Responding to Emergencies: Lessons Learned and the Need for Analysis

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Large-scale emergency incidents, such as acts of terrorism, human-caused accidents, and acts of nature, often overwhelm local first-responder resources. A historical review of five recent major emergencies—the Oklahoma City bombing (1995), the crash of United Airlines Flight 232 (1989), the sarin attack in the Tokyo subway (1995), Hurricane Floyd (1999), and Hurricane Charlie (2004)—shows the need for additional research to develop decision-oriented, operations research models to improve preparation for and response to major emergencies. Local emergency managers need decision guidance regarding evacuation directives, management of near-the-scene logistics, triage on the scene and at hospitals, use of volunteers and off-duty personnel, reducing telephone traffic congestion, and integration of response with second- and third-level responders from other jurisdictions. Especially promising is the potential use of data mining and statistical inference to glean more real-time information from 911 calls that may be reporting a coordinated attack at multiple locations.

Key words: planning; government; government: emergency response.

History: This paper was refereed.

Philip M. Morse and George Kimball, in their landmark 1950s book, Methods of Operations Research (2003), said, “Operations Research... is an applied science utilizing all known scientific techniques as tools in solving a specific problem.” They went on to say, “It often occurs that the major contribution of the operations research worker is to decide what is the real problem.” These words ring true when examining so-called high-consequence, low-probability (HCLP) events, such as substantial acts of nature, large industrial accidents, and major terrorist attacks. For operations researchers to contribute substantially to this research area of international priority, we must first analyze the past. We must understand the “physics” of the HCLP events and the consequences of alternative policies of preparedness and response. We have written this paper as an initial chapter in our collective investigation of HCLP events, with an eye towards eventual major contributions of operations research as the preferred scientific method for structuring improved decision processes related to preparedness and response.

The 1995 Oklahoma City Bombing

Prior to September 11, 2001, the Oklahoma City bombing of April 19, 1995 was the major terrorist attack on American soil. In retribution for the FBI’s 1993 actions in Waco, Texas against the cult led by David Koresh, Timothy McVeigh and others targeted Oklahoma City’s Alfred P. Murrah Federal Building. At approximately 9:00 AM, they detonated a fertilizer bomb in a rented truck that killed 168 persons, mostly federal employees, and injured hundreds of others. McVeigh was apprehended later that day, convicted of murder on June 2, 1997, and executed on June 11, 2001.
To assess the emergency-response effort, we looked at the chronology of events:

9:02 AM  The Alfred P. Murrah Federal Building is bombed.
9:03 AM  The entire north side of the building collapses.
9:04 AM  The first police units arrive on the scene.
9:05 AM  The explosion is reported to the Oklahoma Department of Civil Emergency Management.
9:20 AM  The first fire department personnel arrive on the scene along with the disaster manager.
9:27 AM  The first wounded are transported to a triage unit.
9:30 AM  State and federal authorities arrive.
9:45 AM  Governor Frank Keating declares a state of emergency.
10:00 AM  Ambulance priority is given to the most severely injured.
10:15 AM  A bomb scare is reported.
10:30 AM  200 patients are being treated in hospitals at this time.
11:00 AM  Network news (NBC/ABC/CBS/CNN) goes live on site.
11:50 AM  Military medical personal arrive to assist the triage unit.
1:30 PM  Bomb threats are called to other federal offices throughout the nation, causing evacuations or closings for the day and closings of access streets to some federal offices.
2:00 PM  Rescuers move away from the building in response to another bomb threat. The threat turns out to be an ATF training rocket launcher that is harmless.
2:10 PM  Rescuers extract only three survivors after this time.
4:30 PM  President Clinton signs an emergency disaster declaration.
6:00 PM  Rescuers stop searching for survivors because of a thunderstorm. Workers prop up the building with supports to prevent the floors from pancaking on one another and collapsing.
6:10 PM  Rescuers locate last survivor.
7:30 PM  Rescuing continues.

11:05 PM  Rescuers remove last survivor from the rubble.

According to then Oklahoma City Police Chief Sam Gonzales, each emergency service branch was assigned specific tasks as part of a fully integrated response. The police handled perimeter security while the fire department managed rescue and recovery. Because the police department was so busy, Gonzales asked the FBI to oversee the criminal investigation (Cahn and Metzger 2004). The Emergency Medical Services (EMS) response to the bombing occurred in three phases: the first was the immediate response. Before it received the first 911 emergency phone call at 9:03 AM, several EMS drivers who had heard the explosion were already at the scene. By 9:07, 24 emergency medical technicians (EMTs) and seven ambulances were on site, and within minutes, an EMS command vehicle arrived. At 9:09, EMS operations shifted from normal to disaster mode. At the command headquarters, three people led the response effort, including a disaster coordinator handling communications from the disaster site and a transportation coordinator tracking hospital bed availability. Before 9:10, the first triage unit was set up next to the bombing site where rescue workers assigned patients in urgent need of medical attention a one and all others a zero. By 9:25 more than 30 ambulances were on site, with the first patient transported from the site at 9:27; within an hour of the bombing, they had transported 139 patients to hospitals. Before 10:00 AM, over 50 ambulances had arrived. When officials realized that many victims were going directly from the site to hospitals without triage, they moved the triage unit closer to the bombing site. However, at 10:30, a bomb threat forced them to move the triage further away, frustrating many victims. By the time the bomb threat cleared, most of the victims had been extracted from the building and sent to hospitals, and the triage unit was of little use (Maningas et al. 1997). By the end of the day, area hospitals had treated approximately 450 people for injuries; 10 of the 450 died after being admitted. The hospitals released 355 patients that day, keeping the rest overnight. Overall, the response was considered a success due primarily to interagency planning, training, and interaction that led to an integrated response (Oklahoma Department of Civil Emergency Management 1996).
Crucial components of the rescue operation were a multiagency coordination center (MACC) and an incident command system (ICS). Because the various public services maintained superb working relations, they had developed a plan for a MACC to streamline the rescue process. This central unit housed representatives of most of the major agencies, and most important decisions went through the center. Since each agency was aware of the other agencies’ actions and problems, they developed an integrated response using shared resources. Each unit helped and received help from the others as needed. MACC personnel assigned activities efficiently to the various agencies based on then-current workloads. They used the ICS to log, track, and maintain an overview of all simultaneous rescue operations, manage personnel, develop rescue plans and routes, and allocate supplies. In our interview, Police Chief Gonzales stressed the importance of well-developed relationships among the heads of emergency services and regular interagency training exercises (Cahn and Metzger 2004).

Although the response was successful, some problems hindered the response effort:

**Intake and Storage of Donated and Requested Goods**

A major logistical problem was managing supplies (The Oklahoma Department of Civil Emergency Management 1996). While agencies had little difficulty obtaining the equipment needed for the rescue effort, they faced oversupply rather than shortage, and they had difficulty locating and tracking supplies once they arrived. Commercial tractor-trailers donated for storage overflowed with everything from football helmets to search-and-rescue gear. Because an enormous quantity of donated goods arrived quickly, there were no records of the on-scene inventory. Multiple staging areas in various locations and operated by different agencies exacerbated the logistical headaches. To further complicate matters, workers recorded the arrival and storage of supplies manually following no set system. With no centralized tracking system in place, rescuers had to go to the staging areas and ask volunteers to rummage through piles. These searches often delayed the human search-and-rescue effort.

Clearly they needed a single computer system tracking the entire inventory, incorporating a database containing times of arrival and precise locations of all items. While emergency response teams may need multiple staging areas, they need to link them though one computer system to keep track of supplies. All emergency workers should be trained to use the inventory-management system.

**Telephone Communications**

Lack of reliable telephone communication among the emergency service branches (police, fire, EMS, 911) was a major problem. Soon after the explosion, telephone land lines became jammed. The Oklahoma City officials had a list of names and cell phone numbers, but when they resorted to cell phones, they found them jammed. Communication was almost impossible for some time (Oklahoma Department of Civil Emergency Management 1996). By activating reserve equipment to increase cellular-system capacity and donating over 1,500 cell phones for official use, Cellular One came to the rescue. When this effort still failed to free up telephone land lines, government officials asked cellular providers to give priority to rescue-related calls.

Agencies need to maintain current and accurate cellular phone directories of all rescue managers and staff so that if and when conventional networks become jammed after incidents, cellular providers can give priority to officials’ calls (Oklahoma Department of Civil Emergency Management 1996). It is essential to include local cellular providers in the disaster planning process and to establish a prioritization system with local land-line providers to ensure access to emergency but non-911 calls during postdisaster periods. Creating such agreements is difficult. In the cellular marketplace, multiple providers serve overlapping geographical areas, and reaching an agreement with all of them is a daunting task.

**Radio Communications**

Oklahoma City had an interhospital communication system, based on a common radio frequency, for many years known as the hospital emergency administrative radio (HEAR) system (Maningas et al. 1997). Designed for use during disasters and therefore rarely invoked, the HEAR system had seldom been tested. When the hospitals attempted to use the system, only three of the 15 area hospitals’ systems worked. With
the HEAR system down and the phones congested, ascertaining which hospitals were at capacity became time consuming (Maningas et al. 1997). Law enforcement officials had to drive to the hospitals to determine bed availability.

Each branch of the emergency service operated its own radio frequency, making shared radio communication very difficult (Cahn and Metzger 2004). According to Chief Gonzales, the various agencies need a common emergency frequency so that they can communicate with each other while responding. In Oklahoma City, the donated cell phones helped them to overcome the problem. Oklahoma City hospitals now test the shared communication system daily.

Identification of Workers and Volunteers
Because the Federal Building was officially declared a crime scene immediately after the attack, according to law, everyone entering the building had to be approved and had to possess verifying identification (Oklahoma Department of Civil Emergency Management 1996). Issuing identification to the doctors, volunteers, insurance adjusters, and others who wanted access to the building delayed rescue operations and made it difficult for the police to protect the perimeter of the building. Further complicating matters, the FBI imposed its own elaborate procedure for issuing temporary identification to those desiring access to the crime scene. Fire Chief Marrs asked if a more expeditious system based on photo ID could be implemented, to which the FBI consented. However, problems with access procedures arose with every personnel change, leading to lengthy discussions and delayed rescue operations.

Prior to an emergency, agencies should establish a system to give rescue workers and volunteers temporary identification rapidly.

Operation of a Triage Center
Immediately after the explosion, Emergency Medical Services set up a triage center less than a block from the bombing site to evaluate victims and classify them based on the nature and severity of their injuries. According to the city’s disaster response plan, the hospitals (12 were near the Federal Building) would treat triaged patients based on their emergency room (ER) capacities, the specializations of their staff physicians, and distances from the triage unit. Unfortunately, this system failed when 300 of the 600 victims bypassed the triage unit and went directly to nearby hospitals transported by volunteers and others (Maningas et al. 1997). Many rescue workers were unaware of the triage center, perhaps because it was moved multiple times. At first, it was so far from the Federal Building that people missed it. After it was moved closer, a bomb threat sent it back again.

By the time it was again located near the building, the seriously injured survivors had been transported to hospitals, and those waiting to see a nurse went directly to hospitals instead of relocating with the triage center.

To maximize the effectiveness of triage centers, emergency service providers must situate them in close proximity to the point(s) of the attack, and rescue workers must escort victims to them. When on-site triaging malfunctions, each hospital must operate its own triage unit, shifting rescuers from patient care.

Accountability of Backup Personnel and Volunteers
After the bombing, the local media called for medical and other volunteer personnel to come to the scene, and hundreds responded, some from California. All these well-meaning but superfluous volunteers created a management headache for the fire department. Frustrated because they were not given assignments and wearing little or no protective gear, some entered the building and tried to rescue trapped victims (Maningas et al. 1997). The fire department then had to monitor their safety and removal from the building. According to one report, more volunteer nurses than victims were at the bombsite. The medical volunteers faced risks; for example, a 36-year-old nurse, attempting to rescue a trapped victim, died when a piece of debris fell on her head. According to Chief Gonzales, the greatest problem in the response effort was the caring volunteers trying to help, not realizing they were not needed and detracting from the response effort (Cahn and Metzger 2004).

To be effective, volunteers must be trained and organized and they must have clear objectives and assignments. Cities have formal procedures and computerized systems for managing police, fire, and EMS responses; they should make volunteers an integral part of incident-management systems and take them seriously as they do the other three. Also, the
media should not issue unauthorized calls for medical volunteers.

Importance of Compatible Medical Records
The lack of compatibility and availability of medical records was a problem (McLain 2001). Obtaining and sharing information about the many patients who bypassed local triage and went directly to hospitals was difficult, and figuring out where relatives could find their loved ones was unnecessarily anxiety provoking (McLain 2001). When patients arrived at hospitals that had never treated them, doctors had trouble obtaining their medical records and could not readily determine whether they had special needs.

Sharing computerized medical records is imperative during a disaster but, because the city had both public and private hospitals, no centralized record-tracking system existed. A centralized system would have facilitated appropriate treatment, aided hospital officials in monitoring available beds at other hospitals, improved the allocation of resources, and helped family members to locate victims.

Problems with the Media
Public officials may underestimate the influence of news media during response efforts, as was made evident in Oklahoma City (Oklahoma Department of Civil Emergency Management 1996). In Oklahoma City, supplies arrived faster than workers could inventory them. One rescue worker commented off-handedly to a media person that he couldn’t find gloves, although 100 boxes were on the scene. The media immediately issued a plea for gloves, prompting the arrival of truckload after truckload of gloves, which delayed the arrival of more critical supplies. Also, news people tried to enter the restricted area forcing rescue managers to reassign workers to control media rather than rescue victims. Instead of asking for trauma specialists, the media asked all doctors in the area to report. Clearly, ear, nose, and throat specialists were largely superfluous.

Every emergency response plan should include a method for dealing with the media. Without controls, the media may cause confusion and add responsibilities to already overburdened rescue workers.

Priority Queueing Victims
Prior to 10:00 AM, ambulances transported victims from the triage center to area hospitals as quickly as they could. Despite triaging at the site, EMS workers did not prioritize by the severity of injury or any other factor. They followed a “load-and-go” policy, taking the critically injured from the triage center (usually before a nurse evaluated them) directly to the ER of a private, well-equipped hospital.

Response plans should include well-structured prioritization schemes giving those who need it immediate medical attention, while not neglecting those who are stable but deteriorating. We recommend a mixed dynamic strategy, providing immediate transportation to those who need it but minimizing the number kept waiting and transporting those who are not in critical condition but need medical attention.

The 1989 Crash of United Flight 232
On July 19, 1989 at 2:09 PM MST, United Flight 232, a three-engine DC-10 jumbo jet, took off from Denver, Colorado bound for Chicago’s O’Hare Airport with 285 passengers and 15 crew members (Haynes 1989). After passing over Iowa, the plane turned toward Chicago. At 3:17 PM CST, passengers heard a loud bang and the aircraft shook. The bang was caused by the disintegration of the tail engine fan disk, which caused all three of the aircraft’s hydraulic flight-control systems to fail. The probability that three fully redundant hydraulic systems would fail simultaneously was considered to be so minute that the DC-10’s safety manual did not explain how to respond. The aircraft lost almost all of its control surfaces; the pilot turned back toward Iowa and issued emergency warnings. Although Minneapolis ground control initially directed Flight 232 to land in Dubuque, Iowa, which was over 300 miles from its position, based on the extent of the damage, Minneapolis Air Traffic Control Center gave the flight crew permission to make an emergency landing at the Sioux City Airport, less than 70 miles away. Unable to travel in a straight line, the DC-10 had to circle to remain airborne. This reduced its effective linear ground speed to barely 100 miles per hour, giving the Sioux City fire and police departments about 40 minutes to prepare for the emergency. At 4:01 PM, as the plane crash-landed, its left wing hit the ground, causing the aircraft to split into two sections and catch fire. The almost perfect emergency response to this incident saved 186 lives.
The chronology of events was as follows:

1:45 PM Flight 232 departs from Denver to Chicago with 285 passengers.
3:16 PM Those on board the aircraft hear a loud explosion.
3:17 PM The pilot reports complete hydraulic failure.
3:20 PM The pilot declares an emergency.
3:21 PM Controllers reroute the flight to Sioux City, Iowa.
3:23 PM Minneapolis controllers turn responsibility over to Sioux City controllers.
3:26 PM The Sioux City Airport informs its emergency communications center of the Alert 2 in effect.
3:34 PM The alert is upgraded to Alert 3.
3:35 PM Hospital helicopters are placed on ground alert.
3:40 PM Trauma surgeons are assigned to stations in anticipation of a crash.
3:40 PM The captain informs passengers that the plane has lost an engine.
3:54 PM The captain advises passengers to prepare for an emergency landing.
3:55 PM The hospitals initiate a disaster plan, and the staff begin to mobilize.
4:01 PM The plane crashes on the Sioux City runway.
4:15 PM Forty emergency room physicians are available.
4:17 PM The first injured patient arrives at the hospital.
4:40 PM The last injured patient arrives at the hospital.

The emergency response was successful for six reasons:

Upgrade to a Level 3 Emergency
Prior to the Flight 232 incident, the highest level emergency alert Sioux City Airport had issued before a plane crashed was Alert 2, which indicates that all emergency-operations branches should start preparing for the emergency but could continue normal operations. At 3:26 PM, when it became clear that Flight 232 was making an emergency landing, tower personnel contacted the Sioux City communications center and issued an Alert 2, indicating that as a precautionary measure, a limited number of ambulances and police units should be dispatched to the airport. By 3:34 PM, Sioux City ground control, recognizing the imminent danger, raised the level of emergency to Level 3. By doing so, it gave response agencies an extra 20 to 30 minutes to prepare for the crash because a Level 3 alert allowed emergency vehicles to all but cease other operations and focus on preparing for a crash (Haynes 1989). This action also invoked the mutual aid agreement between Sioux City and its neighboring communities (Charles and Settle 1991). Thus, when Flight 232 crash-landed, all available EMS and other emergency vehicles were poised to respond. Ambulances were waiting next to the runway ready to transport injured passengers.

Triage and Ambulance Transportation
In anticipation of the emergency landing, Sioux City set up a two-class triage center to determine whether victims’ injuries were life threatening or not. If they were, the next available ambulance transported the victim to the hospital; if not, the victim waited until those with life-threatening injuries were taken. The objective was to move priority victims to the emergency room as quickly as possible without providing any on-site medical attention. Since the probability of saving critically injured victims decreases exponentially with time, they should be treated in an emergency room within one hour of the disaster.

The police placed roadblocks on the major highway connecting the airport with the hospital, so that the ambulances traveled much faster to the hospital and back than usual. The first victims arrived at the hospital less than 16 minutes after the plane crashed while the last victim arrived within 40 minutes of the crash. Of the 88 injured people, 78 survived; that is, they were treated and eventually released (Charles and Settle 1991).

An Integrated Emergency Response Plan
A well-thought-out and rehearsed response plan saved lives. In 1987, Sioux City officials decided to integrate their disaster plan among the various rescue agencies to make a living plan they updated frequently to address problems and to incorporate innovations identified through technology, practice, and experiences responding to incidents (Charles and Settle 1991). All the participants rehearsed the plan.
once a year, using a different disaster scenario each time. According to rescuers, the yearly drill enabled them to discern the weaknesses in their coordination efforts and also helped them to know one another (Haynes 1989). This process established a level of trust among the different branches, which many believe helped them to respond effectively when Flight 232 crashed. Rescuers said they were trained so well and were so familiar with the plan that they never needed to refer to it during the response.

The 1987 training exercise had simulated the crash of a jumbo jet aircraft. The only substantive difference between the drill and the actual emergency was that the drill assumed 150 passengers and crew and Flight 232 had 300. During the drill, the director of emergency services realized that the preparation time the first responders needed was too long and changed the patrolling strategy of the ambulances to shorten the response time. Because of the drill, they also expanded the mutual-aid program.

A Mutual Aid Contract
Sioux City had a mutual aid contract with the surrounding areas (Haynes 1989). Unlike many cities, Sioux City had a signed agreement with the neighboring districts that they would respond to Level 3 emergencies by dispatching additional resources. Well before Flight 232 crash-landed, crews from those districts were poised at the runway to respond to the potential disaster.

Positioning Ambulances
Sioux City prepared for the crash by prepositioning ambulances to minimize travel time to the expected crash site. Developed during a training exercise, the idea is that a plane making an emergency landing may not reach its intended runway and may crash somewhere in the surrounding area. The city found that positioning ambulances on the area’s highways would speed the response if a plane crashed before reaching a runway.

The 1995 Sarin Attack in the Tokyo Subway
The sarin attack in the Tokyo subway was the largest peacetime nerve gas attack in history.

On March 20, 1995, members of the AUM Shinrikyo terrorist group launched a sarin nerve gas attack in the Tokyo subway system, killing 12 and injuring over 5,000 passengers. The plan called for each of five teams of two people to release a can of sarin in a different subway car headed for the city center during the morning commute. At this time of day, the number of riders can exceed official capacity by as much as 200 percent, making it impossible to move in the subway cars. The terrorists chose five subway lines that converge at Kasumigaseki Station, which is near some government buildings, including the police department headquarters.

Each can contained 20 ounces of a 30 percent solution of sarin, a human-made chemical weapon (Centers for Disease Control (CDC) 2004) known to be a nerve agent. First developed in 1938 as a pesticide, sarin is used in liquid form and vapor form. People are exposed to sarin through inhaling the vapor or contact with the skin. They show symptoms of sarin poisoning seconds after exposure to the vapor
form and up to 18 hours after exposure to the liquid form. The earlier a victim is decontaminated and given an antidote, the less severe its harmful effects. The most volatile of nerve agents, sarin evaporates quickly and spreads easily (CDC 2004). It burns the eyes and causes many other symptoms, including a runny nose, watery eyes, tightness in the chest, and loss of consciousness. Most pharmaceutical companies sell antidotes.

The chronology of events follows:

7:55 AM  Terrorists board the five subway cars.
8:00 AM  They launch the attack.
8:09 AM  Police receive the first emergency call.
8:16 AM  The police inform the Tokyo fire department of the attack.
8:25 AM  The first victim arrives at a hospital on foot.
8:40 AM  The first ambulance arrives on scene.
10:00 AM  The EMTs misclassify the toxic agent as acetoni-trile.
11:00 AM  The police identify it as sarin.
12:00 PM  The hospitals learn the agent is sarin.
12:45 PM  EMTs set up on-site triage and decontamination centers.
6:00 PM  Germany, France, and England offer to dispatch response teams.

The response had 10 problems that provided lessons:

**Coordination Within the Tokyo Metropolitan Ambulance Control Center**

During the initial stage of the response effort, the Tokyo metropolitan ambulance control center (TMACC) operators suffered from a lack of coordination (Okumura 1998). In the hour following the incident, calls came in from 15 different subway stations reporting emergencies. The TMACC computers and operators, however, did not realize that the 15 calls concerned a single multisite attack and thus dispatched 15 different EMT teams to the 15 stations to determine the nature of the emergencies. Unaware that the events were linked, the EMT teams failed to coordinate to identify the nature of the attacks. This initial lack of coordination caused many victims to suffer needlessly (Okumura 1998).

With better coordination, the operators might quickly have realized these 15 events were linked. They needed a system for logging calls and identifying commonalities. For example, a few minutes after the first few calls, an intelligent computer model could have flagged the trigger phrases, *subway station or burning eyes.*

**Timeliness of a Triage Setup**

The earlier nerve gas victims receive medical treatment, the less ill they become. People exposed to sarin require endotracheal intubation as soon as possible (Okumura 1998). After the attack, the EMTs' primary goal was to “transport as many victims as quickly as possible to the nearest hospital.” Lacking effective communications, the EMTs were not instructed to set up triage centers until more than two hours after the incident. Many victims’ conditions deteriorated for lack of on-site treatment, and some died on the way to the hospital. By the time the Tokyo metropolitan fire department (TMFD) set up a triage center and sent 47 doctors and 23 nurses to the 15 stations to provide on-site treatment, most of the victims had been transported by ambulance to hospitals or had fled the area on foot in search of medical treatment (Okumura 1998).

Without triage, ambulances did not give priority to victims in critical condition and sometimes transported mildly affected victims immediately.

**Information Overload at the TMACC**

The doctor on call at the TMACC lost radio contact with the EMTs because of an information overload. With many people trying to exchange information, radio frequencies become jammed and the doctor on call could not contact the TMACC. As a result, very few victims received medical treatment until they arrived at the hospitals (Okumura 1998). Also, because incoming information was mismanaged, after about two hours TMFD declared the attack the largest disaster since World War II, a gross exaggeration that caused terror and panic in Tokyo.

**Identifying Sarin**

In the attack, the delay in identifying sarin proved deadly. At first, the TMFD thought it was acetoni-trile (Cox 1994). When the police identified the agent as sarin, around 11:00 AM (three hours after the attack), they did not immediately inform the TMFD and the hospitals; they informed the media first. The
hospitals continued treating patients for acetonitrile until they were notified. EMTs were left to rely on clinical observation to determine treatment because they were not equipped with devices to detect sarin. Detection would have been easy because the victims were exposed to large amounts of sarin.

Identifying the agents in chemical attacks quickly is essential to saving victims’ lives. EMTs, or central locations, should be equipped with agent detectors, which are readily available and inexpensive.

Decontamination Facilities and Protective Gear
Because the TMFD had no decontamination centers, there were second-, third-, and fourth-order effects from the attack. EMTs were wearing street clothing and had no protective gear to guard against the spread of sarin. Of 1,364 EMTs, 135 or approximately 10 percent, became ill and were admitted to hospitals after transporting victims (Okumura 1998). Their absence had a second-order effect: the number of ambulances transporting the remaining victims fell by about 10 percent. In addition, 110 doctors became ill after treating patients who had not been decontaminated.

Decontamination centers should be established quickly near the sites of the chemical attacks. Hospitals should also have decontamination centers to process victims arriving on foot and by taxi. Mobile decontamination centers (Okudera 1997) can be attached to ambulances and transported to attack sites. Hospitals without decontamination facilities can construct temporary ones outside the triage entrance, for example, in parking lots.

EMTs need protective gear to block chemical agents in proportion to the strength of the attack. Excess or cumbersome protective gear can increase the time and difficulty of treating and transporting victims.

Ambulance Transportation and Communication Problems
In responding to the sarin attack, the ambulance system functioned poorly. The ambulances transported only 688 of the 4,000-plus victims who received medical attention; taxis transported more (Okumura 1998). This inefficiency was caused partly by overloaded radio channels, which hampered communication between EMTs and their supervising hospital-based doctors. Because the EMTs lacked information on hospital capacities, they took victims to distant hospitals when hospitals close by had available beds. One hospital that was not close to any of the subway stations received a disproportionately large fraction of the victims. Some ambulances traveled from hospital to hospital searching for vacancies, while others dropped patients off at hospitals that were at or above capacity.

Clearly cities need systematic means of deploying ambulances after such disasters. Tokyo ambulances had been spatially allocated based on the city’s residential-population densities. Because the attacks occurred as morning commuters were traveling to Tokyo, neighborhood population numbers bore no relationship to need. Also, one terrorist released two cans of sarin, injuring many people in a subway station in a sparsely populated neighborhood. The assigned EMTs were overwhelmed, and most of the victims traveled by foot or taxi to the closest hospital. As EMTs arrived at affected stations, they assessed the needs and reported them to the TMACC to improve the response. Cities must establish reasonable procedures for determining and responding to emergency needs. They need to assign victims to hospitals, taking into account the victims’ locations and conditions and the hospitals’ capacities.

Taxi drivers saved many lives by carrying victims to hospitals. Since the attack, the authorities have instituted an emergency communications system that tells drivers when and where their help is needed.

Interhospital Ambulance Transfer and Communications
Few EMTs were stationed at hospitals waiting to transfer victims from one hospital to another (Okumura 1998). When hospital officials asked the TMFD to transfer patients, it had no ambulances for the task; they were overwhelmed with rescue efforts. As a result, some hospitals were working over capacity, while others were nowhere near capacity. Because communications were poor, doctors at undercapacity hospitals were not sent to overcapacity hospitals. Ideally, movable patients would be sent to hospitals with unused capacity taking into account distances between hospitals and doctor-to-patient ratios. If there are no ambulances available, officials should activate a backup system using taxis, buses, or military vehicles.
EMT Restrictions

Sarin victims often require an endotracheal tube to maintain a breathing airway, which Japanese EMTs can legally insert only with the consent of a doctor, which depends on their maintaining contact (Okumura 1998).

Antidote Supply and Storage

Hospitals had limited supplies of the sarin antidote, and it took time to obtain backup orders. The city should store backup supplies close to the hospitals, but dispersed to reduce vulnerability to a terrorist attack.

Backup Support

The Japanese national government—members of the Japanese Self-Defense Forces—played only a minor role in responding to the attack. Under Japan’s Fundamental Law of Disaster Management (Okumura 1998), the official in charge of the geographic region where a disaster occurs initiates the response effort.

The 1999 Hurricane Floyd

After crossing the Atlantic from West Africa to the Bahamas, Hurricane Floyd, a category 4 storm (winds 131 to 155 miles per hour and a storm surge of 13 to 18 feet above normal) seemed headed for central Florida. On September 12 and 13, much of the population of the east coast of Florida was evacuated in the largest peacetime evacuation in US history. However, a gale-force wind originating in Canada sent the storm back over the Atlantic, and it missed the Florida coastline entirely. Other states became reluctant to evacuate their residents in planning for the hurricane (National Hurricane Council 2004). On September 15, the storm headed west toward Georgia and the Carolinas, making its landfall on September 16 near Cape Fear, North Carolina. The estimated economic loss caused by Hurricane Floyd was $3.4 billion, much of it from the Florida evacuation (Fraumeni 2001).

Here is the timeline for North Carolina’s emergency and response effort:

September 14
Floyd, a category 4 hurricane, moves north off the Florida coast.

4:30 PM Southeast River Forecast Center in Atlanta predicts flooding of Route I-95 in North Carolina.

September 15
Local officials issue first evacuation notice. The Southeast River Forecast Center in Atlanta predicts six to 12 inches of rain in North Carolina.

September 16
2:00 AM Hurricane Floyd comes ashore in North Carolina.
5:00 AM Floyd drops to a Category 2 hurricane.
11:00 AM The storm falls in North Carolina near I-95.
2:00 PM The storm moves north.
5:00 PM A few firefighters begin the rescue effort.
6:00 PM A Maine helicopter arrives to help with the rescue effort.
11:00 PM The inland rivers in North Carolina rise dangerously.
11:30 PM Local officials ask people living near freshwater to evacuate.

September 17
4:00 AM The inland rivers crest.
1:00 PM Military helicopters arrive to help rescue the estimated 1,500 people still trapped.

September 18
3:00 PM All rescues completed.

Experts said that, while South Carolina did an especially good job in its evacuation and rescue efforts, North Carolina did not (Moore and Barnes 2004). Fifty-seven people died, 50 of them from drowning in freshwater, not saltwater. Between 1972 and 2002, over three-fifths of hurricane deaths were caused by freshwater flooding (Brennan 2002). Kent Frantz of the Southeast River Forecast Center found it hard to get past the focus on the coast even though he predicted extensive inland flooding. “We tried to tell everyone that the main problem was going to be inland flooding, but no one seemed very interested” (Ray 2003).

Prediction Probabilities

Preparing for a large hurricane is difficult because predicting where it will strike with accuracy is impossible. Cautious officials may call for an evacuation
that ultimately proves unnecessary; their credibility will suffer and the economic loss can be huge. Based on weather observations, the National Weather Council (NWC) uses strike probabilities to determine the chance that a hurricane will strike within 65 nautical miles of a certain point. It uses a 65-mile radius to estimate the area of damage and to determine whether an evacuation will be necessary based on the hurricane category. The problem is that the highest probability of the NWC making an accurate prediction two days in advance is 25 percent (National Hurricane Council 2004). Based on the current position of a storm and the NWC’s ability to track it, the maximum probability that it will strike a given region is 25 percent (Table 1). Only within 24 hours of the expected strike time can the updated probability exceed 50 percent. Given the uncertainty, calling for an evacuation is difficult (National Hurricane Council 2004). And the resources needed in the aftermath of a hurricane vary with the amount of time people have to evacuate.

### Freshwater Flooding

If a region has few lakes and rivers, rescue efforts can be concentrated on the coastline. If the region has many rivers, damage can be widespread. People who live inland may not realize the risk of freshwater flooding and may ignore evacuation warnings, leaving their families trapped. Evacuation was a major problem when 20 inches of rain fell in North Carolina swelling the rivers (Ray 2003). Many of the planned evacuation routes, including such highways as I-95, were flooded and closed, forcing evacuees to seek alternate routes (Ray 2003). At one point, over 1,000 roads were closed by flooding. When the rescue efforts began on September 17, helicopters were needed to rescue those trapped on flooded roadways. All of the state’s helicopters were undergoing scheduled maintenance, creating a need for Air National Guard helicopters. As the rivers began to crest on September 16, some inland counties issued evacuation orders—after the hurricane had hit! Many would-be evacuees were trapped by the flooded roads. Federal agencies criticized local public officials for underestimating the risk of inland flooding.

Clearly, when planning evacuation routes, officials should consider the possibility of inland freshwater flooding. In addition to evacuating coastal residents, they must evacuate those living inland. Planned evacuation routes from the coast must avoid areas prone to freshwater flooding. The local topography may make it impossible to consider all these restrictions simultaneously; cautious officials may want to call for early evacuations.

### Communication Problems in Evacuation Planning

North Carolina was widely criticized for having no well-thought-out plan when Hurricane Floyd hit (Ray 2003). Its plan did not specify which residents should evacuate. Presumably, most civilians and officials heard radio or television announcements about the emergency (Dumont 2000). Such announcements are often short and lacking in detail, leaving residents unsure whether they are supposed to evacuate. Many inland residents not at risk thought they were to evacuate and did so, clogging the evacuation routes with traffic. Guessing which routes to take, both inland and coastal evacuees headed toward the same major—congested—highways.

Local radio and TV stations will remain the primary media for communicating evacuation orders to residents. Planners should train broadcasters to make clear emergency evacuation announcements and make sure they recognize their importance in disaster-response efforts.

### Optimizing Evacuation Traffic

During evacuations, all vehicles other than rescue vehicles flee the coast. By reversing coastward traffic lanes so people can travel away from the coast on most lanes, officials can almost double the capacity of the highways. Had North Carolina officials employed this tactic to a greater extent, they could have greatly reduced congestion.

<table>
<thead>
<tr>
<th>Forecast period (hours)</th>
<th>Maximum probability range (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>10 to 15</td>
</tr>
<tr>
<td>48</td>
<td>20 to 25</td>
</tr>
<tr>
<td>36</td>
<td>25 to 35</td>
</tr>
<tr>
<td>24</td>
<td>40 to 50</td>
</tr>
<tr>
<td>12</td>
<td>75 to 85</td>
</tr>
</tbody>
</table>

Table 1: The probability that the National Weather Council will be able to predict within a 65-mile radius where a hurricane will strike land is dependent on how far in advance the prediction is made (the forecast period).
Public Officials’ Oversight of the Evacuation Process

Local officials can monitor traffic situations, traffic management, and equipment, such as backup power supplies at major intersections (Batchelor et al. 2000). Along the evacuation routes, officials must direct evacuees to alternate routes when roads are closed (Ray 2003).

Damage to Rescue Supplies

In the areas affected by Floyd, the hurricane damaged emergency resources, such as police stations, cars, ambulances, and other rescue supplies, causing a shortage of supplies and equipment. Obtaining backup supplies delayed the rescue effort. It is vital to mobilize local rescue personnel and equipment after a hurricane warning so that rescue efforts can start immediately.

Radio Communications

Floyd flooded more than 1,000 roads, and helicopters rescued the stranded victims. As the flooding worsened, the state called in supplementary military helicopters that used military radio frequencies incompatible with civilian radio frequencies (Dow and Cutter 2000). The various rescue teams had difficulty communicating, hampering the rescue process. The increased flooding stranded an estimated 1,500 people. On September 16, with the crisis escalating, the National Guard brought in 60 helicopters and 4,000 troops, and 750 military personnel arrived to help with the rescue. Authorities estimated that helicopters rescued 420 people. By September 18, the water had subsided and everyone had been rescued.

Managerial Problems

Managers were responsible for some of North Carolina’s problems. The state had no plan for coping with regional disasters (Batchelor et al. 2000). With 37 counties affected, the state responded as though it had 37 separate floods, instead of a single regional disaster. In some cases, local officials did not communicate well or at all with neighboring districts and towns. They had done little planning and worked through a lot of bureaucracy to determine when and where to send rescue crews. Moreover, they were unprepared for the rivers’ flooding. Fortunately, military bases in the area helped with the air rescue.

The 2004 Hurricane Charlie

Hurricane Charlie hit a very poor area of west central Florida, destroying many homes and businesses. Remarkably, Hurricane Charlie killed many fewer people than Hurricane Floyd. The chronology follows:

August 11
2:05 PM National Hurricane Council (NHC) upgrades Tropical Storm Charlie to Hurricane Charlie.

Monroe County, Florida issues an evacuation order.

August 12
9:00 AM NHC upgrades the storm to a category 2 hurricane.

Hurricane center moves north toward Havana.

One million people are evacuated from Charlotte, Sarasota, and Manatee counties on the west coast of Florida; officials suspend tolls on I-95 to speed up traffic.

6:00 PM NHC upgrades Hurricane Charlie to a category 3 hurricane.

August 13
NHC upgrades Charlie to a category 4 hurricane.

5:00 AM Hurricane Charlie is 85 miles southwest of Key West.

1:00 PM The hurricane moves inland toward central Florida.

3:45 PM The eye passes over Captiva Island.

4:15 PM Hurricane Charlie hits Punta Gorda and Arcadia, killing four people.

4:42 PM Hurricane Charlie crosses Port Charlotte.

5:00 PM The hurricane travels through state’s center.

7:00 PM The storm passes, cleanup begins, and estimated damage is $15 billion.

August 14

15 people are confirmed dead.

16 counties are declared disaster areas.

Over 9,000 homes are reported destroyed.

Governor Bush sends 2,000 national guardsmen to the area.

State officials assign 400 state law enforcement personnel to the area.

Local officials institute a curfew from 8:00 PM to 7:00 AM to prevent looting.
August 15
Officials estimate 80 percent of the buildings in Charlotte County are damaged.

5,000 emergency workers participate in the rescue effort.
The death toll reaches 18 in the US, four outside the US.

When weather forecasters upgraded Charlie to a category 4 hurricane (McCarthy 2004), they thought it would hit the southern tip of Tampa. Officials advised people in the coastal counties from Key West to Tampa to evacuate, making evacuation mandatory for those on the shore and optional for those inland. An estimated one million people took part in the evacuation.

On August 13, instead of hitting affluent Tampa and St. Petersburg, the storm slowed and headed northeast to “the other Florida,” the poor areas where migrant workers live. The storm hit Punta Gorda and Port Charlotte near the coast and Arcadia inland. This area of Florida is served by US-17, an old, two-lane highway, and filled with recreational vehicle parks, mobile homes, citrus groves, and cattle ranches. Most of the residents are poor migrants. The population of DeSoto County (where Arcadia is the only incorporated city) is estimated to be 25 percent Hispanic (McCarthy 2004).

Tampa residents who were evacuated needlessly complained about being sent from safety into the storm’s path. After this false alarm, they will likely be skeptical about future calls for evacuation.

When Charlie hit the inland county, it ripped through flimsy mobile homes and destroyed businesses. Weather forecasters did not foresee the hurricane’s turn until the morning of the day it hit (McCarthy 2004). Before they realized it was turning, officials issued a voluntary evacuation order to county residents, giving them only two hours to evacuate before the hurricane arrived. Few evacuated. The many poor, uneducated migrant workers may not have understood the necessity of complying or had the means to comply.

Traffic congestion was a major problem. When Monroe County issued the first evacuation orders on the night of August 11, motorists spent over 10 hours on routes that normally took two or three hours, and on the morning of August 12, a truck-car accident on US 1 caused a massive delay. Allowing the outbound evacuees to use normally inbound traffic lanes could have mitigated the backup. Officials did suspend all tolls on I-95 on August 12 to speed up traffic.

Unfortunately, police needed for rescue efforts had to deal with looters and businesses raising prices by over 200 percent. Such price gouging is illegal and can be accompanied by fines of up to $25,000.

In the aftermath of the hurricane, rescuers searched many damaged trailers trying to locate trapped victims, not knowing which had been unoccupied by migrant workers at the time of the storm.

Hurricane Charlie killed fewer people than Floyd, largely because freshwater flooding was not a factor.

Operations Research for Planning Emergency Responses
Operations research (OR) can help decision makers to plan for and respond to emergencies.

Prepositioning Supplies and Equipment
To prepare for major emergencies, communities must consider what types of emergencies are possible or likely. For those for which the risk is high, planners must consider what supplies and equipment they need and where. We have seen the need for this in biological and chemical events, though many acts of nature also require spatially dispersed supplies and equipment.

The OR field most appropriate to such problems is location theory. People usually model transportation mediums as networks or graphs representing the streets of a city or the flight paths of aircraft. The idea is to find optimal locations of facilities on the network. The siting of fire station houses is a good example.

We need new location theories to plan emergency response related to homeland security to incorporate the following elements:
—Possible destruction of located facilities.
—Possible inaccessibility of transportation pathways.
—The proximity of facilities (such as hospitals) to others.

The resulting good locations should be robust to damage done from the emergency event, spread out over the jurisdiction, not concentrated at few points. They might lie on roads used by emergency response
vehicles, minimizing the time taken to collect supplies and equipment.

**911 Inference Algorithms**

Emergency call takers initially interpreted the Tokyo sarin attack as a series of unrelated emergencies in different subway stations, which delayed the city in mounting an appropriate response to what turned out to be a coordinated massive chemical attack. Until people realize a collection of incidents form a major emergency, they cannot assemble a coordinated massive response.

OR researchers could create a data-trawling algorithm for 911 call centers that would continually scan and analyze incoming calls as they are logged onto the 911 computer system, searching for those concerning one large incident rather than separate smaller incidents. It would incorporate probability and Bayes theorem, data-mining techniques, and expert-systems ideas. Such a system could be installed on 911 computer call-taking systems. Had Tokyo had such a system, it might have averted several deaths and many injuries.

**Deciding to Evacuate**

Hurricanes are not the only emergencies that require evacuation. Others are volcanic eruptions, nuclear-power-plant malfunctions, and impending terrorist attacks.

Decisions to issue evacuation orders are generally based on complex risk and probability calculations. While national weather forecasters have developed evacuation-prediction techniques for hurricanes, decision makers have few scientific methods for other types of major emergencies. Even for hurricanes, reliable probability estimates of the locations of landfalls may be available only after the time to evacuate safely has passed. Forecasters may call for an evacuation when the probability of a direct hit is only 25 percent.

Researchers could investigate the evacuation decision process to create a transparent decision model. The decision would be to evacuate or not and would consider the logistics of evacuation, should an evacuation order be issued.

**Triage**

OR researchers should develop rules for triaging, analyzing the queueing-delay consequences of proposed rules, the likely medical outcomes of sets of rules, and the optimal locations for triage units. Some priority-queueing models address components of these problems, but we know of no comprehensive OR analysis of triage issues and problems.

**Second- and Third-Tier Responders**

A major emergency is one in which local first responders are overwhelmed, with inadequate resources to do the work. Additional personnel must be brought in from surrounding communities, from the state, or from federal agencies.

We need dispatching and deployment algorithms and models to coordinate this process. We need to expand and generalize the current approaches to incorporate second- and third-tier responders. We need to address the following questions:

—Under what circumstances should officials call in response units of type X (where X could be specialists, generalists, off-duty personnel, or resident volunteers)?

—Where should officials locate the new units?

—How should they coordinate these units?

—How can they predict the response times of the new units and the risks and benefits associated with those response times?

**Using Volunteers and Off-Duty Personnel**

Officials should establish rules and policies regarding the use of off-duty personnel and volunteers. In Oklahoma City, volunteers diverted skilled personnel from their tasks to controlling the volunteers. In the response to the crash of United Flight 232, the availability of medical personnel scheduled to go off duty greatly improved the quality of the response.

Asset management models for emergency response must include off-duty personnel and resident volunteers. Ideally, they could predict the consequences of employing different policies concerning various types of volunteers. Officials could then select and implement the best policy, which might require labor-management negotiations in the case of off-duty personnel and training in the case of volunteers.

**Near-the-Scene Logistics (for Personnel and Donated Goods)**

In the Oklahoma City case, we learned of problems with locating sites for receiving and distributing
donated goods, for receiving volunteers, and for locating triage centers. Triage-center creation and location was also a problem with the Tokyo sarin attack. Triage-site creation and location were very well performed for United Flight 232.

Planners and on-scene decision makers need decision support to manage logistics and locate centers for triage, receiving and coordinating volunteers, and organizing and distributing donated goods. Triage units should be established quickly near the scene of the emergency event in the general direction of nearby hospitals. They must plan donated goods’ locations and coordinate volunteer agencies to avoid their establishing their own donation and distribution centers.

Because each major emergency is unique, we cannot derive a closed-form solution to these facility-location problems. But OR researchers can study various scenarios and develop general principles for planning among agencies.

**Handling Routine 911 Calls After the World Trade Center Attack**

On September 11, 2001, New York City residents benefited from a computer-based algorithm for repositioning fire resources created by the New York City Rand Institute (NYCRI) 30 years earlier (Kolesar and Walker 1974). The New York City Fire Department (FDNY), despite unprecedented demands on their personnel and the loss of their firefighters, retained average response times to other 911 calls for fire service within one minute of long-term averages. Based on that algorithm, the FDNY directed available fire units distant from the major emergency to locate temporarily in vacant firehouses in anticipation of possible new fire calls.

The NYCRI fire resources relocation algorithm is a useful planning model. OR researchers could create additional planning tools for managing situations in which resources are reduced, including policies for prioritizing and triaging, for educating the public, and for temporarily changing traffic patterns.

**Reducing Telephone and Radio Congestion**

Major emergencies can create telephone and radio traffic jams when communication is essential.

OR needs to solve this queueing congestion problem. Oklahoma City and Cellular One invented a solution on the fly, but we should not expect such good fortune. Tokyo had severe problems. We believe cities should negotiate prioritization schemes with radio and telephone service providers in anticipation of a major emergency, so that when and if they need it, they can switch to a mode of operation that gives priority to emergency-response agencies. Queueing models of communication networks seem promising for such problems.

**End Note**

This paper was written before the major emergencies of the year 2005, including the great tsunami of the Indian Ocean, Hurricane Katrina, Hurricane Rita, the massive earthquake in Pakistan, and many lesser emergencies. We hope to write a sequel paper addressing these catastrophes.

**Acknowledgments**

This research was supported by the United States Department of Homeland Security through the Center for Risk and Economic Analysis of Terrorism Events (CREATE) under grant N00014-05-0630. However, any opinions, findings, and conclusions or recommendations in this document are those of the authors and do not necessarily reflect views of the United States Department of Homeland Security. We conducted the work through a subcontract from CREATE at the University of Southern California to Structured Decisions Corporation, West Newton, Massachusetts. We thank colleagues who offered constructive suggestions.

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