Planning for a disaster: A review of the literature with a focus on transportation related issues

Micah L Brachman
Richard L Church

Department of Geography
1832 Ellison Hall
UC Santa Barbara
Santa Barbara, CA 93106-4060
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Micah L Brachman

Richard L Church

GeoTrans Laboratory
Department of Geography
University of California, Santa Barbara
Santa Barbara, CA 93106-4060

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Preface

The spectrum of possible emergency events ranges from natural events like floods, pandemics and earthquakes to human activity-based disasters like terrorism, train accidents, and nuclear power plant failures. Because disasters do not happen very often, most people become complacent about risks, such as floods and earthquakes. But when one does happen, like hurricane Katrina hitting New Orleans, it is easy to tell when a system response is inadequate. The value of advanced planning and modeling can help to reduce the likelihood of inadequate response to an emergency. It is the responsibility of public agencies to be prepared to deal with such disasters.

Although this report for the most part does not focus on specific types of disasters it is important to understand that there are major risks to the population of California across a wide spectrum of specific types of events. Some events could be particularly disastrous. For example, a study concluded that a terrorist strike on a chlorine tank car along a major railroad route in the Washington, D.C. area could produce a toxic cloud 4 miles by 41 miles and kill and injure up to 100,000 people (Jay Boris, Naval Research Lab). The risk in a number of cities in California is equally great. Even accidents involving bulk shipments of chlorine are dangerous. In 2005 a train accident near Graniteville, S.C. involving a chlorine tank car killed 8 and hospitalized 240 people due to a toxic cloud. Although the probability of such an event has been lowered as some cities have switched to using bleach and other more stable forms of chlorine or other methods of disinfection for water and sewage treatment, this risk is a major issue in the United States.

Another example of risk is flooding in California’s Central Valley. The system of levees in the Central Valley is considered old and inadequate. In a recent report to the California Department of Water Resources (Independent Review Panel Report (2007)), it is stated that the “the outlook for the future under business-as-usual is grim.” The reasons for this prognosis are based upon the current state of the levee system, a better understanding of possible seismic events, the prospect of large and more frequent storms based upon climate change, and the growth of communities and infrastructure within the flood plain. The fact is that major roads and highways may be cut off by floodwaters, reducing the capabilities of emergency response for large areas of the Central Valley.
Even frequent and well planned for events such as wildfires can present transportation challenges. The May 5, 2009 Jesusita Fire constituted a grave threat to the city of Santa Barbara, necessitating the evacuation of nearly 30,000 residents. By most accounts, the threat posed by this hazard was handled well: firefighting resources were allocated efficiently, citizen evacuations went smoothly, and loss of property and life was minimized. Yet during the Jesusita Fire, mandatory evacuation zone boundaries were drawn to specifically exclude nursing homes, hospitals, and other facilities with large evacuation assistance needs. While people remained in these facilities, most major arterial routes in Santa Barbara were extremely congested due to evacuation traffic. Had the winds shifted and these facilities been threatened, could emergency response personnel have moved in and successfully evacuated these vulnerable populations?

Federal agencies such as the Department of Homeland Security (DHS), the Federal Emergency Management Agency (FEMA), and State agencies such as California’s Office of Emergency Services have a primary goal to ensure safety, plan to respond in the event of a disaster as well as promote plans and regulations that will decrease risk, increase safety, and reduce possible damages. In a recent report (State of California: Emergency Plan (Draft, Nov. 2008)) all state agencies, including Caltrans are assigned functions associated with responding to an emergency. Agencies such as Caltrans must be prepared for their roles in disaster/incident response. To do this requires a great deal of advanced planning and analysis, for the risks of not planning and responding too late with too little are great and the benefits of making the appropriate response in a timely manner are considerable.

The goal in planning for major emergencies is to plan for the extraordinary. It is important to develop advanced plans whenever possible as well as support research into model development and data collection that can support real time event tracking and mitigation. It is also important to make the best use of limited resources by maximizing the benefits provided to an area undergoing a disaster, whether that be in providing supplies, inspecting damaged infrastructure, or guiding people in an evacuation. The best response to an emergency is based upon advanced planning and research, frequent emergency drills, and maintaining appropriate levels of resources that may be needed in an emergency. This report presents a review of the literature
associated with techniques that have been developed to support disaster planning, response, management and mitigation as well as discuss how some of these techniques can be used specifically for transportation analysis and planning.

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Preface Notes: Data or material in preface references the following reports or papers

The data on chlorine based toxic cloud deaths was calculated by Dr. Jay Boris of the Naval Research Laboratory in Washington, D.C. He testified that a worst-case scenario for that city could result in up to a hundred thousand fatalities. An independent Homeland Security Council report on possible scenarios estimated that a ruptured chlorine gas tank car could kill as many as 17,500 people and injure an additional 10,000.


State of California Emergency Plan, Office of Emergency Services, Nov. 20, 2008. (Draft)
1. Introduction

Mitigating the impacts of a disaster, like a wildfire, flood or earthquake, rests on doing a number of things right. One can think of all of the elements in disaster planning and operations as links in a chain, in which any link can prove to be crucial and compromise the other elements. To mitigate the impacts of a potential disaster requires considerable forethought, training, and resources. Recent events like 9-11, Hurricane Katrina, and the Oakland Hills fire have demonstrated that many problems can arise requiring quick decisions, crucial information, and plans that can be successfully implemented. In this report, our objective is to review the scientific literature on emergency disaster preparedness, ranging from advanced planning and resource allocation to real-time operations during a disaster. The major objective of this review is to focus on specific tools and modeling approaches that an agency, such as Caltrans, should consider developing or using in emergency management operations.

It is important to recognize that many governmental agencies, like the California Emergency Management Agency (CalEMA), and private organizations like the American Red Cross already play a significant role in disaster planning and mitigation. For example, in California each county is required to set up contingency plans for a wide variety of possible disasters. It is also fundamentally clear that in many circumstances, current systems respond with the necessary capabilities in a timely fashion and gain high marks in subsequent public review. Further, planning drills and mock emergencies also help to focus on critical issues of communication, coordination, and training. Also, modeling tools are being developed which may make it easier to make critical decisions in terms of which roads to close and how to best help an area evacuate.

Past success in dealing with emergencies should not make anyone complacent, as there is still room for improvement in both planning and operations response. For example, there still exist problems of communication between agencies based upon equipment protocols, and the capability to transmit timely event data often doesn’t exist. To highlight this issue, one only needs to look at a recent article in the Santa Barbara Sound that focused on the lack of timely information available to the public associated with the July, 2008 Gap wildfire. Fire maps that were posted on public kiosks were often several days out of date. Traffic information about road
closures was often misleading, leading to more congestion than necessary. Perhaps the most egregious issue raised in the article is that the City of Santa Barbara cable TV channel posted road closure and other fire information about the 2007 Zaca Fire but not the Gap fire of 2008 while the Gap fire was in progress! As a further example of the possible lack of preparation on the part of emergency services in California, it was found in a recent audit by the City of Los Angeles Controller that the city lacks an overall strategic plan to respond to an emergency such as “an earthquake, fire or other calamity” (LA Times; July 15, 2008). The internal audit identified that 16 of the city’s emergency preparedness plans have not been updated for at least three years, and that one of the fire department plans had not been updated since 1992.

Preparedness should begin with a list of needs to be addressed in the event of an emergency. For each need, specific methods should be outlined in terms of how this need is to be met during the emergency. Do resources exist to meet the emergency demand and how much time will it take in order to respond? What techniques will be available to monitor the event and determine exactly where such resources should be allocated? When the demand for a resource outstrips supply, is there an approved priority defined approach to allocate this scarce resource optimally? Managers of state and county agencies need to ensure that their departments have developed contingency plans so that after an emergency has happened, the agencies are noted for their effective response.

Key factors in any emergency include understanding which infrastructure elements are still functional to support emergency response and possible evacuation, the ability to communicate to those involved as to the actions they need to take, the capability to collect and share real time data about the event among agencies, the capability to respond with support teams and resources, and the restoration of immobilized services as quickly as possible. For a transportation agency or public works department, this entails having enough personnel trained and available to inspect infrastructure, support special communication and transportation needs, and develop and implement an evacuation or emergency response plan.

The major focus of this report is on modeling techniques than can aid in emergency management operations. When there exist a multitude of issues and competing needs for resources, models
can be a significant aid to decision makers before, during, and after an emergency. The basic premise is that many problems are difficult to address without good models and appropriate data. Using such tools and data may help smooth operations and avert tragedy.

This report has been developed as a part of the First Responders System Testbed (FiRST) project at the University of California, Santa Barbara. The FiRST project investigates the integration of transportation and communication modeling and simulation to improve understanding of emergency preparedness and response. The report is organized as follows: We begin by defining key terminology commonly used in the academic literature on emergency management. The next section is a detailed examination of emergency evacuation modeling at multiple scales, with special focus on contraflow lane reversal. Disaster preparedness in California is then examined via analysis of state and county emergency plans, followed by several model formulations that may help planners locate emergency warning systems and shelters optimally. Next we cover emergency response, with a specific focus on models that help allocate personnel and resources where they are needed most. One technique that can greatly aid emergency responders is the prepositioning of resources in preparation for a disaster, thus we cover this topic in detail as well. We examine the issue of infrastructure fragility, and then conclude with a series of recommendations.

2. Defining terms

This section is devoted to defining the terminology that is used within the field of disaster management. Throughout this section we use issues associated with Hurricane Katrina to underscore specific points. We begin with the term disaster. In the most general sense, a disaster occurs when a natural or human-caused event exceeds the capabilities of our respond to it, resulting in an adverse outcome. One of the better definitions of disaster found in the academic literature is “an event, concentrated in time and space, in which a community experiences severe danger and disruption of its essential functions, accompanied by widespread human, material or environmental losses, which often exceed the ability of the community to cope without external assistance (Smith 2004).” It is further possible to subdivide disasters into natural and human, with the former referring to a physical earth process beyond human control.
and the later referring to an event caused directly by human actions. This distinction is not absolute, as exemplified by the extensive flooding of New Orleans by Hurricane Katrina that resulted from a natural storm surge overtopping man-made levees.

Underlying any disaster is a **hazard**, which is any natural or technological threat to people or things they value (Cutter 2001). In the case of Katrina, the major hazard was the hurricane itself with storm surge, high winds, and inadequate levee systems as sub-hazards. **Risk** is nearly universally defined as the product of the probability of a hazard occurring and the vulnerability of the people affected by this hazard (Mitigating natural disasters: phenomena, effects and options. A manual for policy and planner, 1991). For example, the people of New Orleans faced a high risk of being adversely affected by Katrina due to the increasing probabilities that it would hit the city (Hurricane Katrina Probabilities Report Number 15 & Hurricane Katrina Probabilities Report Number 21, National Hurricane Center) and the dual vulnerabilities of living in a floodplain and not having the means or desire to evacuate to higher ground.

**Vulnerability** is defined as the potential for loss, with **physical vulnerability** encompassing the interactions between nature and society and **social vulnerability** composed of the demographic and economic characteristics of different population groups. Put simply, physical vulnerability is the likelihood of exposure to a given hazard while social vulnerability is the likelihood of adverse outcomes (Cutter 1996). These two types of vulnerability are not mutually exclusive and depend heavily on the underlying geography of a place. For example, the physical geography of the New Orleans city site lies at the root of vulnerability, which is a city occupying a very low area that relies on a levee system and pumps for protection.

There are several important geographic parameters for any hazard that help determine physical vulnerability. These can also be thought of as “environmental parameters for human response” (Burton, Kates et al. 1993), as they also largely determine how people may respond when faced with a hazard and thus are a component of social vulnerability as well. **Magnitude** can be generalized as a measurement of the energy released by a given hazard. For example, Katrina had sustained winds of 110 knots when it first made landfall on the gulf coast, thus was classified
as a Category 3 hurricane according to the Saffir-Simpson Hurricane Scale (Knabb 2006). Other familiar measures of magnitude include the Richter scale for earthquakes, the Fujita scale for tornados, and could include the surge height of a tsunami or speed of movement of a wildfire front. **Frequency** is how often an event of this magnitude occurs. Katrina was a Category 5 storm shortly before landfall, and the frequency of the formation of a Category 5 hurricane forming in the Atlantic basin is on average once every three years (Atlantic Tracks File, 1851-2007, National Hurricane Center). Over 80 tsunamis have hit the California coast since 1850, thus the frequency of such an event is approximately once every 2 years (The Tsunami Threat to California, CA Seismic Safety Commission). **Duration** is how long the event persists. As an example, Katrina produced hurricane force winds in New Orleans for less than 24 hours, but the subsequent floodwaters inundated the city for weeks afterward. The Gap Fire in the Santa Ynez Mountains near Santa Barbara began on July 1, 2008 and was declared fully contained on July 28th (InciWeb, Gap Wildland Fire). **Areal extent** is space covered by event, which ranges from relatively small such as the 9,443 acres burned by the Gap Fire to very large in the case of Katrina, with hurricane force winds at one point extending 90 nautical miles from the storm’s center. (Knabb 2006) **Speed of onset** is length of time between initial event appearance and its peak. Katrina was classified as a tropical storm five days before reached its peak category 5 strength, thus giving this event a much slower speed of onset than a tsunami (a few hours at most) or an earthquake (instantaneous). **Spatial dispersion** is the pattern of distribution over the space in which the event can occur. Hurricane wind speed and earthquake intensity decrease with distance from the event center, while a wildfire front may jump large areas or change direction in an unpredictable fashion. **Temporal spacing** is the sequence of events. A simple timeline for the events in New Orleans surrounding Katrina could be *storm surge, levee breaches, flooding*, while a timeline for an earthquake could be *ground shaking, building collapse, structure fire, aftershock*. Time periods are also an important component of temporal spacing, particularly when planning evacuations or search and rescue operations.

Understanding the unique history of **social vulnerability** in New Orleans is essential to forming a complete picture of the Katrina disaster. Land value in the city is greatest on the highest ground, not surprising given the geographic advantage of being the last to flood and the
first to dry out. African-Americans have always inhabited the lowest laying land, with Jim Crow laws and redlining practices perpetuating slavery’s legacy of racial segregation (Colten 2002). When floods strike, the poorest citizens suffer most, perpetuating the cycle of poverty and vulnerability. The geographic variation in social vulnerability requires different mitigation, response, and recovery actions – the one-size-fits-all approach is ineffective (Cutter, Emrich et al. 2006). Living in the most flood prone areas is only one component of the social vulnerability of New Orleans’ marginalized populations. With poverty comes limited access to resources, with the inability to secure private transportation playing a significant role in the Katrina tragedy. Mistrust of authority grows out of inequality, leading to a significant communication gaps between government and impoverished citizens. One method that allows emergency management officials to focus disaster mitigation efforts is to identify ‘hotspots’ of vulnerability. For example, Rashed and Weeks (2003) use a Geographic Information System (GIS) to identify census tracts in Los Angeles County that are vulnerable under historic earthquake scenarios. In each scenario, vulnerability is calculated as a function of both the physical geography and socioeconomic population characteristics of affected places. This spatial multicriteria analysis is combined with fuzzy logic to produce a methodology that takes into account the inherent uncertainty in measuring vulnerability, providing a more robust analysis of susceptibility to earthquakes in Los Angeles.

The four **stages of emergency management** commonly used in the United States are mitigation, preparedness, response, and recovery (Waugh and Hy 1990). **Mitigation** actions reduce the long-term risk of vulnerable populations, including but not limited to zoning decisions, building and safety codes, insurance, and hazard mapping. In assessing the extensive building damage caused by Katrina, the FEMA Mitigation Assessment Team concluded that the lack of a building code not only contributed to residential damage but also to essential facilities including hurricane evacuation shelters, police and fire stations, hospitals, and Emergency Operations Centers (FEMA 2006). Inhabitants of areas along the wildland/urban interface are generally advised to create defensible space on their property to prevent a wildfire from spreading from natural fuels to man-made structures. **Preparedness** activities build operational capability for disaster response and include emergency operations planning, personnel training, and emergency warning systems and communication networks. One of the
few positive outcomes of Hurricane Katrina was the successful development and execution of a contraflow evacuation plan which involved switching the direction of travel of one the I-10 freeway segments to accommodate heavy traffic flow in one direction. This procedure is examined in detail in a later section of this report, but it is important to note that during the Katrina evacuation nearly all persons with access to private transportation were able to escape the city well before hurricane landfall and in less time than anticipated by planners (Wolshon, Catarella-Michel et al. 2006). **Prepositioning** of emergency supplies and locating emergency warning systems are two preparedness activities of particular relevance in California, both of which are further discussed in greater detail. Actions taken in the immediate time periods before, during, or after a disaster fall under **response**, encompassing warnings, evacuations, sheltering, and search and rescue. Preparedness largely determines response capabilities, which were severely limited during Katrina by the inadequate allocation of vehicles and emergency shelters. New Orleans city buses picked up residents and transported them to the Superdome, which was only stocked with enough provisions to feed 15,000 people for 3 days. 30,000 evacuees crowded into the Superdome, which lost electrical power and was completely surrounded by water. 500 school buses that could have been utilized to evacuate vulnerable residents were flooded and immobilized, and the national guard barracks and the high water rescue vehicles they contained were flooded as well, forcing guardsmen to concentrate on saving themselves (Smith 2005). A mutual aid agreement allows emergency responders in California to solicit assistance from other agencies, whose help is often critical to appropriate response to large hazards (Akella 2008). **Recovery** activities are focused on restoring vital systems that expedite the return to normal life, such as setting up temporary housing, clearing debris, and rebuilding or repairing damaged infrastructure. The Army Corps of Engineers unit based in New Orleans was concerned about the levees, yet had no external monitoring equipment for them and had to rely on media reports to find out if they were functioning. Since roads and canals were inaccessible, the Army Corps had to rely on helicopters for the levee repairs necessary to hold the water at bay. It took over a month for the combination of levee repair and pumping to finally dry out the city (Penry-Davey and Chinn 2005). A study of recovery from the 1994 Northridge earthquake found that socially vulnerable populations such as the poor, elderly, and ethnic minorities often rely heavily on non-governmental organizations (NGOs) to met disaster relief
needs (Bolin 1998). The four stages of emergency response are distinct but clearly interrelated, as the following conceptual model from Lindell and Perry (2004) shows.

The final key term that we will define in this section is **interoperability**. Soon after Katrina made landfall, electricity, land lines, cellular networks, and local media outlets failed, leaving emergency officials completely unaware of the extent of damage and the massive flooding that had begun in the city’s ninth ward. This massive infrastructure failure contributed to the inability of public safety responders to communicate, but the use of different communication technologies operating on separate frequencies by the multitude of agencies responsible for emergency response looms much larger. Communications interoperability allows personnel from various emergency management agencies to talk seamlessly over one radio and data system across a wide geographic area such as a metropolitan region or state. While achieving interoperability has been a long-standing goal of law enforcement, fire and rescue agencies, funding, governance, and cooperation remain major obstacles to implementation (Mountjoy 2005).
3. Evacuation

Modeling the complex spatial interactions between people and their environment that occur during an evacuation is an important step in developing a successful emergency plan. Despite recent advances in technological capabilities and modeling techniques, coordinating the movement of large numbers of frightened people through a confined space in a short amount of time presents a daunting challenge for researchers. This problem is inherently geographic in nature: spatial and temporal scales are what define the complexity of the evacuation process and dictate the appropriate modeling technique. Spatial scale is important in accounting for the location and characteristics of populations that must evacuate, the layout of the transportation network, and the area affected by a hazard when formulating an evacuation plan. Temporal scale is crucial as well, as event speed of onset largely dictates the start and end times of an evacuation. This scale-based approach has its roots in two classic problems, a large-scale evacuation due to a nuclear power plant accident and the small-scale evacuation of a building. Building evacuation is of great importance even in transportation as techniques developed first for building evacuation now form the basis for most evacuation models in transportation. Disastrous fires such as the 1977 Beverly Hills Supper Club (Southgate, Kentucky), which killed 165 people forced building engineers and fire departments to determine appropriate safe routes from buildings, establish maximum occupancy standards for rooms and change materials to retard the spread of fire. Although the scale of a building is different from a neighborhood or town many of the same issues underlying safe evacuation are present.

Before discussing the nuclear accident and building evacuation problems, it is important to define what is meant by a model. In the simplest construct, a model is a simplified version of a real world process, system, phenomenon, or entity. For our purposes this model must include one or more mathematical equations, thus allowing for a solution through enumeration, an algorithm or a heuristic technique. Often models are solved many times with varying input parameters, thus producing a host of solutions to give researchers a better idea of how certain inputs can affect model results. Introducing an element of randomness in a model can produce a
stochastic simulation, which accounts for uncertainty within the underlying process. When geography is explicitly accounted for in such a model it generally will fall into the classification of spatial optimization or spatial statistics.

Back to the question at hand: how best to model evacuations due to a nuclear power plant accident or building fire? Since these problems are fundamentally different in scale, the best approaches for modeling them are different as well. To get the most accurate representation of how people may behave when leaving a building, each person should be individually represented in the model. This technique is known as agent-based modeling or microsimulation, and is best suited to problems of limited size due to the computational complexity of representing individual people and their interactions. Microsimulation can also refer to the modeling of individual vehicles on a transportation network, but the essential small-scale characteristic of such an approach remains. At the other end of the spectrum is the large-scale evacuation required in the event of an accident at a nuclear power plant. Here the goal is to move thousands of people away from the accident site as quickly as possible, thus the inherent size of the problem makes microsimulation less feasible. Macro-scale models group population into larger units, which can then be moved through the transportation network under different starting conditions producing a generalized evacuation plan. The benefit of such an approach is that it can simplify the complex interactions of large groups and thus be solved quickly, which is essential to real-time modeling for decision support. One downside is that the further away one moves from the reality of individuals as independent actors, the greater the likelihood of individuals or groups of people being unaccounted for in the model. Between these two approaches is the meso-scale model, which is neither microscopic nor macroscopic but rather borrows elements from each. A meso-scale model will not represent people individually but may aggregate them into relatively small population units, unlike the macro-scale model, which seeks the largest feasible unit. The spatial extent of meso-modeling can be at the neighborhood or community level, or the entire area affected, e.g. hazardous material cloud or a plume of radioactive material.

Choosing the appropriate modeling scale to use is an important question that extends beyond the narrow scope of evacuations. One way to aid in making the choice of scale is to group potential hazard responses into a typology of disaster management decisions (Wallace 1985). Using this
framework, a micro-scale model is considered best suited to an operational decision such as a neighborhood evacuation occurring at a small spatial and temporal scale. A strategic disaster management decision is made at a large temporal and spatial scale, thus a disaster preparedness tactic such as resource pre-positioning is best modeled at the macro-scale. Tactical operations incorporate both operational and strategic decision making processes, while meso-scale models are often used for location-routing problems at a medium temporal scale such as providing EMS coverage. Now that these different modeling scales have been defined, we will examine how researchers have used them to model evacuations in response to hazards.

Quantitative modeling is an important compliment to the various qualitative studies of emergency evacuation. The partial meltdown at the Three-Mile Island Nuclear facility in 1979 spurred survey-based research on the geography of evacuee behavior, examining route preferences and travel distance (Zeigler, Brunn et al. 1981) and the spatial distribution of social vulnerability (Cutter and Barnes 1982). Many evacuation modeling approaches are based on the groundbreaking research of Dial (1971), who developed a method to account for the fact that drivers will often choose routes that are not the shortest distance to their destinations. This approach better reflects the dynamic and unpredictable flow of traffic during an evacuation. Other researchers have built on this framework and introduced an element of random route assignment that represents driver behavioral decisions under conditions of distance and network topology uncertainty (Daganzo and Sheffi 1977). Estimation of network clearance time emerges as the central focus of evacuation modeling, thus most of the current research has its roots in a modeling approach that can calculate clearance times given variability in network characteristics, intersection control and design, and evacuation strategies. One of the first examples of this is NETVACI, which uses the mathematical relationships between flow, speed, density, queuing, and other traffic measures to estimate clearance time on a node/arc network representation (Sheffi et al. 1982). Applications of this model to simulate evacuations around several nuclear facilities demonstrated that it could efficiently handle relatively large networks, an important consideration even with the development of faster and more capable computers.

An early example of a decision support system designed to craft an evacuation plan is the Transportation Evacuation Decision Support System (TEDSS), which allows planners to
estimate network clearance times for various evacuation scenarios for nuclear power plants (Hobeika, et al. 1994). Another important component of an evacuation plan is where to house evacuees. Yamada (1996) solved two network transportation problems, a shortest path problem and minimum cost network flow problem, with the goal of allocating residents to places of refuge during a simulated evacuation in Yokosuka City, Japan. Results show that the classical shortest path (Dijkstra 1959) solution results in a more uniform evacuation plan and shortest average distance, while the minimum cost solution will split evacuee flows forcing some residents to go to a place of refuge that is not their closest. One interesting theoretical outcome of this research occurs when evacuees are instructed to go to a location further away than the nearest shelter: the greater the disparity between shortest path and maximum network flow solutions, the greater the potential problem of non-compliance by evacuated populations, resulting in an event which will take longer to clear and where a few shelters are likely to be overwhelmed.

Many early models of building evacuation use a network flow formulation similar to those discussed above. Chalmet and Francis (1982) present some of the first research to address problems such as bottlenecks that may occur during the emergency evacuation of buildings. They present a simple model that can efficiently allocate evacuees to exits, thus helping prevent bottlenecks from occurring. For a given building, let:

\[ k = \text{total number of people to be evacuated} \]
\[ n = \text{total number of exit routes} \]
\[ j = \text{index of exit routes} \]
\[ x_j = \text{people using exit route } j \]
\[ t_j(x_j) = \text{time for } x_j \text{ people to clear exit route } j \]

We can then allocate people to exit routes to minimize the time that it takes the last person to get out of the building using the following formulation:
Minimize $Z = \max\left(t_j(x_j): j = 1, \ldots, n\right)$

subject to:
1) $\sum_j x_j = k$
2) $x_1, \ldots, x_n \geq 0$

This model seeks to minimize the maximum amount of time it takes a given group of people to evacuate using a given exit, while ensuring that the entire building is evacuated. The two major assumptions of this model are that each evacuee has access to every exit route, and that the time to clear an exit route relies only on the number of people using it. Comparison of the estimated clearing time of an eleven story building generated by a related but more complex model to empirical measurement of an actual evacuation showed that the model was overly optimistic, largely due to the inability to account for queuing and inefficient evacuee movement through stairwells. This model weakness is due to a linear equation structure that assumes all flows along arcs between origin and destination nodes are constant. This is the very feature that is faced when evacuating an area, where the speed of traffic decreases as the density or number of vehicles per lane mile increase.

A way to account for this weakness is to introduce nonlinear side constraints to the model which allow dynamic evacuee movement to be accounted for (Choi et al. 1988). Models of this type can often be solved expeditiously for small scale building evacuations, but otherwise offer little advantage when compared with agent-based microsimulation. EXIT89 is an early example of a high-rise building microsimulation model which allows stochastic variation in individual evacuee behavior, queuing, and evacuation speed to be represented, thus producing a result more closely in line with actual emergency conditions (Fahy 1995). The ability to model individuals can be incorporated into a Geographic Information System (GIS) to create valuable tools for emergency planners.

Most evacuation based decision support systems are base upon a model integrated with a Geographical Information System (GIS). These computer programs use the topology and feature attribute capabilities of GIS in conjunction with location decisions and simulation runs produced
by models to assist in the decision processes of emergency planners. One of the first systems
designed specifically for emergency evacuations is CEMPS, the Configurable Emergency
Management and Planning System (Pidd et al. 1996 and de Silva and Eglese 2000). In this
system, the GIS is used first to map the terrain and identify the population to be evacuated.
These data are stored in a database, which is accessed by a discrete microsimulation model that
is used to assess various routing schemes for moving the evacuated population to designated safe
areas. The major limitations of most of this earlier work are due to the inability of the
microsimulation model to account for dynamic route selection due to congestion, traffic effects
such as ‘scrunching’, and the behavior of emergency vehicles. Many of these issues have been
addressed by subsequent microsimulation research, greatly improving realistic representation of
traffic conditions during evacuations.

One novel approach of representing traffic dynamics is to adopt methods commonly used in
physics (Helbing 2001). Using models analogous to micro-scale (particle-base), meso-scale (gas-
kinetic), and macro-scale (fluid-dynamic) approaches, physicists have concluded that it is
possible to simulate complex traffic interactions and develop natural laws that explain driver
behaviors under a multitude of traffic conditions. Of particular interest is a model that
incorporates both macro-scale and micro-scale approaches that is well suited to the traffic jams
and bottlenecks that may occur during an evacuation.

Rapid housing development and population growth in fire prone areas is of particular concern to
California evacuation planners. Most evacuations at the wildand-urban interface occur at the
neighborhood level, thus are well scaled to commercial microsimulation software. (Cova and
Johnson 2002) developed a modeling approach that incorporates a custom evacuation scenario
generator, GIS, and an off-the-shelf microsimulation package to estimate the time it would take
each household to evacuate under a multitude of conditions. Using individual household
evacuation times allows planners to assess the spatial variability of vulnerability to a hazard and
provides a much greater level of detail compared to traditional evacuation measures such as
network clearing time. This enables plans that are tailored to the specific needs of a community
and thus have a greater probability of successful execution.
Timing of evacuations is another important problem that must be addressed by emergency managers, especially when a large population must be relocated on short notice. Inefficient scheduling can lead to traffic gridlock, impeding the evacuation procedure and increasing evacuee risk of being affected by a hazard. Issues of temporal scale were examined in a microsimulation of a large-scale evacuation of San Marcos, Texas, where researchers found that staged evacuations are more efficient than an all-at-once evacuation for densely populated areas with a grid street network (Chen and Zhan 2006). Recent research in modeling of the process of passenger loading and unloading of planes identified that the fastest method of loading and unloading occurred when people are staged, but also separated (e.g. every third row). Thus, it may be possible to show in simulation that staging with separation may aid in evacuation as well.

Many evacuation modeling approaches rely on the delimitation of an emergency planning zone (EPZ). Cova and Church (1997) point out that defining an EPZ in advance is problematic for fast moving hazards where the population that will need to evacuate is unknown in advance. Because of this they developed a critical cluster model (CCM) to identify neighborhoods that may face transportation difficulties if forced to evacuate. As previously noted, most evacuation modeling addresses either macro-scale events like a hurricane or micro-scale events such as a building fire. The Cova and Church model is among the first to address neighborhood, or meso-scale, evacuation vulnerabilities. The first step in finding a vulnerable neighborhood, or critical cluster, is develop a network representing flow capacities along with attaching estimates of the population needing to evacuate at each node of the network. The next step is to apply the CCM to find clusters of contiguous nodes that have the highest average population per exit lane. This problem is closely related to the graph partitioning problem, and can be defined using the following notation:
\( N = \) set of all nodes
\( N_i = \) contiguous partition of nodes containing \( i^* \)
\( N_2 = \) nodes connected to \( N_i \)
\( i = \) index of nodes
\( j = \) index of nodes connected to \( i \)
\( a_i = \) weight of node \( i \) (population)
\( c_{ij} = \) cost of arc \( ij \) (lanes)
\( s = \) maximum size (in nodes) of \( N_i \)
\( i^* = \) index of root node \( \in N_i \)

\[
\begin{align*}
    x_i &= \begin{cases} 
    1, & \text{if node } i \text{ is in } N_i \\
    0, & \text{otherwise}
    \end{cases} \\
    y_{ij} &= \begin{cases} 
    1, & \text{if node } i \text{ is in } N_i \text{ and node } j \text{ is in } N_2 \\
    0, & \text{otherwise}
    \end{cases}
\end{align*}
\]

Using this notation, we can formulate the model as:

Maximize \( Z = \frac{\sum_i a_i x_i}{\sum_i \sum_j c_{ij} y_{ij}} \)

subject to:
1) \( x_i - x_j \leq y_{ij} \quad \forall i, j \text{ and } \forall j, i \in N \)
2) \( \sum_i x_i \leq s \)
3) \( x_{r^*} = 1 \)
4) \( x_i, y_{ij} \in \{0,1\} \quad \forall i, j \in N \)

This model maximizes the total population relative to the capacity of the exit lanes, defined as those links connecting selected cluster nodes and nodes directly outside the cluster. The CC model was applied to data of the Santa Barbara area and each node was assigned an evacuation vulnerability value (associated with the worst case cluster in which that node was a member) resulting in an evacuation vulnerability map of Santa Barbara. The results of this application
clearly showed that evacuation difficulty varied from area to area. Transportation planners already recognized some of the more vulnerable areas, but other areas that were identified were a surprise to many.

Church and Sexton (2002) use a different methodology to research evacuation vulnerability at the micro-scale. The Mission Canyon neighborhood in Santa Barbara was previously identified as a critical cluster due to a sizeable population base reliant on a limited number of routes for evacuation. This neighborhood also lies in the urban-wildland interface and is especially vulnerable to wildfires propelled by sundowner winds moving down canyon with great speed. Previous work had estimated evacuation time for such areas by comparing the total vehicle demand to the number of lanes leaving the neighborhood. This research tests the assumptions of this macro-scale approach by modeling different evacuation scenarios using micro-scale traffic simulation. Running multiple simulations allowing the number of vehicles, number of exit routes, road capacity, and level of traffic control to vary, Church and Sexton found that major evacuation problems might occur without a significant coordinated traffic control effort and extensive resident education. Several interesting problems arise from this microsimulation, including the inability of the software to model vehicles that back out of driveways. During times of high fire risk, emergency officials recommend that people back into the driveway (so they are facing the street) to speed up evacuations, but this recommendation is rarely followed. Another interesting problem is that drivers are given dynamic feedback during the microsimulation, thus mimicking the effect of a special radio channel broadcasting real time information on crowding along specific evacuation routes. This assumption speeds up the simulated evacuations, but may not reflect the actions of drivers (turning on the radio) or local broadcast or information gathering capabilities. Overall, they find that while macro-scale evaluation provides similar evacuation time estimates as microsimulation, neither approach can fully account for driver behavior or the behavior of what might happen during an accident or blocked exit (e.g. people abandoning their vehicles on the street causing a relatively permanent roadblock).
One assumption that is frequently made in evacuation modeling is that drivers will behave rationally. Among these assumed behaviors are that evacuees will understand the instructions given them by officials coordinating the evacuation, follow these instructions exactly and obey all posted speed limits and traffic laws. While it is often necessary to make assumptions in order to limit the size and complexity of models, the fear and panic that often occurs when people are threatened should not be overlooked as it may severely affect their decision making. Pel and Bliemer (2008) help account for this uncertainty by introducing a model that explicitly incorporates driver behavior when assessing both voluntary and mandatory evacuation plans. Their three-stage model includes travel demand, travel choice, and network loading components, with the travel choice module capable of modeling the behavioral responses of the evacuees towards evacuation instructions such that they can be followed fully, followed in part, or rejected completely. Models such as these represent an important advance for researchers who seek to produce the most accurate representation of an evacuation situation possible.

Another problem faced by emergency managers is compliance with a mandatory evacuation order. Dow and Cutter (2002) report that only 65% of South Carolinians ordered to evacuate in response to Hurricane Floyd actually did so, thus greatly compounding the problem of keeping people safe from the storm. A related problem is ‘shadow evacuation’, which occurs when people decide to evacuate despite not receiving any official instructions to do so. This may contribute to traffic delays and emergency resource shortages, impeding the safety of those who are directly threatened by the hazard. Research based in Long Island, NY concluded that evacuation planning areas should be expanded in response to the high likelihood of shadow evacuation in the event of a nuclear accident (Johnson 1985). While this approach may help traffic planners design better evacuation models, it does not address the underlying causes of a shadow evacuation. Environmental cues, such as high winds and smoke during a wildfire, can prompt people to evacuate even if they are not directly threatened. A more troubling cause of shadow evacuations is mistrust of information or the authorities who provide it (Lindell and Perry 2004), a problem that may be addressed by providing the most accurate hazard information as quickly as possible to people in an effected area. Although shadow evacuations have been modeled using microsimulation (Cova 2008), further research on this problem through mathematical modeling techniques may be of great benefit to evacuation planners.
The successful evacuation of New Orleans prior to the arrival of Katrina was made possible through the use of contraflow. Contraflow involves reversing the direction of traffic for a set of lanes along a route, so the capacity of a route to handle traffic in a desired direction is enhanced. The success of using contraflow is highlighted in the following statement by Kathleen Blanco (Former Governor of Louisiana):

“Before Katrina came, I developed a new evacuation plan that includes contra-flow, where both sides of the interstates are used for outbound traffic. I am proud that we rapidly moved over 1.2 million people - some 92% of the population - to safety without gridlock or undue delay prior to Katrina.”

Contraflow lane reversal is a valuable option in emergency evacuations by increasing the outbound traffic capacity of a given road or freeway. The first large scale implementation of contraflow occurred in Georgia and South Carolina for Hurricane Floyd evacuations in 1999, and a majority of hurricane threatened states have now adopted contraflow plans (Urbina and Wolshon 2003). As the quote above illustrates, contraflow can be very effective in efficiently moving a substantial proportion of the population in areas threatened by large-scale disasters. Yet the tragic aftermath of Hurricane Katrina shows that it is not a ‘magic bullet’ solution for evacuation planning, especially in places like New Orleans with large populations without access to private transportation. While the vast majority of contraflow evacuation plans are hurricane-specific, many characteristics could be generalized and implemented for other large-scale disasters.

The state of Florida revised its contraflow evacuation plan in response to the busy 2004 hurricane season. With 4 major hurricanes prompting the evacuation of nearly 10 million people, the Florida Division of Emergency Management and the Florida Department of Transportation determined that an improved contraflow plan was necessary given the probability of its implementation for future hurricane evacuations. Some essential components of the updated plan are daylight only contraflow implementation, pre-positioning of traffic coordination
and emergency response vehicles along the contraflow route, and clear delineations of agency roles and means of communication. Specific routing recommendations include assigning the same number of lanes for contraflow exit points as the contraflow route itself has and keeping highway shoulders open for disabled vehicles and emergency responder use. (Contraflow Plan for the Florida Intrastate Highway System, 2005)

Empirical assessment of contraflow evacuation plans utilized during hurricane events shows substantial improvements in vehicle capacity yet also clearly illustrates drawbacks. During the 2000 Hurricane Floyd evacuation, the South Carolina Department of Transportation (SCDOT) measured a 67% increase in the number of vehicles evacuated per hour with four outbound freeway traffic lanes when compared to the standard two inbound, two outbound configuration. Safety, accessibility and cost emerge as the most pressing problems during a contraflow operation. Freeways are generally not designed to handle opposing flow, thus confusing signage, inadequate collision barriers and limited exit ramp accessibility can lead to accidents and breakdowns that may further traffic delays. Contraflow plans can reduce or eliminate inbound traffic, limiting the ability of emergency service personnel to assist those left behind. Manpower requirements can be substantial, with more than 70 personnel needed for an 18 interchange contraflow plan in North Carolina (Wolshon 2001). These empirical results provide a basis for modeling and simulation-based research, which can address the challenges of contraflow evacuations in a controlled setting.

Microsimulation of contraflow for hurricane evacuation of New Orleans showed how suboptimal entry point design and location could limit the number of evacuees able to leave the city (Theodoulou and Wolshon 2004). A North Carolina coastal evacuation simulation showed extensive queue formation at contraflow termination points, highlighting the need for further research on optimal access points and interchange functionality (Williams, et al. 2007) Another challenge in modeling contraflow is the increased size of network flow problems that must account for each individual lane rather than representing roads as a single arc. Tuydes and Ziliaskopoulos (2006) use a tabu search heuristic to address the computational complexity of modeling a contraflow evacuation on a large urban network. Although most research has been directed towards hurricane evacuation, contraflow can be incorporated into traffic management
models for other large-scale disasters. Research comparing different evacuation strategies for downtown Minneapolis, Minnesota also shows that access to a contraflow corridor is a critical determinant of overall effectiveness. By increasing capacity of key entrance ramps, evacuation time was substantially reduced for an evacuation simulation that included more than 50,000 spectators at a major sports venue. (Kwon and Pitt 2005)

Lane-based traffic routing can improve traffic flow during an evacuation by eliminating congestion at critical intersections. When Los Alamos, New Mexico was evacuated in response to the 2000 Cerro Grande wildfire, a lane-based routing plan helped 11,000 residents escape this isolated mountain community using the one available exit in under 4 hours (Mynard, et al. 2003). The essence of a lane-based plan is that it restricts lane changes and directs traffic to make turns at intersections in order to avoid cross traffic. Cova and Johnson (2003) use a lane-based routing model to simulate traffic during an evacuation of downtown Salt Lake City, generating a 40% improvement in network clearing time when compared to no routing plan.

A new and promising approach to contraflow modeling is taken by (Meng, Ling et al. 2008). The optimal contraflow lane configuration problem (OCLCP) and the optimal contraflow lane-scheduling problem (OCLSP) are addressed by combining the linear programming and microsimulation methods. First, the linear program is used to determine a feasible lane-reversal plan that minimizes total travel time in the central business district of Singapore. This plan becomes an input to a microsimulation model developed with PARAMICS software that mimics the response of drivers to these lane reversals. This methodology allows researchers to systematically evaluate each contraflow plan by providing instant data on traffic flow rates and queuing via the microsimulation software.

Although contraflow under emergency evacuation conditions is not implemented as part of their routing plan, it could be incorporated under a similar modeling framework. This unification of traffic routing methods has the potential to further improve network clearing times for mass evacuations, especially if used to address the access point and queuing problems of contraflow operations. There remains a central question that has not been answered by any of the above
models: What evacuation routes will drivers actually choose? Route choice behavior is largely based on the assumptions of rational driver behavior under perfect information, both of which are questionable in emergency evacuation situations given a large-scale disaster. Chiu and Mirchandani (2008) propose a dynamic feedback information routing system, in which evacuation routes are updated according to the current traffic conditions. Such a system could be implemented using existing traffic monitoring and mass communication technologies, and can significantly improve evacuation effectiveness through real-time management.

Spatial and temporal scales are crucial geographic factors in determining the evacuation modeling approach best suited to a given hazard. Individual (micro), aggregate (macro), and intermediate (meso) spatial scale models all have specific strengths and weaknesses which should be carefully considered based on both the capabilities of researchers and the needs of agencies. Timing is critical: a contraflow evacuation plan requiring 5 hours of lead time for placement of signage and personnel is of little use in the face of a levee that breaks without warning. With careful consideration of these factors, modeling can prove invaluable to the formulation of a successful evacuation strategy. The contraflow operations in New Orleans prior to Hurricane Katrina and lane-based routing of evacuees from the Los Alamos, New Mexico Cerro Grande Wildfire provide two examples that demonstrate the benefits in modeling evacuations.

4. Disaster Preparedness

Counties and state organizations are tasked with the development of disaster plans, involving a coordination of agencies and nongovernmental organizations. Such planning documents often list possible emergencies (from chemical spills to flooding), areas of vulnerability (from high fire risk areas to nuclear power plant evacuation zones), and plans for addressing such emergencies. Typically, counties plan drills that are used to train and test for the ability to respond to an emergency. They often are based upon an emergency scenario, bringing a wide variety of emergency personnel in handling a mock disaster drill. These drills are used to identify weaknesses in plans, strengthen ties of communication and promote a focus on coordination and team building.
The role of Caltrans as defined in a November 20, 2008 draft of the State of California Emergency Plan presents several logistical issues of particular interest to researchers affiliated with the First Responders System Testbed project. The first Caltrans responsibility of interest is the classification of state property suitable for use as temporary emergency housing. Selecting suitable sites can be thought of as a function of accessibility via the existing transportation network, proximity to populations in need of temporary shelter, and cost effectiveness in the transportation and support services necessary to meet the needs of affected people. Another Caltrans role is the support of fire-fighting efforts through traffic control via lane-closures or special OES requests such as movement of emergency supplies. Closure of a lane for emergency-only use or allocation of HOV lanes may provide the extra traffic capacity necessary for fire personnel to respond quickly to a dangerous wildfire, and likewise enable the efficient and timely transport of emergency supplies to places of need. Caltrans responsibilities for dealing with hazardous materials and radiological substances also present opportunities for research. Restoring contaminated highways and other state transportation facilities is essential to maintaining efficient and safe traffic flow. Traffic routing with differing network capacities under emergency conditions and allocation of assets before an emergency event occurs emerge as pervasive themes that can be addressed through various modeling techniques to improve Caltrans disaster preparedness.

Responsibility for emergency management in California counties falls under the auspices of each county office of emergency services (OES). A brief survey of county OES websites shows wide discrepancies in the quality, quantity, organization, and accessibility of various types of emergency information that is provided to the public. For example, the San Luis Obispo County Office of Emergency Services website (http://www.slocounty.ca.gov/OES/) is well organized, with a direct link to the general county emergency operations plan, dam and levee failure evacuation plans and maps of potential inundation areas, and Diablo Canyon Nuclear Power Plant emergency planning information including potential evacuation routes. In contrast, emergency management information for Alameda County, site of the disastrous Oakland Hills wildfire of 1991, is scattered throughout various county agency websites including county sheriff and county emergency medical services. While these websites contain specifically targeted information, including how day care centers should prepare for an earthquake and special considerations for evacuating medically fragile persons, the lack of a single disaster information
clearinghouse appears to be a glaring deficiency. Also missing from any of these web resources is a map showing evacuation routes. This omission may be due to scale discrepancies between the size of the county itself and the areas that may be evacuated or the variable nature of the routes that may be implemented depending on the geographic characteristics of a specific disaster. Whatever the cause of the omission, a simple map directing people to their optimal evacuation route could be extremely valuable to overall preparedness. Added to this is the fact that the web site is probably updated occasionally, rather than being designed to give up to date information during a disaster. This is not a particular criticism of the Alameda county web site but a general criticism of most web sites.

Unfortunately, there still are noticeable problems in coordination for large area disasters. Despite performing mock drills at an airport or some other type of disaster, there has been too little focus on the sum of all emergency capabilities in responding to a major disaster. This issue was recently discussed by Haji and Lewis (2006) in their study of disaster preparedness of hospitals in Los Angeles County. It should be first noted that a hospital by itself is not designed or operated to handle a large-scale emergency. Hospitals normally operate within given bounds of patient flow and emergency demand. Government programs such as Medicare and private insurance companies reimburse hospitals based upon realistic estimates of costs. Beds not occupied by patients add to a hospital's cost of operations, but do not add to revenue. Insurance companies reimburse for patient care and not for maintaining unused facilities. Since hospitals do plan for fluctuating levels in patient care, this means that bed occupancy is not always at 100%. But just how large should a hospital be, or regionally, how large should the combined capacity of hospitals be in order to handle an emergency event? Given that hospitals by themselves are encouraged to operate at a size which matches average demand plus some surge capacity, it would not be surprising to see that many hospitals are at capacity a certain percentage of the time. When that happens they have little flexibility in handling a large surge based upon an emergency. The economics of hospital operations today has probably pushed the operating envelop toward being at 100% capacity a minimum percentage of the time. One can argue that if a hospital never reaches 100% bed occupancy, then it is too large and is not as efficient as it needs to be in the current operating and reimbursement environment. What this means is that hospitals are not rewarded in maintaining surge capacity for the unlikely event of an emergency.
Haji and Lewis surveyed a sample of hospitals in Los Angeles County in order to assess emergency preparedness. Their survey involved 45 hospitals (each interviewed by telephone as well as being the object of a personal visit). This sample represented more than 50% of the existing hospitals in LA County. Their findings are not surprising in light of the economics of hospital reimbursement discussed above. First, only 29% of the hospitals in the survey had a surge capacity that exceeded 20 beds. It was stated that all hospitals maintained an emergency medical supply of at least 3 days, but they did not state that this supply included all elements, including food and water (for both patients and staff). Less than half of the hospitals maintained more than 10 isolation rooms. Fewer than half of the hospitals maintained stockpiles of chemical antidotes and antibiotics. Finally, 60% of the hospitals diverted patients to other hospitals more than 20% of the time. Altogether, this means that 20% of the time a majority of the hospitals lacks the capacity to handle emergency patients. Although it is possible to immediately cancel elective procedures, it is necessary to identify average patient volumes involving elective procedures in order to estimate the level of emergency capacity. Also, since many procedures are now handled in outpatient surgery centers, it may be that the total surge capacity of the hospital system in LA is woefully lacking, especially in terms of beds in satisfying demand in an emergency. But this issue of preparedness could be surveyed across a number of organizations and services. In a recent issue of the LA times (Jan 25, 2009), it was noted that over the last decade the number of pediatric hospital beds in California had declined by 19%, even when the child population has increased. This has resulted in hospitals moving very sick children from their hospitals in order to make way for even sicker children due to the lack of free beds. The lack of capacity to handle anything out of the norm has been lost.

The fact is that hospitals operate as an independent unit in a larger system. The lack of a system wide perspective may mean that emergency capabilities are less than desired. This same issue may be true for a wide variety of critical needs, ranging from bridge inspectors to fuel storage for emergency vehicles. For example, do the highway patrol and Caltrans maintain resources to supply their workers in the event of an emergency, e.g. water, fuel, and food? Are methods in place to track personnel during an emergency? Is there capability to set up a field unit to support an effort oriented at maintaining quarantine or supporting an evacuation? Should agencies such
as Caltrans train people to assist organizations like the Red Cross and local search and rescue groups in an emergency?

It should be noted that the list of local emergency capabilities can often be expanded significantly by mutual aid agreements, which is a common strategy for fighting large wildfires. Through mutual aid agreements, many cities and counties from across a region may donate needed equipment and crews for a lengthy time to fight a large uncontrolled wildfire. But what is less understood is the capability of handling a large demand locally when it would take too long to respond with mutual aid or when an emergency exists that stretches the ability of an agency to cope with an emergency when no mutual aid agreement exists, or when the time taken in seeking and getting outside aid has exacerbated the initial problem. For example, if the lack of hospital beds and associated care is in short supply, patients may need to be transported long distances to other hospitals or it may be that temporary tent hospitals should be erected. But what is the length of time needed to address this need and can it be accomplished in a timely manner? Regardless of which action is taken, contingency plans for such an outcome need to be made, if an event is to be handled effectively.

Given the many overlapping responsibilities of Caltrans in the event of an emergency, coordination and cooperation with state, county, and local agencies and officials is essential to a successful and efficient response. While divergent planning and capabilities among agencies can make this task seem overwhelming, research such as the Los Angeles County hospital survey can help identify strengths and vulnerabilities within a wide variety of systems and infrastructure critical to emergency management. Regional planning via mutual aid agreements and other predetermined coordination can greatly improve the ability of statewide agencies respond to disasters that often transcend jurisdictional bounds, ultimately protecting critical infrastructure and personal property and saving lives. For example, developing a real time equipment inventory and tracking system for Caltrans may help in responding to large scale events that requires a response involving a larger than average amount of equipment. This type of problem should be modeled within the context of analyzing the time it would take to respond to a place in the state with a level of response that equals or exceeds some pre-specified response.
5. Warning System Location

For some emergencies, timing is so important that it is obvious that a warning system needs to be implemented. The classical approach for doing this is to use a set of warning sirens. For example, many cities and counties in the Midwest have warning sirens, so that people can be alerted to an impending tornado. A warning siren is designed to be loud enough to disrupt virtually everyone within its vicinity, alerting them to take some type of evasive action. More recent systems include the reverse 911 systems, where phones within a target area are called with a prerecorded message for some type of issue like “evacuate immediately, wildfire approaching”. Reverse 911 systems are now in vogue as they can be easily targeted to a specific area and can be used with a specific message. The coverage of a reverse 911 systems is based upon homes that have landline telephones as well as those people who have registered their cell phones with system operators. During the recent Tea fire in Santa Barbara County, some people stated that either they didn’t get a 911 call or the call was very late in terms of the value of the warning. Thus, warning sirens have a continued role in emergency warning. Siren systems are used extensively throughout California\(^1\) to warn people of hazards such as a tsunami, dam failure, nuclear accident, or campus emergency. FEMA guidelines dictate that a state or local emergency operations plan should explicitly include the location and geographic reach of warning sirens (FEMA September 1996). One of the fundamental questions when designing an emergency siren warning system is where to locate them so that the configuration of sirens meets the population coverage requirements of an emergency plan.

One of first research papers to deal specifically with emergency siren location is a case study of a tornado that hit Kalamazoo, Michigan in 1980 (Hodler 1982). While tornados are rare enough in California that it is not essential to design siren systems to warn against them, several important transferable findings emerge from this research. The first and most relevant is that geography

\(^{1}\) There are a number of examples in California involving the use of warning sirens. For example, Crescent City uses a warning siren to alert people to a tsunami risk. San Luis Obispo County operates a system of 131 sirens to warn of an accident at Diablo Canyon Nuclear power plant. Ventura County operates a system of 11 sirens to warn of a dam failure at Casitas Reservoir. Cities such as Coronado and Alameda maintain siren systems for emergencies like wildfire, flood, chemical spills etc. and universities like UC Berkeley and UC Riverside maintain campus warning systems. Even industries operate warning sirens. For example, Union Pacific has a warning siren system associated with their operations near Roseville, CA.
matters: Due to the downwind location and scarcity of sirens, more than two-thirds of residents surveyed in the area of town struck first by the tornado reported not hearing them at all. Another interesting finding is that seventeen percent of all survey respondents did not know the meaning of the sirens, despite the fact that they were tested once a month. These results indicate that optimizing the location of sirens is essential to effective warning, as is communication with populations they are intended to protect.

Another important factor in developing an emergency siren warning system is cost. Budget limitations often dictate the type and amount of equipment that is available, thus affecting the spatial extent of siren coverage that planners may work with. Set covering location models can be used to determine where to locate a predetermined number of sirens such that they cover the most population, thus implicitly accounting for cost restrictions. Models of this type allow planners to assess the tradeoffs inherent in using different technologies, siting scenarios, and policy options and can be redeployed to account for changes in population distributions and in the transportation network (Current and O’Kelly 1992). The Current and O’Kelly model can be defined using the following notation:

\[ i = \text{an index used to refer to a small area of population, like a neighborhood} \]
\[ j = \text{an index used to refer to a site for possible siren placement} \]
\[ O_i = \{ j \mid \text{an omnidirectional siren placed at } j \text{ can be heard at area } i \} \]
\[ R_i = \{ j \mid \text{a rotating siren placed at } j \text{ can be heard at area } i \} \]
\[ c_j^O = \text{the cost of locating an omnidirectional siren at site } j \]
\[ c_j^R = \text{the cost of locating a rotational siren at site } j \]
\[ X_j^R = \begin{cases} 1, & \text{if site } j \text{ is selected for a rotating siren} \\ 0, & \text{if not} \end{cases} \]
\[ X_j^O = \begin{cases} 1, & \text{if site } j \text{ is selected for an omnidirectional siren} \\ 0, & \text{if not} \end{cases} \]

Using the above notation, we can define the siren placement model of Current and O’Kelly as follows:
Minimize \( Z = \sum_{j \in O} c_j^O x_j^O + \sum_{j \in R} c_j^R x_j^R \)

subject to:

1) \( \sum_{j \in O_i} x_j^O + \sum_{j \in R_i} x_j^R \geq 1 \) for each area \( i \)

2) \( x_j^O \in \{0,1\} \) for each \( j \in O \)

3) \( x_j^R \in \{0,1\} \) for each \( j \in R \)

The above model is a form of the well-known Location Set Covering Problem that was originally defined by Toregas et al. (1971). Essentially, this model selects both the types and locations of the sirens so that the cost of the siren system is minimized while ensuring that all areas are “covered” or are within the warning zone of at least one siren. The objective function minimizes the total costs of the selected sirens. The first constraint establishes that each small area has at least one siren site selected that is within the siren warning zone. There is one such constraint for each area. This is a relative small and compact integer-linear optimization model. It can be applied to relative large regions involving thousands of sites and small areas. General purpose software packages exist which can be used to solve this problem over a range of options or scenarios. Overall, this type model can be used to design a warning system for a region or for a corridor like a highway or coastline.

Another modeling approach for locating emergency sirens is the \( p \)-center location problem, whose objective is to minimize the greatest distance of all population units from their nearest warning siren. This problem can be conceptualized as having the smallest possible warning radius around all sirens, given a set number of sirens and people to be served (Suzuki and Drezner 1996). Integrating models such as these into GIS can provide a robust platform for planners seeking to locate warning sirens optimally. Accurate measurement of siren coverage is largely a function how well population is represented, thus current research is focused on comparing points, regions, and polygons as population representation units. In a study locating emergency warning sirens in Dublin, Ohio, researchers found that the optimal solution for each representation used the same number of sirens, with region and polygons best suited to situations where complete population coverage is necessary (Murray, O’Kelly, and Church 2008).
The massive toll of the December 26, 2004 Indian Ocean tsunamis served as a chilling reminder of the danger posed by these hazards. In response to that event, the California Seismic Safety Commission published a report citing the great danger posed to the state by tsunamis and finding that public education, warning systems, and evacuation plans were lacking (CSSC 2005). Sirens are a critical component of a tsunami warning system since they can warn both permanent residents and the transient populations that crowd California’s beaches during the tourist season. One important consideration is that warning systems must be designed to withstand the effects of the hazard: a siren will be completely ineffective if toppled by the earthquake that triggers a tsunami (Darienzo, et al. 2005). Likewise, even the most robust siren system depends on public knowledge. If people do not understand the meaning of a siren or are not aware of an appropriate evacuation route, the warning will fail to protect them. It is possible to incorporate warning systems, risk perception, and human response into risk management models that simulate hazards. Research on managing risk associated with volcanic eruptions in New Zealand, along with other associated projects, has led to the development of a five-step approach for effective early warning systems (adapted from Leonard, et al. 2008):

1) Develop event detection and public notification infrastructure
2) Plan organizational responsibilities, evacuation routes, and communication channels
3) Organize communications between government agencies, local emergency managers, scientists, media and the public
4) Educate emergency staff and populations at risk
5) Perform simulations and exercises

The above steps should be viewed as a continuous feedback loop with any one step informing the others at any stage of warning system development. Methodologies such as these that emphasize human considerations can be used in conjunction with geographic location models to design early warning systems that can better protect the public from disasters.

Warning sirens, reverse 911, and other methods of alerting the public of an impending hazard remain valuable resources for many emergency management agencies. Yet it is important to consider changing communication technologies, personal transportation choices, and hazard vulnerabilities when choosing the appropriate warning system. Increasing intraday travel and
frequent variation on the traditional home to work (or school) travel path require the ability of a
system to warn people of hazards based on personal proximity rather than assuming their
location at a given point in time. While emergency sirens traditionally fill this role, decreased
testing and gaps in public knowledge and awareness often render these systems less effective
than would be otherwise. Dependence on land line-based reverse 9-1-1 calls presents obvious
pitfalls in an era of ubiquitous cell phone use, and non-compliance with voluntary cell phone
registration for these calls may leave a large segment of the population uncovered. One
promising new warning technique is an automated system that sends out warning tones and
messages to all cell phones within range of cell phone towers in areas likely to be affected by a
given hazard. Such a system has been proposed for the State of California by Lt. Governor John
Garamendi (it is also called for national implementation in the WARN act. (Christian Science
Monitor; May 15, 2007)) Used in conjunction with an automated radio and television-based
system, this hazard warning infrastructure could be used to direct threat-specific instructions to a
vast majority of threatened people. Dynamic generation of area-specific evacuation routes send
via text message is one example the myriad of research projects made possible by this
technological advance. Perhaps the ideal system is a combination of warning sirens, reverse 9-1-
1 phone and emergency radio broadcasts. In the recent Tea fire (2008) in Santa Barbara,
residents of mission canyon complained that the warning given by reverse 9-1-1 was too late or
didn’t happen and asked why a siren system had not been considered.

Siren systems have been set up in California for a number of purposes. It is important to
recognize that as a community grows it may also outgrow the region covered by the system and
render the system less than effective. Thus it is important to monitor the coverage of such
systems to ensure that they meet the original goals of warning all residents. Identifying specific
areas of hazard vulnerability in the state such as tsunami prone coastal highways can help locate
warning sirens optimally.

6. Emergency Shelter Location

Locating emergency shelters to meet the needs of people impacted by a disaster is a very
important step in the preparedness phase of emergency management. The Louisiana Superdome
and New Orleans Civic Center served as emergency shelters for people displaced by Hurricane Katrina, but inadequate stores of food, water, and medical supplies and the unexpected extent of flooding, among other factors, turned these shelters into the site of disaster itself. Although the academic literature is relatively sparse when addressing emergency shelter location, there is both theoretical and technical research that can help us locate shelters so that future humanitarian disasters may be avoided.

In determining how to locate emergency shelters it is important to first understand a few theoretical concepts so that the problem can be appropriately addressed. Earlier in this report we define social vulnerability, a concept that can readily be applied to the shelter location problem. Bolin’s (1991) analysis of sheltering in the wake of earthquakes in several California communities found that temporary shelters were used disproportionately by low income citizens who were more likely to live in older more easily damaged buildings and largely lacked the financial resources to move. While this finding may seem intuitive, it is important that shelters are located where they are needed most. Many Hispanic residents of a neighborhood affected by the 1987 Whittier Narrow earthquake camped in city parks and yards as opposed to returning to damaged but structurally sound buildings due to fear and a lack of Spanish-speaking building inspectors. The Red Cross developed multi-lingual outreach programs to address these cultural and language barriers, thus helping to ensure all residents were aware of the best sheltering options.

Physical vulnerability also is an important factor to consider when locating shelters. After the aforementioned Whittier Narrow earthquake, a Red Cross emergency shelter had to be evacuated due to severe aftershocks. The powerful 1989 Loma Prieta earthquake left nearly 8000 people homeless in Santa Cruz County thus an emergency shelter had to remain open for 66 days, nearly 3 times longer than emergency managers had planned as necessary for shelter operations. While the location of physical vulnerabilities is more difficult to predict than social vulnerabilities, it is essential that emergency shelter location plans take into account a multitude of potential scenarios with varying physical site impacts.

In a review of emergency sheltering and temporary housing in the aftermath of hurricane Katrina, Nigg (2006) concludes that advanced planning for large-scale multi-hazard disasters across agency and political jurisdictions is essential to meet the needs of evacuated populations.
In California, mutual aid agreements can help meet the needs of people requiring evacuation assistance or medical care, but sheltering location is often left to individual city or county departments. Cross-jurisdictional and interagency cooperation and communication in determining the best sheltering options might be aided by geospatial analysis and modeling techniques.

Agencies such as Caltrans may want to use a decision support system for disaster management (DSS-DM) for flexible and robust prediction of earthquake damage and losses. One such system allows emergency management planners to test specific earthquake intensity scenarios to generate estimates of injuries sustained and infrastructure impairment and destruction to determine the need for emergency shelters (Aleskerov 2005). What is missing from this particular system is a determination of the optimal location of these shelters, and especially important question given the widespread damage to buildings and the transportation network that can occur in a large earthquake.

Kar (2008) used GIS to perform a site suitability analysis on existing and potential emergency evacuation shelters in Florida, thus determining a discrete set of the best shelter locations. Findings show that 48% of existing shelters and 57% of potential shelters are located in flood prone areas, are too close to chemical storage facilities, or are located in other physically unsuitable sites. A methodology was developed using a weighted linear combination of qualitative and quantitative factors to determine if a site is suitable for an emergency shelter in the event of a hurricane storm surge in several Florida counties. Proximity to existing evacuation routes, health care facilities, hazardous materials, and flood zones are among the factors that are measured and weighted using GIS overlays. One limitation of this study is that the physical characteristics of the shelters themselves are not incorporated into the site assessment methodology. Building material, size, and accessibility all could be included for a more robust suitability analysis.

Other modeling approaches can incorporate site suitability as well as decision making by both emergency managers and evacuees under various scenarios to determine the best locations for emergency shelters. Kongsomsaksakul (2005) proposes a location-allocation model for placing shelters when planning for populations evacuated during a flood event. In this bi-level linear programming problem a planning authority determines the number and locations of shelters with
the objective of minimizing total evacuation time on a given transportation network while a
group of evacuees simultaneously decides which shelter to go to by which route given shelter
location and capacity. This model is tested through a simulated flood scenario in Logan, Utah
where a dam collapses with 21% out of a population base of approximately 5000 people live in
the flood inundation zone. Bi-level programming problems can be somewhat difficult to solve to
optimality, so a genetic algorithm was employed to solve the problem. This heuristic was used to
search for the best set of shelter locations. Perhaps the most important finding to emerge from
this research is the trade off between shelter capacity and the number of shelters selected.
Higher shelter capacity means fewer are needed to meet the demand of evacuees, thus total
evacuation time is lower. The major limitation of this modeling approach is the lack of ability to
account for irrational route choice or other complex evacuee behavior. This can be overcome by
adding a finer modeling scale to the larger problem such as a traffic microsimulation or cell
transmission model.

Another interesting modeling technique for locating emergency shelters is proposed by Yazici
and Ozbay (2007). Their cell transmission model takes into account disruptions to vital links in
the transportation network that may result from an event such as a hurricane or earthquake and
adjusts the locations and capacities of emergency shelters accordingly. Based on the results of
simulated evacuation scenarios for Cape May, New Jersey, they find that using a deterministic
approach that assumes a specific traffic capacity at vital nodes on the transportation network can
leave emergency shelters incapable of providing enough food, water, and medicine to evacuees.
This finding is eerily reminiscent of what happened at the Louisiana Superdome during
Hurricane Katrina, where unexpected floodwaters cut off essential supply routes resulting in
massive shortages of necessary supplies. The solution proposed by these researchers is to
calculate the probabilities of disruption for important transportation links, then incorporate these
into a stochastic simulation within the model to determine shelter locations and capabilities
under the uncertainties inherent in an evacuation. This approach is similar to an approach used to
preposition supplies that is discussed in a later section of this report that covers prepositioning
and storage of emergency resources.
Schools and other public facilities are often enlisted to serve as emergency shelters due to easy accessibility, sturdy construction, and the layout and floor space necessary to accommodate the needs of large numbers of people. Usually such considerations such as centralized location given the population distribution and multiple access routes via the existing transportation network are taken into account when determining where to place schools, but vulnerability to hazards is often largely overlooked. Doerner (2008) presents a model that can assist in the decision of where to place a school or other public facility taking into account the flood inundation risk from a tsunami, a hazard that threatens many areas of coastal California. This multi-objective model first determines the shortest distance from each population center to the nearest school within the bounds of a maximum acceptable distance, then takes into account the risk of a tsunami, and finally seeks to minimize the costs associated with locating the facilities. This type of multi-objective model is useful to decision makers in that it can take into account many factors that help ultimately determine where a school or other public facility is located. Also, this type of model can be easily reconfigured to account for the risk of other disasters such as wildfires, earthquakes, or chemical spills.

Although few shelter location models have been developed to support evacuation events, perhaps the one that is most appropriate in making advanced decisions for shelter location is the recently developed model of Alcada-Almeida et al. (2009). This model is based upon designing a system to serve a specific region. Each area or neighborhood of the region is identified as a customer or demand. Potential sites for shelters are identified and routes between demand areas and shelters are identified. Each route between a demand area and a shelter site is analyzed within the context of travel time, risk in terms of the route being compromised by the hazard, a risk factor associated with a shelter being overcome by the event, and the times to move injured patients from shelters to the regional hospital. The model optimizes the location of a given number of shelters by minimizing the sum of weighted distances that people would need to travel to their closest shelter, the sum of the demand weighted risks of the assigned evacuation routes being compromised by the event, the sum of the demand weighted risks that individual shelters may be compromised by the events, and the sum of demand weighted distances that injured victims may be transported from shelters to the regional hospitals.
\[ i = \text{index used to a demand area or neighborhood where} \ S \ \text{is the number of areas.} \]

\[ j = \text{the set of nodes} \ i \]

\[ c = \text{an index referring the} \ c^{th} \ \text{candidate path} \]

\[ d_{ij}^{c} = \text{the distance of the} \ c^{th} \ \text{candidate path between} \ i \ \text{and} \ j \]

\[ r_{ij}^{c} = \text{the risk associated with the} \ c^{th} \ \text{candidate path between} \ i \ \text{and} \ j. \]

\[ P = \text{the number of shelters being located} \]

\[ E = \text{the number of potential sites which can be selected for a shelter} \]

\[ S = \text{the number of demand areas} \]

\[ y_{i} = \begin{cases} 1, & \text{if site} \ j \ \text{is selected for a shelter} \\ 0, & \text{otherwise} \end{cases} \]

\[ r_{j} = \text{the risk associated with shelter site} \ j \ \text{being compromised}. \]

\[ t_{j} = \text{the transit time from shelter site} \ j \ \text{to the regional hospital} \]

\[ a_{i} = \text{the demand population at area} \ i \]

\[ k_{j}^{\max} = \text{the maximum number of evacuees a shelter at} \ j \ \text{can handle} \]

\[ k_{j}^{\min} = \text{the minimum number of evacuees that is needed to justify opening a shelter at} \ j \]

\[ x_{ij}^{c} = \begin{cases} 1, & \text{if demand at} \ i \ \text{is served by a shelter at} \ j \ \text{accesses by candidate path} \ c \\ 0, & \text{otherwise} \end{cases} \]
Given the above notation we can structure the following integer-linear programming model, which contains four separate objectives:

\[
\begin{align*}
\text{Min} & \quad \sum_i \sum_j \sum_c a_{ij}d_{ij}x_{ij}^c \\
\text{Min} & \quad \sum_i \sum_j \sum_c a_{ij}r_{ij}x_{ij}^c \\
\text{Min} & \quad \sum_i \sum_j \sum_c a_{ij}r_{ij}x_{ij}^c \\
\text{Min} & \quad \sum_i \sum_j \sum_c a_{ij}t_{ij}x_{ij}^c
\end{align*}
\]

Subject to:

1) \( \sum_j \sum_c x_{ij}^c = 1 \) for each \( i = 1,2,\ldots,S \)

2) \( \sum_i \sum_c a_{ij}x_{ij}^c \leq k_j^{\max} y_j \) for each \( j = 1,2,\ldots,E \)

3) \( \sum_i \sum_c a_{ij}x_{ij}^c \leq k_j^{\min} y_j \) for each \( j = 1,2,\ldots,E \)

4) \( \sum_j y_j = p \)

5) \( y_j \in \{0,1\} \) for each \( j = 1,2,\ldots,E \)

6) \( x_{ij} \in \{0,1\} \) for each \( i = 1,2,\ldots,S \) and \( j = 1,2,\ldots,E \)

The above contains four objectives: minimize the total distance involved in evacuating all people to shelters, minimize the demand weighted risk of paths chosen, minimize the demand weighted risk of a located shelter not being operable, and minimize the demand weighted distances to the hospital for possible transit of injured people. The first objective ensures that each demand area must assign to a shelter using some route or path alternative. The second constraint ensures that people are assigned to only those locations selected for a shelter and that the total number of people assigned to a shelter does not exceed the capacity of that shelter. The third constraint maintains that at least a threshold level of demand is met at all selected shelter locations. The
fourth constraint specifies that exactly \( p \) sites are selected for shelters, and the remaining conditions represent the binary integer requirements on the decision variables. This model was applied to the city of Coimbra, Portugal for the purposes of locating shelters to serve the area in the event of a wildfire. Although this model does have some elements that could be enhanced or improved, it is representative of the style of model that would be ideal for planning shelters and storage locations for disaster recovery. It would be desirable to develop this style of model in conjunction with a GIS in order to support advanced planning as well as guide event operations (e.g. decide which shelters to open during an emergency).

7. Emergency Response

As can be surmised from the topics in the previous sections, there are elements of emergency response and incident management that have been studied intensively. Emergency response is one of those areas. This is especially true in what is called pre-hospital care, or emergency medical services (EMS). At issue is the capability of responding to an emergency within a desired period of time or standard. Quick response is a feature of most public safety services, like police, fire, & EMS. Even though quick response is needed for transportation safety, such services are often provided by local police departments, county sheriffs, the California Highway Patrol, and local fire departments. Caltrans often responds in a role that supports the actions of the CHP, etc. in installing changeable message signs, closing streets with barriers, and inspecting damage. The traditional focus on modeling emergency response has been on fire and EMS, as those services are oriented towards emergencies, rather than a mix of routine business (e.g. patrolling a highway stretch and stopping unsafe vehicles) and emergency response (e.g. responding to an accident or hazardous material spill).

Emergency response services require significant levels of personnel and vehicles. For example cities like Toronto have nearly 120 ambulances operating around the clock. The City of Los Angeles maintains 106 fire stations and has more than 3,900 personnel and serves an area of approximately 471 square miles. This means that on the average one station serves an area of approximately 4.4 square miles or an area with a service radius of approximately 1.2 to 1.5 miles. The Fire Department budget in Los Angeles totaled $814 million for the fiscal year 2008-
2009. Because the costs of providing such services tends to be high, it is important to be as
efficient as possible in providing and allocating them. This has led to a relatively rich literature
on modeling the allocation of emergency services. The first attempt to optimize fire services and
emergency services in general was proposed by Toregas et al. (1971). Their approach was based
upon a rather simple assumption, that is, the cost of providing fire services was a function of the
number of stations that were located. Since labor is the highest single cost element of providing
fire service and since most stations are allocated a standard number of crew members, then total
costs is roughly a function of the number of stations that are located to serve a given area. Given
this basic, but powerful assumption, they defined the problem of allocating fire services as:

Minimize the number of stations needed to geographically cover all demand areas
and locate them so that each area has a station within a maximum pre-specified
response distance or time.

They called this problem the Location Set Covering Problem (LSCP). To solve this problem they
proposed the following set of notation:

\[ i = \text{index of fire demand zones or blocks} \]

\[ j = \text{index of potential station locations or response positions} \]

\[ d_{ij} = \text{distance or travel time to fire demand zone } i \text{ from potential station site } j \]

\[ S_i = \text{the maximum allowable distance or travel time in serving a demand zone from a station} \]

\[ N_i = \{ j \mid d_{ij} \leq S_i \} \quad \text{the set of sites that can serve demand zone } i \text{ within the maximum time or distance of response} \]

\[ X_j = \begin{cases} 
1, & \text{if a station is located at site } j \\
0, & \text{if not} 
\end{cases} \]

The LSCP problem can then be formulated as the following optimization problem:
Minimize \[ Z = \sum_j X_j \]
subject to:
1) \[ \sum_{j \in N_i} X_j \geq 1 \quad \text{for each demand zone } i \]
2) \[ X_j \in \{0,1\} \quad \text{for each site } j \]

This model is an integer-linear programming problem, which can be solved by special purpose algorithms and general-purpose optimization software. When this model was first proposed, there was limited computer software and computational power to solve a model such as this. But, with the advancement of personal computers and modeling software packages, models like the one presented above can be applied to problems involving thousands of demand zones and sites, providing the capability for easy application. Toegas worked with Public Technology, Inc. for many years and helped to apply this model to more than 100 large cities (by the mid 1980’s) in the US for the purposes of locating or relocating fire stations into efficient service patterns. It is important to recognize that many types of applications of this model are possible, from the location of fire stations to the location of road equipment, highway patrol offices, and emergency shelters.

Given a standard of service, e.g. fire service within a mile and a half, it may take more stations to cover an entire region than exists in a budget to provide such services. This is especially true if a region contains both rural and urban areas. This has led to two different coping strategies: 1) define a rural level of service (e.g. respond in 30 minutes) and an urban level of maximal service (e.g. respond within 10 minutes), and 2) relax the assumption that everyone must be served within the stated maximal time or distance standard. Actually, both strategies are used. First, resources are usually not available to offer the same level of service to those that live in rural areas as compared to those who live in denser communities. Thus, it is common to establish different standards for rural and urban services. Second, many communities are not able to offer services to everyone within a maximum time or distance standard. For example, for many ambulance operations it is often stated as a goal to provide service within \( X \) minutes 90% of the time. To structure a model that captures this type of objective we can define the following emergency resource allocation problem:
Minimize the needed number of stations or vehicles to provide service coverage within S minutes (or distance) for $\alpha$ percentage of the total population and locate them in such a manner as to accomplish this goal.

This problem statement is a form of the maximal covering location problem of Church and ReVelle (1974). To structure this in a formal mathematical statement, consider the following notation:

$a_i = \text{a measure of demand (e.g. population) at zone } i$

$Y_i = \begin{cases} 
1, & \text{if demand at } i \text{ is covered within } S_i \text{ minutes (or distance)} \\
0, & \text{if not} 
\end{cases}$

Using the above notation along with the notation introduced earlier in this section, we can define the following optimization model:

$$\text{Minimize } Z = \sum_j X_j$$

subject to:

1) $\sum_{j \in N_i} X_j \geq Y_i$ for each demand $i$

2) $\sum_i a_i Y_i \geq \alpha \sum_i a_i$

3) $X_j \in \{0,1\}$ for each site $j$

4) $Y_i \in \{0,1\}$ for each demand $i$

This model contains two major types of constraints. The first constraint establishes whether a given demand zone is covered by a station. If a station is selection from among the set of sites, $N_i$, then the sum on the left hand side of condition (1) is 1 or greater, which allows the variable $Y_i$ to equal one in value, thus accounting for the fact that demand zone $i$ is covered. If no facilities are located within the set, $N_i$, then the sum of selected facilities equals zero, forcing $Y_i = 0$. Thus, constraints of type 1 are used to define if coverage has been provided to a given demand zone. The second constraint states that the total coverage provided across all zones has to equal or exceed $\alpha$ fraction of the total demand population. The other constraints are used to
represent the restrictions on the decision variables, as they must be binary in value. The objective of this model is set to minimize the sum of the vehicle/stations/units that are being located subject to the constraints that establish that a high level of coverage must be provided.

This model is a form of the well-known maximal covering location problem, where the objective is to provide coverage to at least $\alpha \%$ of the total demand population while minimizing the resources needed to accomplish this level of coverage. There are a number of variations of this model that are based upon issues that are important in special types of applications. For example, one variant optimizes the resources needed for several types of responding vehicles (e.g. pumper and ladder trucks) where different service distances are set for each type of equipment. The idea is that the above model is quite flexible and can be modified to fit a given problem setting. It is has been applied in a number of resource settings, especially emergency response. For example, it would make sense to apply this type of model to assess the costs of providing certain types of response for incidents along major highway sections, or for inspection teams to survey a road system after an earthquake. A related model has been used to locate salt and sand storage piles for winter snow removal, in order to optimize the efficiency of snow and ice removal.

During the 1970’s the U.S. Government funded studies that were called Research Applied to National Needs (RANN). These projects involved services such as solid waste management, fire protection, police, and EMS. One of the centers for this work was the Rand Corporation partnership with New York City. The New York City–Rand Fire Department study attempted to integrate new computer planning models into fire services in order to make system delivery more efficient. One of the most famous models developed in New York City was the square root law of emergency response time. Essentially, Kolesar and Walker identified a relationship between response time and distance, which was both intuitive and appeared to fit response time data collected from the fire department. This model has been used to identify response patterns in a number of cities. The square root law estimated response time as a function of distance by segmenting the response into two different distance zones, a nearby distance zone with a nonlinear response time function and a further zone with a linear response time function. This two-part function was fitted to the response time means over a large number of small time intervals. For the data used, the R-square value was unusually high in value, indicating that most of the variance found in the travel time data was explained by the square root model. This model
made it a relative simple task to estimate travel times by using distances, and this allowed either
distance standards or response time standards to be applied. The task of estimating response
times has been expanded with recent studies that have used large data sets representing 100’s of
thousands of emergency responses.

There are a number of problems associated with the allocation of resources for emergencies. For
example, one problem is to locate shelters so that people can be served away from a disaster site
(see the previous section). This can be done with a model such as the maximal covering location
problem or the location set covering problem. For example, let’s say that a major emergency has
impacted an area or region. Then it is necessary to decide which shelter locations to open and
operate. From a list of shelter options, a model can then be used to optimize the selection. In
Florida, there are a number of options as to which shelters may be open. Along with deciding
which shelters to operate it is also necessary to decide how such shelters are going to be provided
provisions. For some shelter locations, provisions are already stored for such an event. For other
locations, it will be necessary to truck them in from other locations. Even this storage provision
location problem can be thought of in terms of a covering model. That is, one can use one of the
above models to identify the set of storage provision sites such that any potential shelter site can
be provided adequate provisions within a set number of hours. This is an important problem, as it
is necessary to store provisions for a possible emergency. This type of provisioning problem
must be solved in advance and must be operational long before any emergency support can rely
on such a system.

One of the major issues in emergency response is that when a vehicle is being used or is
inoperable, it is unavailable to serve. For example, in ambulance services, vehicle crews can be
busy as much as 40% of the time on the average. This means that the closest vehicle may be busy
and something further away would need to respond. Thus, it is important to take possible vehicle
availability into account while allocating emergency vehicles in a region. The problem is that
vehicle availability is a function of where other vehicles are placed. For example, if an area of
relative high demand has only one allocated vehicle and is often busy 50% of the time, then
response times to a given call would be delayed on the average 50% of the time, as the closest
vehicle is already busy and something much further away must respond. While if that same area
has several allocated vehicles, the workload of each unit can be reduced, and the percentage of
time that a call cannot be served by several local units is reduced. There are several ways in which this type of problem has been addressed. For example, let’s assume for the sake of analysis that most emergency calls take an hour to serve\(^2\). Given this assumption we can then estimate average vehicle business, \(b_s\), in the following manner:

\[
b_s = \frac{\sum f_i}{24p}
\]

where:

\(f_i\) = the average frequency of calls per day in demand zone \(i\)

\(p\) = the number of service vehicles in operation

Given a level of business of the average vehicle, it is then possible to calculate the probability of whether a response can be made to a given call within the maximal response time standard. If we assume that each vehicle’s busyness is independent of other vehicles, then the probability that \(k\) independent vehicles are busy is: \((b_s)^k\). If \(k\) vehicles are positioned within a maximal coverage distance or time of a demand zone, then the probability that it can be served by one of the \(k\) vehicles without delay is:

\[
q_k = 1 - (b_s)^k
\]

Thus, we can calculate the probability of being served without delay for any number of allocated vehicles, \(k\). This means that if \(k\) vehicles are located within a coverage time of demand \(i\), then demand \(i\) is covered \(q_k\) fraction of the time. To integrate this into the above covering model we need the following variable:

\[
Y_{i,k} = \begin{cases} 
1, & \text{demand } i \text{ is covered by exactly } k \text{ vehicles or units} \\
0, & \text{if not}
\end{cases}
\]

\(^2\) This is an assumption that is often taken in the allocation of ambulances. The 1 hour service time is an inherent assumption of the system status management system of Jack Stout.
We can now formulate an expected coverage model in the same form as the previous model as:

\[
\text{Minimize } \quad Z = \sum_j X_j \\
\text{subject to:}
\]

1) \[\sum_{j \in N_i} X_j \geq k Y_i \quad \text{for each demand } i\]

2) \[\sum_k Y_{i,k} \leq 1 \quad \text{for each demand } i\]

3) \[\sum_i \sum_k a_i q_k Y_{i,k} \geq \alpha \sum_i a_i\]

4) \[X_j \in \{0,1\} \quad \text{for each site } j\]

5) \[Y_{i,k} \in \{0,1\} \quad \text{for each demand } i \text{ and each level } k\]

This model minimizes the resources needed and allocates them so that coverage is provided \(\alpha\) fraction of the time. The main feature is that it accounts for the fact that vehicles are not always available as they may be serving another demand. This formulation is an expanded version of the previous model and can be thought of as a variant of the maximal expected coverage location model of Daskin (1983). The first constraint in this model is used to define the number of units/vehicles that have been located which are within the coverage time of a given zone. It allows a given variable, \(Y_{i,k}\) to equal one in value if \(k\) units have been located in the vicinity of demand \(i\). The second constraint ensures that coverage for a given demand can be accounted for at only one service level, \(k\). Altogether, the objective forces coverage to be accounted for at exactly the highest provided level. Constraint 3 specifies that at least a certain fraction of all demand must be covered by vehicles that are available (and therefore not busy). Overall, this model can help to allocate emergency response vehicles to provide high levels of service coverage while accounting for the fact that some of the time each vehicle is busy and not available to handle a simultaneous call.

The maximum expected coverage model is based upon an assumption that is not always met. That is, vehicle busyness is not always equal across a system. This might be the case for a dense but small city, but on the average, there can be differences between the busyness of individual emergency units. This is an issue that has been modeled by a number of researchers during the past decade. To address this there have been two principal approaches: the use of a queuing
model like the hypercube model of Larson or the use of local busyness estimates developed by ReVelle and Hogan (1989). The ReVelle and Hogan approach begins with an estimate of the demand for emergency response within a neighborhood or coverage area of zone \( i \). This can be expressed as follows:

\[
r_i = \sum_{h \in N_i} f_h
\]

Where \( r_i \) is the local demand among the zones that are within the coverage standard of zone \( i \).

Suppose that there are \( k \) vehicles or responding units within the neighborhood of \( i \). Then the demand within the local region can be spread among the \( k \) units. This means that the local busyness estimate when there are \( k \) vehicles allocated locally can be calculated as:

\[
b_{i,k} = \frac{r_i}{24k}
\]

Given this local busyness estimate, we can then calculate the fraction of the time that an emergency call in the neighborhood of \( i \) can be handled by one of the \( k \) local units as:

\[
q_{i,k} = 1 - (b_{i,k})^k
\]

This estimate allows us to refine the above emergency response model so that it is more accurate within the context of busyness estimates. This can be expressed as follows:

Minimize \( Z = \sum_j X_j \)

subject to:

1) \( \sum_{j \in N_i} X_j \geq kY_i \) for each demand \( i \)

2) \( \sum_k Y_{i,k} \leq 1 \) for each demand \( i \)

3) \( \sum_j \sum_k a_j q_{j,k} Y_{j,k} \geq \alpha \sum_i a_i \)

4) \( X_j \in \{0,1\} \) for each site \( j \)

5) \( Y_{i,k} \in \{0,1\} \) for each demand \( i \) and each level \( k \)
The major difference between this model and the previous model statement is that the busyness estimates that are used in constraints of type 3 are based upon the local busyness estimates rather than global busyness estimates. The description of the objective function as well as the constraints is exactly the same as what was given for the previous model. There are two issues that should be stated here. The local busyness estimates are based upon an assumption that the calls handled from the local region to other areas minus the calls of the local region handled by other areas nets out to be zero. The second assumption is that the vehicles or units within the local region are assumed to be independent. Neither one of these assumptions holds, but this approach is an approximation which yields a tractable model for a problem that is quite difficult to solve analytically. The form of the model given above is a variant of the Local Reliability based Maximal Expected Coverage model developed by Sorensen and Church (2007). The Sorensen and Church model has been tested for a number of problem data sets and has been found to be relatively accurate at estimating expected coverage globally as a sum of local expected coverage estimates, as well to as generate solutions that tend to outperform the original MALP model of ReVelle and Hogan (1989).

Research on modeling emergency/incident response has been concentrated on the provision of fire and EMS services. The difference between these two application areas boils down to the level of individual unit busyness. In fire service provision, most crews are not busy very often handling fire calls, and therefore are usually available to handle a call when received. For EMS response, individual responding units can be quite busy as described above, and being busy impacts potential service for the next emergency call. Good reference papers for this area of modeling can be found in Swersey (1994) and Sorensen and Church (2007).

Few have applied such models to allocating incident management resources for traffic management. In the state of Washington, a study demonstrated that responding very quickly to simple issues like stalled vehicles and stranded motorists could translate to better traffic flow, less congestion, and fuel savings. Providing this kind of incident management can be accomplished by two approaches, roving/patrolling response vehicles along a corridor and posting response vehicles at dispatch points. The second approach has been modeled by Zografos et al. (2002). Their problem involved allocating incident response vehicles (e.g. tow trucks) resources at dispatch locations in order to handle stranded cars, accidents, etc. along major
roadways. They developed an incident response logistics decision support system and tested several models, including the maximal covering location model, the location set covering model, and the $p$-median model. They developed a special form of the $p$-median location model that appeared to perform the best for the type of problem being solved. This is a unique paper in that it appears to be the only paper in the literature devoted to optimizing resource allocation for roadway incident response. Unfortunately, the main issue that was overlooked in their model is that of vehicle busyness. Overall, it makes sense to fine tune the type of models described in this section and apply them for roadway incident response. This is an important area for continued research development and application for roadway incident response.

8. Prepositioning and Storage of Emergency Resources

One of the issues that has gained attention is the need to make a quick response with emergency resources (e.g. water, food, and medical supplies) in the event of a major disaster. For example, during hurricane Katrina, people stranded in New Orleans did not have adequate supplies of food and water. It is also necessary to have a plan for shelters, should evacuation be necessary as well as respond with necessary medical and emergency personnel. Prepositioning can be defined as the storage of critical resources at specific locations in order to ensure that an area or region can be served during or after a disaster with timely delivery of those needed resources.

Recent disasters (like that of the 2004 tsunami in Indonesia which resulted in the deaths of nearly 130,000 people, hurricane Katrina in 2005 which killed more than 1800 people, the cyclone in Myanmar which killed 22,000 people, and the 2008 Chinese earthquake in Sichuan killed nearly 70,000 people) have focused attention on the ability to respond with to an emergency with needed supplies. One of the first references associated with considering the option of supply prepositioning involved an air force operations plan associated with the Berlin blockade after World War II. Since that time, few if any papers have modeled the problem of prepositioning supplies in order to mitigate the effects of an emergency. Our literature search identified only three papers that optimized inventory or located storage facilities for emergency operations. Granted, agencies like the American Red Cross store materials so that they can respond quickly with supplies to support evacuees and house evacuees, but with the exception of these three
papers, no one has modeled supply positions for emergency response using logistics models. The three exceptions are the works of Akkihal (2006), Rawls and Turnquist (2006, and Yushimito and Ukkusuri (2008). These three research papers address this problem using different but related constructs. Akkihal (2006) appears to be the first to model the problem of prepositioning for emergencies. Specifically, he addressed the problem of storing emergency supplies for humanitarian relief.

The United Nations operates a global relief supply depot in southern Europe (Brindisi, Italy), which is known as the UN Humanitarian Response Depot. This depot maintains an inventory of virtually everything, from shelters and tools to food and drugs to help in the emergency relief following a disaster. Akkihal stated that the time to respond was critical and that the UN’s current location could respond within 24 to 48 hours to virtually anywhere in the world using aircraft. Akkihal addressed only the time to load and fly, and not the time to seek approval and other stages in the process of providing relief. He argued for the fact that, such a response was possibly too long for some regions of the world. Thus, he proposed a model to locate additional storage around the world. He reasoned that the objective should be to minimize the time to reach expected events weighted by the population at risk. He developed an approach to estimate population at risk for a number of regions throughout the world. His model can be explained by the use of the following notation:

\[
\begin{align*}
  i &= \text{index used to refer to a demand area} \\
  j &= \text{index used to refer to a potential depot site} \\
  d_{ij} &= \text{the distance between demand region } i \text{ and depot site } j, \text{ measured as the great circle arc distance between the two locations} \\
  H_i &= \text{the mean annual homelessness as a result of natural hazards} \\
  y_j &= \begin{cases} 
    1, & \text{if a depot is located at site } j \\
    0, & \text{otherwise} 
  \end{cases} \\
  w_{ij} &= \begin{cases} 
    1, & \text{if demand region } i \text{ is to be served by a depot at } j \\
    0, & \text{otherwise} 
  \end{cases} \\
  p &= \text{the number of depots to be located}
\end{align*}
\]
Akkihal argued that it would be best to “minimize the delivery lead-time to those people who would need it.” Thus he suggested that depots should be located in such a manner as to minimize the average distance from warehouses to people who were likely to require humanitarian aid. He calculated for each region an estimate of the annual average of homelessness that resulted from natural disasters. He used these estimates as a proxy for the demand that such a system would be called upon to respond with aid. With this he set up the following depot storage location model:

Minimize  
\[ Z = \sum_i \sum_j H_i d_{ij} w_{ij} \]

Subject to:
1)  \[ \sum_j w_{ij} = 1 \quad \text{for each region } i \]
2)  \[ w_{ij} \leq y_j \quad \text{for each region } i \text{ and each depot site } j \]
3)  \[ \sum_j y_j = p \]
4)  \[ y_j \in \{0,1\} \quad \text{for each depot site } j \]
5)  \[ w_{ij} \in \{0,1\} \quad \text{for each region } i \text{ and depot site } j \]

The above model minimizes the total average air distance in serving global disaster-caused homelessness. It assumes that the closest depot will serve each region. This model specifies that \( p \) facilities are to be located in the third constraint. Demand regions are forced to assign to one depot site in the first constraint. The second constraint limits regional assignments to only those sites that have been selected to house a storage depot. The objective forces regional assignments to their closest open depot.

Even though this model is specially defined for the location of emergency relief storage depots, it is an exact form of a classic location model called the p-median problem. The p-median model was originally defined by Hakimi (1964,1965). The integer programming model given above is a
model that was first formulated by ReVelle and Swain (1970) for the location of public facilities. When applied for locating a global system of relief storage depots, Akkihal found that the best location for one depot was in south central Asia and not Italy. The best two depot positions would be in south central Asia and Shanghai. The best three-depot configuration is associated with adding a depot in South America. It is surprising that Africa was not selected for a site until a configuration of four or more depots were specified. Thus, optimal solutions to problems that may seem particularly simple may differ from that of general intuition. This underscores the value of using models to aid in analysis and decision-making. In fact, a site in Europe (like that of the existing site) does not prove to be valuable until nine depots are located. This means that the current depot location is not sited at a location that can provide as quick a relief as it might be possible for many parts of the world.

At first it should be a bit surprising to discuss a global relief supply storage problem, when focused on issues of emergency response for a state like California. Yet the same model can be applied at a state rather than a global scale. It may be important to establish major storage depots with adequate supplies for a major emergency along with a transport structure to supply the needs of an emergency in any region of the state. Thus, the logistics model developed by Akkihal could be redefined for a statewide system.

To be prepared for an emergency, it is important to have a plan for the distribution of emergency supplies. Supplies could entail fuel for transport, food, medical supplies, water, and other needed materials. To develop a plan, it is important to identify the region of interest, e.g. the State of Florida. Then it is necessary to identify the towns and population centers of interest within the region as well as specify the current road network. From this, we need to identify the demand for resources of interest should a disaster strike a city or town. To do this, we can develop a set of planning scenarios, and for each scenario we need to estimate the amount of resource demand for each city. For example, say a city is impacted only in scenarios 1, 4, and 9. This means that emergency supplies are needed for this city only under those specific scenarios. The overall plan should involve the prepositioning/storage of supplies among the towns or cities. To store supplies at a given location requires the location of an emergency storage facility. The major goal would be to minimize the cost of meeting emergency resource requirements for each city or
town over all scenarios, by locating emergency storage facilities, prepositioning a certain amount of each resource at each supply site, and identifying the least cost logistics plan in distributing supplies for each disaster scenario.

It is also necessary to realize that certain transportation links may not be available during a given scenario, or that the capacity of a given link is reduced due to the event. For example, let us assume that in scenario 5, the main highway to town A may be closed due to flooding. This means that alternate routes may be necessary for transporting emergency supplies to town A during that scenario, or that the emergency supply needs to be prepositioned at that town. It is also possible that a scenario may involve the loss of a given storage facility. This means that in some cases a given supply depot may not be available to supply its own population or nearby towns. It is also possible that a supply or route may be partially compromised during an event/scenario that results in either a reduced transport capacity or the loss of some of the prepositioned supply/resource.

To formally define this problem within the context of a logistics planning model, consider the following notation.

\[ i, j = \text{indices used to refer to given nodes or cities} \]

\[ N = \text{the set of nodes } i \]

\[ s = \text{an index referring to a given emergency scenario} \]

\[ S = \text{the set of scenarios } s \]

\[ P_s = \text{the probability that a given scenario will occur} \]

\[ k = \text{an index referring to a given resource type} \]

\[ K = \text{the set of resource types } k \]

\[ l = \text{an index used to refer to a given facility capacity level} \]
\[ L = \text{the set of possible capacity levels } l \]

\[ A = \{(i, j) \mid \text{node } i \text{ and node } j \text{ are connected by a road}\} \]

\[ y_{il} = \begin{cases} 1, \text{if supply capacity level } l \text{ is located at node } i \\ 0, \text{otherwise} \end{cases} \]

\[ r_{i}^{k} = \text{the amount of resource } k \text{ that is allocated to node } i \]

\[ q^{k} = \text{is the unit cost of resource } k \]

\[ u_{ij}^{s} = \text{the capacity of arc } (i, j) \text{ during scenario } s \]

\[ c_{ij}^{ks} = \text{the cost of shipping a unit of resource } k \text{ during scenario } s \text{ along arc } (i, j) \]

\[ v_{i}^{ks} = \text{the level of demand for commodity/resource } k \text{ during scenario } s \text{ at node } i \]

\[ x_{ij}^{ks} = \text{the amount of resource of type } k \text{ shipped through link } (i, j) \text{ in scenario } s \]

\[ \alpha_{i}^{s} = \text{the fraction of allocated supply at node } i \text{ that is available during scenario } s \]

\[ F_{il} = \text{the cost to locate a facility of capacity level } l \text{ at node } i \]

Given the above notation we can structure the following integer-linear programming model:

\[
\text{Min } Z = \sum_{i \in N} \sum_{l \in L} F_{il} y_{il} + \sum_{k \in K} \sum_{i \in I} q^{k} r_{i}^{k} + \sum_{s \in S} \sum_{(i, j) \in A} \sum_{k \in K} P_{s} c_{ij}^{ks} x_{ij}^{ks}
\]

Subject to:

1) \[ \sum_{(j, i) \in A} x_{ji}^{ks} + \alpha_{i}^{s} r_{i}^{k} = \sum_{(i, j) \in A} x_{ij}^{ks} + v_{i}^{ks} \quad \text{for each } i \in N, k \in K \text{ and } s \in S \]

2) \[ \sum_{k \in K} x_{ij}^{ks} \leq u_{ij}^{s} \quad \text{for each } (i, j) \in A \text{ and } s \in S \]
The above model minimizes the expected costs of distributing enough of each resource to places of need over all planning scenarios by minimizing the cost of transporting quantities from points of supply to places of need in each scenario. It also minimizes the cost of placing storage facilities and prepositioning supply at those facilities. This is a strategic prepositioning model. This particular formulation is based upon the work of Rawls and Turnquist (2006). It is a mixed integer linear programming problem, which can be solved using off the shelf software for medium sized logistics problems. Rawls and Turnquist did not address the issue of the time to respond with supplies to a given town. Their objective was to identify a minimum cost logistics plan. It may make sense to cast this problem in terms of making needed supply distributions within a desired time frame. Without a focus on making a timely response, supplies may not arrive when needed. This is a potential area for future work.

The other major model that has been developed for prepositioning of resources was developed by Yushimito and Ukkusari (2008). They described prepositioning as the storage of inventory at or near the disaster locations for seamless delivery of critical goods. Such a strategy is promoted in order to reduce the lead time in responding to a disaster. Yushimito and Ukkusari build their approach by modifying a form of the location vehicle routing problem (LVRP). The LVRP model is associated with locating facilities and routing vehicles from each facility in order to meet some level of predefined demand at each client location. Routes can be defined in two ways: 1) demand is based upon full truckloads, and 2) demand is based upon less than full truckloads. In the circumstance that demand is high enough that it is represented as full truck loads, then supply trips to clients or needed demand locations are simple routes to and from
client locations and the supply facilities. If demand is less than a full truck load, then deliveries can be made as a set of routes, where each route supplies several clients at once and is represented as a set of stops. There are several approaches that can be used to formulate the LVRP, however, the simplest is a model that is based upon a set of predefined route alternatives (LVRP_PR), where routes are selected simultaneously with the selection of facility locations. This version of the LVRP is conceptually simpler than one in which route are determined simultaneously with site selection, because predefining a series of possible route alternatives eliminates the need to embed multiple travelling salesman sub-problems for each selected facility. The LVRP_PR can be formulated using the following notation:

\[ I = \text{the set of client locations} \]

\[ J = \text{the set of candidate locations} \]

\[ i, j = \text{indices use to index client and candidate locations respectively} \]

\[ k = \text{a index of routes for a given candidate facility} \]

\[ f_j = \text{the fixed cost of establishing a prepositioned storage facility at location } j \]

\[ P_j = \text{the set of feasible routes for candidate facility } j \]

\[ c_{jk} = \text{the cost of route } k \text{ associated with candidate facility } j \]

\[ a_{ijk} = \begin{cases} 1, \text{if route } k \text{ associated with facility } j \text{ serves client location } i \\ 0, \text{if not} \end{cases} \]

\[ x_j = \begin{cases} 1, \text{if candidate } j \text{ is selected for a facility} \\ 0, \text{otherwise} \end{cases} \]

\[ y_{jk} = \begin{cases} 1, \text{if route } k \text{ associated with facility } j \text{ is selected} \\ 0, \text{otherwise} \end{cases} \]
The LVRP_PR model can be defined as the problem of selecting sites for distribution/storage facilities while simultaneously selecting routes associated with selected storage facilities to supply clients in a manner that minimizes total prepositioning and routing/delivery costs:

Minimize  \[ Z = \sum_j f_j x_j + \sum_j \sum_{k \in P_j} c_{kj} x_{kj} \]

Subject to:

1)  \[ \sum_j \sum_k a_{jk} y_{jk} = 1 \quad \text{for each client } i \]

2)  \[ y_{jk} \leq x_j \quad \text{for each } j \text{ and } k \in P_j \]

3)  \[ x_j \in \{0,1\} \quad \text{for each } j \]

4)  \[ y_{jk} \in \{0,1\} \quad \text{for each } j \text{ and } k \in P_j \]

The objective involves minimizing costs of site selection/development and the costs of distribution to all clients. The first constraint of this model involves the selection of a delivery routes so that each client is served by a route. The second constraint maintains that the selection of a specific route based at a facility site \( j \) cannot be selected unless site \( j \) has been chosen as a location for supply prepositioning. This is an integer-linear programming model, which can be solved by a variety of techniques employing a column generation approach associated with the vehicle routes.

Yushimito and Ukkusuri modified the above type of problem for the prepositioning problem for emergency supply. At issue in prepositioning is the fact that a system may be compromised in its ability to supply a set of possible clients. Otherwise, the problem of prepositioning can be approached in exactly the same manner as supply location and vehicle routing in classic logistics problems. In such a case, the formulation above can be used without modification. But, in a disaster certain road links may no longer be available as they may be flooded or ruined. This would render certain routes from being usable. Also, a supply depot may also be unusable as it
could be damaged or destroyed in the disaster. To address these types of possibilities, Yushimito and Ukkusuri assumed that each road link could be assigned a probability of failure. They also assumed that such failure events were independent. They defined the probability of a link between \( i \) and \( k \) failing as \( p_{ik} \). This means that the probability of a link \((i,k)\) being usable is:

\[
(1 - p_{ik})
\]

Suppose that a path between \( i \) and \( j \) is comprised of two arcs, one from \( i \) to \( k \) and the other from \( k \) to \( j \). Then the probability of a path being usable from \( i \) and \( j \) can be calculated as:

\[
(1 - p_{ik})(1 - p_{jk})
\]

This was defined as the reliability of the associated path. Such a calculation can be done when the probabilities of edge failure are known \textit{a priori} and are independent across all edges. For every predefined route in the VRP-PR, we can calculate the reliability of the route. This can be designated as \( R_{jk} \). The second assumption made by Yushimito and Ukkusuri is that there are known failure probabilities for each possible facility site, \( q_j \). Thus, the probability that a supply facility is available is \((1 - q_j)\). Using these two elements together, Yushimito and Ukkusari defined a probabilistic version of the LVRP-PR for prepositioning supply as follows:

Maximize \[
Z = \sum_j \sum_{k \in P_j} R_{jk} y_{jk} (1 - q_j)
\]

Subject to:

1) \[
\sum_j \sum_k a_{jk} y_{jk} = 1 \quad \text{for each client } i
\]

2) \[
y_{jk} \leq x_j \quad \text{for each } j \text{ and } k \in P_j
\]

3) \[
\sum_j f_j x_j \leq B
\]
4) \( x_j \in \{0,1\} \) for each \( j \)

5) \( y_{jk} \in \{0,1\} \) for each \( j \) and \( k \in P_j \)

This prepositioning involves locating a set of supply facilities that costs no more than an available budget, \( B \). The objective involves maximizing the sum of service reliabilities, where each reliability value is the product of route reliability and facility reliability. In essence, this model maximizes an un-weighted reliability value of serving all demand. Yushimito and Ukkusuri argue that the above model can be solved by identifying the most reliable path to a given client from a storage site. They show that maximizing the reliability in serving every demand can be achieved when the most reliable path is used to reach a given client. Thus, it is necessary to find the most reliable path between a given storage site and all clients. They show that the problem of finding the most reliable path between a facility and a client can be solved as a form of the well-known shortest path algorithm between an origin and a destination. Thus, the set of route alternatives for a given facility would be comprised of the most reliable routes between a given site and each demand. When they overlap and are within capacity they can then be combined. Thus, it is not necessary to use a column generation scheme in solving the maximum reliability prepositioning problem. Unfortunately, the above model may strike a poor balance between reliably serving small clients as compared to large clients. That is, it would not make much sense to increase the reliability of a very small client demand at the expense of reducing the reliability of a very large client demand. Thus, it would make sense to modify the above model objective to:

Maximize \( Z = \sum_j \sum_{k \in P_j} d_{jk} R_{jk} y_{jk} (1 - q_j) \)

Where \( d_{jk} \) equals the number of clients served by route alternative \( k \) from facility site \( j \). This objective could be used in place of the objective suggested by Yushimito and Ukkusuri without changing the difficulty of solving the overall model.

Prepositioning of emergency resources is an important way to mitigate the effects of a hazard and prevent it from becoming a full-fledged disaster. If a hazard spirals out of control and
becomes a disaster despite our best efforts, having resources prepositioned at critical locations can greatly improve the effectiveness of the response effort. Despite the obvious benefits of prepositioning, this strategy has been the focus of very little research within the emergency management academic community. The $p$-median problem can be solved to optimize the location of global relief supply depots as well as supply depot location problem at the national, state, or local scale and thus provides a solid mathematical foundation for addressing this question. A strategic prepositioning model takes into account the cost of transport, storage, and prepositioning of emergency supplies providing valuable information to decision makers given limited budgets and resources. The location vehicle routing problem can be solved to locate supply storage facilities and route delivery vehicles while taking into account the potential for disruptions along the transportation network, and therefore is an effective way to account for the uncertainty associated with the scale, intensity, and duration of many hazards. All of the modeling approaches described above can greatly assist in decision making and planning under a multitude of disaster scenarios, and can be modified to answer the specific questions an agency such as Caltrans must ask to determine the best actions to take.

9. Infrastructure Fragility

Although emergency planning often addresses issues like that of backup power, there does not appear to be a part of the modeling literature that is devoted to public vulnerability due to the lack of backup power. For example, water supply districts often locate backup generators so that water pressure can be maintained during times of power outages. In addition, sewer districts often maintain backup generators for pumps at critical lift stations, in order to ensure the system works during power outages. Similarly, telephone companies have maintained backup power for landlines by keeping banks of batteries at switching facilities. Cell towers often do not have long-term back-up supplies, so that some services are not guaranteed to operate. Maintaining communication systems during emergencies is an emerging problem as more households are increasingly relying on cell phones as their only form of communication. This trend may also be exacerbated by the use of cable-internet connections, which are also vulnerable to power outages and do not usually have backup power systems. Consequently, it is important to address the fragility of infrastructure in emergency planning.
There is, however, a growing interest in identifying vulnerabilities, especially with respect to infrastructure. In terms of transportation, there are a number of vulnerability issues should something fail or be intentionally taken out. For example, when a trestle fire destroyed a Union Pacific railroad link in downtown Sacramento, CA in March of 2007, most trains had to be rerouted about 125 miles in order to get to their destination. That is, the loss of a structure approximately 300 feet long resulted in rail cars being detoured nearly 125 miles. The sudden loss of infrastructure can result in a significant impact, either limiting transportation or requiring detours that are quite long. In a recent study, Peterson and Church (2008) modeled all freight flows destined for or originating from the State of Washington. This principally involved the Class 1 railroads serving Washington, namely BNSF (Burlington Northern Santa Fe) and UP (Union Pacific). Peterson and Church proposed a methodology for determining the impact of losing a railroad bridge in terms of the needed rerouting of freight. For the State of Washington, there are approximately 999 origin-destination route pairs involving the Washington as either an origin or a destination in the Bureau of Transportation Statistics rail freight database. About a third of these routes typically cross the BNSF bridge at Sandpoint, Idaho. If this bridge is lost due to some type of accident or terrorist event, all traffic that would have used this bridge will need to be rerouted. Without considering issues of track capacity, rerouted distances averaged 350 miles more than what would occur with the bridge. That is, the loss of a rail bridge in Sandpoint, Idaho could have a significant impact on freight associated with the State of Washington. Peterson and Church (2008) also suggest how capacity data could be used to model routes after a possible bridge interdiction. They suggested that since some routes are already operating close to capacity, it may be that detours could be even longer than what had been estimated or that the capacity to handle such traffic along other routes does not exist and some freight might need to be curtailed.

The Legislature of the State of Pennsylvania has considered requiring their Department of Transportation to establish a contingency plan to reroute rail traffic due to a loss of railroad infrastructure such as a bridge, tunnel, or yard. Approximately 30% of the nation’s freight uses rail. This statistic is likely to increase with increasing fuel costs as rail is 4 times more fuel efficient than truck. In terms of moving towards more sustainable activities (like that suggested in California’s AB32), it is clear that rail will play a larger role in freight transport, especially for
distances that exceed 800 miles. Since the Ports of Long Beach and Los Angeles combined handle approximately 40% of all containers imported into or exported out of the U.S., it plays a major role in global transport flows. Most container traffic heading into California through any California port will be placed on rail if the trip exceeds 1000 miles. This means that rail infrastructure within California as well as bridges and tunnels outside California could have a detrimental impact on the ability to handle freight if they should be compromised. It is important to develop an understanding of the major vulnerabilities in advance of a disaster as well as to develop the best possible contingency plans for coping with such disruptions.

Infrastructure could be compromised by either a natural disaster or an intentional terrorist strike. For example, a heavy storm in December 2007 resulted in the closure of a 20-mile section of Interstate 5 near Chehalis, Washington for nearly a week. This would be considered “a piece of cake” event as compared to the events that are possible should the levee system in the Central Valley of California be compromised by a major storm or earthquake. It is imperative to understand the risks and locations of such events and develop appropriate plans to handle such a disaster. The road system in Central California could be compromised to the extent that traffic for many communities could be entirely cut off, something that California has not experienced to any great extent. The fact is that priorities for upgrading levees should be set not just in terms of protecting property and safety, but also within the context of protecting supply routes and evacuation routes for an area. This also means that Caltrans and other State agencies need to coordinate with water resource agencies, flood and levee operations districts so that emergency plans are coordinated with the state of such systems as levees, reservoir operations, etc.

The issue of intentional harm is not one to be taken lightly. The disruptions caused by the terrorist acts of 9/11 are quite small to what could possible occur or what natural disasters might do in harming infrastructure. There is a growing literature associated with identifying infrastructure that is especially vulnerable or critical. If an element is critical but not very vulnerable within the context of a natural disaster, then the only way in which that element might be compromised is due to an intentional strike. Some of the research literature is directed at identifying those elements that are particular important in system operation (facilities, networks, & protocols). For example, Church et al. (2004) presented two models that can be used in supply
logistics systems that are aimed at identifying the critical points of supply and the impacts of a worst-case interdiction. Their presentation also gives a relatively complete list of research papers associated with military interdiction of supply routes. Gubesic et al. (2008) discuss a number of approaches that can be used to assess critical elements of a network system. The basis for much of this work has been to analyze the range of possible outcomes, from worst-case to expected case damages, should a system be compromised by the loss of certain components, e.g. a bridge or a road.

The basic idea is that transport, communication systems, electrical transmission, and pipeline networks should be analyzed in order to identify the range of possible outcomes in terms of the loss of system operability as well as identify strategies in which to lessen those risks and potential damages. For example, a highway may have one bridge that is especially vulnerable to an earthquake or to flooding which might undermine the foundation. Whatever the risk is, it may be that this one component is especially at risk. What if the entire route is useless if that element is damaged? Then, it may be important to ensure that this one component is strengthened or protected so that the risk of losing an important route is substantially reduced. The overall strategy would be to identify the elements that if protected or reengineered could keep lifeline support systems in operation, e.g. water transportation, food, supplies, and communications. Each system needs to be analyzed within this perspective. The transportation system is a critical element in securing many of the lifeline systems (food, medications, personnel) in the event of an emergency so the transport infrastructure should be given a high priority for analysis as well as strengthening. The problem of re-engineering or fortifying a system component in order to minimize losses in the event of a disaster has been addressed only recently (see Church and Scaparra (2007) as an example).

Designing a transportation system so that it can provide lifeline services, like food and emergency services as well as support evacuation when needed was recently proposed by Viswanath and Peeta (2003). Suppose that there exists a region with an existing road network. The network represents roads or highways that connect towns or cities. The major cities represent the origins and destinations of specific services or commodities. The idea is that routes of commodities or services between all major towns should be supported if at all possible.
Although a route between a given origin/destination pair should be efficient, the route cannot traverse along a given road unless that road has been seismically upgraded to withstand a major earthquake. Viswanath and Peeta optimized road improvements subject to a budget constraint so that as many OD pairs are supported by a seismically safe route. The objectives were to maximize the population that were covered by these major routes and hence served by a specific commodity type as well as optimize the efficiency (distance) of each of the routes. Consider the following notation:

\[ \begin{align*}
    i, j, m & = \text{indices used to represent towns and cities} \\
    A & = \{(i, j) | \text{a road connects towns or cities } i \text{ and } j \} \\
    E_m & = \{(i, j) | \text{area } m \text{ is accessible to road link } (i, j)\} \\
    k & = \text{index of commodity or type of service} \\
    O(k) & = \text{the origin node } i \text{ for commodity route } k \\
    D(k) & = \text{the destination node } i \text{ for commodity route } k \\
    c_{ij}^k & = \text{the unit cost of routing commodity or service along link } (i, j) \in A \\
    f_{ij} & = \text{the cost of seismically upgrading road } (i, j) \in A
\end{align*} \]

The Viswanath and Peeta model contains the following three decision variables:

\[ \begin{align*}
    x_{ij}^k & = \begin{cases} 
    1, & \text{if there is a unit of flow of commodity } k \text{ on link } (i, j) \\
    0, & \text{otherwise}
    \end{cases} \\
    y_{ij} & = \begin{cases} 
    1, & \text{if link } (i, j) \text{ is used in a commodity flow path} \\
    0, & \text{otherwise}
    \end{cases} \\
    z_m & = \begin{cases} 
    1, & \text{if demand } m \text{ is accessible from a link on a flow path} \\
    0, & \text{otherwise}
    \end{cases}
\end{align*} \]

The formal multi-objective optimization model can then be stated as follows:

Maximize \[ \sum_m a_m z_m \]

Minimize \[ \sum_k \sum_{(i, j) \in A} (c_{ij}^k x_{ij}^k + c_{ji}^k y_{ij}^k) \]

Subject to:
\[ \sum_{(i,j) \in A} x^k_{ij} - \sum_{(j,i) \in A} x^k_{ji} = \begin{cases} 
0, & \text{if } i = O(k) \\
-1, & \text{if } i = Dk \\
0, & \text{otherwise} \end{cases} \quad \forall i, k \]

2) \[ Z_m \leq \sum_k \sum_{(i,j) \in E_m} (x^k_{ij} + x^k_{ji}) \quad \text{for each area } m \]

3) \[ x^k_{ij} \leq y_{ij} \quad \text{for all } k \text{ and } (i, j) \in E \]

4) \[ x^k_{ji} \leq y_{ij} \quad \text{for all } k \text{ and all } (i, j) \in E \]

5) \[ \sum_{(i,j) \in E} f_{ij} y_{ij} \leq B \]

6) \[ \sum_{(i,j) \in A} x^k_{ij} \leq 1 \quad \text{for all } i \text{ and } k \]

7) \[ \sum_{(i,j) \in A} x^k_{ji} \leq 1 \quad \text{for all } k \text{ and } j = D(k) \]

8) \[ \sum_{(i,j) \in A \text{ where } i,j \in Q} x^k_{ij} \leq |Q| - 1 \quad \text{for all } k \]

9) \[ x^k_{ij} \in \{0,1\} \text{ and } x^k_{ji} \in \{0,1\} \quad \text{for all } k \text{ and } (i, j) \in E \]

10) \[ y_{ij} \in \{0,1\} \quad \text{for all } k \text{ and } (i, j) \in E \]

10) \[ z_m \in \{0,1\} \quad \text{for all } m \]

The above model can be used to identify which routes should be made safe so that services can be transported to as many communities as possible and so that feasible evacuation routes exist after an earthquake. The basic idea is to design the best “safe-routes” system within budget limitations and serve as many communities as possible as well as make the hardened routes as efficient as possible. Although it may be the object to upgrade all bridges over time, such a model can be used to prioritize the upgrading process. Further, all bridges may be upgraded to some standard that is deemed acceptable, however, it may be valuable to then use the above style of model to consider which bridges or road links to upgrade to an even stricter standard, so that should a particularly powerful earthquake hit, there still represents a backbone of roads that can survive and be used in an emergency.

It should be pointed out that the model just described was cast within the context of providing routes that would survive an earthquake. But there are other dangers that might be of great
importance to consider within this context. One is potential flooding. A recent TRB report discussed possible impacts of climate change on transportation infrastructure. The greatest such impact is the possible flooding of low coastal areas due to storm surges and seal level rise. The TRB report suggests that virtually all transportation planning adopt a new perspective of dealing with possible climate change impacts. To do this requires a two step process: 1) identify possible infrastructure risks due to climate change, and 2) mitigate possible risks by planning in light of such risks. The model given above is an example of modeling to provide transportation services given an earthquake, but it could be modified to handle issues like that of extreme weather events, coastal flooding, etc.

Natural disasters such as earthquakes and flooding and human-caused disasters such as a terrorist attack both pose substantial risks to the transportation network. Mitigating the potential impact of these events requires careful identification of critical elements of transportation infrastructure so that steps can be taken to protect them from the multitude of hazards they face. Infrastructure can fail without warning, as demonstrated by the complete collapse of the I-35W freeway bridge in Minneapolis in 2007. Modeling techniques can be used to assess infrastructure fragilities on railways, freeways, levee systems, and any number of other important transportation features to help agencies take necessary steps to mitigate the impact of a worst-case disaster scenario.

10. Findings

This report has covered a number of elements associated with planning, mitigating, and managing events involving a disaster. To adequately serve a region with appropriate transportation, shelter, and life supporting resources it is important to anticipate, plan, train, and maintain an adequate mix of resources and personnel to respond appropriately. Thus far this report has focused on the role of modeling in disaster management, including modeling possible evacuations, prepositioning emergency supplies, designating shelter locations, modeling infrastructure fragility, designing systems so that they operate during disasters, designing plans for response, and designing interoperable communication systems. Yet even the most well thought out models and system designs may suffer from flaws that can only be rectified through careful design and real world validation. The first step in this process is to identify some of the
major shortfalls in current practice involving agencies responsible for emergency disaster response. To this end, the literature review above was complemented by a series of interviews conducted with emergency management personnel from several agencies in California.

The subjects of these interviews included Caltrans personnel, geospatial information specialists, and emergency management professionals from the campus to the county level. Interviews followed a semi-structured format, which allowed us to expand upon interesting topics while keeping focused on the subjects most relevant to the problem at hand. Santa Barbara County has faced four major wildfires in the past three years, thus these events comprised one major focus, along with earthquakes, chemical and nuclear accidents or attacks, tsunamis and other threats specific to the central coast region. Interviews were often followed by impromptu tours of the subject's workplace, including facilities like a Caltrans Traffic Management Center (TMC), an Emergency Operations Center (EOC), several Geographic Information System (GIS) hardware and software installations, and an emergency shelter utilized during the 2009 Jesusita Fire. In the interest of candid and informational discussion, we choose to maintain the confidentiality of our interview subjects. The following findings are informed by both our literature review as well as the series of interviews we conducted:

1) **It is important to identify areas within the State of California that face a significant disaster risk and also face a significant risk in evacuating safely.** This type of analysis would require modeling evacuation vulnerability and mapping event risk, and should be coordinated with data from OES, water resources agencies, MPO’s and other relevant organizations to provide a comprehensive risk map. One such area that was previously modeled (see section 3) is the Mission Canyon neighborhood in Santa Barbara. Due in part to this research, Mission Canyon residents were particularly well organized and actually evacuated before the official order came through during the May 2009 Jesusita fire. Also during this event, an evacuation contingency plan that was developed during the Zaca Fire was used to split most of the Santa Barbara area (Goleta, Santa Barbara, Montecito) into zones that could be evacuated in 1.5 hours or less. These zones were used to conduct a staged evacuation by identifying mandatory evacuation areas and evacuation

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3 A complete list of interview subjects can be found in the references section of this report.
warning areas based on the latest fire and weather conditions assessed by fire officials and CHP. It would be useful for emergency management purposes to have the entire county broken into these 1.5-hour zones using population densities, road network characteristics, and hazard probabilities. This method is not infallible however, as the Jesusita fire was only 40 minutes from Montecito at one point but the threatened area was not under mandatory evacuation. Wildfires remain a threat, as Montecito, Carpentaria, and some areas west of State Highway 154 still have intact chaparral of considerable age and vulnerability in the event of a wildfire. Flooding is now a major concern for the city and county given the extensive fire damage in many watersheds and the El Niño prediction for winter 2009-2010. Maps showing the areas of greatest concern could be helpful for planning purposes, and evacuation procedures for flood-prone areas should be determined well in advance of an event. Earthquakes and the tsunamis they may cause remain a major concern, and the uncertainty of the timing and spatial extent of such events presents a unique challenge in identifying and protecting areas at risk. Another area of concern to central coast emergency managers and Caltrans traffic engineers is the Diablo Canyon Nuclear Power Plant and the surrounding communities of Pismo Beach and San Luis Obispo. A contraflow evacuation plan has been developed for this area but might be improved through modeling and simulation. This topic is further discussed in the third recommendation of this section.

2) **For areas that face specific risks designate emergency evacuation routes and ensure such routes will be as safe as possible based upon infrastructure design and condition.** The 2007 Zaca fire was a significant event but progressed at a speed, which allowed for extensive evacuation contingency planning. Evacuation routes were designated using major arteries as the primary routes out of fire-prone canyon communities, with planned work-arounds should these primary routes be inaccessible. Since the fire never reached highly populated areas, most of these evacuation plans were not executed. Evacuation operations are legally a law enforcement function, with Caltrans assisting with road closures, traffic direction, and signage. Collaboration and data sharing between these two agencies could improve route designation and traffic flow, in particular information on current road construction projects and closures. Other
data used for evacuation routing includes cadastral parcels, Verizon point-of-presence (POP) locations, as well as the locations of nursing homes, day care centers, and schools to determine where assistance to vulnerable populations may be required. These data should be shared amongst agencies as well. Several issues that arise frequently during evacuation that may impede safety are that people will follow habitual routes rather than the routes they are directed to use and often think they can outrun hazards such as wildfires.

3) **Test and refine evacuation simulation models across multiple scales covering options such as contraflow, and develop the capability of analyzing evacuation flows on-the-fly using transportation, census, cadastral and employment datasets in a Geographic Information System (GIS).** Caltrans personnel designed the Diablo Canyon Nuclear Power Plant contraflow evacuation plan in December 2007. There seems to be considerable doubt within the agency as to whether the plan could be successfully implemented due to the considerable CHP and Caltrans manpower required to control traffic. Currently there is not a contraflow plan for the City of Santa Barbara, as the current staged evacuation method seems to work adequately given the relatively slow spread of recent wildfire events. The major challenge in designing a Santa Barbara contraflow plan is finding and allocating the manpower required to control the numerous 101 Freeway on/off ramps. Cities that have successfully implemented contraflow such as New Orleans have more spacing between freeway access points thus reducing the manpower required. There are two trends that have emerged in recent events requiring evacuations: The first is encouraging voluntary early evacuation so that emergency personnel have more time and resources to focus on vulnerable populations if/when the mandatory evacuation order is made. The second is rethinking the necessity of ordering a mandatory evacuation, with a greater focus on teaching people how to create defensible space and to ‘stay-and-defend’ during wildfires. One important task is to develop methods to estimate and model evacuation needs of special needs, like the elderly and youth using public assets like transit buses. Santa Barbara Metropolitan Transit District (MTD) bus drivers are required to pull over and immediately report any hazardous situation (wildfires, floods, traffic accidents, etc) thus might provide a novel source of
geoinformation as well as accessible transportation for vulnerable populations during a
disaster. Especially vulnerable populations include transients, tourists, and recent
immigrants with limited English comprehension. Integration of real-time traffic flow data
from Caltrans into a GIS would be of great use to emergency managers during both the
planning and operational phases of emergency evacuations. Major issues include the
large percentage of the workforce that commutes to Santa Barbara from other parts of the
county, thus leading to major differences in on and off peak traffic flow.

4) **Model shelter locations and supplies for ease of access, size, and capabilities in
supporting an emergency.** According to emergency management personnel, sheltering
operations in response to the Jesusita fire went well. Wednesday, May 6, 2009 and
Thursday, May 7 were the days when the fire posed the biggest threat to the community,
and thus the number of evacuees needing shelter was greatest during these days as well.
Overall, the number of evacuees needing shelter was much less than the 20% of the
evacuated population that the Red Cross generally assumes. The ability to provide
adequate sheltering during this event was largely due to the short time of the mandatory
evacuation order. The longer an event and the subsequent evacuations persist, the more
difficult it becomes to provide shelter to evacuees. Although the Jesusita Fire emergency
shelter on the UCSB campus was well staffed and stocked with supplies, it is notable that
this was the third facility that had been used to house this shelter. The initial location
proved too small to accommodate the influx of evacuees, and the subsequent shelter
location was closed when threatened by the fire itself. This lack of suitable shelter
locations and on-the-fly relocation may become significant impedance to evacuee safety
during future events, especially those that strike without advanced warning such as
earthquakes or terrorist attacks.

5) **Develop resource requirement models so that the need for resources to support
special needs like bridge inspections is understood, and plans for infrastructure
inspection after a disaster can be quickly carried out.** One of the biggest concerns for
Caltrans in the event of a major earthquake is ensuring the structural integrity of bridges
and freeway on and off ramps. The large scale and chaotic nature of an earthquake makes
it especially important to quickly assess freeway damage to provide access to rescue teams and evacuees. Significant damage to freeway infrastructure occurred in the San Francisco Bay Area during the 1989 Loma Prieta earthquake and more recently in the Los Angeles Basin during the 1994 Northridge earthquake. There is a general concern within the emergency management community that the central coast region is 'overdue' for a major earthquake and may be unprepared to handle the immediate infrastructure inspections necessary to facilitate rescue operations and ensure safety along major transportation corridors.

6) Model emergency supply storage and placement in order to estimate what will be needed statewide to respond adequately in a timely fashion, with a focus on locating equipment in hot spot regions of the state. CMS boards are essential in notifying the public of the road closures and designated evacuation routes when hazardous conditions exist. The primary role of Caltrans during emergency events is to respond by closing roads and controlling the placement of and messages on CMS boards. Once the lead command (Fire Department or CHP) determines that a road closure is necessary, a Caltrans maintenance crew places barricades, which are then usually staffed by CHP or local police. These signs are often left in places where they are likely to be put to use: one example is State Highway 192, a major transportation corridor and evacuation route for the foothill neighborhoods of Santa Barbara. There are many factors that should be taken into account when modeling placement of CMS signs, including visibility and the extended traffic queuing that may occur during evacuations.

7) Develop models that route rapid response vehicles to incidents in areas with significant congestion in order to maximize the value provided by such a service. One type of event that agencies such as Caltrans may not be prepared for during emergency operations is a secondary event that forces a road closure at a critical link along the transportation network. An example of such an event is the trailer fire that occurred next to the 101 Freeway during the Jesusita Fire evacuation that forced a temporary closure of the freeway, causing massive traffic gridlock. Fortunately, motorists stuck on the 101 and surrounding side streets were not directly threatened by the wildfire.
itself, but the impact of such secondary events on evacuation safety should be modeled to improve agency preparation and response time.

8) **Analyze, test, and deploy communication systems that can provide geographic information over a wide area to mobile units of different agencies.** The flow of geographic information between agencies and personnel during emergency operations is often disjointed. During the Jesusita Fire, CalFire mappers uploaded fire perimeter GIS layers based on information from personnel in the field to a State OES FTP site, which was then accessed by mappers at the County EOC to create maps. These county mappers were then responsible for creating operational maps incorporating utility, population, and road closure data for use by emergency officials, as well as electronic and hard copy maps for the general public. There were issues in maintaining sufficient mapping personnel to keep up with map requests, as well as making sure that the latest and most accurate geoinformation was used. City GIS personnel were unable to access the map layers they needed and there was considerable redundancy in the maps that were produced, resulting in a large degree of uncertainty regarding the latest and most accurate geoinformation. During the 2008 Tea Fire, the demand for updated fire maps far outpaced the city’s ability to produce them. Part of the problem was that there was no data connection between city GIS server and Emergency Operations Center (EOC) server. This lack of accurate geoinformation led to severe consequences: Several police officers were burned by this fire because they were stationed too close to the active front. Better coordination between the city and county is needed, and a mobile device-based or Internet system that provides consistent reliable information could greatly assist emergency managers in decision-making. The City of Anaheim has an Enterprise Virtual Operations Center that integrates, synthesizes, and distributes real time data (GIS, responder locations, communications) via the Internet for decision support. A tool that incorporates real time traffic information and the latest event maps would be very useful in developing and altering evacuation routes, especially if it could be used in conjunction with the radios already used by emergency personnel. The ability to instantly locate personnel and share information (pictures, text, etc) within defined user groups could also be helpful, provided the system was reliable and easy to use.
9) Establish a mechanism to use participatory/voluntary data provided by people with cell phones, allowing them to send video and images along with descriptive text to a central clearing house, thereby allowing people to provide data on an event as it unfolds. Organized volunteer data gathering by people in the area of harm may aid in their rescue and evacuation by providing valuable information. Since a 911 call center may be overwhelmed by calls during an emergency, many calls providing information cannot be handled. If an individual can send a text message with GPS coordinates (e.g. from an iPhone) or an image, this data could be streamed directly to support personnel in a mobile command center allowing for better information about an event. There is considerable debate concerning the role of citizens in developing and accessing emergency management information. Any disaster information provided by citizens should be crosschecked for reliability, although sometimes the best disaster information comes from the media or from outside of official sources. The Santa Barbara county GIS department used a Google Map to display official evacuation zone and fire perimeter information during the Jesusita fire, but it was difficult to ensure accuracy and maintain this map with other more pressing duties such as providing maps to officials and decision makers. A group of graduate students created a competing Google Map of evacuation zones and fire perimeters relying on data from numerous sources, which one emergency manager found to be more accurate and useful than the official county map. It is very important to strike a balance between volunteered geographic information (VGI) and official sources of geographic information during emergencies so that the public stays informed but people are not overwhelmed and confused by conflicting information.

10) Develop formal emergency communication links and systems so that emergency managers can quickly and effectively convey the most accurate and up-to-date information to the public. Currently there are a multitude of systems used to alert people living in the Santa Barbara area of potentially hazardous situations. As of February 2009 more than 28,000 users had signed up for the UCSB campus alert system with 9,345 wireless devices registered to receive automatic text message alerts. The Santa Barbara City Reverse 911 system uses Verizon phone connection data and GIS to
determine the size of polygons representing the areas to be notified. Goleta uses a different notification system that had several notable mishaps during the 2008 Gap fire, including instructing residents of the seaside community of Isla Vista to evacuate. The best way to convey spatial information during an emergency and exactly what information should be provided remain open-ended questions. For example, the danger in making evacuation routes public is that evacuees may blindly follow them and ignore instructions that route them around hazards such as spot fires that occur far in front of the main flame front. Traditional sources such as television and radio remain important communication outlets for emergency information, but are losing ground to the Internet and mobile devices. The county is considering developing an ESRI ArcIMS site to help disseminate spatial information quickly and coherently over the Internet, including evacuation zones and road closures. Another option is to develop a mobile disaster decision support system (MDDSS) which allows people to access emergency information from official sources as well as volunteered information from other users within their disaster support network (DSN). Such a system could also show the locations of all members of the DSN, and provide a routing service that takes into account road closures and hazard location, all on a mobile device such as an iPhone or Blackberry.

11) **Model the fragility of infrastructure and its potential impact on public safety.**

During the Jesusita Fire, the Santa Barbara county emergency operations center (EOC) had to be relocated to the UCSB campus when the fire threatened its downtown location. Computers and other equipment were moved because there is insufficient funding for two fully operational EOCs, and there was an approximately one hour delay after the move before the phone lines were connected, leaving a dangerous communication gap while the new EOC was set up. Obviously, a non-operational emergency operations center poses a major hazard to the public when a fast-moving wildfire is threatening property and lives. One possible solution to such infrastructure vulnerabilities is development of portable self-contained emergency management units such as the trailer used by CalFire for GIS services. Models should be developed to locate new facilities in such a way that minimizes risk from events such as wildfires, and ensures designs that can withstand the shaking of an earthquake and the strong winds produced by storms.
11. Conclusion

A devastating event such as Hurricane Katrina often leads both the public and the government agencies charged with serving them to rethink disaster preparedness, mitigation, response, and recovery and to ask the omnipresent question, “What would I do if the unthinkable happens?” The power of this tragedy to spur such questions is one reason why it is mentioned frequently throughout this report. It is important to review the lessons learned from Hurricane Katrina and other recent disasters when developing a research agenda for the hazards that affect California.

One of the few things that went right during Hurricane Katrina was the successful implementation of a contraflow evacuation plan. As detailed in the evacuation section of this report, everyone with access to private transportation who chose to evacuate the city was able to do so and in less time than anticipated by planners. This success would not have been possible without extensive research performed at academic institutions such as the Louisiana State University Hurricane Center. A variety of modeling techniques were employed to determine the best strategy, leading to “the most effective highway-based evacuation in the history of the Gulf Coast and, perhaps, in the history of the entire United States.” (Wolshon, 2006, p.1) Of course few would argue that the overall emergency management of Hurricane Katrina was a success. The destruction and subsequent abandonment of large portions of the city and the death of nearly one thousand city residents exemplifies the severe deficiencies that occurred in all four stages of emergency management. Some might argue that the overwhelming and unexpected magnitude of the storm lead to inevitable outcomes, but most hazards researchers agree that more could have been done to accommodate the needs of vulnerable people who were disproportionately affected by this event. It makes sense to expand the notation of the an “area at risk” to an “area at risk with the potential for disproportionate impacts on specific demographic sectors.” The majority of current emergency evacuation research is centered on people who own and drive vehicles, not those who are old, infirm, young, poor, or those with disabilities such as the blind. Emergency operations needs to be based upon good demographic data so that everyone can be considered covered within the plan.
The City of New Orleans was devastated by Hurricane Katrina, a natural event whose effects were amplified by human decisions made over multiple time and spatial scales. Most disasters fit this description: they are a function of both the geographic characteristics of the hazard itself and the vulnerabilities and actions of the people whom it affects. Although government and citizens alike were aware of the destructive potential a direct hit from a strong hurricane posed to New Orleans, they were woefully underprepared for this ‘worst case’ scenario. Many cities in California face similar dire threats, whether from flooding, earthquakes, wildfires, tsunamis, chemical spills, nuclear accidents, or the actions of a terrorist group or rouge state. Much like New Orleans, the cities and the agencies responsible for protecting them are for the most part unprepared for the potential impacts of a major hazard.

The Jesusita Fire nearly became a major disaster for the City of Santa Barbara. The original Red Cross shelter was moved when it was threatened by the fire, thus reducing the number of possible shelter sites increasing the risk of not being able to meet the needs of vulnerable populations. Likewise, the EOC was moved when threatened by the fire, a contingency action that was actually discussed during the Gap Fire, yet still resulted in ‘downtime’ making active management difficult. Despite doubling the size of the sheriffs’ department via mutual aid an event such as the 101 Freeway trailer fire would have pushed manpower requirements and planning abilities to the limit had it persisted. Models should be designed that account for such unexpected events to increase the odds of successful emergency management and reduce the probability of destruction of property and loss of human life. We conclude this report with what is perhaps our most important recommendation: We must assume that the ‘worst case’ disaster scenario will occur and prepare our citizens and government agencies accordingly.
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Richard Abrams, County of Santa Barbara
Zacharias Hunt, County of Santa Barbara
Yolanda McGlinchey, City of Santa Barbara
Frank Quon, Caltrans District 7
Rick Sachse, Global Traffic Technologies
Fred Samuel, University of California, Santa Barbara
Shayne Sandeman, Caltrans District 5
Shashi Shehkar, University of Minnesota, Twin Cities
David Ybarra, Caltrans District 5

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