

Transport Network Reliability in Seismic Risk Analysis and Management

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ABSTRACT:

The transportation network is a lifeline system whose vulnerability to earthquakes is of considerable concern due to its fundamental role for emergency management and the high interdependency with other lifeline systems. Major damage to the transport network can inhibit and significantly delay repairs to the other lifeline systems and affect the resilience response to earthquake events. Nonetheless, because of the complex nature of the phenomena and insufficient data, the implementation of transport network reliability analysis at the country-wide scale within seismic risk analysis has often been oversimplified. Specific objectives of this paper are: a) to review practices and models currently implemented for the assessment of the impact of earthquake events on transport networks; b) to critically discuss the assumptions behind the current practices and the applicability of the available approaches to managing the emergency, response and recovery phases following a seismic event.

Keywords: Transport network reliability, seismic risk assessment and management

1. INTRODUCTION

Recent disastrous seismic events have widely documented the crucial role of the transport network in the management of the emergency and in the facilitation of the response and recovery phases, including the restoration of other lifeline systems that is, clearly, very dependent upon people and equipment being able to move to the sites where damage has occurred (World Bank 2008). The growing concern for the impact that a reduced capacity of the transport network, among other lifeline systems, could have on the management and recovery following a disastrous event has heightened the interest in lifeline engineering and in approaches able to support the identification of proper mitigation and management strategies for lifeline systems (Pitilakis et al., 2006).

Despite the recognised potentialities of transport network reliability in supporting, on the one hand, the planning of mitigation activities before a seismic event, and, on the other hand, the emergency and response management after the occurrence of a seismic event (Nicholson and Du, 1997; Bell and Iida, 1997), its wide application for drafting civil defence plans and/or for managing real events is still rare.

This is because the assessment of network reliability following natural disasters is a complex issue that involves several physical and functional factors, which are not necessarily independent. Considering the case of seismic events, we can identify three main elements: 1) the physical impact of the earthquake on links and/or nodes (e.g. direct or indirect damage to the road component and partial/total obstruction of the road due to landslides, rock-falls, debris; etc.); 2) the consequent behavioral response of network users dealing with a degraded transport networks; 3) the goals that the road network is expected to meet under the different circumstances of the emergency management, response and recovery phases following a seismic event.

The specific objectives of this paper are: 1) to review practices and models currently implemented for the assessment of the impact of earthquake events on transport networks; 2) to critically discuss the

assumptions behind the current practices and the applicability of the available approaches to satisfactorily represent networks condition and functionality during the emergency management, response and recovery phases following a seismic event.

With reference to the physical impact on the transport network of the 6th April 2009 L'Aquila earthquake in Italy, Section 2 of the paper provides a short overview of available approaches for assessing the link/node probability of failure and/or degradation due to a seismic event. The third section discusses the possible response of network users to an unreliable network, while the fourth section analyses possible measures of network reliability, depending on the goals that the transport network is expected to meet during the emergency management, response and recovery phases following an earthquake.

2. ASSESSING THE PHYSICAL IMPACT OF THE EARTHQUAKE ON THE TRANSPORT NETWORK COMPONENTS

2.1 Physical impact on the transport networks following L'Aquila earthquake in Italy

The 6th April 2009 L'Aquila (Italy) earthquake provides an exhaustive example of the physical impact that a seismic event can have on the transport networks at urban and regional levels.

Following the main shock, the highways connecting L'Aquila with the Tyrrhenian and Adriatic coasts, (highway *A24 Roma-L'Aquila-Teramo* and highway *A25 Torano-Avezzano-Pescara*) were closed to allow for technical checks on the several multi-span viaducts. No signs of damage to the bridge decks near expansion joints, nor any spalling of concrete at the beam ends, was noticed in any of the viaducts, so the highways were re-opened to traffic within few hours.

At the urban and regional level, the only significant damage to road network components was the structural failure of the viaduct "Corfinio" on the national roadway SS5 and the collapse of a bridge on the main road SP36 "Forconese". No further significant damage was reported to the components of the road networks, with the numerous tunnels present in the region performing well.

Secondary effects caused the majority of disruptions to the roadway system at both the urban and regional levels (Dolce et al. 2009). In the mountainous areas around L'Aquila rock-falls (Figure 1a) and landslides (Figure 1b), triggered by the earthquake and aggravated by the heavy rain that hit the area in the days following the event, were identified as the most problematic situations affecting the network. In the urban area, mobility limitations were caused by debris from damaged and/or unsafe residential, office and monumental buildings adjacent to the roads (Figure 1c).



Figure 1. Impact of the earthquake on the road network: (a) SS80 "Gran Sasso d'Italia" rock falls, featuring rock-proof tunnels; (b) SS80 "Gran Sasso d'Italia" landslides triggered by the earthquake; (c) Immacolata Church in Paganica, L'Aquila debris and overturning façade affecting the mobility of the main adjacent road

Temporary traffic management measures were extensively implemented in L'Aquila in order to minimize the impact of road closures and to ensure the functionality of the roadways networks at the fullest possible extent; these measures included traffic flow restrictions, alternating one-way lanes and speed restrictions (Figure 2a). Immediate activities for the restoration of normal mobility conditions

were started a few days after the main shock, including: (a) the removal of rocks and soil from the roads; (b) rock slope consolidations; (c) enhancement of soil slope stability; (d) securing of unsafe buildings adjacent to roads (Figure 2b).

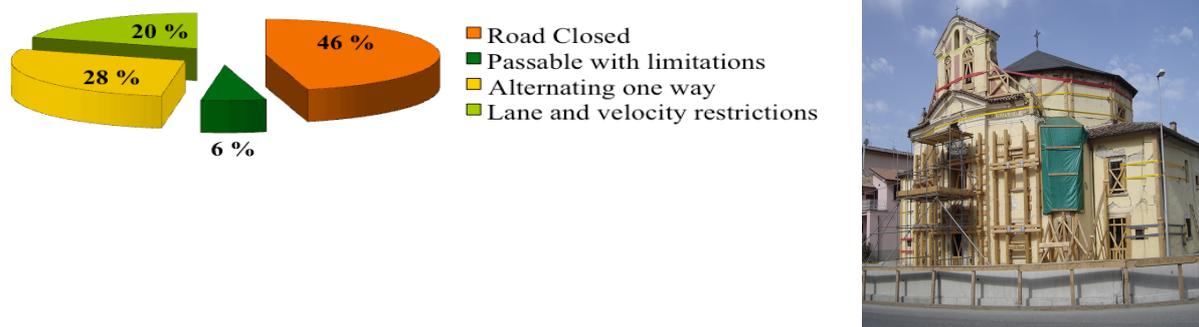


Figure 2. Traffic management measures and activities following L'Aquila earthquake: (a) traffic management solutions (updated to 01/05/09) for the 61 road tracts affected by the earthquake; (b) Immacolata Church in Paganica, L'Aquila, after the securing of the façade to ensure the mobility in the main adjacent road

2.2 A short overview of available approaches to assess the physical impact on road component

An exhaustive overview is beyond the scope of this paper, and this section briefly summarises few currently used approaches for modelling, at a regional or national level, the seismic response of network components.

For highway networks and bridge components, the REDARS tool developed by the Multidisciplinary Centre for Earthquake Engineering Research for the Federal Highway Administration in the USA (Werner et al., 2000) defines and implements traffic state fragility curves, which estimate the probability of a given traffic state as a function of the level of ground shaking or permanent ground displacement at the component site and of the consequent bridge's damage state. Three options for modelling the damage states of bridges subjected to ground shaking are included in REDARS: (a) an elastic capacity-demand approach (Jernigan, 1998); (b) a simplified mechanics-based method by Dutta and Mander (1998); and (c) user-specified fragility curves. A first-order model for estimating bridge damage states due to permanent ground displacement is included in REDARS.

The HAZUS-MH earthquake model (FEMA, 2003) provides estimates of damage induced by ground shaking and ground displacement to four components of the transport system, namely: (a) major roads (i.e. interstate and state highways and other roads with four lanes or more); (b) urban roads (i.e. intercity and other roads with two lanes); (c) bridges; (d) tunnels. Based on empirical data relating to the repair of damaged facilities after earthquakes in the past, HAZUS-MH also provides restoration curves for estimating the percentage of residual functionality for the aforementioned components, the time required to restore their original functionality, and economic losses due to the repair/replacement of the component. Several applications of the HAZUS-MH model for estimating the impact of earthquakes on road networks are available in literature. Kiremidjian *et al.* (2007), focusing on bridges components only, investigate the impact of ground shaking, liquefaction and landslide hazards on highway networks, following the formulation proposed by HAZUS-MH earthquake model.

HAZUS-MH earthquake model is one of the few published methods that allows for the assessment of geotechnical hazards at a territorial scale and their impact on building and road components. It worth remembering, however, that the formulation proposed by HAZUS for the estimation of induced geotechnical hazards is affected by various shortcomings (Bird et al. 2006). Induced geotechnical hazards are a key factor in the damage to transportation systems (Bird and Bommer 2004), and further research is needed for their estimation and representation, to define more region-specific approaches that rely on quantitative engineering parameters. Giovinazzi and Cubrinovski (2007) have made an initial attempt at this, proposing simplified but quantitative models to assess ground distortion caused by liquefaction.

Regarding roadways in urban area, existing approaches agree on considering road blockages mainly generated by building damage, and on disregarding direct damage to the road network components and induced geotechnical hazards (FEMA, 2003; Argyroudis *et al.*, 2003; Goretti and Sarli 2007). Goretti and Sarli (2007) identify three possible causes of road closure induced by the damage affecting buildings adjacent to the roadways, namely: (a) total collapse of the building; (b) partial collapse due to out of plane wall overturning; (c) short-term countermeasures, such as propping. The probability of a certain road being either open or closed is assessed as a function of: (1) the probability that a certain building type suffers a damage grade when subjected to a certain level of ground-shaking; (2) the geometry of both the building (building height and distance between building facade and road) and the road (road width), conditioning the probability that for a damaged building type, a propping is inserted, or a partial or total out of plane collapse occurs, causing blockage of the road.

Generally speaking, except for the representation of induced geotechnical hazards, the available literature provides reliable models for assessing direct and indirect damages to the road components, following a seismic event. It is worth highlighting, however, that among the aforementioned approaches, the ones that, following the estimation of the physical impact on road components, consider the problem of the transportation network as a system and solve a reliability approach, assume a binary behavior for transport network components, where the network links and nodes are either open or closed. The lack of specific correlations between damage states of links and nodes and traffic states (namely their residual capacity to satisfy mobility issues) is a significant shortcoming in the existing literature. Even a small reduction in capacity can result in substantial disruption of transport system performance, and the probability of the road network working (albeit at a reduced level) following a seismic event, can be crucial in the emergency management and response and recovery phases, as demonstrated in the L'Aquila earthquake.

3. MODELLING OF USER RESPONSE

The pattern of movement in a network may change dramatically after a disaster, due to people evacuating an area or people entering an area to render assistance. It is fundamental for network reliability models to take proper account of such changes in travel behavior. In order to predict how people will respond to a changed set of travel conditions caused by the earthquake it is possible to make reference to transportation demand models. The most commonly used demand model is the four-step model (Ortuzar and Willumsen 1994) for predicting the effect of changes in travel behaviour related to: 1) trip generation; 2) spatial or temporal trip distribution; 3) mode choice; 4) route choice.

Regarding trip generation following an earthquake, trip making within particular areas may increase or decrease. Trip generation models estimate the number of trips that begin or end in a zone without identifying where the other ends of these trips are located; this is the function of the trip distribution model. To calculate trip production and attractions following an earthquake, information is required on the location of uninhabitable residences, emergency housing facilities, and unusable business premises. For planning emergency management before an earthquake, it would be necessary to draw, damage scenarios and to know the location of emergency housing and strategic services.

Regarding spatial or temporal trip distribution, after a seismic event existing trips may be made from/to new origins/destinations, or at different times of the day, due to:

1. damage to residential buildings and to services buildings (e.g. school, offices, etc.);
2. people being re-located to emergency camps and/or temporary accommodation;
3. the increased need to access emergency services, including hospitals and medical centres;
4. the need for rescue personnel transport physical and human resources in the affected areas;
5. the desire of people to move away to avoid the risk of after-shocks and further damage.

Once trip generation models have estimated the number of trips emanating from a zone, distribution models distribute them among the trip attractions in the other zones. This involves estimating an origin-destination (OD) trip matrix, where the element in the *i*-th row and *j*-th column represents the

number of trips from the *i*-th zone to the *j*-th zone. This is traditionally done using a gravity model, which is based on the assumption that all trips starting from a given zone are attracted to other zones in direct proportion to the attractive power of the zone, and inversely proportional to the travel impedance between the two zones (Sosslau *et al.* 1978). Whether such a model is appropriate for estimating the spatial pattern of trips after a disaster is not clear. An accurate estimation of the OD matrix following an earthquake is a fundamental step in the assessment of the residual functionality of the road network (Du and Nicholson, 1997). A study the effect of the 1989 Loma Prieta earthquake on the San Francisco Bay Area freeway network (Wakabayashi and Kameda, 1992) found that allowing for changes in the freeway traffic trip matrix gave a 28% larger post-earthquake network capacity than if there was no change in the matrix. Ignoring changes in the trip matrix and modal split resulted in travel times during the post-earthquake period being over-estimated by about 30%.

As for mode choice, it is necessary to consider how existing trips and 'new' trips might be made using different transport modes; it is a common practice to favour public transport following an earthquake, to reduce the demand for private transport. As an example, following L'Aquila earthquake, the organisation managing public transport allowed for free public transport.

For changes in route choice, existing trips can be made via different routes to avoid degraded components of the road network. Trip assignment models enable the prediction of traffic flows on the links of a network. Immediately after a major earthquake, it is expected that the main objective of travellers will be to ensure the safety of themselves and family/friends. It is likely that use of the transport network will be greatly influenced by some "network regulator", acting according to a pre-defined strategy (e.g. evacuation plan and deployment of emergency service vehicles). Specialist tools are available for managing network usage (e.g. Sheffi *et al.*, 1982 and Kurauchi *et al.*, 2001).

During the response and recovery phases, drivers are expected to adapt their travel choices (such as choice of route) in response to the conditions (the location and level of degradation), depending on the level of information they may possess (Sumalee and Watling 2003). Where drivers are well-informed regarding conditions, one can use User Equilibrium Methods (Beckmann *et al.* 1956) for predicting link flows, and there are numerous examples of this approach in the transport network reliability literature (e.g. Asakura, 1996; Du and Nicholson, 1997; Bell *et al.*, 1999; Berdica, 2002; Kurauchi *et al.*, 2001;) and specific application in the framework of seismic risk analysis (e.g. Werner *et al.*, 2000; Orabi *et al.* 2009; Nuti *et al.* 2010). Where drivers are not well informed regarding conditions, they will develop expectations based on their experience over time and will assess the risk of delays for the alternative routes. Examples of approaches for predicting flows in such circumstances include those of Lo and Tung (2000), Yin and Ieda (2001), and Liu *et al.* (2002).

4. MEASURES OF NETWORK RELIABILITY FOLLOWING A SEISMIC EVENT

Bell and Ieda (1997) argue that reliability is measured as the degree of stability of the quality of service, which a system normally offers. When the circumstance under analysis is an unexpected and disastrous event like an earthquake, the quality of the service provided should be judged with respect to the priorities necessary to efficiently manage the emergency situation. It might be required, for instance, that the network should be able to maintain at least one possible travel path between specific OD pairs for emergency service access to affected areas. On the other hand, it might be expected that the network should be able to cope with the variations in demand during the emergency management and response phases, by maintaining a constant average travel time between different OD pairs.

Traditionally, the reliability of transport networks has been studied from two different perspectives namely connectivity and travel time reliability (Sanchez-Silva, 2001), where connectivity is defined as the probability that network nodes remain connected and traffic can reach a destination, while travel time reliability is defined as the probability that the destination can be reached in a time less than some threshold value. Connectivity reliability focuses, generally, on the analysis of the complete network, treated as a pure network and characterised by its topological structures only, while travel time reliability concentrates on a particular link or a set of links representing a path within the network,

characterized by both its topological structures and pattern of flow in the network, and analysed implementing network flow reliability models.

According to Nicholson and Du (1997), neither approach provides a completely satisfactory representation of network reliability degradation and modified functionality following a major event like an earthquake, as pure network models ignore flow demands, user route choice and capacity constraints, as well as allowing for only two states (full or zero capacity). This binary state approach is not applicable to emergency situations where the aim is to enable links and nodes to function at a partially reduced capacity (see Section 2.2). On the other hand, network flow models often assume fixed traffic demand. In addition, the network is defined to be “operating” if the maximum possible flow between each OD pair is not less than the given flow demand and a trip between a given OD pair can be made within a specified interval of time. Asakura (1996) defined travel time reliability as a function of the ratio of travel times in the degraded and non-degraded states. This type of reliability can be used as a criterion to define the level of service that should be maintained despite the deterioration of certain links in the network.

Alternative reliability approaches that should be considered when assessing the effect of an earthquake on road networks include capacity reliability and accessibility reliability. Capacity reliability (Yang *et al.*, 2000) is defined as the probability that a network can successfully accommodate a given level of travel demand, while Chen *et al.* (1999) defined this probability as equal to the probability that the reserve capacity of the network is greater than or equal to the required demand for a given capacity loss due to degradation. Accessibility reliability can be defined as the ability to command the transportation facilities that are necessary to reach desired destinations at suitable times. Moseley (1979), Halden (1996), Geertman and Van Eck (1995) agree that accessibility depends on the opportunities available at a location; and the cost of travelling to the location, while Shen (1998) also included the demand for the opportunities. Accessibility has already been used as a system performance measure in the disaster context, with Chang (2003) and Chang and Nojima (2001) finding that it is especially useful for showing the distributional effects and equity issues of urban transportation, and land use policies and plans, in the post-disaster restoration stage. Accessibility reliability can be used to identify the importance/criticality of networks links/nodes, where a network link/node is critical if its degradation significantly diminishes the accessibility of the network. Table 4.1 identifies the most suitable reliability measures to check the performance of the transport network under different circumstances of emergency management, response and recovery phases.

Table 4.1. Suitable reliability measures for emergency management, response and recovery phases.

	Reliability Measures			
	Connectivity	Capacity	Travel Time	Accessibility
Emergency	✓			
Response		✓		
Recovery			✓	✓

During the emergency management phase, the main concern is the accessibility of rescue and emergency services that can be measured using connectivity reliability (Bell & Iida, 1997; Asakura *et al.*, 2001). Pinto *et al.* (2006) and Franchin *et al.* (2006) used connectivity reliability to show how the disruption in the network following an earthquake may lead to delayed rescue operations and hence may increase the number of fatalities in the event of an earthquake.

During the response phase, it is expected that the demand pattern progressively adjusts back to “normal” level, but the network is still seriously degraded. Reliability is then concerned with the ability of the degraded network to cope with the changing demand pattern. Nicholson and Du (1997) propose the ‘flow decrement level’ as a suitable measure, with the network being said to function if the degraded network can maintain the same acceptable level of activity (represented by the number of conducted trips under the economic concept of the demand-supply equilibrium). A different approach is to look at the effect of the reduction in capacity on the change in travel time.

During the recovery phase, the demand patterns should have returned to normal, and the objective of reliability analysis returns the measure of the quality of service that the system can normally offer.

5. CONCLUSIONS

Practices and models currently implemented for the assessment of the impact of earthquake events on transport networks have been analysed in the paper, critically discussing assumptions and their applicability to enhance emergency management, response and recovery following a seismic event.

Reliable approaches are available on the literature to assess, on the one hand, the direct structural damage to highway and roadways components and, on the other hand, the indirect impact caused by debris falls from damaged/collapsed buildings adjacent to the roadway networks in the urban areas. There are shortcomings in the methods for predicting the effects of induced geotechnical hazards that could cause partial/total obstruction of the road links or damage to other components.

A major limitation of the analysed approaches has been identified in the lack of specific correlations between damage states and traffic states. A binary approach generally is assumed to represent the residual functionality of road components, where the network links and nodes are considered either accessible or closed. This assumption can cause substantial mistakes in assessing the residual capacity of the degraded network to satisfy mobility issues.

The four-step traffic demand model has been identified as a suitable approach for modeling the behavioral response of network users when dealing with a degraded transport networks. Specific models to represent changes in travel behaviour following a seismic event, including trip generation, spatial or temporal trip distribution, mode choice and route choice have been discussed in the paper.

Finally different reliability approaches have been identified to measure the degree of stability and the quality of service provided by the road network, during the different circumstances of the emergency management, response and recovery phases following a seismic event.

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