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THE ECONOMICAL AND ENVIRONMENTAL IMPACT OF BRIDGE MANAGEMENT

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ABSTRACT

Sustainable mobility is a major global challenge that affects the future of humanity and the planet. Economic growth depends on high levels of motorization, which produce greenhouse gases and other pollutants from vehicle emissions. These emissions harm the environment and human health. To address this challenge, we need to optimize traffic flow on busy roads and work zones, and consider the environmental and economic impacts of different bridge designs. In this paper, we present a methodology to quantify and optimize the total costs and vehicle emissions for various concrete bridge solutions. We apply this methodology to a real bridge on the A25 highway in Portugal, which connects Aveiro to Vilar Formoso crossing Portugal from the Spanish border to the sea. It compares different construction materials in terms of their deterioration rate, lifetime, and environmental and economic effects, to support decision making.

Keywords: Bridge management; deterioration; life cycle costing; greenhouse gases.

1. Introduction

This paper seeks to contribute to support the decision makers to choose the best material solutions concerning the budget allocation and the environmental behavior. Bridges are fundamental elements of the communication infrastructure. The impact in the economy of the communication infrastructures is significative for every country. One of the biggest concerns of engineering is maintaining the civil structures in a safe condition. The allocation of financial resources to these structures, not only to build new ones, but also to repair and maintain, in a proper condition, the existent stock, is a major concern. The prosperity and economic growth rely on the reliability and well-functioning of community infrastructures [1]. 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 [2].

More than 90% of inland passenger transport, and more than 75% of inland freight transport, in the European Community is carried out using road infrastructure. Proper management of the road infrastructure is the essential for good quality transportation. Being a critical component of the road infrastructure, bridges require special treatment. Because of economic growth and globalization, management and maintenance of bridges is an important concern in countries that depend heavily on road transport infrastructure to accommodate increasing volumes of commercial transportation [3].

Worldwide the management of the bridge stock is performed using Bridge Management Systems. A Bridge Management System, traditional structure, includes four standard modules [4]. The Inventory Module collects data regarding the bridge stock; the Inspection Module collects inspection data to classify the condition state; the Maintenance, Repair and Rehabilitation Module monitors short-term and long-term plans for intervention; finally, the Optimization Module integrates the previous modules for budget-expenditure forecasts.

Air pollution is the single greatest environmental health hazard in Europe, responsible for over 300,000 premature deaths in the EU-27 in 2019. Transport is a significant contributor toward the emission of air pollutants which reduce life expectancy through increased likelihood of morbidity-associated diseases[5]. Passenger cars and vans ('light commercial vehicles') are respectively responsible for around 12% and 2.5% of total EU emissions of carbon dioxide, which is the main greenhouse gas [6].

In this paper it will be presented a method, sustained in a deterioration module that allows the quantification of the total costs, direct and user costs, and that allows the quantification of the vehicle emissions for different materials solutions of reinforced and prestressed concrete roadway bridges.

2. Methodology

Rebar corrosion is the most fundamental factor accountable for the performance deterioration structures during the lifetime of a reinforced concrete structure [7]. In this research, utilizing a deterioration model, different solutions are analyzed, giving special importance to the resulting problems from the effect of carbonation and chlorides in reinforced concrete decks. The lifetime of the different material solutions is calculated, and direct and user costs are quantified. The user costs are computed considering the vehicle operating costs, the time costs, the accident costs, and the toll costs (when applicable). The operating costs, for the different classes of vehicles, are quantified considering the costs of fuel, tires, oil and engine maintenance and depreciation. The time costs are computed considering the number of passenger and the trip purpose. Accident costs are quantified considering the different type of roads and available data reports of vehicle accidents. Finally, toll costs are added when the bridge is located in a highway with tolls. The global emissions are quantified considering the type of vehicle and the travelled distance. All the costs and emissions are calculated considering the undisturbed scenario and the scenario with the work zones. This methodology is then applied to an existent bridge located in the Portuguese highway (A25).

2.1. Deterioration model

Carbon dioxide and chloride ions attack are known to significantly affect the durability of concrete structures. Furthermore, exposure environment such as the temperature and relative humidity also affect the penetration of chloride and sulfate in the concrete structures. As a result, the diffusivity of carbon dioxide and chloride have a significant impact on corrosion in concrete structures [8,9]. The adopted deterioration model is defined in [10]. This probabilistic model, applicable to reinforced, and prestressed, concrete structures under the XC and XS environmental exposures, considers two stages: initiation stage and propagation stage [11].

2.2. Materials

Considering the reinforced concrete structure as the basic scenario, some other alternative materials was studied. 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. The initiation time was calculated considering the basic scenario and according to the literature [13,14,15,16,17,18] it was estimated the lifetime for the other alternative materials. The predicted lifetime is plotted in Figure 1.

Figure 1: Different material alternatives expected lifetime

From Figure 1 it can be observed that the basic scenario is the one with the poorer behavior, 30 years lifetime. In the opposite side it’s the utilization of solid stainless-steel reinforcement (A3). The lifetime of the stainless-steel reach up to 110 years.

2.4. User costs

For all the alternatives, and considering the situation off the free flow traffic, and the traffic through the work zones, the user costs were calculated considering equation (1).

$$C = VOC + TC + AC + ToC \quad (1)$$

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

Vehicle operating costs can be defined as those associated with the purchase, use and maintenance of vehicles. Those costs are quite consensual in the literature. According to [19], the operating vehicle cost of can be defined through the quantification of the following items: tires, fuel, lubricants, maintenance parts, maintenance labor, interest (when applicable) and vehicle depreciation.

Costs due to additional time consumption are related to the additional time spent by users due to restrictions resulting from the construction/repair works. Usually, the restrictions result from the reduction of speed in the work zone, the reduction of the number of available lanes or the route in alternative roads. Those costs are quantified considering the number of passengers on the vehicle and the purpose of the trip. Considering the level service, the travel velocity was computed as well as the time spent in queues with the correspondent idling costs. Two methods of time cost quantification were considered: the wage method and the Gross Domestic Product method.

The number of accidents on the European Union roads is decreasing. In Figure 2 it can be observed that the number of fatal victims has also the same evolution. In the year 2020 it was observed a huge reduction of the fatalities number because of the circulation restrictions due to COVID 19 pandemic.

Figure 2: Evolution of the number of persons killed in road accidents for the 2013-2022 period.

The costs associated to road accidents are very significative. In Portugal those costs, in 2021, represented 3% of the Gross Domestic Product [21]. According to [22], The number of accidents, with victims, in the Portuguese highways, can be quantified considering the average daily traffic and the length of the section under study. The presented formulae are for highway accident estimation. Since the presented formulation only quantifies accidents in Portuguese highways, supported by the Portuguese accidents database, correction factors were introduced to consider the type of road and its location. Similarly, to the time costs it was used two methods: human capital method and the global cost method.

The costs related with tolls are quantified depending on the travelled length and the type of vehicle.

2.5. Vehicle 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 [23]. According to [24], the gasoline consumption of light traffic is 0.098 L/km, the diesel consumption of heavy traffic is 0.362 L/km. According to[25] and [26] the carbon emission of gasoline is 2.35 kg/L, and the carbon emission of diesel is 2.69 kg/L. We are witnessing an alteration of paradigm with a new way of thinking sustainability. The modal transport is rapidly changing and the greenhouse effect, and the climatic changes, due to transportation is an omnipresent concern.

According to [27] increasing the share of sustainable transport modes, such as walking and cycling, is one of the building blocks of sustainable mobility transformation. But fundamental changes are needed in the society and urban structure to support the integration of walking and cycling into everyday routines. Simulation is a valuable prediction tool to evaluate the impact of climate change interventions prior to disruptive implementations that may yield unintended and unwanted consequences. Advances in agent-based simulation allow us to estimate the dynamic emissions produced by vehicles at a fine resolution, with each vehicle modelled individually. The scalability of these models allows decision-makers to evaluate large-scale scenarios [28].

The path-dependencies of the individual automobility regime are evident: social, cultural, institutional, and infrastructural factors that have historically developed to make individual automobility the norm and normal. This requires a governance approach that challenges the incumbent logic in society, policy, and markets as it would imply a radical reduction in cars, affecting government and business income and requiring large scale behavioural change [29].

3. Case study

This methodology was applied to a real bridge. The chosen bridge is integrated in the A25 Highway, managed by ASCENDI – Autoestradas das Beiras Litoral e Alta, S.A.. The construction of this bridge was carried out between May 2004 and July 2005. The A25 motorway, also known as the E80, is one of the main roads in the north of the country, as it crosses the country, connecting the border of Vilar Formoso to the Atlantic Ocean. This bridge, plotted in Figure 3, has a total length of 122.00 m and consists of five spans (22.00 m + 26.00 m + 26.00 m + 26.00 m + 22.00 m).

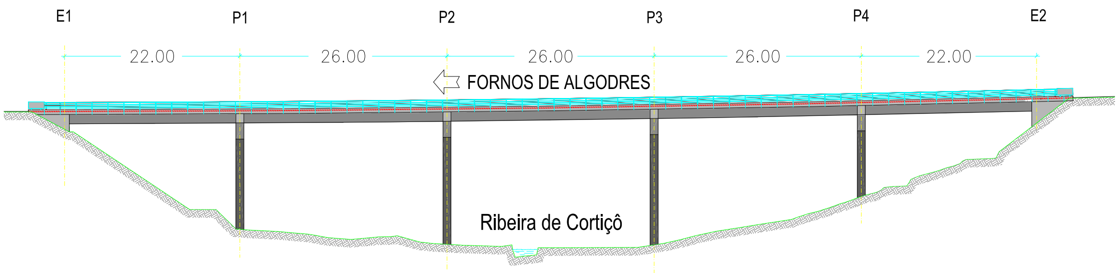

Figure 3: Cortiçô bridge elevation [30].

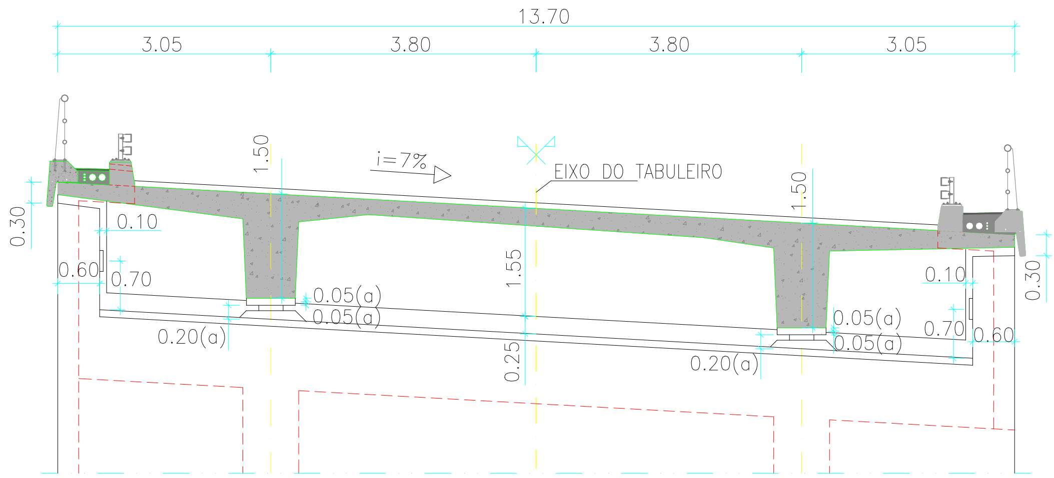

Figure 4: Cortiçô bridge cross section [30].

Considering the applied materials, and the lifetime of each material alternative, the intervention schedule was defined. Those results are plotted in Table 1.

Table 1: Intervention dates.

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	-	-

Its evident that the basic scenario, alternative A0 – common steel is the solution that haves a shorter lifetime, leading to 3 interventions in the studied period (100 years). On the other end is the alternative A3 – utilization of stainless steel, who haves a lifespan bigger than 100 years.

This highway is one the major import export road infrastructures of Portugal. Analyzing the traffic data, it´s clear because the freight transport represents more than 20% of the total number of vehicles. For the quantification of the emissions and the user costs four classes of vehicle were defined: passenger cars; commercial cars; buses; and trucks. The traffic data since 2016 is represented in Figure 5. It can be observed that the average daily traffic had a big reduction in the year of 2020 due to de COVID 19 pandemic. It can be also observed that in the summer months, especially in August, it occurs a peak. The justification for this variation is the large number of Portuguese emigrants that returns to the country in this period.

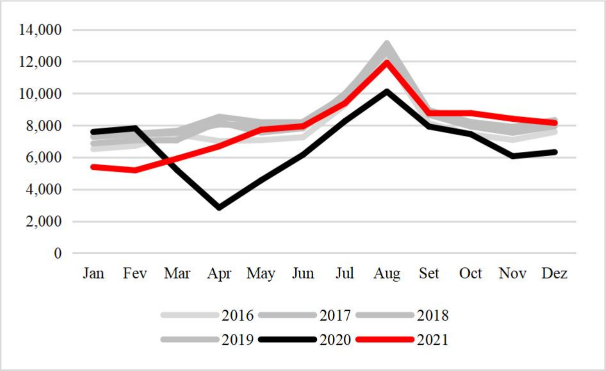

Figure 5: Average daily traffic for the section Celorico da Beira/Fornos de Algodres [31].

Considering the lifetime of each alternative, the correspondent schedule of intervention, the user costs were computed. User costs, consider the costs resulting from the disturbance in both directions, are presented in Figure 6.

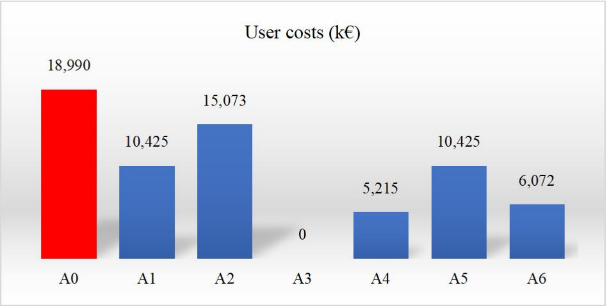

Figure 6: User costs

Examining Figure 6, alternative A0 has higher costs because it imposes a bigger number of interventions (3 in total). It is also noted that, the further the intervention date is from the reference year date, the lower its net present value will be. This results from the fact that an opportunity cost of capital of 5% has been defined. Although costs also increase, either due to the rate of inflation (2%) or due to the rate of growth in traffic volume (1%).

The best alternative, considering only the users' costs, is the one resulting from the use of stainless-steel reinforcement (alternative A3). This solution, as mentioned, has a lifetime of 110 years that's longer than the analysis period, which in this case was 100 years.

Relatively to the total emissions the behavior is similar because the bigger is the number of interventions greater will be the disturbance on the traffic flow. As can be observed in Figure 7, in this situation, for the same reason stated previously alternative A3 doesn't have CO_2 emissions. The worst solution is the utilization of common steel (alternative A0).

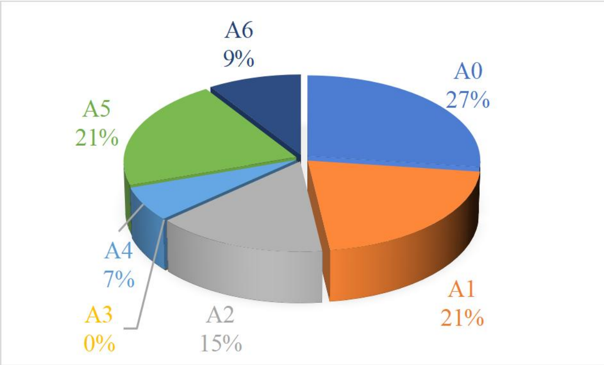

Figure 7: CO_2 emissions

4. Discussion

The presented methodology is supported in the behavior of the reinforced concrete structure. One of the main difficulties of Bridge Management Systems stated in the literature is related with the inspections to evaluate the deterioration rates. According to [32] the current deterioration inspection method for bridges heavily depends on human recognition, which is time consuming and subjective. An ideal inspection regime would record a complete multi-defect inspection panel, however in many organizations this is not the case [33]. The current unavailability of high-quality data and the consequent lack of understanding of bridge performance jeopardize bridge safety and hinder the ability to prioritize resources [34].

Most of the research achievements on operating vehicle emissions focus on the application of existing emission models or the revision and localization of existing emission models. The control of vehicle's running state is mainly based on laboratory data, field data, or simulation results. However, with the rapid development of new energy vehicle technology and the improvement of intelligent transportation systems, the existing vehicle operating emission model method needs to be updated to meet the emission assessment needs of these new technology vehicles [35].

As stated, the design lifetime of bridges is 100 years. In such a large period it can occur a change of transport paradigm. An example of that is plotted in Figure 8. The recent pandemic event demonstrated that long term predictions are very uncertain. Due to the COVID 19 pandemic event and the subsequent ban of public transportation it was registered a change in the modal split of passenger transport.

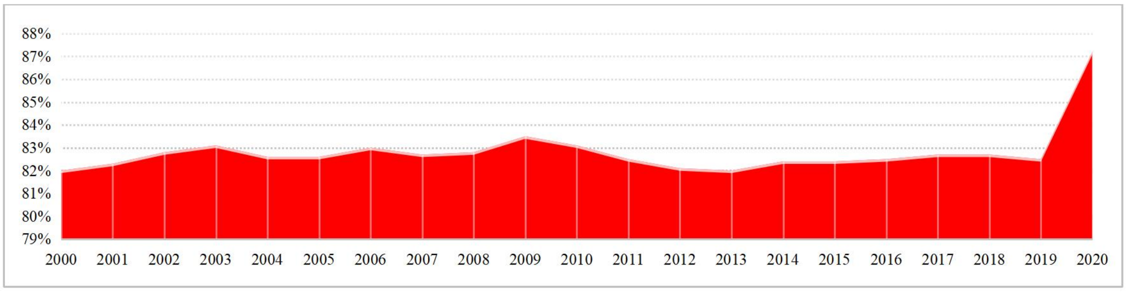

Figure 8: Modal split of passenger transport - Passenger cars [36].

In European Union the total number of vehicles is increasing [37], but as it can be seen in Figure 9 the share of zero emission vehicles in newly registered passenger cars is boosting quickly. This indicator measures the share of zero-emission vehicles in newly registered passenger cars. Zero-emission vehicles release no direct exhaust gases into the atmosphere and include both battery electric vehicles and hydrogen fuel cell vehicles.

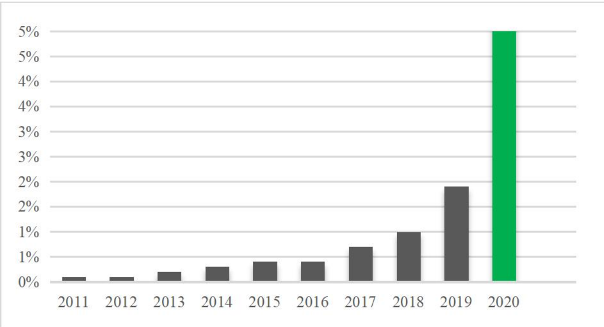

Figure 9: Share of zero emission vehicles in newly registered passenger cars [38].

Some experts argue that automated vehicles will lead to a significant decline in private car ownership and to a rise of a regime of seamlessly intermodal mobility options that are used "on-demand" but not owned [39].

For everything that was stated the forecast of the user costs is associated to a big uncertainty. With the objective to identify the main factors that affect this structure costs it was performed a sensitive analysis of the following parameters: inflation rate, opportunity cost of capital rate, traffic grow rate, cover thickness, time costs method, accident cost method, accident rate, intervention days, number detoured of vehicles, and detour road.

4.1 Recommendation for policy makers and authorities

This research allowed to find some guideline and good practices that can reduce significatively the total costs. It was found that the materials used are the main cost-generating factor, because the shorter its useful life, the greater the number of interventions that the bridge will have to undergo, attributing very important costs to users. It has been proven that small changes to the value of the concrete cover, which are associated with small costs, can lead to significant savings, as this increases the protection of the reinforcement and, therefore, the useful life of the structure. As user costs are a significant part of the total costs, from the analysis of the traffic 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 the intervention time produces savings that can be proportional to the time of execution of the works.

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. It was showed that the main parameters of the financial analysis of the study, inflation, and the opportunity cost of capital, can largely influence the final decision on the choice of materials to adopt. The definition and estimation of these parameters is extremely difficult when considering very long periods of analysis, and it is essential to carry out a sensitivity analysis of the different parameters involved, to make the best decisions. User costs, and considering their magnitude, it appears that the economic performance of alternatives can undergo a significant change depending on the total number of interventions. The solution that foresees the use of stainless-steel reinforcement is, in the bridge under study, clearly the most economical solution due to the non-existence of user costs. It is also noted that the values of user costs are in line with the values presented in the literature, where several authors refer that these can be higher than the direct costs by an order of magnitude.

Relative to the cost of time, it was determined that the cost related to the time spent by occupants of light passenger vehicles represents around 40% of the total cost. The time cost of freight transport represents around 30% of the total. When traffic disturbances are introduced, there is a transfer of the weight of costs from the scenario in which queues are not formed to the scenario in which traffic circulates with queue formation. Considering vehicle emissions and given that those increase with the execution of works, in order to minimize the emission of greenhouse gases, it is necessary to ensure that the material solutions chosen are those that minimize the total number of interventions.

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