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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2022; 32 (4): 0282-0292
DOI: 10.2478/ceer-2022-0058
Original Research Article

ASSET MANAGEMENT. THE POINT OF VIEW OF THE USERS' COSTS

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A b s t r a c t

Bridges by their nature are structures that absorb a large amount of resources. For the promoter, usually public entities, the biggest share of the investment is made when the new structures are raised. However, as will be shown in the study presented in this paper, user costs are often much higher than direct costs and may even be higher by an order of magnitude. In addition to the costs resulting from maintenance/rehabilitation interventions, there are also environmental damages due to the pollution caused by the vehicles. The presented methodology will be applied to a case study where the global costs are highlighted and determined considering the scenario in which there are no disturbances in the circulation of vehicles and when they occur due to maintenance and rehabilitation works.

Keywords: sustainability, bridges, life cycle costs, user costs, greenhouse gas emissions

1. INTRODUCTION

This paper explores the potential to improve transport costs efficiency through efforts made in the design and planning stage. In literature it can be found that aging of bridges is responsible for an increase of users' costs. Choosing the best materials is mandatory because reducing the amount of rehabilitation works leads

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to a long-term reduction of costs, mainly due to the reduction of the user costs. Alongside with the reduction of the users' costs a reduction of the total greenhouse gas emission also occurs. This phenomenon is related with the reduction of the total travel time by avoiding the inevitable queuing when construction works are executed.

The quality of life of modern societies relies on the ability of the road network to allow the transport of people and goods. Bridges, and infrastructures facilities, assure the connectivity between communities. Bridge damage can cause direct monetary losses due to the necessary repair interventions to be carried out to restore the bridge loading capacity and transit safety, as well as indirect losses due to network downtime and traffic delay [1].

Rebar corrosion is the most fundamental factor accountable for the performance deterioration structures during the lifetime of a reinforced concrete structure [2]. It's the main cause of degradation of reinforced concrete structures, affecting the load carrying capacity of the structure as well leading to a significant financial investment for their rehabilitation [3]. Along with the corrosion, the spalling of the concrete cover occurs, potentiating the ingress of aggressive agents from the external environment and accelerating the degradation process [4].

Ageing and increased structural performance demand may significantly affect the vulnerability of constructed facilities [5]. Environmental stressors are the primary factors that drive the ageing process. The effect of structural ageing is perhaps most widely apparent in bridge deterioration, exacerbated by increase in traffic over time [6].

The intervention in the early phases of the design stage it's the way to maximise the benefits because it is very difficult to turn an inefficient solution into an efficient project [7].

Sustainable development is development that meets the needs of the present without compromising those of future generations [8]. To make society more sustainable, it is essential to conserve and use what currently exists rather than constantly investing in new structures. Instead of demolishing / replacing old bridges and infrastructures it is necessary to focus on their preservation and improvement.

2. METHODOLOGY

In this research different models of deterioration of reinforced concrete structures are analysed, giving special emphasis to the problems resulting from the action of carbonation and chlorides in reinforced concrete bridge decks. Based on these two main deterioration mechanisms, a probabilistic deterioration model was adopted that allowed the modelling of the behaviour of reinforced concrete structures, allowing to quantify the time required for the initiation of corrosion as well as the time required for its propagation. This methodology was applied to different alternative materials: A1 – epoxy coated reinforcement; A2 – galvanized steel reinforcement; A3 – solid stainless-steel reinforcement; A4 – coated stain-less steel reinforcement; A5 – use of corrosion inhibitors; and A6 – protection/cathodic prevention.

According to the literature it was defined, for the different adopted construction materials, and based on the adopted deterioration model, the lifetime of each alternative. Then the correspondent life cycle costs were calculated.

The proposed model, applicable to new and existing structures, is based on the methodology to estimate the performance of concrete that allows to fulfil the design life of reinforced, and prestressed, concrete structures under the XC and XS environmental exposures provided in the specification LNEC E-465 [9]. This specification, with a probabilistic approach, bases its groundwork on the model developed in [10]. In the adopted model, the periods of time necessary for the development of the initiation phase and the propagation phase due to the action of carbonation and chlorides are estimated.

The initiation time for carbonation is presented in equation (2.1).

$$t_i^C = \left(\frac{\frac{1.4}{X^2} \cdot 10^3 \cdot k_0 \cdot k_1 \cdot k_2 \cdot {t_0}^{2n}}{Rc_{65}} \right)^{\frac{1}{2n-1}} \tag{2.1}$$

Where,

t_i^C – initiation time due to carbonation; X – depth of carbonation front; k_0 – test conditions parameter; k_1 – relative humidity factor; k_2 – concrete curing factor; t_0 – reference period; Rc_{65} – carbonation resistance; n – influence of wetting/drying over time factor.

The initiation time for chlorides is presented in equation (2.2).

$$t_i^{Cl} = 27^{\frac{1}{n-1}} \cdot \left(\frac{2^{3+2n} \cdot 5^{-3-n} \cdot 7^n \cdot 73^{1-n} \cdot D_0 \cdot K_{D,c} \cdot K_{D,RH} \cdot K_{D,T} \cdot \xi^2}{X^2} \right)^{\frac{1}{n-1}} \tag{2.2}$$

Where,

t_i^{Cl} – initiation time due to chlorides; D_0 – initial diffusion coefficient; $K_{D,c}$ – concrete curing factor; $K_{D,RH}$ – exposition class factor; $K_{D,T}$ – concrete temperature factor; n – type of cement factor; ξ – error function inverse.

The maintenance of bridges requires carrying out works on the structure that often produce significant disturbances on the free traffic flow depending on the type of works carried out as well as their scope.

These construction works generate costs that result not only from the construction itself, the so-called direct costs, but also from costs for the users of the structure when carrying out these same works. Often, the execution of works leads to the traffic speed being affected, thus causing disturbances in the free flow of traffic. Users' costs may arise from the increase in the time spent crossing the works, due, for example, to the imposition of a lower traffic speed, the increase in the time spent in queues, the increase in vehicle consumption, the increase in the distance to travel when traffic is diverted, as well as the increase in the accident rate resulting from the introduction of construction works. For each material alternative, considering the correspondent lifetime of each solution, users' costs were calculated.

The quantification of costs was carried out by accounting for the expenses resulting from the following stages:

- normal use – user costs associated with the use of the road, during periods in which there isn't construction works in progress;
- crossing the work area – costs result from the investment that users have to make to cross the road when works, maintenance or rehabilitation, are taking place, which create a disturbance to the normal flow of traffic; these costs, among other parameters, depend directly on the intensity of the works, duration, and type of restriction caused, i.e.: number of closed lanes, length of the work area, traffic using the lane.

Users' costs were computed considering the costs provided in equation (2.3).

$$C = VOC + TC + AC + ToC \tag{2.3}$$

where: VOC – vehicle operating costs; TC – time costs; AC – accidents costs; ToC – toll costs (when applicable).

Vehicle operating costs – include all expenses that users incur to travel a certain distance. According to [11], vehicle operating costs can essentially be divided into the following items: fuel consumption; repairs and maintenance; tire wear; engine oil and vehicle depreciation;

Additional time consumption costs – these costs are related to the additional time spent by users due to restrictions resulting from the construction works. Usually, the restrictions result from the reduction of speed in the area of the works, the reduction of the number of available lanes or circulation in alternative roads;

Accident costs – these costs are related to accidents that occur on the roads. The existence of works causes disturbances to the free flow of traffic through the reduction of crossing speed, by forcing manoeuvres to avoid obstacles or by using roads with higher accident rates. These costs result from the attribution of a monetary value for each fatal victim, serious injury, minor injury and for each accident with material damage only; those costs are calculated considering the number of accidents in the roads. The number of accidents in the Portuguese highways, according to [12], was quantified using the formulae represented in equation (2.4).

$$AC = 9.42 \cdot 10^{-4} \cdot AADT^{0,9} \cdot L^{0.931} \tag{2.4}$$

Where: AC – number of accidents with bodily harm on the section considered, for a period of 6 years; $AADT$ – annual average daily traffic [veh/day]; L – length of the section under study [km].

According to the available traffic data of serious injuries, light injuries and material damage only, the total accident costs were computed.

Toll costs – these costs occur every time motorways are used. In the research it was considered 4 classes of vehicles. Those are represented in figure 1.

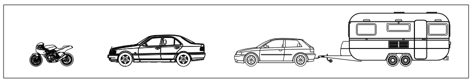
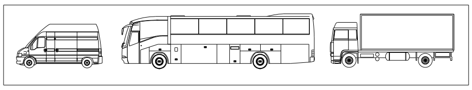
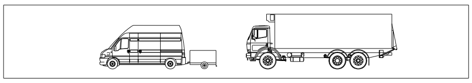
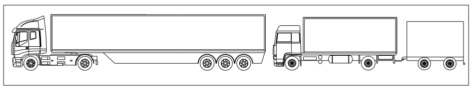
Class	Vertical height front axe	N.º of axes	Vehicle type
1	< 1.10	≥ 2	
2	≥ 1.10	2	
3	≥ 1.10	3	
4	≥ 1.10	≥ 4	

Fig. 1. Vehicle classes

Additional to users' costs, the environmental impact was also quantified. The disturbance of the normal traffic flow generates greenhouse gases due to additional carbon emissions. Nowadays, and in the near term, motor vehicles emerged as the greatest contributor to atmospheric warming. Cars, buses, and trucks release pollutants and greenhouse gases that promote warming [13]. The gasoline consumption of light traffic is 0.098 L/km [14], the diesel consumption of heavy traffic is 0.362 L/km [15]. According to [16] the carbon emission of gasoline is 2.35 kg/L, and the carbon emission of diesel is 2.69 kg/L.

3. CASE STUDY

For the application of the methodology, it was chosen a bridge integrated in the Highway A25, explored by ASCENDI – Autoestradas das Beiras Litoral e Alta, S.A.. The construction of this bridge, over the brook of Cortiço, was carried out between May 2004 and July 2005. The bridge under study is located between the cities of Guarda and Viseu, more specifically in the section Celorico da Beira (pk. 137+800) / Fornos de Algodres (pk. 125+842) which has an approximate length of 12.1 km. This prestressed concrete bridge, with two lanes in each direction, has

a total length of 122.00 m, and has five spans (22.00 m + 26.00 m + 26.00 m + 26.00 m + 22.00 m).
The costs quantification of this investigation was carried out considering a base scenario considering an inflation rate of 2%; an opportunity cost of capital of 5%; 1% traffic rate growth; and 30 mm of concrete cover. For the time costs two approaches were studied: the wage method and the GDP method. For the accident costs the simulation was performed considering the human capital costs and the global cost method. The considered annual accident rate was -1%. The intervention day considered was 100 days. The maximum number of queued vehicles admitted was 500. It was also modelled the possibility of taking a detour by the national route EN16, with a total length of 13.3 km, or performing a traffic deviation to the other direction lane.

3.1. TRAFFIC CHARACTERIZATION

The bridge over the Cortiço brook belongs to the A25 highway. This highway is one of the most import import/export axes of Portugal. Analysing the traffic flow data, it is found that the share of heavy vehicles using the highway is about 25% of the overall traffic.

In Figure 2 it's plotted the average daily traffic (ADT) for the highway section Celorico da Beira/Fornos de Algodres for the period 2016-2022. It can be observed that annually a peak occurs in August. This can be explained by the huge number of Portuguese emigrants that returns in that month to Portugal for holidays. It is also plotted the ADT for the 2020 year. It can be observed that the COVID restrictions had a large impact in the traffic flow.

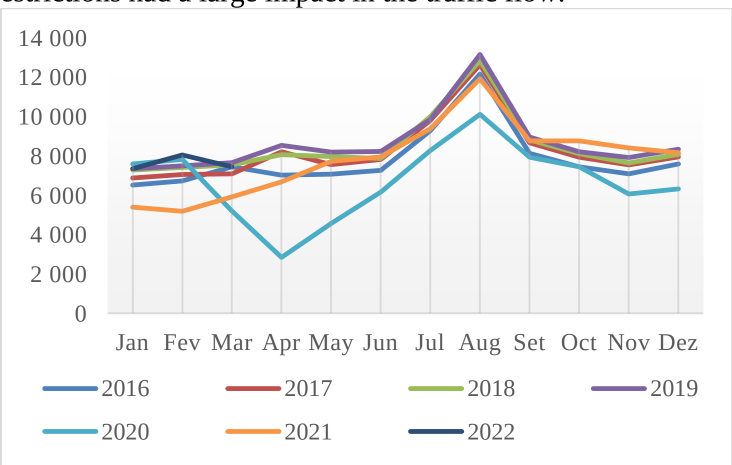


Fig. 2. Average daily traffic for the section Celorico da Beira/Fornos de Algodres [17]

3.2. INITIATION TIME

The determination of the initiation time was computed for the common steel solution considering the materials properties and the environmental envelope. The values are plotted in table 1. The lifetime for all the other alternatives were calculated according to the literature values.

Table 1. Lifetime

Option		Lifetime [years]
A0	Common steel	30
A1	Epoxy coated reinforcement	A0 + 20
A2	Galvanized steel reinforcement	A0 + 5
A3	Solid stainless-steel reinforcement	A0 + 80
A4	Coated stainless steel reinforcement	A0 + 50
A5	Corrosion inhibitors	A0 + 20
A6	Cathodic protection/prevention	A0 + 35

Considering the lifetime of each alternative, and taking in consideration that the bridge was erected in 2005, the schedule of the interventions was defined. Those values are presented in table 2.

Table 2. Intervention scheduling

Alternative	Construction year	Service life	1st intervention	2nd intervention	3rd intervention
A0	2005	30	2035	2065	2095
A1		50	2055	2105	-
A2		35	2040	2075	-
A3		110	-	-	-
A4		80	2085	-	-
A5		50	2055	2105	-
A6		65	2070	-	-

3.3. USER COSTS

Considering the lifetime of each alternative, the correspondent time of intervention, the user costs were computed. User costs, consider the costs resulting from the disturbance in both directions, are presented in table 3. In this table, it is also presented the classification of each of the options relatively to the lowest cost alternative. The costs are quantified considering the free traffic flow, the disturbed traffic flow and the idling costs.

Analysing the cost distribution represented in table 3, it can be observed that the alternative A3, the stainless-steel alternative, doesn't generate any cost. In opposition the alternative A0, common steel, generates the biggest amount of user costs.

Table 3. Net present user costs

Alternative	A0	A1	A2	A3	A4	A5	A6
Total	18 990 k€	10 425 k€	15 073 k€	0 k€	5 215 k€	10 425 k€	6 072 k€
Rank	7	4	6	1	2	4	3

3.4. ENVIRONMENTAL IMPACT

Transportation systems generate plenty of carbon emissions from two primary sources: vehicle exhausts and construction materials. Vehicles discharge greenhouse gasses directly into the atmosphere. Construction materials commonly used for transportation infrastructure, such as steel and concrete, produce greenhouse gases production processes. Considering the number of vehicles [18], the type of vehicle and the type of fuel, the total emissions for each alternative was computed. In table 4 are presented the total amount of emissions for each construction alternative. Once more, because the alternative A3 has a lifetime higher than the studied period, 100 years, it can be observed that it is an emission free alternative.

Table 4. Total emissions

Alternative	A0	A1	A2	A3	A4	A5	A6
Period between interventions	30	50	35	110	80	50	65
Number of interventions	3	2	2	0	1	2	100
Emissions (ton)	223	173	126	0	53	173	76
Rank	6	5	4	1	2	5	3

4. DISCUSSION

From the computed results it’s clear that the user costs, and the total emission that result from the existence of construction works, increases with the total number of interventions. The common steel alternative (A0) due to is lower lifetime it’s the solution that causes the higher number of interventions (3). It can be observed that the optimal solution is the one resulting from the application of stainless-steel reinforcement. This solution is the only one that does not origin cost users, as these materials usually have a useful life longer than the considered period of analysis. On the other hand, the conventional solution, using standard steel reinforcement, is the one with the worst economic performance, with a cost increase of more than 1 500%.

5. CONCLUSIONS

The main conclusion drawn from the joint analysis of user costs and direct costs is that investment options should not be made considering only direct costs.

Direct costs vary fundamentally with the materials used. It was found that the materials used are the main cost-generating factor, because the shorter the life the greater the number of interventions that the bridge will have to undergo, leading very important costs to users. It has been proven that small changes to the value of the covering, which are associated with reduced costs, can lead to significant savings, as this increases the protection of the reinforcement and, therefore, the useful life of the structure.

User costs are a significant part of the total costs. Analysing the traffic data for this route, user costs for the summer months (July, August, and September) can suffer a strong increase, since for this route seasonal traffic is very significant. Therefore, it is imperative that the planning of the works tries, whenever possible, not to affect the months with the highest volume of traffic. It has been proven that the effective control of intervention time produces savings that can be directly proportional to the time taken to carry out the works.

The total emissions related to the total amount of vehicles that crosses the work zone. The existence of work zones can lead to detour traffic from alternative and longer routes. On multi-lane highways, usually traffic shifts can replace a detour, as detours often congest turn lanes. The reduction of traffic speed, the queue formation and traffic idle causes the increase of carbon emission.

This research clearly indicates that the reduction of the users' costs is directly related to the total amount of interventions.

ADDITIONAL INFORMATION

This work was supported by the Portuguese Foundation for Science and Technology (FCT) under Projects UIDB/04131/2020 and UIDP/04131/2020.

REFERENCES

1. Capacci, L, Biondini, F, and Frangopol, DM 2022. Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks: Review. *Resilient Cities and Structures* **1(2)**, 23-41.
2. Andrade, C, Garcés, P Baeza, FJ, Galao, Ó, and Zornoza, E 2015. Electronic and Electrolytic Conduction of Cement Pastes with Additions of Carbonaceous Materials. In: Andrade, C., Gulikers, J., Polder, R. (eds) Durability of Reinforced Concrete from Composition to Protection. Springer, Cham. Springer: Cham (ZG), Switzerland.
3. Balestra, CET, Nakano, AY, Savaris, G and Medeiros-Júnior, RA 2019. Reinforcement corrosion risk of marine concrete structures evaluated through electrical resistivity: Proposal of parameters based on field structures. *Ocean Engineering* **187**, Article 106167.

4. Melchers, RE and Chaves, IA 2018. Service Life Estimation of Concrete Infrastructures. Eco-Efficient Repair and Rehabilitation of Concrete Infrastructure, 15-41.
5. Tsompanakis, Y 2010. Vulnerability assessment of structures and infrastructures. *Structure and Infrastructure Engineering* **6 (1–2)**, Special Issue, 1-301.
6. Ellingwood, BR 2005. Risk-informed condition assessment of civil infrastructure: State of practice and research issues. *Structure and Infrastructure Engineering* **1(1)**, 7-18.
7. Welde, M and Volden, GH 2022. Improving value for money through better front-end management: An attempt to reduce costs and increase user benefits in the planning of a motorway project. *Case Studies on Transport Policy*, **10 (3)**, 1611-1619.
8. WCED 1987. Our common future, World Commission on Environment and Development, Oxford University Press, New York, U.S.A.
9. LNEC E-465 2007. [Concretes – Methodology to estimate the performance properties of concrete that allow satisfying the design life of reinforced or pre-stressed concrete structures under XC and XS environmental exposures]. Laboratório Nacional de Engenharia Civil, Lisbon, Portugal.
10. Tuutti, K 1982. Corrosion of steel in concrete, Report n.º CBI Research FO 4:82, Swedish Cement and Concrete Research Institute, Stockholm, Sweden.
11. AUSTROADS, 2011. Update of vehicle/road relationships underpinning road user costs and externality costs – Literature review. Technical Report AP-T189-11, Austroads, Sydney, Australia.
12. Lopes, SA and Cardoso, JL 2007. Accident prediction models for Portuguese motorways. Laboratório Nacional de Engenharia Civil, Lisbon, Portugal.
13. Unger, N, Bond, TC, Wang, JS, Koch, DM, Menon, S, Shindell, DT and Bauer, S 2010. Attribution of climate forcing to economic sectors. *Proceedings of the National Academy of Sciences of the United States of America* **107(8)**, 3382-3387.
14. FHWA, 2016. Highway statistics. Federal Highway Administration, Washington, D.C., U.S.A.
15. Schoettle, B, Sivak, M and Tunnell, M 2016. A Survey of Fuel Economy and Fuel Usage by Heavy-Duty Truck Fleets. Arlington, Virginia: The University of Michigan. U.S.A.
16. U.S. Environmental Protection Agency 2018. Greenhouse Gas Emissions from a Typical Passenger Vehicle. Ann Arbor.
17. IMT 2022. [National Highway traffic report. 1st semester 2022]. Instituto da Mobilidade e dos Transportes, I.P. Lisbon, Portugal.
18. PORDATA 2022. [Motorized road vehicles in circulation: total and by type of vehicle]. Retrieved September 7, 2022 from

https://www.pordata.pt/portugal/veiculos+rodoviarios+motorizados+em+circulacao+total+e+por+tipo+de+veiculos-3100

Editor received the manuscript: 08.10.2022