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Methodology for Estimating Bridge Failure Costs

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Abstract: The optimal maintenance strategy for aging bridges is one that minimizes the total cost to the community. For each bridge, this total cost is calculated as the sum of the costs of necessary interventions and of the damages resulting from exceeding limit states, multiplied by the probability of such exceedances. The most challenging and complex aspect of this calculation is estimating the damages, as numerous uncertainties are involved. These uncertainties, along with the variability of certain parameters, can significantly influence the results. Damages are typically divided into direct and indirect costs. Direct costs, such as rebuilding collapsed sections, addressing social consequences like injuries or fatalities, and dealing with environmental impacts, are relatively straightforward to calculate, but they tend to be less significant. On the other hand, indirect costs—such as disruptions to infrastructure and psychological effects—are harder to quantify but often have a much larger impact. By leveraging available research and learning from past accidents, we can better estimate these indirect costs. The economic and social consequences of many historical bridge failures are well-documented, allowing us to identify key factors that drive the costs and determine the true magnitude of different types of damage. This article offers valuable guidance for reliably estimating the failure costs of a typical bridge.

Author keywords: Risk analysis; failure costs; maintenance strategies; damages; aged bridges; past accidents

Introduction

Most of Italy's highway bridges were built between the late 1950s and the early 1970s. This significant number of critical transport structures will inevitably reach the end of their design working life within the next 30 years. Infrastructure managers are increasingly aware that complete demolition and reconstruction of the entire stock in a short period would not only be economically unsustainable but also paralyze the entire transportation system. Therefore, timely planning for the renewal of infrastructure is crucial. Moreover, the frequency of bridge collapses seems to be increasing (not only in Italy); numerous studies analyzing collapses in recent years are available in the literature, such as those by Zhang et al.,[1] Wardhana and Hadipriono,[2] and Xiong et al.[3].

For these reasons, it is becoming increasingly evident that traditional qualitative management methods must be progressively abandoned in favor of new technical procedures. These methods would allow the distinction between bridges that will still have a sufficient level of reliability in the coming years and those requiring intervention. Simultaneously, they would enable long-term maintenance or reconstruction planning, starting a gradual replacement process that minimizes costs, distributes them over time, reduces inconvenience to users, and, most importantly, maintains an acceptable safety level at all times.

Available procedures

Recent research trends aim to define calculation or evaluation methods that, given a predefined set of bridges, enable ranking based on one or more priority criteria.[4–6] However, such classifications cannot be practically used as-is. The assumption is that bridges to be repaired, upgraded, or rebuilt would be chosen from the top-ranking items until a predefined economic budget is reached. Unfortunately, unacceptable safety levels cannot be justified solely based on the economic convenience of the manager.

Many regulatory bodies propose calculating a minimum acceptable reliability level for existing structures, different from the standards imposed for new structures. When a bridge's reliability falls below this threshold, it becomes necessary to immediately plan interventions to restore an acceptable safety level. The primary reference document considered here is FIB Bulletin No. 80, "Partial Factor Methods for Existing Concrete Structures," as it contains the most innovative considerations. In its first part (Chapter 3), a target reliability index is proposed for bridges, calculated based on economic and human safety considerations.[7] See also Steenbergen et al.[8]. These considerations also form the basis of new Italian standards.[9] Moreover, studies available in the literature (e.g., Tatangelo et al.[10]) estimate the time trend of a structure's collapse probability, enabling planning for necessary improvement interventions.

The reliability limit indices proposed in the FIB Bulletin are somewhat arbitrary and depend only on the length of the

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collapsed section and the consequence class of the structure. However, as discussed in this article, the failures of bridges within the same infrastructure (thus with the same consequence class) and of similar dimensions can have radically different economic and social effects and should not share the same threshold reliability index. Furthermore, systems based solely on collapse probability do not address durability issues and provide no guidance on the most appropriate type of intervention. It is therefore clear that existing methodologies need to be revised and updated.

New methodology

In any Bridge Management System, regardless of the calculation method used, restoration costs must be evaluated in relation to the potential damages caused by structural failures. It is impossible to precisely determine what types of interventions should be planned without estimating the economic and social risks associated with maintaining the structures.

From this perspective, this article is a logical continuation of a previous study presenting a general calculation model based on a classic risk analysis.[11] This methodology allows for a case-by-case evaluation of the reliability required for existing structures and the optimal scheduling of interventions. The innovation introduced here lies in directly estimating all societal costs due to structural failures, both economic and social. The maintenance strategy minimizes these costs without predefining a limit threshold for collapse probability.

A part of the previously proposed method is further developed here, providing guidelines for estimating the damages caused by the collapse of a generic bridge and expanding upon prior indications by the authors.[12] The calculation leverages experience from recent past collapses in Italy and worldwide. Specifically, a more precise estimate of the number of casualties involved in a collapse is provided compared to the FIB Bulletin, demonstrating that proper risk exposure assessment significantly changes the final analysis results.

Notably, it is unnecessary to calculate the exact total damage magnitude, but understanding at least the order of magnitude of risk scenarios is crucial. This article does not aim to provide a procedure applicable to every situation and bridge but demonstrates that such an analysis can be conducted, is relatively simple to implement, and can yield reliable results.

Reference Time

The most critical parameter for this type of risk analysis is the reference period t_{ref}, during which the bridges in an infrastructure must be ensured safe. This value must be chosen carefully. For short time intervals, the most economical maintenance interventions will be more convenient; for longer timeframes, more intensive interventions, such as demolition and reconstruction, become economically advantageous. FIB Bulletin No. 80 considers a 30-year horizon, which has also been adopted by Italian guidelines as the threshold for so-called *Operability*. However, from a public interest perspective, a 50-year period may be reasonable.

It is evident that the reference period should be imposed at the regulatory level, as each concessionary company, particularly if private, might consider the time from now until the concession expiration date (which could be very short) as the reference period. In contrast, public interest lies in having the longest possible period.

Estimating Economic and Social Damages

The risk analysis component where many studies have stalled, leading some researchers to deem the approach impractical, is determining the damages D_j, related to a bridge's structural failure. The involved uncertainties are many, and these parameter values significantly influence the calculation results.

According to the classification proposed by the FIB Bulletin, damages can be estimated as the sum of the following contributions:

- Reconstruction cost of the collapsed structural section.
- Infrastructure disruption cost: Including lost revenue for the managing company (e.g., toll roads) and *costs to the regional economy* due to road closures.
- Social consequences (human losses).
- *Unfavorable environmental effects* and harm to affected areas.
- *Psychological effects (loss of reputation)*.

The higher the bridge's importance and risk exposure, the greater the damage. Notably, this estimate also depends on the structure's robustness: the smaller the collapsed section, the lower the damage likelihood.

The subsequent paragraphs provide damage assessments. These values were calculated for Italy in 2024, unless otherwise indicated, but the same reasoning should allow estimates for other countries. For this study, past costs were updated to 2024 using data from the National Institute of Statistics (ISTAT). However, it is evident that inflation-induced cost increases can generally be neglected, as only the order of magnitude of the figures is relevant given the uncertainties involved.

Restoration intervention costs

To estimate the costs of each type of restoration intervention for a generic bridge, numerous past projects are available that can be used for this purpose. This study proposes in Table 1 the following parametric costs, shown per square meter of deck surface, obtained by rationally averaging the figures from the cost estimates of the considered projects:

It is important to note that usually, if the height of the piers is not excessive and the deck is accessible from below, the first two types of interventions can be carried out without interrupting or disturbing traffic flow. Conversely, demolition and reconstruction sites (if the bridge is rebuilt on-site) could cause significant delays for users, which should be considered by adding the values calculated using the methods presented in the following chapters.

Table 1. Costs of restoration works

Type of work	€/mq
Remaking of concrete surfaces	1000
Repairing and reinforcing beams and piers	2500
Complete rebuilding of the deck	3600

Infrastructure interruption

The most important parameter in this section is the duration T of restoration works after the collapse of a bridge. The following data in Table 2 shows the actual number of days required for reconstruction in past incidents in Italy.

We can divide the entire period into three parts. The first part is necessary for judicial activities, which are carried out to determine the cause of the collapse. The duration of this period can be considered zero when the reasons for the incident are obvious (earthquake, hydrogeological event, etc.), and a few months when the causes are not as clear and need investigation. Considering the dates of the incidents that occurred, and wishing to consider the minimum, we propose 6 months for collapses due to traffic load and 0 months for all other types of incidents.

The other parts, which are the design and prefabrication time, and the actual construction time, can be considered quite short but cannot be reduced to zero because some processes, such as concrete curing, cannot be infinitely accelerated. Each managing company should assess its ability to operate under tight deadlines. In this article, we propose 1 month for design and the empirical formula (obtained by imposing 100 days for a 100-meter span bridge) $t = 50 \log L$ for reconstruction time in days (in the case of a complete collapse of a part of the deck), where L is the length in meters of the collapsed part. For better understanding, the following graph in Fig. 1 shows the results of the formula.

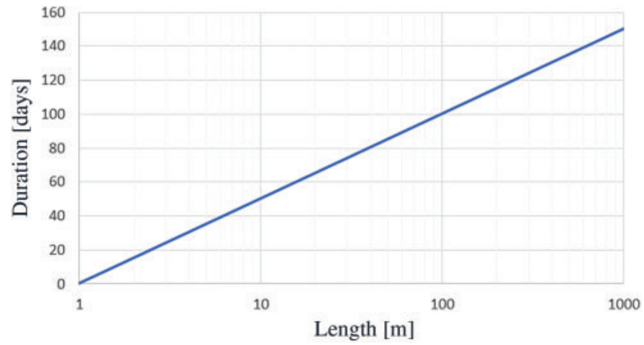

Figure 1. Reconstruction duration

Missed toll payments

Another parameter to consider is the economic loss due to missed toll payments (naturally only for highways or other toll roads). It depends on the amount of traffic and the applicated toll rates. In the absence of specific data on the tolls for the road passing over the collapsed structure, we can roughly estimate this cost as $c_{toll} = 2.0$ euros per vehicle, and obtain the total daily cost by multiplying it by the ADT (average daily traffic) value.

Delay and congestion costs

It should be considered that, from the date of the collapse until the reopening of the bridge, users will no longer be able to use the collapsed bridge and will have to take an alternative route, which leads to increased travel time and higher traffic on the alternative route.

A complete analysis, as can be found in the literature, should consider an entire network of road connections, where the collapsed structure represents only a branch of the

Table 2. Principal accidents in Italy in the last 10 years

Bridge	Cause	Collapse date	Construction start date	Reopening date
Ponte Sturla di Carasco	Flood	22/10/2013	14/11/2013	18/04/2014
Viadotto Petrulla	Construction issues	07/07/2014	23/08/2015	06/03/2018
Ponte dell'Annone	Extra-heavy vehicle	28/10/2016	03/05/2018	01/07/2019
Cavalcavia A14 No. 167	Restoration issues	09/03/2017		06/2018
Cavalcavia Svincolo Marene	Degradation of prestressing cables	18/04/2017	2019	09/08/2019
Viadotto svincolo Borgo Panigale	Explosion	06/08/2018	07/08/2018	01/10/2018
Viadotto Polcevera	Degradation of prestressing cables	14/08/2018	25/06/2019	04/08/2020
Viadotto Madonna del Monte	Landslide	24/11/2019	13/12/2019	21/02/2020
Ponte fiume Magra	Construction issues	08/04/2020	21/03/2021	30/04/2022
Ponte fiume Sesia	Flood	03/10/2020	–	–
Ponte di Longobucco	Flood	04/05/2023	–	–

network. When this connection is interrupted, traffic is redistributed on the other branches, altering the travel time for every traveler in the network.[13] However, for our purposes, this approach is too complicated and perhaps unnecessary. When a road is closed unexpectedly and for a short period, almost all drivers who should use it will follow the alternative route suggested by their satellite navigator and will choose to take the same secondary road. For simplicity, we assume that users of the secondary road will not change their habits and will continue to travel the same route. The result is that the amount of traffic on the chosen secondary road increases (it is the sum of the regular traffic and the traffic diverted from the closed road), while the impact on all other roads is negligible.

It is proposed to calculate the damage due to the increased travel time by assuming an hourly amount (VoT, value of time) for each vehicle that has to travel a longer distance due to the collapsed bridge. The following data are taken from the "European DG MOVE Handbook on External Costs of Transport"[14] and the Italian ministerial decree "Linee guida per la valutazione degli investimenti in opere pubbliche nei settori di competenza del Ministero delle Infrastrutture e dei Trasporti" (Annex 4).[15] The VoT for cars is reported in European Table 87; the values for Italy, in € (2016), are in Table 3 as follows:

Table 3. Values of time (DG MOVE Handbook) in $€_{2016}$/h per person

Sshort distance (<32 km)		Long distance (>32 km)	
Commuting-business	Personal	Commuting-business	Personal
12.8	5.9	16.7	5.9

Since the alternative route is usually longer than the original, the delay costs for a vehicle are calculated with the following formula (DG MOVE Chapter F.2.8):

$$c_{del} = (T - T_0) \cdot VoT \cdot OF \tag{1}$$

where

- T is the actual travel time on the original route (before the bridge collapse), in hours,
- T_0 is the travel time on the alternative route (before the bridge collapse), in hours,
- VoT is the value of travel time, in €/hour, and
- OF is the occupancy factor.

Regarding cars, in this study, in the absence of data for the road under consideration, we propose $OF = 1.2$ and a traffic composition of 80% commuting and business and 20% personal travel; the result for motorways (long distances), using the DG MOVE values, is therefore $c_{\text{del}} = (T - T_0) \cdot 17.5$ € per car.

For freight transport, the corresponding table (No. 88) for Italy provides 1.4 € per ton and 28.1 € per driver. Again, in the absence of data, we assume an average weight of 20 tons and one driver per heavy goods vehicle, so the cost will be $c_{\text{del}} = (T - T_0) \cdot 56.1$ € per truck.

On the chosen secondary road, the amount of traffic increases, so the speed of all vehicles is reduced. In addition to the costs due to the longer path, the damage caused by the reduced speed for all users must also be considered. The congestion costs c_{con} can be evaluated using the following data in Table 4, taken from the "European DG MOVE Handbook", tables 105 and 106 (Italian values), where the figures are in €-cents/km per vehicle (2016); "near capacity" refers to traffic flow/capacity ratios between 0.8 and 1, "congested" refers to ratios between 1 and 1.2, while "over capacity" is considered when the ratio exceeds 1.2.

Table 4. Congestion costs in €-cent$_{2016}$/km per vehicle

	State of road traffic	Motorway	Other roads
Cars	Over capacity	22.3	45.2
	Congested	10.7	23.5
	Near capacity	4.4	10.5
Trucks	Over capacity	93.6	157.2
	Congested	45.2	81.5
	Near capacity	18.5	36.5

Total interruption cost

Summarizing the considerations presented, the estimate of the damage caused by the disruption of the infrastructure can be calculated using the following formula:

$$D_{id} = T\,(c_{toll} + c_{del} + c_{con}L_{con})\,V_{ADT} \tag{2}$$

where

- T is the duration of the reconstruction works, in days,
- V_{ADT} is the average daily total traffic of the collapsed structure,
- c_{toll} is the toll revenue loss, in €/vehicle,
- c_{del} is the delay cost, in €/vehicle,
- c_{con} is the congestion cost, in €/km per vehicle, and
- L_{con} is the length of the road segment where traffic will be congested, in km.

Social consequences

In this chapter is presented the estimate of the economic damage resulting from the possibility that people may die in the hypothetical collapse. Naturally, there is no intention to establish the value of human life; the proposed calculation is merely a mathematical tool that allows for a rational assessment of how much society should invest in safety. It is important to remember that anyone making decisions that do not lead to an infinite level of safety (which is impossible) implicitly assigns a value to the lives of users; it is probably better to do so consciously.

As cost per casualty, the DG MOVE Handbook in table 7 proposes for Italy 2'888'866 (human cost) + 354'695 (production loss) + 2'672 (medical costs) + 1'873 (administrative costs) ≅ 3'250'000 € (2016). Here the costs of injuries are overlooked.

Bulletin FIB 80 (Chapter 3.3.2.2.) contains a very simple formula to estimate the most probable number of casualties as a function of the length of the collapsed structural part: the number of victims is calculated as $N = 0.09 \cdot L$, where L is the collapsed length. Nevertheless, a correct formula should take into account also the ADT, the height of the bridge, the average travel speed, and should depend also on the type of the limit state (if traffic loads are decisive for the collapse, the probability that some users are involved is much greater). Given the importance of this aspect, a more precise calculation than that of the FIB Bulletin is proposed in the following paragraph.

Evaluation of the most probable number of casualties

Consider the limit state of failure of a beam and/or the entire deck. This event can theoretically occur for two reasons: either the advancement of material degradation or an unforeseen overload of the roadway. When degradation is particularly rapid, the bridge could collapse even under its own weight (this happened in the case of the collapse of the Svincolo di Marene viaduct). However, it is correct to assume that in both cases, failure will occur when the stresses in the deck structure are at their maximum, that is, when the bridge is occupied by a high number of vehicles. Therefore, regardless of the typical traffic volume on the bridge, it is reasonable to assume that the collapse will happen when vehicles are backed up, perhaps due to an accident or a construction site just after the bridge, and occupy the entire roadway. In this study, we assume that the first lane (only if there are multiple lanes) is occupied by a line of trucks spaced such that there is one every 25 meters, with only one passenger per truck; all other lanes are occupied by light vehicles, one every 10 meters, with the usual occupancy factor OF of 1.2. Thus, this is the number of people involved in the collapse:

$$n = L/25 + OF\,(n_c - 1)\,L/10 \tag{3}$$

where L is the collapsed deck section length and n_c is the number of lanes.

For example, considering a highway bridge with three lanes and a collapsed section of 50 meters in length, as in Fig. 2, the number of people involved is $2 + 1.2 * 2 * 5 = 14$.

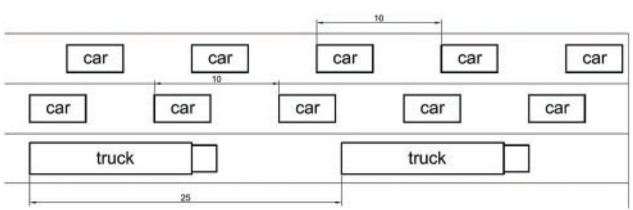

Figure 2. Road traffic considered at the time of the collapse (failure of the deck)

It is necessary to evaluate the consequences of the collapse for each person. The impact speed when hitting the ground, assuming that nothing slows down the fall, will be $v = \sqrt{2gh}$, where h is the height of the bridge (the distance between the underside of the bridge and the ground below). To calculate the probability of death in the fall, a study published by NHTSA regarding horizontal vehicle collisions was used,[16] assuming that the consequences are approximately the same. The following graph in Fig. 3 was created by plotting the impact speed as a function of the bridge height using the formula of the velocity above.

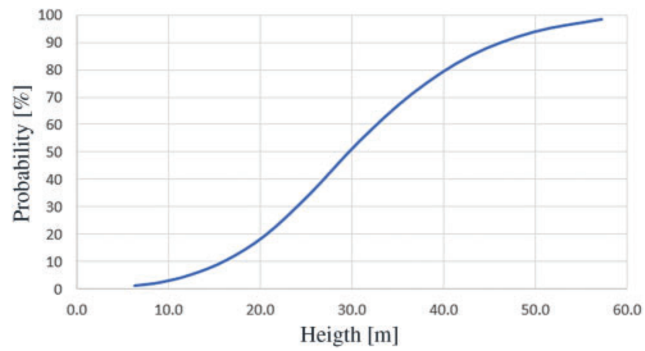

Figure 3. Probability of death

For all other limit states, particularly those related to the piers, the external forces causing the structure's collapse (earthquakes, wind, landslides, floods, etc.) are all statistically independent of the vehicular traffic passing over the bridge. In these cases, which are more frequent, the quantity n of vehicles passing over the bridge at the time of failure depends not only on the length of the collapsed section but also on the ADT and the average speed v_m of the vehicles on the bridge, according to the following formula:

$$n = OF\,((L + d)/v_m)\,V_{ADT}/(24 \cdot 60 \cdot 60) \tag{4}$$

where d represents the stopping distance and the speed is expressed in m/s. The stopping distance d can be calculated as a function of the average speed using a typical deceleration value of -6.5 m/s^2: $d = -v_m^2/2a = v_m^2/13$.

For example, for a highway bridge with a span of 50 meters, assuming an average speed of 110 km/h (approximately 30 m/s) and a daily traffic volume of 10'000 vehicles/day, the number of vehicles involved in the collapse of a pier (i.e., two spans) would be: $n = 1.2\left(\left(2 \cdot 50 + 30^2/13\right)/30\right) \cdot 10000/(24 \cdot 60 \cdot 60) = 0.78$.

However, the impact speed should also take into account the horizontal component, using the formula $v = \sqrt{v_m^2 + 2gh}$. The following graph in Fig. 4 shows how the probability of death increases dramatically as the average speed increases.

This number of casualties could be used as a minimum also for the limit state of failure of the deck.

Obviously, pedestrian walkways (and also bridges with pedestrian sidewalks) require a different consideration, as they are subject to much higher congestion, and the consequences of a collapse on people, who are not protected by a vehicle, will be much greater.

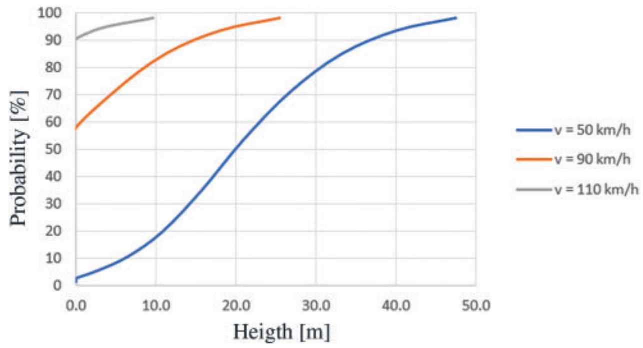

Figure 4. Probability of death for different speeds

Environmental effects

For damages to areas beneath the bridge, a single formulation is not possible. The issue must be studied case by case, as it can vary significantly. Consider the following scenarios:

- For viaducts crossing uninhabited areas, only environmental damage should be considered. Experience shows that road or railway interruptions are so brief that their effects may be negligible.
- If the bridge crosses urbanized areas or if houses are near the piers, the damage will be significantly higher and should be carefully assessed. Note that there could also be casualties among people passing through areas beneath the bridge. Wong et al.[17] provide valuable guidelines on calculating the most probable number of casualties.
- If road closures beneath the bridge also block access to an inhabited area, as in the case of viaducts at the end of closed or steep valleys, the need to relocate people during the closure period should be considered.

For this analysis, the case of the Polcevera Viaduct is emblematic. A document prepared by the Genoa Chamber of Commerce a few months after the tragedy estimated the city's damages at approximately one billion euros.[18] In addition to the mentioned costs, nearly 600 people were relocated, and certain protected areas ("Red Zone" and "Yellow Zone") were established to isolate the disaster zone, effectively blocking part of the city for many months. Therefore, each bridge's immediate surrounding area and any structures that could be affected by a collapse must be examined.

Psychological effects

Estimating damages due to reputation loss is undoubtedly the most challenging aspect, as there is no confined domain within which economic damages can be assessed. Instead, the total loss affects society as a whole. Moreover, the figure depends significantly on the mentality of the affected population, its wealth, and its experience (e.g., past notable events). Consequently, values can vary significantly from one country to another. Finally, these damages also depend heavily on how the tragic collapse event is communicated.

The only reliable way to determine the phenomenon's magnitude is to examine past events and learn as much as possible from them. The idea used in this study is to assess the financial and patrimonial consequences of each event on the concessionary company responsible for the collapsed structure.

In Italy, the only large-scale event was the Polcevera Viaduct tragedy. In 2017, the value of the highways managed by Autostrade per l'Italia was estimated at 12.22 billion euros.[19] News of the collapse spread worldwide, and at that tragic moment, the concessionary company made some significant communication errors. As is well known, the collapse of the Polcevera Viaduct resulted in the deaths of 43 people. A few years after the tragedy, Autostrade per l'Italia's concessions were sold for 9.31 billion euros.[20] Consequently, the company's value loss could be estimated at 2.9 billion euros.

In other recent events in Italy, where the maximum number of casualties was two, the same psychological phenomenon does not seem to have occurred. There are no traces of particular losses or upheavals in the management companies, and news of these events quickly disappeared from the headlines (or did not reach them at all).

Therefore, we can infer that the magnitude of psychological effects may depend on the probable number of casualties and the cause of the collapse. This study proposes considering that if the number of casualties is very low (three or four at most) or the collapse cause appears unavoidable, public opinion may perceive the event as a *tragic accident*. Conversely, if the death toll is higher, the event will be perceived as a *disaster*. As previously mentioned, much depends on how the event is managed and communicated, but to estimate the magnitude of this problem, the following cost formula is proposed (in millions of euros for collapse due to nonnatural events), where N is the number of casualties, obtained simply by ensuring that the result is very low for small events and equals the losses mentioned above for $N = 43$. Fig. 5 illustrates the graph of the function:

$$\begin{cases} D = 3.523^{N} - 1 & \textit{if } N < 5 \\ D = 1800\,\textit{log}\ (N-3) & \textit{if } N \geq 5 \end{cases} \tag{5}$$

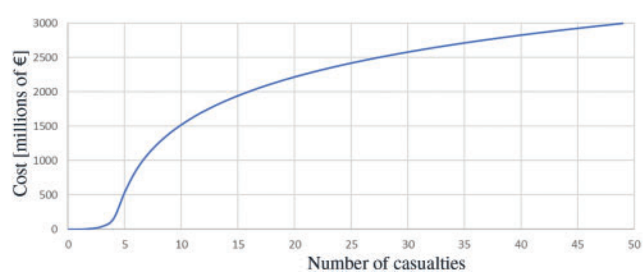

Figure 5. Psychological effects cost function

It should be understood that the proposed formula is highly dependent on the specific society. Managers in countries outside Italy, particularly those outside the European Union, are advised to critically review the formula to adapt it to their social context, possibly based on past experiences.

Risk Analysis

Estimating the economic and social damages associated with a bridge collapse can be used to select the best maintenance strategy, following the method proposed in a previous study.[11] A maintenance strategy refers to a set of various maintenance activities for the examined bridge, ranging from simple repairs to complete demolition and reconstruction, performed at different times during the reference period t_{ref}, which represents one of the risk scenarios.

We select the most significant limit states of the structure. Each limit state is associated with a different probability of occurrence and resulting damage, which can vary significantly (e.g., damages associated with a slab section failure will likely be much lower than those caused by a girder failure). Typical limit states for a medium-sized viaduct could include the following:

- Girder collapse (and therefore an entire deck section collapse) due to traffic overload.
- Slab section failure due to concentrated vertical load.
- Pier collapse or bearing group failure due to seismic activity.
- Collapse of the entire structure or part of it due to a hydrological event.

The risk assessment associated with selecting a maintenance strategy can be performed by multiplying, for each limit state, the probability of collapse (representing hazard and vulnerability) by the sum of the resulting possible damages (representing risk exposure). Additionally, consider the costs of planned maintenance as certain damages with a probability of 1. The maintenance strategy to be adopted should minimize societal risk, where the risk for each bridge is expressed as the total cost using the following formula, summing the contributions of individual limit states:

$$C_{tot} = \sum C_i + \sum D_j P_j \tag{6}$$

where

- C_i indicates the total cost of the intervention on the examined bridge,
- D_j indicates the total damage caused by exceeding the jth limit state, and
- P_j indicates the probability of exceeding the jth limit state, calculated for the considered time period, as a function of material degradation and planned maintenance actions.

A maintenance strategy involving a series of heavy interventions will incur high costs, thus maximizing the first term of the formula, but will also reduce the probability of collapse, minimizing the second term. Conversely, a strategy with less invasive interventions will eliminate costs but maximize the probability of collapse.

Total collapse probabilities can be approximated as the sum of annual collapse probabilities $p_j(t_i)$, as in the following formula. The subscript j indicates the limit state considered. Note that annual probabilities generally vary over time, especially due to material degradation and any restoration interventions performed:

$$P_j = 1 - \prod_i^{t_{ref}} \left(1 - p_j(t_i)\right) \cong \sum_i^{t_{ref}} p_j(t_i) \tag{7}$$

Unfortunately, the proposed method remains only a general framework that is not immediately applicable because practical methodologies to reliably estimate the effects of interventions on structural durability are not available in the literature. In other words, we are still unable to predict how collapse probabilities of a structure evolve over time, not only due to the structure's deterioration but also due to the chosen maintenance strategy.

Case Study

To demonstrate the possibility of using this method, we considered a very simple case study, a hypothetical highway bridge with one span of 30-meter length that overpasses just a country road and has a height of 6 meters. The bridge has three lanes and is 15 meters wide. As with every highway bridge, the class considered is CC3 according to the definition provided in the Eurocode: "High consequence for loss of human life, or economic, social, or environmental consequences very great." The ADT consists of 9000 cars and 3000 trucks, with a medium speed of 110 km/h. This kind of structure usually does not have seismic issues nor hydrogeological problems, so the only limit state considered is the failure of the deck caused by the cracking of a beam.

We assume we know all the characteristics of the test bridge. As with the vast majority in Italy, this bridge is made of reinforced concrete and was built between 1960 and 1970, so the main structural parts are 60 years old. We also suppose that the steel bars adopted in the original project were barely enough to meet the standards of the time and that the permanent loads are more or less equivalent to the traffic loads. With these assumptions, the starting safety factor of the bridge (without any deterioration) is $SF = R/E = 0.86$, using for R the resistance of the control section and E the actions requested by actual standards (Eurocodes). It is possible to estimate the collapse probability in the next 50 years using the following simple formula: $\beta = \beta_{EC} + ln(R_d/E_d)/\sigma = 3.8 + ln(0.86)/0.14 = 2.73$.[11] According to the FIB Bulletin, this value meets the criterion for safeguarding human life ($\beta_{0t,human\ safety}$), but it is below the threshold ($\beta = 2.8$) under which it is considered more cost-effective to carry out an improvement intervention. For the same reason, the Italian standard classifies these bridges as *Transitabili* (just passable) and requires managers to carry out adjustments to the Eurocodes within 5 years.[9]

The other data entered in the calculation are as follows:

- due to the infrastructure disruption, the travel time for users increases from 4 minutes to 20 minutes;
- the state of traffic on the chosen secondary road is congested;
- the length of the road segment where traffic will be congested is 15 km;

- the importance of the road under the bridge is minimal, so we can neglect the environmental effects.

The total duration of the restoration works will be 284 days. Given the limited height of the structure, the probability of death, in the case of vehicles stopped in a queue, is low (1.2%). For this reason, the possibility that the failure occurs when traffic is flowing has been considered. The theoretical number of victims would then be 0.5. (According to the FIB Bulletin, the casualties would be 2.7.)

In Table 5 the main results are shown.

Table 5. Main failure costs in €

Type of damage	Cost
Cost of replacing the collapsed structural part	1’620’000
Cost of missing toll payments	6’820’000
Cost of delays	24’680’000
Cost of congestion	32’910’000
Social consequences	1’710’000
Psychological effects (loss of reputation)	1’000’000
Total cost	68’740’000

For t_{ref}, in this study, we will use 30 years, as indicated in Chapter 3.6 from the aforementioned Italian guidelines, but it would also be possible to make a different choice.

We assume that the progress of degradation, due to carbonation and chloride attack, begins today and continues over the next 30 years. In this hypothetical analysis, without interventions, the final safety factor will be 0.62, as shown in the following graph in Fig. 6.

To demonstrate the effectiveness of the mathematical method presented in this paper, four different hypothetical intervention strategies have been considered, described in Table 6 and in the following graph in Fig. 7.

In this example, repairing and reinforcing the beams is the best strategy, as the costs of complete rebuilding are increased by road disruption during the works, while the repair work is supposed to be conducted while always operating from under the bridge.

It is important to highlight that some parameters are extremely important. For example, let us see what happens when the height of the bridge is changed from 6 to 40 meters. Under these conditions, the collapse of the bridge becomes fatal in most cases. The number of victims becomes 6.7, and the overall damages increase exponentially. The cost related to the psychological effects amounts to one billion euros. Table 7 shows the results for the 40-meter-high bridge.

Table 6. Strategy costs in €

Strategy	Intervention cost	Total cost
1. No interventions	0	3’870’000
2. Remaking of concrete surfaces every 10 years	3 × 450’000	2’530’000
3. Repairing and reinforcing beams after 10 years	1’130’000	1’290’000
4. Complete rebuilding of the deck	1’620’000	2’670’000

Remarks

The method proposed in this article allows for selecting the best maintenance strategy for each bridge, considering multiple factors, particularly the geographical and economic context, which strongly influence the structure’s hazard, vulnerability, and risk exposure.

It is important to note that the proposed procedure cannot be independently adopted by a single management company, whether public or private, but should be used to integrate current regulations. The reason is that some of the listed costs would only be borne by the company managing the bridge (e.g., lost tolls and reputation loss), while other costs are external and would be paid by society (e.g., traffic congestion and delay costs). Any company, whether public or private, will tend to focus only on its costs and ignore damages it does not directly bear, whereas societal interest would require imposing a management method that considers all cost components.

Currently, the proposed procedure calculates costs very well in the case of “extreme” maintenance strategies, such as

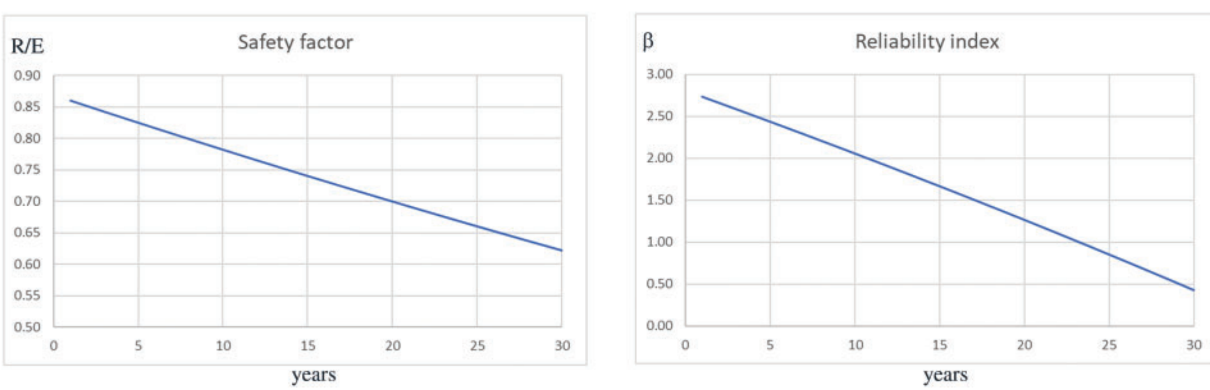

Figure 6. Hypothetical decrease of the resistance over the years

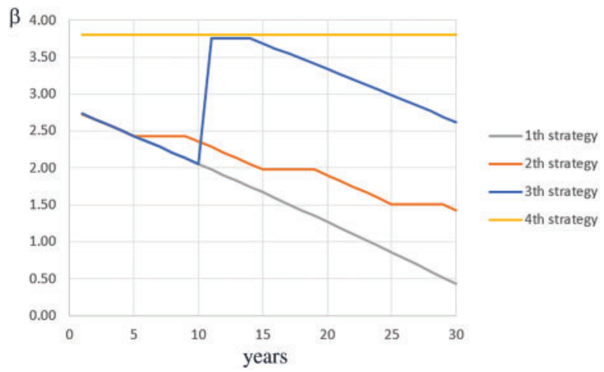

Figure 7. Reliability index for every strategy

Table 7. Strategy costs in € (40-meter-high bridge)

Strategy	Intervention cost	Total cost
1. No interventions	0	62’740’000
2. Remaking of concrete surfaces every 10 years	3 × 450’000	20’510’000
3. Repairing and reinforcing beams after 10 years	1’130’000	3’760’000
4. Complete rebuilding of the deck	1’620’000	2’710’000

demolition and reconstruction or doing nothing. However, it is not yet sufficiently reliable when considering programs consisting of more or less invasive repair or improvement interventions, as there are no studies in the literature that correctly evaluate the effects of such interventions on structural durability. This area of research still has significant progress to make and could be a future development allowing for the concrete practical application of the methodology proposed here.

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