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# ACUTE CARE HOSPITAL RESOURCE ALLOCATION PROBLEM UNDER SEISMICALLY DAMAGED TRANSPORTATION SYSTEMS

Hope A. SELIGSON[1], Yuko MURACHI[2], Yueyue FAN[3], and Masanobu SHINOZUKA[4]

## SUMMARY

This paper describes a methodology currently under development to optimize the post-earthquake routing of the injured to functioning hospitals. The methodology considers the geographic distribution of injuries of various severities, earthquake damage to hospitals and their functionality, and impacts on transportation networks. Past experience has shown too often that earthquake damage to highway components (e.g., bridges) can severely disrupt traffic flow, thus it is important to develop a methodology to model hospital resource allocation relative to the damaged transportation network. The basic problem can be formulated as a linear programming problem. The objective is to minimize the travel time or delay in transporting injured patients to the appropriate hospitals, subject to the status and capacities of the hospitals and the post-earthquake traffic condition. Individual scenario earthquakes are modeled, and the corresponding post-event damage state of the transportation network is evaluated using custom fragility functions for highway bridges integrated into a Monte Carlo simulation analysis. Travel time between the injury location and each hospital is obtained from the conventional user equilibrium model. The resulting methodology could be used to develop a real-time decision support tool for use in emergency response and preparedness planning, as well as for consideration in mitigation decisions regarding hospitals and transportation infrastructure. The methodology, once developed, will be pilot-tested in Orange County, California.

## INTRODUCTION

Earthquake loss estimation methods are widely available to analyze many elements of the built environment, such as buildings, utility facilities and transportation infrastructure (see, for example, the HAZUS methodology and software developed by FEMA/NIBS [1]). Fewer methods consider the cumulative impacts of the damaged elements on the community's ability to provide emergency response services, e.g., how the combination of damaged hospitals and damaged transportation infrastructure impacts a community's ability to treat the injured in the wake of an earthquake. The proposed

[1] University of California, Irvine, California, USA. Email: seligson@uci.edu
[2] Keikaku Engineering Inc, Tokyo, Japan. Email: murachi@kke.co.jp
[3] University of California, Davis, California, USA. Email: yyfan@ucdavis.edu
[4] University of California, Irvine, California, USA. Email: shino@uci.edu

methodology attempts to identify and model factors influencing the provision of post-earthquake emergency medical services, with the intent of developing a real-time decision support tool to optimize the post-earthquake routing of the injured. The components of the methodology are identified in Figure 1, and are discussed in the following sections.

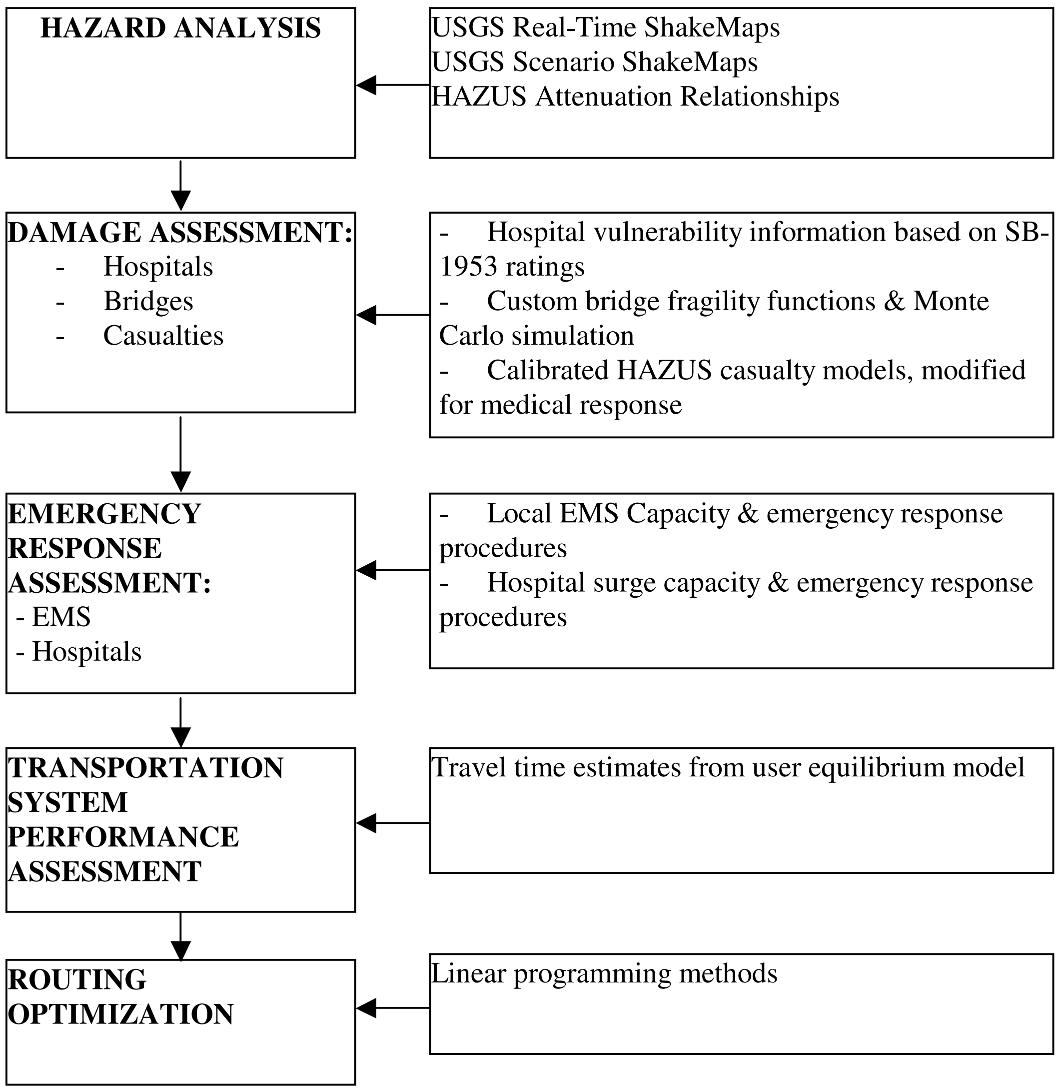
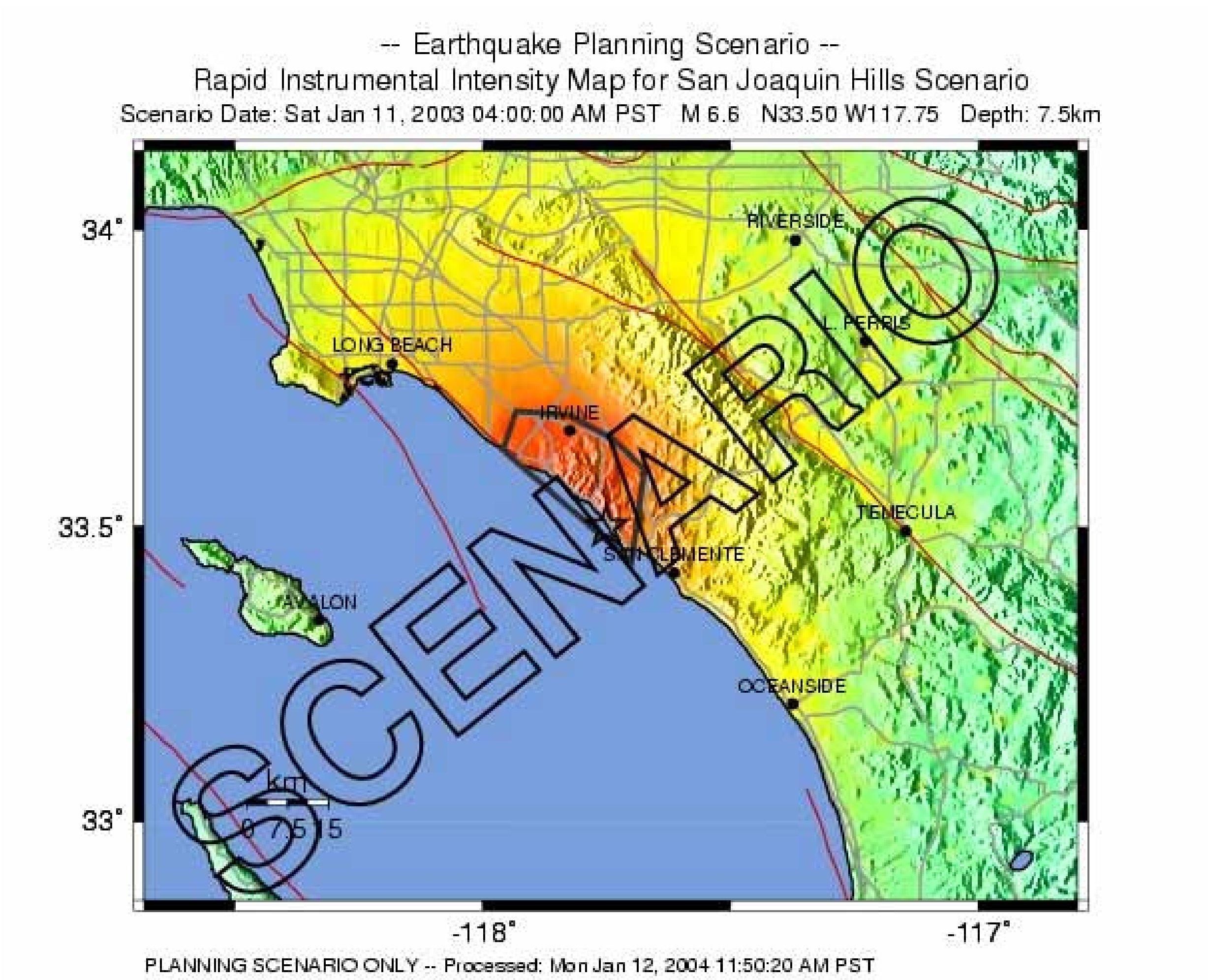



**Figure 1: Methodology for a Decision Support Tool to Optimize Post-Earthquake Routing of Injured**

## HAZARD ANALYSIS

To assess regional earthquake hazards within the Orange County pilot study area, the proposed methodology will make use of standardized ground shaking map products produced by the United States Geological Survey (USGS). ShakeMaps (Wald [2]) are regional maps of estimated (instrumental) intensity, peak ground acceleration, peak ground velocity and spectral acceleration, generated in real-time (i.e., within a few minutes of an earthquake). In addition, the USGS makes postulated scenario

ShakeMaps available for planning purposes. ShakeMaps are available in a number of areas, including Northern and Southern California, the Pacific Northwest, and Utah. For the area of interest to the current pilot study (Orange County, California), a number of scenario ShakeMaps have been generated including a M6.9 Newport-Inglewood, M7.4 southern San Andreas, a M6.8 Elsinore, and a M6.6 on the recently discovered San Joaquin Hills Fault (shown in Figure 2). The developers of ShakeMap anticipated their usefulness for preparedness planning and mitigation, and automatically generate HAZUS input files for each ShakeMap. Accordingly, selected scenario ShakeMaps will be imported into HAZUS for use in the subsequent damage assessment.




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

**Figure 2: Scenario ShakeMap for a Magnitude 6.6 Earthquake on the San Joaquin Hills Fault (http://www.trinet.org/shake/San_Joaquin_Hills_se/intensity.html)**

## DAMAGE ASSESSMENT

### Injury Modeling

Recent research in earthquake-related injury modeling has focused on integrating medical and public health information with engineering data on building characteristics and performance (see, for example, Seligson [3, 4], Shoaf [5], Peek-Asa [6], and Mahue-Giangreco [7]). The goal of these recent studies has been to standardize data collection and analysis of injury and damage data to facilitate the improvement or refinement of available engineering-based casualty models.

Published casualty models include the models employed within the HAZUS [1] and EPEDAT [8] software tools. HAZUS, developed by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS), is a standardized, nationally applicable earthquake loss estimation methodology, implemented through geographic information system (GIS) software. HAZUS estimates building-related casualties (both indoor and outdoor) at four severity levels, as given in Table 1, from models based on available U.S. and worldwide data.

**Table 1: HAZUS-99 Injury Severity Scale (NIBS/FEMA [1])**

| **Injury Severity Level** | **HAZUS 99 SR-2 Severity Level Definition** |
|---|---|
| Severity 1 | Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self treated are not estimated by HAZUS. |
| Severity 2 | Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure. |
| Severity 3 | Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome. |
| Severity 4 | Instantaneously killed or mortally injured. |

EPEDAT, the "*Early Post-Earthquake Damage Assessment Tool*" is GIS-based software designed to produce regional damage and casualty estimates specifically for southern California. EPEDAT was developed for the California Office of Emergency Services (OES) for use in emergency response and planning. Casualty models within *EPEDAT* are based on earlier published models (ATC [9], Whitman [10]) which estimate mean death and injury rates for any building within a given damage state, where each damage state includes a considerable range of possible damages (e.g., the ATC damage state “Moderate” includes damage ranging from 10 to 30% of replacement cost). To adequately reflect the range of possible injuries within a given damage state, a beta probability distribution utilizing the mean casualty rate for each damage state has been applied (EQE [8]). In essence, EPEDAT’s injury rates are distributed within a given damage state such that injuries are more likely to occur in buildings at the upper end of the damage state than at the lower end.

While these published casualty models can be used to estimate casualties for general planning purposes, to make the information useful to the medical and public health communities, the injury categories must be translated into more meaningful categories. One of the recent inter-disciplinary research efforts (Seligson [3]) took this approach. In addition to calibration of an EPEDAT model prediction to actual Northridge data, the research suggested modifications that translate simple estimates of "injuries" and "deaths" to estimates of fatalities (non-hospital, i.e., dead on arrival), fatalities requiring hospital care (i.e., care in the intensive care unit), trauma cases, non-trauma hospital admissions, emergency room treat and release, and out of hospital treatment. The results of the calibration indicated that that *EPEDAT* estimated casualties for the Northridge Earthquake, while not matching casualty patterns precisely, provide a reasonable order-of-magnitude estimate of deaths and injuries. The resulting recommended model for estimating the various levels of injuries for medical planning from *EPEDAT* estimates is provided in Table 2. A similar calibration exercise and classification translation model will be developed for HAZUS as part of the current methodology development.

For injury transportation planning, it is important to know how people with various types of injuries are likely to arrive at the hospital emergency department (ED) for treatment. As shown in the last column of Table 2, it is anticipated that all trauma injuries will arrive at the ED by ambulance, as will injuries that eventually result in death. Further, it is anticipated that 80% of post-disaster hospital volume arrives "by convergence" (i.e., walk-in), and is not transported by ambulance.

**Table 2: Refinements to *EPEDAT*'s Casualty Models for Injury Planning (Seligson [3])**

| Injury Type | Suggested Model Refinement | Description of Injury Category | Likely Mode of Transportation to Hospital |
|---|---|---|---|
| Non-Hospital Fatalities | 82% of *EPEDAT* "best estimate" of Deaths | instantaneous death – no hospital care required. | no treatment, no transportation required. |
| In-Hospital Fatalities | 18% of *EPEDAT* "best estimate" of Deaths | Majority require intensive care | transportation by ambulance |
| Trauma Cases | 6.5% of *EPEDAT* "best estimate" of Serious Injuries | Injury severity scale (ISS) >15 (some require intensive care) | transportation by ambulance |
| Hospital Admissions (Non-Trauma) | 93.5% of *EPEDAT* "best estimate" of Serious Injuries | ISS ≤15 | approx. 80% walk-in, 20% by ambulance |
| Emergency Department (ED) Treat & Release | 16.5% *EPEDAT* upper bound Total Injuries | Extremities (esp. in night), falls, blunt trauma, lacerations | approx. 80% walk-in, 20% by ambulance |
| Out of Hospital Treat & Release | 33% *EPEDAT* upper bound Total Injuries | Similar to ED, may spill over into ED | no transportation required. |

**Hospital Performance**

California's Hospital Seismic Safety Legislation was put in place after the 1971 San Fernando Earthquake. The most recent modifications to the law (Senate Bill 1953, or SB1953) were passed in 1994 in response to poor hospital nonstructural performance in the Northridge Earthquake. SB1953 identifies structural and nonstructural performance standards for acute care hospitals, requires hospitals to evaluate their safety relative to the standards, and to develop plans to meet the standards within a specified timeframe (OSHPD [11]). SB1953's Structural and Nonstructural Performance Categories are identified in Tables 3 and 4, respectively, and Table 5 provides a summary of hospital ratings for Orange County, California. Ratings were reported for 35 of the 39 hospitals in Orange County, providing data on 181 hospital buildings.

The HAZUS software provides a simple mechanism for the assessment of damage to hospitals in earthquakes. Default data provided with the software are limited to one database record for each hospital. To more accurately reflect variations in performance among different hospital buildings, a more detailed database will be assembled, including one database record for each acute care hospital building in Orange County. SB1953 performance categories will be used to assign appropriate HAZUS fragility functions to each hospital building. The resulting HAZUS damage state probabilities will be used as input in determining the hospital's operational status, and other operational characteristics required for the analysis, such as whether the emergency department (ED) will be closed to ambulance traffic. For example, it is expected that EDs will close to ambulance traffic only if the building suffers significant damage (i.e., HAZUS damage state extensive or complete damage).

**Table 3: SB 1953 Structural Performance Categories (OSHPD [11])**

| | |
|---|---|
| SPC-0 | The hospital evaluated this building but did not provide any rating in its report to OSHPD. |
| SPC-1 | These buildings pose a significant risk of collapse and a danger to the public after a strong earthquake. These buildings must be retrofitted, replaced or removed from acute care service by January 1, 2008. |
| SPC-2 | These are buildings in compliance with the pre-1973 California Building Standards Code or other applicable standards, but are not in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act. These buildings do not significantly jeopardize life, but may not be repairable or functional following strong ground motion. These buildings must be brought into compliance with the Alquist Act by January 1, 2030 or be removed from acute care service. |
| SPC-3 | These buildings are in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act. In a strong earthquake, they may experience structural damage that does not significantly jeopardize life, but may not be repairable or functional following strong ground motion. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They can be used to 2030 and beyond. |
| SPC-4 | These are buildings in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act that may experience structural damage which could inhibit the building's availability following a strong earthquake. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They may be used to 2030 and beyond. |
| SPC-5 | These buildings are in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act, and are reasonably capable of providing services to the public following strong ground motion. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They may be used without restriction to 2030 and beyond. |

**Table 4: SB 1953 Nonstructural Performance Ratings (OSHPD [11])**

| | |
|---|---|
| NPC-0 | The hospital evaluated the building's non-structural components but did not report any rating. |
| NPC-1 | In these buildings, the basic systems essential to life safety and patient care are inadequately anchored to resist earthquake forces. Hospitals must brace the communications, emergency power, bulk medical gas and fire alarm systems in these buildings by January 1, 2002. |
| NPC-2 | In these buildings, essential systems vital to the safe evacuation of the building are adequately braced. The building is expected to suffer significant nonstructural damage in a strong earthquake. |
| NPC-3 | In these buildings, nonstructural systems are adequately braced in critical areas of the hospital. If the building structure is not badly damaged, the hospital should be able to provide basic emergency medical care following the earthquake. |
| NPC-4 | In these buildings, the contents are braced in accordance with current code. If the building structure is not badly damaged, the hospital building should be able to function, although interruption of the municipal water supply or sewer system may impede operations. |
| NPC-5 | These buildings meet all the above criteria and have water and wastewater holding tanks—sufficient for 72 hours of emergency operations—integrated into the plumbing systems. They also contain an on-site emergency system and are able to provide radiological service and an onsite fuel supply for 72 hours of acute care operation. |

**Table 5: Summary of SB1953 Ratings for Acute Care Hospitals in Orange County (OSHPD [11])**

| Rating Category | Number of Hospital Buildings |
|---|---|
| Structural Performance Ratings | |
| SPC0 | 14 |
| SPC1 | 61 |
| SPC2 | 9 |
| SPC3 | 15 |
| SPC4 | 63 |
| SPC5 | 19 |
| TOTAL | 181 |
| Nonstructural Performance Ratings | |
| NPC0 | 14 |
| NPC1 | 139 |
| NPC2 | 23 |
| NPC3 | 0 |
| NPC4 | 4 |
| NPC5 | 1 |
| TOTAL | 181 |

**Transportation System Damage**

Methods for the evaluation of transportation system performance in earthquakes have been developed by the research team (see for example, Shinozuka [12]), and tested using the California Department of Transportation (Caltrans) Los Angeles area transportation network. The performance of highway networks in earthquakes is highly dependent on the functionality of bridges. Bridge fragility curves, expressed as a function of peak ground acceleration or peak ground velocity, have been developed from empirical damage data from the 1994 Northridge Earthquake using the maximum likelihood method. The fragility curves were validated relative to actual earthquake performance using a Monte Carlo simulation analysis to estimate bridge damage states. The fragility curve developed assuming the entire population of 2,209 bridges is homogeneous is given in Figure 3. In the context of the decision support tool for emergency medical transportation, the custom fragility curves will be used to assess the damage state of bridges in Orange County for each scenario earthquake.

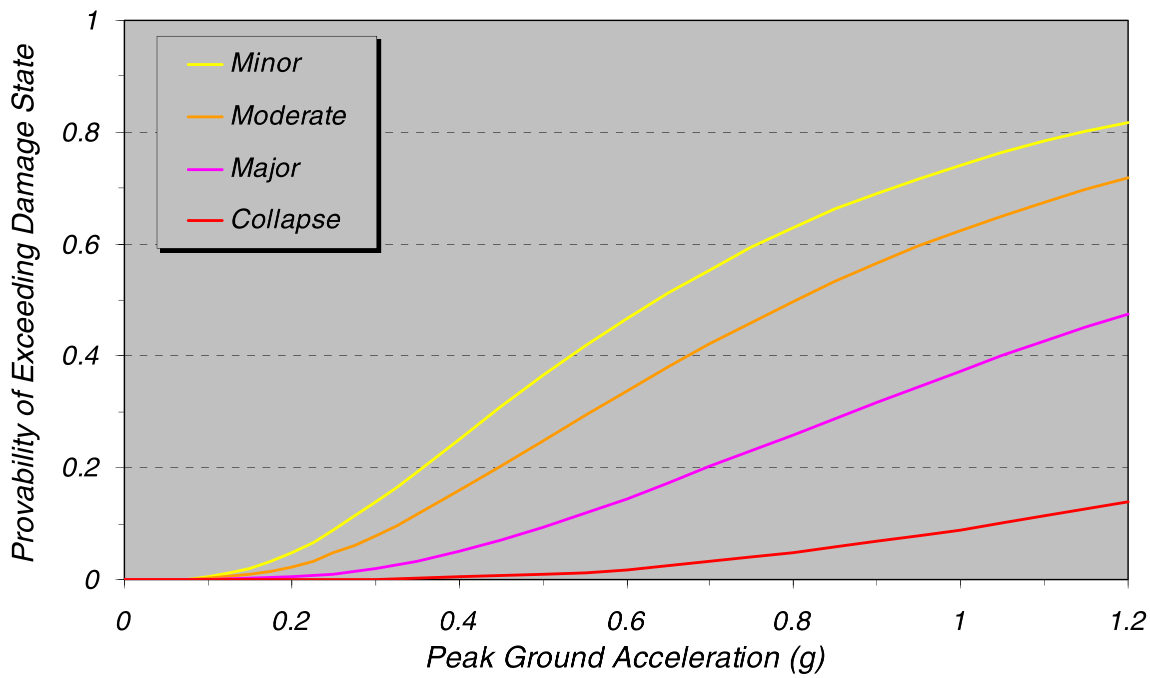



**Figure 3: Sample Empirical Bridge Fragility Curve**

## EMERGENCY RESPONSE CONSIDERATIONS

Because the intent of this research is to develop a real-time decision support tool for use in optimizing the routing of the injured to hospitals, operational procedures of emergency medical services (EMS) as provided in California in general, and specifically in Orange County will be addressed. EMS will be studied to better understand and model standard operating procedures for transporting injured to hospitals under normal and disaster conditions. Mapped "catchment" areas for trauma and other emergencies will be incorporated into the model as limiting conditions on transportation. In addition, emergency response procedures at hospitals will also be considered.

## TRANSPORTATION SYSTEM PERFORMANCE ASSESSMENT

For the current application to post-earthquake emergency medical transportation, the transportation network performance measure of interest is travel time. Travel time on a link is calculated using a link performance function developed by the United States Bureau of Public Roads:

$$t_a = t_a^o\left[1+\alpha\left(\frac{x_a}{Ca}\right)^{\beta}\right] \qquad (1)$$

Where:
$t_a$ = the travel time on link *a* (in hours per Passenger Car Unit)
$t_a^0$ = the travel time at zero flow on the link *a* = the link's length divided by the speed limit
$x_a$ = the flow on link *a* (in Passenger Car Unit per day)

$C_a$ = the "practical capacity" of the link
$\alpha = 0.15$
$\beta = 4.0$
It is important to note that this empirically derived expression asserts that the travel time on a link carrying 100% of capacity is 15% greater than the free flow time. Determining the flow on each link depends on the availability of origin-destination (OD) data, and the flow between links is solved using an equilibrium analysis (user optimizing deterministic assignment).

Bridge damage states as determined from the fragility functions and Monte Carlo simulation are used to evaluate link damage states; link damage is determined by the worst performing bridge on the link. Assumed link damage impacts on capacity and free flow speed for the Caltrans freeway network, including consideration of emergency re-routing capability, are given in Table 6.

**Table 6: Assumed Change in Road Capacity and Free Flow Speed Considering Emergency Re-routing Capability**

| State of Link Damage | Capacity Change Rate | Free Flow Speed Change Rate |
|---|---|---|
| No Damage | 100% | 100% |
| Minor Damage | 100% | 75% |
| Moderate Damage | 75% | 50% |
| Major Damage | 50% | 50% |
| Collapse | 50% | 50% |

Typical OD data required for travel time estimates consist of matrices that tabulate number of trips by purpose (e.g., home-work, home-shop, home-other, etc.). The ongoing research will examine the implications of estimating travel time for emergency vehicles using standard OD matrices, and explore alternative methods and data.

## ROUTING OPTIMIZATION

The optimization of the routing of injured to hospitals must consider hospital performance (e.g., hospital capacity should increase for surge capacity, but decrease given significant structural or non-structural damage), injury severity (e.g., which injuries require ambulance transport), and transportation network performance (e.g., reflect bridge closures). Despite the variety of issues to be considered, it appears that the basic problem can be solved using a linear programming construct, with appropriate constraints. The basic formulation is as follows:

$$\min z(x) = \sum_i \sum_j \sum_s t_{ij} i_{ij}^{(s)} w^{(s)} \qquad (2)$$

Subject to:

$$C_j \geq \sum_i \sum_j i_{ij}^{(s)} \qquad (3)$$

$$I_i^{(s)} = \sum_j i_{ij}^{(s)} \qquad (4)$$

Where:
$z(x)$ = total travel time
$t_{ij}$ = travel time from zone i to hospital j
$i_{ij}^{(s)}$= number of people with injury of severity s, being transported from zone i to hospital j
$w^{(s)}$ = priority weight for injury of severity s
Cj = total treatment capacity for hospital j
$I_i^{(s)}$ = total number of people with injury of severity s in zone i.

In this case, treatment capacity can be set to reflect available surge capacity and/or capacity reductions reflecting facility damage. Injury models can be used to identify location and type of injuries requiring ambulance transport, and the travel time estimate can consider transportation network performance (e.g., bridge closures). While the full methodology has yet to be developed and exercised, a small linear programming test is underway to identify any significant problems or issues.

## CONCLUSIONS AND FUTURE RESEARCH

This paper documents a methodology currently being developed to optimize the post-earthquake routing of injured to hospitals. The methodology will consider the regional distribution of injuries, performance of hospitals and the transportation network, and emergency response considerations with the intent of developing a real-time decision support tool. The development of the methodology is currently in its early stages, and although the general framework has been outlined, future research efforts will focus on working out the details.

## ACKNOWLEDGEMENTS

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