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## MEASURING ROAD NETWORK RESILIENCE THROUGH LOSS OF SERVICEABILITY INDEX FOR CRITICAL ROAD LINKS

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### Abstract

In a complex network such as a road infrastructure system, disruptive events have direct consequences (loss of lives, structural damage, economy losses etc.) related to the sub-system level directly affected, as well as indirect consequences on the overall system level such as loss of functionality and related monetary consequences. To quantify the influence of component failures on the network performance, complex network analysis allows representing the relation among its components and the consequences in order to estimate the functionality of the system. The serviceability of a road network is the possibility to use it during a given time period as representing the performance of the system. Thus, the time to restored serviceability after a disruptive event is measuring road transportation resilience. In this paper, network analysis with the help of OSMnx Python package, supplied by road network data from OpenStreetMap, is applied to a Spanish motorway case study. Loss of serviceability index is obtained combining the results of road links failure scenarios based on shortest paths and travel times in order to estimate road network resilience. The proposed methodology allows a suitable evaluation of the influence of road links in the risk assessment and management strategies by road infrastructure owners and managers.

**Keywords chosen from ICE Publishing list**

Roads & highways, Climate change, Conservation, Data, Hazards, Risk & probability analysis, Statistical analysis

**List of notations**

- $A$  is the adjacency matrix
- $i, j$  is the origin and destination points
- $A_{ij}$  is the element of adjacency matrix
- $r$  is the arbitrary length of a path of the network [m]
- $N_{ij}^{(r)}$  is the total number of path of length  $r$  between  $j$  and  $i$  [-]
- $s$  is the set of nodes
- $n$  is the number of nodes in the set/graph [-]
- $t$  is the travel time of the shortest path [s]
- $\alpha_s$  is the reference value for the non-degraded configuration of the road network [s]
- $\beta_{k,s}$  is the reference value for the degraded configuration of the road network with removed edge  $k$  [s]
- $n_{ip,k}$  is the number of paths crossed by the removed edge  $k$  [-]
- $LoS_{k,s}$  is the Loss of Serviceability Index [s]

## 1 **Introduction**

2 Transportation infrastructure has an important role for regional and global communities.  
3 Climate change related-events, combined with hazard events such as earthquakes or  
4 flooding, increasingly expose road infrastructure to ever-increasing actions that leads  
5 the failure possibilities. For this reason, the recent challenge for transportation  
6 networks, including Road Infrastructures (RIs) is to improve their resilience by  
7 maintaining a given level of functionality during the hazard event, and by permitting  
8 them to quickly recover after (Vugrin, Warren and Ehlen, 2010; Shakou *et al.*, 2019).  
9 To this end, it is useful to have an efficient assessment method to identify the  
10 vulnerabilities of RI components and their impact on the RI functionality in order to  
11 maintain and to protect RI against hazard events and to perform risk assessment.  
12 Considering the multiple definitions of resilience (Faber, 2018) to adopt for transport  
13 infrastructures, road network resilience is referred to as the assessment of its  
14 performance and closely related to the concept of vulnerability and accessibility of  
15 components (Wang *et al.*, 2015). Many studies on transportation networks are based  
16 on modelling the infrastructure network according to graph theory and complex system  
17 methods, which makes it possible to perform network analysis in order to estimate  
18 performance measures and indexes (Knoop *et al.*, 2012; de Oliveira, Portugal and  
19 Porto Junior, 2016; Bell *et al.*, 2017, Kurant and Thiran, 2006, Soh *et al.*, 2010).  
20 The work presented in this paper aims to identify critical links within a road  
21 infrastructure by proposing an index to assess the loss of accessibility of the link based  
22 on shortest path and travel time measurements. To this aim, a network analysis is  
23 carried out on the graph structure model of the road network case study by applying an  
24 iterative algorithm to consider degraded network scenarios that correspond to the  
25 removal of road links. The proposed index and network analysis method can give RI  
26 operators and decision-makers an accurate indication of the most vulnerable sections  
27 of the road networks using only topological data.

28 The paper methodology is developed as follows. In the next Section, a definition of  
29 resilience for critical infrastructure and road infrastructure is given, and main measures  
30 of network performance are briefly introduced. In Section 3, the loss of serviceability  
31 index is presented in relation to the concept of road serviceability and network  
32 measures used for the calculation of the proposed index. Section 4 is dedicated to the  
33 description of the selected case study and to the presentation and discussion of  
34 network analysis results. In the last Section, final conclusions are reported with regard  
35 to the most important outcomes of this work.

## 36 **2. Road Network Resilience**

37 RIs are included in the definition of Critical Infrastructures (CIs) according to the  
38 European Union (Mansfield, 2018) since they are essential for the growth of a society,  
39 to the daily mobility of citizens, goods, and to the maintenance of economical and  
40 societal functions of human community. The disruption or destruction of CIs may have  
41 significant impact in a European Union member state because of the failure to maintain  
42 those functions. A resilient infrastructure is capable of dealing with scenarios linked to  
43 disastrous events with the aim of minimizing service interruptions and quickly  
44 recovering (RESILIENS consortium, 2016) resorting to 4 Rs (Robustness,  
45 Redundancy, Resourcefulness and Rapidity) properties (Bruneau *et al.*, 2003). The  
46 concept of resilience for road network can be related to level of functionality exposed to  
47 hazard or disruptive events that can be assessed for estimating for estimating the  
48 actual resilience status (or performance) of the RI network.

49 There are two main types of methods for assessing the resilience of an infrastructure  
50 system, namely qualitative and quantitative methods. The former models provide an  
51 evaluation through performance criteria or level of service requirements for the different  
52 Technical, Organizational, Social and Economic (TOSE) dimensions (Bruneau *et al.*,  
53 2003; Brabhaharan, 2006). The latter models propose a measure of resilience with  
54 respect to failure due to specific events or to time-recovery considering a required level

55 of service. A performance index is evaluated regarding a specific component of the  
56 network system for a specific hazard event (Nogal *et al.*, 2017).

57 Accordingly, measures from graph theory concepts applied to transportation networks  
58 can be used to measure network performance based on topological features and  
59 structure of transportation network. Topological measures related to graph node's  
60 properties include, for example, degree and closeness centrality, betweenness  
61 centrality (Golbeck, 2013). They can be combined with measures taking into account  
62 distances and paths in the network such as the efficiency and straightness centrality to  
63 assess the network performance as its robustness (Erath, Löchl and Axhausen, 2009).  
64 Berdica and Mattsson, (2007) use measures of road/connection characteristics are  
65 used to evaluate the performance and therefore the vulnerability of a road network. In  
66 this paper, the effects of reduced capacity (physical failure, traffic accidents or  
67 maintenance work) of critical road links are studied for several scenarios, assessing the  
68 travel time, trip length and travel speed. Then, an index is proposed to assess road  
69 network resilience through distance and travel time measures.

### 70 **3. Loss of Serviceability (LoS) Index**

71 In the field of transportation networks, the classical graph theory integrated with  
72 complex network methods allows the analyses of structures and dynamics of such  
73 systems of infrastructure (Albert and Barabási, 2002; Boccaletti *et al.*, 2006). Network  
74 analysis requires modelling of the transportation network as a graph structure (i.e.,  
75 nodes or vertices linked by edges that can be directional as in the present study). A  
76 network graph can be described through measures such as network size (number of  
77 nodes and edges), network length and diameter, network continuity in terms of  
78 connected components, connectivity in order to evaluate the transportation network  
79 topology and performance (Xie and Levinson, 2007; Appert and Laurent, 2013; Ducruet  
80 and Lugo, 2013). These measures can be associated with the concept of road  
81 vulnerability for the protection against the risks and natural hazard. In this Section, a

82 definition of road serviceability is given related to the road vulnerability; then the  
83 method and network measure, LoS index is selected for the network analysis is  
84 presented.

### 85 **3.1 Concept of road serviceability**

86 A reduction of capacity/operation for a road transport system can occur for various  
87 reasons, such as physical (partial) failure or deterioration of structures or the reduction  
88 of some lanes due to maintenance activities. According to that, road vulnerability can  
89 be defined as the “*susceptibility to incidents that can result in considerable reductions*  
90 *in road network serviceability.*” (Berdica, 2002). This definition combines the concept of  
91 road vulnerability with that of accessibility. Indeed, serviceability of a road, intended as  
92 the possibility to use it during a given time period, is affected by the potential failure of  
93 a road/edge, also influencing road network performance (Adey, Hajdin and Brühwiler,  
94 2003; Orcesi and Cremona, 2010, 2011). Depending on the degree of reduced  
95 serviceability, a road/link failure may cause an increase in travel time due to a  
96 reduction in the speed of a particular path or due to the length of the alternative path if  
97 the road is completely inaccessible, up to and including disconnection of the road  
98 network.

99 Then, the effects of the reduction of serviceability can be assessed according to  
100 different aspects such as travel time reliability, capacity reliability, and connectivity  
101 reliability (Taylor, Sekhar and D’Este, 2006). With reference to road serviceability and  
102 to a road network serving Origin and Destination (O-D) demand, two different types of  
103 vulnerability indices are distinguished such as distance-based and the cost-based  
104 approaches. The former approaches only take into account the calculation of the length  
105 of alternative routes suitable for sparse regional network; the latter approaches assess  
106 indices according to travel time and O-D demand (Balijepalli and Oppong, 2014) well  
107 adapted for dense urban network or more generally for cases where the road network

108 includes a primary and secondary road (alternative routes shorter or longer in terms of  
109 travel time).

### 110 **3.2 Index through shortest path and travel time measures**

111 According to graph theory applied to transportation networks, a Road Infrastructure (RI)  
112 network can be modelled as an approximated planar network defined by a two-  
113 dimensional Euclidean space whose edges are real physical connections. More  
114 specifically, the edges that are the roads of the real network are defined by  
115 characteristics such as direction, length and travel time, then one can define the road  
116 network as a weighted directed graph (Boccaletti *et al.*, 2006). For a directed network,  
117 considering an edge between the nodes or vertices  $i$  and  $j$  denoted by  $(i, j)$ , the  
118 adjacency matrix  $A$  is the mathematical representation of the network, with elements  
119  $A_{ij}$  such that:

$$A_{ij} = \begin{cases} 1, & \text{if there is an edge from } j \text{ to } i \\ 0, & \text{otherwise} \end{cases}$$

120 1.

121 The direction of the edge is defined from the second index to the first; for weighted  
122 graph the elements  $A_{ij}$  have values equal to the weight of the corresponding  
123 connections. In the case of road networks, two nodes can be connected by two edges  
124 when considering, for example, the two parallel directions of a road infrastructure. In  
125 this case, the multi-edge is represented by setting the corresponding matrix element  
126  $A_{ij}$  equal to the multiplicity of the edge; for the case study of this paper, it is 2 so we  
127 have  $A_{ij} = A_{ji} = 2$ .

128 Length and travel time as weight of an edge/road can be used as main cost of driving it  
129 in order to evaluate measures and indexes to measure network performance.  
130 Reflecting the concept of the importance measure (Jenelius, Petersen and Mattsson,  
131 2006), which is based on the user equilibrium principle where the route choice is meant  
132 to minimize personal travel cost, in this paper one refers to the concept of the shortest



133 path. The related calculated travel time is a criterion for the user when choosing a route  
 134 between two points of origin and destination in the road network. In classical graph  
 135 theory, a geodesic path or shortest path is the path between two nodes of a graph such  
 136 that no shortest path exists (Newman, 2010). In network analysis, a path is the  
 137 sequence of vertices such that every consecutive pair of nodes in the sequence is  
 138 connected by an edge in the network. The length of the path is the number of edges  
 139 crossed along the path, considering Equation 1, we have:

$$A_{ik}A_{kj} = \begin{cases} 1, & \text{if a path of length = 2 from } j \text{ to } i \text{ via } k \\ 0, & \text{otherwise} \end{cases}$$

140 2.

141 Then the total number  $N_{ij}^{(2)}$  of paths of length equal 2 from  $j$  to  $i$  via any other node, is:

$$N_{ij}^{(2)} = \sum_{k=1}^n A_{ik}A_{kj} = [A^2]_{ij}$$

142 3.

143 Considering paths of the network of an arbitrary length  $r$ , we have:

$$N_{ij}^{(r)} = [A^r]_{ij}$$

144 4.

145 The length of a shortest path or shorter distance, it is the smallest value of  $r$ , such  
 146 that:

$$[A^r]_{ij} > 0$$

147 5.

148 The calculation of the shortest path is done resorting to proper algorithm such as  
 149 Dijkstra's algorithm (Newman, 2010) used in this work. This algorithm also uses the  
 150 weights of the edges to find the path that minimizes the total distance or travel time  
 151 (weight) between the source node and all other nodes. For a given network graph, it  
 152 finds the shortest distance of a given source node to every other node by recording all  
 153 the shortest distance calculated to each vertex and at the end keeping the shortest  
 154 distance possible by any route. For the index proposed in this paper, the Dijkstra's

155 algorithm is applied to find the shortest path between two given nodes, origin and  
156 destination nodes, with; travel time used as weight.

157 Then, the index to measure the performance of the road network in terms of  
158 serviceability by considering the travel time reliability is based on the calculation of the  
159 shortest path and the related travel time considering a free-flow speed. Two  
160 configurations of the road network, i.e. non-degraded and degraded, will be taken into  
161 account.

162 For a non-degraded configuration of the road network, i.e. the serviceability of all edges  
163 is not changed by any failure, considering a set  $s$  of  $n$  randomly chosen nodes as  
164 nodes or points of origin  $i$  and destination  $j$ , shortest paths weighted by travel time are  
165 evaluated. A reference value  $\alpha_s$  is calculated for this scenario as the sum of the travel  
166 times  $t(i, j)$  of the shortest paths considered, as in Equation 6.

$$\alpha_s = \sum_{i=1}^n \sum_{j=1}^n t(i, j)$$

167 6.

168 A degraded configuration is when an edge/road of interest labelled  $k$  and defined as  
169 impactful edge, is eliminated increasing the vulnerability of the road network. For each  
170 degraded configuration, the shortest paths and their travel times are recalculated,  
171 considering the same origin and destination nodes of the non-degraded configuration.

172 For each of them,  $\beta_{k,s}$  is calculated according to Equation 7.

$$\beta_{k,s} = \sum_{i=1}^n \sum_{j=1}^n t(i, j)$$

173 7.

174 Based on these two values, it is possible to calculate an index to assess the Loss of  
175 Serviceability (LoS) of the motorway network in terms of increased travel time for each  
176  $k$  edge/road related to a set  $s$  of nodes as the difference between the reference values

177 calculated. This difference also takes into account the number of paths  $n_{ip,k,s}$  affected  
178 by the considered  $k$  edge, so the index is calculated according to Equation 8:

$$LoS_{k,s} = \frac{\beta_{k,s} - \alpha_s}{n_{ip,k,s}}$$

179 8.

180 The introduced index considers the interaction between the main network, i.e. those  
181 consisting of the motorway links, and the secondary network, consisting of the  
182 secondary and tertiary roads providing alternative routes in the event of a motorway  
183 link failure. In the following performed network analysis, node sets of highway ends  
184 points are considered in order to take into account the demand on the main network  
185 and to complete with the demand of the secondary network considering node sets of  
186 origin and destination points in the whole studied road network.

## 187 **4. Application of Complex Network Analysis**

### 188 **4.1 Case-study**

#### 189 *4.1.1 Description of A2 Spanish highway*

190 The Spanish Road network system has its origins in Roman times (second to fourth  
191 centuries A.C.) initially consisting of a mesh of the east to west main roads running  
192 along the valleys connected to the secondary north to south and diagonal roads. Later,  
193 after the Spanish War of Succession (1714), the Bourbons, following the French model,  
194 to improve land communications, undertake the construction of a radial network  
195 centralised in Madrid in order to establish the political and economic position of Madrid  
196 as the capital of the kingdom. Several parallel roads were built: to the Mediterranean  
197 (between Barcelona and Alicante), to the Portuguese border (between Benavente and  
198 Seville), and another one connecting Burgos and Medina del Campo via Valladolid  
199 (López Ortiz, Melgarejo Moreno and Montaña Sanz, 2016). Then, the road network  
200 was further integrated with other radial and transversal road networks, so the road plan  
201 can be considered completed in the 1860s. Since then, the existing road system has

202 been rehabilitated with new road surfacing materials (1926), and the construction of  
203 modern highways structures (Modernisation Plan for the Spanish Road Network,  
204 1950), leading to the current Spanish road network system shown in Figure 1. The  
205 structure of the Spanish road network as described above is suitable for applying the  
206 methodology proposed in this paper, since it is made up of a network with primary and  
207 secondary roads. This is essential in order to evaluate alternative routes in case of  
208 failure of one or more RIs components, as it is presented in section 3.1.

209 A section of the A2 Spanish Highway is the case-study, on which complex networks  
210 analysis is presented as a demo site of PANOPTIS European project (2018), which is  
211 provided by project's industry partner Acciona (Sevilla *et al.*, 2021), whose  
212 Concessions Division is in charge of the highway operation and maintenance. The  
213 analysed section of the network, located in the province of Guadalajara, has a length of  
214 77.5 km with 4 lanes (2 per traffic direction) (see Figure 2). This motorway section is  
215 one of the main highways linking the two largest cities of the country, Madrid and  
216 Barcelona, playing a strategic role in the Spanish road infrastructure network. The  
217 climatic conditions of the region crossed by this road section are characterized by long  
218 and severe winters, and long, dry and hot summers. Besides, a diverse climatic  
219 phenomena such as fog, frequent freezing/thawing cycles, landslides, precipitation  
220 intensity, strong wind and storm increasing road structures vulnerability and  
221 consequently could affect the road stretch's functionality.

#### 222 4.1.2 *Modeling the road network through OSMnx*

223 To obtain the topology of the selected stretch, data of the network structure are  
224 retrieved and processed from OpenStreetMap (OSM) (Barrington-Leigh and Millard-  
225 Ball, 2017) through OSMNx, an open-source Python package to perform network  
226 analysis (Boeing, 2017). The road network model has been obtained considering the  
227 geographical areas crossed by the highway section with a related buffering distance of  
228 100 km (Figure 3a); 38399 nodes and 74015 edges constitute the resulting graph

229 structure. In order to optimize the computation time and to consider exclusively the  
230 roads of interest for the evaluation of the network functionality, a process of  
231 simplification of this network model is necessary. This consists of eliminating all nodes  
232 that are not determined by junctions, namely any connection point between different  
233 roads and by road ends. Then, depending on the road hierarchy classification  
234 (motorway, trunk road, primary, etc.), the edges without a strategic role for the network  
235 analysis are removed, i.e., those considered as residential and living roads (Figure 3b)  
236 and the related nodes become obsolete. This simplification processes produced in a  
237 graph structure of 2428 nodes and 4488 edges (Figure 3c).

#### 238 *4.1.3 Choice of node sets: random and extreme nodes*

239 The model obtained represents the non-degraded configuration of the road network.  
240 For the network analysis, 6 sets  $s$  of 6 nodes were randomly identified corresponding to  
241 the origin (O) and destination (D) points (Figure 3d). In function of this statistical  
242 sample, the shortest paths are calculated and the related travel times. The shortest  
243 paths for these sets of O-D points include some or almost all of the 237 highway edges  
244 pertaining to the highway section under consideration. The highway edges involved in  
245 the calculated shortest paths are defined as impactful edges. In addition to random  
246 node sets, two reference paths are considered, i.e., those between the start and end  
247 points of the section, which are defined as extreme nodes.

248 Table 1 shows the number of edges classified as motorways for each set  $s$  of nodes  
249 and the related reference value  $\alpha$ .

#### 250 **4.2 Failure Scenarios and LoS index**

251 The removal of an impactful edge, representing a service interruption in case of  
252 damage, maintenance or incident, generates a failure scenario and consequently a  
253 degraded configuration of the road network. This implies that, the considered shortest  
254 paths between the origin and destination nodes may no longer be viable in the absence

255 of a connecting link. For this reason, alternative paths are required to restore the link  
256 between the nodes. For each selected set, several failure scenarios are considered,  
257 corresponding to the removal of each impactful edge, such as the roads classified as  
258 MotorWay (MW), at a time. Network analysis is performed by assessing the loss of  
259 serviceability at set or local level and at global (network) level, the main results are  
260 discussed in the following sub-sections.

#### 261 *4.2.1 LoS index at set level*

262 For the analysed case study, 164 MW edges are involved in the network analysis,  
263 contiguous MW edges with the same calculated index are grouped in a MW trunk. 71  
264 MW trunks are defined for this highway network. For each degraded configuration of  
265 the road network, the LoS index is calculated for each impactful edge at the set level  
266 considering the alternative paths. This index allows assessing the influence of that  
267 specific road link on the road network performance as a function of the O-D nodes.

268 Figure 4 shows an example of network analysis results at set level. MW trunk 60 for the  
269 3 node sets (2,5,6) it is part of shortest paths between O-D nodes of these sets in the  
270 non-degraded configuration out of the selected 6 sets. The impact of MW trunk 60 on  
271 network performance is greater in set 6, for which the LoS index is 658.3s, compared  
272 to a lower value of 244.7s in set 2. Although in both sets, MW trunk 60 affects the same  
273 number of shortest paths, i.e. 4, the decrease of serviceability is more critical for set 6.  
274 This can be explained by the fact that its location is central to the nodes position of set  
275 6, so the removal of this trunk requires alternative paths with higher travel times  
276 increasing the value of the serviceability loss by twice compared to set 2's alternative  
277 paths. By comparing the different sets' LoS indexes, it is possible to identify whether an  
278 impactful edge is a critical link for the network performance in specific O-D nodes  
279 paths, as MW trunk 60 is a critical road link for set 6.

280 In Table 2 the most MW Impactful trunk edge for each node set is reported as well as  
281 the related LoS value. For sets 1, 2, 3 and 4, there are similar LoS values between 200

282 s and 400 s. For the combination of the O-D nodes of the sets 2, 3 and 4, MW trunk 10  
283 is the most critical (Figure 5). Higher values of LoS index are observed in sets 5 and 6,  
284 for which the most influential MW trunk edges for the network performance, i.e. MW  
285 trunk edge 43, 45 and 47, as shown in Figure 6.

#### 286 4.2.2 *LoS index at global/network level*

287 The results of the above network analysis can be combined to obtain an overall  
288 assessment of the road network under consideration. This refers to LoS index at  
289 global/network level as it covers all considered cases of total reduced serviceability of a  
290 motorway link. A statistical analysis of the LoS index values for the six sets allows  
291 evaluating the median values of the indices (Figure 7), as measure of central tendency,  
292 the first quartile Q1 (25<sup>th</sup> percentile), the third quartile Q3 (75<sup>th</sup> percentile), and the  
293 minimum and maximum values of the index. The value of LoS index at global level is  
294 the calculated median value. The box-plot graph in Figure 8 shows the distribution of  
295 the index according to the calculated values comparing all the MW trunk edges. The  
296 width of the box between Q1 and Q3 values is the InterQuartile Range (IQR) as a  
297 measure of how spread-out the values of the observed sets are.

298 In consideration of the selected O-D pathways of the performed network analysis, the  
299 functionality of the motorway section is mostly impacted by the MW trunk edges 43,45  
300 and 47 with a maximum median value of about 600 s. MW trunk edges 54, 58 and 60  
301 follow successively with median LoS values from 520 4s to 547.3 s. All other MW  
302 trunks resulted in much lower median values, below 360 s, and more widely in MW  
303 trunks with LoS values below 200 s. One should observe that IQRs values of these  
304 edges are the highest; observing the graph Q1 value deviates from the median value,  
305 this could be explained by the presence of efficient alternative paths of one of the  
306 observed sets. This shows that the analysis is affected by the choice of node sets.

307 Therefore, the analysis results in the identification of those MW links that should be  
308 considered critical to the operation of the motorway section under study, such as MW

309 Trunk Edges 43, 45 and 47. This means that, regarding the critical MW links of the  
310 road infrastructure under consideration, maintenance operations must be reinforced  
311 against events that may reduce serviceability to zero. In this case, operators can  
312 assume proactive measures against this risk as relying on primary and secondary  
313 roads that provide alternative routes.

## 314 **5. Conclusions**

315 Road network resilience is defined as the ability to maintain an adequate level of  
316 functionality against disruptive events; therefore, it is related to the measurement of  
317 network performance. In a road network, what measures its functionality is the  
318 accessibility of the various points of the network by users, assured by the  
319 accessibility/use of the road/links of the network, which is defined as road  
320 serviceability. RI component failure or deterioration, traffic incidents or maintenance  
321 activities can cause a reduction of serviceability increasing travel times. The proposed  
322 index assesses the increase in travel time by exploiting knowledge of the road network  
323 topology.

324 The loss of serviceability index has been used to measure the vulnerability of individual  
325 roads/links in a Spanish highway case study in order to obtain a measure of network  
326 resilience. The calculation of the index is based on the evaluation of two main  
327 measures in the complex network analysis such as travel times and the shortest paths.  
328 The network analysis was possible as the selected highway section is part of a wider  
329 road network that includes a system of primary (motorway) and secondary (provincial,  
330 tertiary, etc.) roads. In fact, the analysis evaluates the increase in travel time of the  
331 shortest path in the case of a degraded situation (total reduction in serviceability) which  
332 requires the existence of alternative routes to those of the non-degraded situation  
333 (maximum serviceability capacity).

334 Since it is proposed to use information on the road network structure, without therefore  
335 using travel demand or capacity data, 6 sets of origin-destination nodes were



336 considered to evaluate the shortest paths and the related LoS indices. The results at  
337 the set level allow determining the most critical links with respect to the specific set of  
338 O-D nodes. In a general consideration, the results of the analysis showed that the  
339 highest values of LoS are found for those edges that have a centrality with respect to  
340 O-D nodes. A statistical combination of the results, evaluating the median and quartile  
341 values of the LoS indices allows an overall assessment of the vulnerability of the road  
342 links and thus of the functionality of the road network. Therefore, the edges with the  
343 highest value of loss of serviceability in case of failure scenarios were identified, this  
344 shows that the analysis is obviously influenced by the choice of node sets.

345 The network analysis and the index proposed in this paper show an assessment of the  
346 road network performance by exploiting easily accessible information, such as the  
347 structure of the network using an open source geographical database. In this work, the  
348 estimation is based on travel times (based on free-flow speed) related to shortest path  
349 as travel time reliability. With additional information on travel demand, it is possible to  
350 implement the presented network analysis and to estimate the resilience of the network  
351 in terms of capacity. By implementing such information, the methodology could be used  
352 to develop network asset management tools. This constitutes one of the research  
353 perspectives of the work presented in this paper.

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441 **Figure captions (images as individual files separate to your MS Word text file).**

442 Figure 1 Road network of the main Spanish highways (source [https://about-](https://about-spain.net/travel/map.htm)  
443 [spain.net/travel/map.htm](https://about-spain.net/travel/map.htm)).

444 Figure 2 A2 Highway section localization (source <https://www.google.com/maps>, edited by  
445 corresponding author).

446 Figure 3 A2 Highway highlighted in red in the network graph by OSM (a); (b) Network graph-  
447 structure by OSMnx (b), simplified Network graph-structure by OSMnx (c), random nodes and  
448 highways edges of the stretch highlighted in red (d).

449 Figure 4 LoS index for MW Trunk 60 calculated in sets 2 (a), 5 (b) and 6 (c).

450 Figure 5 LoS index of MW Trunk 28 calculated in set 1 (a), LoS index of MW Trunk 10  
451 calculated in set 2 (b), 3 (c) and 4 (d).

452 Figure 6 LoS index of most MW Impactful Trunk edges (43, 45 and 47) calculated in set 5 (a)  
453 and in set 6 (b).

454 Figure 7 Median values of LoS of the MW trunk edges involved in the network analysis.

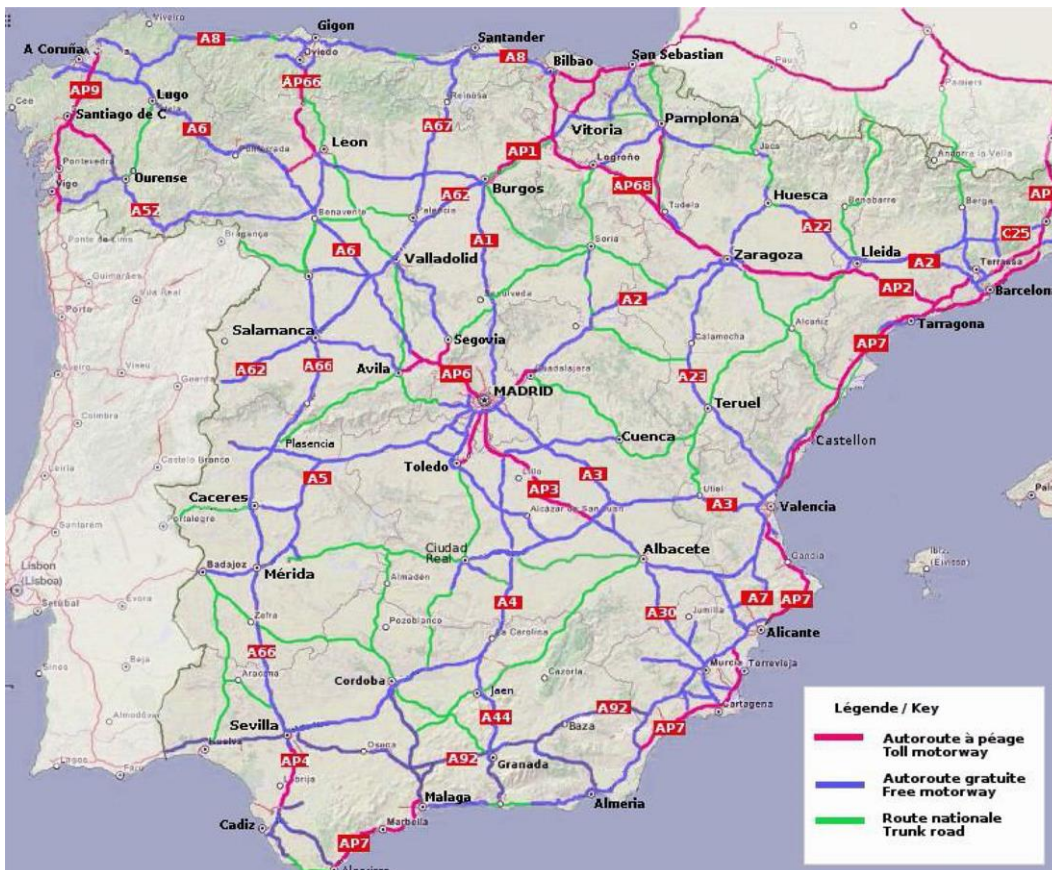
455 Figure 8 Q1, Min, Median, Max and Q3 values calculated by LoS indexes of sets for each MW  
456 Impactful Trunk edge.

457 **Table captions**

458 Table 1 Sets of random nodes and related impactful edges and  $\alpha$  reference values of  
459 the network analysis.

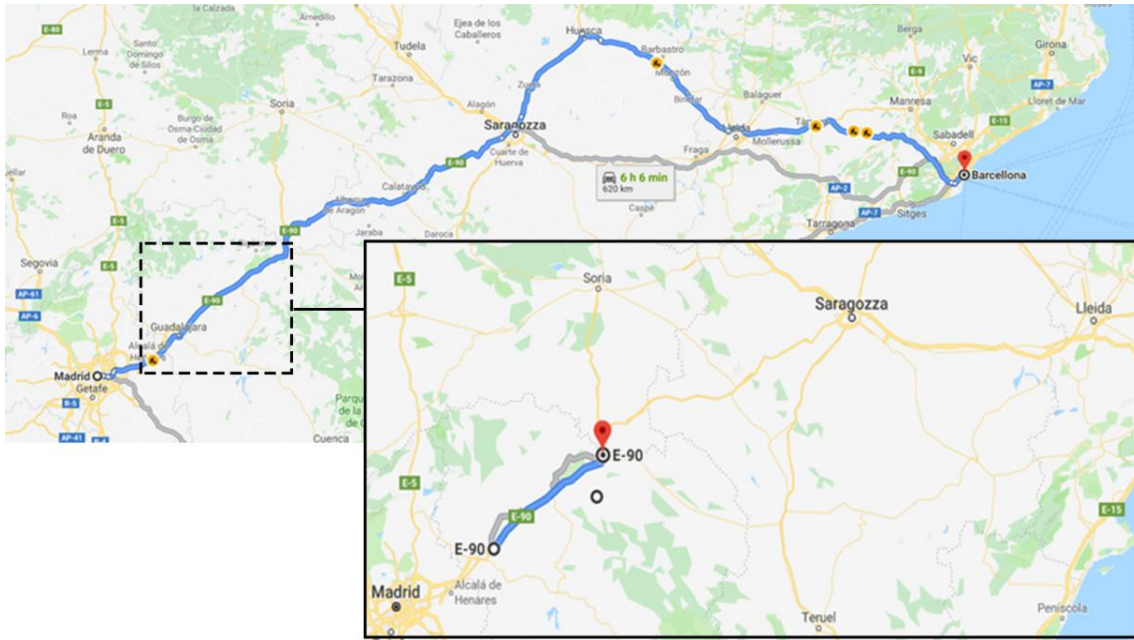
460 Table 2 Most MW Trunk impactful edges and LoS values for each node set of the  
461 network analysis.

462



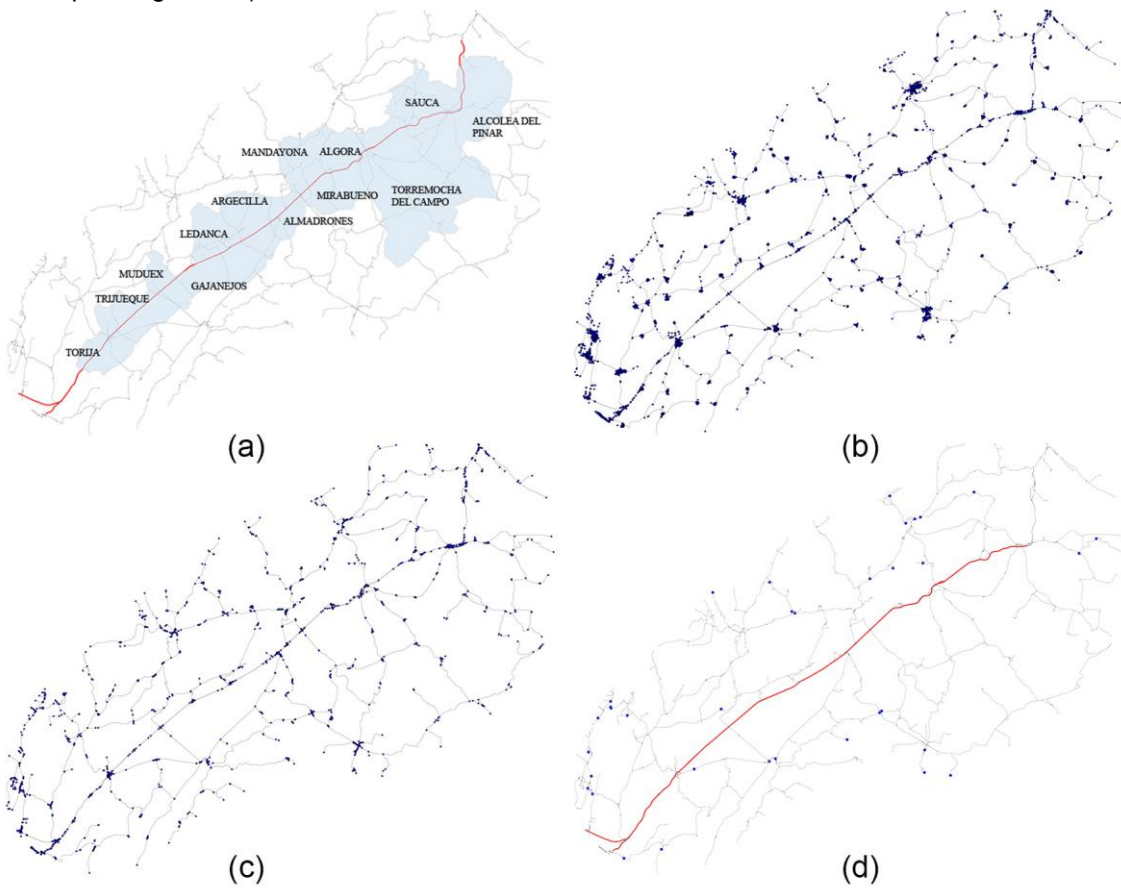
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464 Figure 1 Road network of the main Spanish highways (source [spain.net/travel/map.htm](https://about-</a><br/>465 <a href=)).



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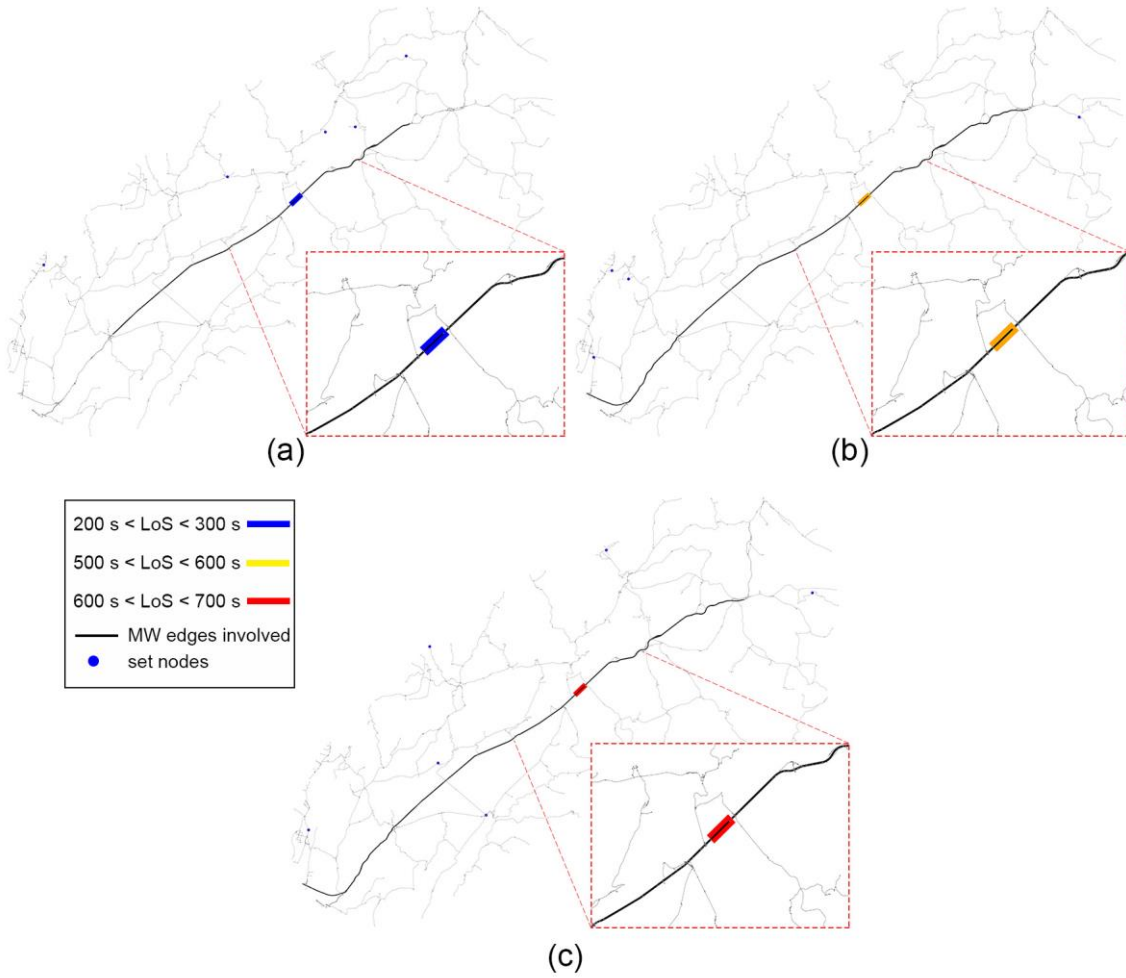
Figure 2 A2 Highway section localization (source <https://www.google.com/maps>, edited by corresponding author).



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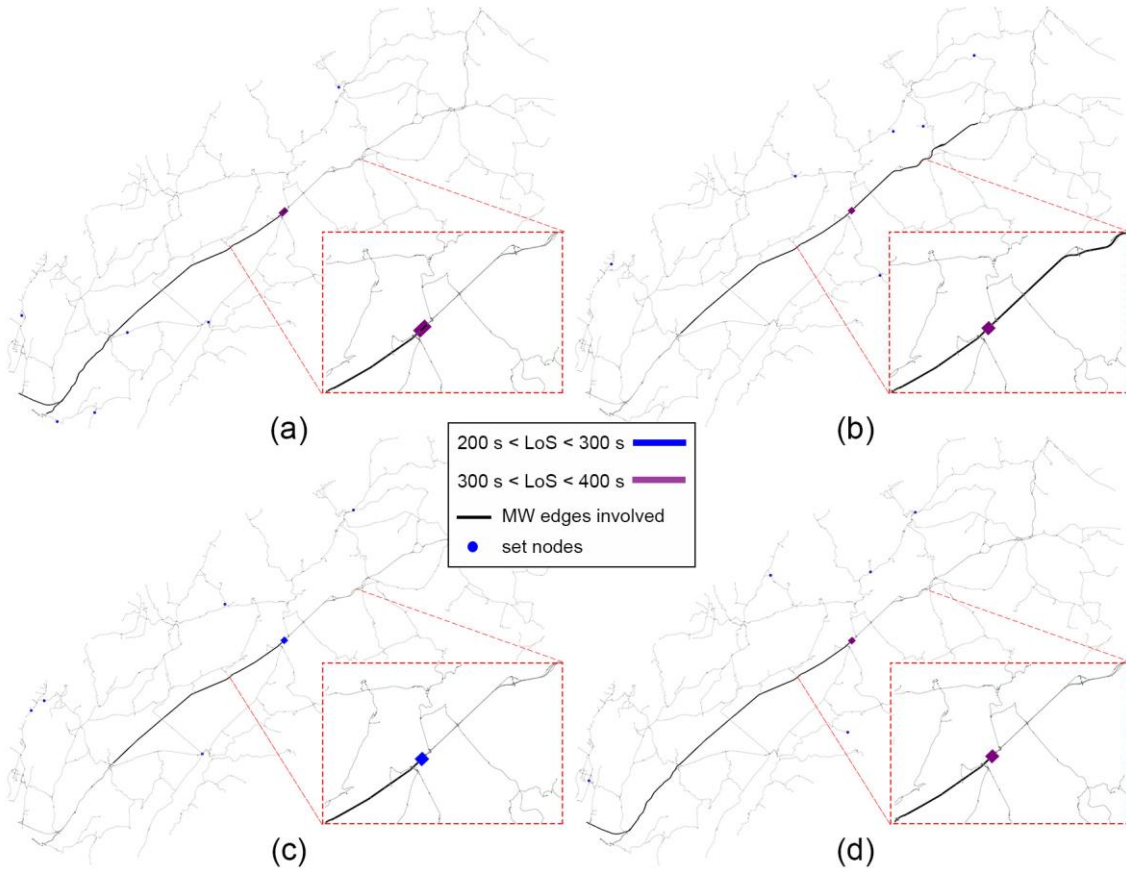
Figure 3 A2 Highway highlighted in red in the network graph by OSM (a); (b) Network graph-structure by OSMnx (b), simplified Network graph-structure by OSMnx (c), random nodes and highlighted edges of the stretch highlighted in red (d).





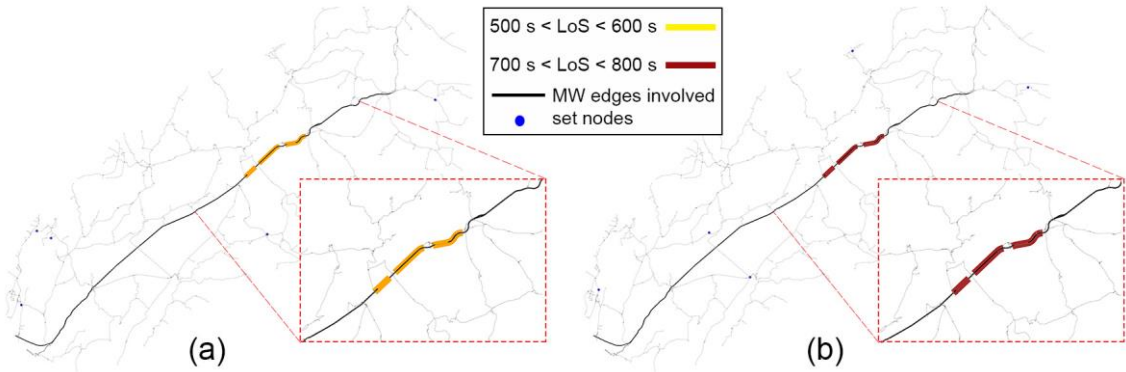
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Figure 4 LoS index for MW Trunk 60 calculated in sets 2 (a), 5 (b) and 6 (c).



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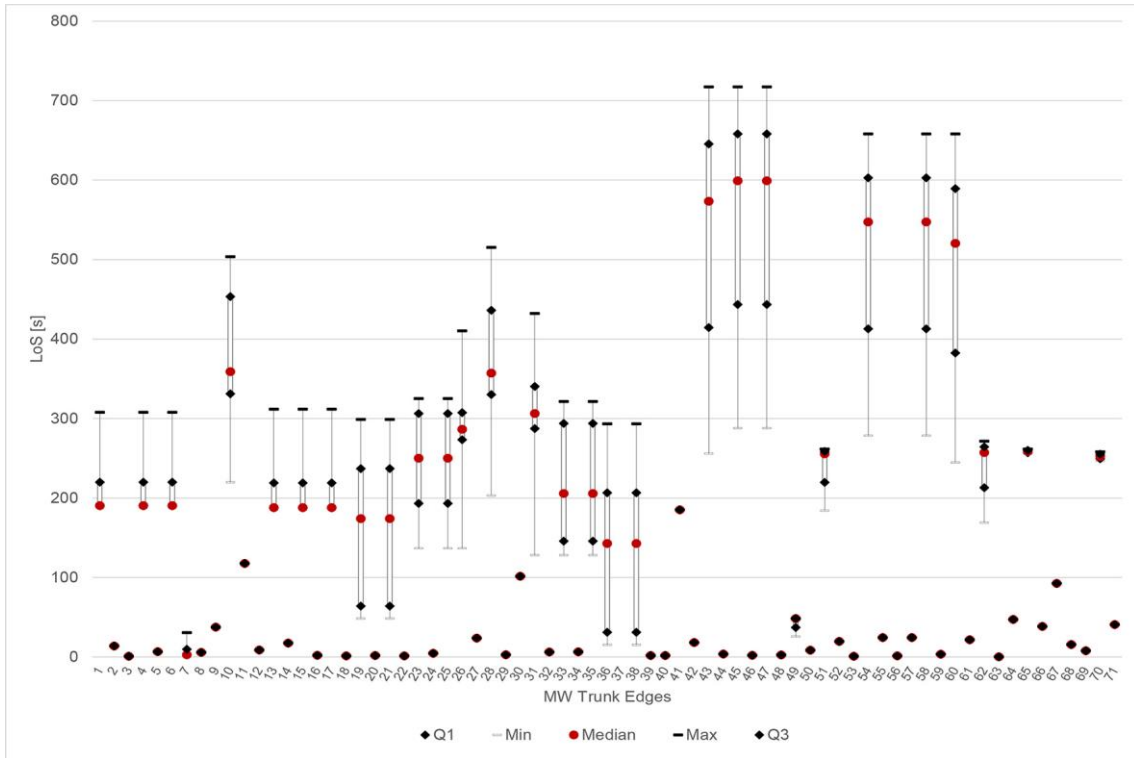
Figure 5 LoS index of MW Trunk 28 calculated in set 1 (a), LoS index of MW Trunk 10 calculated in set 2 (b), 3 (c) and 4 (d).



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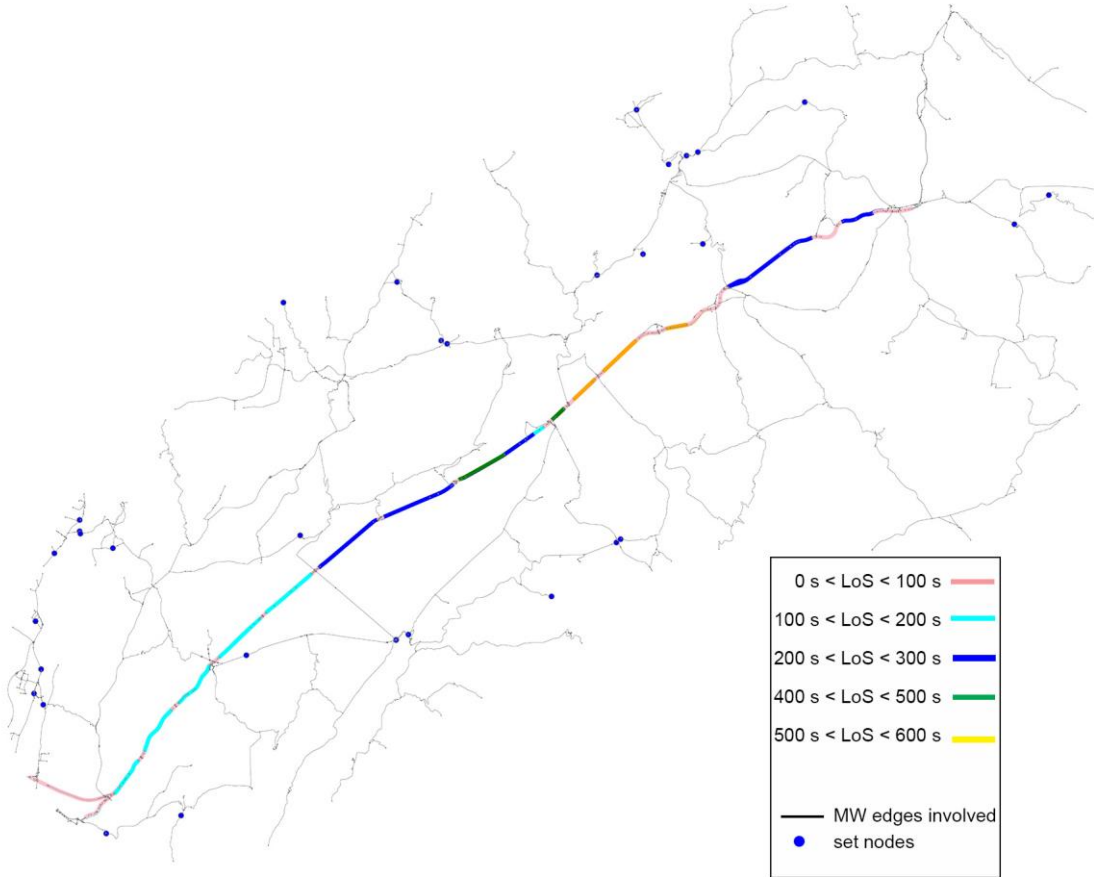
Figure 6 LoS index of most MW Impactful Trunk edges (43, 45 and 47) calculated in set 5 (a) and in set 6 (b).





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Figure 7 Median values of LoS of the MW trunk edges involved in the network analysis.



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Figure 8 Q1, Min, Median, Max and Q3 values calculated by LoS indexes of sets for each MW Impactful Trunk edge.

Set	N° Impactful edges [-]	$\alpha_s$ [s]
Set_1	100	44402.39
Set_2	97	47068.19
Set_3	51	53762.48
Set_4	86	54344.19
Set_5	150	61379.91
Set_6	150	62028.68
Set_extreme nodes	153	5092.79

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Table 1 Sets of random nodes and related impactful edges and  $\alpha$  reference values of the network analysis.

Set	MW Trunk impactful edge	LoS [s]
Set_1	28	356.29
Set_2	10	341.62
Set_3	10	219.77
Set_4	10	376.57
Set_5	45	599.24
	47	599.24
	43	717.35
Set_6	45	717.35
	47	717.35

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Table 2 Most MW Trunk impactful edges and LoS values for each node set of the network analysis.