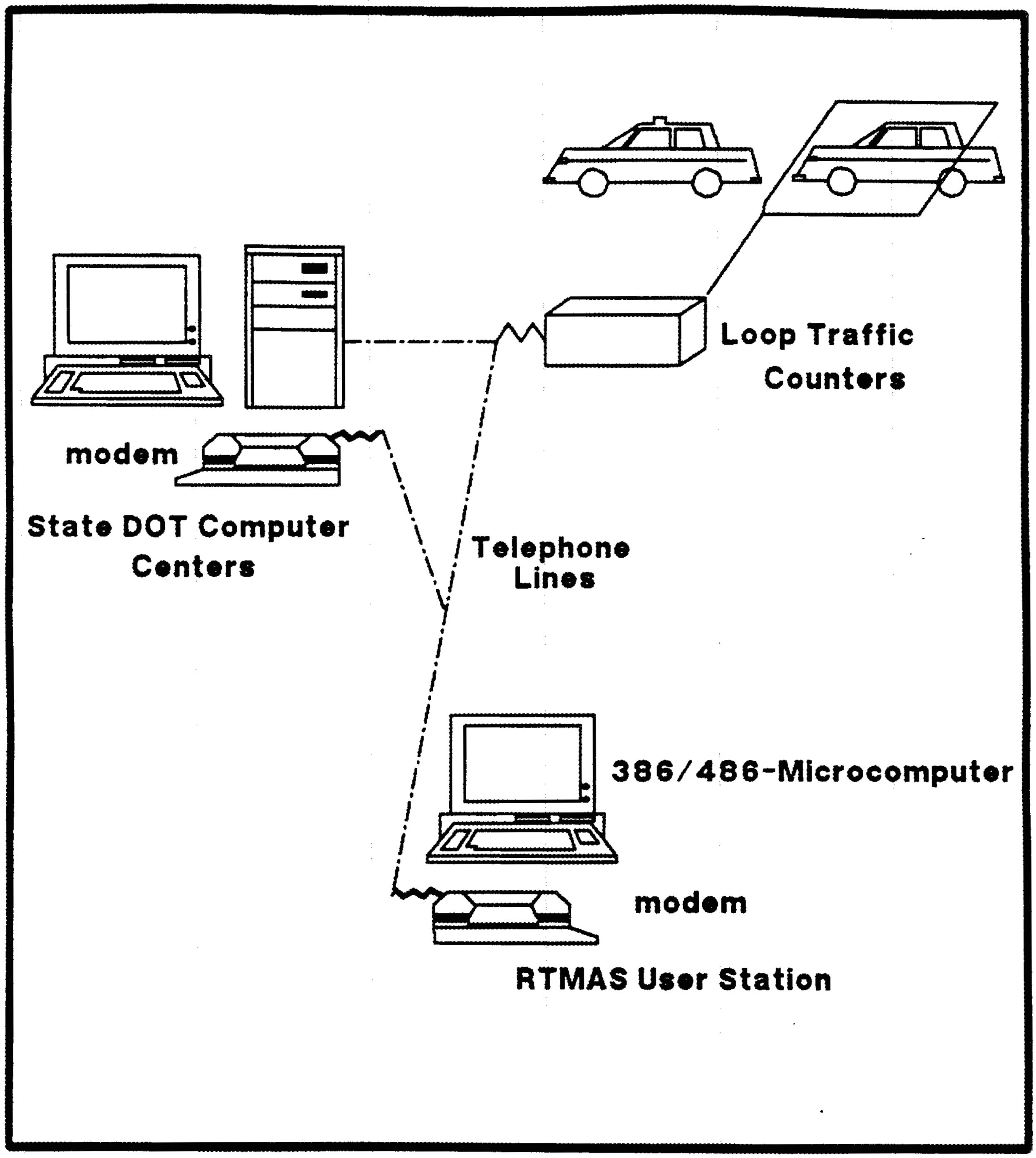


Figure 7. RTMAS: Hardware and Communications

not equipped with traffic sensing systems could benefit significantly from this information should they need to evacuate for any reason.

A "technological fix" may also help us solve the dilemma of "guestimating" vehicle occupancies during mass evacuations. This is the use of video-computer linked technology to photograph and subsequently analyze the characteristics of a particular traffic stream (see Royal Institute of Traffic Engineers, 1989; NEWS, 1990). However, on the basis of the current literature plus discussions over recent years with a number of traffic engineers who collect as well as use such data, it would seem that reliable vehicle occupancy counts will remain a manual occupation until further breakthroughs in image processing take place.

Whatever the eventual mix of real time traffic information gathering hardware (summarized in Figure 8) and software , the opportunities for real time emergency planning *and* control are clear. Such information can and should revolutionize evacuation planning: from a game of guesswork to one of reasoned direction and re-direction in the face of crisis.

Of course, much remains to be done in order to take advantage of this information revolution. It may be some years, perhaps at least two decades, before urbanized areas of any size are placed upon sufficiently elaborate traffic monitoring networks, or have extensive access to real time in-vehicle information and guidance systems. And, traffic information is not the only information flow to be dealt with. The real world process of managing a mass evacuation is of course far more complex than the multi-step evacuation modeling process described above. A number of different agencies, including the police and possibly medical, fire and other public and private service organizations, may need to be involved at both local and regional levels. Speed of access to this information will often therefore be just as important as its accuracy. The decision-maker needs a way to filter the incoming signals, a way to separate the important problems from the rest of the noise. Relational database and graphical animation tools, perhaps supplemented by expert system logic attached to real time traffic surveillance and control, is perhaps the ultimate expression of this sort of user assistance for evacuation planning purposes. All of the pieces to such a system currently exist, if separately at the present time.

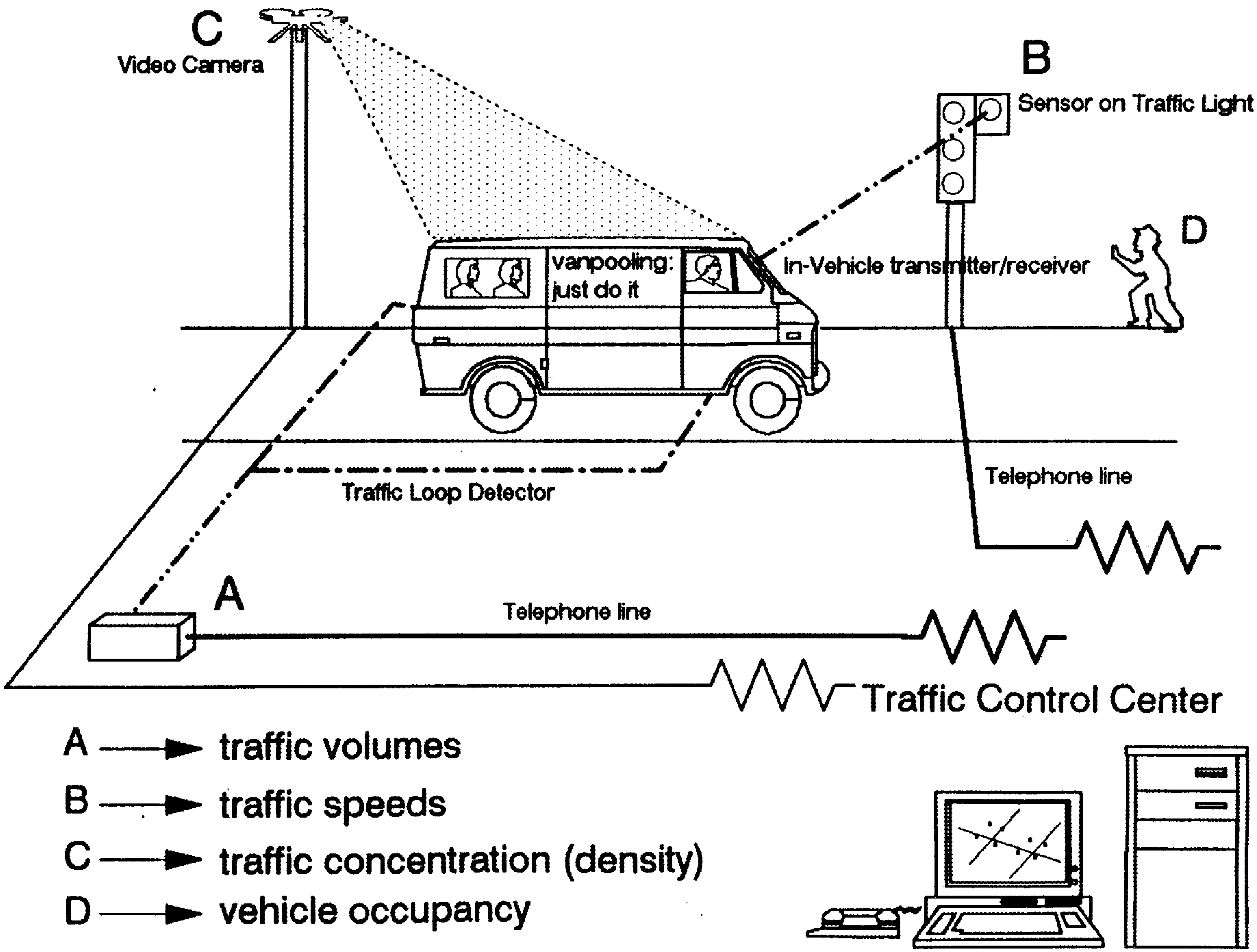


Figure 8. Emerging Real Time Traffic Monitoring and Control Technologies.

9. SUMMARY AND NEXT STEPS

Most of the progress in evacuation modeling in the decade of the 1980's took place in the areas of network traffic route and destination modeling, drawing directly from technical advances in the fields of transportation planning and traffic engineering. Some of this progress has been illusory, however. No amount of detailed traffic flow simulation can compensate for poor trip generation data, or for a poorly specified evacuee mobilization time model. Some, though to date limited, progress has also been made in translating the wealth of knowledge about evacuee behavior into quantitative estimates of the size and timing of community response. Realistic response curves and their translation into evacuee mobilization rates are critical inputs to the subsequent evacuation time estimation process. The author concurs with the view expressed by Golding and Kasperson (1988, page 34) who suggest that "the next generation of plans should be built bottom-up from what is known about actual behavior rather than trying to 'fit' behavior into rational, engineered notions of evacuation."

In the meantime, regardless of whichever of the evacuation modeling codes reviewed above is used, expert playing with the software is a requirement. Their application by the layman is not recommended. Indeed, this may be an important reason behind the apparent lack of confidence in such analytic methods among at least part of the emergency planning community (as also commented upon by Golding and Kasperson). Plans generated by the more sophisticated, dynamic models have not, to the author's knowledge, as yet been compared with an actual evacuation event of any magnitude. Given the very high levels of congestion that would be experienced by densely populated urban areas, and conversely, the low levels of congestion associated with small urban places, the models ought to perform satisfactorily. How well they perform between these two extremes (which is perhaps where they would be most useful) still remains a matter for some speculation.

Hopefully, much of the cause for such skepticism will disappear over the coming decade as we move towards real time traffic monitoring and control systems within our larger cities. Once we have real time information on actual traffic flows, less reliance need be placed upon traditional forms of simulation modeling. How well we make use of this data will rest in large part on how well we are able to develop near real time traffic routing procedures that can be used to revise evacuation routing plans on the basis of latest information.

The move towards real time traffic information systems is seen as a key issue for this future research and development effort, especially if supplemented by similarly timely information on the nature and spread of an hazard. Cutting edge research into real time traffic monitoring and control and its application to real time emergency management practices has already begun. This is an ability on which we can expect to improve noticeably, perhaps dramatically, over the coming decades: with the advent of telemetric road sensors and in-vehicle navigation devices linked to regional traffic control centers. These same traffic sensing devices hold the promise for our first truly reliable information on the relationship between the timing of evacuee responses to notification of threat, and the effects of this timing on traffic build-ups and resulting area clearance times.

Workstation based graphics, animation, and data retrieval and manipulation software offer the opportunity to simulate, or even view in near real time, the spatial and temporal coincidence of at risk populations and the hazards they face. Such tools ought to place the next generation of evacuation planning models within highly sophisticated man-machine interfaces, offering a more effective coupling of the decisions usually associated with evacuation models (i.e., when to leave, which routes to evacuate, which destinations to head for) with decisions usually associated with public warning models (when and how to warn). Evacuation decision support systems such as RTMAS (Chin and Southworth, 1990), TEDSS3 (Hobeika and Kim, 1991), and REMS (Kisko and Tufekci, 1991) offer some early beginnings in this area.

Still to be tackled is the issue of how to model, and how to plan for, the appearance of an areawide threat during a major commuting period. To date, there has been no serious effort to plan for "peak traffic period" evacuations where the major directions of the evacuation would run counter to the dominant commuter traffic flows. Modeling this situation using current methods is more than a little problematic. Similarly, more attention is required to pedestrian activities during evacuations, and to the incorporation of network evacuation modeling results into the selection of emergency planning zone boundaries. Limited progress has also been made in the number of vehicles evacuees will use during the evacuation process. The ability of video cameras to monitor traffic streams during an evacuation, using currently available (though as yet not widely adopted) technology, remains to be verified. The current method for counting vehicle occupancy, during normal conditions, is still manual. The variability in the size and location of large urban area populations remains a fundamental weakness in current estimation methods. Much remains to be done, and opportunities to use new data collection and analysis technologies seized, if we are to feel completely comfortable with the preparation of our evacuation plans.

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