Diffusion of Emergency Warning: Comparing Empirical and Simulation Results

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ABSTRACT

As officials consider emergency warning systems to alert the public to potential danger in areas surrounding hazardous facilities, the issue of warning system effectiveness is of critical importance. The purpose of this paper is to present the results of an analysis on the timing of warning system information dissemination including the alert of the public and delivery of a warning message. A general model of the diffusion of emergency warning is specified as a logistic function. Alternative warning systems are characterized in terms of the parameters of the model, which generally constrain the diffusion process to account for judged maximum penetration of each system for various locations and likelihood of the public's being in those places by time of day. The results indicate that either telephone ring-down warning systems or tone-alert radio systems combined with sirens provide the most effective warning system under conditions of either very rapid onset, close proximity or both. These results indicate that single technology system provide adequate warning effectiveness when available warning time (after detection and the decision to warn) extends to as much as an hour. Moreover, telephone ring-down systems provide similar coverage at approximately 30 minutes of available public warning time.

KEYWORDS: Emergency warning, warning diffusion, chemical spills, warning systems, warning contagion

INTRODUCTION

Under the Emergency Planning and Community Right to Know Act [also known as Title III of the Superfund Amendments and Reauthorization Act (SARA)], communities are required to develop emergency response plans for fixed-site facilities that store hazardous chemicals. A critical part of that planning is the means to warn the public in the event of a release. Emergency warning systems for potentially hazardous facilities must be effective, and effectiveness depends on a number of factors. How many people will be alerted to hazards presented by potential emergencies? How will they know what to do in response to such signals? When will they receive the warning? This paper analyzes the dissemination of warning information; it deals with alerting the public and delivering a warning message.

A general logistic model for the diffusion of emergency warning is specified. Each alternative warning system is characterized in terms of the influence of the model parameters on the maximum penetration of each system. The parameters include locations

Risk Analysis, Edited by C. Zervos
Plenum Press, New York, 1991

and the likelihood of the public's being in those places by time of day. There are four independent warning systems that are considered separately:

1. a system consisting of sirens and alarms, prompting people to obtain additional warning information from the media;
2. a system comprised of tone-alert radios which are centrally activated and subsequently broadcast a warning message;
3. a system using automatic-dialing telephone systems, which hang up all telephones in the system, block out incoming calls, and then ring the phones and play a warning message; and
4. a dual media and route alerting system in which the Emergency Broadcast System (EBS) is activated and officials go through areas at risk to disseminate the warning.

Alternatives are then combined to achieve maximum warning system effectiveness. These two combined systems are as follows:

1. a combination siren- and tone-alert-radio system and
2. a telephone ring-down and siren system.

The probability that people located at various distances from a hazardous facility will receive a warning before exposure to airborne releases of toxic materials is compared for each warning system under three scenarios of hazard-onset speed. This analysis integrates a complex set of information to assist emergency managers in selecting effective emergency warning systems for use in conjunction with potentially hazardous facilities.

THE WARNING PROCESS

Warning people of impending danger encompasses two conceptually distinct aspects—alerting and notification. Alerting deals with the ability of emergency officials to make people aware of an imminent hazard. Alerting frequently involves the technical ability to break routine acoustic environments to cue people to seek additional information. In contrast, notification focuses on how people interpret the warning message. People's interpretation of the warning message is critically important in their selection of appropriate behavior in response to emergency warnings.

Emergency warning messages are received through a series of pathways that color their meaning. Some of this coloring is the result of cognitive processes; some is the result of the social structure. People interact with others, forming social networks, even though the forms of these networks vary. The routine and established nature of social networks has led to widely accepted generalizations concerning their function in society.[1,2,3,4] Social networks also function in emergency situations and shape the response to emergency warnings. Two general propositions are strongly supported by the disaster literature.[5]

1. People respond to emergency warnings in the context of prior experience and the existing social and physical environs that interact with the warning message; and
2. The extent to which the warning message is received depends on the nature of the warning message and the prior behaviors of all social actors.

Emergency warning messages are processed in the context of the social network. This means that people have pre-existing estimates of the threats presented by their environments. Furthermore, these estimates, together with personal experience, provide the basis for selecting behavior (i.e., whether to accept, ignore, disseminate, challenge, or confirm the warning message).[6]

One of the results of an emergency warning is the recognition of threat, which creates psychological discomfort. Many people alleviate this discomfort by reducing the uncertainty associated with the message.[7] The warning process (Fig. 1) involves factors that affect both the message and the characteristics of the receiver[8] or the sender and receiver.[9] Once the warning is received, its content is evaluated in terms of the certainty and ambiguity associated with the event—its estimated severity, timing and location of impact. This evaluation considers the likelihood of personal impact (will it affect me?), timing of impact (when will it occur?), and its anticipated effects (is the threat significant?).[10,11] The evaluation of the warning message leads to the determination of its relevance, which in turn leads to the perception of personal risk. If the message content is deemed irrelevant (I am not at risk), no emergency response is likely to ensue. However, should the warning message be considered relevant (I may be at risk), the message is processed in the context of prior disaster experience, relative proximity to the source of disaster, confidence in the source of warning, interpretation of the warning, and discussion with members of the social network. The warning message is processed in the context of the existing social structure, which leads to the initial perception of threat. The cumulative process provides the foundation for the selection and evaluation of emergency response behavior.

However, the warning response process is not a linear stimulus-response process.[12] The first issuance of warning sets in motion an information-seeking process by which people attempt to confirm and reconfirm the contents of the warning,[13] and to discover what friends, neighbors, or relatives are doing in response to the warning.[9] As a result, members of the public become part of the informal warning system by disseminating the message further.[8]

Public response to emergency warnings is heavily influenced by warning content. Janis[14] describes effective warning messages as requiring a balance between fear-arousing and fear-reducing statements. Fear-arousing statements provide sufficient description of the impending danger to evoke vivid mental images of the potential crises which reduce the chance of surprise as the event evolves. Fear-reducing statements present the realistic mitigating factors of the situation, while providing information concerning realistic responses by both authorities and individuals. The fear-arousing content of the warning message alerts the public to the potential for harm, whereas the fear-reducing content provides notification of appropriate avoidance, protective, and mitigative emergency actions. Empirical research provides ample evidence of the message factors that shape response.[9] These factors include credibility of the warning source; clarity, consistency, accuracy, and detail of the information; and frequency of the message issuance.

DIFFUSION OF EMERGENCY WARNINGS

The diffusion of emergency warnings resembles diffusion of other types of information or communication, except that it occurs over a shorter time period. The basic mathematical function is a logistic function. The cumulative proportion of people receiving the warning forms an S-curve which is determined by the exponential form of the initial alerting process and the logistic form of the subsequent contagion of the warning and message through the population.[8]

The alerting, characterized as a "broadcast process" that disseminates the emergency warning, is centralized in the sense that many are alerted simultaneously. Contagion, on the other hand, is characterized as a "birth process" whereby people first hear of the event and then sequentially tell others.[15] The general mathematical specification of the diffusion curve is

$$dn/dt = k[a_1(N-n)] + (1-k)\,[a_2 n(N-n)]\,.$$

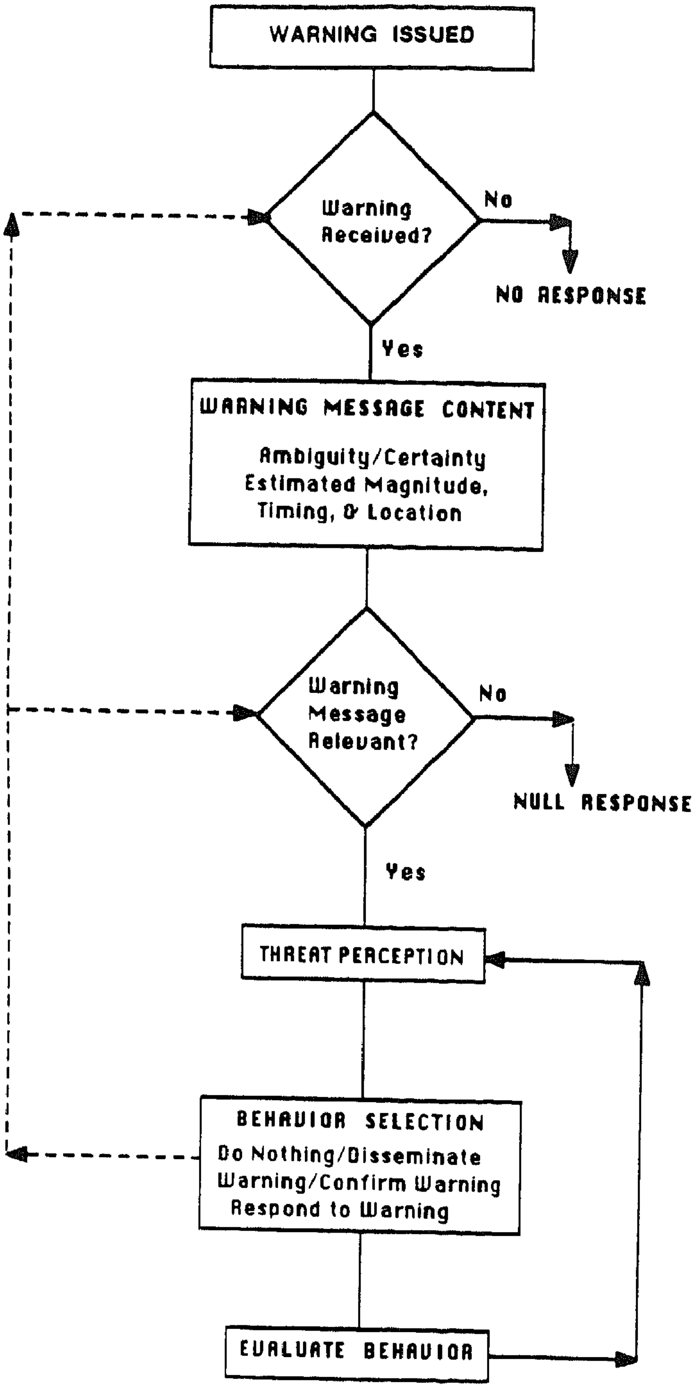

Fig. 1. Emergency warning and response process.

where k is the portion of the population alerted via the broadcast process, that is, the proportion of people who are alerted to the potential for harm who immediately recognize the meaning of the alert signal. The quantity $(1 - k)$ represents the proportion of people left to be warned. The broadcast parameter, a_1, summarizes the efficiency of the alerting process, and the birth parameter, a_2, summarizes the effectiveness of the contagion process. N is the proportion of the population to be warned, and n is the proportion warned at the beginning of each period $(t_0, t_1, \ldots, t_i, \ldots)$. Because each warning system provides differing degrees of information concerning the appropriate action to protect oneself from harm, or to mitigate the potential for harm, the broadcast and birth parameters represent the dependence of each system on alerting and contagion, respectively. For example, the contagion parameter for a siren system will be relatively high because it depends on recipients taking an active role in their own warning (i.e., they must do something). Usually this entails seeking further information via another (secondary) source.

DATA AND METHODS

Ideally, the process of estimating diffusion curves would first gather data concerning the timing of individual receipt of warnings in historical warning events that used different warning systems and then fit a logistic curve to the data and empirically derive the parameters. Unfortunately, due to methodological problems, reliable data of this kind do not exist. The most serious problem is obtaining data that are relatively free of recall problems. One such problem is the "suspended" time often reported by disaster victims. Typical interpretations of duration are seldom valid in emergencies.[16,17,18] Another form of this problem occurs as a function of time and the dissipation of accuracy in time estimates. Another problem is simply that the heterogeneity of accidents and disasters makes cross-hazard comparison, or even comparison within a single hazard (when other significant differences exist), difficult at best.

The method used here first specifies the parameters of the model based on the character of these warning systems, which are based on a limited set of data from warning events. The diffusion curve is then mathematically generated. And finally, they are fit to some limited data from several different disasters. This method provides a greater validity than would be obtained through simulation alone. The parameters are assigned to reflect the qualitative differences in warning systems. The results of this procedure are summarized in Table 1.

These warning diffusion curves are then compared with four warning cases where reasonably continuous data concerning receipt of first warning were collected: First, warning in two communities 20 miles (i.e., Toutle/Silverlake) and another that is approximately 35 miles (i.e., Woodland) from the cone of Mt. St. Helens as reported by Lindell and Perry.[19] Toutle and Silverlake are less than a mile apart and lie in flood plains of rivers that drain the Mt. St. Helens area; these were combined into a single sample. Woodland is on the Lewis River on the southwest side of the mountain. The second case involves two train derailments in western Pennsylvania, one in Pittsburgh and the other in Confluence.

Approximately 10 percent of the residents of Toutle, Silverlake and Woodland were sampled. The interviews were conducted in August and September 1980, approximately 10 to 18 weeks after the May 18, 1980 eruption. The completion rate for interviews conducted in Toutle/Silverlake was 89%, while the completion rate in Woodland was 90%. The data collection method is described in greater detail by Perry, Greene and Lindell.[20]

Two surveys of residents in the Bloomfield section of Pittsburgh were conducted by the University Center for Social and Urban Research at the University of Pittsburgh (UCSUR). The self-administered mail-back survey was distributed to 750 households in the

Table 1. Model Parameters Used to Estimate Diffusion of Warnings

System	k	Alerting Parameter		Contagion Parameter		30-minute limit	Release rate (%)
		Dependency	a_1	Dependency	a_2		
Sirens	0.2	Low	0.2	High	0.3	0.75	0.3
Tone-alert radios	0.4	High	0.3	Low	0.2	0.90	0.1
Media	0.3	Moderate	0.2	Moderate	0.25	0.50	0.5
Telephones	0.4	Very high	0.35	Low	0.2	0.93	0.1
Siren and tone-alert	0.4	High	0.3	High	0.3	0.95	0.1
Siren and telephone	0.4	Very high	0.35	High	0.3	0.95	0.1

emergency area in mid-June 1987, approximately 9 weeks after the April 11, 1987 accident. These households proportionally represent the 1980 population residing in each Census tract in the affected area of the city. Households were selected from each street in each Census tract in the affected area to assure even coverage. No follow-up letter or contact was initiated by UCSUR, although the cover letter gave contact information for respondent-initiated follow-up. A total of 220 questionnaires were returned by mid-August, yielding a response rate of 29.3%. In addition, 129 telephone interviews of area residents were made between July 14 and 22, 1987. A non-systematic, non-random procedure was used by UCSUR to represent each street in the impacted area. A total of 214 working residential telephones were selected, representing households in the affected area and not selected for study via the mail-back survey. A three call-back procedure is employed by UCSUR, which means three attempts to complete the interview are made at various times-of-the-day and days-of-the-week for each selected number. This procedure yielded an effective response rate of 60.3%. When combined, the two surveys represent 7000 households in the Bloomfield area; 349 completed instruments constitute a combined response rate of 36.2%.

Approximately 12% of the listed and unlisted residential telephone numbers in Confluence were sampled. The interviews were conducted from October 20 to 28, 1987, approximately 22 weeks after the May 6, 1987 accident and precautionary evacuation. Interviews with 106 residents of Confluence resulted in an 89.8% response rate. The method is discussed in greater detail by Snyder and Schlarb.[21]

SPECIFYING THE DIFFUSION MODEL

As with any simulation process, the selection of the parameters of the model is critical and tends to become the central focus of discussion of the simulation results. Alternative parameters for such simulations can be examined, adjusted, and analyzed as more empirical evidence becomes available.

The proportion of people receiving the alert signal and immediately recognizing its meaning, k, depends on the capability of the warning system to produce a signal that will be heard and understood immediately. The choice of k reflects the partition between people fully warned via the warning system (broadcast), including both alerting and notification, and those warned through contagion, requiring a secondary step of notification (birth). Warning systems which alert people to the potential for harm and which clearly and immediately notify them of appropriate protective action depend on the broadcast process. Telephone and tone-alert radio systems and systems combining telephones and tone-alert radios with sirens are the systems that are most dependent on the broadcast process. At the other end of the spectrum, siren systems depend on a second step in the warning process that requires the recipient to acquire information concerning appropriate action from another (secondary) source. Media-based systems are moderately dependent on the broadcast process.

Warning systems that include systems based on telephone and radio-alert are least dependent on the contagion process. Siren-based systems, however, are highly dependent on contagion in that people are not likely to know what to do. Media-based systems are moderately dependent on contagion. Because some members of society cannot be expected to understand the meaning of warning signals regardless of their effectiveness, all emergency warning systems depend on the contagion process to some extent. For example, no one expects all children to comprehend the warning message and be able to carry out protective action. Dependency on contagion also occurs because of the complexity of the warning process. Emergency warning is not a simple stimulus-response situation. The simplified warning process depicted in Figure 1 represents a complex of social and psychological processes which suggest that people will seek additional information to reduce uncertainty.[8,9,11,]

The alerting parameter, a_1, depends on the efficiency of the broadcast process. It reflects the ability of the warning system to reduce uncertainty through the broadcast process. The alerting parameter, a_1, represents the proportion of previously unwarned people who are warned (including both alerting and notification) during the period t_i to t_{i+1} via the broadcast process. The selection of the exponential growth curve thus represents the efficiency of the broadcast process in providing complete warning.

The most efficient warning system is a telephone system because most people hear and answer phones when they ring. Furthermore, nearly all will listen to the message, particularly if the message makes it clear that "this is an emergency." The telephone system also offers the recipient two-way communication via information numbers, further reducing uncertainty by providing additional information. Tone-alert radios are slightly less efficient than the telephones because some people will not hear the radio activate, some will have trouble understanding the message, and radios are one-way communication channels. Although these differences are subtle, they are likely to reduce efficiency. The media has a low alerting parameter because at any given time, including peak use hours, the vast majority of people are not engaged with the electronic media. Media-based systems work only if the recipient happens to be listening at the time of warning. This means that people must act by coincidence prior to the warning.

Siren systems are less efficient than other systems for a variety of reasons. The most important reason is the dependence of siren-based systems on an active participation in the warning process. People must do something immediately to find out what the siren means, which protective actions are required, and how to take them. A number of factors contribute to one's not hearing the siren(s), not recognizing its meaning or not recognizing that a warning situation exists when the siren is heard.

The contagion parameter, a_2, is based on the efficiency of the birth process. It reflects the ability of the warning system to reduce uncertainty through the contagion of warning. The contagion parameter, a_2, represents the proportion of previously unwarned people who are warned (including both alerting and notification) during the period t_i to t_{i+1} via the birth process. The selection of the logistic growth curve represents the efficiency of the birth process in providing complete warning.

Siren systems are evaluated as highly dependent on people's search for additional information to determine the meaning of the siren signal. However, once such information is sought, which is represented as $1 - k$, the notification is assumed to be quite effective (i.e., a_2 is relatively high). This occurs because people actively seeking information are more receptive of the information provided (i.e., they are listening).

Media-based warning systems are characterized by a process in which people hear a warning and tell others to listen. Hence, these systems are moderately dependent on the birth process for initial alerting, even though they are relatively effective in notifying people who are tuned in about what to do. Both media- and siren-based systems depend on contagion $(1 - k)$. However, the former requires contagion for initial alerting that an emergency exists, and the latter requires it for notification of appropriate protective actions to be taken. Because siren-based systems represent official warning, they are expected to be slightly more efficient than media-based systems that require social network alerting. Systems based on tone-alert radios and autodial telephones are least dependent on contagion $(1 - k)$; in addition, they can provide information only to limited numbers of people at one time. They are therefore judged to have the least efficient contagion process, represented by low contagion parameters.

Limits on the diffusion rates were imposed based on judgments of the level of warning that could theoretically occur in the next 30 minutes (t_i to t_{i+30}) under good warning conditions. These limits were derived from empirical observations and their extrapolation.[22] Because warning is a cumulative process, all systems are expected to warn almost 100% of the population at some point. The initial limits imposed on each system are presented in Table 1. To represent the cumulative nature of the process, the initial limits are gradually released throughout the warning period. This is equivalent to recognizing that the capability to warn people in the next 30 minutes depends in part on the number warned in previous periods. For example, warning in the next 30 minutes has only 30 minutes initially, but 10 minutes into the warning period, the cumulative warning window time is 40 minutes. The release rate values in Table 1 allow the limits imposed on each system to increase, approaching 100% of the population warned in the long run. Conceptually, the release rate characterizes the constraints associated with different warning systems.

Because of the synergistic effect associated with combined systems, the parameter specification for them selects the least restrictive release rate associated with the two combined systems. This reflects the complementary nature of the combined systems, providing the primary reason for using the two systems. All emergency warning systems depend on the contagion process.

ADJUSTING FOR LOCATION AND TIME OF DAY

Warning systems are generally characterized by their ability to alert people and transfer information. The penetration of the emergency warning systems varies for people in different locations and engaged in different activities. Each warning system has a different penetration capability in five fundamental locations/activities: (1) home asleep, (2) indoors at home or in the neighborhood, (3) outdoors in neighborhood, (4) in transit, and (5) working or shopping. In addition, two activities are allowed to "override" the other locations/activities, that is, watching television and listening to the radio. Such electronic-media-"exposed" activities are relevant for warning because some of the systems depend on these forms of media. Figure 2 summarizes the average percentage of the population in these location/activity categories over a 24-hour period starting with 12 midnight.[23] Table 2 provides estimates of the percentage of the population reached by each warning system

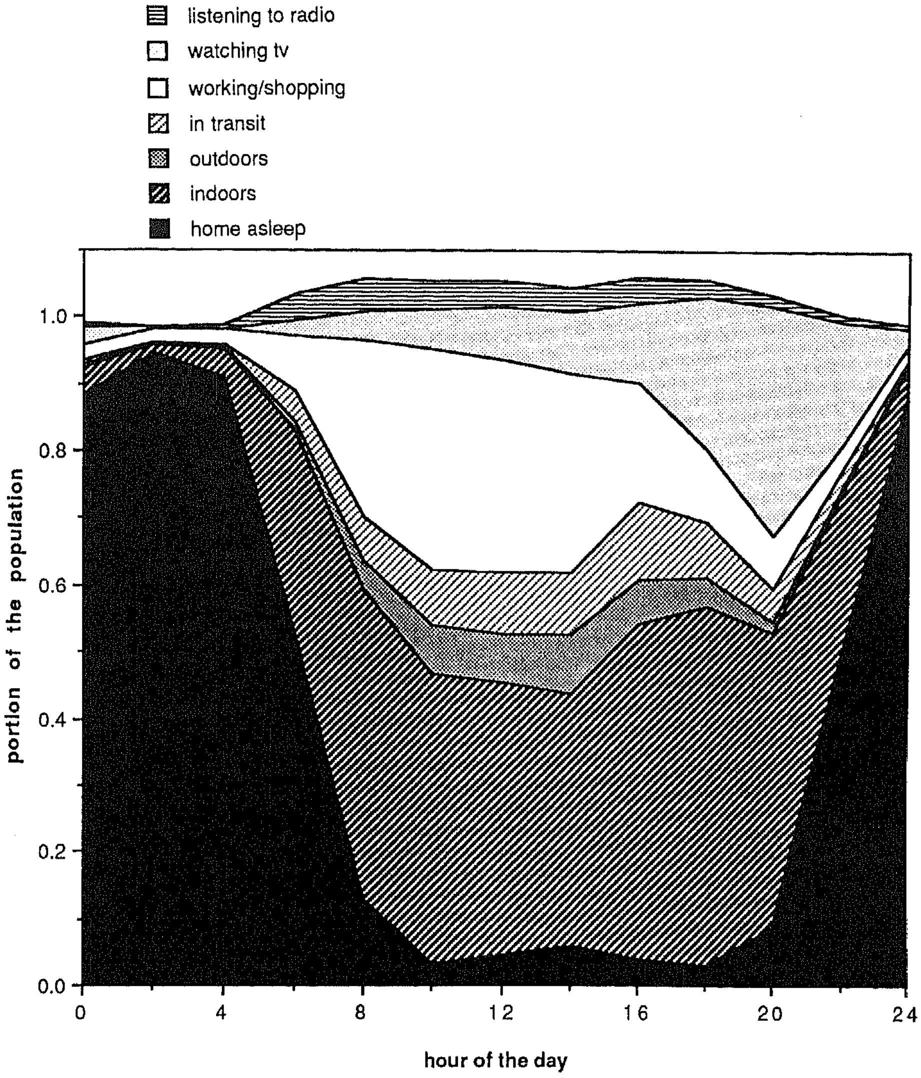

Fig. 2. Average time budget.

while engaged in the different activities. The effect of these locations is presented in greater detail in Ref. 24. The logical process is illustrated through the discussion of the effects of being at home asleep.

One of the most vulnerable positions, at least in terms of perception, occurs when people are at home asleep. In a regional survey, Nehnevajsa[25] asked people what kinds of things awaken them at night, for example, between 2 a.m. and 4 a.m. The results indicated that 69.1% of the residents in southwestern Pennsylvania are aroused from sleep by sirens in their area, and 93.3% reported that telephone calls wake them up. These empirical data are used as estimates of the penetration rate for the siren and alarm and the telephone ring-down systems, respectively. Because tone-alert radios are similar to telephones but may or may not be physically located in the bedroom, as are many phones, the penetration rate for tone-alert radios is estimated at 85%. Furthermore, because media and the emergency broadcast system are dependent on having either a radio or a TV on at the time of warning

Table 2. Warning Systems Effectiveness by Location and Activity

	Alternative Warning Systems				Siren and Alarm Systems Combined With	
Location/Activities Alarms	Sirens and Radios	Tone-Alert Phones	Auto-Dial Media	EBS/ Radios	Tone-Alert Phones	Auto-Dial
Assumed Penetration by Location/Activity						
Home asleep*	0.691	0.85	0.933	0.0	0.90	0.933
Indoors at home or in neighborhood	0.80	0.90	0.95	0.40	0.90	0.95
Outdoors in neighborhood	0.90	0.0	0.0	0.20	0.90	0.90
In transit	0.90	0.0	0.0	0.20	0.90	0.90
Working or shopping	0.60	0.70	0.80	0.10	0.70	0.80
Television	N/A	N/A	N/A	1.0	N/A	N/A
Radio	N/A	N/A	N/A	1.0	N/A	N/A
Time-Adjusted Warning System Effectiveness						
Annual average	0.665	0.685	0.745	0.287	0.784	0.826

*Reported arousal by sirens and telephones is derived from a survey in 1985 by the University of Pittsburgh, Center for Social and Urban Research. (See Ref. 25.)

and because most people do not sleep with them on, the penetration rate is assumed to be zero for media/EBS warning systems.

Existing data are used to estimate directly the parameters of some systems and logically extended to reflect the known characteristics of the other warning systems. People who are watching television or listening to the radio are assumed to be engaged with the media, so that they would be warned even if they are doing other things while they are watching TV or listening to the radio. For example, people that are working around the house while listening to the radio would be likely to receive emergency warning broadcast on that medium.

ADJUSTING FOR HOW PEOPLE SPEND THEIR TIME

The probability that people would be located in a specific location was estimated on the basis of data collected by the Survey Research Center at the University of Michigan for a national probability sample of U.S. households in 1975 and again in 1981.[23,26] This analysis employs a daily schedule data structure.[27] Figure 2 summarizes the average annual daily time budget.

Each type of warning system is evaluated in terms of the likelihood that people in the different locations will be warned; moreover, the locational capabilities of each system are mapped onto the probability that people will be in these locations at various times of the day. This mapping of locational system effectiveness on the likelihood of the presence of people in these locations provides a relative effectiveness in terms of the likelihood that people will be engaged in various activities in various locations (Table 2).

The warning dissemination process is adjusted to account for time-dependent activities by multiplying the location activity adjustment factor in Table 2 by the average portion of the population engaged in each activity in a 24-hour period. This value represents the portion of the population in each activity assumed to receive the warning. This is then summed for each warning system to achieve the time-adjusted warning system effectiveness score. The resulting score is then used to weight the original alerting parameter (a_1) in the diffusion model. This weighting reduces the influence that the initial alert has on diffusion according to the average distribution of people in various activities who would not receive an initial alert. The time adjusted model was run with these parameters to derive the adjusted curves of Fig. 3. This procedure can also be altered slightly to produce time-specific curves to reflect the locations/activities of the population for any 2-hour period.

EMPIRICAL FIT WITH EXISTING DATA

The warning diffusion curves, which are now adjusted for location-specific penetration on the basis of the likelihood that people will be in a specific location, are presented, with six empirical cases of emergency warnings. The first case represents an emergency warning summary of the Big Thompson Flood of 1977.[28] The study found that approximately 30% of the population a received warning in a manner other than by seeing the water coming. It is difficult to estimate how much time was spent warning people. The incident suggests that downstream residents received a 45-minute warning time, whereas residents further upstream had only a 15-minute warning. The average of 30 minutes is employed here. The second observation is the Fillmore Flood, in which 72% of the population at risk were warned in about 60 minutes.[10] There are two observations at the 2-hour mark: one reports a complete warning of nearly 100% during the Mississauga chemical accident;[29] in the other incident, the Sumner flood, 84% of the population were warned in about a 2-hour period.[10] Two additional cases are reported with an approximately 2.5-hour warning time: a 96% warning is reported by Perry and Mushkatel[30] in response to a nitric acid spill in Denver, Colorado; in the Mt. Vernon, Washington, chemical accident, 82% were notified as the result of emergency response effort.[30] Figure 4 qualitatively compares siren- and media/EBS-based warning systems with these empirically observed emergency warnings.

The data from the two train derailments and Mt. St. Helens concerning the receipt of warning are compared with the siren- and media-based systems in Fig. 5 in terms of the cumulative proportion warned by time into the event. The measurement difficulties are clearly evidenced by the proportion of respondents that reported receiving warning prior to the occurrence of the train derailments. This seems to occur at least partially because of the way people think about and recall time. For example, the noontime Pittsburgh event actually occurred at 12:25 p.m., but many of those reporting warning receipt prior to that time said they were warned at noon. It is not hard to construct that many people would recall the time in terms of what they were doing at the time (e.g., eating lunch) and report it as noon (i.e., 12:00 p.m.). The proportion warned initially (i.e., at the time of the eruption) is assumed to be zero in the communities impacted by the eruption of Mt. St. Helens.

The communities of Toutle and Silverlake were assessed at greater risk prior to the eruption than Woodland. As a consequence the sheriff's office made special efforts to make

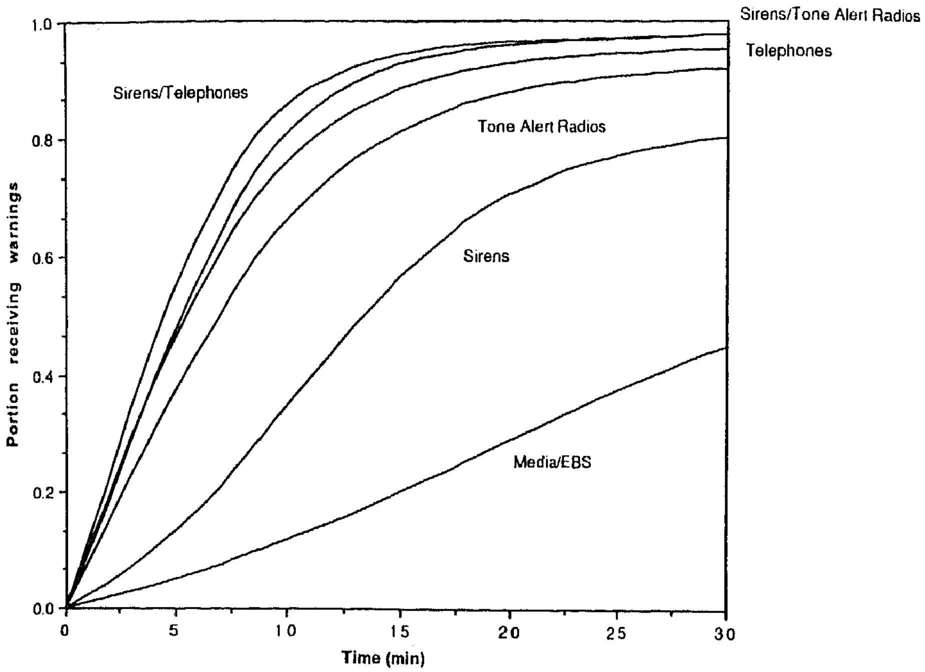

Fig. 3. Time adjusted warning diffusion.

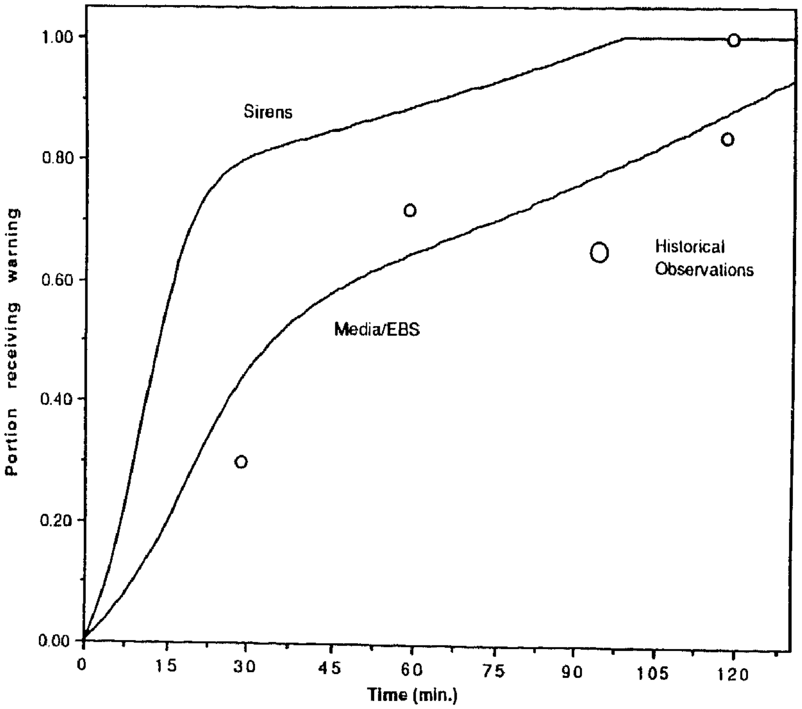

Fig. 4. Time adjusted warning diffusion compared with historic cases.

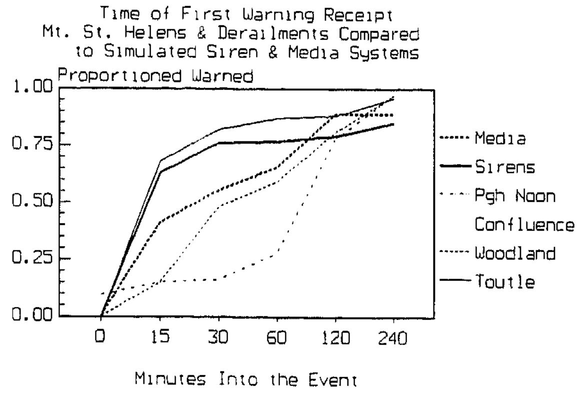

Fig. 5. Time of first warning receipt.

residents of these areas aware of the hazard. Hence, it was anticipated that residents of the Toutle/Silverlake area would receive warning more quickly than Woodland area residents, because of the effort to setup a warning system and because of the social networks known to emerge in disasters. Toutle/Silverlake residents were expected to rely more on officials and neighbors than Woodland, where media sources were deemed more important. The data indicate that social networks were the most frequently cited source of first awareness in both cases, with recognition of environmental clues being the second most cited source in Toutle/Silverlake and media being the second most cited source of warning in Woodland.[19] The result is that social network warning sources stimulated on the basis of direct environmental evidence (i.e., in Toutle and Silverlake) generated 82% coverage in 30 minutes, while the media driven social network warning system (i.e., in Woodland) reached 81% in two hours.

Both train derailment warning situations consisted primarily of route-alerting and door-to-door warning systems. Each is characterized by an S-shaped curve, with the Confluence warning reportedly approaching 90% warned in about two hours and the Pittsburgh event reportedly approaching 80% warned in about three hours. However, because of methodological uncertainties it is possible to identify only people that positively report having received some kind of warning. It is not possible to identify those not receiving warning. While the warning situations in Confluence and Pittsburgh are characterized by rapid dissemination in the first hour and half of the event, only 12.5% report being warned in the first 15 minutes in Pittsburgh while 36.8% reported being warned in the same period in Confluence. This may be a function of a number of factors, including the type of event, the size of the area to be warned, distance from the source, the time of day, or a bias associated with attributable experience gained vicariously in Confluence when the Pittsburgh event occurred about a month earlier. In Confluence, almost 70% report receiving warning in the first hour, while only 23% report having received a warning in the same period in Pittsburgh. Neither event is characterized by complete (100%) warning, and both indicate that very rapid onset emergencies can result in people being engulfed in danger prior to receiving warning.

WARNING SYSTEM EFFECTIVENESS

From an emergency management standpoint, the most appropriate measure of effectiveness is the ability of a warning system to provide populations at risk with adequate time to respond appropriately to the situation. Hence it is not necessarily the time it takes to warn people but the timing with respect to the onset of hazard that provides a measurement of warning system effectiveness. For example, a warning system that takes only 10 minutes to warn a population that will be exposed to hazard in 8 minutes is certainly less effective than a system that provides warning in 1 hour when exposure occurs in 1-1/2 hours.

Three hypothetical situations are posited to compare the onset of hazard emanating from a source at a rate of 1, 3, and 6 meters per second. These could occur as a flash flood brought on by a cloudburst or a dam failure upstream, such as those at Buffalo Creek or the Teton Dam failure; as a toxic-vapor cloud emanating from a noxious facility; or as a transportation accident, such as the accidents in Mississauga, Ontario; Bhopal, India; or Institute, West Virginia. In the case of airborne toxins, the variable rates are attributable to differing meteorological conditions and, in particular, wind speed. The variable rates of downstream exposure in river basins are the consequence of various hydrological characteristics, such as vertical drop per kilometer.

Because the warning systems examined here are concerned with public warning, they do not treat time needed for hazard detection or communication and decision making by authorities as a variable factor. It is assumed that the process of deciding to warn takes an average of 10 minutes and that the warning procedure begins at that point in time. If the decision time is longer or shorter, the numbers reported would change, but the overall relative performance would remain unchanged. Such organizational decision-making time is variable, given the events in question. At Bhopal, approximately 20 minutes elapsed prior to any alarm, and the public alarm was apparently shut down completely for nearly 30 minutes after that.[31] In the Cheyenne flash flood, public warnings began to be issued 5 minutes after detection.[32] This analysis considers a critical area of 35 km from the hazard source. Beyond 35 km, no specialized warning effort would be needed, because sufficient time would exist to disseminate a warning using an ad hoc procedure.

The probability of warning people prior to exposure at various distances is estimated by combining the estimates based on the models for each warning system alternative with hypothetical "downwind/downstream" times (Table 3). The most important insight provided by these results is that the amount of time it takes an organization to decide to warn, which includes hazard detection, is critical to warning system effectiveness. The results in Table 3 demonstrate the critical nature of organizational decision-making under conditions wherein warning time is most limited. People cannot fully protect themselves from hazard when they do not receive warning before exposure to emerging emergency conditions.

A second significant implication of the analysis concerns the feasibility of alternative forms of population protection. Many fatalities from floods result when people attempt to evacuate or cross a flooded stream in an automobile.[32] In chemical emergencies, eight out of every 100 evacuees are injured by inhalation of toxic vapors.[33] Alternatives to formal evacuation in fast-onset events include escape and sheltering. Escape is the movement on foot out of the flooding area or the toxic plume.[34] Sheltering involves moving to a secure place in a structure and taking steps to keep the hazard agent from entering the structure. In chemical incidents, sheltering may be an extremely effective way of self-protection.[35] Our analysis supports both actions as practical alternatives to formal evacuations because of the relatively short time to implement these actions.

The combination of either telephone ring-down or tone-alert radio warning systems with sirens provides the most effective warning system under conditions of very rapid onset (e.g., 6 meters/second), close proximity, or both. These results indicate that alternative individual systems provide adequate warning effectiveness when available warning time (after detection and the decision to warn) extends to as much as an hour and that tone-alert radios and telephone ring-down systems provide similar coverage at approximately 30 minutes of available public warning time.

Table 3. Available Time and Distance for Warning System Alternative

Warning System	Distance in kilometers				
	1-2	2-5	5-10	10-20	20-35
Onset speed of 1 m/sec: minutes (+0.5) =	15.5	48.8	115.5	240.5	448.8
A. Sirens and alarms	0.563	0.855	1.000	1.000	1.000
B. Tone-alert radios	0.811	0.939	0.999	0.999	0.999
C. Auto-dial telephones	0.882	0.971	1.000	1.000	1.000
Media/EBS	0.199	0.595	0.843	0.927	1.000
A and B	0.925	0.993	1.000	1.000	1.000
A and C	0.941	0.993	1.000	1.000	1.000
Onset speed of 3 m/sec: minutes (+0.5) =	-1.2	10.0	32.2	73.9	143.3
A. Sirens and alarms	0.0	0.296	0.809	0.922	1.000
B. Tone-alert radios	0.0	0.610	0.922	0.963	0.999
C. Auto-dial telephones	0.0	0.713	0.955	0.996	1.000
Media/EBS	0.0	0.102	0.473	0.693	0.893
A and B	0.0	0.759	0.977	1.000	1.000
A and C	0.0	0.816	0.977	1.000	1.000
Onset speed of 6 m/sec: minutes (+0.5) =	-5.3	0.3	11.4	32.2	66.9
A. Sirens and alarms	0.0	0.0	0.390	0.809	0.903
B. Tone-alert radios	0.0	0.0	0.697	0.922	0.957
C. Auto-dial telephones	0.0	0.0	0.792	0.955	0.989
Media/EBS	0.0	0.0	0.132	0.473	0.668
A and B	0.0	0.0	0.842	0.977	1.000
A and C	0.0	0.0	0.882	0.977	1.000

The results indicate that a combination warning system is the most effective system in the 10-km radius. Given an instantaneous release (e.g., of water from a dam failure or toxic chemical from an accident) at low-onset speeds, most people in the 10-km zone will receive a warning. At the onset speed of 3 meters per second, the combination systems do not lead to adequate warnings within 2 km but perform well within the 5- to 10-km range. Under very-rapid-onset, it will be difficult to adequately warn people within 5 km.

Within 35 km, some multiple-method warning systems may also be desirable, although 100% overlap is not necessary. A combination of sirens, tone alerts and media/EBS warning could be used to warn populations within 10 to 20 km. The exact mix needs to be determined on the bases of local geography, potential hazard and population distribution. Beyond 20 km, it seems appropriate to rely principally on the media/EBS systems, except for institutional populations, which require prompt notification in the entire emergency planning zone.

This analysis provides a preliminary basis for planning warning systems for fast-moving events, such as dam failures or chemical spills or explosions, and for assessing the effectiveness of warning systems currently being used. Although this analysis has focused on the timing of warning, it is recognized that the organizational structure for issuing the warning and the style and content of the warning and the possible availability of protective actions are also critical factors in the overall effectiveness of the systems. As society creates more and more potential hazards, such as industrial facilities, chemical weapons, biotech facilities, nuclear power plants, and other unforeseen technologies, the need for careful planning for emergency warnings increases in importance.

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APPENDIX A: DESCRIPTION OF TRAIN DERAILMENT ACCIDENTS AT PITTSBURGH AND CONFLUENCE, PENNSYLVANIA

Pittsburgh Phosphorous Oxychloride Release

On Saturday, April 11, 1987 at 12:29 p.m., a westbound Conrail freight train derailed in Pittsburgh, Pennsylvania. In the process of derailing the westbound train sideswiped an eastbound train causing it to derail. Four tank cars containing hazardous materials on the eastbound train were derailed. Sparks resulting from the accident ignited a fire, however, "...contrary to reports circulated at the time of the accident, none of the hazardous materials ignited" (Railroad Accident Investigation Report, No. A-63-87, Consolidated Rail Corporation, Pittsburgh, Pennsylvania, April 11, 1987). Because of the involvement of hazardous materials, Pittsburgh emergency personnel initiated an evacuation upon arrival at the scene; about 20 minutes after the accident. Some local residents in immediately adjacent areas had already begun to evacuate. Up to 22,000 people were evacuated as the initial evacuation area was expanded to accommodate changing weather conditions. The fire was extinguished by 3:30 p.m., however, the primary concern centered around a derailed tank car containing phosphorus oxychloride. This tank car developed a crack in the dome permitting between 30 and 100 gallons of lading to escape. Emergency response teams inserted a tennis ball in the vent pipe to prevent further release and neutralized the chemicals that had escaped with hot ash and sand. By 5:50 p.m., the affected areas had been declared safe and the initial evacuation order was rescinded. Emergency officials planned a second precautionary evacuation for 1:00 p.m. the following day to upright the leaking tank car; however, a close inspection of the damaged tank car shortly after midnight detected continued degradation of the tank car. At 1:30 a.m., an evacuation order affecting between 14,000 and 16,000 residents within a half mile of the scene was issued. This second evacuation order was not rescinded until 4:30 p.m. on Sunday, April 12, 1987. Approximately 25 people were treated for eye and throat irritation at area hospitals, and three people were hospitalized during the course of the accident.

Confluence Precautionary Evacuation

On Wednesday, May 6, 1987 at 4:00 a.m., 21 of 27 "empty" tank cars carrying product residues, including propane, chlorine, caustic soda, carbon disulfide, methyl chloride, chloroform and isobutane derailed in Confluence, Pennsylvania. Because tank cars carrying residue can haul up to 3% of the load, emergency officials had no way to determine the exact amount of products remained in cars. Upon examination of the train's manifest, emergency management officials initiated a precautionary evacuation of the 986 residents. A three-minute non-stop siren blast was sounded, which primarily alerted the volunteer firemen as residents could not be expected to know what the siren blast meant. At approximately 4:30 a.m., a door-to-door and portable loudspeaker alert and notification of the emergency began using volunteer firemen and untrained volunteers. Public shelters were set up in the area's high school, local school buses and ambulances provided transportation for those needing it, and within 45 minutes the evacuation was complete. Assistance from area-wide emergency personnel sealed two leaking propane tankers by 9:48 a.m., but the chance of explosion and/or fire during wreckage cleanup prevented return until 6:10 p.m.