Post Earthquake Transportation Network Performance: Transportation of Injured to Medical Facilities

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ABSTRACT: Understanding and modelling both the supply of and demand for transportation services after an earthquake event are vitally important for emergency managers, and government agencies to mitigate, prepare for, respond to, and recover from the potential impacts effectively. The changes in the supply side of transportation networks includes failure of and capacity reduction for bridges and roadways, as discussed in several studies; while the demand side, capturing changes in travel patterns, has drawn less attention.

Models to estimate travel demand after an earthquake are necessary to estimate the performance of the whole system. The purposes of trips after an earthquake are completely different from the normal situation. This paper analyzes the performance of the transportation system for the purpose of transferring injured to medical facilities. Using a simple demand model the number of trips are estimated and then assigned to the disrupted network with reduced capacity. Performance measures are computed including the network total delay for medical trips, and potential human loss due to delays. Moreover, to be able to use this study for mitigation planning, probabilistic performance measures based on earthquake scenarios can be developed.

1 INTRODUCTION

1.1 Background

Following earthquakes and other disasters, a functional transportation system is needed to support search and rescue operations, debris removal, supply chain operations for relief efforts, and the restoration of other services and general community functions. The post-earthquake performance of the transportation network cannot be inferred from normal operations as both supply and demand have been disrupted.

Studies of the post-event supply of transportation systems focus on how components such as tunnels, bridges and pavements withstand the earthquake forces, and predict the systems' condition based on the intensity and location of the event. Very little research has focused on the demand side. Furthermore the demand changes over time as search and rescue operations wind down and the response effort changes to focus on recovery.

Recognizing this gap in knowledge this paper begins to explore the changes in demand for transportation during earthquake response by concentrating on one type of trip, the transportation of injured to medical facilities and how this demand changes over time.

Modelling the trips that occur during emergency response starts with a list of emergency response activities. Disaster response activities typically include (Martin, 2010):

- Rapid damage assessment:
- Search and rescue

- Emergency medical care.
- Emergency restoration of essential services.
- Fire-fighting.
- Emergency communications.
- Crisis decision-making.
- Evacuation, protection of lives and property.
- The provision of emergency shelter for victims.
- Debris removal.
- Other activities that take place during the immediate post-impact emergency period.

Eventually, the trips associated with each of these activities and any linkages must be understood to improve emergency response.

1.2 Motivation

Experiences in the Great East Japan Earthquake in Sendai, Japan (March 2011), the Haiti Earthquake (January 2010), the Darfield Earthquake (September 2010) and the Christchurch Earthquake (February 2011) underscore the challenges faced in emergency response. For the Sendai earthquake, physical damage has been estimated to be from $195 billion to as much as $305 billion. More than 27,000 people were killed or are missing, and more than 202,000 homes and other buildings have been totally or partially damaged (Nanto et al, 2011). Japan's transport network suffered severe disruptions. Many sections of Tohoku Expressway serving northern Japan were damaged. The expressway did not reopen to general public use until 24 March 2011(NHK World, 2011). All railway services were suspended in Tokyo, with an estimated 20,000 people stranded at major stations across the city. The transportation system hobbled the distribution of essential medicines and equipment (Valeo, 2011). Providing medical aid, dispatching rescue team and supplies, and debris removal are vital emergency response operations after a disaster like this. In Port-Au-Prince, differential settlement at bridge approaches, and extensive damage to the port during the Haiti Earthquake limited mobility (EERI, 2010a). Damage from the Darfield Earthquake is estimated at $3 billion (EERI 2010b), and four weeks after the Christchurch Earthquake bus services had only been partially restored (Kam et al, 2011).

Transportation systems are a class of critical civil infrastructure systems that must be able to respond to disruptions and continue to provide mobility critical to providing timely response and reducing human and property loss. A reliable transportation system can be designed if the system’s functionality and performance after a disaster is understood and rigorously analyzed. To understand the transportation system performance after a disaster, like other systems, predicting both the supply and demand sides are necessary.

1.3 Objectives

The objective of this study is to estimate performance measures for the whole transportation network for transporting injured to medical facilities after an earthquake. Recent studies have focused on modelling the supply side of the transpiration system after an earthquake using probabilistic risk analysis methods. These studies are successful in capturing both the probability of failure of transportation elements and the whole system performance considering the disrupted elements (Chang et al, 2000, Başöz and Kiremidjian, 1995, Kiremidjian et al, 2007, Shiraki et al, 2007). But all these studies either do not deal with demand at all or make the assumption that the demand for transportation services is the same before and after an earthquake. Using network modelling, the study relies on current supply models and a proposed demand model. These models can be used to plan ahead for the post disaster situation, and to minimize the level of disruption. Presenting the most effective strategies to enhance the network functionality after an earthquake is the final objective of this study. Modelling just one activity – transporting injured to medical facilities – is an important first step in developing comprehensive models.

2 METHODOLOGY

In this paper a hypothetical deterministic earthquake (7 M_w) scenario is considered for a city in the United States. This method can be modified to use probabilistic earthquake scenarios for real cases.

Applying Hazus-MH, “a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes (Federal Emergency Management Agency, 2007)”, the damage to bridges and the number of casualties for each census tract is estimated. Using these data the reduction in the capacity of transportation network (supply side) and the trips generated to transfer the injured to medical services (demand side) is modelled. Each element is elaborated on below.

2.1 Supply

Hazus-MH uses the earthquake scenarios as input and applies fragility curves for bridges to estimate the damage state of each bridge in the transportation network. Based on Hazus-MH and standard fragility curves the damage states for bridges are: None, Slight, Moderate, Extensive, and Complete. Hazus-MH output for bridge damage is in the form of probabilities for the bridge being in each damage state and the probability for exceeding each damage state. In this paper the most probable damage state for each bridge is chosen as the damage state for that bridge for further analysis. Understanding the damage state for each bridge in the study area, it is important to know how this damage to the bridge affects the traffic capacity of the bridge and consequently the whole network.

Shiraki et al (2007) suggest a method to quantify the damage states and use it to identify the capacity reduction for a link with damaged bridges in it. First, using the bridge damage index from Caltrans' report on bridge damage in the Northridge earthquake (Caltrans 1994), the bridge damage index (BDI), a number between 0 and1, is assigned to each damage state, with 0 is for no damage, 0.1 for slight, 0.3 for moderate, 0.75 for extensive and 1 is for complete damage. Then two methods are suggested to find the link damage index (LDI) based on BDI:

Method 1- LDI is the square root of the sum of the squares of the BDI values assigned to all bridges associated with the link:

$$LDI = \sqrt{\left(\sum_{j=1}^{N} (BDI_j)^2\right)} \qquad (1)$$

Where N=total number of bridges associated with the link; and

BDI_j=bridge damage index for bridge j.

Method 2- LDI value equals to the maximum in a set of BDI values for the link:

$$LDI = Max_j\,(BDI_j) \qquad (2)$$

The second method is used in this paper since it is assumed that the capacity of a link is equal to the minimum capacity of each section of the link. That is any bridge that acts as a bottleneck determines the capacity of the section.

Finally, a correspondence between LDI and representative changes in traffic capacities is suggested by Shiraki et al (2007). Table 1 shows the reduction in capacity and free flow speed based on link damage status. In Shiraki's paper LDI is calculated using method 1; some modifications on LDI lower and upper bounds are done to make it applicable for method 2 as well. However, the values used here are just an expert guess and there is no data to back it up.

Table 1 Reduction in Link Capacity Based on Link Damage

Link Damage State	**LDI Lower Bound**	**LDI Upper Bound**	**Capacity (%)**	**Free-flow Speed (%)**
No damage	0.0	0.1	100	100
Minor damage	0.1	0.3	100	75
Moderate damage	0.3	0.75	75	50
Major damage	0.75	1	50	50

In summary, the supply side of transportation network is modelled by the capacity and free flow speed reduction consistent with the damage to the bridges. The severity of damage is determined by Hazus-MH using bridge fragility curves and the data for the earthquake scenario. The effect of this damage on the capacity and free flow speed of transportation links is estimated using the models presented by Shiraki et al (2007) considering the damage state determined from the Hazus-MH analysis.

2.2 Demand

To determine demand for transportation of casualties to medical facilities, the number and severity of casualties for each census tract are estimated using Hazus-MH. Four levels of severity are defined for casualties labelled 1 through 4. By definition, severity levels 2 and 3 need hospitalization. So, predicting the number of medical trips in this analysis is based on summation of the number of level 2 and level 3 casualties. After finding the total number of people that need to be transferred to medical centres in each census tract, the hourly number of trips to transport all the injured is needed. The hourly distribution (by percentage) of people extracted from damaged structures and transported is investigated for Kobe earth quake by Kuwata and Takada (2004). The maximum hourly percentage of excavated people is 15% of the total injured. In this paper a scenario with 15% of total demand is explored to see the effects on the network.

It is assumed that there are a sufficient number of ambulances to serve the hourly demand. Two trips, one from and one to the medical centres, for each injured person are loaded on the network to represent the transportation of injured to medical centres after earthquake. The shortest path is used to find the route from each origin (census tract) to medical centres as destinations. The transportation system with only the demand for these medical trips is modelled first on the undisrupted network then on the damaged network; travel time between each census tract and the associated medical centre is calculated and compared for undisrupted and damaged network. A network performance measure, Disruption Index (DI), is defined based on this travel time:

$$DI = \frac{\sum_{j \in M} \sum_{i \in N} (t'_{ij})}{\sum_{j \in M} \sum_{i \in N} (t_{ij})} \qquad (3)$$

In which t'_{ij} is the travel time between zones in the damaged network and t_{ij} is the travel time between zones in the undisrupted network. N is the set of origins and M is the set of destinations. This is similar to the Degradation Index which is the ratio of sum of shortest distances between nodes for the damaged network over the same parameter for the undisrupted network (Chang et al, 2000) but captures both changes in supply and demand.

Another performance measure is delay. In this study, delay is the difference between travel time for the undisrupted and the damaged network. Total Delay (TD) is the difference of these two travel times for all origin and destination zones times the number of trips between these two zones.

$$TD = \sum_{j \in M} \sum_{i \in N} (t'_{ij} - t_{ij}) * V_{ij} \qquad (4)$$

In which t'_{ij}, t_{ij}, N, and M are the same as Equation (3) and V_{ij} is the number of trips between zone j and zone j.

3 CASE STUDY

The City of Newark, Delaware, United States is used to explore the changes in transportation demand and supply following an earthquake. Newark is home to the University of Delaware and its 21,000 students. The city has as a population around 31,000 and covers about 23 square kilometres. This city, bordered by the states of Maryland, New Jersey and Pennsylvania, is located in the Mid-Atlantic region of the east coast of the United States, which is not an earthquake prone area. The historical earthquake data for this area is trivial (the most recent event being the minor tremors from the 5.8

Virginia earthquake in August 2011), but the authors' knowledge of the network, and ability to check the results were important factors in choosing this area. Moreover, this manageable relatively small area helps in controlling results for this first simulation attempt. This work can be expanded for a larger area with actual historical earthquake data in future.

The selected area comprises 9 census tracts. The hospital that serves as the destination of the trips is not located in the city. The study area is the city of Newark and supply and demand changes are taken into account for the nine census tracts in the city, but the transportation network has been modelled for the greater area which includes the hospital. The study area with the numbered tracts is shown in Figure 1. Each census tract is considered as a traffic zone in this research and the trips between zones are studied. The network was coded and modelled using VISUM, a software system for transportation planning, travel demand modelling and network data management.

Hazus-MH was used to determine the number of casualties for each census tract and the damage to bridges. For the simulated earthquake a total of 623 injuries of severity level 2 and 3 were incurred. Table 2 shows the number casualties level 2 and 3 for each census tract. Fifteen percent of this number is considered for maximum hourly traffic from each zone to zone 90012 in which the hospital, as the destination, is located. Moreover, assuming that all these trips are done by ambulances sent from the hospital, the same number (15% of total casualties) is considered for the hourly demand from zone number 90012 to each zone in the city.

Hazus-MH also indicated that 13 bridges were damaged. The damage state (None, Slight, Moderate, Extensive, and Complete) for each damaged bridge in the study area is shown in Table 3. The reduced capacity and free flow speed for the links the damaged bridges are located in is calculated based on the method explained previously.

The transportation system is modelled in VISUM, the travel demand modelling component of the integrated transportation planning suite ptv vision®. VISIM applies the shortest path method to assign the trips to the network. Ambulances are the only mode used in this model. Travel times between zones for undisrupted and damaged network, generated by VISUM, are shown in Tables 4 and 5 respectively. For this scenario Total Delay equals to 183 Minutes and Disruption Index is 1.13.

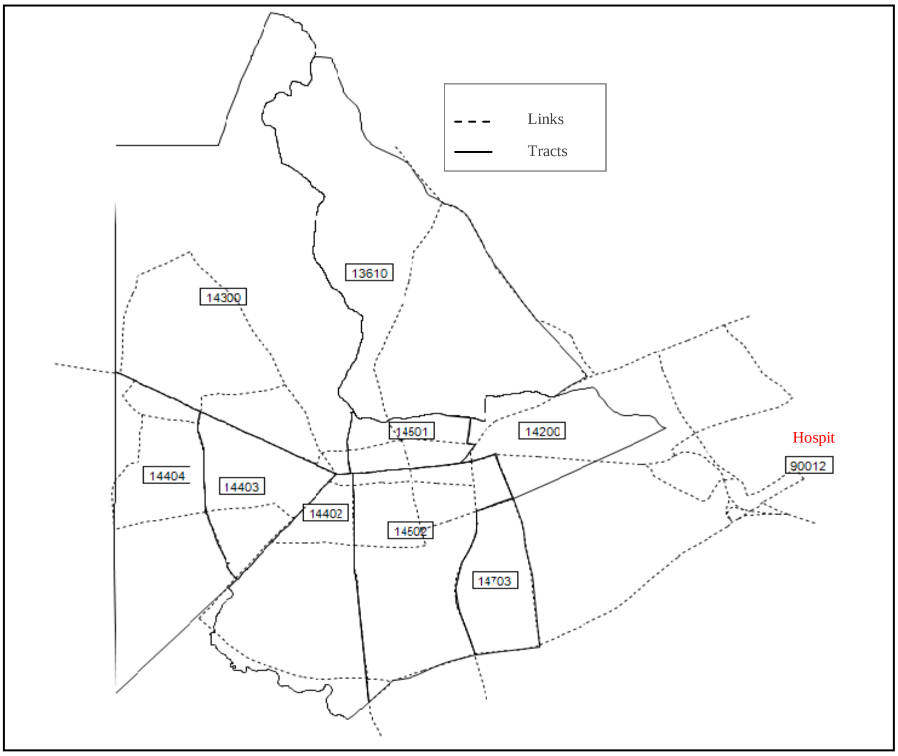

Figure 1 Study Area with Tracts Numbers

Table 2 Number of Casualties for Each Census Tract

Census Tracts	Casualties (level2+level3)
13610	79.1
14200	25.4
14300	84.1
14402	55.0
14403	90.1
14404	46.8
14501	26.5
14502	153.7
14703	62.3

Table 3 Damage State Probability for Damaged Bridges

Bridge No	Tract	None	Slight	Moderate	Extensive	Complete
1	14402	0.41	0.13	0.12	0.18	0.16
2	14200	0.01	0.04	0.06	0.20	0.68
3	14501	0.39	0.15	0.12	0.18	0.16
4	14300	0.41	0.15	0.12	0.17	0.15
5	14300	0.40	0.15	0.12	0.18	0.16
6	14404	0.40	0.15	0.12	0.18	0.16
7	14402	0.39	0.00	0.00	0.25	0.36
8	14404	0.42	0.14	0.12	0.17	0.15
9	14502	0.35	0.00	0.00	0.25	0.40
10	14502	0.36	0.00	0.00	0.25	0.38
11	14200	0.42	0.08	0.12	0.19	0.19
12	14200	0.42	0.08	0.12	0.19	0.19
13	14403	0.32	0.00	0.00	0.25	0.43

As expected, the results show small changes in travel time between zones (less than 2 minutes). The analysis does show that it is possible to model changes in demand, and the interaction with changes in supply and evaluate network performance. The effects of a damaged transportation network on delays and consequently the survival rate cannot be explored for this case study since the demand is very limited relative to a normal day peak hour. The available survival rate versus time models are very crude and use time intervals of the order of 10 hours (Fiedrich et al, 2000). More accurate models needed to show the potential human loss due to delay for this case.

Table 4 Travel Time between Zones for Undisrupted Network (Minutes)

10 x 10			13610	14200	14300	14402	14403	14404	14501	14502	14703	90012
	Name											
		Sum	44.09	35.07	42.95	27.21	28.51	36.11	26.35	21.89	44.39	59.41
13610		46.88	0.00	5.49	6.09	4.54	4.95	6.06	2.93	3.65	6.66	6.52
14200		32.08	4.78	0.00	5.38	3.10	3.53	4.64	2.31	1.42	2.71	4.20
14300		44.23	6.09	5.47	0.00	3.88	2.89	2.71	3.62	4.10	6.64	8.84
14402		27.95	4.29	3.29	3.88	0.00	0.92	2.03	1.82	0.60	4.46	6.66
14403		28.91	4.81	3.83	2.89	0.92	0.00	0.35	2.34	1.56	5.01	7.21
14404		36.66	5.92	4.94	2.87	2.03	0.35	0.00	3.45	2.67	6.12	8.32
14501		29.49	2.93	3.02	3.62	2.07	2.49	3.60	0.00	1.18	4.20	6.39
14502		25.66	3.84	1.96	3.61	0.60	2.47	3.58	1.38	0.00	3.02	5.21
14703		37.23	5.23	2.82	5.83	3.56	3.98	5.09	2.77	1.88	0.00	6.08
90012		56.88	6.20	4.25	8.79	6.52	6.94	8.05	5.73	4.84	5.57	0.00

Table 5 Travel Time between Zones for Damaged Network (Minutes)

10 x 10			13610	14200	14300	14402	14403	14404	14501	14502	14703	90012
	Name											
		Sum	59.1	35.8	46.1	30.4	31.7	39.5	29.5	25.1	48.1	68.1
13610		61.2	0.0	5.1	8.2	6.6	7.1	8.2	5.0	5.7	8.8	6.5
14200		33.5	5.1	0.0	5.4	3.1	3.5	4.6	2.3	1.4	2.7	5.3
14300		47.6	8.2	5.5	0.0	3.9	2.9	2.9	3.6	4.1	6.6	9.9
14402		31.1	6.4	3.3	3.9	0.0	0.9	2.0	1.8	0.6	4.5	7.7
14403		32.1	6.9	3.8	2.9	0.9	0.0	0.4	2.3	1.6	5.0	8.3
14404		39.9	8.0	4.9	2.9	2.0	0.4	0.0	3.5	2.7	6.1	9.4
14501		32.7	5.0	3.0	3.6	2.1	2.5	3.6	0.0	1.2	4.2	7.5
14502		28.9	5.9	2.0	3.6	0.6	2.5	3.6	1.4	0.0	3.0	6.3
14703		40.4	7.3	2.8	5.8	3.6	4.0	5.1	2.8	1.9	0.0	7.2
90012		66.1	6.2	5.3	9.9	7.6	8.0	9.1	6.8	5.9	7.2	0.0

4 CONCLUSIONS

The changes in the supply side of the transportation network and the demand for transporting injured people to medical centres after an earthquake are studied in this paper. For simulating the changes in supply side the damage to bridges in the study area are considered and the consequent capacity and free flow speed reduction for the link including that bridge is estimated.

For demand side, it is assumed that the only demand is the patients' transportation trips. Number of casualties is estimated for each census tract and the hourly demand is calculated based of total number of casualties.

Travel time between traffic zones for the study area is the output of the model which does not show a big difference comparing undisrupted and damaged network. The reason is that the demand for the transportation network is much greater than just medical trips, the damage is relatively minor and the network has evolved to serve much larger demands under normal conditions. The transportation network system may be robust enough to handle just the medical trips even for big earthquakes but adding other trips (emergency responders' and individuals') may make the network more congested.

This study is a first step in developing priorities for network improvements. In a realistic case, a set of representative scenarios with their probabilities will be chosen, each scenario will be run exactly the same as the earthquake scenario that has been used here, at the end the system performance index will be calculated for each scenario; applying the probability of each scenario, the annual probability of exceedence for different highway system performance level will be estimated. Understanding the level of consequences and their probabilities based on event experiences provides important quantitative information to decision makers. The development of effective and cohesive strategies that recognize both the changes in supply of and demand for transportation networks, is contingent on capturing the complexities presented because of the interrelationships among the network levels. The network level performance measures that capture these impacts add value to the analysis. Implementing a realistic scenario on a network in a seismically active region and comparing the results with actual experiences will be an important next step in this research.

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