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Evacuation time estimates for nuclear power plants

Thomas Urbanik II [*]

Texas Transportation Institute, College Station, TX 77843-3135, USA

Abstract

Evacuation time estimate (ETE) analyses are conducted to accomplish three objectives. First, they provide data to emergency decision-makers that indicate if evacuation can be implemented in time to significantly reduce radiation exposures. Second, they can be used to determine if ETEs are significantly affected by uncontrollable events such as adverse weather. Third, they indicate whether traffic management actions would significantly reduce evacuation times and provide information relevant to the development of effective traffic management plans. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Before 1979, transportation analyses for evacuations from natural and technological hazards were rare and largely qualitative. However, the accident at the Three Mile Island nuclear power plant provided a major impetus for developing systematic procedures to assess the length of time required to evacuate a threatened population. The initial guidance on evacuation time estimates (ETEs), which the Nuclear Regulatory Commission and the Federal Emergency Management Agency published as NUREG-0654/FEMA-REP-1 [1], provided limited guidance on preparing ETE studies. At about this same time, the Nuclear Regulatory Commission sponsored an examination of techniques for estimating evacuation times at nuclear power plants [2]. This analysis, together with work by Federal Emergency Management Agency contractors, became the basis for the ETE guidance in NUREG-0654/FEMA-REP-1 Rev. 1, Appendix 4 [3].

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[*] Tel.: +1-409-845-1536; fax: +1-409-845-6001.
E-mail address: t-urbanik@tamu.edu (T. Urbanik II).

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As Lindell [4] has observed, ETEs are just one part of a complex process that includes events associated with a radiological release and events involved with response to that release. The wide range of possible accidents and responses makes it impossible to provide a single ETE, on the one hand, and impractical to provide ETEs for each of the many possibilities that could occur. Therefore, it is appropriate to develop a range of ETEs as part of the planning basis for a given site.

According to NUREG-0396 [5] and NUREG-0654/FEMA-REP-1 Rev. 1 [3], the standard planning basis for nuclear power plant emergency response plans includes a plume exposure pathway Emergency Planning Zone (EPZ) radius of about 10 miles (16 km). This is the area within which exposures from plume inhalation could exceed the Environmental Protection Agency's Protective Action Guides (PAGs). If the PAGs are likely to be exceeded, then protective actions such as expedient respiratory protection, sheltering in-place, or evacuation should be required. Evacuations require an especially thorough analysis because of the substantial logistical complexities involved in their implementation. In this regard, it is noteworthy that nuclear power plant EPZs cover a very large area (over 300 mile^2 or 900 km^2) and some contain hundreds of thousands of people. Consequently, a well designed ETE study must provide ''best estimate'' ETEs based on accurate data about the risk area population and the capacity of area roadways. In addition, the analysis must assess the sensitivity of ETEs to key variables, including variations in the size of the risk area population, the degradation of the capacity of area roadways by potential impediments, and the effectiveness of traffic management actions.

2. Transportation analysis considerations

At the most fundamental level, ETE analysis simply involves a comparison of an evacuating population's demand for access to the roadnet (i.e., the number of evacuating vehicles per hour) and the available capacity of the roadnet to service that demand. There are five factors that govern the flow of evacuation traffic:

- The number and distribution of evacuating vehicles, which is time- and space-dependent;
- The loading rate at which the evacuating vehicles enter the roadway system, which is influenced by the distribution of warning and preparation times;
- The capacity of the roadway system, which is a function of roadway types and routine traffic control actions;
- Any unforeseen degradation to roadway capacity caused by uncontrollable events such as flooding or traffic accidents; and
- Any planned enhancements to evacuation performance caused by special traffic management actions that decrease demand (e.g., evacuation routing) or increase capacity (e.g., lane reversals).

The Highway Capacity Manual [6] provides simple analysis techniques for evaluating operations along various points along a roadway system. This document is not specifically intended for developing ETEs, but the techniques provide satisfactory estimates of roadway capacity in sparsely populated areas having simple road networks. As the number of evacuating vehicles and the complexity of a roadway network increase, these techniques become increasingly inappropriate for evacuation planning. In particular, level of service analysis should not be used because it is predicated on the desire to provide capacity in excess of expected demand. Providing sufficient capacity to provide a high level of service during an evacuation is practical only in EPZs having very low populations. For most EPZs, computer models provide the only feasible method of accurately estimating ETEs.

2.1. Basic methodology

The basic methodology for analyzing ETEs is to determine whether the time- and space-dependent evacuation demand rate exceeds the available roadway capacity. If the evacuation demand rate is less than available roadway capacity, then evacuation time is the time required for the last evacuee to begin evacuating, plus this evacuee’s driving time in leaving the area. A critical part of evacuation is the trip departure time discussed below. If the rate of trip departures exceeds available roadway capacity, the time required by the excess vehicle demand must be added to the evacuation time.

A simple example illustrates the process. Suppose that 1000 vehicles are attempting to evacuate in a 1-h period and available roadway capacity is 2000 vehicles per hour. The first vehicle enters the roadnet at the beginning of the hour and the last vehicle enters at the end of the hour. Because there is no significant roadway-induced delay, evacuation time is essentially 1 h plus driving time out of the evacuation area. Alternatively, suppose that 3000 vehicles attempt to evacuate in a 1-h period and available roadway capacity is 2000 vehicles per hour. As before, the first vehicle enters the roadnet at the beginning of the hour, but in this case the last vehicle cannot enter until 90 min (3000 vehicles divided by 2000 vehicles per hour). Consequently, the last vehicle to leave experiences a 30-min delay time that is added to the driving time out of the evacuation area.

Obviously, an actual evacuation is more complex because there are many vehicles leaving many different areas at many different times over many different roads that may differ from their normal traffic capacities because of weather conditions. Nevertheless, the methodology simply requires an analysis of all the vehicles trip departures and any delay due to an evacuation demand that exceeds the rate at which the roadway can accommodate the vehicles that are attempting to evacuate.

2.2. Scenarios

The principal goal of an ETE study should be to evaluate the sensitivity of the ETE in a specific area to variation in controllable and uncontrollable variables such as traffic routing, signalization, population, weather, and traffic accidents. Once protective action analysts understand the sensitivity of evacuation time to each of these variables, they can estimate the evacuation time for any set of conditions not specifically analyzed in the study.

Sensitivity analysis can be conducted by systematically varying *evacuation scenarios*, which are the alternative sets of input variables that represent combinations of conditions that might occur at the time of a nuclear power plant accident. When developing plans for emergency response, planners are well aware that the EPZ population is not uniformly distributed in space and the roadway system does not consist of straight roads directed radially out of the EPZ. However, it is somewhat less obvious that population size is time- as well as space-dependent. Evacuation scenarios should recognize that the size of the risk area population varies over the seasons of the year, days of the week, and times of day. Likewise, vehicle speeds and roadway capacity depend significantly on weather conditions and other impediments such as road construction and traffic accidents. Weather conditions to be considered in ETE analyses should include adverse (rain, fog or snow) conditions as well as good (clear) conditions. Road construction and vehicle accidents also must be anticipated, but these generally are limited in number, scope, and duration, so their effects can be minimized with an effective traffic management plan.

The purpose of formulating several different scenarios is to determine if there are combinations of conditions that cause evacuation demand to exceed roadway capacity and, if so, the length of the delay that is expected to result. The scenarios should be constructed to show plausible combinations; it is not useful to analyze illogical or mutually exclusive combinations of conditions (such as a large daytime beach population and snow-covered roads) in a misguided attempt to provide conservatism in the analyses. Systematically overestimating evacuation time is not desirable because such an estimate is likely to lead decision-makers not to order evacuation as a protective action when it is actually the best alternative. It also is not necessary or desirable to determine a ‘‘worst case’’ ETE. The worst case almost always will be one in which evacuation is not possible.

Instead, the analyst should attempt to identify plausible evacuation scenarios that are likely to generate the highest typical demand on a recurring basis. In most EPZs, these are likely to include evacuation on a weekday during school hours because separated households will take a long time to reunite before departure. In resort communities, ETEs will tend to be highest during tourist season because the population will be substantially larger than in the off season. Scenarios to be analyzed also should include periodic events or conditions that generate a large, transient population within the EPZ (e.g., athletic events or festivals), or a temporary reduction in capacity (e.g., road repairs or flooding).

2.3. Demand estimation

The first step in estimating evacuation demand is to assess the size of the evacuating population. This typically is accomplished by subdividing the EPZ population into three groups. *Permanent residents* are those who live in the risk area year-round. *Transients* are visitors, including tourists and daily employees, who live outside the EPZ but might be inside it at the time of an accident. *Special facility populations* include those in institutions and schools. Some individuals are members of more than one group, but this does not pose analytic problems if the duplicate membership is recognized by the analyst.

The second step in the ETE analysis is to define the *unit of analysis*, that is, what is meant by an ‘‘evacuee’’. Although the goal of evacuation is to remove people from the

EPZ, it is the number of evacuating *vehicles* that defines the demand for roadway system. The number of vehicles evacuated by the permanent population typically is estimated from the number of evacuating persons which, in turn, is taken from census data (often updated for growth). Since it is well established that people evacuate as a household unit [7], the number of evacuating households must be estimated from the risk area population. Finally, one must estimate the number of vehicles evacuated by each household. It is likely that — on average — more than one vehicle, but less than the number of vehicles registered to the household will be used. Data from one evacuation indicate that an average of 1.3 vehicles per household was evacuated, and this was only 52% of the available vehicles [8].

Returning commuters need to be identified in an ETE analysis because they are permanent residents who work outside the EPZ and are likely to return home before evacuating as part of a household. Returning commuters move in a direction opposite to the general evacuation during the early portion of an evacuation while other members of the permanent population are at home preparing to evacuate. The time required to return home is likely to take place concurrently with household evacuation preparation if there is someone else home who can perform the preparation activities. Returning commuters are not considered evacuation trips for purposes of estimating ETEs because they move counter to the evacuation flow and, hence, do not compete with evacuees for roadway capacity.

The size of transient populations is derived from other local sources of data, including records of attendance athletic events and festivals. In some cases, the analyst might have archival data, either about the number of people or the number of vehicles. In other cases, special field studies may need to be conducted to estimate the size of transient populations. For example, one can estimate the number of vehicles at a beach by counting them in the parking lots during holiday weekends during the summer. Alternatively, a reasonable upper bound to the number of evacuating vehicles might be estimated from the number of available parking spaces.

Special facilities — including schools, hospitals, athletic stadiums, shopping malls, and jails (see Ref. [8], for a more complete list) — must be addressed individually because the transportation needs of their users vary so greatly. These facilities vary in the mobility of their users, their periods of use, and the density of their users. They also vary in the availability of sheltering in-place and the type of transportation support required, such as buses or ambulances. The analyst can identify specific vehicle requirements for transportation support only by interviewing representatives at each individual facility.

Once the number and type of vehicles for each special facility have been determined, ETEs are calculated by estimating mobilization time, loading time and travel time. If enough vehicles are available to evacuate the facilities in a single trip, then evacuation time is determined by those vehicles' mobilization time, loading time, and travel time out of the EPZ. If multiple trips are required due to vehicle limitations, time will be required for the additional trips.

Careful analysis is necessary to avoid unrecognized double counting although, as noted earlier, double counting is necessary and will not cause significant problems if handled properly. For example, school children are counted both as permanent residents and as special facility populations. This is because in some cases the school children may evacuate from school (week-day/school-year/daytime) and in others, from home (summer or evening). The school children must be counted separately in order to determine vehicle needs for a direct evacuation from schools. As long as this double counting is recognized, it has no adverse effect on the accuracy of ETEs.

There are two types of extraneous traffic in the EPZ that are added to the demand on the available roadway capacity. These are *voluntary evacuees* and *background traffic*. Voluntary evacuees are those who decide to evacuate without being advised to do so. The terms ‘‘spontaneous evacuation’’ and ‘‘shadow evacuation’’ are also applied to this phenomenon. There are two different groups of voluntary evacuees to be considered. The first is made up of individuals living within the EPZ but not within the area where evacuation has been advised. This group is a part of the EPZ population (permanent residents, transients, or special facility populations) and so has been addressed in the ETE study. The second group is made up of those living *outside*, but near the EPZ, who may relocate in response to an evacuation order directed at people living within the EPZ. This group typically has not been considered in ETE studies.

It is important to recognize that voluntary evacuees are a problem only to the extent that they interfere with those whom the authorities have advised to evacuate. Some voluntary evacuees can be ignored in the analyses because they are expected to leave the EPZ using roads other than the designated evacuation routes. Other voluntary evacuees are a problem because they are very likely to use the designated evacuation routes. In this case, the analyst can estimate the number of voluntary evacuees and include them in the estimate of evacuating traffic demand. Alternatively, voluntary evacuation can be controlled though appropriate traffic management plans that direct voluntary evacuees away from evacuation traffic. Of course, this latter procedure diverts traffic management resources away from traffic control on the evacuation routes. The choice between accommodating voluntary evacuees on the evacuation routes and diverting them away from the evacuation routes should be made on the basis of which alternative minimizes evacuation time.

The second source of extraneous traffic demand, background traffic consists of vehicles that are present during an evacuation but are not associated with permanent residents, transients, special facility populations, or voluntary evacuees. The most common example of background traffic would be *through traffic* on major inter-city routes such as interstate highways. The preferred method for controlling background traffic is to institute access control measures to direct it onto alternative routes outside the EPZ. If this traffic is not rerouted before it enters the EPZ boundary, it must be considered part of the evacuating traffic.

2.4. Capacity estimation

Transportation analysts classify roadways using a hierarchy ranging from locals, to collectors, arterials, and freeways. Local streets primarily provide access to individual residences. Collectors concentrate local traffic and, ideally, provide access to arterials. Arterials are the roads and streets whose principal function is to move traffic. Freeways are a special type of arterial with controlled access.

In ETE analyses, the primary evacuation roadway system generally is limited to arterials and freeways. It is unnecessary to analyze all roadways in an EPZ because the critical elements of the evacuation roadnet typically are those points at which large volumes of traffic converge. Delay on the evacuation roadway system (if it occurs) generally will be located at the convergence of two arterials, or at arterial access to freeways. However, collectors or even local streets may be used to improve the operation of the evacuation roadnet. Opportunities to improve an evacuation by using any roadway that could reduce evacuation time should not be overlooked. That is, an effective traffic management plan could use a minor roadway, such as a local street, to improve evacuation capacity.

To determine roadway capacities, the roadway characteristics (number of lanes, lane widths, shoulder widths, grades, etc.) and traffic control measures (traffic signals, stop signs, lane use restrictions, one-way streets, etc.) must be determined through field surveys. Maps and other available databases should not be to be relied on without field verification.

2.5. Capacity under adverse conditions

Many studies have found that roadway capacity can be significantly reduced by weather conditions such as rain, snow, ice, and fog [9–18]. Specifically, rain reduces speeds up to 10% and capacity 10% to 20%. Capacity is affected more than speed because drivers increase the distance between vehicles in addition to decreasing speed. Light snow is similar to rain, reducing capacity from 10% to 20%. Heavy snow reduces capacity up to 30% in heavy traffic. The largest capacity reductions have occurred for heavy snowfall or for heavy rates of rain that obscure visibility. Based on this research, weather-related capacity reductions of 20–25% typically should be used in evacuation studies.

Extreme conditions (e.g., high wind, debris, flooding, deep snow, or ice) can make a roadway impassable. In such cases, the time required to make a roadway suitable for evacuation must be added to the ETEs. Because these times can only be estimated on a case-by-case basis, the impact of adverse weather conditions must be assessed at the time protective action recommendations are being evaluated. However, different evacuation routes may vary in their vulnerability to some hazards such as flooding. This vulnerability can be assessed in advance and considered in the selection of evacuation routes.

The impact of roadway construction usually is not considered in developing ETEs because construction disruption usually is temporary. Roadway construction can greatly reduce roadway capacity, but protective action analysts must consider these effects on a case-by-case basis. Protective action analysts can make appropriate adjustments for conditions such as construction activities if they are aware of the sensitivity of ETEs to changes in evacuation route capacity as this has been demonstrated in their analyses.

An evacuation could conceivably be delayed by accidents or breakdowns, but ETE studies normally include no special analyses of the effects of traffic accidents on evacuation route capacity because accidents and breakdowns are relatively rare, isolated, and transient events. That is, they are likely to occur only infrequently and affect only limited segments of the evacuation roadnet. In addition, they would be expected to have only a temporary effect because vehicles that both are traveling outbound would be expected to have only a minor collision. Instead, emergency planners can minimize the potential impact of traffic accidents and breakdowns on ETEs by providing for tow trucks to remove disabled vehicles. The rapid clearance of damaged or stalled vehicles will significantly reduce any negative effect on roadway capacity.

2.6. Traffic management

The typical means of reducing evacuation time is the implementation of traffic management actions. These can achieve improved traffic flow on the roadway network either through demand reduction or capacity enhancement. In turn, capacity enhancement can be classified as either permanent or expedient.

Permanent capacity enhancement, achieved by constructing additional lanes of roadway, usually is not cost-effective because extremely high demand is very rare. However, expedient capacity enhancement can be achieved at minimum cost by temporarily reversing the direction of specific lanes. This latter tactic is appealing because it would appear to double evacuation capacity. However, converting all the roads leading out of the EPZ to one-way traffic is not an acceptable alternative because it ignores the need to provide access to the EPZ for emergency workers and returning residents. Consequently, at least some routes out of the risk area should have inbound lanes. Other expedient measures include waiving tolls at tollbooths and changing signal times or assigning traffic control personnel to decrease the portion of the signal cycle that is allocated to cross-traffic.

Demand reduction also can be achieved in a number of ways. Load balancing can be achieved by diverting evacuation traffic from routes with excess demand to those with excess capacity. Access control precludes entry into the EPZ by those who do not belong there. However, to be effective, access control must reroute traffic around the evacuation area and keep it from affecting the flow of evacuation traffic. Traffic routing can be achieved through the use of traffic cones or barricades, but traffic control points often must be staffed by traffic control personnel to ensure driver compliance. In light of these resource constraints, the ETE study should identify the locations in which traffic management actions are most urgently needed to achieve the minimum evacuation time.

Alternatively, these resource limitations can be avoided through the use of Intelligent Transportation Systems. Some of these systems have the capability of monitoring weather conditions, roadway conditions, and traffic conditions. In addition, some ITS systems have various ways of communicating with travelers (including changeable message roadside signs, highway advisory radio, and eventually in vehicles) and changing traffic control devices such as traffic signals. Where available, ITS offers a substantially enhanced capability for efficient evacuation management.

2.6.1. Trip generation time (TGT)

TGT is the interval between the issuance of an evacuation recommendation and the beginning of households’ departure from the EPZ. TGT includes four distinct activities — warning receipt, preparation to leave work, return from work, and preparation to leave home — that are bounded by the five events in Table 1. Thus, the normal sequence of evacuation events during working hours is 1, 2, 3, 4, and 5. These trip generation activities normally are dependent (occur in series), but can be independent (occur in parallel). For example, people at work cannot prepare to leave home until after they arrive home. Thus, these normally are considered to be dependent events. However, a spouse might be able to make preparations for the household to leave while a worker is returning home, thus making these independent activities. Moreover, some of these activities can take zero time. This would be the case, for example, if an evacuation warning were received at a time when workers already are at home (e.g., evening or weekend).

The time required for event sequence 1–2 is the time required for the activity ''population warning''. The time required for event sequence 2–3 is the time required for the activity ''preparation to leave work''. The time required for event sequence 3–4 is the time required for the activity ''travel home''. Finally, the time required for event sequence 4–5 is the time required for the activity ''preparation to leave home''. The TGT required for a given household is simply the sum of the times required for each activity.

Determining the aggregate TGT required for the entire EPZ population (i.e., for all households) is more complex. If everyone had the same time requirements for each activity, the process of estimating trip generation would be straightforward. It only would be necessary to estimate the time required to complete each activity and then add these estimates to compute the aggregate TGT. Obviously, this is incorrect because the time required for any given activity varies across households. Less obvious is the fact that ''conservatively'' assuming this is so can produce extremely inaccurate ETEs. Because households differ in their time requirements, the time required by the household taking the longest time obviously will be longer than that required by most others. If the capacity of the roadway system is the limiting factor, which will be the case in most EPZs, assuming all households require the maximum TGT will result in excessive ETEs. This is because most households actually would have left earlier.

The correct method of analysis is to determine the *distribution over time* of households that have completed each event (warning receipt, departure from work, arrival at home, departure from home). The probability distribution for an activity shows what fraction of the population has completed that activity in a given span of time. Such probability distributions can be constructed in any one of a number of different ways, depending on the data available. A typical approach is for the analyst to construct a

Table 1
Component events for trip generation times

Event number	Event description
1	Warning initiation
2	Warning receipt
3	Departure from work
4	Arrival at home
5	Departure from home

Table 2
Notification distribution (activity 1–2)

Elapsed time (min)	Cumulative percent notified
5	20
10	60
15	100

subjective estimate of the distribution from assumed average and extreme (minimum and maximum) time values. Alternatively, surveys of evacuees from previous emergencies can be used to characterize these distributions [8,19].

The distribution of evacuation departure times is determined by assuming that the probability distributions for all event are mutually statistically independent and by recognizing that the probability distribution of each successive event is conditional upon the distribution for the activities that preceded it. Thus, the probability of a given level of one event is multiplied by the probability of each level of the successive event. The following example illustrates the process.

If the evacuation protective action recommendation is issued when most people are at home during the night, the events with non-zero times will be: (1) warning initiation, (2) warning receipt, and (3) departure from home. Table 2 shows the assumed warning system effectiveness in providing notification (activity 1–2). Because everyone is assumed to be at home and, thus, activities 2–3 and 3–4 have zero times, Table 3 shows the assumed time required to prepare to leave home (activity 2–5).

Table 4 shows how to use the distribution of assumed warning (Table 2) and preparation (Table 3) times to estimate the distribution of trip generations times (Table 5). The two columns on the left of Table 4 contain the warning times and their associated probabilities from Table 2, while the two rows at the top of the table contain the preparation times and their associated probabilities from Table 3. Each cell entry in Table 4 is the product of the marginal probabilities from the respective row and column. For example, the probability of a household having a warning time of 5 min *and* a preparation time of 5 min, $P(t) = 0.03$, is equal to the probability of having a warning time of 5 min, $P(t) = 0.20$, times the probability of having a preparation time of 5 min, $P(t) = 0.15$. Table 5 is computed from Table 4 by summing the cell probabilities for all cells that sum to the same total TGT. For example, a TGT of 15 min can result from

Table 3
Preparation distribution (activity 2–5)

Elapsed time (min)	Cumulative percent ready to evacuate
5	15
10	30
15	60
20	75
25	90
30	100

Table 4
Computing the product of warning time and preparation time

			Preparation time distribution					
			$t=5$	$t=10$	$t=15$	$t=20$	$t=25$	$t=30$
			$P(t)=0.15$	$P(t)=0.15$	$P(t)=0.30$	$P(t)=0.15$	$P(t)=0.15$	$P(t)=0.10$
Warning time distribution	$t=5$	$P(t)=0.20$	0.03	0.03	0.06	0.03	0.03	0.02
	$t=10$	$P(t)=0.40$	0.06	0.06	0.12	0.06	0.06	0.04
	$t=15$	$P(t)=0.40$	0.06	0.06	0.12	0.06	0.06	0.04

either a warning time of 5 min and a preparation time of 10 min *or* a warning time of 5 min and a preparation time of 10 min, so the probability of a TGT of 15 min is equal to the sum of these two cells. The cumulative probability of a TGT of 15 min is equal to the sum of the probability of a TGT of 15 min plus the probability of a TGT of 10 min.

The computations shown in Table 5 indicate that the maximum notification time (15 min as shown in Table 2) plus the maximum preparation time (30 min as shown in Table 3) is equal to the *maximum* TGT, 45 min. The alternative analysis without distributions would ignore the roadway capacity available before 45 min because all evacuees would be assumed to leave home at 45 min. Thus, the use of distributions is essential in accurately estimating evacuation times for EPZs where roadway capacity causes delays to those evacuating.

2.7. Factors affecting ETE components

The time required for warning receipt depends upon the types of technology available (e.g., sirens, tone alert radios, route alerting) and people's involvement in informal warning networks [4,8]. Moreover, the time required to prepare to leave work after an evacuation warning will depend upon whether workers have received any preliminary

Table 5
Trip generation time

Elapsed time (min)	Cumulative percent ready to evacuate
5	0
10	3
15	12
20	30
25	51
30	72
35	86
40	96
45	100

threat information that has led them to engage in any preparatory actions before warning receipt.

The time required to return from work will depend upon the distance from work to home, the capacity of the roadways along that route, and the volume of traffic competing for those roadways, and the amount of cross traffic. If a worker's home is farther from the nuclear plant than is his or her workplace, then the return home can be considered as part of the evacuation traffic flow. This will add to the evacuation time (compared to receiving a warning at home), but will not be especially problematic. If the workplace is farther from the nuclear plant than is the home, then the worker's trip home will be counter to the flow of evacuation traffic. This also will add to the evacuation time, and will not be especially problematic. However, if the workplace is about the same distance as the workers' homes from the nuclear plant, then the workers' return to home must cross the evacuation traffic flow. A significant amount of cross-traffic is problematic for evacuation because it limits any reduction in green time for cross-traffic that intersects an evacuation route.

At minimum, preparation time requires only that the members of a household assemble and get into their car. This could occur if they received a warning message that indicated an immediate threat. More generally, the warning message will indicate that the threat is imminent, not immediate, and that evacuation will require an extended stay away from home. Thus, preparation time will include the time required to prepare the members of the household and the house itself for a lengthy absence.

2.8. Analysis tools

Conducting an ETE analysis simply involves estimating the number of vehicles that will initiate evacuation during each time period (the demand) and comparing those numbers with roadway capacity. As noted earlier, ETEs can be calculated manually when populations are small and the roadway system approximates a series of straight lines radiating from the center of the EPZ. The analysis becomes increasingly complex as the number of evacuation routes increases and when evacuation demand exceeds the capacity of the roadway network.

Computer models can reduce the computational effort and also allow for the consideration and refinement of more scenarios. However, they do require a competent transportation analyst. A computer model can handle only an approximate representation of reality, and the process of simplifying a real roadway system into a computer representation requires a significant degree of expert judgment. The fact that an ETE analysis has been conducted on a computer can easily give the protective action analyst a false sense of confidence. In fact, it is only the quality of the input data and the analyses themselves that should instill confidence in the resulting ETEs.

The IDYNEV computer model is a public domain program that is available through the Federal Emergency Management Agency and has been used successfully at a number nuclear power plants around the United States [20,21]. More recently, the OREMS model has been made available [22]. Other transportation operations oriented models also can be used. However, the use of transportation planning type models are generally not appropriate.

3. Other considerations

ETE studies should include a number other considerations. These include the nature of the ETE analyst's assumptions about driver behavior, ETEs for public transit dependent populations and special facility populations, and confirmation of appropriate warning response by the risk area population.

3.1. Assumptions

A number of significant assumptions must be made in order to develop ETEs for a particular site. If a site differs in significant ways from the ‘‘typical’’ site, it may be necessary to conduct surveys or collect site-specific data. However, regardless of their basis, any assumptions used should be documented. Documenting the assumptions that went into a particular ETE allows the protective action decision-maker to make more accurate adjustments for conditions arising during an actual emergency that differ from those in the scenarios used to generate the ETEs. One particularly important assumption concerns driver behavior. It has been widely observed that people do not panic in an emergency [7]. More specifically, drivers generally act in a manner that promotes good traffic flow during evacuations by obeying the rules of the road and acting in an orderly manner [23]. Furthermore, it is likely that the best driver in the family will be driving during the evacuation of a family group. Consequently, one can assume that there will be a very low incidence of traffic accidents and that the accidents that do occur will be minor and easy to clear.

Another important assumption is that evacuees will move in a radial direction away from the nuclear plant. While it is true that evacuees will want to evacuate radially away from the plant, this goal cannot always be completely satisfied in any actual roadway system. It is important that evacuation routing should not be contrary to the desired radial dispersion solely for the purpose of more effectively using available roadway capacity. However, the limited availability of roads might make it necessary for evacuees to move laterally or, in extreme cases, even toward the power plant for some part of their trip out of the area. To the degree that evacuees consider such routing as exposing them to danger, they are likely to choose an alternate evacuation route that they consider to be safer. The evacuation analyst must recognize this possibility and anticipate the possibility that the apparently safer route will become overloaded.

3.2. Public transport dependent populations

All EPZs have some portion of the risk area population that does not own or have access to a personal vehicle in which to evacuate. Many of these people are given occasional transportation assistance by friends, relatives, neighbors, or coworkers, and very likely to be given rides by these individuals in an emergency. However, public authorities cannot assume that offers of rides will be forthcoming from private citizens and, therefore, must plan to provide emergency transportation. In most cases, surveys must be conducted to determine the demand for public transportation and the types of vehicles that are needed. Once the level of demand has been determined, emergency planners must identify the sources of the vehicles that will be used to transport these people.

If a sufficient number of vehicles is available so that all of those requiring special transportation can be evacuated in a single trip, the analysis is relatively straightforward. The TGT components to be assessed are (1) the time required to mobilize the vehicles, (2) the time required for the vehicles to travel to their respective assignments, and (3) the time required to load the vehicles. Public transit dependent populations generally will be dispersed throughout the community, so pickup routes must be developed. Once the vehicles are loaded, they can enter the evacuation roadnet.

The analysis is more complicated when multiple trips are required of these vehicles because their outbound speed may be limited by other evacuation traffic on portions of the route. Delay in the outbound travel times on the first trip could significantly increase the ETEs for completing later trips and make the evacuation of the transit dependent population longer than that for the general population.

There are many alternatives for providing for the transit dependent population. The final choice will depend on local circumstances and the preferences of those providing the service. The critical issues are to determine (1) the number of persons requiring transportation, (2) the available vehicles, (3) the number of trips required, (4) the mobilization time, (5) the inbound travel time, (6) the pickup route time, and (7) the outbound travel time (taking proper account of traffic conditions).

3.3. Special facility populations

Special facility populations are similar to the public transit dependent. The first step is to identify the location and number of persons at special facilities (e.g., schools, nursing homes, hospitals, jails, see Ref. [8] for a more complete list). The next step is determine the number of vehicles available, the number of trips required, the mobilization time, the inbound travel time, the loading time, and the outbound travel time. A special facility population is by its very definition located in a single place so, unlike the public transit dependent population, pickup routes are not required. However, special facility populations often have limited mobility, so they may take as much time in loading as the public transit dependent population. As with public transit dependent populations, evacuation traffic on the outbound trip segments may cause delays when there are multiple trips or trips to multiple facilities. Moreover, some facility residents have unique mobility restrictions, so evacuation planners must make special arrangements such as security for the movement of prisoners.

By definition, special facilities must be addressed individually because of their distinctive requirements. Calculation of ETEs for these facilities is important but, as with the public transit dependent population, the primary issues are to determine (1) the number of persons requiring transportation, (2) the available vehicles, (3) the number of trips required, (4) the mobilization time, (5) the inbound travel time, (6) the pickup route time, and (7) the outbound travel time (taking proper account of traffic conditions).

3.4. Confirmation time

The principal reason for confirmation is to assure that the entire population has been notified. Additional reasons for confirmation include providing assistance to those having difficulty evacuating and the need to provide security once residents have left the EPZ. It is very difficult to provide timely confirmation of evacuation for everyone in a plume exposure EPZ with a large population, but there are methods of sampling the population to assess the effectiveness of the warning systems.

One common approach to confirmation of evacuation is to have patrol vehicles pass through the EPZ along planned routes. Drivers can tally the number of homes in which the occupants still remain and can provide a warning if there is no evidence of evacuation preparation activity. However, this process is slow.

An alternative approach is to conduct telephone sampling of the EPZ population. Statistical analysis can determine the appropriate sample size, while random digit dialing can be used to call households 1 h before the expected completion of evacuation. If no one answers the telephone, it is presumed that residents have been warned and have evacuated. The process can be continued through after the time that the evacuation is expected to be completed. Those at home during the telephone survey can report if they did not receive a warning, if the warning messages lacked credibility, or if they lack access to transportation. One potential impediment to telephone sampling is the substantial increase in demand for telephone lines that occurs during emergencies. Consequently, prior arrangements must be made to ensure priority access to the telephone system.

4. Conclusion

ETEs are important data for emergency response planning. To choose the best protective action to recommend in an emergency, emergency managers must have ETEs that are based upon accurate data and correct analysis. This will provide data that indicate if evacuation can be implemented in time to significantly reduce radiation exposures. However, ETEs are significantly affected by uncontrollable events such as adverse weather. Such conditions must be addressed by scenarios in the ETE analysis so that protective action analysts can make appropriate adjustments during an emergency. This is particularly important if the ETE analyst is not available to emergency managers during an event. Finally, ETE analyses provide important information regarding whether traffic management actions would significantly reduce evacuation times and can be used to guide the development of effective traffic management plans.

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