438

Urban-regional dynamics of street network resilience

The spatial outcomes of Genoa's and Bologna's bridge crashes

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ABSTRACT

The configurational approach enables understanding the behaviour of road-network systems in the face of sudden physical disruptions. Previous studies show that Space Syntax analysis can assist in evaluating how urban systems respond to punctual network interruptions, both in the short and medium-term, and help managing associated risks. The events which followed the crash of the *Polcevera* bridge in Genoa and that of Bologna *Borgo Panigale* bridge in 2018 demonstrated in practice that localised urban network interruptions can propagate, affecting movement dynamics, well beyond the boundary of a city and compromise the functioning of the regional motorway network. However, representing the associated effects across the urban to the regional network levels remains a challenge due to computational limitations which constrain Space Syntax studies to use simplified networks in their analyses. This in turn causes discrepancies in cross-scale comparisons, as urban and regional road-morphologies are represented at different levels of detail. The paper studies the effects of the two dramatic events from a multi-scale configurational standpoint by comparatively analysing the through-movement patterns of the urban road-, the regional primary- and the regional motorway- circulation systems. The goal of this research is to discuss, using a real-world example as a benchmark for assessment, the viability of adopting the configurational approach to study failure propagation and gauge levels of street network resilience across spatial scales. The results of this study clarify the importance of weak ties for the resilience of road infrastructure systems and further demonstrate the homothetic behaviour of Normalised Betweenness Centrality measures.

KEYWORDS

Betweenness Centrality, Bridge Disaster, Multi-scale Analysis, Space Syntax, Street Network Resilience

1 INTRODUCTION

Urban street networks are major and long-enduring features of the urban form. They dictate the conditions for urban growth and development and can positively contribute to the general resilience of urban systems and their self-(re)organisation capacity (Abshirini and Koch, 2017; Cutini, 2013; Cutini and Pezzica, 2020; Feliciotti et al., 2016; Fusco and Venerandi, 2020; Sharifi and Yamagata, 2018). However, they need to be adequately designed, considering their geometric characteristics and orientation as well as their topologic properties (Boeing, 2019; Chokhachian et al., 2019; Sharifi, 2019). From a road transport perspective, the quasi-planarity of the road infrastructure represents a structural vulnerability, as it tends to polarise movement around its barycentre and create topological vulnerabilities along its shortest paths, causing bottlenecks. Indeed, the failure of a central link can have a cascade effect on the functioning of the entire road system (Sharifi and Yamagata, 2018).

Bridges, tunnels, and overpasses are key elements of the road network. They increase its connectivity and help overcome natural and manmade physical obstacles (e.g., rivers, rail infrastructure etc.) and so they represent strategic - and yet topologically vulnerable - links, which need to be better considered in risk mitigation plans, to promote the continued service of the urban grid in supporting human activities (Arrighi et al., 2021; Lhomme et al., 2013).

Previous studies showed that performing a configurational analysis of the street network system enables assessing changes in road-circulation patterns before and after physical disruptions and appreciating their impact at different spatial and temporal scales (Cutini and Pezzica, 2020; Gil and Steinbach, 2008; Penchev, 2016; Pezzica et al., 2021). As a matter of fact, the effects of a local interruption can propagate, affecting movement dynamics well beyond the boundary of a city (Amirfeiz et al., 2018). However, to date, linking regional and urban scales for studying the cross-scale effect of local network disruptions is still a challenging task due to computational limitations which constrain configurational studies to use simplified networks in their analyses (Krenz, 2017a; Serra and Hillier, 2019; Turner, 2009). This is bound to cause discrepancies in cross-scale comparisons, as urban and regional road-morphologies are represented at different levels of detail, and represents a limitation to the application of the method in broader Disaster Risk Reduction projects. Therefore, to obtain meaningful information for informing a resilient design and planning of road infrastructure, the different scales must be analysed in a joint fashion and the geometry of the street network must be retained at all scales.

This paper seeks to demonstrate, using two bridge crashes as paradigmatic real-world examples suitable to establish a benchmark, how the configurational approach can be effectively applied in a multiscale street network analysis. Consequently, the paper presents a comparative assessment of these two disaster events in the urban road- (micro-scale), regional primary- (meso-scale), and regional motorway- (macro-scale) circulation systems. Furthermore, it aims to discuss how the latter can be exploited to study failure propagation and, by extension, the urban-regional dynamics of street network resilience. To this end, the research leverages - and further confirms - recent insights into the homothetic behaviours of Betweenness Centrality measures (Altafini and Cutini, 2020) and highlights how weakly connected road segments, such as bridges, add to the resilience of street networks at different spatial scales.

The paper is structured as follows: Section 2 introduces the theoretical background of the research; Section 3 explains the methodology and introduces the two case studies; Section 4 presents the analysis results, while the discussion and conclusions can be found in Section 5.

2 THEORETICAL BACKGROUND

This section presents the theoretical background of this research by focusing on two main points: (i) the concept of weak ties and how it links to bridges in road network studies (Section 2.1); and (ii) the issue of the multi-scale in Space Synatx analysis, including a brief explaination of different modelling approaches and relevant metrics (Section 2.2).

2.1 Bridges as weak ties

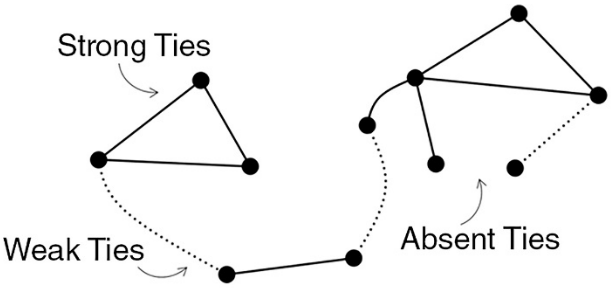

Figure 1: Graph representation of *Strong* and *Weak* ties in a network system.

In social science studies *Weak ties* (Figure 1) have been defined as a form of interpersonal link characterized by occasional interactions among individuals that have a certain degree of mutual knowledge about each other (Felder, 2020; Granovetter, 1973). Defined by their *degree of connection*, different interpersonal links have been found to determine the manner and the pathways on which novel information moves in a network, with weak ties being instrumental to receive and disseminate it across various social groups. Granovetter (1973) therefore stresses their key role in strengthening social network structures.

If we transfer this notion to the study of road network systems, we can affirm that bridges are *weak ties* by definition, since they provide the sole path between two points in a street network. By enabling faster interactions among systems which would be separated otherwise, bridges contribute to the efficiency of road-circulation networks. Hence, the removal of a bridge is more problematic than the removal of a *strong tied* element as it forces individuals and vehicles to follow alternative paths to move across a network which are, on average, longer than before. Furthermore, from a street network resilience standpoint – a concept discussed in (Cutini and Pezzica, 2020) - the removal of a *weak tied* element, such as a bridge, decreases the overall connectivity of the street network system and the redundancy of available paths to move across it. This, in turn, increases the vulnerability of the network, as further discussed by Altafini et al. (2022).

When analysing urban-regional dynamics of street network resilience it is therefore interesting and appropriate to observe how the removal of bridges affects the configurational behaviour of a network at different scales. In this paper this will be demonstrated through the results of the multi-scale analysis of the Bologna and Genoa's bridge crashes as described in Section 3.

2.2 Multi-scale analysis approaches and homothetic behaviour of NACH

The Angular Segment Analysis (ASA), introduced in Space syntax studies by Turner (2007), was conceived to enable a finer-grain appreciation of configurational properties' distribution in a road-circulation network. Despite it may offer a valuable support in the study of regional movement patterns, to date, the ASA has been applied in its original form mainly to urban street networks as available tools do not deal well with large-scale systems (Hillier, 2007).

To allow an efficient modelling with reasonable time-lapses, past studies have often overcome this obstacle by reducing the complexity of the geo-dataset used in the ASA. This commonly involves simplifying the network geometry via generalisation (a method used by cartographers to produce maps which are readable at smaller scales) and/or partial remodelling. However, a trade-off in terms of network representation and completeness is rooted in this simplification process and, although the results may be acceptable in a mono-scale analysis, it becomes problematic when the goal is to study a phenomenon across different territorial scales. Moreover, it reduces the time-scale-precision of the ASA and consequently its capacity to render the configurational properties of physical infrastructure systems in a way that accurately reflects their morphology.

An alternative to the simplification approach is to search for recursive regularities in relational patterns across different spatial scales. Kalapala et al. (2006) and Chan et al. (2011) argue that different road-network systems tend to have a similar network structure with similar geometric qualities. Barthélemy (2004) and Kirkley et al. (2018) advance that scale-free road networks present some structural invariances, among which *Betweenness Centrality* (Freeman, 1977) patterns. Indeed, the notion of Centrality is a key instrument for analysing hierarchical properties of (road) network systems (Freeman, 1977; Freeman et al., 1979; Golbeck, 2015).

On these basis, Altafini and Cutini (2020) advance that certain *Betweenness Centrality* measures, such as the Space Syntax *Normalised Angular Choice* (NACH), exhibit an homothetic behaviour. The premise of this behaviour is that, in a multi-scale analysis, the road-circulation networks present similar distribution patterns, and values, in their centrality hierarchies' (i.e., *recursive regularities*) regardless of differences in the networks' size. Specifically, NACH shows how often a road segment falls into the shortest angular path connecting every origin-destination pair and, in its calculation, the *Angular Total Depth* (TD_α, the total of all shortest paths to a selected segment) is used to make the measure independent from the dimension of the system. The TD_α establishes a positional reference to *Angular Choice* (Ch_α), as it relates each segment's count value (sum) to the depth of the system in that point. Since the addition of new segments affects equally Ch_α and TD_α, NACH tends to maintain the hierarchical position of road-elements; what makes it exhibiting homotheties. This means that each network and network sub-section, when individually analysed, retain a certain regularity in the hierarchical distribution of NACH values, which translates into a visual similitude of the analysis results in the corresponding colour-coded maps. If we disregard the ever-present edge effects, due to artificial boundaries being imposed onto a real street network system before running a relational analysis (Gil, 2017), the network sub-section will therefore maintain some of its characteristic relational qualities (configuration, hierarchy and values) across scales.

The paper will exploit this property of NACH to draw a link among road network models at different spatial scales, which present a sensibly different number of elements. This enables discussing their ASA results jointly and without compromising on their accuracy and level of detail. Furthermore, the use of NACH in the analysis is particularly indicated for the presented study because this measure is considered a good predictor of through-movement (Hillier et al., 1986) and the latter is a good proxy for vehicular traffic since it identifies the most rapid access to all other spaces in a road network system.

3 DATASETS AND METHODS

The background of the presented study is briefly described in the first part of this section, followed by an explanation of the methodology adopted to analyse the selected cases in Section 3.2.

3.1 Background of the empirical study

Bridge disasters are particularly interesting to study as they can be considered extreme examples of network disruption, involving one road line, which is as much strategically important as it is topologically vulnerable. Therefore, two exceptional and dramatic bridge crashes which affected two hubs of the Italian motorway network, namely Bologna and Genoa, almost at the same time (Figure 2, Table 2) have been chosen as the background for the empirical study. When the Borgo Panigale bridge in Bologna and the Polcevera (also known as Morandi) bridge in Genoa collapsed in the summer of 2018, their crash provoked a larger crisis affecting the national, regional, and urban road network systems. Additionally, the two cases present some common characteristics, which help establishing the ground for a study having a parallel focus on them:

- Bologna and Genoa are medium sized cities of around 400k and 850k inhabitants respectively.
- Both bridge disasters have stricken a bridge ordinarily subjected to crowding due to continuous and intense vehicular traffic and belonging to a motorway passing through a metropolitan area.
- In both cases most of the traffic originated from vehicles moving across the urban area.

Figure 2: Aerial and 3D view of Bologna (a) and Genoa (b) bridges, Google Earth capture 2020.

Table 2. The two bridge disasters in a nutshell.

	Genoa	**Bologna**
Date of Disaster	14th of August 2018	6th of August 2018
Type of bridge	Bridge of the motorway passing through the city	Overpass of the motorway going around the city
Cause	To be confirmed	Fire after a car accident
Damages	1 dead, 100 injured and several damages to vehicles and buildings	43 deaths, 500 people homeless
Immediate consequence on traffic	A10 motorway link closed: north Italy motorway network in crisis and major impact on local circulation (disruption to airport travels, traffic, and several incidents)	A1-A14 motorway link closed: north Italy motorway network in crisis and impact on cross-town circulation
Immediate policy action	Long-distance travellers told to avoid the city	Long-distance travellers told to avoid the city
Emergency management actions	Albareto road re-engineered and widened to 4 lanes to host traffic from Genoa West to the city centre. Parking lots and yellow stripes areas taken, sidewalks eliminated and speed of traffic locally increased, putting under pressure small economic activities	Timing of traffic lights in the area surrounding the overpass modified
Duration actions	8 months	2 months
Recovery time	2 years	2 months

3.2 Analysis methodology

To extract the Road Centre Lines (RCL) data necessary to perform the ASA in the cases of Bologna and Genoa, the Open Street Map (OSM) API was queried using the OSMnx python library (Boeing, 2017). The OSM RCL data was filtered by exploiting the OSM tag system using the principles described by Pezzica et al. (2019) and cropped using four different boundaries to run the analysis at the following three scales:

- **Macro-scale: regional motorway network (M)**. Only segments tagged as Motorway and Motorway Link were included and the boundary was set to include the six North Italy regions (namely Emilia-Romagna, Liguria, Piedmont, Valle D'Aosta, Lombardy, Trentino and Friuli) using a buffer of 60km, which allows retaining some important connections at the border with Tuscany.
- **Meso-scale: regional primary network (P)**. In addition to motorway segments this network includes those tagged as Trunk and Primary and associated road links. The boundary and buffer are the same used to extract the regional motorway network.
- **Micro-scale. urban road-circulation network (U)**. This level includes drive segments only, meaning streets accessible to both pedestrians and vehicles, which fall within the administration limits of the cities of Bologna and Genoa (connections within a buffer of 500m are retained).

Besides filtering OSM data, it is common practice in Space Syntax studies to undergo some additional data preparation steps before performing the ASA (Pezzica et al., 2019). These often involve the manual or automatic re-modelling of localised (traffic management) features to produce a new graph model; what triggers the immediate redistribution of the configurational weights. Re-modelling generally aims to remove elements which cause unwanted noise in the ASA (Krenz, 2017b), but its desirability ought to be evaluated case by case. In this study we assessed the appropriateness of simplifying the winding highway entrance and exit routes via their re-modelling, by comparing the results of the analysis with and without the simplification. Based on the outcome of this test (presented in Section 4.1), which was performed considering the necessary unlinks, it was decided to maintain the original geometries in all models, without applying any simplification via re-modelling.

In the end, a total of 8 models (2*M + 2*P+ 4*U) were prepared to analyse the cross-scale road-network configurations *ex-ante* and *ex-post* using DepthmapX (Varoudis, n.d.) and compare the situations Before (*B*) and After (*A*) the bridge disasters. The *A*-models were generated from the *B*-ones by simply removing the segment corresponding to the collapsed bridge. As anticipated in Section 2.2, the study focuses on the distribution of NACH, which shows where the traffic bottlenecks are likely to be found, as crowding usually happens where all shortest paths overlap in a graph. Since the segments where flows concentrate are identified by the highest values of NACH, the results of the ASA were imported in a GIS environment and then filtered to isolate the highest 30% (for the primary highways structures) and 20% (for the motorway highway

structures) of values, which remark the *preferential routes* of *through-movement.* A similar filter is also applied to the urban models to highlight the highest 20% NACH values at this scale. These are visually differentiated in all cases using a greater line thickness. These sets were determined after ordering all NACH values in GIS and dividing them into 20 different groups with the same number of elements using an *Equal Count* method. The output maps enabled to interpret results and extract relevant insights (discussed in Section 4), whose goodness was qualitatively checked against facts from post-disaster reports published by the national and local press or by the traffic authorities, which were gathered for a previous study (Cutini and Pezzica, 2020).
Additionally, overlaying the maps in GIS enabled observing the visual similitude of through-movement patters and hence the homothetic behaviour of NACH. To return an accurate picture of this phenomenon, the ASA results were imported in RStudio (RStudio Team, 2015), where we retrieved the Lorenz Curve (Lorenz, 1905) of each analysed configuration, namely M(*B&A*), P(*B&A*) and U(*B&A*), considering the segments falling within the boundaries of Bologna and Genoa's municipalities. In economics, this curve is used to represent differences in income distribution (which are greater or smaller depending on the shape of the curve) and is plotted in a graph in which a 45° line represents the ideal condition of perfect equality. In this research the Lorenz Curve will be used to compare the distribution of NACH values across different networks representing a system at different scales, as the presence of overlaps in the curves indicates a substantial correspondence of through-movement patterns between the networks. Using this relatively simple statistical analysis seems appropriate for the cross-scale exploration because it aims to compare measures that, if we considered the whole network system, would be totally correlated. Furthermore, *Betweenness Centrality* measures (such as NACH) have been found to be highly robust to network model boundary conditions, including changes in size and position, with respect to their capacity to retain information about the street network hierarchy (Gil, 2017).

4 RESULTS

After a brief presentation of the re-modelling test in Section 4.1, this part of the paper will show the results of the multi-scale analysis by commenting its implications for the cases of Bologna and Genoa (Section 4.2). Finally, Section 4.3 will bring together the analysis results by presenting the corresponding Lorenz curves.

4.1 Re-modelling test

Figure 3 presents the distribution of NACH in the part of the North Italy motorway network which passes through Bologna and its three neighbouring municipalities along its Western limit. This boundary is chosen for the test to preserve the continuity of the motorway routes, to which *Betweenness Centrality* measures are sensitive. The map shows both the original OSM *B&A* models and the re-modelled ones. The re-modelling attempt was performed to check if the complex geometries of highway access and exit links (see the zooms in Figure 3) were skewing the ASA results by penalising connections between different highways. The maps show that this is not the case. On the contrary, inter-highway connections in the original OSM model (1*B*) seem to have slightly higher NACH values than in the re-modelled one (2*B*). Additionally, when looking at the maps representing the situation following the crash, we can observe that the re-modelled version (2*A*) returns a result which is less convincing than that returned by the original model (1*A*) since we expected an increase in the NACH values of the traits of the motorway next to the interrupted link.

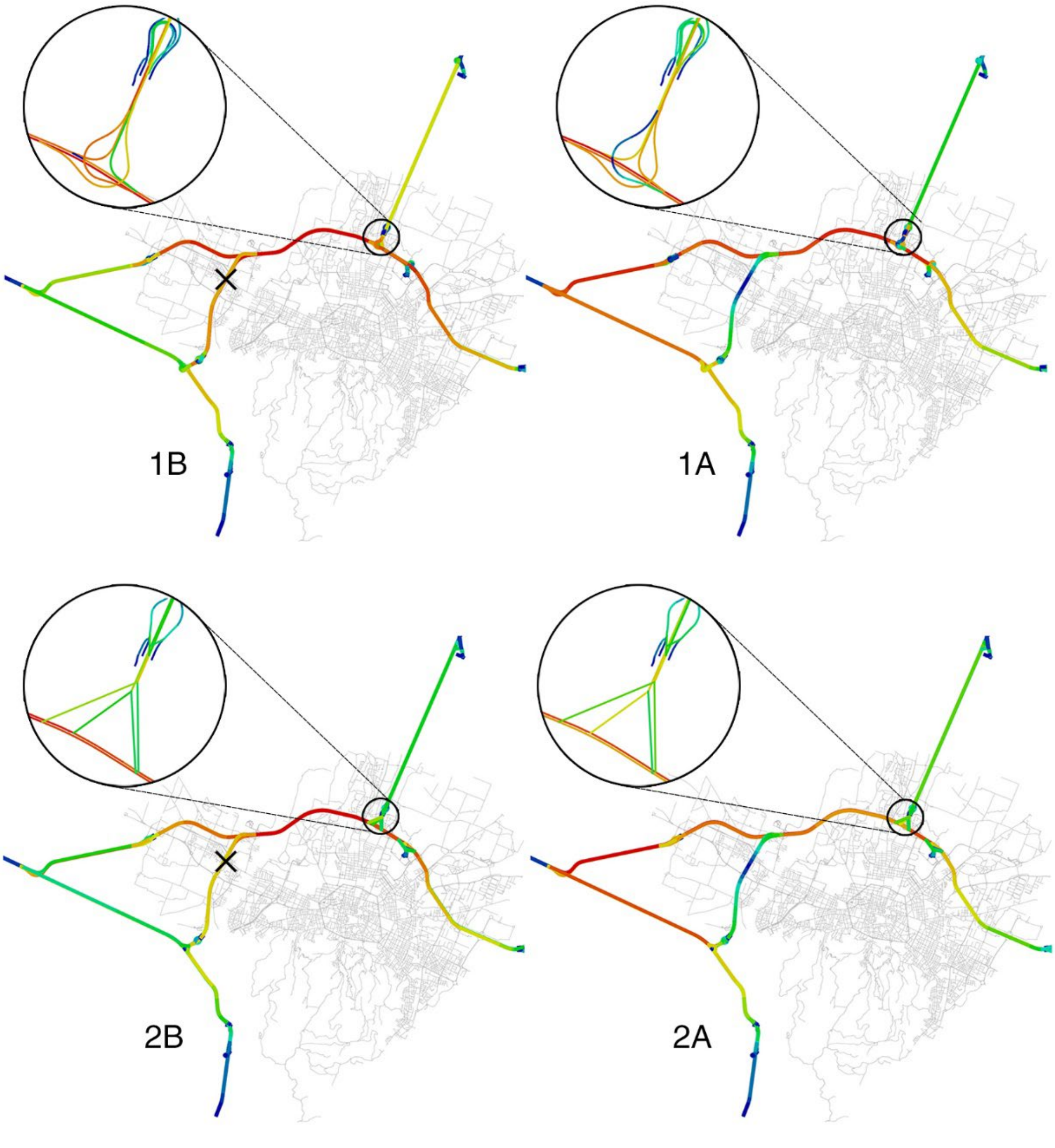

Figure 3. Visual comparison of outputs, including a zoomed extract, from 1) the original OSM motorway network of Bologna and 2) the corresponding re-modelled version before (*B*) and after (*A*) the bridge crash.

4.2 Multi scale analysis

The results of the analysis at the macro- and meso- scales are shown in Figure 4. By comparing the map of the motorway network before (M*B*) and after (M*A*) the bridge crashes, it is possible to notice the increase of NACH in the trait of the A22 highway (Brenner-Modena) connecting Modena to Mantua and Verona (framed by the rectangle in Figure 4). This follows the local interruption of the network in Bologna, which can be interpreted as the removal of a weak tie: the link between the A1 (Milan-Naples) with the A13 (Bologna-Padua) and A14 (Bologna-Taranto). Interestingly, the maps show how the macro-scale effects of Bologna's bridge crash were absorbed by the closest (and weaker) alternative link connecting the Est-West and North-South axes of the Italian motorway network. By comparison, the motorway links which connect to Genoa do not show an equivalent behaviour at this scale, as there the only visible change after the disruption is the strengthening of the southern trait of the A7 (Milan-Genoa) and the parallel weakening of the initial trait of the A12 (Genoa-Rome) motorway. This could be in part due to the relatively segregated position of Genoa with respect to the whole North Italy motorway system (the city is close to its Western edge although more than 100km away from the limit of the national network), so results may have changed if we extended the boundary of the analysis to include the South France motorway system. However, this analysis falls out of the scope of this study.

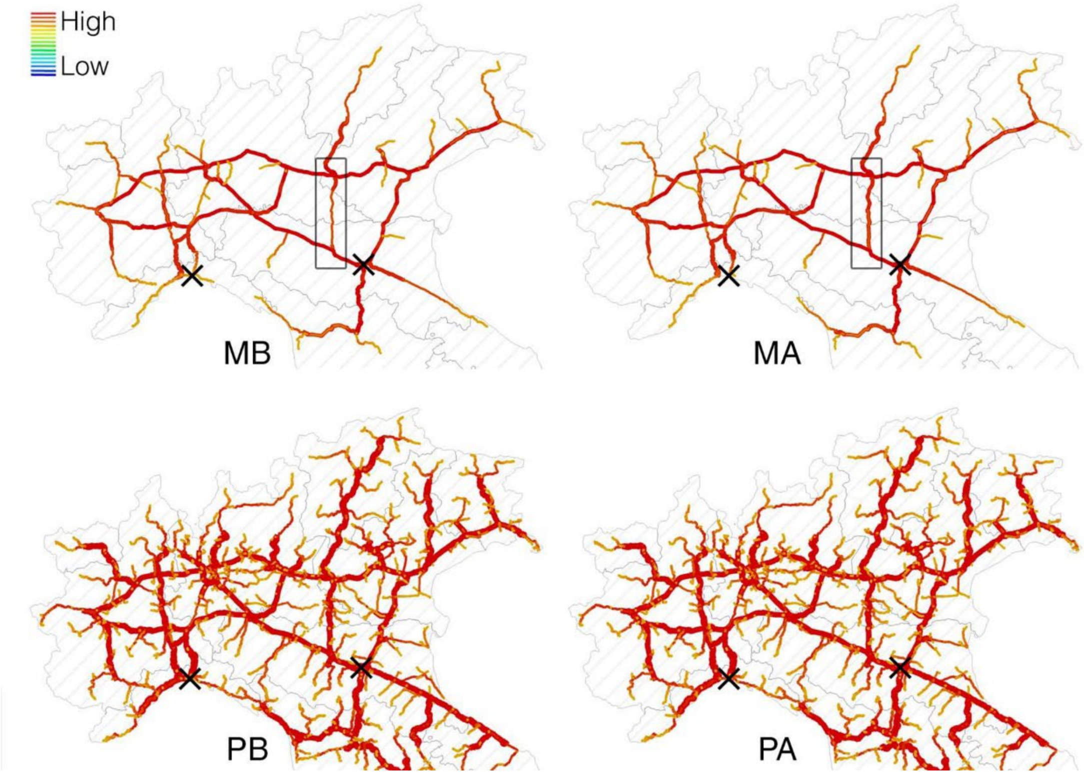

Figure 4. Distribution of NACH in the North Italy Motorway network before (M*B*) and after the crash of the two bridges (M*A*) and in the North Italy Primary circulation-network before (P*B*) and after (P*A*).

This effect looks comparatively less strong in the meso-scale analysis, possibly because of the higher number of road-elements considered. In fact, the primary network before (P*B*) and after (P*A*) maps evidence in a clearer way the importance of the Western coastal motorway link between Genoa and Ventimiglia (A10) as well as of the link between this and Turin and the A12 (going southwards), which belong to the West-East European route E80 (also known as Trans-European Motorway) connecting Lisbon, in Portugal, with Gürbulak in Turkey. Other connections in the North-East and the South borders of the North Italy motorway are also better portrayed at this scale, however the density of the elements does not allow to adequately appreciate changes between before and after the bridge disasters. Therefore, the meso-scale analysis results are displayed also by zooming in the urban areas of Bologna and Genoa together with those from the micro-scale analysis (Figures 5 and 7), and further discussed.

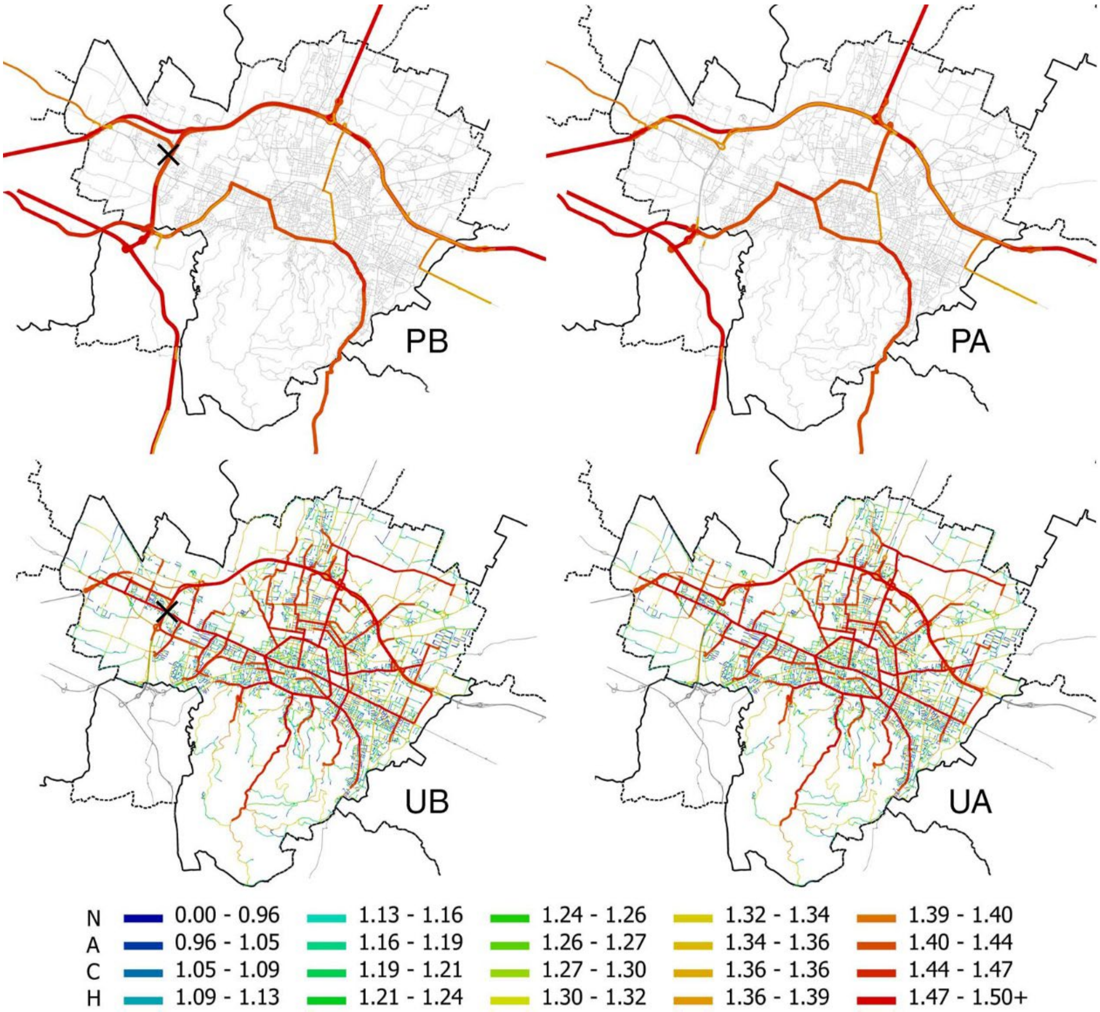

Figure 5. Figure 4. Distribution of NACH in Bologna considering the Primary circulation-network before (P*B*) and after (P*A*) and the Urban road-network before (U*B*) and after (U*A*).

Bologna's P*B* and P*A* maps in Figure 5 clearly show that the bridge crash caused non-negligible changes in urban movement patterns as middle-range vehicular flows were naturally redirected towards the city's inner ring road (in direction North) to compensate for the missing motorway link. This results find confirmation in the official traffic redirection strategy by the local municipality and the motorway management company, which planned a 7km re-routing towards the West, for travellers going North, in the attempt to avoid overcrowding in this already busy area (Bologna today, 2018). At the same time, the maps of the urban network before (U*B*) and after (U*A*) show that local drivers who travelled mainly across the city probably had to modify their routes mainly in the area surrounding the collapsed bridge (shown in detail in Figure 6) while possibly experiencing slowdowns in the streets used for longer-range journeys.

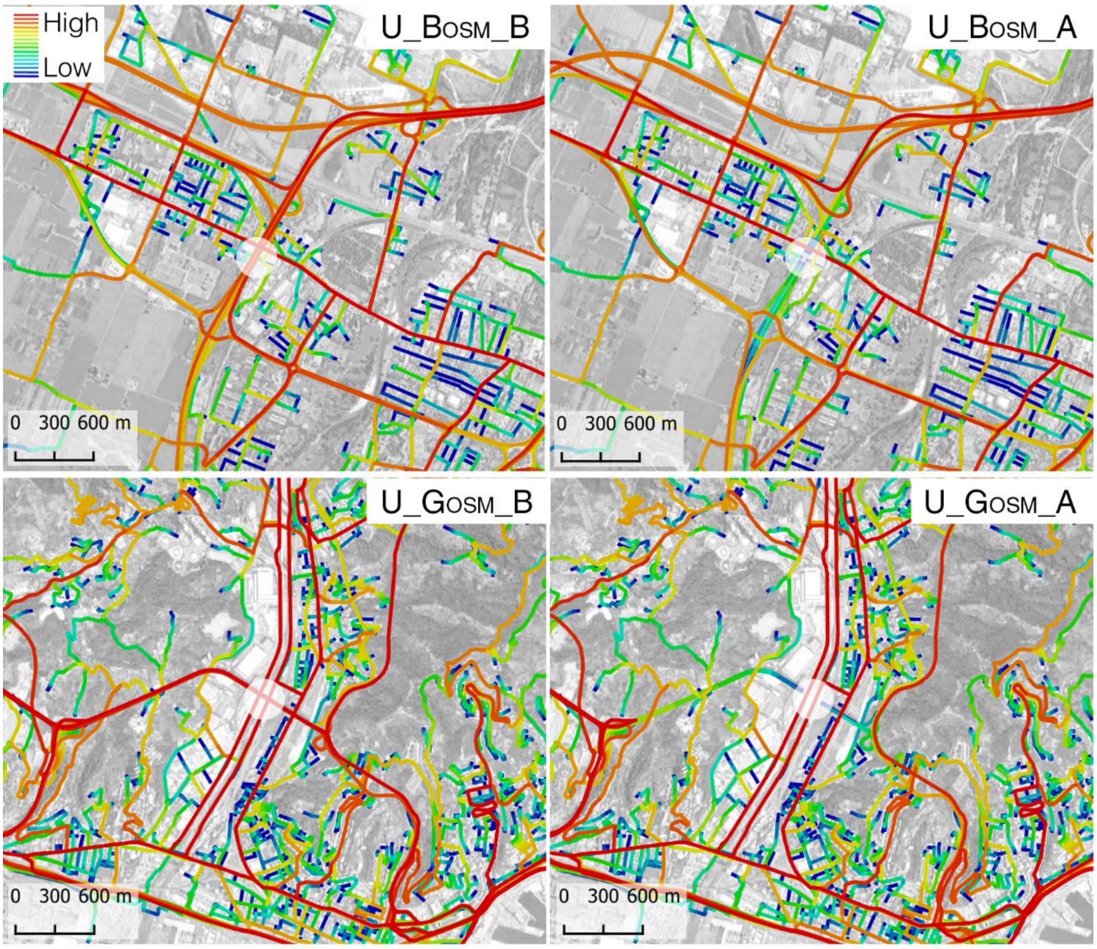

Figure 6. Distribution of NACH in the Urban road-network of Bologna (U_BOSM) and Genoa (U_GOSM) in the surroundings of the collapsed bridges Before (B) and after (A), 1:6000 scale.

Genoa's P*B* and P*A* maps in Figure 7, indicate that after the collapse of the bridge, the middle-range vehicular traffic was naturally redirected in the primary road running along the industrial port, the SS1 (also known as *Via Aurelia*). This tendency was accommodated by the local municipality through the parallel removal of parking spaces and the enlargement of the carriages in *Via Albareto* and *Via Hermada* to accommodate the flow of vehicles moving from the West (*Sestri Ponente*) towards Genoa city centre (Genova24.it, 2019). Another visible consequence of the bridge collapse at this scale is the weakening of the SS45 (Genoa-Piacenza) primary road-link running along the *Bisagno* river and connecting the SS1 with the A12. Similar to the case of Bologna, besides showing local through-movements patters in greater detail, the micro-scale maps of Genoa before (U*B*) and after (U*A*) the crash do not add a lot of new meaningful information to the analysis.

Although local changes in the distribution of NACH at the urban level are better evidenced in the zoom in Figure 6, in the case of Genoa, changes in local flows would have probably been better captured by using another network centrality metric called Normalised Angular Integration (NAIN), which shows road-segments' accessibility levels or to-movement patterns. Although NAIN is not used in this study, the interested reader can find maps which illustrate its distribution in Genoa before and after the event in (Cutini and Pezzica, 2020).

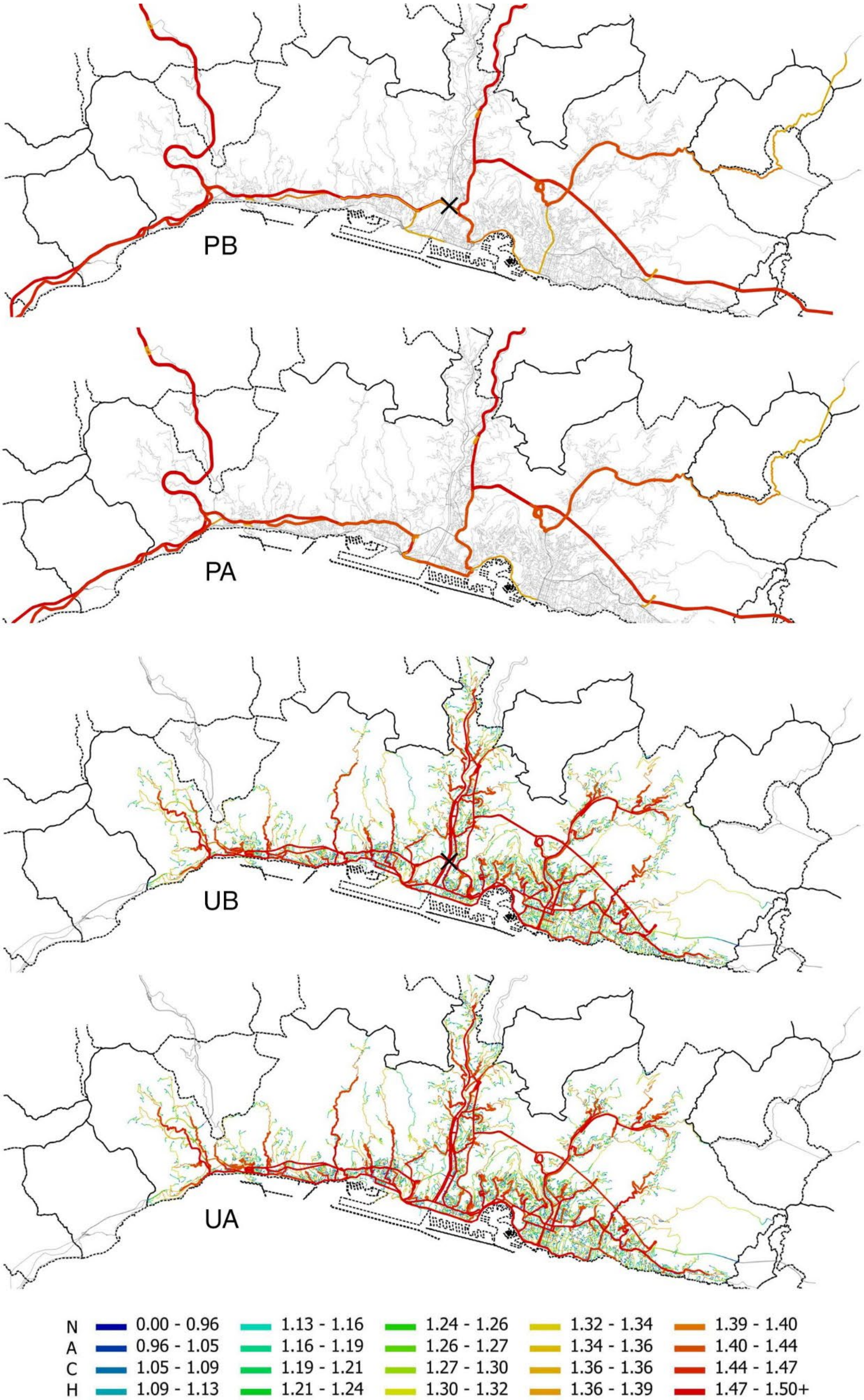

Figure 7. Distribution of NACH in Genoa considering the Primary circulation-network before (P*B*) and after (P*A*) and the Urban road-network before (U*B*) and after (U*A*).

4.3 Lorenz Curves

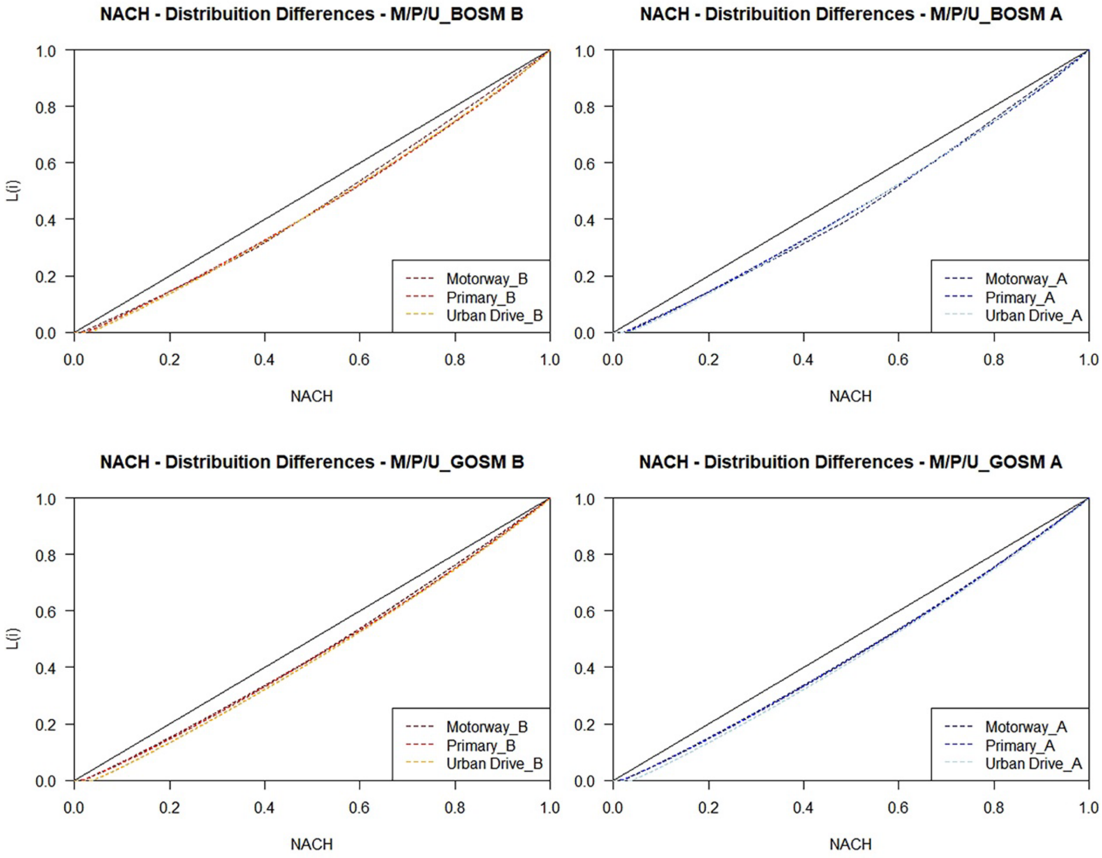

Figure 8. Lorenz curves showing the distribution of NACH in the segments which compose the Motorway (M), Primary (P) and Urban (U) networks of Bologna (BOSM, *B* and *A*) and Genoa (GOSM, *B* and *A*).

Figure 7 shows an overall overlap of the Lorenz curves obtained for Bologna and Genoa at the three analysed scales. The proximity of NACH distribution in the analysed cases can be appreciated also through the calculation of the corresponding summative Gini coefficients (Gini, 1910), which range from 0 (perfectly equal distribution) to 1 (highly unequal distribution), and in this case are all approximately 0.1. The before (left, warm colours) and after (right, cold colours) curves are plotted separately to enable a better discussion of results in relation to local deviations which can be observed in the shape of the curves, and which are an unavoidable consequence of the sensibly different size of the M, P and U models. For instance, the curves show that micro-scale urban models present a greater number of segments having low NACH values, which is not surprising considering that urban network models present a comparatively higher amount of poorly connected elements. While this and other differences can be observed and discussed, it seems more interesting to note that the overlap of the curves is rather good in the portion showing the last percentile, which represents the distribution of the 20% highest NACH values (from 0.8 to 1); except perhaps Genoa's motorway network due to the edge-effect as discussed in Section 4.2. This correspondence confirms the cross-scale correlations which were previously observed in a qualitative way in the maps. Therefore, not only the Lorenz curves in figure 7 offer a further, quantitative, appreciation of the homothetic behaviour of NACH hypothesised by

Altafini and Cutini (2020) but also support the choices made in this paper concerning the research methodology and the proposed multi-scale analysis approach to study urban-regional dynamics of network resilience.

5 CONCLUSIONS

The paper started to address some of the current limitations of the Space Syntax analysis in relation to cross-scale configurational assessments by proposing and testing a method which enables performing an urban and regional movement pattern analysis without relying on high computational capacity nor extensive time availability. The focus of the research has been on NACH as this metric showcases homothetic properties, meaning it maintains its foreground network at different scales of analysis as further demonstrated in this research. This offers practical advantages since NACH can be effectively used in practice to support prioritisation of infrastructure reconstruction (if needed) and/or to inform design for logistics by pinpointing configurations which can create traffic bottlenecks, besides to identify vulnerable points of the road network system. Additional research is nonetheless needed to move further steps towards enlarging the pool of instruments available to spatial planners and decision-makers at a time of crisis, contributing to enabling the achievement of Sustainable Development Goal (SDG) 11 "sustainable cities and communities", in line with the New Urban Agenda’s resilient infrastructure targets. For instance, future research can explore if the configurational approach can offer useful insights with respect to the role that the regional railway network plays in enhancing the physical resilience of the cities. Moreover, future research may study the effects of the removal of strong ties in urban and regional systems and assess, as theorised in this paper, if they offer a minor contribution to the redundancy of road network systems. If this is confirmed, and in light of the importance that weak ties seem to have in terms of network resilience as illustrated by the cases of Bologna and Genoa’s bridge crashes, then the mathematical development of a configurational index able to capture the location of the weak ties of a street-network will undoubtedly offer an important contribution to the field both at a conceptual and at a practical level. In fact, their identification may not be trivial (such as in the case of actual bridges) since, while all bridges are weak ties, not all weak ties are bridges. Further analysis on the subject can consider integrating novel instruments and configurational measures, such as the Markov-based measures developed by Altafini et al. (2022). In fact, these metrics appear perhaps even better tailored to address the urban road-circulation network resilience than the *betweenness centralities* depicted by the NACH, being them more suited to identify which road-elements are crucial to the redundancy of the road system structure.

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