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Development of a functional priority index for assessing the impact of a bridge closure

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ABSTRACT: The paper moves from the recognition of the relevance of developing managerial tools and instruments for dealing with the progressive aging of civil infrastructures in a context in which resources for carrying out maintenance activities are shrinking. In order to contribute to the definition of the priority of intervention for the development of an adequate maintenance planning, the work proposes a functional priority index, that allows to rank the infrastructures based on the impact associated to their closure. The impact is expressed in terms of induced travel delay for people. To estimate this delay an analytical strategy is introduced and applied to assess a sample of 290 bridges in Lombardy. Relevant information are gathered through a data fusion approach, aggregating road network data and Origin Destination matrices. The results of this application show that the method is actually suitable for identifying the most critical infrastructures and, for each bridge closure, the most impacted municipalities of the region.

1 INTRODUCTION

Civil structures and infrastructure facilities are critical assets in the current economic context and constitute one of the main drivers of socio-economic development. They are fundamental for ensuring the accessibility of territories, connecting one area to the other and to the local and regional network. As such, they have a relevant impact on the attractiveness and the competitiveness of different areas and territories.

Therefore, maintaining civil infrastructures and ensuring their functioning is a crucial problem for those entities that are responsible for their management. 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). In order to allow these infrastructures to be safe and to perform their function, maintenance activities are necessary. Still, maintenance requires considerable resources and time for visiting the facilities, assessing their conditions, and then planning and carrying out the needed activities. 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, that range from the age of the infrastructure, its technical characteristics, the operating conditions, and also the consequences of the unavailability of the infrastructure (Arena, Bianchi, Biondini, Torti, & Vantini 2020). All these variables are relevant for explaining the risk of a crisis of the infrastructure, due to its vulnerability and hazard, as well as the consequences of its unavailability due the road network exposure.

In this manuscript, we will focus on one specific variable that is relevant in the definition of the priority of intervention - i.e. 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. From this perspective, 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 delays in the peak hours will be presented; second, the variability of the delays along time and space will be evaluated, in order to understand how delays change in different hours of the day and which are the areas that are most affected by the

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closure of an infrastructure. This information can be relevant to decision-makers in order to schedule maintenance intervention in a more efficient way, limiting the consequences deriving from the unavailability of the infrastructure.

The rest of the manuscript is organized as follows. In Section 2 we present the research context (i.e. the Lombardy region), the sample of the infrastructures analyzed and the data sets used for carrying out the analysis. In Section 3, we introduce the methodology used to evaluate the impacts of a bridge closure, explaining how the global index is calculated and how the time-space variability is addressed. In Section 4 we report the results of the analysis of a sample of 290 bridges in Lombardy. In Section 5 we illustrate a valorization of the delay through the value of time, a monetary value considered as an important input for investment analysis in transportation studies. In section 6 we illustrate our conclusions and the paths for future research.

2 DATA

2.1 *The research context*

The proposed methodology is applied to estimate the impact of a bridge closure for a sample of bridges in Lombardy. Lombardy is one of the twenty administrative regions of Italy with an area of 23,844 square kilometers and a resident population of about 10 million people. The road network of Lombardy counts 70,000 km of roads: 560 km are highways, 900 km are state roads, 11,000 km are provincial roads, and 58,000 km are municipal roads. On this road network there are almost 10,000 infrastructures (e.g. bridges, tunnels, overpasses). The infrastructures are managed and maintained by different local authorities that are responsible for verifying their conditions and planning maintenance interventions.

These characteristics make Lombardy region particularly interesting for the scope of this paper. In fact, the high number of the infrastructures that are present on the road network, the heterogeneity of their characteristics and the diversity of their connection to the network call for an instrument that is able to support decision-makers in planning maintenance activities, in a systemic way, allocating effectively the available resources. At the same time, the proposed approach should be applicable, with relatively limited effort, to a large number of items.

2.2 *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 with Regione Lombardia. 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 for each of 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 section, the province it belongs to, and its GPS position.

2.3 *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 (i.e., road intersections) and 82,000 directional edges (i.e., segments of road between two intersections), which model all types of roads of the real network. For each directed edge of the network, an identification code of the road section, the length (km) and the typical travel time (hour), are known. Each bridge has been assigned to an edge of the network by matching its identification code with those of the road sections.

The OD matrices of Lombardy contain the number of hourly trips between 1,450 internal mobility areas, during a typical working day observed in the time span between February and May 2016. A mobility area corresponds to the geographical area occupied by a municipality of the region except for small and big municipalities; very small municipalities have been aggregated into a single area, whereas big municipalities have been split into districts, each one represented by a mobility area. For example, the municipality of Milan, the main city of Lombardy, is split into 16 mobility areas. For each area, the GPS position of the area centroid is also known. Each OD matrix reports the number of trips departing from one area to another in a given hour of the day (00:00-00:59, 01:00- 01:59, …,2 23:00-23:59). Trips are classified according to eight modalities (car driver, car passenger, motor- bike, 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. For the scope of our analyses, we pass through a data fusion step which aggregates our two sources of information, the road network data model and the OD matrices. The road network is weighted by travelling time in the first part, and successively these weights are substitute by trips contained in the OD matrices.

3 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 approach used to measure the indicator.

3.1 *The selection of the indicator*

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). These approaches allow to estimate, in different ways, the consequences of the closure of an infrastructure, generally considering the induced delay, in terms of disutility of travel or extra vehicle-miles traveled, or an economic valorization of this delay. However, all these approaches, even if they are key to help decision makers for planning the maintenance of a road infrastructure, do not address two issues which we consider important for understanding the consequence on the accessibility of a damaged network: the temporal and spatial variability of the effects. Since daily traffic profiles are characterized by a large within-day variability, we think that a natural way to analyze mobility between an origin and a destination during the 24 hours, is to represent it by means of a point belonging to a space of continuous functions defined on the time domain (0,24). Moving from these considerations, we propose an approach that relies on prior literature evaluating the consequences of the closure of the infrastructure in terms of induced delay, but enriches prior research, considering how this delay changes over time and space.

3.2 *The calculation of the global index*

The first step of analysis is the so-called traffic assignment step in which the route on the road network of each trip is estimated. First, for each mobility area, its centroid is associated to the closest node of the road network data model, 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). This assignthe number of trips which pass through it; this simply 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,

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

or the total number of trips in the day

$$F_e = \sum_{(O,D):e \in O \rightarrow D} \int f_{(O,D)}\left(t - t_{(O,e)}\right) dt$$

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. To measure the impact of a bridge closure, 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 (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 impact 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:

$$t^{-e}_{(O,D)} - t_{(O,D)}$$

where $t_{(O,D)}$ is the travel time from O to D on the full network, while t^{-e} is the (possibly) new travel time 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:

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

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 region, due to the closure of a bridge belonging to the edge e.

3.3 *Spatial-temporal indexes*

The global index I_e has the benefit of providing an estimate of the total impact of a bridge closure but is not able to explain how this impact spreads during the hours of the day and across municipalities 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 $t \in [0, 24]$. Hence, to measure along time the impact of the closure of a bridge belonging to the edge e, we measure the temporal impact function

$$i_e(t) = \sum_{(O,D):e\in O\to D} \left[t^{-e}_{(O,D)} - t_{(O,D)}\right] f_{(O,D)}\left(t - t_{(O,e)}\right)$$

Obviously,

$$I_e = \int i_e(t)dt.$$

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 but now we fix the origins or the destinations:

$$I_e^O = \sum_{D:e\in O\to D} \left[t^{-e}_{(O,D)} - t_{(O,D)}\right] \int f_{(O,D)}\left(t - t_{(O,e)}\right)dt$$

And

$$I_e^D = \sum_{O:e\in O\to D} \left[t^{-e}_{(O,D)} - t_{(O,D)}\right] \int f_{(O,D)}\left(t - t_{(O,e)}\right)dt.$$

Obviously,

$$I_e = \sum_O I_e^O = \sum_D I_e^D.$$

4 RESULTS

In this section we report the main results of the analysis of the sample of 290 bridges under investigation in Lombardy.

4.1 *Analysis of the global index*

Figures 1 and 2 show the value of I_e for each bridge. In these figures, each bridge is colored according to its global impact in terms of person-hours per day using a log-scale. Looking at the Figures 1 and 2, it 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. It is also possible to notice two bridges with an elevate impact, around 2000, in the south-west (province of Pavia) and in the southern (province of Mantova) of the region, respectively. Both of them are over the river Po, the main river of Italy, which is flowing in a large flatland (i.e. the Po Valley) and characterized by a reduced number of crossing bridges. 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.

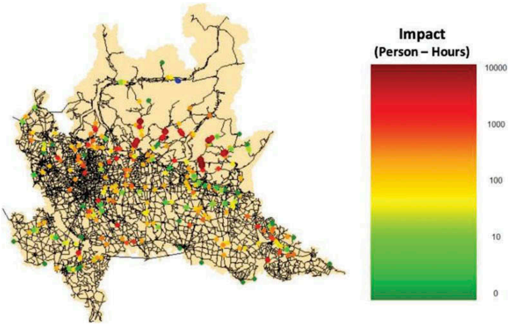


Figure 1. Map of Lombardy highlighting the 290 analysed bridges according to their global impact in terms of person-hours. The only isolating bridge is coloured in blue.

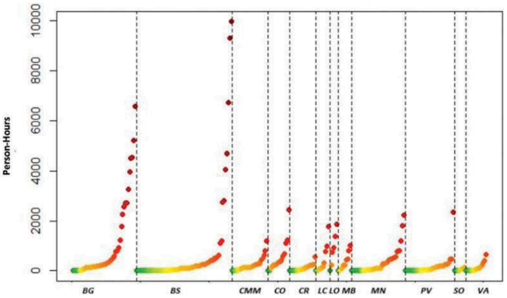


Figure 2. Distribution of the global impact (person-hours) of the 290 bridges for each province.

4.2 *Analysis of the spatio-temporal effects*

We now characterize each bridge closure by its temporal and spatial impact during the day using the functions $i_e(t)$. An illustrative example related to a one- way bridge is reported in Figure 3 which shows the spatio-temporal effects due to the closure of the most critical afternoon-peak bridge: on top, the selected bridge is highlighted together with the temporal impact function of its closure; at the bottom, the spatial impacts on both origins and destinations are reported. The range of values goes from no impact to a maximum of 476 person-hours per day. 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.

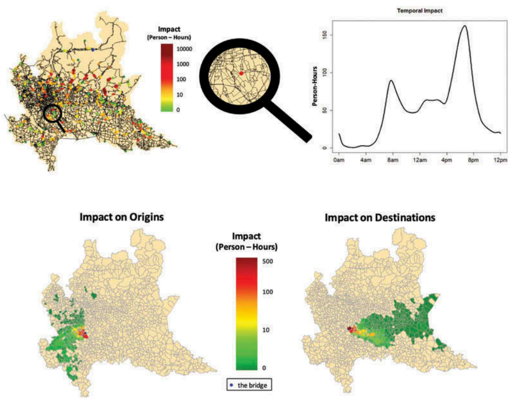


Figure 3. Top: the selected bridge on the road network of Lombardy and its temporal impact function. Bottom: the spatial impacts of the bridge closure, highlighted with a blue point, on both origins and destinations.

5 MONETARY QUANTIFICATION

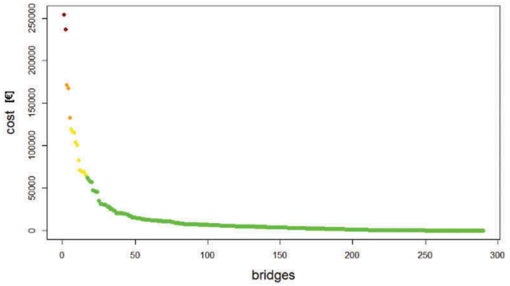
Delays caused by the unavailability of an infrastructure can be expressed in monetary terms through the Value of Time (VOT), also called the value of travel time savings. The VOT is of central interest in transportation research, because it is one of the most relevant components in the evaluation of mobility and infrastructural investments and it is a very important parameter for explaining travel behavior and modal choices. The VOT represents, in fact, the monetary value associated with the time needed for the trip and, more precisely, represents the additional cost that a user would be willing to support to reduce travel time for a given trip that is, the value that the user would accept as compensation for a delay.

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 and research conducted internationally and at the Italian level, 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.

Based on the VOT, the hours of delay for the users have been translated in a monetary value, which, in our case, indicates the socio-economic cost for one hour of infrastructure disruption for people moving at peak times. To simplify the communication with stakeholders, bridges have been divided in four impact categories using a linear scale. In Figure 4 bridges are ranked according to the estimated impacts. In details,

- each point of the graph indicates a bridge,
- each bridge is associated with its cost for one hour of interruption for the users moving at peak times (y-axis),
- colors recall the categories of impact (namely: class 1, in red, includes bridges for which the impact is between three quarters and the maximum value; class 2, in orange, includes bridges for which the impact it is between two quarters and three quarters of the maximum value; class 3, in yellow, includes bridges for which the impact is between a quarter and two quarters of the maximum value; class 4, in green, includes bridges for which the impact is less than a quarter of the maximum value).

In Figure 5 bridges are spatially located.



	1	2	3	4
Min	237.085 €	132.725 €	65.124 €	3 €
Max	254.216 €	171.623 €	119.566 €	62.274 €

Figure 4. The estimated impact due to the closure of the selected bridges. Bridges are ranked according to the corresponding impact and colored according to their impact category.

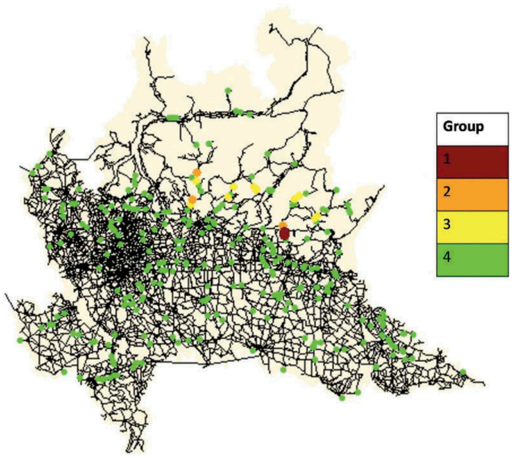


Figure 5. The selected bridges on the road network of Lombardy colored according to their impact category.

6 CONCLUSIONS

This work proposes a methodology aimed to assess the functional priority of one particular type of critical infrastructure in a road network, bridges, with the purpose of helping decision-makers in prioritizing their interventions for maintaining and repairing infrastructure segments. Specifically, we addressed the impact of the closure of the infrastructure in connection to its function of ensuring the accessibility of an area, connecting origins and destinations. Accordingly, we defined an indicator for estimating the impact on a bridge closure on the users and estimated this impact in terms of induced travel delay for people.

From a methodological point of view, we provided different levels of impact assessments, evaluating the impact of a bridge closure by means of a global index (which can be used for ranking) and exploring both its temporal and spatial effects. From a temporal point of view, we evaluated how the impact of a bridge closure varies according to the time of the day. From a spatial point of view, we evaluated how the impact of a bridge closure is distributed over origins and destinations. This has been obtained by modeling a road network as a time-varying graph with fixed nodes and with functions as weight of the edges. The analysis of the results allows to identify the most critical bridges of the region, highlighting for each bridge the most impacting hours of the day. These results are useful for anticipating the damage on the users caused by maintenance interventions on road infrastructures and planning the maintenance activities in a context where resources are limited and should be properly allocated. The information on the spatio-temporal effects of a bridge closure can be passed before the bridge closure to the stakeholders of the affected origins and destinations, limiting the inconvenience to the travelers. Moreover, the same information can be instrumental in optimizing the road maintenance schedule. For example, knowing the most impacting hours of the day for each bridge closure, road works can be planned by choosing the timeslots in which to do the maintenance work or by opening and closing the lanes of the road accordingly to mitigate the effects of its closure. Indeed, the developed methodology has proved to be scalable and repeatable, thus ready to be extended to a larger set of bridges and to be applied to other contexts. Specifically, the proposed methodology can be applied to other geographical areas in order to evaluate the impact of bridge closure or extended to any other road infrastructure that can be modeled as a directional edge, such as tunnels and overpasses, or as a set of connected directional edges in the road network model including road sections.

In conclusion, we want to highlight potential paths for future research. First, the proposed methodology focuses on one particular impact dimension, that is the impact on users. This dimension has to be complemented in order to consider the broader socioeconomic impact, considering the impact on freight and evaluating, in the same way the delay induced on freights. Furthermore, the proposed approach can be applied to evaluate the impacts of the simultaneous closure of more than one bridge/infrastructure in order to understand the potential consequences that are associated to multiple events.

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