Project Title: **Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain**

Acronym: SYNER-G

Project N°: 244061

Call N°: FP7-ENV-2009-1

Project start: 01 November 2009

Duration: 36 months

**DELIVERABLE INFORMATION**

Deliverable Title: **D2.6 – Definition of system components and the formulation of system functions to evaluate the performance of transportation infrastructures**

Date of issue: June 2011

Work Package: WP2 – Development of a methodology to evaluate systemic vulnerability

Deliverable/Task Leader: University of Rome La Sapienza

---

**Project Coordinator:**

Institution: Aristotle University of Thessaloniki

e-mail: [kpitilak@civil.auth.gr](mailto:kpitilak@civil.auth.gr)

fax: +30 2310 995619

telephone: +30 2310 995693
Abstract

After an introduction dealing with the possible levels of analysis and the model of a Road Network (RDN), the main typologies of the elements of a RDN are identified. Such typologies include only the vulnerable elements. This work has been also carried out with the purpose of producing a state-of-the-art of available performance indicators, useful to assess the performance of the whole system and its elements when subjected to a seismic hazard. Some of the reported performance indicators (PI’s) are defined at the component level, i.e. for the generic origin-destination (OD) pair, while the remaining ones describe the overall performance of the system. Most of the considered PI’s do not analyze the network on the plain level of connectivity, concerning the existence of a path between a specific OD pair. Instead, they aim at assessing the serviceability of the RDN, by considering quantities such as flows, demand, capacity and travel time.

Keywords: component-level, system-level, connectivity, capacitive, travel time, user equilibrium, reliability.
The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061.
Deliverable Contributors

UROMA  Paolo Emilio Pinto
        Francesco Cavalieri
        Paolo Franchin
        Alessio Lupoi
# Table of Contents

Abstract ........................................................................................................................................ i  
Acknowledgments ...................................................................................................................... ii  
Deliverable Contributors ........................................................................................................... iii  
Table of Contents ....................................................................................................................... iv  
List of Figures ............................................................................................................................. v  
List of Tables ................................................................................................................................ vi  

1 Taxonomy of road networks .............................................................................................. 1
   1.1 LEVELS OF ANALYSIS OF A ROAD NETWORK ....................................................... 1
   1.2 ROAD NETWORK MODEL ..................................................................................... 2
   1.3 IDENTIFICATION OF THE MAIN TYPOLOGIES FOR ROAD NETWORK ELEMENTS .................................................................................................................. 5

2 Performance Indicators ...................................................................................................... 6
   2.1 EXISTING PERFORMANCE INDICATORS ............................................................. 7
      2.1.1 Component-level PI's ....................................................................................... 7
      2.1.2 System-level PI's ............................................................................................. 8
   2.2 PROPOSED PERFORMANCE INDICATORS ........................................................... 9
      2.2.1 Component-level PI's ....................................................................................... 9
      2.2.2 System-level PI's ............................................................................................. 9
   2.3 DISCUSSION ............................................................................................................. 10

References ................................................................................................................................ 12
List of Figures

Fig. 2.1 Evolution of the expected value of SSI (left) and MAF of SSI (right) .......................... 7
List of Tables

Table 1.1 Main typologies of RDN components........................................................................ 5
1 Taxonomy of road networks

1.1 LEVELS OF ANALYSIS OF A ROAD NETWORK

A fundamental distinction among the studies related to the seismic performance of road or transportation networks can be made based on the importance of the role played by the network itself. In a way of simplification, available studies can be assigned to the following three levels:

- **Level I**: the attention is focused on the functioning of the network in terms of pure *connectivity*. This type of studies focuses on just one of the services provided by the network, e.g. most typically the rescue function immediately after the earthquake, and may be of interest in identifying portions of the network which are critical with respect to the continued connectivity of the network.

- **Level II**: the scope of the study is widened to include consideration of the network capacity to accommodate traffic flows. The damage to the network causes traffic congestion, resulting in increased travel time which is in turn translated into monetary terms. This indirect loss summed to direct loss incurred due to damage to the building stock results in a first partial estimate of the overall economic impact of an earthquake.

- **Level III**: The most general approach, which aims at obtaining a realistic estimate of total loss, inclusive of direct physical damage to the built environment (residential and industrial buildings as well as network components), loss due to reduced activity in the economic sectors (industry, services), and network-related loss (increased travel time). Economic interdependencies are accounted for, such as the reduction in demand and supply of commodities (due to damaged factories, etc.), hence in the demand for travel, and due to the increased travel costs. At this level the relevance and the complexity of the economic models become dominant over that of the transportation network. This is a full systemic study requiring important inputs from the economic disciplines.

The treatment of the third level involves reaching beyond the area of structural engineering and involves important inputs from the economic disciplines. Further, the practical feasibility of these studies requires data which are seldom available, both in terms of quantity and quality. In particular, studies of the third level necessitate of detailed data on the demand and supply of goods and commodities disaggregated by economic sector and spatial location. Collection of this information requires the involvement of governmental bodies.

Two similar examples of Level I studies can be found in Nuti and Vanzi (1998) and in Franchin *et al* (2006). In both studies the road network serves the purpose of connecting the hospitals in a regional health-care system. The mortality rate of casualties, in case of seismic event, is substantially reduced if they receive care in a short time. After a strong earthquake, damage and/or congestion of hospitals, and of the transportation network, cause an increase in the distance to be covered, because casualties exceeding the hospitals capacity have to be moved to non full ones and because of interrupted links which result in a decrease in the transportation speed. The first study proposes the distance covered by each casualty, defined in probabilistic terms, as a meaningful system performance measure. Comparing the distance distribution after an earthquake (accounting for damage to hospitals and road network, as well as for casualties and congestion), under different seismic retrofit/upgrade scenarios with the baseline distribution gives useful indications for the allocation of resources.
Examples of Level II studies are those in Shinozuka et al (2003) and Chang et al (2011). The approach in Shinozuka et al. (2003) aims at the determination of direct and indirect economic loss due to damage to a transportation network. Direct loss is related to physical damage to vulnerable components, while indirect loss is related to functionality of the system, whose degradation is measured in terms of a system-level performance index called Driver’s delay (DD), i.e. the increase in total daily travel time for all travellers. Indirect loss is expressed as the DD times a unit cost of time. Traffic flows are evaluated by equilibrium analysis under a static origin-destination matrix. The vulnerable components are the bridges within the network, for which four states of increasing damage and corresponding fragilities are employed: minor, moderate, major and collapse. The state of each link, corresponding to a different residual traffic capacity, equals that of its most severely damaged bridge. Total DD is obtained by summing the values for all days over which the delay persists. However, the DD decreases over time due to repair activity taking place after the event, modelled in an admittedly over-simplified manner. This study is extended in Zhou et al. (2004), to consider the effect of retrofit strategies in improving the performance in future events.

The work by Chang et al (2011) advances a proposal for going beyond the use of the pre-earthquake (static) origin-destination matrix as an input for traffic flow analysis. The post-quake travel demand is complicated and the change of traffic pattern after the event is coupled with the damage of transportation infrastructures. To arrive at a new origin-destination matrix the paper modifies the trip generation and distribution stages of a traffic analysis to accommodate for earthquake-induced damage. Traffic Analysis Zones (TAZ) are classified into four types, depending on the presence of attractants (e.g., hospitals or emergency shelter) and repellents (e.g., hazardous materials (HAZMAT) release, fire following earthquake, or damaged facilities). Then the pre-earthquake travel demand of each TAZ is modified according to the classification. Several general assumptions are made on post-earthquake travel behaviour and emergency traffic management measures. The paper reports also an extensive literature review on attempts to model traffic pattern changes in the aftermath of an earthquake.

Finally, among the few available Level III studies, an example is the work by Karaca (2005). The work reports a regional earthquake loss methodology that emphasizes economic interdependencies at regional and national scales and the mediating role of the transportation network. In an application to the Central U.S. under threat from earthquakes from the New Madrid Seismic Zone, regional and national losses from scenario earthquakes are evaluated, together with a quantification of the corresponding uncertainty including contributions from seismicity, attenuation, fragilities, etc. The effectiveness of alternative mitigation strategies is also considered. The loss assessment methodology includes spatial interactions (through the transportation network) and business interaction (through an input-output model) and extends geographically to the entire conterminous U.S. The losses reflect damage to buildings and transportation components, reduced functionality, changes in the level of economic activity in different economic sectors and geographical regions, and the speed of the reconstruction/recovery process. Evaluation of losses for a number of scenario earthquakes indicates that losses from business interruption may be as significant as infrastructure repair costs.

### 1.2 ROAD NETWORK MODEL

The modelling and the analysis of a transportation network for the purpose of seismic performance assessment relies on tools and methods of increasing complexity depending on which approach to the problem is adopted. Level I studies require a simple description of the network in terms of a graph and analysis tools are limited to basic graph theory results. Level II and III studies require
additional information and specialized algorithms for the determination of traffic flows on the congested, damaged network. In the following, a short, and non exhaustive, introduction to the concepts of transportation engineering that are employed in level II and III studies is presented.

The most common methodology applied for Urban Travel Forecasting is the four stages transportation/land-use model, also known as the **sequential procedure**, originally developed in the fifties by transportation engineers and planners for the Detroit Area Transportation Study (DATS) and the subsequent Chicago Area Transportation Study (CATS). It is important to note that it was not conceived as a “real-time” predictor of the state of traffic on a damaged network at discrete time instants after a seismic event. In fact, the application of aggregate trip distribution models (see later) has only proven to be effective for relatively long term forecasting (Levinson and Kumar 1994).

Typically the region of interest is subdivided into $n$ TAZ’s and, by either trend or regression analysis, population and employment levels are determined for each zone. The four stages of the procedure are:

- **Trip Generation.** In each zone, the frequency of origins and destinations, i.e. the number of *trips generated* from or *attracted* to each zone, are evaluated by trip purpose as a function of land use, household demographics and other socio-economic factors.

- **Trip Distribution.** Movements between zones are evaluated, i.e. the total trips originated from zone $i$ are distributed among all the other zones as a function of the *zonal demands* and *inter-zonal distances*.

- **Mode Split.** Movements between origins and destinations are disaggregated by type of transportation or mode (bus, railway, car, airplane, etc..) depending on the availability of each mode, their respective costs and user preferences.

- **Traffic Assignment.** All the estimated trips between zones, disaggregated by purpose and mode, are *loaded* on the transportation network to determine the total flows on each arc. Typical traffic assignment algorithms account for the fact that users want to minimize their travel time.

It should be noted that the four stages are to a large extent interrelated. For example when traffic flow exceeds the capacity of a specific arc, resulting in congestion and affecting travel time, this, through a feedback process, may influence trip generation and distribution. The procedure is hence inherently iterative. Convergence is often measured in terms of *minimal transportation generalized cost* (e.g. distance, time, money, etc.).

Models of different types are applied at the four stages of the procedure.

For the purpose of the *trip generation* stage, **Land Use Models** are used. These models account for the spatial structure of macro- and micro-economic components. For instance, by using a set of economic variables, such as population, employment and consumption levels, it is possible to calculate the *generation* and *attraction* of passenger and freight trips.

*Passenger trips* are usually divided in categories according to trip purpose, such as home-to-work, home-to-shop, home-to-other, etc. *Freight trips* are also grouped, usually as a function of the transported goods: durable, non-durable, mining, oil, etc. While data on passenger trips are usually available, either as the result of surveys and/or by manipulation of census data, the estimate of freight trips is a more challenging task. This type of traffic is originated by several sources, both external (airport, seaport, etc.) and internal (local industries) to the region of study; data are usually available in terms of *goods production* (measured in monetary units), and they have to be converted to *passenger car units* (PCU); inter-industry relationships (the so-called *input-output*
models) have to be established to derive the trip production and attraction of commodities, etc. Determination of freight trips is intrinsically related to the description of the economics of the region and it is the natural domain of level III studies. For what follows it is assumed that the trips production and attraction (the product of the trip generation stage) are known.

For the purpose of the trip distribution and mode split stages, Spatial Interaction Models are used. These models produce flow estimates between TAZ’s, in terms of origin-destination pairs, which can be disaggregated by nature, mode and time of the day. In available earthquake engineering applications, the attention is focused exclusively on the road network, i.e. on the public and/or private transportation by car, making unnecessary the mode split stage. Input data of the trip distribution stage are the total number of trips originated from and destined to all the TAZ’s in which the region of study is subdivided. Originated trips can be regarded as the trip-productions or capacities $C_i$’s (index $i$ spanning TAZ’s), destined trips as the trip-attractions or demands $D_j$’s. The output of the trip distribution stage is the $n \times n$ “trip table” matrix $T_{ij}$, also called origin-destination matrix, which displays the number of trips from each origin to each destination.

Once the trips among the zones are (tentatively) established, the next stage is to “load” them on the road network (the traffic assignment stage). The models currently in use are the network equilibrium models. They are based on the so-called two principles of equilibrium by Wardrop (1952):

1. First principle: All used routes from node $i$ to node $j$ have equal travel times, and no unused route has a lower travel time;
2. Second principle: At equilibrium the average travel time is minimum.

The first principle implies that each user non-cooperatively seeks to minimize his cost of transportation, and cannot lower his transportation cost through unilateral action. The traffic flows that satisfy this principle are usually referred to as user equilibrium (UE) flows, since each user chooses the route that is the best. The second principle implies that each user behaves cooperatively in choosing his own route to ensure the most efficient use of the whole system. Traffic flows satisfying Wardrop’s second principle are generally deemed system optimal (SO) flows.

The UE flows can be found by solving a nonlinear programming problem. Once convergence is achieved, the volume of traffic on each link and the corresponding average travel time are available.

These issues are further explained and dealt with in deliverable report D5.5.
1.3 IDENTIFICATION OF THE MAIN TYPOLOGIES FOR ROAD NETWORK ELEMENTS

The elements of road networks comprise bridges, tunnels and roadways. The first two are vulnerable. Concerning the roadways, that are classified as major and urban, the vulnerable and most important segments can run on embankments, in trenches or along unstable slopes. Table 1.1 takes into account this distinction and reports five main typologies of road network elements.

<table>
<thead>
<tr>
<th>Code</th>
<th>System Description</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDN01</td>
<td>Bridge</td>
<td>Bridge</td>
<td>Bridge can be girder bridges, arch bridges, cable-supported bridges, etc. Girder bridges can have simply-supported or continuous deck, single column, multiple column, or solid wall piers, monolithic or bearings deck-piers connection. Material: concrete, steel, mixed.</td>
</tr>
<tr>
<td>RDN02</td>
<td>Tunnel</td>
<td>Rock or alluvial tunnels. Bored, NATM (circular, petaloid section) or Cut &amp; Cover (rectangular section). Various supporting systems (concrete etc).</td>
<td></td>
</tr>
<tr>
<td>RDN03</td>
<td>Embankment (road on)</td>
<td>Described by geometrical parameters (slope, etc), soil conditions, water table.</td>
<td></td>
</tr>
<tr>
<td>RDN04</td>
<td>Trench (road in a)</td>
<td>Described by geometrical parameters (slope, etc), soil conditions, water table.</td>
<td></td>
</tr>
<tr>
<td>RDN05</td>
<td>Unstable slope (road on, or running along)</td>
<td>Described by geometrical parameters (slope, etc), soil conditions, water table.</td>
<td></td>
</tr>
</tbody>
</table>
2 Performance Indicators

Within the seismic reliability analysis of an RDN it is needed to assess the performance of the whole system and its components when subjected to a seismic hazard. The quantitative measure of this performance is given by Performance Indicators (PI's), that express numerically either the comparison of a demand with a capacity quantity, or the consequence of a mitigation action, or the assembled consequences of all damages (the "impact").

In general, for an Infrastructure (system of systems) performance indicators can be categorized according to the level in the hierarchy of the Infrastructure to which they refer. Thus one has:

- Component level PI's
- System level PI's
- Infrastructure level PI's

With reference to the system RDN, the following sub-section presents some performance indicators existing in the literature, belonging to the first two categories above. For all indicators, two properties are indicated, each of them with two possible values:

- Connectivity / Capacitive modelling
- Deterministic / Probabilistic

The first property tells if the indicator is able to capture the system performance focusing on connectivity only or accounting for the actual power flows in the network.

If the indicator is deterministic, its value can be computed within a single run of a simulation (performed according to the Monte Carlo method, for instance). A probabilistic indicator, on the other hand, can be computed only when the results of two or more runs of a simulation are available, thus accounting for the uncertainty modelling, as explained in deliverable report D2.1. This latter indicator most commonly consists of a moment (e.g. expected value) or distribution of a deterministic indicator, or a function of the above. As an example, Fig. 2.1, left, shows the evolution, with the number of runs, of the expected value of a common PI, the System Serviceability Index (SSI), while in Fig. 2.1, right, is displayed the Mean Annual Frequency of exceedance of SSI, computed at the end of the simulation.

A probabilistic indicator can also be defined as probability of events (e.g. \( P(PI > 0) \approx \frac{\sum_{i=1}^{N} I(PI > 0)}{N} \)), where \( N \) is the total number of runs and \( I \) is the indicator function).
2.1 EXISTING PERFORMANCE INDICATORS

2.1.1 Component-level PI's

- **Connectivity reliability** [probabilistic, connectivity modelling]. Connectivity reliability is concerned with the probability that the network nodes remain connected. A special case of connectivity reliability is the *terminal reliability* (Iida and Wakabayashi, 1989), which concerns the existence of a path between a specific origin-destination (OD) pair. For each node, the network is considered successful if at least one path is operational. A path consists of a set of components (roadways or arcs), which are characterized by a zero-one variable denoting their state (operating or failed). Capacity constraints on the arcs are not accounted for.

- **Travel time reliability** [probabilistic, capacitive modelling] (Asakura and Kashiwadani, 1991). This is defined as the probability that a trip between a given OD pair can be made successful within a specified interval of time. This measure is useful to evaluate network performance under both normal daily flow variations and seismic conditions. With reference to the latter case, and hence to capacity reduction due to road damage, let $C$ and $C_0$ be the vectors of damaged and undamaged states of the arcs in the paths and the corresponding travel times between the OD pair $w$ in these two states be denoted as $t_w(C)$ and $t_w(C_0)$. The travel time reliability is defined as the probability $\tau_w(\theta)$ of the ratio of $t_w(C)$ to $t_w(C_0)$ being lower than an acceptable level $\theta$:

$$\tau_w(\theta) = P\left(\frac{t_w(C)}{t_w(C_0)} \leq \theta\right)$$

The value $\theta$ can be interpreted as the level of service that should be maintained despite the capacity reduction that has occurred on certain arcs in the network. This index expresses a functional consequence for OD pair $w$ of the physical damage to the whole network. When interactions with other systems are modelled, $\tau_w(\theta)$ expresses the functional consequence.
Performance Indicators

for OD pair \( w \) of the physical damage to components of all the interacting systems, i.e. it is the value of the index that changes due to the inter- and intra-dependencies, not its definition.

2.1.2 System-level PI’s

- **Simple Connectivity Loss**, or SCL [deterministic, connectivity modelling] (Poljanšek et al, 2011). This index, whose definition is based on the concept of connectivity, for a generic system measures the average reduction in the ability of sinks to receive flow from sources:

\[
SCL = 1 - \left\langle \frac{N_i'}{N_0'} \right\rangle_i
\]

where \( \left\langle \cdot \right\rangle \) denotes averaging over all sink vertices, while \( N_i' \) and \( N_0' \) are the number of sources connected to the \( i \)-th sink in the seismically damaged network and in non-seismic conditions, respectively. With reference to a RDN, all the single TAZ’s, taken one at a time, are considered sinks, whereas all the remaining TAZ’s are sources.

- **Driver’s Delay**, or DD [deterministic, capacitive modelling] (Shinozuka et al, 2003). This system-level performance index is defined as the increase in total daily travel time (hours/day) for all travellers, not distinguishing between commuters and commercial vehicles:

\[
DD = \sum_a x'_a t'_a (x'_a) - \sum_a x_a t_a (x_a)
\]

where \( x_a \) and \( x'_a \) denote the traffic flows (in PCU/day\(^1\)) on the \( a \)-th link in the pre-event undamaged and the damaged conditions, respectively, while \( t_a (x_a) \) and \( t'_a (x'_a) \) denote the corresponding travel times (hours/PCU), which depend on the congestion level through the model:

\[
t_a = t^0_a \left[ 1 + \alpha \left( \frac{x_a}{c_a} \right)^\beta \right]
\]

where \( c_a \) is the “practical capacity” of the link (in PCU/day), \( t^0_a \) is the travel time at “zero” flow in the link, and \( \alpha \) and \( \beta \) are model parameters (frequently assigned values for \( \alpha \) and \( \beta \) are 0.15 and 4, respectively).

- **Capacity reliability** [probabilistic, capacitive modelling] (Chen et al, 1999). This quantity is defined as the probability that the network can accommodate a certain traffic demand at a required service level, while accounting for drivers’ route choice behaviour. Travel time reliability can also be obtained as a side product. This measure provides important information for efficient flow control, capacity expansion and other relevant works to enhance the reliability of a road network. The maximum capacity of the network, \( \mu \), can be computed from the capacities of all the arcs:

\[
\mu = g (c_1, c_2, \ldots, c_a)
\]

Let \( \mu_r \) denote a required demand level. The capacity reliability is given as the probability of \( \mu \) exceeding \( \mu_r \):

---

\(^1\) PCU=Passenger Car Unit.
\[ R(\mu_i) = P(\mu \geq \mu_i) \]

This probability predicts how reliably the existing network with damaged arcs can accommodate a given level of required demand. It is easy to see that the boundary conditions must satisfy the following cases:
(a) \( R(\mu_i = 0) = 1 \)
(b) \( R(\mu_i = \infty) = 0 \)

It should be noted that connectivity reliability is a special case with binary-state variables and no capacity constraints.

- **Overall travel time reliability** [probabilistic, capacitive modelling] (Chen et al, 2002). The OD travel time reliabilities give a detailed reliability measure of a road network. It is sometimes more convenient to use a single index to describe the overall performance of the system. However, it is difficult to define such an index because of the interdependence of the individual OD travel times. In the literature, three possible indices representing the overall travel time reliability of the system are provided:
  1. \( \tau_{min}(\theta) = \min_w \{ \tau_w(\theta) \} \)
  2. \( \tau_{avg}(\theta) = \frac{1}{W} \sum_{w=1}^{W} \tau_w(\theta) \)
  3. \( \tau_{wgt}(\theta) = \sum_{w=1}^{W} \tau_w(\theta) \cdot q_w / \sum_{w=1}^{W} q_w \)

\( \tau_{min}(\theta) \) takes the minimum of all OD travel time reliabilities as the overall travel time reliability for a given level of service \( \theta \). It is a conservative measure and may not truly reflect the performance of the system. \( \tau_{avg}(\theta) \) is a simple, arithmetic average of all OD travel time reliabilities. \( \tau_{wgt}(\theta) \) is a weighted average of all OD travel time reliabilities by weighing the contribution of each OD pair by its travel demand \( q_w \).

### 2.2 PROPOSED PERFORMANCE INDICATORS

#### 2.2.1 Component-level PI's

- **Minimum travel time** [deterministic/probabilistic, connectivity modelling], needed to reach one of the hospitals, computed for each TAZ centroid. It can be computed both for the single scenario and as averaged on the whole simulation.

#### 2.2.2 System-level PI's

- **Weighted Connectivity Loss**, or \( WCL \) [deterministic, connectivity modelling]. This index upgrades the simple connectivity loss by weighting the number of sources connected to the \( i \)-th sink, in the seismically damaged network and in non-seismic conditions, respectively:
  \[
  WCL = 1 - \left( \frac{N'_s \cdot W'_i}{N'_0 \cdot W'_0} \right)
  \]

where the weights \( W'_s \) and \( W'_0 \) can be defined in different ways. The authors here defined them as the sum of the inverse of the number of edges composing the single paths between the \( i \)-th sink and the sources, in the seismically damaged network and in non-seismic conditions, respectively:
\[ W_i = \sum_{j \neq i} l_{ij} \cdot \frac{1}{TT_{ij}} \]

\( l_{ij} \) is the indicator function (indicating the existence of a path between the \( i \)-th sink and the \( j \)-th source), \( TT_{ij} \) is the travel time of the path between the \( i \)-th sink and the \( j \)-th source and \( j \) spans all the source nodes, i.e. all TAZ’s excluded the \( i \)-th one.

- **Moving average \( \mu \) and moving standard deviation \( \sigma \) of deterministic indicators** [probabilistic, connectivity modelling]. These parameters represent the evolution of the expected value and the standard deviation of the PI’s during the simulation, until the current run.

- **Mean Annual Frequency (MAF) of exceedance of deterministic indicators** [probabilistic, connectivity modelling]. The MAF of the generic performance measure \( Y \) exceeding threshold value \( y \) is computed as:

\[ \lambda_y(y) = \sum_i \lambda_o, G_{y_i} (y | i) = \lambda_o \sum_i p_i G_{y_i} (y | i) = \lambda_o G_y (y) \]

by post-processing of the vector of sampled values of \( Y \) to first obtain the complementary (experimental) distribution function \( G_y(y) \). Then this distribution is multiplied by the MAF of all earthquakes in the region, \( \lambda_o = \sum_i \lambda_{o,i} \). The probability \( p_i = \frac{\lambda_{o,i}}{\lambda_o} \) that, given an earthquake, it occurs on source \( i \) is respected in the complementary distribution \( G_y(y) \) where results come from events sampled in the correct proportion among the different sources.

### 2.3 Discussion

The terminal reliability may be suitable for abnormal situations, such as earthquakes, but contains an inherent deficiency since it only allows for two operating states: operating at full capacity or complete failure with zero capacity. The binary state approach prevents the application to situations where arcs are operating in-between these two extremes. Thus, road network reliability and risk assessment results obtained through this approach may be misleading.

The travel time 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. When the ratio of \( t_{w}(C) \) to \( t_{w}(C_0) \) is close to unity, it is essentially operating at ideal capacity, while when it approaches infinity, the destination is not reachable because certain links are too severely damaged. This extreme case is consistent with network connectivity reliability.

Concerning the capacity reliability, the problem of computing the network capacity \( \mu \) arises. For simple networks with arcs connected in series or in parallel, a closed functional form is available. However, when the network contains complicated couplings among the used paths between each OD pair, the function \( g(\;\;) \) may not exist analytically. Nonetheless, it can be determined by an optimization procedure. For example, the maximum flow problem, which is to find a feasible flow that leads to maximum flow capacity, can be formulated as a linear program (Ahuja et al, 1993). However, this method is not appropriate for road networks, because the movement of flows involves people rather than physical commodities and travel delays will increase as a result of
congestion. A more detailed discussion about this subject will be included in deliverable report D5.5.

Recently, Du and Nicholson (1997) proposed a theoretical framework for the analysis of damaged transportation systems. A conventional integrated network equilibrium model with variable demand is used to describe flow on a road network whose link capacities are subject to a range of levels of reduction. System surplus is used as a performance measure to assess the socio-economic impacts of system damage. The reliability of interest is the probability that the reduction in flow of the system is less than a certain threshold, as a result of capacity reduction of the network.
References


