Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

How to prioritize bridge maintenance using a functional priority index

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ABSTRACT: The progressive aging of civil infrastructures makes it essential to develop managerial tools and instrument for planning maintenance activities. As public entities, typically in charge of the management of infrastructures, have limited resources, it is crucial to define clear prioritization criteria. Addressing this need, this work introduces the usage of a functional priority index for ranking infrastructures on the basis of the impact of their closure. The impact is expressed in terms of induced travel delay for people due to path detour. To estimate this delay an analytical strategy is introduced and applied to assess the priority index on a sample of 290 bridges in Lombardy. Relevant information are gathered integrating two data sources providing information on the transportation network and on the travel demand, i.e. road network data and Origin Destination matrices. The results of this application show that the method enables the identification of the most critical infrastructures and the detection, for each bridge closure, of the most impacted areas of the region and the most impacted hours of the day.

1 INTRODUCTION

Maintaining civil infrastructures and ensuring their functioning is a crucial problem for those entities that are responsible for their management as these structures are naturally subject to both obsolescence and deterioration caused by the effects of natural hazards, operational and environmental conditions (Wang, Zhang, & Li 2017). Among civil infrastructures, bridges are crucial elements characterized by high vulnerability in terms of both natural and man-made risk. The impact of aging and natural deterioration processes could be detrimental to the infrastructure system performances under service loadings or extreme events, such as earthquakes. Moreover, considering their relevance for the transportation network system, they often represent bottlenecks as they are designed to cross obstacles as water flows or highways. Hence, the detour of these infrastructures could result in substantial extra travelling time (Biondini & Frangopol 2016). Given the importance of infrastructures for transport network users, the reliability of nodes of the network represents a key element for evaluating the quality of transport. In order to allow infrastructure reliability and safety for transportation network management purpose, maintenance activities are necessary. In the current economic context, resources available to public entities, that are typically in charge of the management of these infrastructures, are limited, making crucial the identification of some criteria for planning maintenance activities based on clear priorities (Frangopol & Liu 2007).

The evaluation of the priority of intervention and the development of an adequate maintenance planning is a complex task, because it requires to take into considerations many different variables characterizing the level of risk, that range from the age of the infrastructure, its technical characteristics, the operating conditions, and also the consequences of the unavailability

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of the infrastructure (Arena, Bianchi, Biondini, Torti, & Vantini 2020). It is worth to highlight that concepts of vulnerability, risks and reliability are still not uniquely defined (see Jenelius et al., 2006 and Pan et al., 2021 for discussions on the definitions of these concepts). In this study, we adopted the definitions provided by Simmons et al., in 2017. The authors identified three different components influencing the level of risk: i) hazard, ii) vulnerability and iii) exposure (Simmons, Corbane, Menoni, Schneiderbauer & Zschau 2017). The first component refers to detrimental events that may cause losses or damage, such as long-term gradual stress events and shock events (Hughes & Healy 2014). Vulnerability refers to the likelihood of occurrence of disruptive events. Exposure is related to the consequences of the hazard on the social community; hence it requires the assessment of the impact on the societal needs. Loss of functionality or temporary closure of an infrastructure is an example of the exposure of the system.

In this paper, we will focus on the system functionality and, more specifically, on the consequence of the unavailability of the infrastructure in terms of impact on users. More in details, we will propose a methodology to evaluate the impact of a bridge closure in connection to its function of maintaining a proper connectivity between all areas of a region, allowing users to move from one point to another and reach their destinations. Despite concepts of vulnerability, reliability and risks do not have widely accepted definitions, authors agree on the usage of the increased cost of travel (measured through time, distance or money) for the users as a reasonable measure of the reduced function of the network (Jenelius et al., 2006). Therefore, this work will assess the impact of the closure of a bridge on the users in terms of delays induced on traveling people. First, a global index, measuring total travel cost in terms of travel time will be presented; second, the variability of the additional travel time along time and space will be evaluated, in order to understand within day variability and identify areas that are most affected by the closure of an infrastructure.

The rest of the manuscript is organized as follows. In Section 2 we introduce a brief review of related literature. The sample and the data sources s follow in Section 3. In Section 4, we present the methodology used to evaluate the impact of a bridge closure. In Section 5 we report the results of the analysis on the selected sample. In section 7 we illustrate our conclusions and some of the potential future research paths.

2 RELATED RESEARCH

The assessment of transport failure has recently drawn the attention of both scholars and practitioners. The increasing vulnerability of infrastructures due to climate change (Schneider, Semenov, Patwardhan, Burton, Magadza & Oppenheimer 2007) and the recent collapses of transportation infrastructures, contributed to the enhancement of the relevance of the topic. Several measures of impact assessment have been introduced in the literature, looking at different indicators, such as generalized costs, user costs, efficiency measures, network topological features and congestion effects (Jenelius, Petersen, & Mattsson 2006, Taylor, Sekhar, & D'Este 2006, Stein, Young, Trent, & Pearson 1999). Jafino, Kwakkel and Verbraeck in 2020 reviewed the different measures that have been introduced in prior studies for rank-ordering transport infrastructures on the basis of the consequences deriving from the closure of the infrastructure. Referred to as criticality analysis measures, seventeen measures have been described and compared. A first set of metrics are built on the concept of generalized travel costs derived from an infrastructure disruption. Total travel cost can be assessed only in terms of additional travel time or can be weighted according to the travel demand. A second set of measures is based on the concept of accessibility of the geographical area. In these cases, the impact is assessed in terms of reduced accessibility characterizing the area. Authors often used the Hansen's index for measuring accessibility index (Taylor et al., 2006; Hernández & Gómez, 2011; Taylor & D'Este, 2007). The third set of criticality measures are built for measuring connectivity among different places. A decrease in connectivity implies that some places of the network become unreachable from other places of the network, due to disruption of single or multiple infrastructures. However, it is worth to highlight that these measures are highly sensitive to inaccuracies in the network data (Jeulieus et al., 2006).

These approaches allow to estimate, in different ways, the consequences of the closure of an infrastructure, generally evaluating the impact of a disruption, in terms of travel costs for the users, accessibility or connectivity of the area. However, all these approaches do not address one element crucial to the understanding of the consequence of a damaged network: the temporal variability of the effects. Since daily traffic profiles are characterized by a large within-day variability, analyzing mobility flows between an origin and a destination during the 24 hours is fundamental to investigate the consequences of closing a transportation infrastructure over the day. In this paper, the object of the analysis is the additional travel cost considering both the induced delay and the travel demand on the network. Regarding the former we represented the induced delay by means of a point belonging to a space of continuous functions defined on the time domain (0,24). As for the latter, the spatial aggregation is the network wide aggregation. This approach allows to estimate the impact of the closure of one infrastructure on the overall transportation network. The impact will be assessed considering the additional delay for the trips of the whole set of origin destination pairs, hence capturing interdependencies among elements of the transportation infrastructure (Scott, Novak, Aultman-Hall, & Guo, 2006).

3 DATA

3.1 *The sample*

In this manuscript, for supporting the development of the methodology, we will focus on a reduced sample of road infrastructures, made of 290 bridges, selected in accordance with regional authorities from Lombardy Region. This area is characterized by a large and heterogeneous territory with an area of 23,844 square kilometers and a resident population of about 10 million inhabitants. The road network of Lombardy counts 70,000 km of roads. On this transport network there are almost 10,000 infrastructures, including bridges, tunnels and overpasses. The sample will allow us to test the methodology, understand potential criticisms and limitations before extending the approach to all the 10,000 infrastructures of the road network. The sample includes the most relevant bridges located in the twelve provinces which the region is divided into: Bergamo (BG), Brescia (BS), Milano (CMM), Como (CO), Cremona (CR), Lecco (LC), Lodi (LO), Monza Brianza (MB), Mantova (MN), Pavia (PV), Sondrio (SO) and Varese (VA). Each bridge is identified by an identification code of the road network section, the province it belongs to, and its GPS position.

3.2 *The datasets*

As follows we describe the datasets available for developing the project: the regional road network model and the regional OD matrices, both provided by the regional government of Lombardy. The road network model is a spatial network made of about 37,000 nodes and 82,000 directional edges, which model all types of roads of the real network. Nodes represent the intersections between two or more roads, whereas edges are segments of road between two intersections. For each directed edge of the network, an identification code of the road section, the type of the road (e.g. highway, regional, provincial, local) the length (km), the typical travel time (hour) and the velocity without traffic (km/h) are known.

Regione Lombardia, the administrative body of Lombardy, publishes every few years an OD matrix, containing the number of trips across different mobility areas during a typical working day. OD matrix has been estimated starting from survey data on travel behavior and merging this information with data related to the socioeconomics features of the different areas of the region. The OD matrices of Lombardy contain the number of hourly trips between 1,450 internal mobility areas. Trips are classified according to eight modalities (car driver, car passenger, motorbike, bus, train, bike, foot and others) and five purposes (work, study, business, occasional and return home). For the scope of our analyses, we aggregated all trips with respect to their purpose and we considered only those of people moving with a motor vehicle on the road, hence aggregating the modalities car driver, car passenger, motorbike and bus, while disregarding the trips related to the other modalities. In this way, we obtain a total of almost 12.4 million of trips distributed over the day, accounting for almost 75% of the total trips contained in the matrix. For the scope of our analyses, we integrated our two sources of information, the road network data model and the OD matrices.

4 METHODOLOGY

In this section, we illustrate the main methodological choices made in this work in connection to the selection of the indicator used to measure the impact and the methodology for the assessment of the impact for the selected bridges. Specifically, we propose an approach that relies on prior literature focusing on the evaluation of consequences of the closure of the infrastructure in terms of additional travel cost, but enriches prior research, considering how this delay changes over time and space, i.e. time and space variability.

4.1 *The calculation of the global index*

The first step of analysis is the so-called traffic assignment step and consists in the estimation, for each trip, of the route on the road network. First, for each mobility area, its centroid is associated to the closest node of the road network data model. The assignment of the centroid is computed by minimizing the Euclidean distance in kilometers between the two. Next, for every OD couple the shortest time path $O \rightarrow D$ on the road network data model is found by means of the Dijkstra's algorithm (Newman 2018). Through this algorithm, the number of trips passing through it is computed. This latter is obtained by summing over all OD pairs whose shortest connecting path goes through *e*. The relevant indicator could either be the flow function describing the number of trips passing from *e* at any time *t* of the day:

$$f_e(t) = \sum\nolimits_{(O,D):e\in O\rightarrow D} f_{(O,D)}\left(t - t_{(O,e)}\right) \tag{1}$$

where $f_{(O,D)}(t)$ is a standard function indicating the number of travelers departing from O at time t and heading at D, $t_{(O,e)}$ indicates the travel time necessary for reaching the midpoint of edge e starting from O, and $f_{(O,D)}(t - t_{(O,e)})$ the number of travelers at time t on edge e departed from O and heading at D. Coherently with previous studies we define an index on the basis of the importance of bridges in maintaining a proper connectivity between all origin and destination couples of the OD matrices in order to measure the impact of the bridge closure (Berdica & Mattsson 2007, Sullivan, Aultman-Hall, & Novak 2009, Rupi, Bernardi, Rossi, & Danesi 2015). We evaluate the effects of a bridge closure on the movement of people, by estimating an index expressed in terms of extra person-hours traveled. To measure the consequences of the closure of a bridge belonging to the edge e of the road network data model, we virtually remove the edge e from the network. Then, for every OD pair we measure the increase in travel time of the shortest time path connecting O and D after the removal of the edge e. Hence, to obtain the extra traveled person-hours we simply multiply this extra travel time by the number of trips associated to edge e:

$$I_e = \sum\nolimits_{(O,D):e\in O\rightarrow D} \left[t^{-e}_{(O,D)} - t_{(O,D)}\right] \int f_{(O,D)}\left(t - t_{(O,e)}\right)dt. \tag{2}$$

I_e is measured in person-hours and indicates the cumulative extra-time, spent on road in the typical working day by people traveling within the area, due to the closure of a bridge belonging to the edge *e.*

4.2 *Spatial-temporal indexes*

The global index I_e has the benefit of providing an estimate of the total impact of a bridge closure but does not consider the spatio-temporal variability, i.e. how this impact spreads during the hours of the day and across geographical areas of the region. To this purpose, we provide a novel two-way approach exploring both the temporal and the spatial dimensions. From a temporal perspective, we estimate how the impact of a bridge closure changes along time. To this end, we follow the same argument used above to build the global impact index I_e, but separately for each time $t \rightarrow [0, 24]$. Hence, to measure along time the impact of the closure of a bridge belonging to the edge *e,* we measure the temporal impact function

$$i_e(t) = \sum\nolimits_{(O,D):e\in O\rightarrow D}\left[t^{-e}_{(O,D)} - t_{(O,D)}\right]f_{(O,D)}\left(t - t_{(O,e)}\right) \tag{3}$$

From a spatial perspective, we want to estimate how the impact of a bridge closure is distributed across the region, namely the most impacted areas of Lombardy. Hence, we apply again the same argument used above for the construction of I_e (2) but now we fix the origins or the destinations:

$$I^O_e = \sum\nolimits_{D:e\in O\rightarrow D}\left[t^{-e}_{(O,D)} - t_{(O,D)}\right]\int f_{(O,D)}\left(t - t_{(O,e)}\right)dt \tag{4}$$

And

$$I^D_e = \sum\nolimits_{O:e\in O\rightarrow D}\left[t^{-e}_{(O,D)} - t_{(O,D)}\right]\int f_{(O,D)}\left(t - t_{(O,e)}\right)dt. \tag{5}$$

5 RESULTS

5.1 *Analysis of the global index*

Figure 1 shows the value of I_e for each bridge. In this, each bridge is colored according to its global impact in terms of person-hours per day using a log-scale. Looking at the Figure 1, it

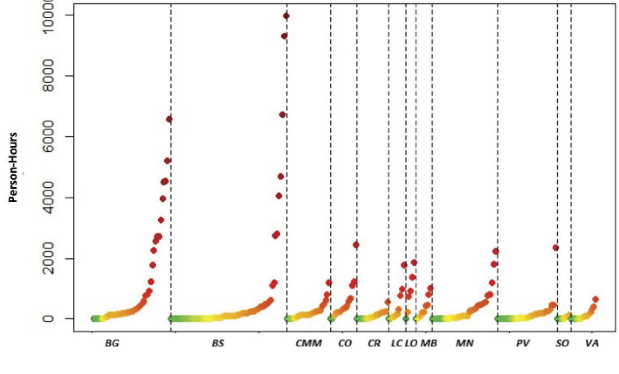

Figure 1. Distribution of the global impact (person-hours) of the 290 bridges for each province.

appears that the most critical bridges are located in the north side of the region in the provinces of Bergamo and Brescia, which are mainly in a mountain area with a sparse road network made of few main roads mostly located at the valley bottom with very time-consuming alternative paths. Moreover, the values of I_e in the different provinces follow a strongly right-skewed distribution characterized by few bridges with high values and many bridges with low values.

5.2 *Analysis of the spatio-temporal effects*

We now investigate the impact of each bridge closure by its temporal and spatial effect during the day using the functions $i_e(t)$. An illustrative example related to a one-way bridge is reported in Figure 2 which shows the spatio-temporal effects due to the closure of the most critical afternoon-peak bridge: on top left, the geographical position of the selected bridge is highlighted; in the top right we show the temporal impact function of its closure; at the bottom, the spatial impacts on both origins (left) and destinations (right) are reported. Results reveal a clear difference between the impacted origins, all of them located west of the bridge, and the impacted destinations, all of them located east of the bridge. This is due to the fact that the selected bridge is on a one-way road going from west to east. Looking at the temporal impact function, the afternoon peak appears to be higher than the morning peak, due to the fact that people moving on this road are likely to be mostly commuters coming back home after going west to work in the morning.

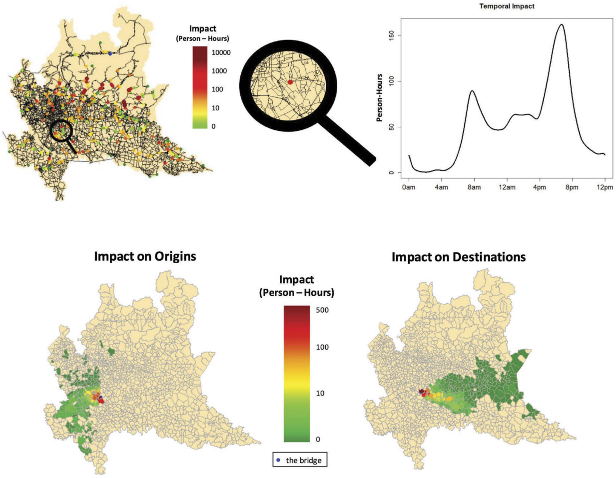

Figure 2. Top: the selected bridge on the road network of Lombardy and its temporal impact function. Bottom: the spatial impacts of the bridge closure, highlighted with a blue point, on both origins and destinations.

6 MONETARY QUANTIFICATION

Delays caused by the unavailability of an infrastructure can be expressed in monetary terms through the Value of Time (VOT), also called the value of travel time savings. The Value of Time is defined as "*the monetary value attached to the possibility of save a determined amount of travel time*" (Zamparini & Reggiani 2007). In other words, the VOT can be seen as willingness-to-pay indicator (Hess 2005), that links time to the cost that individuals have to face in order to accomplish their mobility activities (Zamparini & Reggiani 2007). The VOT is of central interest in transportation research, because it is one of the most relevant components in the evaluation of mobility and infrastructural investments and it is a very important parameter for explaining travel behavior and modal choices.

Obviously, the VOT is not unique as it depends significantly on the characteristics of the individual, the means of transport and, more generally, the conditions in which a trip is made. In the literature, very different VOTs, estimated on the basis of the various studies are available. One relevant example is the meta-analysis provided by (Wardman, Chintakayala, & de Jong 2016), that covers more than 3100 monetary valuations deriving from 389 studies conducted in Europe between 1963 and 2011. The valuation of VOT also refer to the Italian transportation context, in line with the geographical scope of this analysis. Moreover, the study introduces different segmentation factors including travelling mode and travelling purpose, hence enabling the estimation of the VOT for people using the car as transportation mean.

7 CONCLUSIONS

This work proposes a methodology aimed to assess the functional priority of one critical infrastructure in a transport network, bridges. Specifically, we focused on the exposure risk addressing the impact of the closure of the infrastructure in connection to its function of ensuring the accessibility of an area, connecting different geographical areas. From a methodological point of view, we provided different levels of impact assessments. First and foremost, we introduced the global index for estimating the impact of a bridge closure, hence providing a means for ranking infrastructures.

Secondly, we explored both temporal and spatial variability. From a temporal point of view, we evaluated how the impact of a bridge closure varies according to the hour of the day. From a spatial point of view, we evaluated how the impact of a bridge closure is distributed over origins and destinations of trips. The analysis of the temporal results allows to identify the most critical bridges of the region and to highlight for each bridge the most impacting hours of the day. These results can be used by decision makers for communication or planning purpose. Regarding the former, decision makers can anticipate the damage on the users caused by maintenance interventions on road infrastructures. Moreover, the information on the temporal variability of the consequences of bridge closure can be instrumental in optimizing the road maintenance schedule. The impact of bridge closure is also assessed in economic terms. Using the concept of the value of time (VOT), the hours of delay for the users have been translated into monetary value, hence highlighting the socio-economic cost for one hour of infrastructure disruption for people using the examined infrastructure.

The developed methodology has proved to be scalable and repeatable, thus providing possibility for application on a larger set of bridges or to other contexts. Specifically, the proposed methodology can be applied to other geographical areas and extended to any other transportation infrastructure that can be modeled as a directional edge, such as tunnels and overpasses. In conclusion, we want to highlight some of the potential paths for future research. First, the proposed methodology focuses on one specific impact dimension, that is the impact on users. This dimension has to be complemented in order to consider the broader socioeconomic impact, including the impact on the economic activities operating in the area related to supply chain management (Bell, 2000; Smith et al., 2003). The proposed approach could also be enhanced by considering elastic demand function. Further research could also be directed towards the consideration of other maintenance strategies, such as the reduced capacity due to closure of one of the two road directions.

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