FP7 2013 Cooperation Work Programme
Theme 6: Environment (Including Climate Change)

Novel indicators for identifying critical *INFRA*structure at *RISK* from Natural Hazards

Deliverable D5.3

Infrastructure Platform

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WP	5
Submission Date	22/March/2016
Primary Reviewer	Bryan Adey and Jürgen Hackl/ Eidgenoessische Technische Hochschule Zurich (ETH Zurich)
Dissemination Level	PU

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 603960.

Project Information

Project Duration: 1/10/2013 - 30/09/2016

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Work Programme: 2013 Cooperation Theme 6:
Environment (Including Climate Change).

Call Topic: Env.2013.6.4-4 Towards Stress Testing of Critical Infrastructure Against Natural Hazards-FP7-ENV-2013-two stage.

Project Website: www.infrarisk-fp7.eu

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Stiftelsen SINTEF, Norway.

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Document Information

Version	Date	Description	Primary Author
Rev01	25/11/15	Submission	Khaled Taalab & Francesca Medda
Rev02	22/03/16	Final version for Submission	Khaled Taalab & Francesca Medda

Executive Summary

Road networks can be damaged and disrupted by natural hazards. Using vulnerability analysis as a framework, this report identifies vulnerable elements (those which are susceptibility to incidents that can result in considerable reductions in road network serviceability) in the Bologna road network based on network topology and exposure to a range of natural hazards. Roads which are critical to the functionality of the network (essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact) were identified based on betweenness centrality analysis. This was combined with a hazard exposure metric based on the spatial location of the roads to identify highly vulnerable roads. Using a case study in the Bologna region, the Autostrada Del Sole and primary road SS64 in the south of the region were found to have high betweenness and be highly exposed to a range of natural hazards.

To demonstrate the consequences of damage to vulnerable roads in the network, the study used a traffic equilibrium model Nexta to simulate traffic delay on a national scale based on damage to roads in the Bologna region. There are very many damage scenarios which could be tested and compared to an undamaged network. This study has used two: one based on total damage of the Bologna network and another based on the topological vulnerability analysis and the location of bridges that carried vulnerable roads. The results of the total damage scenario demonstrated that that widespread damage to the roads in Bologna would have substantial negative effects on traffic flow for the whole of Italy and even damage to four bridges in the Bologna region that have not been designed to withstand large seismic events would lead to substantial delays for many travellers across central and northern Italy.

TABLE OF CONTENTS

TABLE OF CONTENTS IV
1.0 INTRODUCTION 5
1.1 Critical Infrastructure 6
1.2 Network Topology and Traffic Modelling 6
1.3 Hazard identification 8
2.0 METHODOLOGY AND CASE STUDY 9
2.1 Models 9
2.1.1 Betweenness centrality 9
2.1.2 Hazard exposure 9
2.1.3 Traffic Modelling 9
2.2 Study area 11
2.3 Data 12
2.3.1 Road network data 12
2.3.2 Traffic data 13
2.3.3 Hazard data 15
3.0 RESULTS 17
3.1 Hazard exposure 17
3.2 Betweenness centrality 17
3.3 Scenario identification 18
3.4 Modelling Consequences 20
3.5 Model Applications 23
4.0 CONCLUSION 24
5.0 REFERENCES 25
APPENDIX A: NEXTA USER GUIDE
APPENDIX B: ZONE IDENTIFICATION

1.0 INTRODUCTION

There is a need to consider the vulnerability of all lifeline systems (e.g. water, energy, communication, transport) to damage and disruption. Most critical is the transportation system, as the restoration of any other systems is dependent on being able to move people and equipment to damaged sites (Dalziell & Nicholson, 2001). Road networks, in particular, need to provide sustainable transport facilities for individuals and industry. They should be safe, accessible and have a positive impact on regional development (Berdica, 2002). Natural hazards have the potential to cause catastrophic damage to infrastructure networks. They can damage roads which in turn can disrupt traffic flow on the network causing congestion or the need for diversion. In turn, this can lead to increased travel time which inconveniences individual travellers and can collectively have serious economic consequences. In order for infrastructure managers and national agencies to plan mitigation strategies and policy, it is vital to have an understanding of the vulnerability of a network prior to the occurrence of a hazard event.

There are many definitions of vulnerability, and the meaning of the term is often context-dependent (Jenelius 2006a). INFRARISK defines vulnerability as the risk related to a specific event or combination of events. It is seen as a subset of risk. For example, the vulnerability related to an earthquake occurring leading to a bridge collapsing is estimated assuming that an earthquake occurs and estimating the probability of the ground accelerations knowing that the earthquake has occurred and multiplying these probabilities with the probable consequences (Adey et. al., 2014). It has also been described more generally as sensitivity to numerous threats and hazards which will substantially reduce the ability of the system to maintain its intended function (Holmgren, 2004). Other definitions focus on the system's response to rare, unpredicted events (Laurentius, 1994). The serviceability of the network, which is the ability of the network to allow you to complete a desired journey at a cost (either financial or in terms of travel time) that makes the journey worthwhile (Goodwin, 1992), is another element which has been considered. In terms of the road network, vulnerability has been defined as "a susceptibility to incidents that can result in considerable reductions in road network serviceability" (Berdica, 2002, p.119). Rather than attempting to further define the term, this report will conceptualise vulnerability analysis as a framework within which different studies and methodologies can be used to investigate how well the road network functions when it is put under various stresses (Berdica & Mattsson, 2007).

There are two primary objectives of this deliverable. The first is to identify vulnerable roads in the road network. This consists of two elements: 1) identifying critical roads (those whose closure will cause the most substantial decrease in serviceability of the network) based on network topology 2) Identifying the exposure of roads in the network to a range of potentially damaging natural hazards. The second objective is to assess the consequences of closure to these roads in terms of travel time delay. This involves quantifying the consequences of damage, based on scenarios two damage scenarios, using a traffic equilibrium model. One scenario represents total damage of all major roads within a given region, another shows the effects of closing a limited number of critical roads

Deliverable 5.3 is structured as follows: The following section discusses the concept of critical infrastructure and road hierarchies, network topology as it related to road traffic, modelling the consequences of disruption to the road network and the identification of hazards. Next the methodology explains details of the modelling approached used in the deliverables. This is followed by an introduction to the case study area of Bologna, Italy, including a description of the data used. Finally the results of two damage scenarios are presented along with a conclusion.

1.1 Critical Infrastructure

There are two conflicting viewpoints relating to the relative importance of roads in a network. The equal opportunities perspective values all roads equally, whereas the social efficiency perspective advocates a hierarchy of roads based on their position in the network and use (Jenelius et al., 2006a). This report adopts the social efficiency perspective. The most important roads in this hierarchy can be described as critical. One measure of quantifying criticality is to examine the consequences of said infrastructure being non-operational (Adey et. al., 2014). Demšar et al. (2008) state that a critical object in a road network (e.g. road, bridge, tunnel) is one whose removal substantially alters the structure of the network in terms of flow and connectedness. The removal of the critical object can either disconnect large sections of the network from one another or causes substantial rerouting of flow along a longer detour path. Specific elements may also be critical because they then represent the only connection between subparts of the network or because they form part of the 'best routes' (i.e. quickest) between many locations. In a road network, some objects are predisposed to being critical. Bridges and tunnels, for example, often form the only connection between otherwise separate subparts of the network. Main roads are also typically critical as they generally form part of the 'best route' between multiple origins and destinations (Demšar et al., 2008).

1.2 Network Topology and Traffic Modelling

To prepare for damage and disruption, infrastructure managers need to have an understanding of the locations of critical objects in the network. The concept of using road hierarchies is explored by Jiang (2009) who claims road networks can be characterised by an 80/20 principle. This means that in general 80 percent of traffic on a network will be carried by 20 percent of the roads. Moreover the top one percent of roads will carry 20 percent of the network's traffic. Generally, roads which carry the more traffic can be considered more critical than those which carry less. In many cases, data on traffic flow for individual roads is unavailable which means other methods must be used to infer the criticality of objects in the road network (Jayasinghe & Munshi, 2014). Many studies used to assess the vulnerability of the road network use methods to analyse the topological structure of the network using graph theory (Zhang & Virrantaus, 2010). Graph theory examines how sections (in this case roads) in the network are connected to one another in order to identify potentially critical elements. One topological metric that has been used to estimate the location of critical objects and represent the distribution of traffic flow on a road network is betweenness centrality.

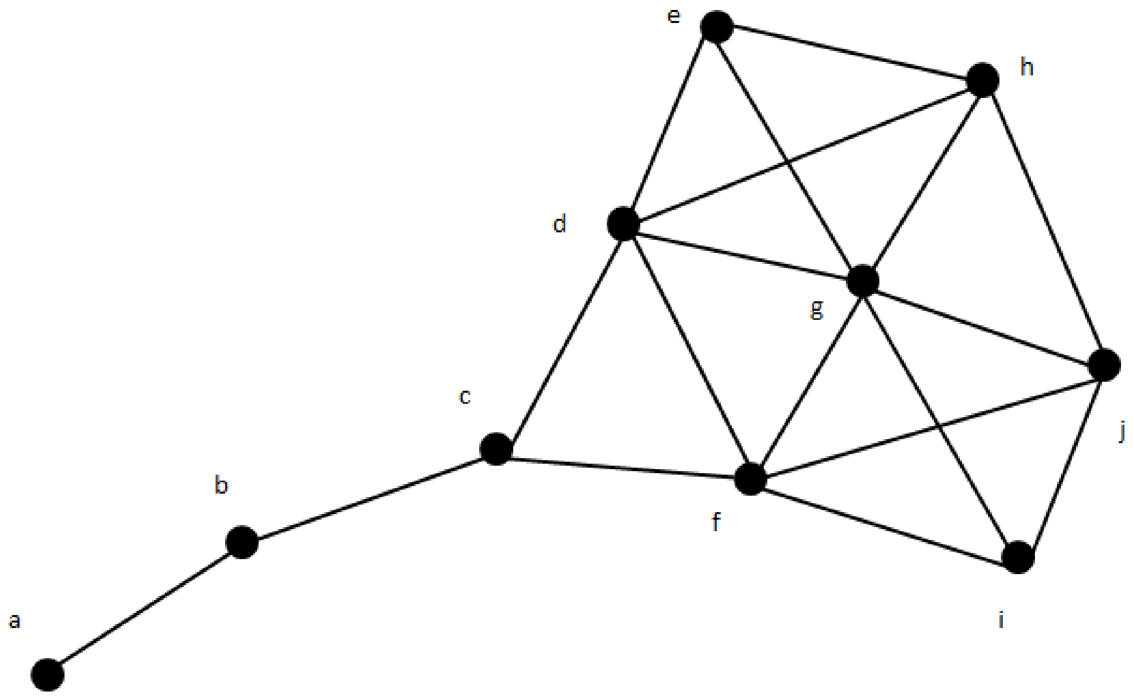

Figure 1: Example network (Adapted from Jiang, 2009)

Originally applied to the analysis of communication among small groups, betweenness centrality can be defined as the number of shortest paths from all nodes to all others that pass through the node (Freeman, 1978). The betweenness centrality of a network measures the extent to which a node is between any two parts of the network. Betweenness is the number of geodesic paths that pass through node k which can be described as the exclusivity of k's position, considering journeys from all nodes in the network to all other nodes (Borgatti, 2005). Removing nodes with high betweenness would effectively split the network in two separate parts. Using the example shown in Figure 1, node c has the highest betweenness in the network. Removing an edge with high betweenness will typically disrupt many shortest paths through the network, which is one of the essential properties of a critical object. As such, betweenness can be used as part of the vulnerability assessment of a road network (Demsar et al., 2007; Demsar et al., 2008; Zhang & Virrantaus, 2010). Another reason that betweenness is used for vulnerability assessment is that it has been shown to be highly correlated with traffic flow on an urban street network (Jiang, 2009; Kazerani & Winter, 2009; Jayasinghe & Munshi, 2014, Toole et al., 2015).

1.1 Consequences of Disruption

As well as identifying critical objects in the network, vulnerability analysis should also examine the extent of consequences if a critical object is disrupted (Jenelius et al., 2006a). One approach is to use traffic modelling software to assess how the traffic flow changes as a consequence of road closures, reductions in speed limit or capacity due to damage on the network. This approach has been used to model the consequences of damage to a congested road network in Europe (Berdica & Mattsson, 2007). One issue with this approach is that, due to the computational time required to run models, it is only feasible to run a limited number of scenarios (Jenelius et al., 2006a). It is therefore useful to identify criteria to determine which roads should be tested (Erath et al., 2009). A common method of quantifying the consequences of damage to roads is to measure the additional travel time experienced by road users. Apart from inconvenience to individual road users, knowing the additional travel time is useful as it can be used to calculate indirect economic consequences of damage. For example, Yee et al., (1996) found that the cost of delay associated with the closure of a single highway due to the 1994 Northridge Los Angeles Earthquake was almost $1 million per day (figure not adjusted to account for inflation).

1.3 Hazard identification

The location of the occurrence of natural hazards that can disrupt road networks differs spatially. Some areas are more susceptible to certain hazards than others. As road networks are physical entities embedded in geographical space, different sections or the network are likely to be exposed to different hazards or different levels of the same hazard (D'Andrea et al., 2005). It is important to identify significant potential causes of closure across the network, especially when it is exposed to natural hazards (Dalziell & Nicholson 2001). Doing this allows us to identify infrastructure that is likely to be disrupted given a specific hazard. For example, if flooding is predicted, some roads are more likely to be affected than others.

2.0 METHODOLOGY AND CASE STUDY

2.1 Models

2.1.1 Betweenness centrality

Betweenness centrality identifies the number of times a node is used as part of the shortest path between any other two nodes in the network. High betweenness has been shown to correlate with traffic flow across an urban street network (Demsar et al., 2007). Betweenness centrality C^B of node i is defined as:

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j,k \in G, j \neq k \neq i} n_{jk}(i)/n_{jk} \qquad (2)$$

where n_{jk} is the number of shortest paths between j and k and $n_{jk}(i)$ is the number of shortest paths between j and k containg node i (Crucitti et al., 2006). Betweenness centrality was derived for the network using the sDNA (spatial design network analysis) extension for ArcGIS (Cooper et al., 2013).

2.1.2 Hazard exposure

To get a general combination hazard susceptibility maps for the region, the hazard maps shown in Figure 5 have been disaggregated to the same resolution (100 m² grid) and overlaid using GIS. The very low-very high classification will be converted into a numeric classification (1= very low, 2= low etc. relating to the probability of occurrence) and the numbers of the cells will be added when the various hazard layers are overlaid. It should be noted that the classification of seismic hazards in the area is either high or very high meaning that the seismic hazard will have a value of either four or five, respectively. For example, when overlaying all three hazard layers (flood, landslide and seismic), the minimum total value (indicating the lowest overall hazard) will be six and the maximum 15. From this hazard base map, the maximum values will be extracted for each road to give a relative hazard exposure value for each road in the network.

The two metrics, betweenness and hazard exposure will be normalised and combined with equal weighting to give a vulnerability measure for the network. This approach is based on multi-attribute value theory, often used as a tool for decision analysis (Pöyhönen et al., 2001). Zhang & Virrantaus (2010) applied this approach to topological road network vulnerability assessment.

2.1.3 Traffic Modelling

To model the consequences of disruption to critical sections of the network, a traffic equilibrium model will be used to calculate additional journey time for travellers. These models are based on Wardrop's principles of traffic equilibrium (Wardrop & Whitehead, 1952) which centre around the premise that all road users seek to minimise their travel time and that no individual trip maker can further reduce travel time by switching routes. This modelling approach has been used to examine the economic effects of road closures (Paz et al., 2011) as well as comprising part of network vulnerability assessment (Erath et al., 2009; Berdica & Mattsson, 2007; Dalziell & Nicholson, 2001).

In many cases commercial software is used for equilibrium modelling (e.g. SATURN, Van Vliet, 1995), however, this is costly (many thousands of pounds per year for a licence) and beyond the means of many transport managers across Europe. This study uses a free, open-source software called NEXTA (Network Explorer for Traffic Analysis) which is the graphical user interface for a traffic assignment model DTALite (Light-weight Dynamic Traffic Assignment Engine) (Zhou & Taylor, 2014). This implements an iterative user equilibrium model where vehicles can be diverted between a number of alternative routes until an optimum path is determined (Schroeder et al., 2014). As well as being free, this software allows the user to convert GIS shapefiles to a network set of roads and links. This is particularly useful when working with data from sources such as OpenStreetMap. In NEXTA, the user can control the capacity and speed limit on all links in the network, meaning it is possible to test a huge variety of detailed scenarios. The model will output travel times and distances between all zones in the network where trips have been made.

DTALite implements Newell's kinematic wave model, a computationally inexpensive but theoretically sound traffic queuing model (Newell, 1993). This approach makes use of a number of theories, principally kinematic wave theory, which relates traffic flow to traffic density using partial differential equations (Lighthill & Whitham, 1955). This work developed the flow-density curve which shows the fundamental relationship between traffic flow and traffic density that underpins many modern traffic flow models (Figure 6).

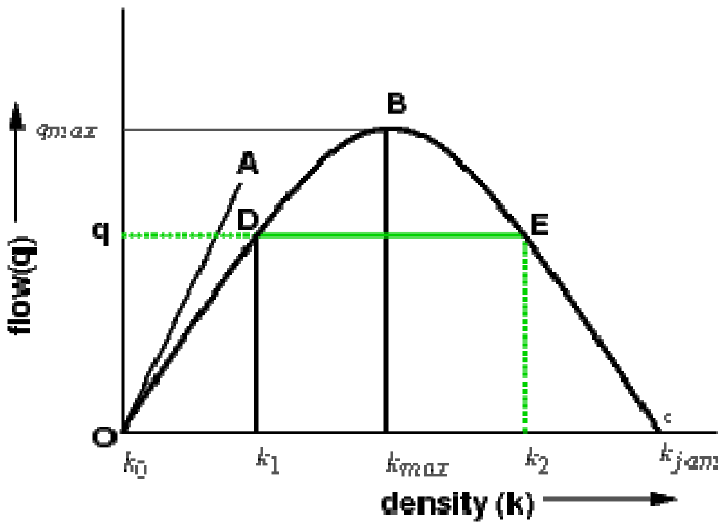

Figure 2: Flow-density curve (Indian Institute of Technology, 2015)

With reference to Figure 2, at point O there are no vehicles on the road hence flow and density are zero. As the number of vehicles increases, so does both the flow and the density until it reaches point B which is the maximum flow. Flow cannot increase beyond B, however, by increasing the number of vehicles, density can increase to a maximum of K_{jam} where the flow is reduced to zero. This can be thought of as gridlock. The line OA is the tangent of the parabola at O and represents the free flow speed. The points D and E represent identical flows at different traffic densities, the (hypothetical) lines OD and OE represent the respective speeds of the flow. The steeper line between OD in comparison with OE shows that speed will be considerable higher at density k_1 in comparison to k_2 despite the identical flows. A detailed mathematical description of the implementation of Newell's Simplified Kinematic Wave Model using DTALite can be found in Zhou & Taylor, (2014).

There are a number of assumptions associated with using an equilibrium model to estimate the consequences of disruption caused by natural hazards. Travellers are assumed to have perfect knowledge of the network, know which roads are closed and which are the fastest alternative routes. It is also assumed that the demand remains the same, i.e. that the same number of people still want to make the same journeys. There is no accounting for people changing transport modes (e.g. from road to rail) or deciding not to travel (e.g. working from home).

2.2 Study area

To demonstrate use of betweenness centrality analysis, we will us a case study area of Bologna city, a 989 km² region of Emilia-Romagna, surrounding the city of Bologna (Figure 3). The study area is intersected by the Autostrada del Sole, Autostrada Bologna-Padova and Autostrada Adriatica which are motorways which form part of the European TEN-T network (Figure 2A). The TEN-T network has been identified by the European Union as being a vital part of the transport network. The study area was also chosen as it is susceptible to a number of natural hazards, namely floods, landslides and earthquakes.

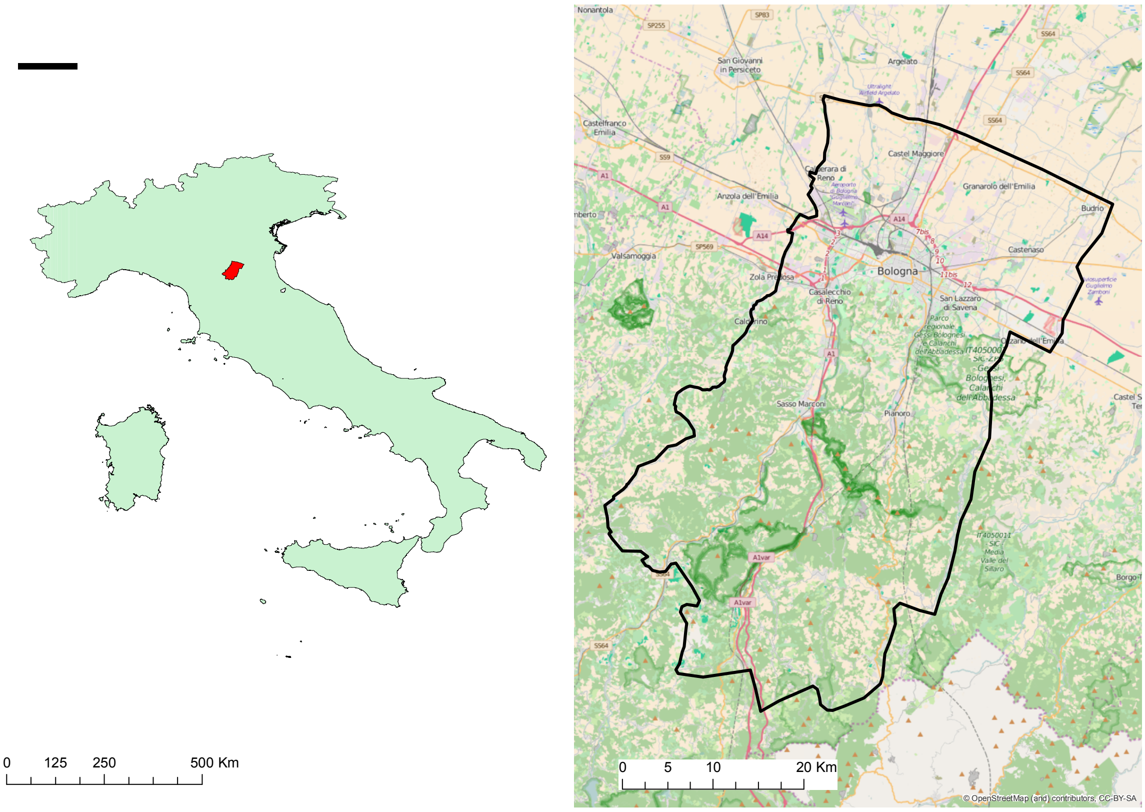

Figure 3: Location of the Bologna study area in relation to Italy and the Road network within the study area

2.3 Data

2.3.1 Road network data

In the Bologna city region, the road network is made up of motorways, primary, secondary, tertiary and residential roads (Figure 4B) taken from OpenStreetMap data (Haklay & Weber, 2008). The open street map data can also be used to identify the locations of objects such as bridges and tunnels. The national road network (Figure 4A) is taken from ETIS-plus European FP7 project which aims to provide good quality, integrated transport data for the whole of Europe (ETIS 2012a). The network contains main national and strategic roads (i.e. those of regional importance). Detailed links within urban networks are generally omitted as they are typically less important to long distance travel. This data includes details of lane capacity and speed limits of the roads (Table 1).

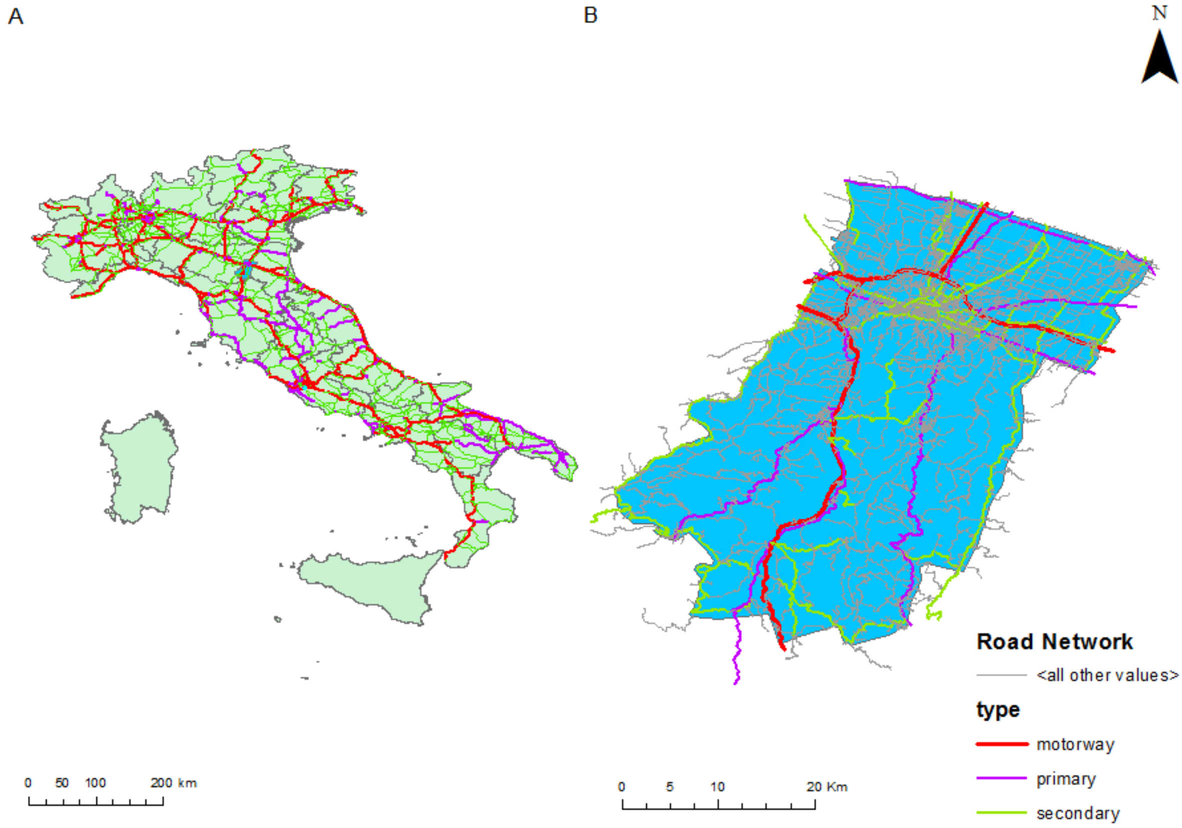

Figure 4: A) Bologna study area in the contest of Italy and the major road network in Italy B) The Bologna Road network

The national road network (Figure 3A) road network consists of 3522 links and 2468 nodes. Other attributes of interest are shown in Table 1.

Road Type	Lane Capacity (Vehicles per hour)	Speed Limit (Kph)	Number of lanes
Motorway	1950	130	3
Dual carriageway	1875	110	2
Single carriageway	1700	90	1

Table 1: Road attribute data

2.3.2 Traffic data

The national scale network is introduced to facilitate the use of a traffic equilibrium model to examine the consequences of disruption to the network. This modelling approach requires traffic data, which details the origin and destination of journeys and the number of journeys made between these origins and destinations. The traffic data used for this deliverable is origin-destination (OD) data between regions in Italy. In the ETIS dataset (ETIS 2012b), there are 90 regions or zones that make up mainland Italy (Figure 5). A list of the zones is shown in Appendix B. The traffic data divides trips between zones into four types:

- Business (trips for working purposes with different destination than the usual workplace)
- Private (non-business related trips with duration of up to 4 days)
- Vacation (non-business trips with duration of more than 4 days)
- Commuting (daily trips for working or studying purposes)

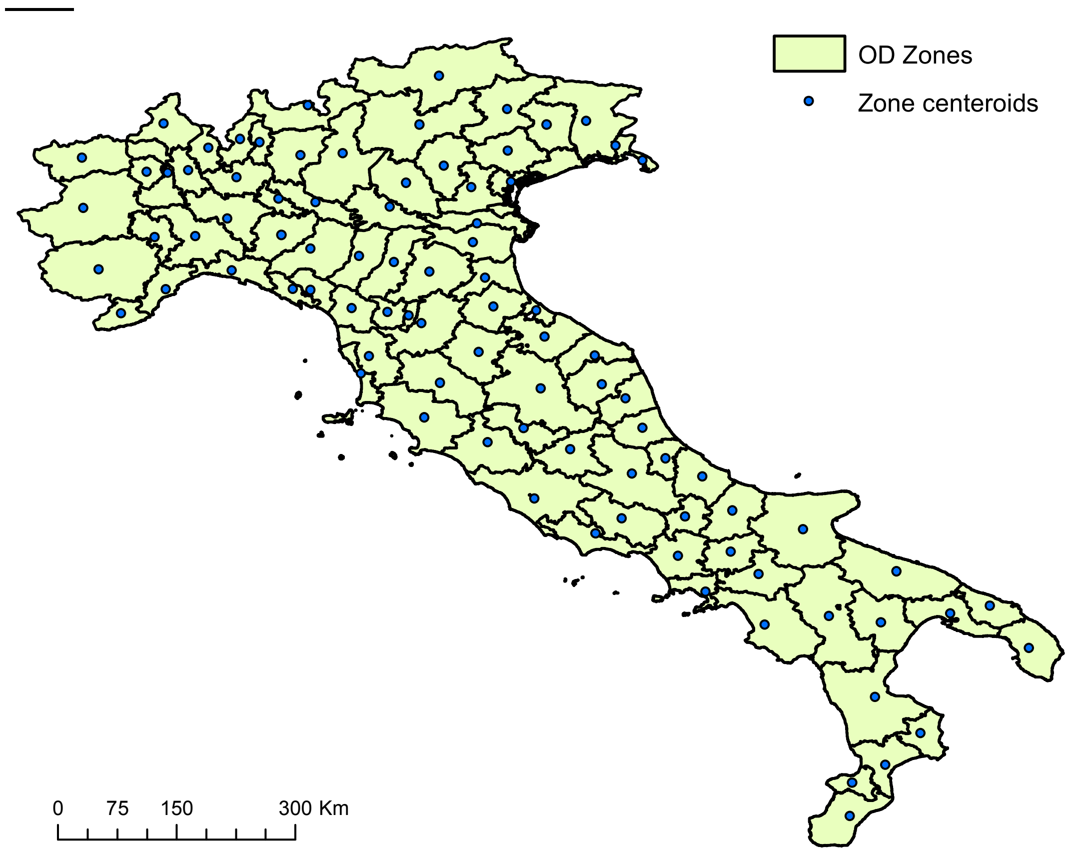

Figure 5: Italian OD traffic zones

The data is in the form of an OD matrix when trips are distributed between zones (Table 2). It should be noted that the matrix is not symmetrical, meaning that Origin Zone 1-Destination Zone 2 includes all trips made by people living in Zone 1, travelling to Zone 2 and making the return journey.

	Destination		
Origin	**Zone 1**	**Zone 2**	**Zone 3**
Zone 1	0	500	400
Zone 2	1000	0	350
Zone 3	1500	200	0

Table 2: Example of origin-destination matrix

The data is derived from a combination of observed data from EUROSTAT, national agencies, national travel surveys and census data. Missing data has been modelled using a four stage procedure detailing traffic generation, distribution, mode choice and route assignment. A comprehensive explanation of the data and methods used is available from ETIS (2012b). Using the ETIS data, it was possible to derive a representative rush-hour hourly traffic flow on the ETIS network, in this case 924,839 vehicles enter the network in an average week day rush hour. This approach is typically used to assess consequences of disruption of the road network using traffic equilibrium models (Maheshwari & Paz, 2015).

2.3.3 Hazard data

The region is prone to a number of natural hazards. Hazard susceptibility is a relative measure of the spatial likelihood of the occurrence of a hazard (Pourghasemi et al., 2013). The three most prominent are floods, landslides and earthquakes. Figures 5 show the relative susceptibility of the Bologna study areas to flooding, landslides and seismic hazards respectively. The landslide susceptibility map (Figure 6A) is taken from the 1 km grid resolution ELSUS v1 pan-European landslides susceptibility assessment (Günther et al., 2014). The flood susceptibility map (Figure 6B) comes from the pan-European flood-hazard map showing the probable depths of flooding given a 100 year flood event at a 100m grid resolution (Alfieri et al., 2014). The seismic hazard map (Figure 6C) is taken from the European Commission FP7 SHARE project which produced a seismic hazard map for the whole of Europe (Giardini et al., 2014). This map shows the 10% probability of exceedance within the next 50 years on a 15 km resolution grid. As the map was produced for the whole of Europe, the classifications (High and Very High) are relative to the rest of Europe. All maps have been classified to five susceptibility levels and disaggregated to 100m grid cell resolution to allow combination. The purpose of this is to provide an indicative map of overall hazard susceptibility for the Bologna region. These maps can be used to differentiate between areas that are likely to be affected by natural hazards and those that are less likely. The maps cannot be used as risk maps to show the probability of hazards occurrence.

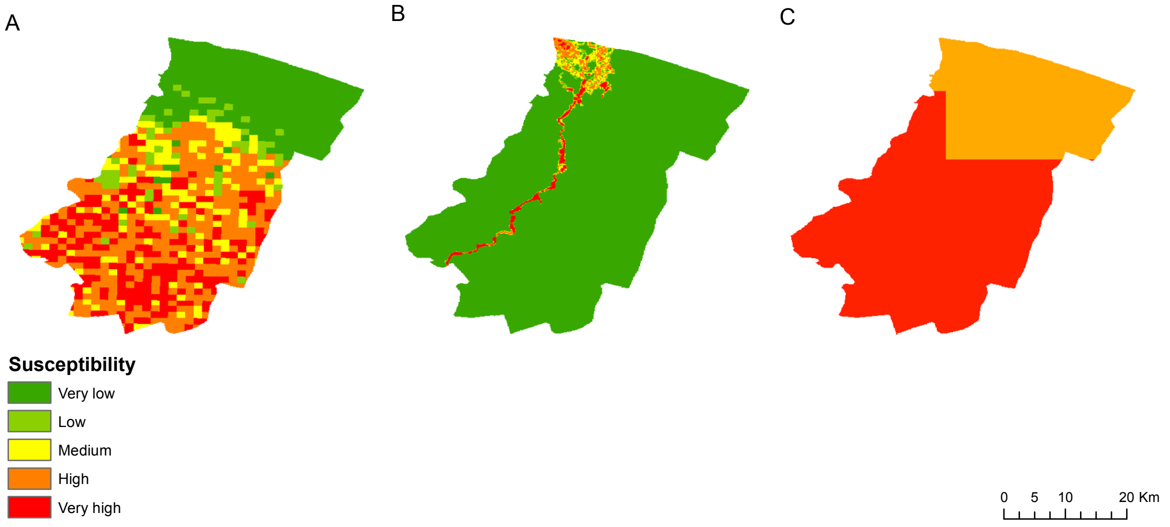

Figure 6: Hazard susceptibility in the Bologna region. 5A) susceptibility to landslides 5B) susceptibility to flooding 5A) susceptibility to seismic hazards

3.0 RESULTS

3.1 Hazard exposure

The combination of susceptibility maps are shown in Figure 7. Broadly, there is a north-south divide between less susceptible areas (North) and more susceptible areas (South) in the region. The areas of overall highest susceptibility to multiple hazards are in the south, surrounding the river Reno which is susceptible to flooding. This is reflected in the exposure of the roads to the combination of natural hazards shown in Figure 8B.

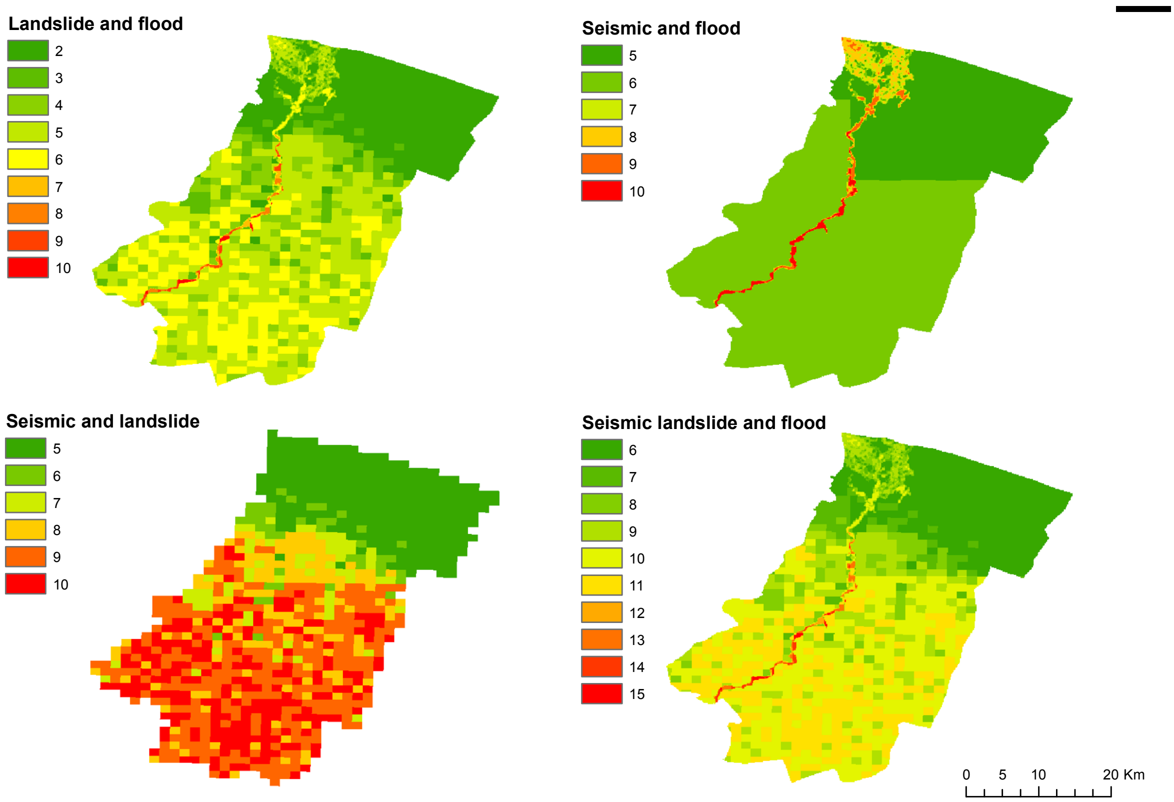

Figure 7: Hazard susceptibility combination maps.

3.2 Betweenness centrality

The betweenness centrality results for the network are shown in Figure 8A. Here, the high-to-low scale represents betweenness centrality measures for all the roads in the network. The red links have high betweenness, indicating that they are important to the connectivity (and hence serviceability) of the network. Echoing the results found in Demšar et al. (2008) and Jiang (2009) for the road networks of Helsinki metropolitan area and Gavle City respectively, the road segments with high betweenness correspond very well to the network of main roads in the Bologna region. In particular, the Autostrada Del Sole and primary roads SS64 and SP65 are shown to be highly important to the network. Figure 8C shows the combination of hazard exposure and betweenness centrality metrics. Here, the high values indicate roads with high betweenness that interest areas that have high overall hazard susceptibility. According to this analysis, the most vulnerable roads are main roads located in the south of the region.

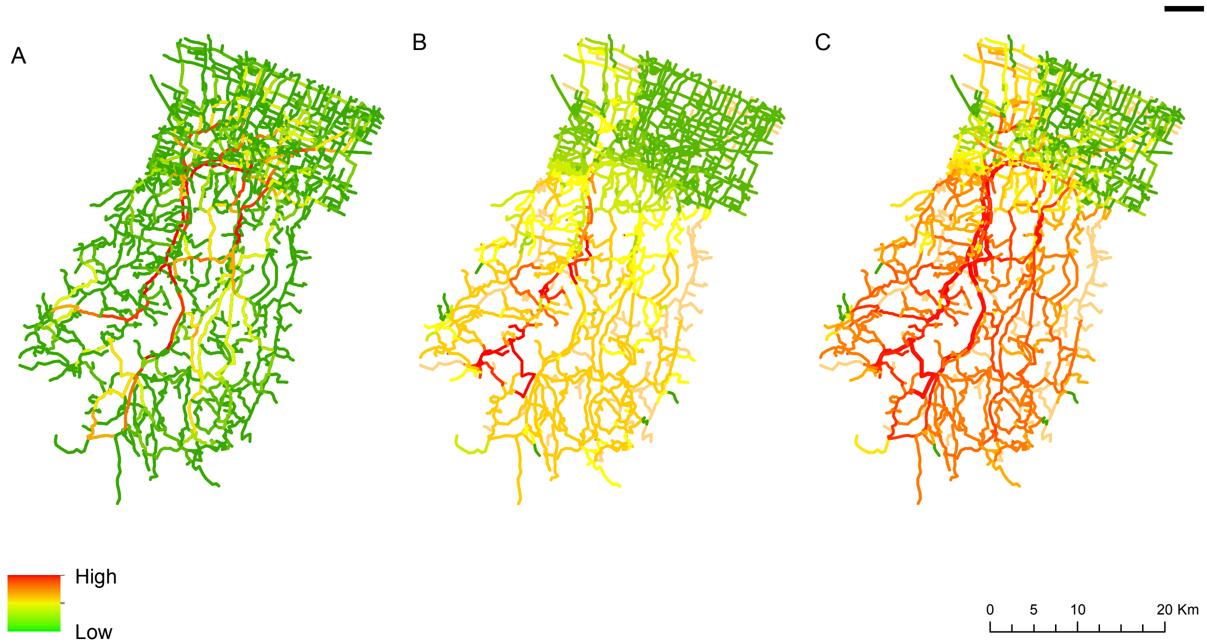

Figure 8: A) Betweenness centrality analysis B) exposure to natural hazards C) combination of betweenness and exposure to natural hazards

3.3 Scenario identification

On a large road network, there are an almost infinite number of damage scenarios (combinations of road closures, capacity reductions and speed restrictions). As stated, due to computational costs, it is only feasible to run a limited number of damage scenarios (Jenelius et al., 2006a). To demonstrate how to assess the consequences of damage using a traffic equilibrium model, the following section will test three scenarios. The first is an undamaged network, which gives a baseline of the traffic flow and travel times in the network under normal conditions. The second is a 'total damage scenario' representing a situation where all roads in the network are non-operational and the third, labelled 'damage scenario one' is a damage scenario based on the betweenness centrality and hazard exposure analysis. In this scenario, a number of roads that have a high combination of betweenness centrality and hazard exposure (Figure 8C) are selected to be non-operational.

Much of the cost of associated with damage to a road network caused by natural hazards comes from the economic losses incurred due to reductions to the serviceability of the network (Yee et al., 1996). In particular, there is a cost associated with increase in travel times for passengers and freight. As the impact of damage to the road network will extend far beyond the geographical extent of damage (in this case, the Bologna case study region), it is necessary to assess consequences at a national scale. The purpose of damage scenario one is to identify objects in the network with high betweenness and high hazard exposure. This still leaves a lot of objects which may be damaged. To narrow the focus of the scenario, only roads which are supported by bridges designed to a low seismic code will be considered. The rationale behind this is that bridges are often deemed to be vulnerable object on a road network (Berdica & Mattsson, 2007) and much of the work of INFRARISK has been concerned with the fragility of bridges to seismic hazards. Moreover, bridges that have been designed to a low seismic code are designed withstand a substantially lower seismic load than many newer bridges and therefore more likely to be seriously damaged by a given seismic load.

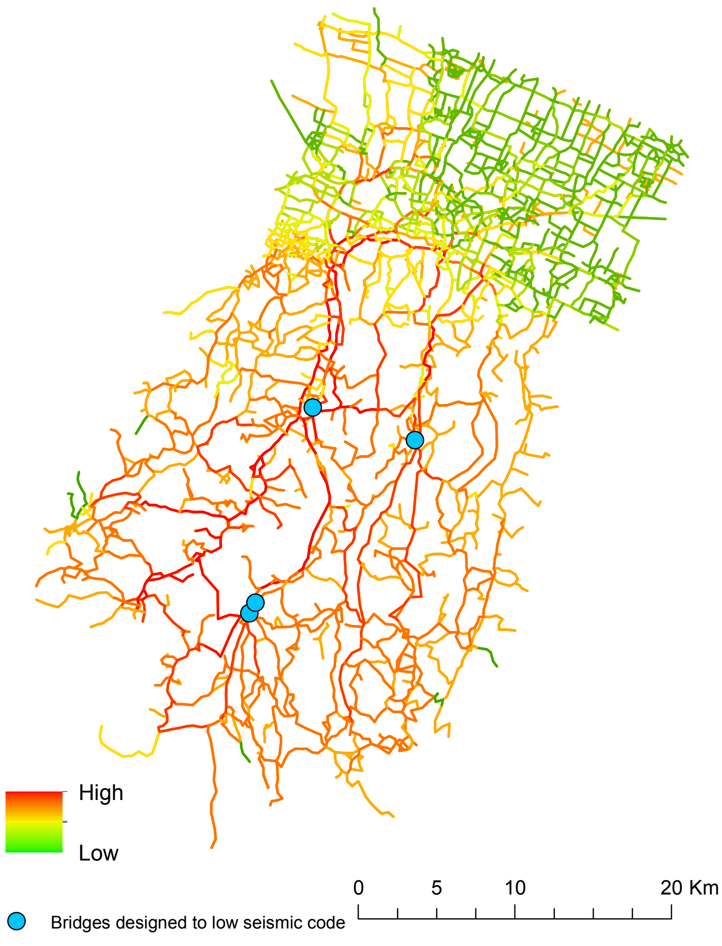

Figure 9: location of the damaged bridges used in damage scenario one

Damage scenario one has selected a total of four bridges that will be unusable in the equilibrium model. The bridges all satisfy the criteria that they are on the top 1 percent of vulnerable roads according to the betweenness centrality and hazard exposure analysis (Figure 8C). This has identified the bridges in Figure 9, which will be closed for the traffic modelling of damage scenario one. The 'total damage scenario' will simulate traffic flow if all roads in the region were unavailable for use. This will show the consequences if the entire Bologna region was impassable.

3.4 Modelling Consequences

The results of damage scenario one and the total damage scenario are shown in Table 3-4 and in Figures 10 and 11. Table three shows the average time for all trips in the network and the percentage increase due to damage in comparison to the travel time on an undamaged network. The travel time is based on 924,839 vehicles entering the network over a 1 hour period. The simulation then runs until all vehicles have reached their destinations.

Scenario	**Average travel time (mins)**	**Percentage increase (travel time)**
No damage	266	NA
Total damage	302	13.5
Damage scenario one	268	0.8

Table 3: Average travel time for all trips in the network

While the overall increase appears small, especially for damage scenario one, it should be noted that in virtually all scenarios there are both winners and losers (albeit winners in the minority). When a link is closed, and a route is abandoned, travel demand is reduced on all other links on the abandoned route. Travellers who still use these links will therefore experience less congestion and therefore can reduce some people's travel time. Similarly, user equilibrium is based on speed not distance. This means that road closures can results in a previously slower, shorter rout (e.g. one with a lower speed limit) becoming the new quickest route. This would result in the trip distance decreasing. Because of this, the average effect across the entire network can be negligible. However there can be substantial changes across sub-regions or between specific OD pairs (Berdica & Mattsson, 2007).

For this reason, it is necessary to examine how the delay affects trips between the individual OD pairs. As stated, there are 90 zones nationally making a total of 8010 OD pairs (no OD pairs start and end in the same zone). Trips which were substantially delayed (by a minimum of 10 percent to total travel time) due to the total damage scenario are shown in Figure 10 and Table 4. Travel time was more than doubled for 283 OD trips (over 3.5 percent of the total possible OD trips in the network). More than a quarter of the 8010 OD pair trips across the whole of Italy were substantially (at least 10 of travel time) delayed by the total damage scenario.

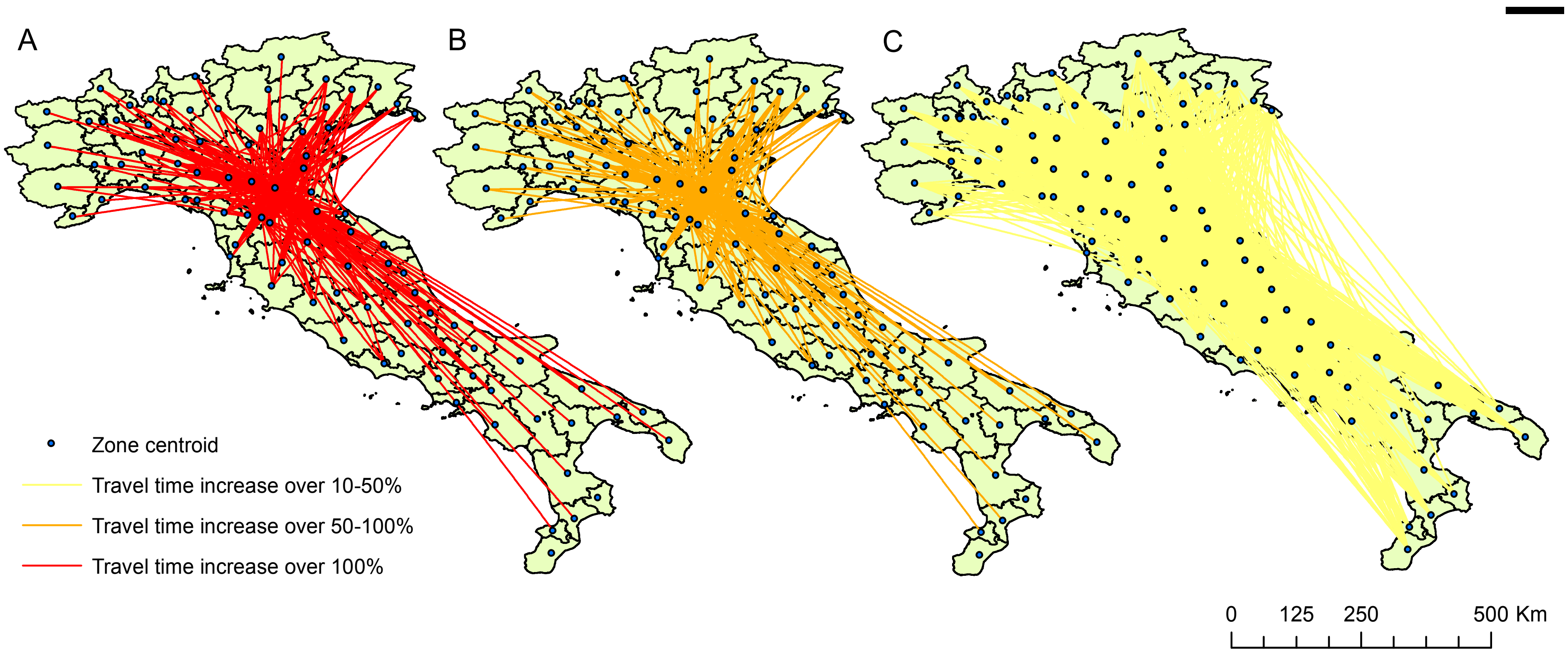

Figure 10: Increase in travel times between zones due to the total damage scenario. A) OD pairs where travel time was increased by more than 100% B) OD pairs where travel time was increased by more than 50-100% C) OD pairs where travel time was increased by more than 10-50%

Scenario	Increase travel time- over 100% (Number of OD pairs)	Increase travel time- over 50-100% (Number of OD pairs)	Increase travel time- over 10-50% (Number of OD pairs)
Total damage	283	354	1399
Damage scenario one	0	1	276

Table 4: Number of OD pairs where travel time was substantially increased due to damage

The effects of damage scenario one are much less pronounced than the total damage scenario. They are shown in Figure 11. None of the trips are delayed by more that 100 percent and only a single OD pair, those travelling between Prato and Bologna, could expect to be delayed by over 50 percent. Despite this, the closure significantly delayed 277 individual OD pairs which, using the ETIS travel demand data equates to 8588 vehicles per hour.

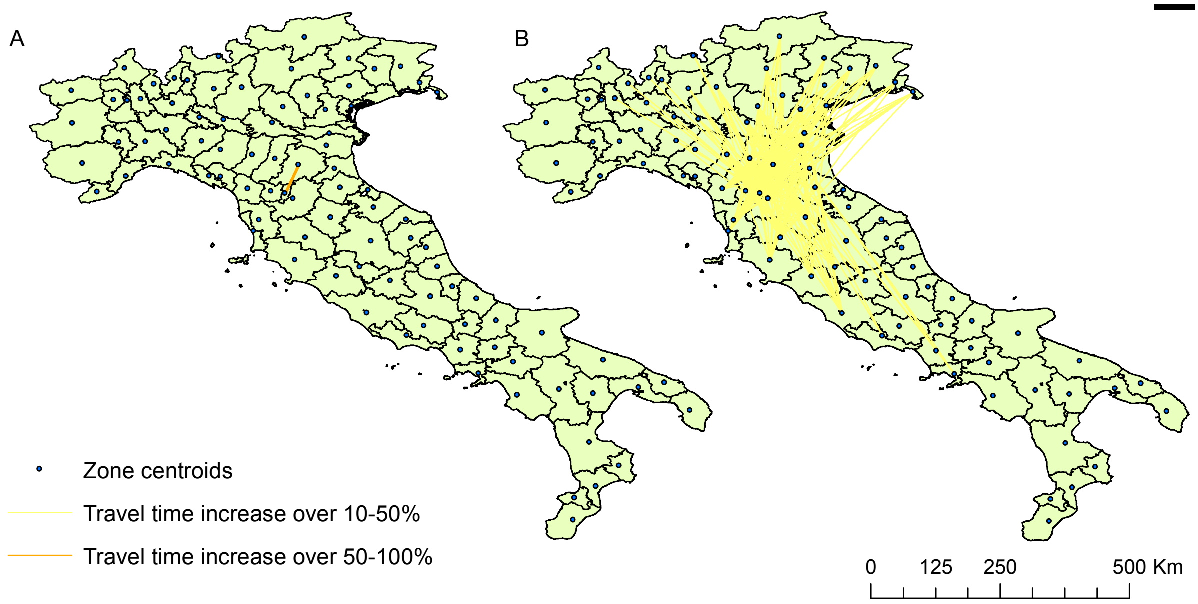

Figure 11: Increase in travel times between zones due to the total damage scenario. A) OD pairs where travel time was increased by more than 50-100% C) OD pairs where travel time was increased by more than 10-50%.

3.5 Model Applications

Calculating travel time delay for given scenarios can be used to calculate indirect economic losses caused by damage to the road network. This is done by assigning an economic value to people's time. The indirect economic cost will depend on both the delay and the duration of the reduction in the network's serviceability. As well as modelling the effects of damages, the traffic equilibrium modelling approach can be used to model the effects of restoration. After a hazard event causes damage, the entire network will not be restored instantaneously. There will be many phases of restoration based on the damage that has occurred and the recovery plan that exists. Over time different parts of the network will be restored to various capacities. At various stages during the restoration process, the traffic model can be rerun to observe how the restoration is impacting traffic flow and hence indirect economic costs (although restoration sequences are not considered in the context of this report).

4.0 CONCLUSION

Road networks can be damaged and disrupted by natural hazards. Using vulnerability analysis as a framework, Deliverable 5.3 identifies vulnerable elements in the bologna road network based on network topology and exposure to a range of natural hazards. Roads which are critical to the functionality of the network were identified based on betweenness centrality analysis. This was combined with a hazard exposure metric based on the spatial location of the roads to identify highly vulnerable roads. In this instance the Autostrada Del Sole and primary road SS64 in the south of the region were found to have high betweenness and be highly exposed to a range of natural hazards, making them particularly vulnerable.

To demonstrate a method of quantifying the consequences of damage to vulnerable roads in the network, the study used a traffic equilibrium model Nexta to simulate traffic delay on a national scale based on damage to roads in the Bologna region. There are virtually limitless damage scenarios which could be tested and compared to an undamaged network. This study used two: one based on total damage of the Bologna network and another based on the topological vulnerability analysis and the location of bridges. This demonstrated that that widespread damage to the roads in Bologna would have substantial negative effects on traffic flow for the whole of Italy and even damage to four bridges that in the Bologna region that have not been designed to withstand large seismic events could cause substantial delays for many travellers across central and northern Italy.

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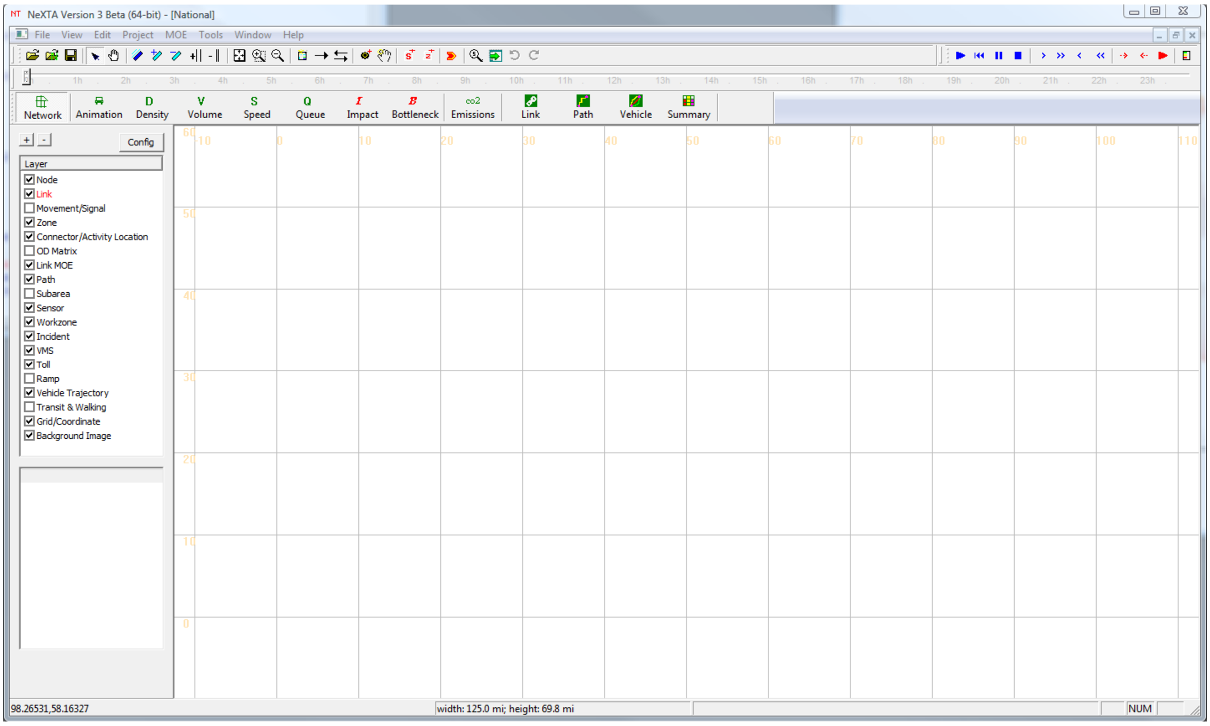
APPENDIX A: NEXTA USER GUIDE

Model Input Preparation

Open Nexta



File/save project as/ *navigate to folder and save as Italy.tnp*

Open folder location and you will see a number of .csv flies representing the input data.

Name	Date modified	Type	Size
AMS_movement	18/09/2015 14:40	Microsoft Office E...	1 KB
AMS_phasing	18/09/2015 14:40	Microsoft Office E...	1 KB
AMS_traffic_data_settings	20/11/2013 21:02	Microsoft Office E...	1 KB
input_activity_location	18/09/2015 14:40	Microsoft Office E...	1 KB
input_base_cycle_fraction_of_OpMode	01/02/2013 10:09	Microsoft Office E...	2 KB
input_cycle_emission_factor	29/01/2013 14:35	Microsoft Office E...	14 KB
input_demand	03/01/2013 00:10	Microsoft Office E...	1 KB
input_demand_meta_data	08/01/2013 12:51	Microsoft Office E...	2 KB
input_demand_type	17/09/2012 10:39	Microsoft Office E...	1 KB
input_link	18/09/2015 14:40	Microsoft Office E...	1 KB
input_link_type	18/09/2015 14:40	Microsoft Office E...	1 KB
input_MOE_settings	12/09/2012 18:45	Microsoft Office E...	2 KB
input_node	18/09/2015 14:40	Microsoft Office E...	1 KB
input_node_control_type	18/09/2015 14:40	Microsoft Office E...	1 KB
input_pricing_type	13/07/2012 10:16	Microsoft Office E...	1 KB
input_scenario_settings	20/04/2013 23:05	Microsoft Office E...	1 KB
input_subarea	18/09/2015 14:40	Microsoft Office E...	1 KB
input_vehicle_emission_rate	15/11/2012 21:21	Microsoft Office E...	27 KB
input_vehicle_type	08/01/2013 21:30	Microsoft Office E...	1 KB
input_VOT	13/07/2012 10:16	Microsoft Office E...	1 KB
input_zone	18/09/2015 14:40	Microsoft Office E...	1 KB
ms_signal	22/08/2012 07:33	Microsoft Office E...	1 KB
ms_vehclasses	22/08/2012 07:33	Microsoft Office E...	1 KB
ms_vehtypes	22/08/2012 07:33	Microsoft Office E...	1 KB
output_zone	18/09/2015 14:40	Microsoft Office E...	1 KB
Scenario_Dynamic_Message_Sign	18/09/2015 14:40	Microsoft Office E...	1 KB
Scenario_Incident	18/09/2015 14:40	Microsoft Office E...	1 KB
Scenario_Link_Based_Toll	18/09/2015 14:40	Microsoft Office E...	1 KB
Scenario_Work_Zone	18/09/2015 14:40	Microsoft Office E...	1 KB
ODME_settings	18/09/2012 07:05	Text Document	1 KB
Italy.tnp	18/09/2015 14:40	TNP File	1 KB

Open **input_node.csv**.

This specified the nodes in your network.

The columns that require input are

node_id	Identification number
x	X co-ordinate
y	Y co-ordinate

When you have input the data for your network, close the .csv and save the changes. Do this for all inputs.

Open **input_link.csv**.

The columns that require input are

name	Road name (if known)
link_id	Road code (if known)
from_node_id*	The node_id where the link originates*
to_node_id*	The node_id where the link originates*
link_type_name[ɣ]	See **input_link_type.csv**
direction	1
length	Miles
number_of_lanes	
speed_limit	Mph
lane_capacity_vhc_per_hour	
link_type[ɣ]	1/2/3… (see **input_link_type.csv**)[ɣ]
geometry[+]	In the google earth KLM format e.g <LineString><coordinates>11.909840,45.375340,0.0 11.906284,45.372557,0.0 11.901438,45.370672,0.0 11.868858,45.364075,0.0

	11.855181,45.363067,0.0</coordinates></LineString>

*In this format, links are single direction meaning that if you want traffic to flow from point A to point B you have to create link A-B and link B-A.

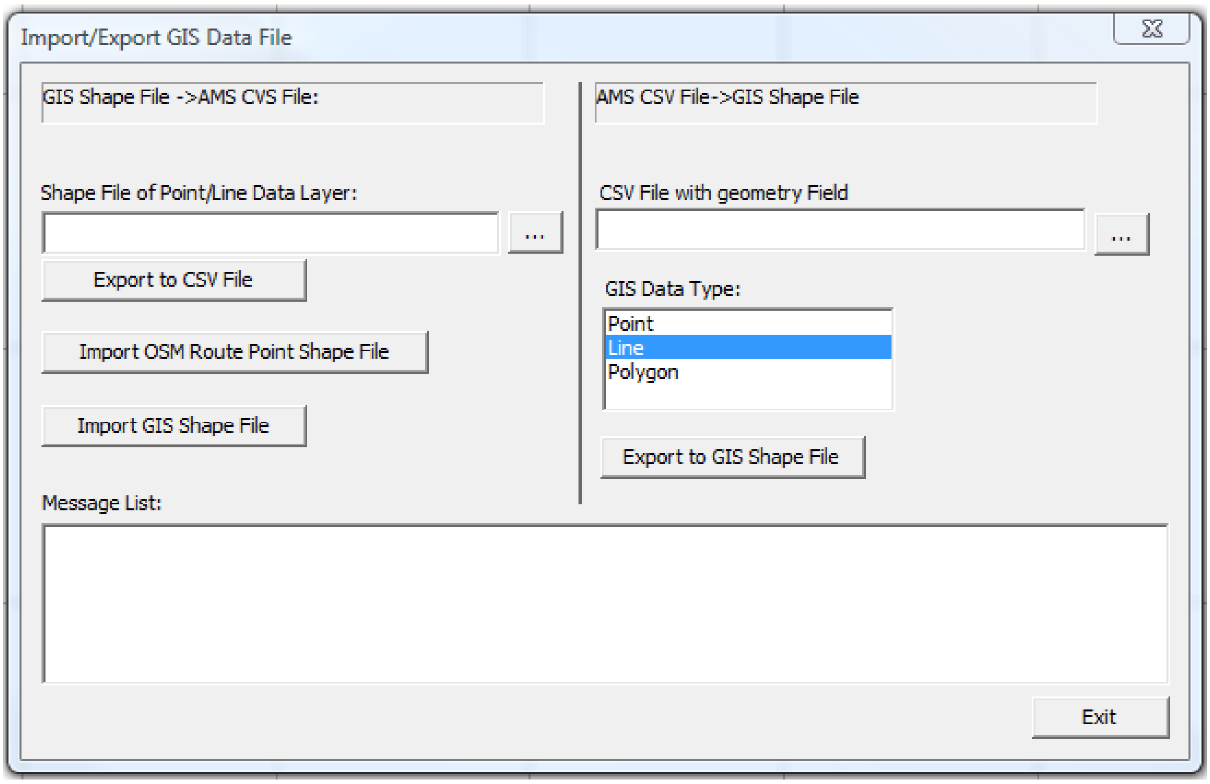
ᵞ The link type and name is hard coded into Nexta. The link_type_name and associated link_type are shown in **input_link_type.csv** (below)

link_type	link_type_name	type_code	default_lane_capacity	default_speed_limit	default_number_of_lanes
1	Freeway	f	1000	50	2
2	Highway	h	1000	50	2
3	Principal arterial	a	1000	50	2
4	Major arterial	a	1000	50	2
5	Minor arterial	a	1000	50	2
6	Collector	a	1000	50	2
7	Local	a	1000	50	2
8	Frontage road	a	1000	50	2
9	Ramp	r	1000	50	2
10	Zonal connector	c	1000	50	2
100	Transit link	t	1000	50	2
200	Walking link	w	1000	50	2

The default_lane_capacity, default_speed_limit and default_number_of_lanes need to be edited to match the **input_link.csv.** The names and codes however must remain the same (e.g. you cannot change [1, Freeway, f] to [100, Motorway, m].

⁺the geometry of the links is required if you want then to be displaced accurately. If you have a shapefile, Nexta can export the geometry to CSV using the GIS shapefile utility tool. **IMPORTANT** Importing and exporting data can only be done using **Nexta 32 bit**

In the menu bar select Tools/Network Tools/ GIS shape file utility



Load the Shapefile into the 'Shape file of Point/Line Data Layer:'

Select GIS Data Type (in the case of roads, this is 'Line'. For nodes use 'Point'. For zones use 'Polygon').

Open **input_link_type.csv**

Edit this to match the capacity, speed limit and number of lanes used in **input_link.csv**. remember not to change the link_type, link_type_name_ or type_code.

Open **input_zone.csv**

Zones are areas that the traffic is travelling to/from. It can be the case that each node is a zone. In the Italy network, zones are regional.

The columns that require input are

zone_id	Identification number. This must start from 1.
geometry	In kml format. Use the GIS shape file utility if you are converting a shapefile

The zone ID must start from 1 and increase by 1 as Nexta is hardcoded to create a matrix that is equal in size to the largest zone_id. Therefore if the zone_id is set to 1000000, Nexta will crash as it tries to produce a 1000000x1000000 matrix.

Open **input_link_type.csv**

This links zones with nodes. Here we list every node that is in each zone.

The columns that require input are

zone_id	zone_id must match all zones in **input_zone.csv**
node_id	node_id must match all nodes in **input_node.csv**

Open **input_demand.csv**

This tells us how many vehicles are travelling to/from each zone

The columns that require input are

from_zone_id	zone_id from which the vehicles originate
to_zone_id	zone_id to which the vehicles are travelling
number_of_trips_demand_type1*	Number of vehicles making the trip

*The number of vehicles travelling is time dependent. In this instance we are modelling one hour of traffic flow, meaning that we are saying that all the vehicles defined in **input_demand.csv** enter the network within an hour. Depending on their destination, it may take more than one hour to reach their destination.

Open **input_demand_meta_data.csv**

Here we specify when vehicles enter the network.

The columns that require input are

format_type	Change ‘matrix’ to ‘column’
start_time	Based on minutes from midnight (e.g. 60 is 1 am)

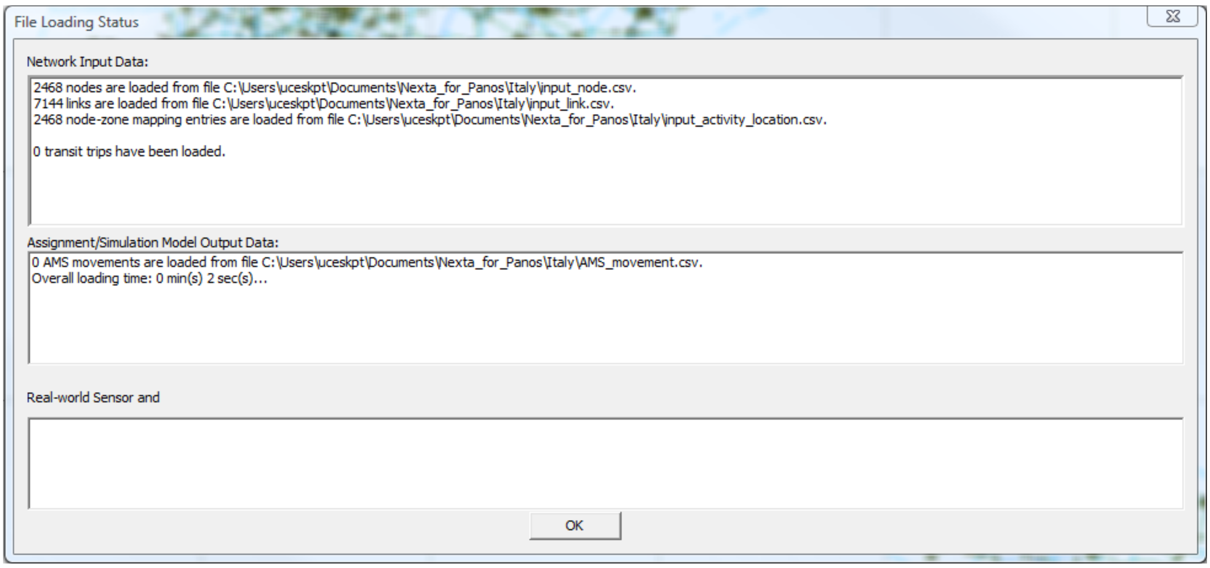
end_time	Based on minutes from midnight (e.g. 120 is 2 am)
Time '00:00 format*	Select the proportion of traffic to enter the network in 15 minute intervals

*Example below shows 20% of vehicles entering network at 2pm, another 20% at 2:15 pm, a further 30% entering at 2.30pm and the final 30% entering at 2.45pm.

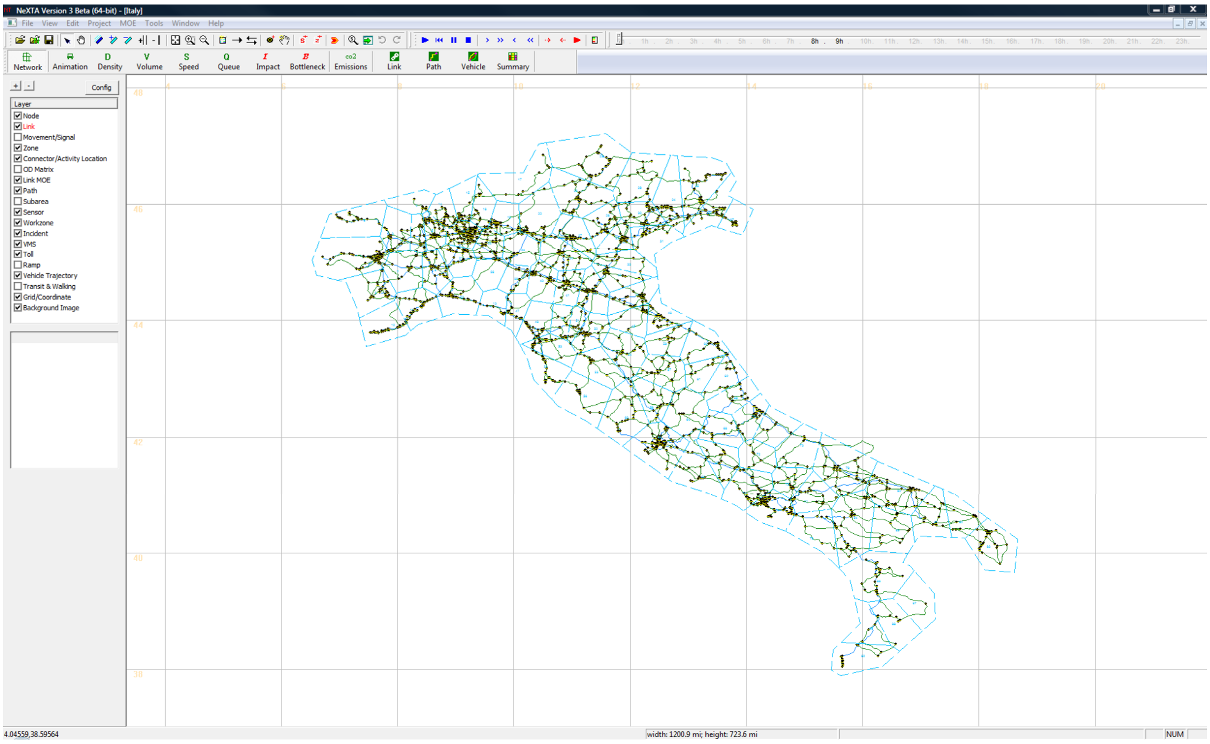
'14:00	'14:15	'14:30	'14:45
0.2	0.2	0.3	0.3

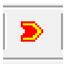
Running The Model

To run the model, open Nexta 64 bit. In the menu, open file/open Traffic Network Project and navigate to Italy.tnp. you should see the following message when the data is imported.

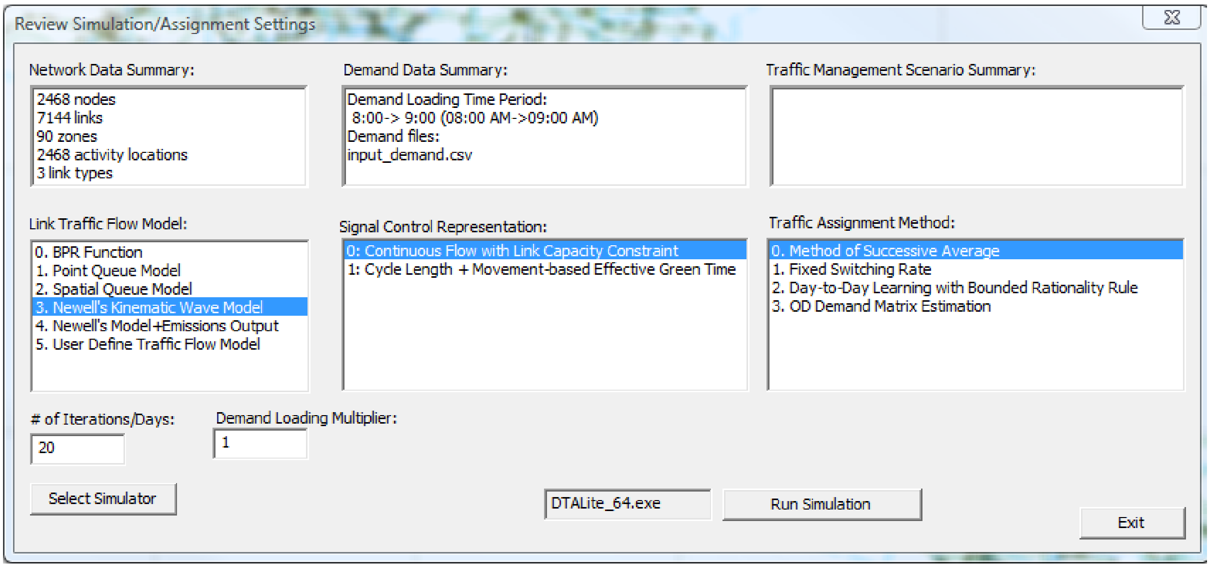


The network should look like this

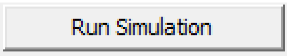


To run the model, press the  button on the menu bar.

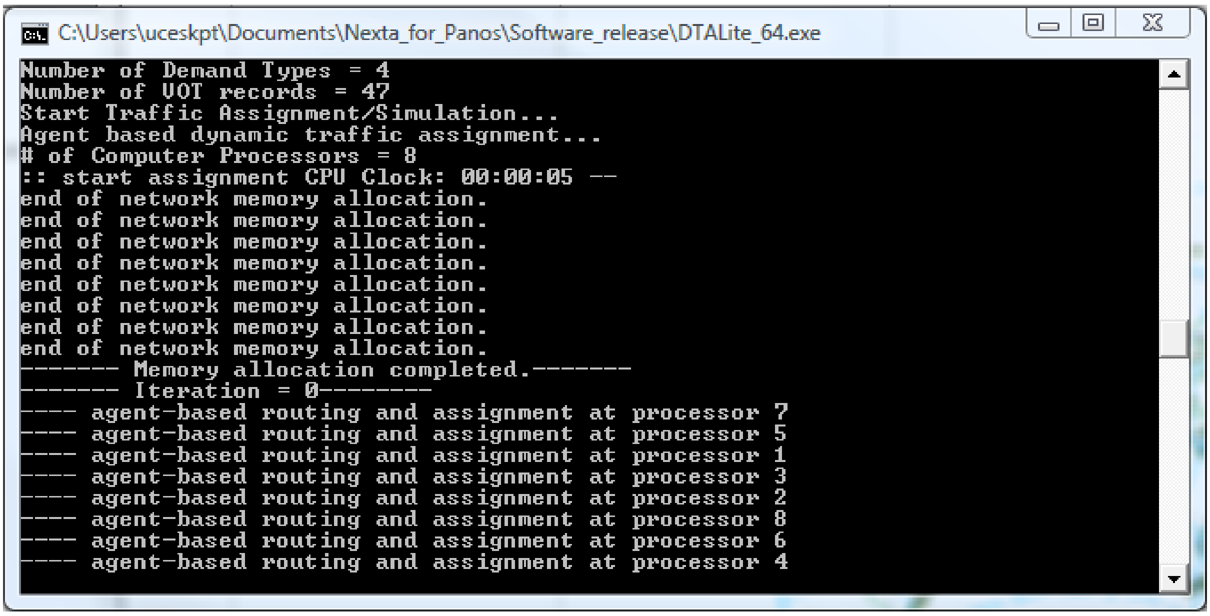
This will bring up the simulation options box.



We are using Newells Kinematic Wave Model. It is suggested that the modeller uses at least 20 iterations to produce a stable model. When you have selected the scenario you want, press



This will bring up the following box. Please wait for the model to run. In this example, this can take 15-20 minutes.



When the model has complete, view the summary output file.

To view detailed output of the travel time simulation, navigate to the folder where you have saved the Italy.tnp and open the **output_ODMOE.csv** which shows travel time and distance for the modelled ODs.

APPENDIX B: ZONE IDENTIFICATION

Zone ID	Zone name	Zone ID	Zone name
1	Crotone	46	Firenze
2	Pesaro e Urbino	47	Lucca
3	Savona	48	Massa-Carrara
4	Verbano-Cusio-Ossola	49	Ferrara
5	Trento	50	Bologna
6	Udine	51	Modena
7	Pistoia	52	Reggio nell'Emilia
8	Latina	53	Parma
9	Foggia	54	Piacenza
10	Brindisi	55	La Spezia
11	Salerno	56	Ascoli Piceno
12	Reggio di Calabria	57	Macerata
13	Vibo Valentia	58	Ancona
14	Catanzaro	59	Perugia
15	Cosenza	60	Arezzo
16	Matera	61	Rimini
17	Lecce	62	Forla-Cesena
18	Taranto	63	Ravenna
19	Bari	64	Trieste
20	Potenza	65	Gorizia
21	Avellino	66	Pordenone
22	Napoli	67	Rovigo

23	Benevento	68	Venezia
24	Caserta	69	Treviso
25	Campobasso	70	Belluno
26	Isernia	71	Padova
27	Chieti	72	Vicenza
28	Pescara	73	Verona
29	Teramo	74	Bolzano-Bozen
30	L'Aquila	75	Mantova
31	Frosinone	76	Cremona
32	Roma	77	Brescia
33	Rieti	78	Bergamo
34	Viterbo	79	Sondrio
35	Terni	80	Lodi
36	Genova	81	Pavia
37	Imperia	82	Milano
38	Alessandria	83	Lecco
39	Asti	84	Como
40	Cuneo	85	Varese
41	Grosseto	86	Valle d'Aosta
42	Siena	87	Novara
43	Pisa	88	Biella
44	Livorno	89	Vercelli
45	Prato	90	Torino

Table 4: Zones in the Italian OD matrix