Tomorrow's CITIES

Urban Risk in Transition

Disaster resilience analysis of urban transportation networks to support decision-making on planning and expansion

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TOMORROW'S CITIES WORKING PAPER

April 2022

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Summary

HUB-Istanbul work package (WP) 2.6 aims to evaluate multi-hazard resilience analysis of urban transportation networks and suggest the potential approach for analysing the case study area, Fikirtepe, Istanbul, Turkey. Research outcomes will be conveyed by five deliverables. The first deliverable summarised the overall framework of analysis and required data for assessing physical vulnerability. Based on the framework, this second deliverable deals with the collection and handing of the data required to evaluate traffic functionality of roadways and system, while discussing characteristics and challenges in analysing transport systems, methods for quantifying system functionality, probabilistic analysis framework and selected analysis parameters in the present study. Based on the framework and datasets summarised in the first two deliverables, the third deliverable will develop a probabilistic model to incorporate multi-layered analysis and data, which will be demonstrated by pilot examples. The fourth deliverable will present a thorough analysis of real-world transportation networks in the case study area, including mapping, network analysis and network performance evaluation. The evaluation results should be used to support decisions through mathematically formulated decision tasks, which will be illustrated in the fifth deliverable.

This second deliverable summarises the risk assessment of urban transportation networks, including the characteristics of urban transportation networks, evaluation of system functionality and probabilistic inference to support decision-making. Based on the investigation, this deliverable proposes the analysis framework and parameters to be used in this project, with a focus on the study area, Fikirtepe, Istanbul, Turkey.

Subtasks:

WP 2.6 – Subtask 1.3:	Social roles of transportation networks under disaster scenarios
– Subtask 1.4:	Traffic supply and demand under disaster and normal scenarios
– Subtask 1.5:	Decision-making and investment strategy for planning and expanding transport infrastructures

Table of Contents

List of Figures

List of Tables

2 Introduction

Transportation networks play a crucial role in sustaining daily-life and disaster-emergency activities. To ensure that they are resilient enough to deliver traffic flows even after experiencing a disruptive event, their holistic design should be underpinned by dis-aster resilience assessment. To this end, HUB-Istanbul work package (WP) 2.6 aims to develop a toolkit for multi-hazard disaster resilience analysis of urban transportation networks. Such approach requires multiple disciplines, including hazard engineering, structural engineering, social science, graph/transport theory, reliability engineering, decision theory and optimisation theory (D'Ayala et al. 2020). This document is the second of the two initial deliverables, of which the first deliverable summarises the overall framework of the analysis to be performed and identifies data needs and data availability for deter-mining the physical vulnerability of real individual structures constituting the network. In this second document, the discussions are extended to evaluating the vulnerability of transportation networks, whose functionality depends on the joint functionality of structures. Therefore, this second document illustrates the procedures chosen for evaluating network performance based on the vulnerability analysis of individual structures.

The paper is organised as follows: Section 2 illustrates the characteristics of transportation networks subjected to hazard, particularly in terms of urban environment which is the focus of this project and is different from rural conditions. Section 3 discusses defining and evaluating the functionality of transportation networks, which can be incorporated into probabilistic analysis to support decision-making, as illustrated in Section 4. Based on preceding discussions, the process and relevant parameters of disaster resilience analysis of transportation networks are summarised in Section 5, as well as the selected analysis scopes by HUB-Istanbul WP 2.6.. Section 6 briefly explains the transportation network in the testbed area, which is an extended area of Fikirtepe, Istanbul, Turkey. Section 7 concludes the report with summary, which includes the remaining challenges respectively for the remaining period of HUB project and for the research beyond the project.

3 Urban transportation network subjected to natural hazards

3.1 RISKS AND ROLES

When a transportation network encounters a disruptive event, the roadways, which constitute the network, may fail to deliver traffic flows, e.g. structural failure due to ground-shaking, inundation by floods and road blockage by dislocated adjacent objects. Such failures may disable the network to deliver traffic demands of people and goods be-tween certain pairs of regions. Such degradation would incur societal and economic losses since transportation networks play a pivotal role in responding to and recovering from a disruptive event, including transporting emergency goods and services, facilitating repair works and enabling daily lives.

Davies et al. (2017) provide insightful illustrations on how a transportation network is affected, adjusted and recovered after a hazard event. They present a detailed reconnaissance report on New Zealand's transportation network during the first one hundred days after the 2016 Mw 7.8 Kaikoura earthquake. The earthquake incurred fault rupture, ground shaking, liquefaction, co-seismic landslides and ground settlement, which affected widely distributed infrastructures (e.g. major highways, local roads and railways) and increased the risk of local communities becoming isolated and supply chains being disrupted.

The experience revealed that lightly damaged roadways could be opened in the first couple of days after safety inspection. On the other hand, roads disrupted by landslides and rockfalls took much longer (in case of Kaikoura earthquake, up to 1 year) due to the clearance work of slide mass. Severely damaged roads by earthquakes required major re-pair works and thus, had to be closed from several weeks to months. Apart from such physical damages, multiple roads had to reduce their service capacity during the first few days in response to the remaining risk of landslides and the heightened potential impact of motor vehicle clashes. In other words, the authorities had to enforce partial lane closure or lower speed limits to control the risks. Based on such experiences, Davies et al. (2017) emphasise the importance of balancing three priorities: (1) repair of roads, (2) emergency and ordinary supplies for and evacuation from damaged areas and (3) access for residents and workers.

While disaster resilience of transportation networks can be evaluated in terms of both effective organisational/legislative systems and the functionality of roadways, this project focuses on the latter. Such functionality can be disrupted mainly by two causes: disruptions of traffic flow and inefficient layout of roadways. Enhancing these two factors can increase the likelihood of a network fulfilling traffic demands under a disruptive event.

3.2 CHARACTERISTICS OF URBAN TRANSPORTATION NETWORKS

Transportation networks in urban environment are substantially different from the ones serving rural environments in terms of dense development, congestion and rapid expansion. These issues, strictly related to the level of formal and robust urban planning, result in various types of inequalities between neighbourhoods and individuals, such as limited service for non-motorised transport (i.e. walking and cycling), unequal distribution of employment prompted by infrastructure provision, access to basic facilities (i.e. water, schools, markets and health facilities), unequal commute time, informal (or sometimes illegal) public transport, disproportional risk of accidents (due to more travelling as a pedestrian and using motorcycles) and unequal exposure to air pollution (Hine 2014). Such daily-life inequalities would have adverse impacts on the inequality of disaster resilience, requiring for multi-disciplinary investigation. For example, disproportionate access to transport means and facilities can be magnified during disaster situations, which would have detrimental impact on basic living and health against the deprived.

In addition, particularly for urban transportation networks, disaster resilience is also affected by the structural performance of adjacent objects, e.g. overpasses, buildings and slopes. This is owing to the dense development of urban environments, by which the failure of a structure is likely to trigger failures of other adjacent objects as well. For example, collapsing overpasses and buildings would block their adjacent roadways, making them unable to deliver traffic flows. This type of failure may lead to unequal disaster resilience between neighbourhoods, for poor neighbourhoods are more likely to suffer from poorly-designed buildings (Hope *et al*. 2020).

To provide the scale and development of Istanbul, relevant figures are summarised as follows (http://www.allaboutistanbul.com/numbers.html):

- Area: 5,461 km^2
- Population: 15,519,267 in 2020 (which is 18.66 % of the total population)
- Density: 2,987 person / km^2 (27 times of Turkey, which his 108 person per square km)
- Population growth rate: 1 % yearly
- Around 35 % live on the Asian side (Anatolia); and around 65 % on the European side (Thrace)
- Housing: 1,528,782 buildings or 5.5 million single units (in 2017)
- Motor vehicles: 4,173,312 (1 car for each 5 person) as of December 2018
- Roads: 25,000 km
- Hospitals: 238 institutions and 36, 124 beds (in 2016)

3.3 HIERARCHY OF ROADWAYS

In properly designed roadways systems, a clear hierarchy of roads and road networks can be identified, depending on their traffic volumes, vehicle speeds and accessibility, whereby they can be divided into arterials, collectors and local roads. However, it is noted that, under certain environments, such hierarchy may not be preserved, resulting in substantially disturbed traffic flows, e.g. development over long-period, rapid and poorly regulated urban expansions, organic spontaneous growth, or challenging topography. Arterial roads aim to provide high levels of mobility and high speeds, while limiting the access from other roads. They can be further divided into those connecting different regions and those connecting shorter distances within a region. The collectors connect local roads to arterials, by collecting traffic from local roads, and distributing it to arterials and vice versa. The local roads indicate minor roads at the bottom hierarchy, which carry low volumes of traffic and have the lowest speed limit. The case study metropolis, Istanbul has a large-size transportation network with unique orography and topography, which consists of numerous major networks of arteries, connecting Europe and Asia, and myriads of small networks, with their own hierarchy, serving local neighbours and connecting old and new districts.

Because of the limited interactions between arterials and local roads, it is possible to consider two different scales of analysis, focusing on either arterials or local roads, while collectors can be incorporated in both cases. The choice depends on the objective of analysis, i.e. the decision tasks to be supported by the analysis. For example, the first scope would be selected to decide the optimal location of a new arterial road. Such analysis would mainly concern the unequal connectivity between regions, which is critical for securing supply chains in normal situations and serving emergency goods and services in disruptive events. On the other hand, the second scope should be chosen to address decision tasks such as improving the layout of local roads or eliminating potential risk sources (e.g. retrofitting buildings in particularly vulnerable areas). In this case, the analysis would concern neighbourhoods' unequal accessibility to arterial roads or essential services (e.g. foods, hospitals and shelters), which is pivotal for basic living and health for residents. Observing the equally important and unique implications of both types of roads, this study will perform resilience analysis at both levels and draw the relevant decision support schemes.

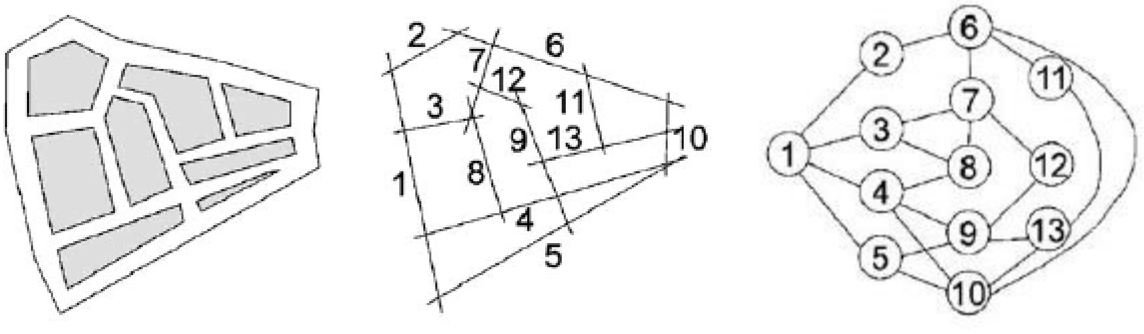
4 Evaluation of system functionality

Evaluating functionality of transportation networks is a challenging task as it involves multiple analysis parameters that arise from the abstract representation of network, traffic flows taking place on the network and related physical structures. As a result, one needs to make various choices such as the graphical representation of a given network, the computation scheme of traffic flow and the measures of network functionality. To this end, various approaches have been proposed as summarised and contemplated in the following sections.

4.1 GRAPHICAL REPRESENTATION: PRIMAL AND DUAL APPROACH

While a road network consists of two types of elements, i.e. roads and their intersections, it needs to be converted to an abstract graph consisting of edges and nodes. To this end, two approaches can be employed: primal and dual. The primal approach is intuitive as it represents streets and intersections using edges and nodes, respectively (Porta *et al*. 2006b). In contrast, in the dual approach, streets and intersections are respectively represented by nodes and edges (Porta *et al*. 2006a). Owing to their contrasting representation, the two approaches have complementary advantages to each other.

The primal approach has the advantage of comprehensibility as distance is measured not in topological terms (e.g. the number of edge or intersections required to journeys between two locations), but in spatial terms (e.g. physical distance of two locations). As a result, this approach has been adopted by most geospatial datasets. On the other hand, the dual approach enables us to evaluate the continuity of streets rather than a plurality of edges. As a result, it can reveal typological characteristics that cannot be identified by the primal approach, e.g. measuring the importance of individual roadways in terms of the accessibility and connectivity to other roadways. The examples of primal and dual representations are illustrated in Figure 4.1 (Porta *et al*. 2006a).



(a) (b) (c)

Figure 4.1. (a) A hypothetical urban system, (b) its primal axial map and (c) its dual connectivity graph (Porta et al. 2006a)

4.2 COMPUTATION

Computing network analysis can be divided largely into two categories: (1) topological analysis and (2) traffic simulation. The first category indicates evaluating *network connectivity* and *flow*, which assumes static supply and disregards traffic demand. This approach can evaluate the efficiency of network topology and requires minimal data, i.e. network topology and in case of network flow, (static) flow capacities of roadways.

The second approach, *traffic simulation* acknowledges interactions between supply and demand, which is particularly relevant for decision tasks related to traffic operation, such as scheduling traffic signals or imposing regulations. This approach is also imperative when analysing urban local roads whose traffic is constantly interrupted by either congestion or traffic signals, and thereby, the static assumption of supply and demand may not be valid. This type of analysis provides higher accuracy and better details, while requiring extensive data, including mathematical models of traffic operation and traffic demand data represented by a system of typical origin-destination (OD) pairs, and their proportional relevance with the study area.

Both types of analysis can be used to evaluate performance measures that are discussed in Section 4.3, as the variables used to evaluate the measures can be generalised to fit the adopted analysis approach. For example, the variables *geodesics*, *distance* and *node weights* used in topological analysis can be generalised for traffic simulation respectively into *available routes*, *travel impediment* (e.g. travel time and cost) and *relative significance of locations*. In other words, the choice on network analysis methods does not depend much on the choice on performance measures; rather, it should be chosen based on analysis purpose (i.e. the decision tasks of interest) and data availability.

4.3 MEASURES OF NETWORK FUNCTIONALITY

Despite the clear role of transportation networks to reliably deliver traffic demands, it is not straightforward to quantify such functionality. This is because the functionality of transportation networks manifests multiple dimensions, such as travel modes, activity types, users and travel impediments. Moreover, while trips take place locally between a single OD pair, the analysis should be performed within a global context by considering multiple pairs, for which the journeys would be randomly distributed and deeply influenced by various physical and socioeconomic factors, e.g. the hierarchy of road systems and their typology, and the socioeconomic environment that the transport system operates.

While several classifications have been proposed for network performance measures (Baradaran and Ramjerdi 2001; Curtis and Scheurer 2010; Papa *et al*. 2016), in this study, they are classified into four categories: (1) topological efficiency measure, (2) system-based functionality measure, (3) contour measure and (4) social and economic measure. As illustrated in the following subsections, the categories are not exclusive of each other. Rather, they can be combined to exploit their complementary merits.

4.3.1 Topological efficiency measures

Topological efficiency measures evaluate the layout of roadways, for which various measures have been proposed to capture different properties (Mattsson and Jenelius 2015; Porta *et al*.

2006b). It is noted that while this type of measures focuses on topological properties, they can be readily extended to other types of measures by generalising the definition of variables as discussed in Section **Error! Reference source not found.**. One of the most common measure is *global efficiency*, which is defined for a graph $G = (\mathcal{N}, \mathcal{A})$ with the node set $\mathcal{N}$ and the arc set $\mathcal{A}$ as

$$E^{\text{glob}}(G) = \frac{1}{N(N-1)} \sum\nolimits_{i \neq j \in \mathcal{N}} \frac{1}{d_{ij}} \tag{1}$$

where N is the number of nodes, i.e. $N = |\mathcal{N}|$; and d_{ij} is the shortest path length between the nodes *i* and *j*. By construction, a higher value of E^{glob} indicates better connectivity between nodes. The measure can be normalised so that the value always falls in the interval [0, 1] as

$$E_1^{\text{glob}}(G) = \frac{E^{\text{glob}}(G)}{E^{\text{glob}}(G_{\text{id}})} \tag{2}$$

where G_{id} is a graph with the same nodes with G while having a direct link between every node pair. Another normalization choice is

$$E_2^{\text{glob}}(G) = \frac{1}{N(N-1)} \sum\nolimits_{i \neq j \in \mathcal{N}} \frac{d_{ij}^{\text{Eucl}}}{d_{ij}} \tag{3}$$

where d_{ij}^{Eucl} is the Euclidean distance between nodes *i* and *j*, i.e. the shortest path possible.

The topology can also be evaluated by the *local efficiency*, which is defined as

$$E^{\text{loc}}(G) = \frac{1}{N} \sum\nolimits_{i \in \mathcal{N}} E_1^{\text{glob}}(G_i) \tag{4}$$

where G_i is the subgraph of G consisting of all neighbouring nodes of i and the links between them. While global efficiency assesses direct connectivity between all node pairs, the local efficiency evaluates that between neighbouring nodes, i.e. the nodes that are directly connected by arcs.

In contrast to global and local efficiencies that evaluate the overall graph, the *centrality* compares individual nodes, which can be largely divided into four families: (1) being *near others* (degree and closeness centrality), (2) being *between* (betweenness centrality), (3) being *direct to the others* (efficiency and straightness centrality) and (4) being *critical for all the others* (information centrality) (Porta *et al*. 2006b). It is noted that centrality measures are also equivalent to the measures used in *spatial syntax*, which is widely used for urban planning.

Degree centrality assumes that important nodes have the largest number of ties to other nodes, which is measured for node $i \in \mathcal{N}$ as

$$C_i^{\text{D}} = \frac{k_i}{N-1} \tag{5}$$

where the *degree* k_i of node i refers to the number of edges incident with the node. Closeness centrality measures the distance to all other nodes, i.e.

$$C_i^{\mathrm{C}} = L_i^{-1} = \frac{N-1}{\sum_{j\in\mathcal{N};\, j\neq i} d_{ij}} \tag{6}$$

where L_i is the average distance from node *i* to other nodes. Betweenness centrality evaluates the contribution of the node to the interactions between other nonadjacent nodes, i.e.

$$C_i^{\mathrm{B}} = \frac{1}{(N-1)(N-2)} \sum_{j\neq k\in\mathcal{N};\, j,k\neq i} \frac{n_{jk}(i)}{n_{jk}} \tag{7}$$

where n_{jk} is the number of geodesics linking nodes j and k; and $n_{jk}(i)$ is the number of such geodesics that include node i. Efficiency and straightness centralities assume that the efficiency in the communication between a node pair is equal to the inverse of the shortest distance. Accordingly, efficiency centrality is defined as

$$C_i^{\mathrm{E}} = \left(\sum_{j\in\mathcal{N};\, j\neq i} \frac{1}{d_{ij}}\right) \Big/ \left(\sum_{j\in\mathcal{N};\, j\neq i} \frac{1}{d_{ij}^{\mathrm{Eucl}}}\right) \tag{8}$$

Straightness centrality is a variant of efficiency centrality with a different normalization, i.e.

$$C_i^{\mathrm{E}} = \frac{1}{N-1} \sum_{j\in\mathcal{N};\, j\neq i} \frac{d_{ij}^{\mathrm{Eucl}}}{d_{ij}} \tag{9}$$

Information centrality of a node *i* is defined as the relative drop in network efficiency caused by the removal of the edges incident in *i*, i.e.

$$C_i^{\mathrm{I}} = \frac{\Delta E_2^{\mathrm{glob}}}{E_2^{\mathrm{glob}}} = \frac{E_2^{\mathrm{glob}}(G) - E_2^{\mathrm{glob}}(G')}{E_2^{\mathrm{glob}}(G)} \tag{10}$$

where G' is the modified graph by the edge removals.

Another measure is *gravity index* $Gravity^r[i]$ which measures the centrality of node *i* within a geodesic distance r (Sevtsuk and Mekonnen 2012), i.e.

$$Gravity^r[i] = \sum_{j\in\mathcal{N};\, j\neq i; d_{ij}\leq r} \frac{w_j}{e^{\beta - d_{ij}}} \tag{11}$$

where w_j is the weight of destination node j; and β is the parameter that controls distance decay rate, i.e. how strongly the distance between i and j affects the result, which can be decided depending on the travel mode (e.g. walking, cycling and driving) and the unit of distance.

For road networks, while different measures can support different decision tasks, the efficiency measures in Eqs. (1)-(4) can be used to evaluate the overall performance of a network and thereby, make decisions to enhance the global performance. On the other hand, the centrality measures in Eqs. (5)-(11) are useful for measuring the varying characteristics of individual locations, which can support decisions of allocating investment resources to local neighbourhoods. Unlike abstract networks such as social networks, in road networks, distance (or travel time) is a critical variable, which makes purely topological measures such as Eqs. (5) and (7) less relevant. It is noted that transportation networks are multi-dimensional systems in terms of their roles and functionality, which cannot be summarised by a single measure, but rather by a set of several complementary measures.

4.3.2 System-based functionality measures

In contrast to the purely topological analysis illustrated in Section 4.3.1, system-based functionality accounts for additional factors such as traffic simulation (i.e. investigating interactions between capacity and demand), restoration of degraded functionality and socio-economic impacts (Mattsson and Jenelius 2015). Multiple measures/attributes have been developed to this end as summarised in Table 4.1 with their general definition (Faturechi and Miller-Hooks 2015).

Table 4.1. Common system-based functionality measures

Measure/ Attributes	General definition
Reliability	Probability that a system remains operative at a satisfactory level
Robustness	Ability to withstand or absorb disturbances and remain intact
Vulnerability	Susceptibility to threats and incidents causing operational degradation
Elasticity	Ability to recover original performance after degradation
Resilience	Ability to resist, absorb and adapt to disruptions and return to normal functionality
Risk	Combination of probability of an event and its consequences in terms of system performance
Flexibility	Ability to adapt and adjust to changes through contingency planning
Transformability	Ability to transform into a different kind of system
Sustainability	Equity of current and future generations

Despite the varying definitions of the measures in Table 4.1, they all aim to quantify a system's resistance against disruptive events. To this end, *reliability* evaluates the probability of system's survival. On the other hand, the two complementary concepts, *robustness* and *vulnerability* measure the instant reduction of system performance after a disruptive event. *Elasticity* quantifies the recovery speed to original or even improved functionality. Since they all reflect essential properties for a system, these measures can be unified into *resilience*, which evaluates the system performance over a comprehensive timeline from hazard occurrence to full recovery (Faturechi and Miller-Hooks 2015).

Another commonly used concept is *risk* which quantifies the expected consequences of a disruptive event, e.g. its economic or social impacts. On the other hand, the system functionality can be defined focusing on dynamic properties (Wang 2015). *Flexibility* and *transformability* evaluate the adaptive ability of transportation networks, which respectively stand for short-term and long-term measures of adaptation. *Sustainability* reflects the ability to guarantee welfare and resources equally for current and future generations. Especially for the last three measures, although their importance has been recognised increasingly, it is not straightforward to quantify and incorporate them into numerical analysis and policy-making (Markolf *et al*. 2019; Xu *et al*. 2016).

Among these various types of measures, this study will adopt the measure *resilience* for analysing the case study area, in order to take into account the instantaneous degradation immediately after a disruptive event as well as the recovery trend of the global network performance. The measure will be evaluated by use of topological efficiency measures (which are summarised in Section 3.3.1), for which the topological measures need to be carefully scaled so that their units are commensurable with the additional unit, *time*. Following the common definition of resilience, while the efficiency would improve as the system recovers from the event, to evaluate such dynamic trend, the resilience will be quantified based on the lost efficiency during the relevant time window, with unit (efficiency) x (time).

4.3.3 Contour measures

Contour measures, also known as cumulative opportunity models, plot the contour of the areas that can be reached from a reference point with a certain amount of travel resources (Bhat *et al*. 2000; Curtis and Scheurer 2010; Geurs and van Eck 2001). An example is illustrated in Figure 4.2. It is common to express such resource thresholds as maximum desirable travel times for different types of activities and travel modes. Curtis and Scheurer (2010) point out that this approach can incorporate land use patterns and infrastructure constraints. However, they also note that the indicator cannot differentiate between travels inside the contour, which would vary in travel time, travel cost and user’s desirability.

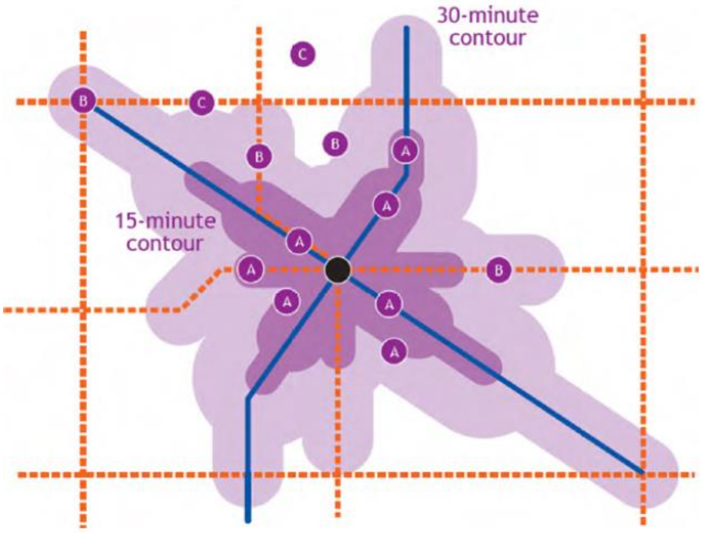


Figure 4.2. Contour measure. Opportunities (purple dots) are classified by travel time zones (A = up to 15 min, B = 15-30 min, C = over 30 min) from the point of reference (black dot). (Curtis and Scheurer 2010)

4.3.4 Social and economic measures

Network analysis provides engineering quantities such as traffic flow, travel time and travel cost. For planning or communication, such terms often need to be transformed into social or economic quantities. To this end, they are often converted to utility values, e.g. an indicator for social equity or as a monetary value for economic utility (Curtis and Scheurer 2010). While this approach can reform engineering quantities in socio-economic perspective, the major challenge is that scaling such utility values is subjective and often, conservative.

Utility can be incorporated either during network analysis or into analysis result. In the first case, traffic simulation can be performed by having travellers choose their travel plans with maximum utility (instead of travel cost), which would vary depending on accessibility, travel modes and the attractiveness of activities (Baradaran and Ramjerdi 2001; Bhat *et al*. 2000). In the second case, analysis results (e.g. unfulfilled demands or travel time delay) can be transformed into utility values by reflecting varying consequences. For example, (Markhvida *et al*. 2020) evaluated well-being loss of households by assuming that given the same amount of income loss, different levels of household consumption would experience different levels of well-being loss.

On the other hand, the socioeconomic inequality in transport service has been widely studied, including the disproportionate accessibility to transportation means depending on socio-economic strata (Teunissen *et al*. 2013) and the affordability of transport service (Gates *et al*. 2019). International Transport Forum (2017) found that lower-income populations suffer from restricted transport options, lower quality transport services and worse travel conditions (safety, security, reliability and comfort), recommending multiple academic and operational missions such as improving relevant data, developing effective performance indicators, adjusting hosing policies and urban development, mobilising increases in land value for social inclusion, and providing efficient and financially sustainable transport subsidies. Similarly, Di Ciommo and Shiftan (2017) suggest that transport systems need to be planned by a wider analysis based on needs of people, not solely resorting to the cost-benefit analysis.

It is therefore clear that such descriptors need to be integrated into the transport model being developed within WP 2.6 for resilience analysis, to gauge the influence of disruptive events on the Istanbul Municipality urban regeneration and development plans, so that we can ensure maximum efficacy in addressing inequality.

5 Probabilistic analysis for risk-informed decision-making

When analysing real-world infrastructures, a probabilistic approach is imperative since real-world variables contain aleatory uncertainties by nature as well as epistemic uncertainties from lack of knowledge and data (Byun *et al*. 2019; Gehl and D'Ayala 2018). This approach allows for properly considering uncertainties and thereby, understand possible outcomes and their likelihood. The analysis results can be utilised for various types of decision tasks, and different methods might be suitable depending on the strategy that the analysis is proposed to underpin. In the following subsections, we consider analysing the distribution of outcomes of interest, which can be obtained with probabilistic inference or optimisation of specific decision scenarios.

5.1 PROBABILISTIC INFERENCE

Probabilistic inference evaluates the probability distribution of a quantity of interest, such as unfulfilled traffic demands, total/average travel time and socio-economic loss. This type of evaluation is required to adequately account for the uncertainties in real-world parameters, e.g. structural damage of physical components, functionality of roadways and their recovery (Byun *et al*. 2019). Accordingly, the probabilistic analysis will be adopted in this research work for evaluating the functionality and resilience of transport infrastructures.

The analysis results can support various types of decision problems. For example, it can identify particularly vulnerable or important components to support planning optimal investment strategy. An example is illustrated in Figure 5.1 (Markhvida *et al*. 2020). It can also compare candidate decision scenarios, which is useful when there are only a few possible scenarios due to practical constraints. It can highlight the variables that contribute most to system vulnerability, which can aid planning preventive measures, e.g. selecting optimal locations of new roads and road expansions, and/or prioritising structures to be retrofitted.

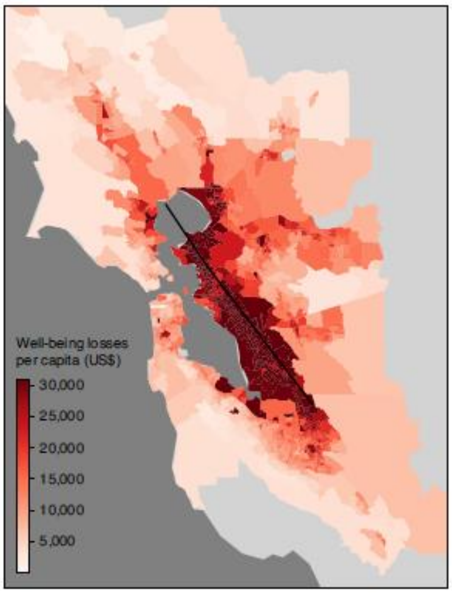
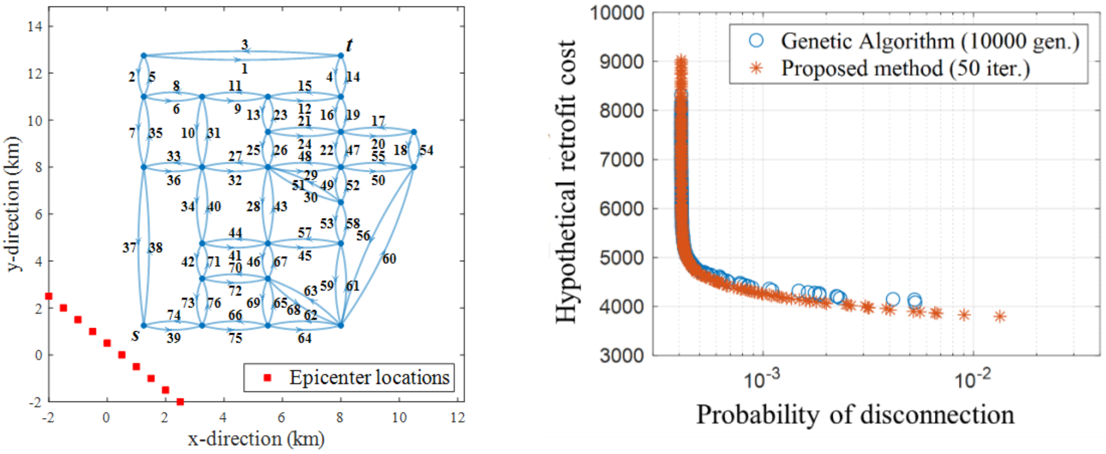


Figure 5.1. Spatial distribution of average well-being losses per capita in San Francisco Bay Area following an earthquake rupture scenario (Markhvida *et al*. 2020)

5.2 OPTIMISATION FOR RELIABILITY-BASED NETWORK DESIGN

Probabilistic analysis can also be applied for optimisation, providing more direct decision support than simple inference, as illustrated in Section 5.1. Optimisation requires three types of elements, i.e. decision variables, objective functions and constraints. Decision variables reflect the decision scenario of interest, e.g. adding new roads or increasing traffic capacities of existing roads (Lou and Zhang 2011). Objective functions reflect global goals, e.g. maximising global efficiency or minimising construction cost, while constraints account for minimum requirements of solutions, e.g. thresholds on local efficiency of individual neighbourhoods. While considering multiple constraints is relatively straightforward, it is challenging to consider more than one objective function. However, the presence of multiple objectives is commonly observed in real-world decision tasks, e.g. economic loss, societal loss and budget efficiency, for which multiple methods are available including exact, approximate and metaheuristic approaches (Byun and Song 2020). Figure 5.2 illustrates an example of multi-objective optimisation where the objectives are hypothetical retrofit cost and probability of network dysconnectivity.



(a) (b)

Figure 5.2. Example of multi-objective optimisation: (a) Sioux Falls benchmark network and potential locations of epicentres and (b) nondominated solutions (i.e. solutions whose domination cannot be concluded due to conflicting decision criteria) in regards to probability of disconnection and hypothetical retrofit cost, which are computed by genetic algorithm and the optimisation method proposed by Byun and Song (2020)

In the context of planning and designing urban transport infrastructures, various approaches have been developed as summarised by Farahani *et al*. (2013). For designing road networks, they identified a list of design objectives such as minimising total travel time/cost, minimising construction cost, minimising total travel distance and maximising reserve capacity, while listing decision tasks such as street capacity expansion and new street construction. They also noted that these problems have been tackled by multiple optimisation methods, including exact methods (e.g. Branch and Bound), heuristic (or approximate) methods and metaheuristics (e.g. genetic algorithm). These problems are often formulated as bi-level problems where the upper- and lower-level problems account for the decision-maker's decision on planning roads and the users' choice on trips, respectively.

5.3 SENSITIVITY ANALYSIS AND UNCERTAINTY QUANTIFICATION

Sensitivity analysis aims to quantify the relevance of a variable to the analysis' results, whereby the most influential variables can be identified and effectively controlled, e.g. retrofitting critical roadways. An example is illustrated in Figure 5.3 where parameter sensitivity is evaluated for each component type in regards to system reliability (Byun *et al*. 2017). On the other hand, uncertainty quantification evaluates the contributions of the uncertainty in a variable to that of the result. This can support planning strategic data collection or model refinement so as to efficiently reduce the uncertainty related to specific queries or objectives.

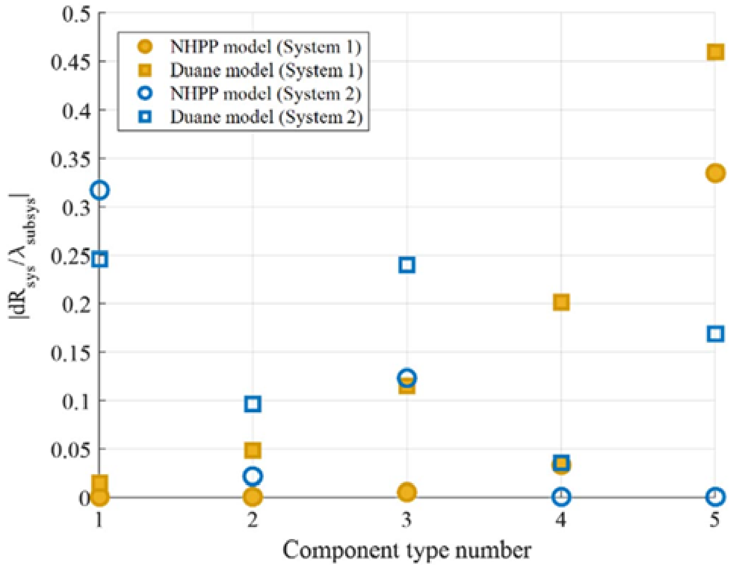


Figure 5.3. Example of evaluating parameter sensitivity in regards to different models and system types (x-axis: component type and y-axis: parameter sensitivity) (Byun *et al*. 2017)

6 Summary and discussions

6.1 PARAMETERS FOR TRANSPORTATION NETWORK ANALYSIS

Disaster resilience analysis of transportation networks consists of multiple parameters, summarised in Table 6.1. Most of all, a given network needs to be represented as an abstract by identifying nodes and edges, for which one needs to decide between primal and dual representations (Section 4.1) and the levels of roadways to be included (Section **Error! Reference source not found.**).

Table 6.1. Analysis parameters for disaster resilience of transportation networks (bolded are the selected parameters in this study)

Parameter	Options
Nodes and edges	• Graphical representation: **primal** or dual • Road inclusion: **arterials**, collectors and **local roads**
Travel modes	• **Uni**- or multi-modal
Traffic demands	• **Static demand** (network connectivity and flow) or supply-demand interaction (traffic simulation) • **Deterministic** or stochastic demands
Travel impediment	• **Travel distance**, time, cost or utility

OD pairs	• All node pairs, **selective pairs** or single pair
Routes	• **Pre-designated routes** or geodesics (i.e. minimum travel impediment)
Travel preference (or significance of unfulfilled demand)	• Weights of nodes (origins and destinations), trips (activities) or routes (travel modes and service preference)
Traffic disruption meachnisms	• **Structural damage of roadways** • **Collapses of adjacent objectives (e.g. overpasses, buildings and slopes)**
Socio-demographic distribution	• e.g. income, age, gender and disability
Network functionality	• Topological efficiency, **system-based functionality**, **contour measure** or social/economic measure
Analysis type	• **Probabilistic inference**, optimisation or sensitivity/uncertainty analysis

Then, details of trips should be determined, which include travel modes, amount of demands and travel impediment of the roadways. Traffic demands can be considered being either static or dynamic, which determines the type of traffic analysis (Section **Error! Reference source not found.**). The demand can be either deterministic or stochastic, where the choice depends on the level of uncertainties. Travel impediment can be set as travel distance, time, cost or utility (Section 3.3).

Trips are defined between OD pairs, which can be selected as all existing node pairs (e.g. topological efficiency), selective pairs (e.g. origins as residential areas and destinations as hospitals/shelters/access to arterials) or a single pair (e.g. from hazard location to exit for evacuation). During the analysis, those trips take place along the allowed routes, for which pre-designated routes can be provided, or routes to be taken can be computed concurrently with the analysis. In addition to travel impediment, the preference or significance of trips can further be elaborated, through assigning different weights on nodes (e.g. origins and destinations), trips (e.g. activities) or routes (e.g. travel modes and service preference) (Section 3.3.1).

The network performance is mainly degraded by physical damages of roadways and adjacent objects, while another dimension that can be augmented to the analysis is socio-demographic information, e.g. distributions of income, age, gender and disability, which can provide valuable insights on the socio-economic role of engineering systems (Section 3.3.4). Finally, after determining all parameters, analysis can be performed to evaluate network functionality. The analysis can take various forms such as probabilistic inference, optimisation or sensitivity/uncertainty analysis (Section 5). It is noted that the parameters for analysis are closely related to each other, and thus, they cannot be specified independently.

As summarised in Table 2, various choices can be made on the analysis parameters without significant modification of methodology. The choices exercised in making the model for the Hub-Istanbul (as an output of the WP 2.6 research work) are highlighted in bold in Table 6.1. For graphical representation, the *primal approach* will be adopted so that the neighbourhoods can be accounted for as nodes, which will allow us to explicitly model the vulnerability of the construction within a neighbourhood. For analysis level of roads, we will examine separately both *arterials* and *local roads* separately. For the moment, only roadways for motorised vehicles will be considered, without considering the interaction between traffic supply and demand. Travel impediment will be measured by expected distance between *selected OD pairs*. The functionality degradation of networks is measured by two traffic disruption mechanisms, *structural damage of roadways* and *collapses of adjacent buildings* (in this research work, overpasses, buildings and slopes are considered). The network functionality will be measured by contour maps of expected travel time and *capacity loss*, which will be combined with the time dimension so as to consider the comprehensive period for which the impact of a disruptive event lingers on. Those measures will be computed as probability distributions as probabilistic analysis will be performed to account for the uncertainties in various factors, e.g. structural capacity of physical components, functionality of roadways and their recovery.

The major challenge with performing analysis is data availability on which analysis details and quality greatly depend. For example, designing trips requires an extensive dataset and often includes significant uncertainties, e.g. quantity of traffic demands for each OD pair after hazard events and socio-economic impact of unfulfilled demands. Such challenge can be addressed by strategic data collection, experts survey and development of theoretical models.

6.2 DECISION-MAKING ON TRANSPORTATION: PLANNING AND EXPANSION

This study focuses on planning and expansion of a network in alignment with the vision of the project. This task can be addressed in two perspectives: (1) identifying optimal locations and traffic capacities of new roads and (2) quantifying disaster vulnerability of neighbourhoods to promote optimal investment. The first challenge can be addressed by solving an optimisation problem where objective functions and constraints would reflect the desired functionality. Decision variables would be the locations and traffic capacities of roads, while the setting depends on the flexibility of decision scenarios, e.g. the affordable number of new roads, available locations and feasible designs. On the other hand, the second approach requires defining and evaluating the resilience measure for individual neighbourhoods, while the measure should reflect relevant failure modes and the desired performance of transportation systems.

For both approaches, it is crucial to define the functionality of transportation systems, for which there is no universal answer. In alignment to the objectives of the HUB, the functionality needs to be defined primarily in the perspective of equity so that the urban underprivileged would not be left out from the benefits offered by transportation networks. To this end, it will be defined as the loss of traffic capacity in regards to the origins being each district or neighbourhoods and destinations being essential services locations such as connectivity to other regions, entrances to main arterials, health facilities and shelters (given a multi-hazard scenario as illustrated in Deliverable 1 produced by the same WP). As illustrated in Section 3.3.2, the measure will incorporate the concept of *resilience*, for which the capacity loss will be measured for the entire time horizon that the hazard scenario would have impact on. By generating the map that illustrates the contour of disproportionate access to those destinations, one can compare the vulnerability of neighbourhoods, which can be even overlapped with the distributions of socioeconomic strata to investigate the correlations between the two factors. On the other hand, the functionality measure can be used as a decision objective for deciding the locations of new roads, i.e. identifying the layout of roadways that maximises the functionality.

7 Transportation network in Fikirtepe, Istanbul

As a testbed, HUB-Istanbul WP 2.6 analyses the extended area of Fikirtepe, Istanbul, Turkey, which is illustrated in Figure 7.1(a) where the yellow pins indicate the 99 bridges identified in the region (D'Ayala *et al*. 2020). The area – which is around 16 km^2, corresponding to around 0.30 % of the entire Istanbul – has a densely developed transportation network which contains both a large number of arterials and local roads. It also includes multiple neighbourhoods around, such as Fikirtepe, Dumlupinar, Hasanpasa, Egitim, Zuhtupasa, Merdivenkoy, Unalan, Acibadem, Sahrayicedit, Ornek, Fetih, Kucukcamlica (Figure 5(b)), offering the opportunity for a systematic comparison of disaster resilience between neighbourhoods.

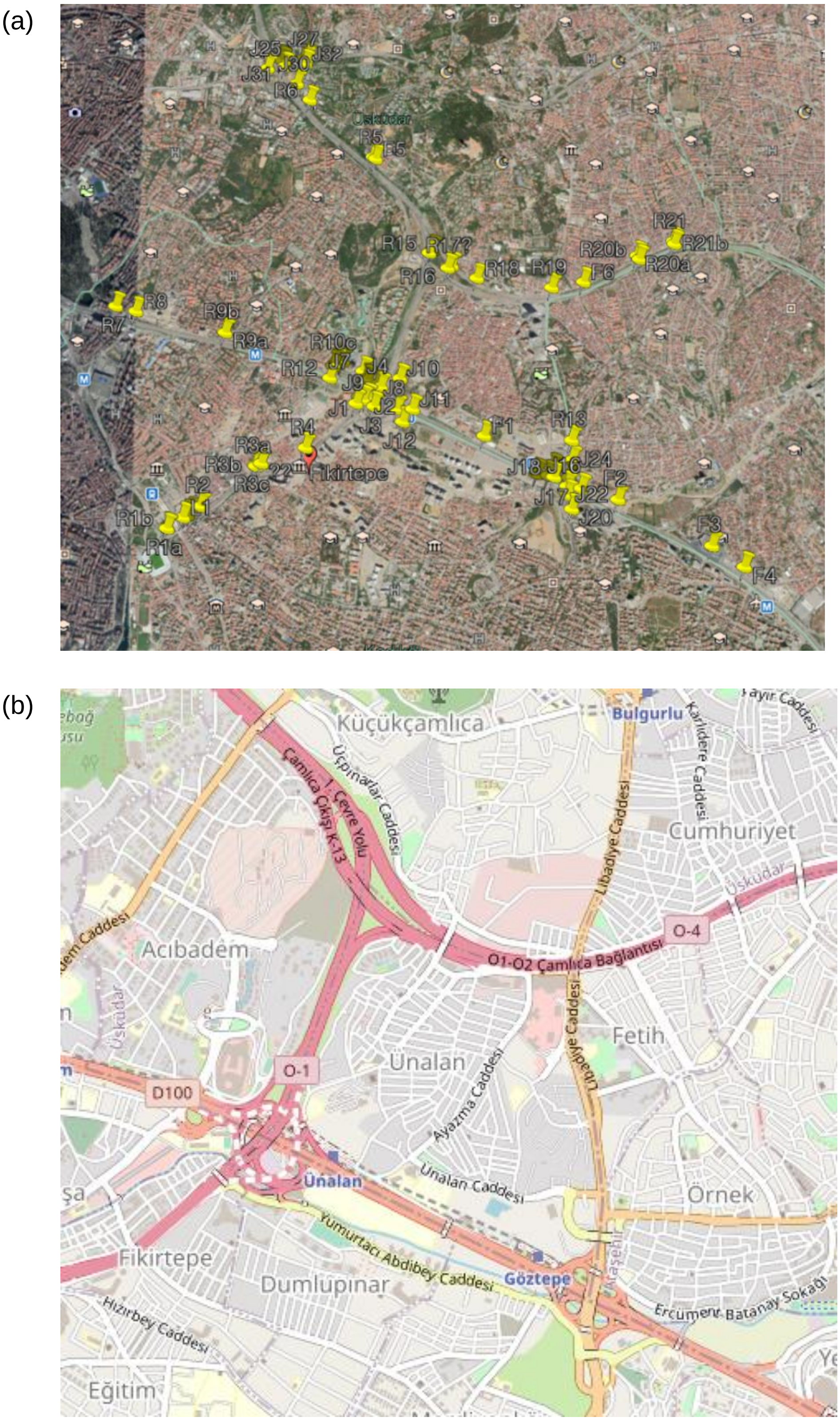


Figure 7.1. Extended study area of Fikirtepe: (a) satellite image with bridges marked by yellow pins (image provided by Google Earth) and (b) road map network and neighbourhood limits (image provided by OpenStreetMap)

8 Conclusions

HUB-Istanbul work package (WP) 2.6. aims to evaluate disaster resilience of urban transportation networks. To this end, this deliverable illustrates literature reviews and reflections on the analysis process. The characteristics of urban transportation networks are discussed, including potential risks, expected roles, difference between rural environments and road hierarchy. To evaluate network performance, it is crucial to define the performance measure properly, for which literature review and discussions are presented on graphical representation of roadway systems, computation of network analysis and available measures for the functionality of transportation networks. In particular, the classification of functionality measures is proposed in the perspective of disaster resilience. The results of resilience analysis can be utilised for various types of decision tasks as illustrated in the text. The summary and discussions of pertinent parameters to such analysis specify the data requirement and availability, while outlining the research plan and selected analysis parameters set up by HUB-Istanbul work package (WP) 2.6. The illustrated analysis framework will be applied to the transportation of the extended area of Fikirtepe, Istanbul, Turkey. In performing the analysis, it should be noted that the most critical issue is data availability, which governs the completeness and accuracy of analysis. To this end, the data will be continuously collected through collaborations with other WPs in the HUB and local authorities, while structural models will be replaced by the outcomes of WPs 2.5 and 2.6 (e.g. overpasses).

Multi-hazard disaster resilience analysis of transportation networks requires extensive and long-term efforts, for which there are some remaining questions that will not be addressed within this project but, based on its anticipated outcomes, should be addressed by further research. For example, the analysis can be performed by collectively taking into account arterials and local roads, which would provide insights for planning transportation networks, but is not straightforward for the two road types have limited interactions with each other through specified accesses. Another issue is incorporating emerging norms such as flexibility, transformability and sustainability, for whose concrete definition, extensive discussions are required across disciplines and stakeholders.

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