Transportation network vulnerability analysis for the case of a catastrophic earthquake

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\section*{A R T I C L E   I N F O}

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\section*{A B S T R A C T}

The aim of this paper is to propose a post-disaster vulnerability analysis for the designed emergency transportation networks in Tehran, an earthquake-prone metropolis in a developing country. The situation of Tehran is somewhat disheartening as it has developed haphazardly with little attention to construction and building codes, which leaves structures, transportation routes, and residents vulnerable. This paper attempts to demonstrate the challenges of trying to develop transportation vulnerability analysis in a developing country, especially one as a major population center in a geographic area prone to earthquakes. After a catastrophic earthquake in a developing country, the conventional network analysis methods may not be employed because first, the post disaster travel demand can be fundamentally altered from the usual daily travel demand and, perhaps, the forecast of the trip demand in the highly uncertain condition seems impossible. Second, the behavior of passengers may not be rational. In line with this idea, a comprehensive study on urban seismic disaster prevention and management for the greater Tehran is held in this paper. This paper proposes an approach to evaluate post-earthquake response and recovery routes by identifying redundancy-based isolation measures to find out which zones in this city are most susceptible to disruptions of the transport system due to a devastating earthquake, and which emergency response trips are most vulnerable in the super-chaotic situation after the earthquake.

\section*{1. Introduction}

This paper tries to address the question: How could one perform a transportation network vulnerability analysis for the urban transportation regulation exerted in developing countries to deal with and alleviate the consequences of a huge and destructive earthquake? Attempts to answer this question lead to the following questions which we try to answer in this paper: (a) Which factors determine the robustness of a road network against a catastrophic earthquake? (b) How can the indicators be computed to quantify such robustness factors?

Many causes can be numerated for the transportation network disturbance or interruption as [1–5]: (i) natural disasters and freak events like earthquakes, hurricanes, blizzards, floods, landslides, and extreme weather; (ii) incidents such as severe traffic crashes, special events, road works, vehicle breakdowns, and civil emergencies; (iii) social events like football matches and big fairs; and finally (iv) malicious attacks. These disturbances can be classified as recurrent/non-recurrent or intended/unintended causes.

Hopkins et al. [6] stressed the fact that the transportation system is the most important lifeline system, because damage to it imposes extra burden on the other lifelines (as cited in [7]). Perhaps this can be regarded as one of the main reasons for the widespread interest in the development of the theory of transportation network vulnerability analysis in the last decade which has been pioneered by Berdica [8]. In this leading research, vulnerability has been defined as: “Vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reduction in road network serviceability.” The term vulnerability is tied to the availability of critical locations where the most severe (socioeconomic) impacts would be seen as a
## Table 1
A taxonomic review of some vulnerability studies.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Time (analysis for pre or post analysis of hazard)</th>
<th>Multiple link (ML) single link (SL) failure</th>
<th>Consider the link degradation?</th>
<th>Indicator(s) to capture consequences</th>
<th>Real case study</th>
<th>Software used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snelder et al. [5]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Vehicle loss hour</td>
<td>South Holland of Netherland</td>
<td>Indy</td>
</tr>
<tr>
<td>Scott et al. [20]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Network robustness index (NRI) derived from the system-wide, travel-time cost calculated using the user equilibrium assignment model</td>
<td>No case study</td>
<td>TransCAD</td>
</tr>
<tr>
<td>Taylor [21]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Consumer surplus and inclusive value parameters</td>
<td>Adelaide, capital city of the state of South Australia</td>
<td>CitiLabs CUBE Voyager N.M.</td>
</tr>
<tr>
<td>Kurauchi, Uno [22]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Link critically index derived from the OD-connectivity index</td>
<td>Kansai region of Japan</td>
<td>N.M.</td>
</tr>
<tr>
<td>Taylor et al. [23]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Hansen integral accessibility index as an(a) accessibility/remoteness index of Australia</td>
<td>Australian national transport network</td>
<td>N.M.</td>
</tr>
<tr>
<td>Taylor and D’Este [24]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Generalized travel cost and the Hansen integral as an accessibility index</td>
<td>Australian national transport network</td>
<td>N.M.</td>
</tr>
<tr>
<td>Chen et al. [14]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Relative changes in network efficiency by using the results of reliability-based user equilibrium assignment</td>
<td>Hong Kong road network</td>
<td>N.M.</td>
</tr>
<tr>
<td>Bono and Gutiérrez [16]</td>
<td>Post</td>
<td>ML</td>
<td>Yes</td>
<td>Cost distance computed, as the distance from each single cell in GIS as a source to all the other cells in GIS on the basis of the defined impedance of each link</td>
<td>The Port Au Prince and Carrefour areas of Haiti</td>
<td>ArcGIS 9.x</td>
</tr>
<tr>
<td>Chang and Nojima [15]</td>
<td>Post</td>
<td>ML</td>
<td>No</td>
<td>Total length of network that is open</td>
<td>Kobe city/San Francisco Bay area/Los Angeles metropolitan area</td>
<td>N.M.</td>
</tr>
<tr>
<td>Nagae et al. [4]</td>
<td>Pre</td>
<td>ML</td>
<td>No</td>
<td>Restoration cost plus transportation disutility (calculated through the result of user equilibrium with elastic demand traffic assignment)</td>
<td>Kobe urban network</td>
<td>N.M.</td>
</tr>
<tr>
<td>Jenelius et al. [9]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Link importance and site exposure indexes derived from the shortest path algorithm</td>
<td>The road network of northern Sweden</td>
<td>C++</td>
</tr>
<tr>
<td>Jenelius and Mattsson [3]</td>
<td>Pre</td>
<td>ML</td>
<td>No</td>
<td>Cell importance and regional exposure indexes calculated based on both waiting time and increases in the actual travel time due to a disruption</td>
<td>Swedish road transport system ArcGIS 9.x and C++/C#</td>
<td>N.M.</td>
</tr>
<tr>
<td>Jenelius [25]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Link importance index calculated from the link flow and regional exposure index (i.e. expected total exposure (TE) and expected user exposure (UE))</td>
<td>Swedish road transport system ArcGIS 9.x and C++/C#</td>
<td>N.M.</td>
</tr>
<tr>
<td>Jenelius [2]</td>
<td>Pre</td>
<td>ML</td>
<td>No</td>
<td>Flow-based redundancy importance index and impact-based redundancy importance index (both calculated based on the flows on links)</td>
<td>Swedish national road network</td>
<td>N.M.</td>
</tr>
<tr>
<td>Sullivan et al. [26]</td>
<td>Pre</td>
<td>SL</td>
<td>Yes</td>
<td>The network trip robustness index by summing the NRI values of Scott et al. [20] (above) across all individual links and dividing that sum by the total trip demand</td>
<td>Road network of the Chittenden County Metropolitan</td>
<td>TransCAD</td>
</tr>
<tr>
<td>Sohn [27]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Accessibility indexes based on the distance-only and the distance traffic volume criteria</td>
<td>Highway network system in Maryland</td>
<td>ArcView Network Analyst (AVNA) N.M.</td>
</tr>
<tr>
<td>Knoop et al. [28]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>9 different indicators computed based on the result of the equilibrium assignment</td>
<td>Small part of the network of Delft and the network around the city of Rotterdam UK national railway system</td>
<td>N.M.</td>
</tr>
<tr>
<td>D’Este and Taylor [1]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Two indexes derived from the Logit based multipath assignment</td>
<td>Road network of the Chittenden County Metropolitan</td>
<td>TransCAD</td>
</tr>
<tr>
<td>Taylor and Susilawati [29]</td>
<td>Pre</td>
<td>SL</td>
<td>Yes</td>
<td>ARIA (Accessibility/Remoteness Index of Australia) which is an index for a location determined using the activities of the location, the configuration and state of the transport network, and the facilities and services accessible using the network</td>
<td>A region in the southeast Australia, which lies midway between Adelaide and Melbourne</td>
<td>ArcGIS 9.x</td>
</tr>
<tr>
<td>Chen et al. [13]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>Four accessibility measures using the result of the equilibrium solution of the combined travel demand model as: 1) Network accessibility, 2) Zonal accessibility, 3) O-D accessibility, and 4) O-D accessibility by each mode</td>
<td>No case study</td>
<td>N.M.</td>
</tr>
<tr>
<td>Chen et al. [12]</td>
<td>Pre</td>
<td>SL</td>
<td>No</td>
<td>A utility-based accessibility measure which is consistent with</td>
<td>No case study</td>
<td>N.M.</td>
</tr>
</tbody>
</table>
Table 1 (continued)

<table>
<thead>
<tr>
<th>Indicator(s) to capture consequences</th>
<th>Time (analysis for pre-disaster vs post-disaster)</th>
<th>Real case study</th>
<th>Software used</th>
<th>Consider the link degradation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random utility theory (Mori et al. 2016)</td>
<td>Pre</td>
<td>Bangkok metropolitan area road network</td>
<td>SATURN, Matlab R2011a</td>
<td>Yes</td>
</tr>
<tr>
<td>A normalized form of the Hansen integral accessibility index</td>
<td>Pre</td>
<td>Central North Island (New Zealand) road network</td>
<td>SATURN</td>
<td>No</td>
</tr>
<tr>
<td>Probit-based stochastic user equilibrium assignment</td>
<td>Pre</td>
<td>Central North Island (New Zealand) road network</td>
<td>SATURN</td>
<td>No</td>
</tr>
<tr>
<td>The sum of the changes in the whole operating occupation trip time</td>
<td>Pre</td>
<td>Central North Island (New Zealand) road network</td>
<td>SATURN</td>
<td>No</td>
</tr>
<tr>
<td>Vehicle miles traveled (VMT) calculated based on a shortest path traffic assignment approach</td>
<td>Pre</td>
<td>Central North Island (New Zealand) road network</td>
<td>SATURN</td>
<td>No</td>
</tr>
</tbody>
</table>

**Table 1**

The work of D’Este and Taylor [1] provides clear reasoning for the need to consider network vulnerability analysis. Their reason was to enable the analysis of disrupted networks where connectivity between O-D pairs still existed (and thus the network passed the earlier tests of connective reliability), but the resulting detours were so tortuous or excessive that they did not provide realistic alternatives.

Several studies in the literature have proposed methods for vulnerability analyses of transportation networks. Table 1 presents a taxonomic review of some of these methods mostly related to the vulnerabilities due to natural disasters. The important finding is that the context of vulnerability analyses changes substantially from one network failure mode to another. So first, it is necessary to specify the type of crisis or disaster and, moreover, the mechanism of its effect on the transport network. In other words, the failure modes of transport network should be clearly identified so that appropriate vulnerability analysis could be devised for it. In line with this idea, the purpose of this paper is to establish a tool for the network vulnerability analysis of a catastrophic earthquake.

From the literature it appears that to determine the consequences of a failure or loss of network capacity, one approach is to analyze the network performance by traffic assignment techniques following the equilibrium or system optimizing perspective (e.g. see [1,4,12–14]). Although this approach may be valid when damage to the transportation network is low and the time interval after the event is sufficient for converging to the re-equilibrium state, for serious and major hazards like the catastrophic earthquake considered in the current paper, equilibrium conditions and normal travel behavior may no longer exist. This may be why accessibility indexes (some of which are merely topological) serve in many studies as indicators of network vulnerability (see Column 5 of Table 1).

One of the key studies on the vulnerability analysis due to an earthquake has been performed by Chang and Nojima [15], in which an attempt was made to provide a sound network accessibility measure to evaluate the post-disaster performance of the transportation network in Kobe within several months of the restoration period. More recently, Bono and Gutiérrez [16] also computed a Geographic Information System (GIS)-based post-disaster accessibility index of the urban space of damaged road network using the data received from the post-disaster damage surveys. Both of these studies are confined to the post-disaster network analysis. It is worth noting that adopting an approach for the evaluation of the damaged road network for the post-disaster network analysis is much simpler than the pre-disaster one as only one definite failure mode exists in the former case (i.e. what really happened in the post-disaster analysis) and no likelihood of damage is required.

Perhaps the paper most similar to the current study is that of Nagae et al. [4], although there are key fundamental differences. They provided a framework for a vulnerability analysis, which helps in solving the anti-seismic reinforcement problem. This framework takes traffic congestion and travelers’ route-choice behavior into account and performs a user equilibrium assignment to predict the post-disaster situation. It seems that both Chang and Nojima [15] and Nagae et al. [4] are confident that the demand will return to the initial state after the earthquake and commuter trips would start like before.

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For further details on this topic, interested readers could refer to the special issue of “Transportation Research Part A: Policy and practice” [10], or the review paper of Murray et al. [11].
However, in a developing country like Iran, the situation is completely different. Reviewing the 2003 Bam catastrophic earthquake (Mw=6.6) reveals that the disastrous consequences and damage were so great that conditions were never able to return to normal and desired status. The earthquake was particularly destructive and ruined more than 90% of the city [17]. From the total population of roughly 97,000, more than 26,000 people died in the quake and over 20,000 people were injured, and about 400 people were permanently disabled (i.e. almost two-thirds of the inhabitants were injured or died) [18].

Hence, in contrast to Nagae et al.’s study [4], which assumed that the total number of potential users for each origin–destination (O–D) pair is equivalent to the actual traffic volume for the O–D pair in the normal network, the travel pattern of the city of Bam was dramatically changed after the earthquake. In the short and medium term, it was limited to search and rescue, emergency evacuations, restorations, and other disaster response activities, while in the long term, it was dedicated to a very slow and time-consuming reconstruction and the survivors’ new patterns of trips (which might be changed in all aspects of a trip, i.e. trip origin, destination, mode, route, and departure time because of the fundamental changes in the pattern of activities after the earthquake).

Furthermore, a much worse chaotic situation is expected in a developing metropolis like Tehran, the capital and most populated city of Iran. Tehran is located in a highly earthquake-prone area surrounded by major active faults and has experienced a rapid and unplanned growth of urbanization with highly vulnerable built environments. As a result, Tehran is further exposed to natural catastrophes, in particular, seismic hazard. The potential for large damaging earthquakes and their overall social, economic, and political consequent impacts could be far more devastating than was originally thought.

As the earthquake catastrophe varies from developing countries to developed ones, obviously different studies and dissimilar preparation phases should be devised for these two. That is, unlike the developed countries where the main concern in the response phase is to rapidly return the city to the productivity of the pre-crisis conditions, after a severe earthquake in developing countries, the main concern is first, to enable more people to survive in the search and rescue phase, and second, to lessen the victims of homelessness, crime, contagious diseases, poor nutrition, etc.

Japan International Cooperation Agency (JICA) performed a comprehensive study on urban seismic disaster prevention and management for the greater Tehran area in 2004 [19]. One of the outcomes of that study has been a plan for the emergency response, just after the earthquake, which is part of the comprehensive master plan on urban seismic disaster prevention and mitigation. This plan introduced two primary and secondary emergency road networks which should be controlled for the earthquake response phase. These two networks have recently been updated and a strict discipline of control has been determined as well.

The aims of this paper are: (i) to briefly describe the aforementioned updates which can be useful for specialists in developed countries to show how approach is followed in the network emergency management in a highly vulnerable network after a severe earthquake in a developing country; and, (ii) to provide a measure to recognize vulnerabilities in the above-mentioned emergency transportation network. We introduce a redundancy-based accessibility measure to find out which zones in the city of Tehran are most susceptible to disruptions in the transport system, and which emergency response trips are most vulnerable in the super-chaotic situation after the earthquake. Accordingly, an isolation index is defined for each O–D pair and then the exposure indexes of traffic zones are calculated.

2. Disaster management cycle and vulnerability analysis

A disaster management cycle is shown in Fig. 1a. Fig. 1b shows the general outline of the steps of the network vulnerability analysis for the response phase of Fig. 1a. Most of the studies listed in Table 1 have only analyzed the failure of the transport network, irrespective of the cause of failure. However, to adequately model the intact and degraded network, understanding the failure mechanisms and damage patterns of the transportation network is essential.

Step 1 of Fig. 1b indicates the essence of understanding spatio-temporal features of a disaster. The second step in Fig. 1 is to review the existing administrative regulations and guidelines in response to a given incident, accident, disaster, or malicious attack. In addition to the disruptive damage, the traffic network can be significantly affected by the traffic regulations after the events. In the third step of Fig. 1, the changes in the travel demand and trip patterns due to the network disruption(s) or degradation(s) are investigated. This step aims to answer this question: How do transportation users respond to events? In Step 4, it is necessary to draw the supply system with disrupted or degraded links under the prevailing failure mechanism. Furthermore, the period of recovery and reconstruction to return the system to normal conditions is also determined in this step. The results of Step 4 combined with Step 2 yield the post-disaster supply system. Step 5 denotes the method of vulnerability analysis, which depends on: (1) the mechanism of damage caused by an event, (2) the regulations devised for the emergency and relief process, and (3) travelers’ reaction to the event.

Fig. 1b demonstrates an ideal framework of a network vulnerability analysis within the response phase. This paper turns to earthquake response operation phase, but as it will be explained later in subsequent sections, regarding a severe earthquake in a developing country, all of the above steps cannot be taken.

3. Outline of the methodology

The outline of the proposed method in this paper is shown in Fig. 2. As shown in this figure, holding group creativity techniques among specialists and eliciting their ideas are the key steps in the identification of the post-earthquake management strategies. In the following, the steps shown in Fig. 2 are described.

3.1. Snapshot of a catastrophic earthquake in Tehran

Located in the central part of the active Alpine-Himalaya Oro- genic belt and based on the geological and morphological characteristics, Iran is one of the most seismically active developing countries in the world. A review of the statistics reveals that the large earthquakes in Iran have always led to the widespread loss of human lives and assets. Statistical analyses show that Iran has experienced almost 130 earthquakes with 7.5 or more in the moment magnitude scale ($M_w$) during the last century [33]. Many Iranian cities have suffered from earthquakes (e.g. earthquakes of Booin Zahra in 1962 with $M_w=7.2$ and 20,000 victims, Tabas earthquakes in 1978 with $M_w=7.8$ and 15,000 victims, Golbaf earthquakes in 1981 with $M_w=6.6$ and 3000 victims, Manjil and Roodbar earthquakes in 1990 with $M_w=7.4$ and 35,000 victims, and Bam earthquakes in 2003 with $M_w=6.6$ with 50,000 victims).

The natural disasters such as earthquake result in much devastating damage in developing countries compared to the developed ones due to inappropriate and nontechnical infrastructure development, ignoring the quality and security issues, concentrating on the short-term rather than the long-term planning, weak or no manpower training programs, neglecting technical
principles, and poor disciplines of planning and design. In this context, some Iranian cities are much more susceptible to seismic hazard due to their geological and morphological characteristics and among them, Tehran is one of the most-exposed. Tehran is the most populated city in Iran with 8,300,000 inhabitants and about 12 million in metropolitan areas, which extends about 730 km². It is known as one of the most vulnerable to earthquakes metropolises in the Middle East region, where an impending earthquake disaster is inevitable due to being located in a highly earthquake-prone area bounded by long and short faults (e.g. Mosha, Niavaran, Tarasht, and Parchin faults). The location of Tehran’s active faults is shown in Fig. 3a.

Table 2 summarizes thirteen different threatening earthquakes for our seismic analyses of Tehran and lists their consequent damage and casualties. As can be seen in this table, increasing building damage (Columns 5) leads to the largest number of injured people, deaths and refugees. According to Abbasi and Farbod [34] and based on the collected field data by Tehran Disaster Mitigation and Management Organization (TDMMO), the Niavaran earthquake with 7 moment magnitude scale ($M_w$) is considered as the most probable and reasonable earthquake scenario in Tehran among all of the reasonable worst case scenarios [35]. Based on seismographic data on fault motions of Tehran region, although potential damage and fatalities due to Tarasht fault movement are much higher than other faults (as shown in Table 2), it is less probable that it will shake in comparison to Niavaran fault. Moreover, there is no historical record of Tarasht fault shaking.

![Disaster Management Cycle](image)

![Transportation Network Vulnerability Analysis Module: The conceptual model](image)

Fig. 1. (a) Disaster management cycle [32], and (b) the vulnerability analysis framework proposed by this paper.
The maps of damage estimation in census block are demonstrated in Fig. 3b. Darker colors indicate the regions with higher damage while brighter colors represent lower casualties. The methods used to calculate the spread of the damage and number of fatalities will be described in the next subsection.

3.2. Damage estimation

3.2.1. Seismic damage estimation of buildings considering north Tehran fault scenario earthquake

The residential building damage was calculated for Niavaran fault scenario earthquake by JICA [36]. The recent updates on JICA’s study [35] were employed as input data for the analysis. In the study conducted by JICA [36], commercial buildings and factories were not included in the analysis and the term “damaged buildings” implies that the buildings were heavily damaged or collapsed, and were inappropriate for living without proper repair. Furthermore, the cause of the damage was limited to the seismic vibration itself. The damage caused by secondary disasters such as liquefaction, landslides, fire and explosions were not included in this calculation.

The earthquake resistant property of buildings differs from area to area and from country to country. The relationship between the seismic force and the damage ratio is not always the same, even if the type of buildings are similar. Different methods of construction are the main reason for such differences. Moreover, the collection of the seismic national disaster record and the establishment of a damage function based on the local experiences seemed to be important factors in the damage estimation. In doing so, damage reports of Ghir [37], Tabas [38,39], Golbaft [40], and Manjil [41] earthquakes were adopted to the damage estimation by Karimi [35].

In the damage estimation process, it was supposed that the main structures having key roles in the emergency and relief operation (e.g. hospitals, fire stations, etc.) had been retrofitted.

3.2.2. Human casualty estimation considering north Tehran fault scenario earthquake

The number of fatalities due to the Niavaran fault earthquake scenario was also estimated by JICA [36] and updated by Karimi [35]. “Fatalities” refers to those people who died just as a result of building collapses and not because of any cause in the aftermath of earthquakes like diseases or crimes in the refugee camps. Furthermore, only the building collapses due to earthquake shock have been considered as the cause of human casualty in Tehran, and other causes like tsunami, landslide, and flame spread are not considered. Tsunamis could not happen in Tehran because of its distance from water sources. Slopes of potential landslides are distributed in only a few parts of the northern edge of the city. Besides, there is very little possibility of fire spreading as fire protection facilities have been prepared.

JICA [36] and later on Karimi [35], adopted the basic concept introduced by Coburn, Spence [42] and Coburn and Spence [43] for the estimation of casualties.

3.3. Post-earthquake traffic management strategies

The Tehran transportation network has a structure with 432.5 km freeway (16.1% of the network), 776 km arterial roads (28.9% of the network), and 1468 km collectors and local streets (54.8% of the network). In this study, in order to make the vulnerability analysis, a subset of road network, including freeways with 1314 nodes and 2188 links is selected.

To manage the transportation network in the response phase, the JICA’s study [19] (and more recently the updated version made by the current study on the mainstreams of the JICA’s idea), divides the Tehran transportation network into the two sub-networks, primary and secondary. The primary network is a higher level network mainly composed of urban freeways and highways which is not open to public and is controlled by police. In return, the secondary network is a network which is open to public traffic and all types of emergency trips. To determine which links must be dedicated to primary network and which to the secondary one, and also to specify which trip types are allowed to use each network in the aftermath of a devastating earthquake, the experts’ judgment was elicited using group creativity techniques (as shown in Fig. 2). That is, instead of intuitive single ideas based on subjective evaluations, group creativity techniques attempt to construct a sound framework embodying all the expert views and to create synergy among specialists [44]. The procedure is as follows:
Firstly, the primary and secondary networks were determined through two brainstorming sessions. Brainstorming is a group creativity technique applied to create a large number of ideas to resolve decision-making problems and it can be designed to help find solutions to many kinds of open-ended problems. These sessions included various committee members of the TDMMO. The result of such sessions led to categorizing the freeways, expressways and a few of the 1st-order arterials of Tehran transportation network as the primary network and the remaining network links, including remaining 1st-order arterials and 2nd-order arterials as the secondary network (see Fig. 4). Through these sessions it was determined that all the collectors, local streets, and some secondary arterials should be removed from the two primary and secondary networks as there exist too many unpredictable reasons for the closure and inoperability of these roads after a severe earthquake.

Fig. 3. (a) Overview of the faults surrounding Tehran; (b) estimated damage resulting from the Niavaran fault earthquake [36].
Secondly, to distinguish the type of trips within the disaster emergency and relief operation phase, four brainstorming sessions were held.

Finally, in order to plan and manage the post disaster trips derived from the previous step and to determine the transportation planning process of the city after the earthquake, eight sessions of nominal group technique (NGT) were held. Through these sessions, the following items were specified regarding the post disaster emergency and relief trips:

- Organizations undertake the trips.
- The key responsible actors of the trips.
- Disciplines of the trips in using the primary and secondary networks.
- Origins and destinations of the trips.
- The usual range of start and end periods of the trips.
- Priority and importance.
- Special considerations about the trips.

About 523 person-hours were spent in the brainstorming sessions and 336 h in the NGT sessions.

The reason for employing the NGT in the last stage above was due to the fact that the NGT uses a more structured format to obtain multiple inputs from several people on a particular problem or issue and also because it prevents the domination of discussion by a single person, encourages the more passive group members to participate, and results in a set of prioritized solutions or recommendations.

<table>
<thead>
<tr>
<th>Earthquake scenario/ fault</th>
<th>Length (km) (^a)</th>
<th>Peak ground acceleration (gal) (^b)</th>
<th>Magnitude (Mw) (^c)</th>
<th>Building damage</th>
<th>Injured people</th>
<th>Number of deaths</th>
<th>Number of refugees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mosha</td>
<td>200</td>
<td>0.443</td>
<td>7</td>
<td>15120</td>
<td>9640</td>
<td>2640</td>
<td>1469500</td>
</tr>
<tr>
<td>Niavaran</td>
<td>43</td>
<td>0.443</td>
<td>7</td>
<td>\textbf{186100}</td>
<td>\textbf{65350}</td>
<td>\textbf{28570}</td>
<td>\textbf{5101460}</td>
</tr>
<tr>
<td>Parchin</td>
<td>27</td>
<td>0.650</td>
<td>7</td>
<td>230960</td>
<td>78920</td>
<td>34880</td>
<td>5519940</td>
</tr>
<tr>
<td>Mosha</td>
<td>200</td>
<td>0.394</td>
<td>6.5</td>
<td>1140</td>
<td>1540</td>
<td>220</td>
<td>290410</td>
</tr>
<tr>
<td>Niavaran</td>
<td>43</td>
<td>0.394</td>
<td>6.5</td>
<td>68770</td>
<td>28290</td>
<td>11230</td>
<td>3273590</td>
</tr>
<tr>
<td>Parchin</td>
<td>27</td>
<td>0.591</td>
<td>6.5</td>
<td>86240</td>
<td>34850</td>
<td>15060</td>
<td>3308130</td>
</tr>
<tr>
<td>Mosha</td>
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<td>0.337</td>
<td>6</td>
<td>60</td>
<td>260</td>
<td>10</td>
<td>49370</td>
</tr>
<tr>
<td>Niavaran</td>
<td>43</td>
<td>0.337</td>
<td>6</td>
<td>3070</td>
<td>1840</td>
<td>330</td>
<td>352260</td>
</tr>
<tr>
<td>Parchin</td>
<td>27</td>
<td>0.515</td>
<td>6</td>
<td>22820</td>
<td>12680</td>
<td>4230</td>
<td>1720260</td>
</tr>
<tr>
<td>Mosha</td>
<td>200</td>
<td>0.277</td>
<td>5.5</td>
<td>30</td>
<td>160</td>
<td>10</td>
<td>29790</td>
</tr>
<tr>
<td>Niavaran</td>
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<td>0.277</td>
<td>5.5</td>
<td>590</td>
<td>920</td>
<td>110</td>
<td>188380</td>
</tr>
<tr>
<td>Parchin</td>
<td>27</td>
<td>0.432</td>
<td>5.5</td>
<td>6290</td>
<td>5000</td>
<td>1160</td>
<td>783720</td>
</tr>
</tbody>
</table>

\(^a\) km: Kilometer.
\(^b\) gal: A cgs unit of acceleration, equal to one centimeter per second.
\(^c\) Mw: Moment magnitude scale.
\(^d\) This fault may be connected to its surrounding faults and in this case, it is 40 km long.
### Table 3
Post-earthquake trips derived from the NGT sessions.

<table>
<thead>
<tr>
<th>Trip type</th>
<th>Key responsible</th>
<th>Trip purpose</th>
<th>Origin</th>
<th>Destination</th>
<th>Trip type (One-way/Return)</th>
<th>Time interval</th>
<th>Network usage (Primary/Secondary)</th>
</tr>
</thead>
</table>
| 1-Restoration activities   | ● Water and Wastewater Organization  
● Electrical Distribution Company  
● Gas Company  
● Telecommunication Company | To inspect the facilities and restore them                                    | The place of the responsible organizations/companies                      | Centroids of mahallehs                                                     | R                           | i– Till the 3rd day ii– 3rd day– 3rd month | P&S                              |
| 2-Search and rescue operation | ● Red Crescent Society of the Islamic Republic of Iran | Rescue people trapped under debris                                           | Red Crescent Centers in Tehran                                           | Centroids of mahallehs                                                     | R                           | Till the 1st week                | S                                 |
| 3-Medical and relief trips | ● Ambulance centers of Tehran                                                  | (a) To send ambulances to triage injured people  
(b) To carry injured people to hospitals  
(c) To return the ambulances from hospitals to ambulance centers | (a) Ambulance stations (Total numbers: 88)  
(b) Centroids of mahallehs  
(c) Centroids of the mahallehs located in the districts | (a) The nearest non-private hospital  
(b) Centroids of mahallehs  
(c) Ambulance stations (Total numbers: 88) | (a) O  
(b) O  
(c) O | Till the 1st week | S                                 |
| 4-Emergency settlement     | ● Tehran Disaster Mitigation and Management Organization | To transfer citizens to emergency/temporary shelters | Centroids of mahallehs                                                  | Center of emergency settlements located in mahallehs                        | O                           | Till the 1st month               | S                                 |
| 5-Fire brigade responses    | ● Firefighting Organization of Tehran                                          | Emergency firefighting and rescue services                                  | Fire stations (Total numbers in Tehran: 92)                            | Centroids of mahallehs                                                     | R                           | Till the 4th day                 | P&S                              |
| 6-Logistic trips           | ● Tehran Disaster Mitigation and Management Organization                      | To prepare and transfer food and essential goods for citizens               | Disaster Management Centers                                              | Centroids of mahallehs                                                     | R                           | Till the 2nd week                | P&S                              |
| 7-Entrance and settlement of the teams from supporter provinces | ● Other provinces’ disaster mitigation and management organization  
● City Service Center | Supporting neighbor provinces to reach the disaster basements               | The entrance gates to Tehran                                               | Relief and rescue centers                                                  | O                           | Within the 1st to 3rd days       | P&S                              |
| 8-Debris removal trips     | ● Tehran Waste Management Organization of the  
● City Service Center | To clear the debris and restore them out of the city in the pre-defined debris depots (mostly in city suburbs) | Centroids of mahalle                                                     | Depot locations                                                            | R                           | 1st week–6th month               | P&S                              |
| 9-Organizational and administrative traffic | –                                                                 | To control the operation of the emergency management plan                  | –                                                                      | –                                                                           | R                           | Till the 1st month               | P&S                              |
| 10-Security initiatives    | ● Police, military,  
● Traffic police forces | To provide security after earthquake and control the emergency road networks | Police stations and military centers                                       | Centroids of the sectors                                                   | R                           | Till the 6th month               | P&S                              |
| 11-Burial affairs          | ● Citizens                                                                     | To bury the dead                                                            | Centroids of mahallehs                                                   | The cemetery of Tehran                                                     | R                           | Till the 1st week                | S                                 |
| 12-Other urban trips       | ● Citizens                                                                     | To respond primary needs                                                    | Centroids of a mahalleh                                                  | Centroids of mahallehs                                                     | R                           | Starts from the                 | P&S                              |
It was necessary to leverage the anonymous voting of the NGT and minimize the dominance of some participants over others in the technical matters through providing equal opportunities for participation in the NGT. Furthermore, this method minimizes the communication noise that is customary in other team creativity techniques.

3.4. Investigating the post-earthquake travel demand

As shown in Fig. 2, all types of trips after the earthquake are identified through expert judgments. Experts are selected from among those who have good knowledge and experience of previous earthquakes and are acquainted with the travel demand patterns in the aftermath of it.

Like conventional travel demand estimation methods, the generated trips here are also assigned to the homogeneous spatial units. Such geographical areas vary from small zones to municipal districts defined by administrative borders. Accordingly, Tehran has been divided into 22 municipal districts and through a much finer subdivision, into 117 zones. Each zone is then divided into smaller regions called mahalleh (i.e. certain portions of municipal districts in Tehran) and the mahallehs are divided into smaller census blocks. In total, Tehran comprises 374 mahallehs and 3173 census blocks.

Each of the organizations involved in the relief and emergency operations after the earthquake has a specific regulation and undertakes the restoration of their own facilities within a certain territory called sectors. In Tehran, for example, Water and Wastewater Organization is divided into 6 sub companies which are located in 6 different spots throughout the city. Tehran is divided into six Water and Wastewater sectors and each company undertakes the restoration of the Water and Wastewater networks of a sector. Their centroids of the geographical units are determined in the GIS software as the origins or destinations of the emergency and relief trip. For example, the spots representing the Water and Wastewater Companies are regarded as the origin of the Water and Wastewater restoration trip and the centroids of their own sectors as the destination.

Table 3 provides detailed information about the emergency and relief trips, their origin and destinations, their constraints in network use, and the specified disciplines. As mentioned above, this table, which is deemed to be the pattern of emergency trips after a severe earthquake, is constructed through eight rounds of NGT sessions among professionals.

An explanation on the trips of Table 3 is provided in Appendix A.

4. Proposed method of the network vulnerability analysis

It is important to note that only the emergency and relief trips within the Golden timeframe (72 h after the earthquake) are brought into the proposed network analysis procedure.

This section aims to perform a post-earthquake network vulnerability analysis of the proposed emergency transportation network. Before addressing the vulnerability relationship, the basic concepts of binary O–D matrix and network adjacency matrix are described. These concepts and their various aspects are firstly followed through Fig. 5.

Fig. 5a shows a test network. This network contains 8 nodes and 16 links. It is important to note that for the sake of simplicity, each node in the test network could also be a zone centroid, which is the points at which journeys may begin and end.
4.1. Binary O–D matrix of travel demand

As indicated in the previous section, a certain pattern of disaster response trips is supposed to be initiated throughout the primary and secondary networks after the occurrence of an earthquake. Although the trip purposes and the locations of the origins and destinations of these trips are known (according to the derivations of the trip patterns in the previous part), the number of these trips, their modes, times, and route choices are highly uncertain and, in particular, any modeling may be reasonably inaccurate. For example, after the earthquake, the number of medical and relief trips from a district to a hospital is very difficult or impossible to predict due to several diverse and uncertain contributing factors, making their likelihood calculation with sufficient accuracy almost impossible.

For example, after a catastrophic earthquake, it is not accurately known from a district: how many buildings will be destroyed or demolished, what the level of destruction is, who will be injured, what the exact level of injured people is, if enough vehicles exist to transport the injured to hospitals (because after a catastrophic earthquake in a third world country many cars will be stuck beneath collapsed debris and some cars may be stolen), will the roads leading to hospitals be open (various factors such as building debris, falling trees, abandoned cars, and heavy traffic after the earthquake are the main reasons closing the roads), etc. Because of these uncertain factors that cannot be accurately estimated, the demand for all types of trips after a catastrophic earthquake may not be correctly derived.

Taking this into consideration, the concept of the binary O–D matrix is introduced. Within this matrix, the rows and columns are exactly the same as that in the conventional O–D matrix; however,
the matrix entries are only zero or one so that 1 indicates the presence of the disaster response trips between the related certain O–D pair (according to the trip purposes in Table 3).

As an example, for the test network shown in Fig. 5a, assume that after the earthquake there exists only one O–D demand with the type of medical response trips from node 1 to node 8. For this trip demand, the binary O–D matrix is shown in Fig. 5b. Zeros in this matrix indicate no travel demand between relevant origins and destinations. But the cell located in the first row and the eighth column of this medical response demand matrix contains the value 1, pointing to the travel demand (with unknown magnitude) between node 1 and node 8.

The binary O–D matrix implicitly refers to the certain amount of travel demand between an origin and destination for a determined and specific trip purpose, when this amount is unknown. Any number 1 in the binary O–D matrix has important implications for the network analysis. That is to say, any O–D pair equal to 1 suggests a connection between this O–D pair with sufficient accessibility to tackle the disaster response activities.

4.2. Adjacency matrix of supply

A transportation network is represented as a directed graph. This directed graph is defined as: \( G = (V, A) \), where \( V \) is a set of sequentially numbered nodes (vertices), listed as \( v_1, v_2, \ldots, v_n \), and \( A \) is a set of numbered directed links (arcs). Adjacency matrix \( [A] \) is a way of representing this graph. The adjacency matrix of the directed graph \( G \) is an \( n \times n \) matrix \( A(G) = (a_{ij}) \) in which the \((i,j)\)th entry (i.e. \( a_{ij} \)) could be 1 or 0 according to whether nodes \( v_i \) and \( v_j \) are adjacent or not. That is to say, the adjacency matrix, which is also called the connection matrix, is a way of showing which nodes of the graph are adjacent to which other ones. As an example, Fig. 5c shows the adjacency matrix \( A(G) \) of the test network of Fig. 5a. For instance, 1 in the first row and fourth column of this matrix shows that there is a link from node 1 to 4.

4.3. Redundancy index: finding link-disjoint paths

In engineering, redundancy is the doubling of the elements of the system in order to increase the system reliability. Although this concept is widely used in communication systems, to the best knowledge of these authors, only Jenelius [2] has used it in the transportation network analysis when he considered the importance of road links as backup alternatives when other links in the network are disrupted. In our paper, this term (i.e. the “redundancy”) is used from a different point of view to draw the network analysis of the transportation network after a severe earthquake.

In order to measure the robustness of the transportation network after a hypothetical earthquake, it is necessary to define an indicator to evaluate how accessible each binary O–D pair is in a disrupted network. The methodology for vulnerability analysis in this paper originates from the idea that the existence of more independent and short parallel paths between each O–D pair would provide greater opportunity for the O–D pair to be connected and operable.

The term “connection” in this paper refers to the situation where there is no considerable damage to the road structure or existence of insurmountable obstacles (like large amount of building debris) to limit and/or prevent the emergency and relief activities. On the other hand, a road may be connected but not “operable.” The operability is confined by a variety of operational factors such as high traffic volume or the concentration of rescue operations in a given point of the transportation network. Stated more precisely, in this paper, “connection” points to the physical and structural causes of road blockages, while “operation” points to the functional aspects that could alter the operability of the roads. A road segment could be connected but not operable, while the opposite is not true. If we have an open and operable road, then the road is “accessible.” The term accessibility covers both the connectivity and operability of the road. That is, when the road is connected (structurally) and operable (functionally) then it is accessible.

As mentioned above, no previous studies, to the best of our knowledge, have pointed to these concepts from the current perspective, and none of the vulnerability analyses make the distinction between the connectivity, operability, and accessibility. In general, previous studies mostly pointed to the word accessibility (or “remoteness” as opposed to “accessibility”) as “the ease with which desired destinations may be reached” [50]. It implies that they never analytically investigate the vulnerability of the road networks against the chaotic situation of a highly destructive earthquake.

On the basis of the experiences of these authors of the latest earthquakes with a large number of victims in Iran (e.g. Manjil and Roodbar earthquake in 1990 with \( M_w = 7.4 \) and 35,000 victims, and Bam earthquake in 2003 with \( M_w = 6.6, 50,000 \) victims), considering the following two categories of network node/link-blocking causes may be reasonable:

1. Lack of seismic resistance of structures: Damage to the road surface, bridges, tunnels, viaducts, embankments, and buildings are the main causes of blocking the links. There are also miscellaneous components in the transport network that may block roads such as trees, light poles, variable message signs, pedestrian overpasses, etc.

2. Behavioral reasons due to the panic spread through the city: The wave of panic after a catastrophic earthquake causes a state of total confusion with no order in the city, when normally the extent of the damage is high and the media and the tools of mass communication with citizens have been cut off. Hence, when people want to quickly escape from the city and when there is no information on the choice of destination and their paths, heavy traffic is expected, which would stop the search and rescue operation. In this case, the road is connected but not operable and hence not accessible. In addition, some people may abandon their vehicles due to the heavy traffic, which can easily block the path for any post-disaster response activity.

In these cases and under such very chaotic environment after the catastrophic earthquake, where there is great uncertainty in the possible closure of the transportation network elements, it may be deduced that the existence of more independent and short parallel paths between each O–D pair would provide a greater likelihood that the O–D pair is connected and operable.

Methodologically, disconnectivity and inoperability of the road segments could be classified into the following four types:

- Traceable disconnectivity.
- Indiscernible disconnectivity.
- Traceable inoperability.
- Indiscernible inoperability.

Any disconnectivity or inoperability is called traceable when the devised method describes and models it. For example, in Nage et al.’s study [4], they only focused on the road bridge as the transportation facility and examined the fragilities against the seismic intensity. Hence, in their method, the disconnectivity of road links due to bridge disruption was methodologically captured and traceable. However, they have not brought the tunnels, viaducts, embankments, and buildings in their analysis; hence, these facilities may cause indiscernible disconnectivity of road segments.
when one traces the method of Nagae et al. [4]. To the best of our knowledge, no study has come to model the inoperability causes of road closure; as a result, we are constantly faced with indiscernible inoperability of road segments when employing the available literature.

The question remains as to whether a disconnectivity or an inoperability remains indiscernible (instead of traceable) within the proposed vulnerability method. The answer is, it depends significantly on the data availability and computational affordability of the method.

It is ideal to have the precise data on vulnerable facilities (their places, fragilities against seismic intensities, etc.) and employ a simulation method which randomly generates several damaged patterns of the urban system from the calculated failure probabilities, and then control the relative variance of the simulation method to specify an adequate sample size and to increase confidence in the simulation results. Afterward, the network analysis modules would be applied on the disrupted networks.

However, in accomplishing the project, we faced a common developing-country-specific problem, which is the lack of a comprehensive database. Hence, all the disconnectivity and inoperability causes are indiscernible.

The proposed approach is based on the idea that the more independent the parallel pathways, the higher the possible accessibility. Being independent means that the paths in the network are link (arc)-disjointed or node (vertex)-disjointed. At the urban network level, there are many such latent alternative paths [23, 24] that would make the transport network more robust.

Given a graph $G = (V, A)$ and a collection $V = \{(s_i, t_i), \ldots, (s_k, t_k)\}$ of pairs of O–D, the disjoint-paths problem consists of determining whether each pair of nodes in $V$ can be linked in $G$ by node (or link) disjoint $s_i - t_i$ path. The disjoint paths problem is known to be very hard: it is NP-complete in directed graphs [51]. Finding the maximum number of disjoint-paths connecting any $s_i, t_i \in V, s_i \neq t_i$, was first introduced in Menger’s theorem [52]. In line with this idea, the disaster response redundancy index between $s_i$ and $t_i$, $r(s_i, t_i)$ proposed in this paper is to find the maximum number of link-disjoint paths connecting $s_i$ and $t_i$. Dealing with this fact at length here would take us far from the scope of this paper. Suffice it to say that, the Brandes and Wagner’s [53] linear time algorithm for the link-disjoint Menger problem is employed in this paper and briefly introduced in Appendix A.

The codes of the analysis were written in Matlab 7.10.0 (Mathworks, Inc.) and the following limitations are also considered:

- We define a jointness index ($\zeta \in [0, 1]$) for two parallel paths (i.e., routes with a common origin and destination), which limits the maximum ratio of the number of links per path that can be shared with another path. The value of zero indicates that the two paths are completely link-disjointed. The value of 1 denotes that for two different paths, the larger one can embody all the links of the shorter one. Another value like 0.5 means that on average, half of the total links of the two paths are jointed. Fig. 5d shows two fully link-disjointed paths from node 1 to node 8.

- The link-disjointed paths should not be unrealistic, meaning that the detour and zigzag paths should be removed from the link-disjoint path set. In doing so, in the process of accessibility index calculation, an excessive link index ($\gamma > 0$) is defined. This index controls how many times each path can be longer than the shortest path. The shortest path here is defined as the path having the minimum number of links between the specified origin and destination. The term $\gamma = 0$ indicates that the size of the paths should be equal to the shortest path. Fig. 5e shows the shortest path from 1 to 8 along with a three times longer zigzag path. For $\gamma > 3$, the long path is excluded from the set of acceptable paths.

- The paths are loop-less. Fig. 5f shows an unacceptable five-link path with loop.

Taking all the above into consideration, Fig. 5g shows the link-disjoint path between nodes 1 and 8 in the test network when there are no links in common ($\zeta = 0$) and when there is no limitation for the number of links in paths ($\gamma = \infty$). Fig. 5h, as another example, demonstrates all the link-disjoint paths with $\zeta = 1$ and $\gamma = 2$. As the shortest path has two links, $\gamma = 2$ means that the longest path has no more than three links. Another example is shown in Fig. 5i. In this figure, the disjoint paths with only four links when half of their links can be identical ($\zeta = 0.5$) are shown.

![Fig. 6. Tehran transportation network and redundant paths from vertex 967 to vertex 952 in the Tehran transportation network when $\zeta = 0$, $\gamma = 2$.](image-url)
In Fig. 6a, a part of the Tehran transportation network where we aim to find redundant paths between nodes 967 and 952 is shown. Using the above-mentioned concept, the set of link-disjoint paths when $\zeta = 0$ and $\gamma = 2$ is drawn in Fig. 6b. It is important to note that the link-disjoint paths between a given O-D pair are not necessarily unique.

The question that arises here is, how are the geographical data used in the calculation of the redundancy indexes and to find link-disjoint paths? When the transportation network is finalized in the ArcGIS (version 10.2) environment, the binary O-D matrix of travel demand and the adjacency matrix of supply must be exported to spreadsheets. To do so, after the origins and destinations of the emergency and relief trips and their constraints in network use are added to the GIS maps (according to the guidelines mentioned in Table 3), the binary O-D matrix of demand is derived straightforwardly. That is, for any O-D pair, this matrix can contain one of the values 0, 1, or 2; where 0 refers to the absence of the travel demand, 1 points to the existence of the travel demand for the O-D pair with the discipline of using the primary network, and 2 indicates that the travel demand between the related O-D exists and must pass only through the secondary network.

In order to construct the adjacency matrix of supply, it is first necessary to generate a query from the GIS network data. This query is a table with $K$ rows ($K$ is the number of O-D pairs) and 4 columns, where the 1st column is related to the link number, the 2nd and 3rd columns correspond to node numbers as the two endpoints of links, and the 4th column indicates the type of network (i.e., primary or secondary) to which the link is devoted. Then, from this table and by writing a simple code in MATLAB software (version 7.10.0), the adjacency matrix of supply is derived. Any cell $(i,j)$ in this matrix could have one of the values 0, 1, or 2; where zero indicates no link between the two nodes $i$ and $j$, 1 points to the existence of a link in the primary network, and 2 points to the existence of a link in the secondary network. The codes for finding the number of redundant paths between every O-D from the binary O-D matrix are written in MATLAB software (version 7.10.0) and the spreadsheets (binary O-D matrix of demand and adjacency matrix of supply) are read by these codes to calculate the redundancy measure for each O-D pair.

However, only finding the redundant paths with presumed $\zeta$ and $\gamma$ (i.e., redundancy index) between every O-D greater that zero is not analytically and sufficiently sound. In order to clear up the
Table 4
Zones’ exposure indexes by ERT types.

<table>
<thead>
<tr>
<th>Emergency and relief trip (ERT) type</th>
<th>Factors in the exposure index formulation</th>
<th>Zone’s exposure index formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ERT₁</strong>: To carry injured people (point s) to hospitals (point t)</td>
<td>- $E₁^{(s)}$: Zone s exposure index with respect to ERT₁ (trip type 1)</td>
<td>$E₁^{(s)} = \sum_{t\in T} l_t \times B_t^{-1} \times f(s, t)$</td>
</tr>
<tr>
<td></td>
<td>- $I_s$: Number of injured people in the zone (assigned to the centroid of zone s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $B_t$: Number of hospital beds at the destination (i.e., point t)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between point s and the hospital at point t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $T₁$: Set of only three nearest hospitals around zone s</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₂</strong>: To send ambulances (at point t) to triage the patients (at point s)</td>
<td>- $E₂^{(s)}$: Zone s exposure index with respect to ERT₂ (trip type 2)</td>
<td>$E₂^{(s)} = \sum_{t\in T} A_t^{-1} \times I_t \times f(t, s)$</td>
</tr>
<tr>
<td></td>
<td>- $I_s$: Number of injured people in the zone (assigned to the centroid of zone s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $A_t$: Number of ambulances in the emergency response center (point t)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between ambulance center at point t and point s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $T₂$: Set of ambulances of emergency response centers and not the ambulances owned to the hospitals</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₃</strong>: Fire Brigade responses (from fire station at t for conducting firefighting and rescue services at point s)</td>
<td>- $E₃^{(s)}$: Zone s exposure index with respect to ERT₃ (trip type 3)</td>
<td>$E₃^{(s)} = \sum_{t\in T} F_t \times C_t \times f(t, s)$</td>
</tr>
<tr>
<td></td>
<td>- $F_t$: Number of fire engines in the fire station located at point t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $C_t$: Fire extension in zone s (in km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between fire station at point t and point s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $T₃$: Three nearest fire stations to point s</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₄</strong>: Logistic trips to send foods and medical supplies (at point t) to a zone (in point s)</td>
<td>- $E₄^{(s)}$: Zone s exposure index with respect to ERT₄ (trip type 4)</td>
<td>$E₄^{(s)} = \sum_{t\in T} S_t^{-1} \times H_s \times f(t, s)$</td>
</tr>
<tr>
<td></td>
<td>- $H_s$: Number of people in emergency settlement centers at zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $S_t$: Storage capacities of food depositories</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between food depositories and the centroid of zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $T₄$: All the food and medical supply depositories in Tehran</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₅</strong>: Security and military trips (from the police station or military center at t to prevent and solve crime, keep the peace, and respond to criminal activities at point s)</td>
<td>- $E₅^{(s)}$: Zone s exposure index with respect to ERT₅ (trip type 5)</td>
<td>$E₅^{(s)} = \sum_{t\in T} P_t \times D_s \times f(t, s)$</td>
</tr>
<tr>
<td></td>
<td>- $P_t$: Number of police forces in the police station at point t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $D_s$: Number of damaged buildings of zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between police station (point t) and the centroid of zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $T₅$: The police stations or military centers in a district serves to maintain law, protect people and their property, prevent crime, and reduce the fear of crime only in their district</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₆</strong>: Funeral trips from the centroid of zone s to cemetery at point c</td>
<td>- $E₆^{(s)}$: Zone s exposure index with respect to ERT₆ (trip type 6)</td>
<td>$E₆^{(s)} = f(t, c) \times V_c$</td>
</tr>
<tr>
<td></td>
<td>- $V_c$: Number of fatalities (victims) in zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,c)$: Isolation index between the centroid of zone s and the only cemetery in Tehran</td>
<td></td>
</tr>
<tr>
<td><strong>ERT₇⁽⁻⁾</strong>: Trips from Water and Wastewater Company at point t to the centroid of zone s</td>
<td>- $E₇^{(s)}$: Zone s exposure index with respect to ERT₇ (trip type 7)</td>
<td>$E₇^{(s)} = f(t, s) \times D_s$</td>
</tr>
<tr>
<td></td>
<td>- $D_s$: Number of damaged buildings in zone s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- $R(s,t)$: Isolation index between the centroid of zone s and the Water and Wastewater Company assigned to this zone</td>
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</tbody>
</table>
matter. Fig. 7 presents four test networks. In test network I, node i, apparently, seems to be closer to node j than the same nodes in network II and, therefore, any accessibility index should reflect this fact. But, only employing the aforementioned redundancy indexes does not reflect any difference between networks I and II when \( \zeta = 0 \) and \( \gamma = 1 \), and conversely, it enumerates more redundant paths in network II than network I when \( \zeta \leq 0.5 \) and \( \gamma = 1 \).

Before dealing with this problem, two points must be noted regarding network redundancy index:

1- The set of all possible redundant paths is not necessarily unique. For example, regarding test network II in Fig. 7, the two paths \( \{i \rightarrow m_1 \rightarrow m_4 \rightarrow m_8 \rightarrow j\} \) and \( \{i \rightarrow m_3 \rightarrow m_4 \rightarrow m_2 \rightarrow j\} \) could be considered instead of what has been shown in this figure. What was shown in Fig. 7 is only a sample set of all possible redundant paths from i to j. However, it should be noted that the number of all possible redundant paths from i to j is unique. In the test network II, it is always 2 when \( \zeta = 0 \), \( \gamma = 1 \), and 6 when \( \zeta \leq 0.5 \), \( \gamma = 1 \).

2- Small values of \( \zeta \) (near zero) would confine the set of all possible redundant paths to the topology of the sparse parts of the network. For example, as shown in Fig. 7, in test network III, the link between \( m_3 \) and \( m_8 \) is the most important element in the network, limiting the total number of all possible redundant paths.

3- In the grid network, for the small values of \( \zeta \) the links connected to the source (i) and sink (j) limit the set of all possible redundant paths.

4- For example, as shown in the test network IV of Fig. 7, no matter how the network is stretched, when \( \zeta = 0 \), \( \gamma = 1 \), there are still two possible redundant paths (similar to networks I and II).

### 4.4. Isolation index

Coming back to the problem of the redundancy index in the context of the vulnerability analysis, we suggest the distance between source and sink nodes \((i, j)\) be taken into account as a factor of spatial isolation of travel demand in \( i \) from the facilities in \( j \). In Fig. 7, it is recognized that by increasing the distance between two nodes \( i \) and \( j \) in the grid network the number of intermediate nodes increases rapidly and nonlinearly, implying more redundant paths between the O–D pair \( i \) and \( j \) when \( \zeta \) and \( \gamma \) are high enough. For example, when \( i \) and \( j \) are within the size of one diameter of the grid network, two intermediate nodes, \( m_1 \) and \( m_2 \), exist (see test network I). But when they have a two-diameter distance, seven intermediate nodes \((m_1 \rightarrow m_2)\) exist. For an \( m \)-diameter distance between \( i \) and \( j \), \((m + 1)^2 - 2\) intermediate nodes exist. Furthermore, the number of redundant paths passing these intermediate networks rapidly grows when the number of intermediate nodes increases (the disjoint paths problem is known as an NP-complete problem).

To sum up, in order to estimate the isolation \((I)\) of origin \( s \) from destination \( t \) with the number of redundant paths between \( s \) and \( t \) and by considering the distance between them, the following equation is defined:

\[
I(s, t) = \left(r^{1-\gamma}(s, t)\right)^{-1} \times e^{(\alpha d(s, t))}
\]

where, \( r^{1-\gamma}(s, t) \) is the redundancy index between \( s \) and \( t \) regarding the predefined \( \zeta \) and \( \gamma \) indexes, \( \alpha \) is a coefficient, and \( e^{(\alpha d(s, t))} \) is the exponential function of the average length of the redundant paths (i.e. link-disjoint paths) in kilometers between this O–D pair. The term \( e^{(\alpha d(s, t))} \) tries to balance the non-polynomial increase of the redundant path because of the increased distance.
It seems clear that the higher the isolation index for traveling from \( s \) to \( t \), the greater the difficulty of traveling from \( s \) to \( t \) on the specified network (i.e. primary and secondary networks). In the following, the isolation index is applied to calculate the two subsequent indexes: zone exposure index and trip-type isolation index.

Eq. (1) is applied when the uncertainties of demand values and supply disruptions are similar to what are presented in this paper. When travel demand is known even with levels of uncertainty (with stochastic or fuzzy variables), and the transportation network component failure modes are identified, the conventional methods of network analysis should be applied.

A parallel study by this research team was conducted in which simulations of the hypothetical urban test networks were implemented by which the urban system failures and the number of killed and wounded people, and the exact location of damaged facilities were determined accurately. The conventional network analysis method determined the accessibility measures of the disrupted networks for different types of emergency and relief trips. Then again, the network vulnerability analysis was performed by the method presented in this paper with different default values of \( \alpha \), \( \zeta \), and \( \gamma \). Through this procedure appropriate values of the parameter were determined.

4.5. Trip-type isolation index

To see which of the post-earthquake emergency and relief trips have more problems and limitations, for each trip type in Table 3, a trip-type isolation index is calculated by summing up the isolation indexes over all \( O-D \) pairs related to the trip types as:

\[
I_i = \sum_{i \in O} \sum_{t \in D} \left( r_{i,t}(s, t_i) \right) \times e^{(\alpha \times \frac{D_{s,t}}{D_{s,t}})}
\]

(2)

where, \( I_i \) is the trip-type \( i \) isolation index, \( O \) and \( D \) are the set of origins and destinations associated to trip type \( i \), \( t_i \) is the origin and \( s_i \) is the destination of the \( O-D \) pair of the trip type \( i \) (see Table 3, Columns 3 and 4). Other notations are similar to Eq. (1).

4.6. Zone's exposure indexes

To understand for any type of travel which zone is more isolated and, hence, needs further attention, an exposure index is defined as a site-dependent measure to capture the consequence of the hypothetical earthquake in each zone only for a period of three days after the earthquake.

Some of the emergency and relief trips listed in Table 3 (within the three days after the earthquake) are used to calculate this index. The emergency and relief trips presented in Table 4 are those that are thought to play a prominent role in the post-disaster operations during the first three days after the earthquake.

In Table 4, Column 1 shows emergency and relief types, Column 2 enumerates the factors determining the exposure index of zone \( s \), and Column 3 shows the formula of the exposure index. It is important to note that in this table, the index of zone is \( s \) and the index of place where emergency and relief activities are started from or terminated to (e.g. hospitals, fire stations, etc.) is \( t \). The coordinates of the zones are concentrated in the center of the areas (i.e. centroids) on the GIS maps. An emergency and relief trip could be started from a centroid and terminated to an emergency and relief center (for example, hospitals) or it could be from an emergency center (like fire stations) to a zone centroid. In the former, \( I(s, t) \) is put in the Zone's Exposure Indexes in Table 4, while in the latter, \( I(t, s) \) is inserted. Each emergency and relief trip may have its relative importance when compared to other ones. These relative weights are elicited from the specialists and quantified by the pairwise comparison methods as shown in Fig. 2.

5. Results and discussion

Among all the trips of Table 3, the medical and relief trips owned the highest value of trip-type isolation index (when \( \zeta = 0 \) and \( \gamma = 2 \)). It means that this trip type is more vulnerable due to the hypothetical earthquake and necessary changes in the current emergency plan of the city of Tehran should be devised.

The normalized exposure indexes related to the type of trips (e.g. restoration, emergency response trips, etc.) were determined with \( \zeta = 0 \) and \( \gamma = 2 \) for all the spatial units, including census block, sector, zone and districts. However, due to the space limitation, in Fig. 8a, only the results of zones' exposure indexes for the emergency response trips were demonstrated.

Based on Table 3, these types of trips use only secondary network. The redundancy index of the secondary network and consequently the exposure values which have been illustrated by bright yellow are lower in the central part of Tehran. These regions represent the areas with higher number of rescue and relief centers, denser secondary network and less damage. In return, as we approach the suburban areas, the redundancy index and exposure values increase and the regions are illustrated with darker colors. Such regions with less dense secondary network represent the areas with higher damage.

An interesting result is obtained through mapping the normalized overall exposure index derived from the sum of weighted exposure indexes related to various trip types. As can be seen in Fig. 8b, the darker color indicating higher values of the estimated overall exposure index (last row of Table 4) can be found in the northeast, the western and the southwestern part of the study area. However, the brighter colors which indicate the lower values of overall exposures are seen in central zones toward the south.

A vulnerability analysis is not sufficient per se. But it is used as a module of a planning problem as shown in Fig. 9. A planning problem starts with the definition of its goal (i.e. Goal setting). For the post disaster emergency and relief planning problem the goal is achieved through answering the question: “Why is the transportation system important after a disaster?”

When the goal is identified the objectives are specified. The objectives could be: keep the serviceability of a certain section of the transportation system as one of the important lifelines within the specified time frame, under the crisis scenario, and through considering the budget; manage to retain the accessibility to new origins and destinations within the post-crisis period; reduce the number of casualties; etc.

Having the objective(s), one could outline the mathematical formulation of the problem. For example, it could be anti-seismic reinforcement of the bridge, network design with respect to emergency management activities, post-disaster reconstruction prioritization, optimal placement of facilities (like fire stations and hospitals) etc.

Vulnerability analysis is used to analyze iteratively the effect of different scenario of planning model. It gives the indicators as the measures of effectiveness (MOE) as a feedback to a solution of the model.

This paper was the result of the team working on the construction of the vulnerability assessment module of a planning problem. Through the module provided by this study, each emergency and relief organization in Tehran could define a planning problem to boost their activities and post-disaster operations. Moreover, the global emergency response plan and the comprehensive master plan on Tehran seismic disaster mitigation could be checked and revised.

6. Conclusion

Disaster planning and response is well underway and incorporated into national and state transportation agency operations in developed
This paper demonstrates the challenges of trying to develop comparable plans in developing countries, especially those with immediate natural disasters—in this instance a major population center in a geographic area prone to earthquakes—as a fact of everyday life. The paper provides an approach to evaluate post-earthquake response and recovery routes by identifying redundancy-based accessibility measures.

The situation of Tehran is somewhat disheartening as it has developed haphazardly with scarce attention to construction and building codes, which leaves structures, transportation routes, and residents vulnerable. Vulnerability analysis has expanded in three broad directions. First, it is for long term planning (for typical planning horizons of 1–3 decades), where broader socioeconomic issues are considered at the regional scale, and for which vulnerability analysis based on changes in accessibility provides important information.

![Fig. 8.](image-url) (a) Zones’ normalized exposure indexes related to emergency response trips; and (b) normalized overall exposure index.
about the role of the transportation network in fostering economic opportunity and in uncovering ‘weak spots’ (critical infrastructure locations). Second, it is for the shorter term, but ongoing vulnerability analysis of the travel impacts of network closures or degradations due to short term disturbances and events such as flooding, storms, landslides and the like, and as exemplified by the importance-exposure method for vulnerability analysis. Third, it is for vulnerability studies applied to emergencies and catastrophic events (e.g. earthquakes) where substantial damage may have occurred to the network infrastructure and there are immediate needs for search and rescue missions. This final case is the one dealt with in this paper.

A transportation network vulnerability analysis for the greater Tehran held in this paper, and the normalized exposure indexes related to different trips were presented. The results could provide a good resource and perspective for the Tehran Disaster Mitigation and Management Organization.

In this paper, the authors intended to introduce the supply systems provided for the search and rescue operation and emergency and relief activities after a disastrous earthquake. Then, the image of activity-travel patterns after the destructive earthquake was drawn. Hundreds of person-hours of skilled professionals having good experience of earthquakes in an earthquake-prone country like Iran, took part in the sessions to shape these concepts and brainstorm the ideas. Introducing the pattern of post-earthquake necessary emergency and relief trip, the idea brainstormed from group-creativity techniques pointed out that the phase of introducing the emergency and relief trips was confined to only the origin and destination, discipline in network usage, and usual interval (start and end time) of these trips. The amount of travel demand (between O and D pairs) is not predictable due to the many uncertainties of the transportation system after a severe earthquake. Hence, instead of the O–D matrix of demand, the binary O–D matrix of demand was introduced. The binary O–D matrix implies that a certain amount of travel demand between O–D pairs exists, but the amount is unknown. Focusing on the concept of binary O–D matrix, a redundancy index to measure the level of accessibility between each binary O–D pair was introduced. That is to say, a redundancy-based accessibility measure was employed as the network analysis method after a severe earthquake.

This paper attempted to answer these two questions: (i) Within the emergency management context, which urban transportation regulation should be exerted to deal with and alleviate the consequences of a huge and destructive earthquake?; and (ii) How could a transportation network vulnerability analysis be performed for this pre-determined management plan? Attempts to answer the latter one leads to the following questions which we endeavored to answer in this paper: (a) Which factors determine the robustness of a road network against the catastrophic earthquake? and (b) How can the indicators be computed to quantify such robustness factors?

The result of this study demonstrates which emergency and relief trips are more vulnerable as a consequence of the hypothetical earthquake which stressed the necessary changes in the current emergency plan of the city of Tehran. The results also indicated which zone has the highest exposure index with respect to different activities after the earthquake.

In order to apply the analytical method proposed in this paper for wider applications, we recommend that the related planning and network management authorities ensure that the following information is available (i.e. it would be too late after the catastrophe occurring):

- Network topology and details.
- Travel databases associated with the metropolitan travel demand models.
- Travel demand origins and destinations after the earthquake for each emergency and relief trip type.
- Potential spots for emergency settlement camps.
- Structural data on tunnels, bridges, etc.
Appendix A

All trips shorter than 3 km are made on foot. All the important trips after a severe earthquake used for the vulnerability analysis are as follows:

- **Trip Type 1–Restoration trips**: These trips start in the aftermath of the earthquake to inspect and if needed, preliminarily recover the lifelines such as communication, electricity, water, wastewater, and gas networks. In the first stage, these trips take 3 days to check the damage and, if possible, restore and temporarily repair the most important parts of the networks for the primary utilization. Then the complete restoration of the whole network takes up to three months. These trips contain return trips because the inspection team should come back to the organization, unlike the settlement trips in which people go from their places to the emergency/temporary shelters and mostly do not return to their places. These trips begin from the organizations/companies towards the centroids of their sectors which are not necessarily the same as municipal districts. As mentioned above, each organization may have several branches and for each one, parts of the city are assigned. These parts are named in this paper as sectors, e.g., Power Organization sectors. These sectors may not necessarily correspond with zones. The branches of each organization are only acting under a predefined instruction and serve only the parts of the city that are relevant to them.

- **Trip Type 2–Search and rescue operation**: These trips are performed to rescue people from the debris of collapsed buildings or other urban entrapments. Rescuers use life detectors to search for survivors and try to grasp the “golden time” of 72 h after the earthquake to save as many people as possible.

- **Trip Type 3–Medical and relief trips**: Medical and relief trips aim to: (a) transmit ambulances from ambulance centers to participate in the triage process, (b) take injured people to hospitals (carrying injured people with civilians’ private cars to hospitals are also included in this category), and finally, (c) return to the ambulance centers for the next mission if there is no announcement of new mission when they are out of the centers. As the golden time period for life saving is 72 h after the earthquake, these trips are important for our analysis just within 3 days after the earthquake. The discipline to transport injured people to hospitals is to carry them to the nearest non-private hospital. Hence, due to intra-regional assignments, ambulances are forced to utilize secondary roads unless there is an exception. It is important to note that only the ambulances of the emergency response centers are dispatched regardless of ambulances owned by hospitals.

- **Trip Type 4–Emergency settlement**: Emergency settlement sites have been established in each mahalleh inside mosques, schools and parks of the mahalleh. The necessary equipment has already been provided in these sites. As people usually tend to stay near their properties after the earthquake, it takes some time to settle them completely in the emergency settlement sites. Trips terminated to emergency settlement sites are done mostly on foot using local and secondary arterials excluded from the primary and secondary networks. The people are not allowed to use the primary routes, but they can use the secondary road network.

- **Trip Type 5–Fire brigade responses**: Firefighting trips begin right after the earthquake and mostly last for about 4 days. Although there is some evidence of past earthquakes when fire was not put out after the first 4 days, it is not a general situation. In Tehran, there are a certain number of firefighting sectors. Within each sector, there are some fire stations. Any station serves only parts of the city within the sector itself, unless unusual circumstances due to the large extent of fire in a particular neighborhood occurs. Hence, for each sector, the origins of fire brigade trips are the places of fire stations inside the sectors and the destinations are the centroids of mahallehs located within the sector.

- **Trip Type 6–Logistic trips**: Logistic trips are held during the first week after the earthquake to transfer essential foods and goods from disaster management centers to citizens in emergency settlements.

- **Trip Type 7–Entrance and settlement of the teams from supporter provinces**: In Iran, each province has its own disaster mitigation and management organization. Some of them, which are called supporter provinces, have been appointed to be responsible for service and support of Tehran after a severe earthquake and each one should serve its own predefined district. Just after the earthquake, they head toward Tehran’s Disaster Management Centers.

- **Trip Type 8–Debris removal**: Debris removal trips aim to clear the debris and transfer it out of the city in debris depot sites. Primary roads have the first priority to be cleaned, and then, this operation continues along the secondary and local roads. The debris removal trips could last for 6 months or even longer.

- **Trip Type 9–Organizational and administrative traffic**: These trips are related to the arrangements and work which are needed to control the operation of the emergency management plan or the task of organizations. Usually government and senior government officials make several trips after the earthquake to cooperate and coordinate the process of disaster management relief activities. As an example of an O–D pair, suppose that a certain number of foreign rescuers unexpectedly arrive in Tehran from the international airport of Tehran and settle in the Tehran Disaster Mitigation and Management Organization. Or as another example, suppose that the secretary of health and human services is going to personally visit key hospitals in Tehran. Such trips are among the most uncertain and most unknown trips. Both origins and destinations comprise a complete list of the various organizations or places necessary to take action after the earthquake. We do not know exactly what type of trips between them may be made, but they should be connected together to make secretaries, executives, managers, and various specialists able to make their possible trips. Radio/TV station and major airports and helicopter pads are also added to the origin and destination spots.

- **Trip Type 10–Security initiatives**: Security trips are produced to prevent burglaries and social crimes. As after disasters a growth in the number of crimes occurs, security controls by police and military organizations should be stricter. During the response and recovery phase after earthquakes, security trips are produced through both primary and secondary (and local) routes to inspect and maintain people’s properties and lives. Additionally, police are responsible for emergency road security.

- **Trip Type 11–Burial affairs**: As Tehran’s cemetery is located in an open area in the south of the city and close to several highways, people will use primary roads to approach the cemetery and return to their houses/settlements.

- **Trip Type 12–Other urban trips**: Urban trips made by citizens approximately one week after the earthquake to respond to their primary needs. As the primary roads will be open several days after the earthquake, people can also use them in addition to the secondary routes for their long distance travels. Specialists who participated in creating this table believed that each mahalleh should be readily accessible by the mahallehs around it.

- **Trip Type 13–Damage assessment after earthquake**: Damage assessment trips are done by several organizations such as the
Construction Engineering Organization, Housing Foundation, and Civil and Technical Deputy of Tehran Municipality to evaluate damage to the buildings, bridges, critical facilities and structures. In most cases, secondary roads are used for assessment, but for some facilities like bridges, inspections are carried through primary routes.

- **Trip Type 14–Trips related to the reconstruction process:** These trips are mostly held by governmental organizations and construction companies and can continue for two years depending on the extent of destruction.

References


