Hazard Loss Estimation and Transport Network Reliability

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1 INTRODUCTION

During the last 35 years there has been growing concern about 'lifeline systems' (e.g. water supply, energy supply, sewage disposal, communication, and transportation systems) and their vulnerability to damage and disruption as a result of natural hazards (e.g. earthquakes, tsunamis, storms and flooding). While lifeline engineering initially focused on considering each lifeline system in isolation, a study of the inter-dependence of lifeline systems (Centre for Advanced Engineering, 1991; Hopkins et al., 1991) found that the transportation system is the most important lifeline system, because it facilitates:

- the evacuation of vulnerable areas prior to foreseeable events (e.g. storms, flooding);
- the provision of medical and other assistance to people in areas affected by disasters;
- the movement of people and equipment to areas affected by disaster, to restore other lifeline systems.

Lifeline engineering initially focused on reducing the expected costs of repairs to lifeline systems, through relocating and/or strengthening lifeline systems, but these costs are invariably much smaller than the other costs (e.g. the cost of temporary works and increased user costs during the period of disruption). For instance, Yee et al. (1996) found that the cost of motorist delay associated with the closure of Interstate Highway 10 after the 1994 Los Angeles (Northridge) earthquake, even after the establishment of detours around closed highway facilities and carpool lanes, plus the enhancement of rail and bus services, was almost US$1 million per day. In addition, the socio-economic costs due to the disruption of commercial traffic movements and business are also likely to be much greater than the direct cost of replacing damaged infrastructure. For instance, the business interruption losses resulting from the collapse of the World Trade Center buildings were estimated (Münchener Rück, 2001) to "far exceed" the cost of replacing the structures and the equipment in them).

Risk management has been used for assessing transport network reliability for some time (e.g. Nicholson and Dalziell, 2001; Dalziell and Nicholson, 2001), who noted that a considerable effort is needed to estimate the probabilities of hazard events and transport network degradation. This was seen as a potential impediment to widespread use of risk management for assessing transport network reliability. Recent years have, however, seen considerable growth in several countries in the development and implementation of risk management methods for use by Government and other organisations responsible for preparing for and responding to the occurrence of natural hazards.

At the same time, there has been growing interest in developing and implementing appropriate methods for the analysis and design of transport networks to improve their reliability. These two areas of activity have generally been quite separate, and the aim of this paper is to review developments in natural hazards risk management, with a view to demonstrating the considerable potential for collaboration and 'cross-fertilization' between the two areas of activity.

The paper starts with an overview of four models developed for assessing and mitigating the impact of natural hazards. Two models are then described in more detail, with particular attention to how they address issues related to transport network reliability. The paper then describes research which shows that a cost-reliability relationship, used by Nicholson (2007) in a study of transport network reliability improvement, is consistent with relationships developed from empirical data and implemented in natural hazards risk management models. The paper concludes with comments on the value of greater collaboration and cross-fertilization' between the transport network reliability area and the natural hazards risk management area.

2 NATURAL HAZARDS RISK MANAGEMENT MODELS

2.1 HAZUS-MH MODEL

The HAZUS-MH model is an empirical model, based on observation and experiment, for estimating potential damage and loss associated with three types of natural hazard (earthquakes, hurricane winds and floods). It has been developed for/by the U.S. Federal Emergency Management Agency (FEMA). It is designed to be a nationally applicable standardized methodology, and uses state-of-the-art Geographic Information Systems (GIS) software to map and display hazard data, plus the results of damage and economic loss estimates for buildings and infrastructure. It also allows users to estimate the impacts of earthquakes, hurricane winds, and floods on the physical, social and economic vitality of a community (FEMA, 2009).

The HAZUS-MH earthquake model (FEMA, 2003) was the first in the HAZUS suite, and it provides estimates of damage and loss to buildings, and essential facilities, including transportation networks. The model allows the estimation of losses associated with earthquake damage to building, utilities and transportation systems, using estimates of the ground motion (characterised by the peak ground acceleration and/or the peak ground velocity and/or the permanent ground deformation and/or the ground acceleration at specified frequencies), fragility curves (to estimate the damage) and restoration curves (to estimate the duration of degradation). The direct and indirect socio-economic costs are then estimated. A more detailed description of the earthquake model is given below.

The HAZUS-MH models are largely focused upon estimating the direct costs of disasters, with little attention to the impact of damage to particular links of a network on the performance of the whole network.

2.2 REDARS MODEL

The REDARS (Risks from Earthquake Damage to Roadway Systems) has been developed by the Multidisciplinary Centre for Earthquake Engineering Research (MCEER) for the Federal Highway Administration (FHWA) in the USA since the mid-1990s (Werner et al., 2004). It uses models to estimate:

- the seismic hazards (ground motion, liquefaction, surface fault rupture) throughout the system;
- the resulting damage states (damage extent, type, and location) for each component in the roadway system;
- for each component, how the damage will be repaired, the repair cost, the 'downtime', and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake).

The aim of REDARS is to allow users to evaluate and prioritize:

- pre-earthquake seismic-risk-reduction strategies (e.g. strengthening of particular bridges, construction of new links to increase redundancy in the transportation system);
- post-earthquake emergency-response strategies (e.g. traffic management, emergency bypass road construction);

to improve traffic flows after a major earthquake and reduce the associated losses (Werner et al., 2004).

While this model is focused on the effect of earthquakes on highways, it incorporates a more comprehensive network analysis method (a highway-network link-node model), in order to form a set of system-states that reflect the extent and spatial distribution of link closures at various times after the earthquake, and estimate how closures affect system-wide travel times and traffic flows. In addition, this model is being extended to include variable travel demand and freight flow impact assessment. A more detailed description of the model is given below.

2.3 MIRISK MODEL

The MIRISK (Mitigation Information and Risk Identification System) model has been developed at Kyoto University, in the Urban Management Department's Research Laboratory for Lifeline Engineering & Earthquake Disaster Prevention Systems (Mina et al. 2008). The project has been funded by the World Bank in agreement with the Alliance for Global Open Risk Analysis (AGORA).

This model provides a tool for the assessment the effect of a range of natural hazards (namely, earthquakes, typhoons, flooding and volcanic eruptions) on the performance of buildings and transportation networks under natural hazards. The aim is to support decision making on strategies to mitigate risk, especially in relation to development projects, by:

- identifying natural hazards affecting a region;
- defining the kinds of infrastructure that make up typical development projects;
- describing the vulnerability of these assets to natural hazards, and how vulnerability can be reduced;
- analyzing the natural hazards and vulnerability data, to assess whether projects should follow normal design practices, or whether the cost of some enhanced design for natural hazards is justified by the benefits (of avoided losses).

The MIRISK model allows decision makers to quickly assess whether the risk associated with a hazard is very significant in a region where a development is planned. If so, MIRISK provides information on what can be done, and permits estimation of the added cost to guarantee a moderate level of protection from the hazard. It can also help identify the "optimum" level of enhanced construction to mitigate the risk, based on the nature of the hazard and the type of facility, and the project's benefit-cost ratio (where benefit, including some monetised estimate of future social benefits, is divided by the total cost, including the indirect costs of damage).

2.4 RISKSCAPE

The RiskScape model is a multi-hazard risk/loss modelling system being developed by the Institute of Geological and Nuclear Sciences (GNS Science) and the National Institute of Water and Atmospheric Research (NIWA), in collaboration with the University of Canterbury, Massey University and GeoScience Australia. The main goal of Riskscape is to develop and implement a decision-support tool to estimate the likely consequences of multiple hazards. RiskScape currently focuses on five natural hazards: river floods, earthquakes, volcanic eruptions (ashfall), tsunamis and wind storms. Snow, landslides (both rainfall and earthquake triggered), storm surges, pyroclastic flows and lahars, plus climate change effects, will be included as part of the future development of the project.

RiskScape allows the quantification of a range of consequences (including direct damage, replacement costs, casualties, number of people that may need evacuation or medical assistance, plus indirect effects such as disruption to transport and tourism) across a range of communities and assets (buildings and infrastructure, including lifeline utilities and the transport network).

RiskScape is intended to provide end-users (e.g. governmental bodies, civil defence managers, decision makers, urban planners, etc.) with specific information to support the:

- prioritizing of risk-reduction and mitigation measures;
- assessment of the best use of risk-reduction investment;
- effectively managing emergencies;
- planning for land use;
- improvement of building codes and design;
- identification and quantification of risk in their region/town;
- planning for evacuation & contingency;
- raising of risk awareness in the local authorities and in the public;
- creating realistic scenarios for exercises.

The RiskScape model development is taking account of overseas experience with such models (e.g. HAZUS-MH) and the perceived end-user requirements. Preliminary results are summarised in Giovinazzi and King (2009a and 2009b).

3 HAZUS-MH EARTHQUAKE MODEL

The HAZUS-MH earthquake model provides an earthquake loss estimation method for:

- buildings (residential and commercial);
- utility systems (water supply; waste water collection/treatment; oil, gas and electricity distribution; communications);
- transportation systems.

Seven transportation systems are considered:

- Highways (roadways, bridges and tunnels);
- Railways (tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities);
- Light Rail (tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities and DC power substations);
- Buses (maintenance, fuel, and dispatch facilities);
- Ports (waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses.
- Ferries (waterfront structures (e.g., wharf, piers and seawalls); fuel, maintenance, and dispatch facilities; and passenger terminals.
- Airports (runways, control tower, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures.

The basic methodology involves estimating:

- the potential earth science hazard;
- the direct physical damage;
- the induced physical damage (e.g. fire following an earthquake which results in damage to the gas reticulation system);
- the direct socio-economic losses (i.e. facility repair or replacement costs, temporary housing costs);
- the indirect socio-economic losses (e.g. business disruption costs, unemployment costs).

The loss estimation methods for the different transportation systems are essentially the same, and the method for highways is described below.

Roadways are classified as:

- major roads (i.e. interstate and state highways and other roads with four lanes or more);
- urban roads (i.e. intercity and other roads with two lanes).

Bridges are classified (there are 28 bridge types) according to:

- whether it has been designed for seismic loading;
- the number of spans and span continuity (e.g. simply supported, continuous, etc.);
- the type of structure (e.g. concrete, steel, etc.);
- the type of pier (e.g. single or multiple columns, pier walls);
- the type of abutment (monolithic or non-monolithic);
- the type of bearing (e.g. high or low bearings, bearing material).

Tunnels are classified as:

- bored/drilled;
- cut & cover.

The HAZUS-MH earthquake model defines the potential earth science hazard (PESH) as follows:

- for roadways ~ the permanent ground deformation (PGD) at the roadway location;
- for bridges ~ the spectral accelerations (Sa) at 0.3 sec and 1.0 sec, the PGD and the peak ground acceleration at the bridge location;
- for tunnels ~ the PGA and PGD at the tunnel location.

These hazard indicators must be predicted from knowledge of earth science (i.e. the location of potential earthquakes, the energy released, and the propagation/attenuation of the earthquake energy waves).

The model categorises the physical damage to components of the highway system as follows; none (DS_1), slight/minor (DS_2), moderate (DS_3), extensive (DS_4) and complete (DS_5). The probability of the damage state equalling or exceeding a specified level (i.e. the 'exceedance probability') is described by a log-normal distribution (called a 'fragility curve'). This defines the conditional probability of reaching or exceeding the specified damage state, DS_i, given the value of the appropriate PESH parameter (k), as follows:

$$P_E\left(DS_i \mid k\right) = \Phi\left[\left(1/\beta_{DS_i}\right) log_e\left(k / k_{M,DS_i}\right)\right] \tag{1}$$

where $k_{M,DSi}$ is the median value of k at which the facility reaches the threshold of damage state, DS_i;
β_{Dsi} is the standard deviation of the natural logarithm of k for damage state, DS_i;
Φ is the standard normal cumulative distribution function.

Table 1 shows the median ground motion parameter and a dispersion parameter provided by HAZUS-MH for urban and major roads, while Figure 1 shows examples of HAZUS-MH fragility curves for major roads.

	Damage State	Median PGD	Dispersion
Major Road	DS_2: slight/minor damage	12	0.7
	DS_3: moderate damage	24	0.7
	DS_4: extensive/complete	60	0.7
Minor Road	DS_2: slight/minor damage	6	0.7
	DS_3: moderate damage	12	0.7
	DS_4: extensive/complete	24	0.7

Table 1: Median PGD and dispersion for each damage state.

The assessment of the expected economic losses, for each component of the transportation network, requires the computation of a 'compounded damage ratio' (DR_c) which is defined as follows:

$$DR_c = \sum_{i=2}^{5} \left[DR_i \times P\left(DS_i \mid k \right) \right] \tag{2}$$

where DR_i is the damage ratio for each damage state DS_i and $P(DS_i \mid k)$ is the probability of being in a particular damage state (calculated from the exceedance probabilities). Note that the summation is from 2 to 5, as there are no losses are associated with damage state DS_1. The expected economic losses are obtained by multiplying the compounded damage ratio (DR_c) by the replacement value.

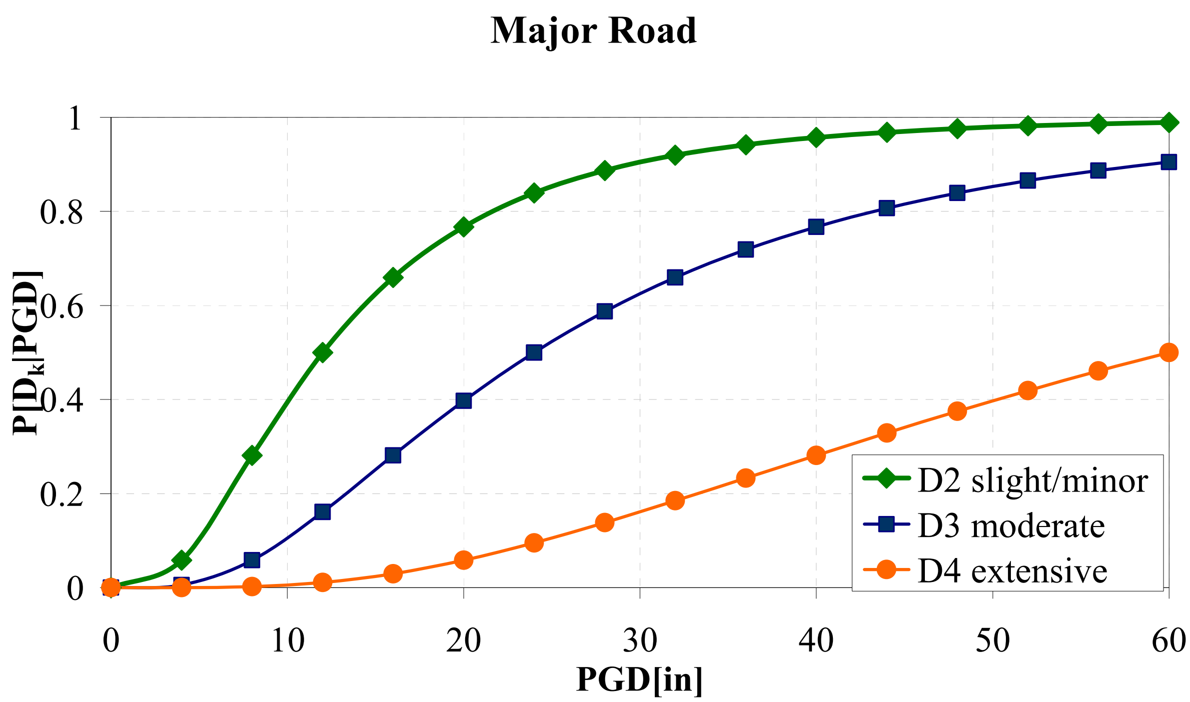

Figure 1: Fragility curves for major roads after HAZUS-MH earthquake model (FEMA 2003).

The impact of damage to a facility depends upon the 'functionality' of the facility in the period after an earthquake. The functionality depends upon the probability of each possible damage state immediately after an earthquake and the associated fraction of the component that is expected to be functional after specified periods of time. The latter is defined by 'restoration curves', which are provided within the HAZUS-MH earthquake model for each facility type for each damage state, and are based on empirical data relating to the repair of damaged facilities after earthquakes in the past. The restoration curves are cumulative normal curves, characterized by given means and standard deviations. Figure 2 shows examples of HAZUS-MH restoration curves that are assumed to be the same for major and urban roads.

The HAZUS-MH suite of models uses GIS software to map and display hazard data, plus the results of damage and economic loss estimates for buildings and infrastructure. The earthquake model requires an inventory of buildings, utility systems and transportation system, that includes the geographical location, type and replacement cost of all facilities comprising the systems. The inventory data allow estimation of:

- the potential earth science hazard for each facility;
- the level of damage for each facility (using the appropriate fragility curve);
- the functionality of each facility over time (using the appropriate restoration curve);
- the direct socio-economic costs (using the replacement cost and the level of damage for each facility);

- the indirect socio-economic costs (this is done using classical input-output economic models).

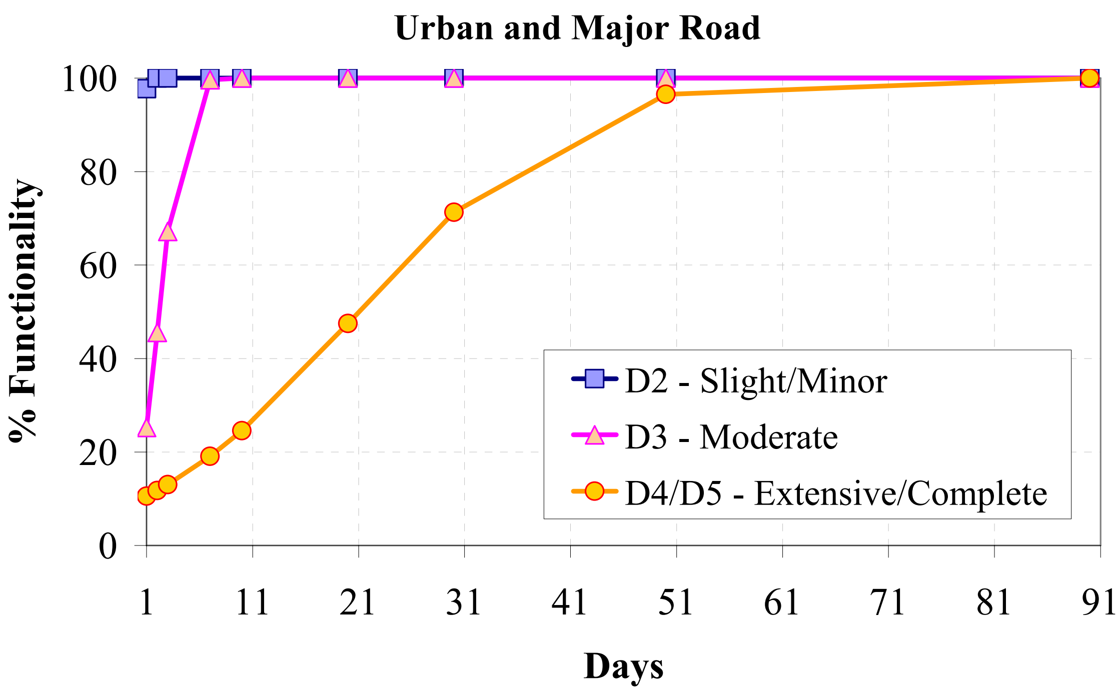

Figure 2. Restoration curves for roads after HAZUS-MH earthquake model (FEMA 2003).

It should be noted that the fragility and restoration curves are based on a combination of expert judgement and empirical data relating to previous earthquakes, most of the replacement costs are based on estimates of the Applied Technology Council (1985 and 1991). It should also be noted that the HAZUS-MH earthquake loss estimation model does not allow for any inter-dependence of the components of the transportation systems on the functionality of the complete systems.

4 REDARS TRANSPORT MODELLING

REDARS contains two transportation network analysis methods (Werner et al., 2004). A standard user equilibrium (UE) method is used for 'deterministic' seismic risk analysis for a limited number of earthquake scenarios. This provides an exact mathematical solution to an idealized model of user behaviour, which assumes that all users follow routes that minimize their travel times. There is considerable uncertainty regarding the damage to the transportation network after an earthquake, however, and the REDARS model has been extended to allow 'probabilistic' seismic risk analysis, which involves assessing the affect of many earthquake damage scenarios and developing a strategy for repairing damaged links.

This entails estimating network flows many times and the use of the standard user equilibrium method for this would be very time consuming. For instance, it takes about 150 s of CPU time on a personal computer to solve one user equilibrium problem, using the Frank-Wolfe algorithm, for the highway network of the San Francisco Bay area in California, with about 1,120 zones and 10,647 nodes (Naga and Fan, 2007). A method for obtaining rapid estimates of traffic flows in a large network was required, and resulted in the development of an Associative Memory (AM) procedure (Moore et al., 1997, Naga and Fan, 2007) and its implementation in REDARS.

Naga and Fan define the 'network recovery problem' (NRP) as being to determine an optimal repair strategy for a given damaged network, where the resources are limited and it is necessary to decide a priority ranking for repairing damaged links (if the resources are not limited, then the solution would be to repair all damaged links without delay). They suggest the NRP can be formulated as a bi-level problem, where:

- the upper-level problem is to determine the optimal repair decision (i.e. which damaged links to repair) such that the savings in total travel time are maximized and the total repair cost is not greater than the budget;
- the lower-level problem is to identify the UE traffic assignment minimizing travel time, for the various network configurations resulting from feasible repair decisions.

That is, the NRP is to identify the set of damaged links that, when repaired, will yield the maximum societal benefit under certain resource (budget) constraints.

They formulate the NRP as follows: identify the repair strategy X to maximise

$$TT\,(\Phi) - TT\,(X) \tag{3}$$

such that

$$C\,(X) \leq B \tag{4}$$

where X = binary vector (elements are 0 or 1) indicating the links to be repaired;
Φ = null vector (all elements are 0), representing 'no repairs';
$TT\,(X)$ = total travel time computed from UE model when strategy X is implemented;
$TT\,(\Phi)$ = total travel time computed from UE model when no links are repaired;
$C\,(X)$ = cost of implementing strategy X;
B = available repair budget.

Naga and Fan assumed that all links cost the same amount (C_0) to repair, so that the problem becomes one of determining which N (say) links should be repaired, such that:

$$\mathrm{N} \times C_0 \leq B \tag{5}$$

They also assumed that recovery of a link is a binary decision (i.e. partial recovery is not considered). Both these assumptions are strong assumptions, as it means links can only be fully open or completely closed, and this limits the usefulness of the research somewhat.

The Associative Memory (AM) procedure is based on Artificial Intelligence methods, and involves identifying the association between stimulus and response matrices (i.e. the network state and network flows, respectively). It entails two phases (training and testing):

- creating associative memory matrices, which relate 'known' stimulus and response matrices;
- using the associative memory matrices to estimate response matrices for stimulus matrices not used for training, and comparing the estimated network flows with 'known' network flows.

It should be noted that the AM procedure does not produce a relationship which can be described using an equation or equations (i.e. the relationship is not transparent and is a 'black box').

Naga and Fan (2007) report on the accuracy of the solutions to the NRP obtained using the AM approach, concluding that while the prediction errors were "reasonably low", the AM approach may be appropriate only in situations where it is necessary to "compromise on accuracy in exchange for computational time savings". They did conclude, however, that the AM approach does seem to perform far better than the traditional practice of using link flows to decide on which links to strengthen prior to an earthquake occurring and which damaged links to repair after an earthquake has occurred.

The REDARS model originally assumed the post-earthquake travel demand is the same as the pre-earthquake travel demand. That is, the travel demand was assumed not to depend upon the level of congestion and the cost of travel after an earthquake, with a traveller's route selection depending on route congestion, while the propensity to travel is unchanged. As noted by Nicholson and Dalziell (2001) and Nicholson and Dalziell (2001), estimates of the economic losses can be quite inaccurate if the elasticity of demand for travel is not taken into account. This will be particularly true after a major earthquake which results in closures of major roadway links within a heavily used road network. Under such conditions, post-earthquake trip demands can be expected to be much lower than pre-earthquake trip demands. It is interesting that the REDARS network analysis procedure has been upgraded to allow for an elastic demand for travel (Cho et al., 2003) and the fact that the economic losses will depend on the economic value of trips foregone because of damage to the highway system.

After a major earthquake, the spatial pattern of travel might be somewhat different to that before the earthquake, as a result of efforts to repair or replace damaged facilities. It appears that this is not allowed for in the REDARS model.

With the growing reliance upon just-in-time production methods, the effects of earthquake damage on freight flows are important. The original REDARS model assumed that freight traffic is simply a proportion of the total traffic (i.e. it was not possible to identify the specific effect on freight flows. This deficiency has been addressed in the later REDARS model, which includes a method for estimating freight O-D trip demands, using intra- and inter-regional commodity flow data by industrial sectors (Cho et al., 2001).

5 RELATIONSHIP BETWEEN COST AND RELIABILITY

The issue of prioritising links in a network for strengthening prior to a disaster or repairing after being damaged during a disaster, in order to maximise 'terminal reliability', has been addressed by Nicholson (2007). He assumed proposed a 'cost-reliability function' as follows:

$$C_a = -S_{ao}\ ln(1 - r_a) + C_{ao} \tag{6}$$

where C_a is the cost of providing a link (a) with a reliability r_a ($0 \le r_a \le 1$);
S_{ao} is a positive constant;
C_{ao} is a non-negative constant and is the value of C_a when r_a equals zero.

It can be seen C_a increases as r_a increases, and it follows that the marginal cost (dC_a) of a marginal improvement (dr_a) in the reliability of link a increases as r_a increases, as follows:

$$dC_a = \frac{S_{ao}}{(1 - r_a)}\, dr_a \tag{7}$$

Note that dC_a equals ($S_{ao}dr_a$) when r_a is zero, and tends to infinity as r_a tends to unity.

Nicholson found that while "intuitively, it would seem reasonable to measure the importance of a component in contributing to system reliability by the rate at which system reliability improves as the reliability of the component improves" (Barlow and Proschan, 1975), for a simple network with two parallel links, the 'reliability importance index' of Birnbaum (1969):

$$RI_a = \frac{\partial R}{\partial r_a} \tag{8}$$

where R is the system reliability, indicates that one should improve the reliability of the more reliable link.

Nicholson suggested that while this result may be considered counter-intuitive, it is not inconsistent with what happens in practice, if there is a motorway and parallel arterial routes in a corridor. In such circumstances, the motorway authority might well argue that it is necessary to improve the motorway, to ensure it remains open, even though it is less likely to be degraded or closed than are the neighbouring parallel arterial routes. The rationale for this is that motorways are very important 'lifelines' during emergencies and it is especially important that they are not severely degraded or closed. He also suggested that further research is required to identify the cost-reliability function, and research to identify how the cost-reliability function relates to the relationships within the HAZUS-MH earthquake model is now described.

Assuming that the reliability of a road component is given by the probability of damage not exceeding damage state DS_2 (i.e. slight/minor damage), plots of the HAZUS damage ratio versus reliability were drawn for major and minor roads. The process for doing this comprised the following steps:

- determine the fragility functions using the median ground motion parameter and a dispersion parameter provided by HAZUS-MH for urban and major roads (see Table 1), giving fragility curves as shown in Figure 1;
- calculate the compounded damage ratio (DR_c) as a function of PGD, by combining the probability of reaching each damage state with the default value of damage ratio for each damage state, as provided in HAZUS-MH (DR_i = 0.05, 0.2 and 0.7 for i = 2, 3 and 4, respectively, for both major and minor roads);
- plot the compounded damage ratio (DR_c) versus the reliability (i.e. the probability of the damage state not exceeding DS_2), as shown in Figure 3.

Figure 3 also shows the cost-reliability curve proposed by Nicholson (2007). In order that the cost lie in the same range (zero to unity) as the compounded damage ratio, the value of C_{ao} was set to zero and the value of C_a was divided by $(C_a)_{max}$ (i.e. the maximum value of C_a obtained for the reliability $r_a \cong 1$). It should be noted that the 'normalising' of the cost-reliability relationship means that the relationship is not sensitive to variation in the value of S_{ao}. It can be seen that there is a good agreement between the HAZUS-MH curves and the cost-reliability relationship proposed by Nicholson.

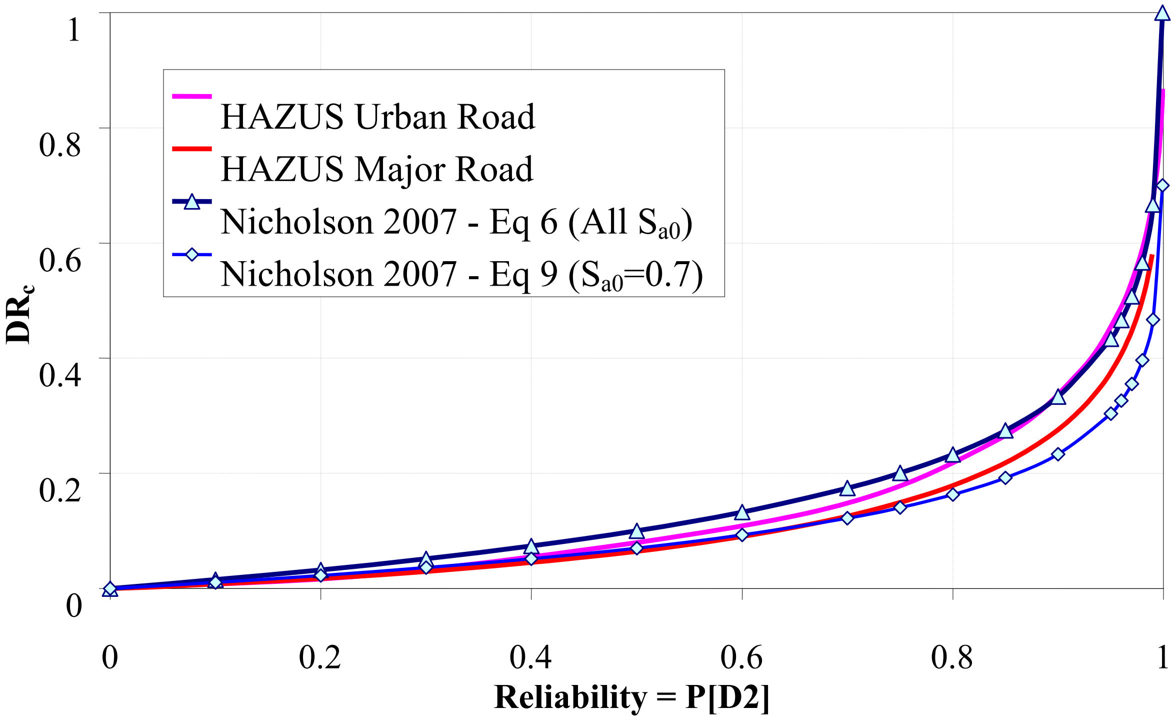

Figure 3: HAZUS-MH (FEMA 2003) Damage Ratio v. Reliability curves for major and minor roads, compared with Nicholson (2007) Cost-Reliability functions (Eq.6 and Eq.9).

To assess the effect of variation in the value of S_{ao} a different formulation of the cost-reliability relationship was developed. The re-formulated relationship

$$C_a = S_{ao}\left[\frac{ln(1-r_a)}{(C_a)_{max}}\right]+C_{a0} \tag{9}$$

is also shown in Figure 3, for S_{ao} = 0.7. It can be seen that this re-formulated cost-reliability relationship means that the value of S_{ao} can varied to maximise the agreement between the HAZUS-MH and cost-reliability curves.

6 CONCLUSION

It is clear that those involved in natural hazards risk management have made considerable efforts to improve the methods for assessing the probability of natural hazard events (i.e. earthquakes, hurricanes and floods). There has recently been more attention given to improving the assessment of the consequences of such events, including developing more appropriate methods for identifying the effect on the performance of the transport network. Given the growing concern about greenhouse gas emissions and an increase in extreme weather events, it is likely that those efforts will continue, and that natural hazards risk management methods will implemented more widely by governmental and other bodies.

It is also clear that making transport systems more robust and less vulnerable to natural hazards will assist considerably in reducing the impact of natural hazards, and an increase in the demand for expertise in the analysis, design and management of transport networks is therefore likely. One area where there appears to be substantial scope for such expertise to be applied is developing sound and robust methods for predicting transport demand and network performance. Another is the development of techniques for taking proper account of inter-dependencies within the transport system, and between the transport and other lifeline systems.

It appears that estimation of the probabilities of hazard events and transport network degradation is not such an impediment to using of risk management methods as it appeared to be. It also appears that the cost-reliability relationship used by Nicholson (2007) is consistent with relationships developed in the natural hazards risk management area, and based on empirical data. This suggests that the paradoxical result that one should strengthen the more reliable of two parallel paths, to maximise the improvement in network reliability, is not the consequence of using an inappropriate cost-reliability relationship.

Finally, this research has shown that there is considerable scope for collaboration and 'cross-fertilization' between the areas of natural hazards risk management and transport network reliability.

7 REFERENCES

Applied Technology Council (1985). *Earthquake Damage Evaluation Data for California*. Report ATC-13, Applied Technology Council, Redwood City, CA, U.S.A.

Applied Technology Council (1991). *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*. Report ATC-25, Applied Technology Council, Redwood City, CA, USA.

Barlow, R.E. and Proschan, F. (1975). *Statistical Theory of Reliability and Life Testing: Probability Models*. Holt, Rinehart and Winston, New York, USA.

Birnbaum, Z.W. (1969). On the Importance of Different Components in a Multi-Component System. *Multivariate Analysis II* (ed. P.R. Krishnaiah), Academic Press, New York, USA.

Centre for Advanced Engineering (1991). *Lifelines in Earthquakes: Wellington Case Study*, University of Canterbury, Christchurch, NZ.

Cho, S.C., Gordon, P., Moore, J.E., Richardson, H.W., Shinozuka. M. and Chang, S.E., (2001). Integrating Transportation Network and Regional Economic Models to Estimate the Cost of a Large Urban Earthquake. *Journal of Regional Science*, 41 (1): 39-65.

Cho, S.C., Fan, Y.Y. and Moore, J.E., (2003). Modeling Transportation Network Flows as a Simultaneous Function of Travel Demand, Earthquake Damage, and Network Level Service. *Proceedings of 6th U.S. National Conference on Lifeline Earthquake Engineering*, Long Beach, CA, U.S.A.: 868-877.

Dalziell, E.P. and Nicholson, A.J. (2001). Risk and impact of natural hazards on a road network. *Journal of Transportation Engineering*, 127 (2): 159-166.

FEMA (2003). *HAZUS-MH Multi-hazard loss estimation methodology, Earthquake Model - Technical Manual.* Federal Emergency Management Agency. Department of Homeland Security, Washington D.C., U.S.A.

FEMA (2009). *HAZUS-MH Overview: What Could Happen?* Federal Emergency Management Agency. Department of Homeland Security, Washington D.C., U.S.A.

Giovinazzi S. and King A. (2009a). Estimating seismic impacts on lifelines: an international review for RiskScape. *Proceeding of NZSEE 2009 New Zealand Society for Earthquake Engineering Annual Conference*, Christchurch, NZ.

Giovinazzi and King, A. (2009b). Toward the Seismic Performance Assessment of Lifelines within the Regional RiskScape Model in New Zealand. *Proceedings of 13th Italian Conference on Earthquake Engineering, ANIDIS 2009,* Bologna, Italy.

Hopkins, D.C., Lumsden, J.L. and Norton, J.A. (1991). Wellington's lifeline in earthquakes project: an outline of a major review. *Proceedings of 3rd US Conference on Lifeline Earthquake Engineering*, Los Angeles, American Society of Civil Engineers.

Mina C., Kobayashi K., Scawthorn C. and Porter K. (2008). Open Risk Analysis Software: Data and Methodologies. Japan Society of Civil Engineers, *Journal of Applied Computing in Civil Engineering*, 17: 1-12.

Moore, J.E., Kim, G., Cho, S., Hu, H.H, and Xu, R. (1997), Evaluating System ATMIS Technologies via Rapid Estimation of Network Flows: Final Report. PATH Report UCB-ITS-PRR-97-54, University of California (Berkeley), U.S.A.

Münchener Rück (2001). *11th September 2001.* Münchener Rückversicherungs-Gesellschaft, Munich, Germany.

Naga, P. and Fan, Y.Y. (2007). Quick Estimation of Network Performance Measures Using Associative Memory Techniques. *Transportation Research Record* 2039: 75 - 82

Nicholson, A.J. and Dalziell, E.P. (2001). Risk Evaluation and Management: A Road Network Reliability Study. *Proceedings of 1st International Symposium on Transport Network Reliability*, Kyoto, Japan.

Nicholson, A.J. (2007). Optimising Network Terminal Reliability. *Proceedings of 3rd International Symposium on Transport Network Reliability*, The Hague, The Netherlands.

Werner, S.D., Lavoie, J.P., Eitzel, C., Cho, S., Huyck, C., Ghosh,S., Eguchi, R.T., Taylor, C.E. and Moore, J.E.(2004). REDARS 1: Demonstration Software for Seismic Risk Analysis of Highway Systems. *Research Progress and Accomplishments Report 2001-2003*, Multidisciplinary Centre for Earthquake Engineering Research, State University of New York at Buffalo, U.S.A.: 17-34.

Yee, A., Leung, S.K. and Wesemann, L. (1996). The 1994 Northridge Earthquake: A Transportation Impact Overview. *Transportation Research Circular 462*, Transportation Research Board, Washington D.C., U.S.A.