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Research Article

A Mathematical Model to Evaluate the Impact of the Maintenance Strategy on the Service Life of Flexible Pavements

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The structural failure of a flexible pavement occurs when the accumulated fatigue damage produced by all the vehicles that have passed over each section exceeds a certain threshold. For this reason, the service life of pavement can be predicted in terms of the damage caused by the passage of a single standard axle and the expected evolution of traffic intensity (measured in equivalent standard axles) over time. In turn, the damage caused by the passage of an axle depends on the vertical load exerted by the wheels on the pavement surface, as given by the technical standard in application, and the depths and mechanical characteristics of the layers that compose the pavement section. In all standards currently in application, the unevenness of the road surface is disregarded. Therefore, no dynamic effects are taken into consideration and the vertical load is simply given in terms of the static weight carried by the standard axle. However, it is obvious that the road profile deteriorates over time, and it has been shown that the increase in the pavement roughness, when considered, gives rise to important dynamic effects that may lead to a dramatic fall in the expected structural service life. In this paper, we present a mathematical formulation for the fatigue analysis of flexible pavements that includes the effects of dynamic axle loading. A pavement deterioration model simulates the sustained growth of the IRI (International Roughness Index) over time. Time is discretized in successive time steps. For each time step, a road surface generation model provides a profile that renders the adequate value of the IRI. A QHV (Quarter Heavy Vehicle) model provides the dynamic amplification function for the loads exerted on the road surface along a virtual ride. This function is conveniently averaged, what gives the value of the so-called effective dynamic load amplification factor (DLA); this is the ratio between the effective dynamic loading and the static loading at each time step. Finally, the damage caused by the passage of the standard axle can be evaluated in terms of the dynamic loading. The product of this damage times the number of equivalent standard axles gives the total fatigue damage produced in the time step. The accumulated fatigue damage at each moment is easily computed by just adding up the damage produced in all the previous time steps. The formulation has been implemented in the software DMSA (Dynamic & Maintenance Simulation App). This tool has been specifically developed for the evaluation of projects in applications for financing submitted to the European Investment Bank (EIB). DMSA allows for quantifying the expected structural service life of the pavement taking into account both the rise of the dynamic axle loads exerted by the traffic as the road profile deteriorates over time and the different preventive maintenance strategies to be taken into consideration.

1. Introduction

It is commonly accepted that heavy vehicles are the main causal agent of the fatigue damage on flexible pavements. As early as in the 1820s, McAdam proposed specific tolls for heavy vehicles due to the road damage they produced [1]. The problem in those times was the lack of a common unit for measuring the road damage caused by each class of vehicle, which at that time depended on the number of horses.

In 1958-60, right after the World War II, the American Association of State Highway Officials (AASHO) together with the US Army Corps conducted a very large number of road test in Ottawa, Illinois ([2, 3]). A result of those tests is probably the most relevant concept in terms of pavement design and fatigue analysis: the "fourth power law." This "law" refers to the relationship between the deterioration of the pavement service conditions and the static load carried by each axle. In accordance to this law, the service life of a flexible pavement section, that is, the number of load cycles until failure, could be estimated in terms of the load carried by each vehicle. The term "fourth power" means that the damage caused by a particular load is roughly related to the load by a power of four. The standard unit for measuring the loads applied, Equivalent Standard Axle Loads (ESALs), was established at that time and has remained unchanged since then [4]. The modern methods for pavement design are based on the concepts established at that time [5].

Road transport is a key element for the economic growth and development in modern societies. For example, in the European Union, road infrastructures are a fundamental element of social cohesion and prosperity, representing about 45% of the transported goods and over 80% of the passengers in the EU. However, due to the economic crisis of 2008, the maintenance expenditure of the European countries had suffered, according to the OECD [6], a reduction of over 30% between 2008 and 2011.

Basically, all national highway agencies recognize the importance of an adequate preventive maintenance during the road pavement life-cycle. It is believed that if preventive maintenance is programmed to be applied too infrequently, the maintenance and user costs will increase. On the other hand, if it is applied too frequently, the maintenance program cost will be reduced, but due to the traffic interruption, there are costs in terms of user delay and inconvenience. Recently, there has been a great deal of interest in studying the interaction between pavement roughness and dynamic axle loads generated by heavy vehicles. The progressive deterioration of the road surface accelerates the fatigue damage accumulations [7]. In order to reduce it, a preventive maintenance program could be performed. A reduction of the road roughness would reduce the dynamic load and therefore the expected service life of the road would be increased, but also other factors, such as comfort and safety, would be improved.

The aim of this paper is to study the increase of the fatigue damage of a pavement section along its lifetime. The study includes the dynamic effects generated by heavy vehicles. Finally, different conservation strategies will be analyzed in order to extend the road service life.

In order to carry out the study, a new software financed by the European Investment Bank Institute, named "Dynamic & Maintenance Simulation App (DMSA)" has been developed. The heavy vehicle dynamics are included in DMSA by means of a coupled mathematical model that takes into account the pavement deterioration over time. In this paper, the process and its subprocesses are presented, explaining their respective role in the model. In order to show the potential of this software, the results of the DMSA app for a sample case are presented. Finally, an example is presented, in which different maintenance strategies are applied to a given flexible paved road.

2. Schematic Process

In this work, the effect of preventive maintenance on flexible pavement lifetime considering dynamic axle loads is analyzed. All the essential factors (traffic, weather conditions, the specific fatigue law under consideration, the structural characteristics of the pavement, the project lifetime, etc.) are included in the proposed formulation.

The schematic process is divided into three different subprocesses, each one intended for the computation of a specific function (Pavement Deterioration Model, Dynamic Load Amplification Factor, and Accumulated Fatigue Damage Indicator).

Pavement Deterioration Model (PDM). International Roughness Index (IRI) is a worldwide accepted index used for calculating the roughness of a road. Its variation over time is chosen as the representative variable for the progressive deterioration of a road profile. The model used for computing the evolution of the IRI over time takes into account multiple effects, such as the vehicles' characteristics, the initial road profile, the structural specifications of the pavement, and the project lifetime, among others.

Dynamic Load Amplification Factor (DLA = $\Phi(T)$). The DLA factor quantifies the ratio between the effective dynamic loading and the static loading. For the calculation of the DLA, the so-called Quarter Heavy Vehicle (QHV) model is used. This model was developed by Navarrina et al. in 2015 [7] as a variant of the Quarter Car (QC) model [8], which is routinely used to calculate the IRI.

Accumulated Fatigue Damage Indicator Including Dynamic Effects ($\Psi_d(\tau)$). This indicator quantifies the dynamic counterpart of the accumulated fatigue damage suffered by the pavement along its lifetime. The accumulation of the fatigue damage decreases the structural integrity of the firm. One of the required parameters for the computation of this indicator is the so-called reference strain (ϵ_r). In this work, we have used a Multilayer Elastic Model based on Burmister's theory [9] to calculate this reference strain.

The computational models used in this work for the different phenomena involved in pavement deterioration are the bases on which the software DMSA relies.

3. Pavement Deterioration Model

The main objective of the PDM is to simulate the time evolution of the superficial roughness for a given flexible paved road. This evolution is needed for the study of different maintenance scenarios and their effects onto the lifetime of the firm. Also, this time evolution is used to estimate the variation of the DLA factor along time.

Several deterioration models can be found in the literature, each one with its own advantages and disadvantages. IRI is worldwide employed for surface roughness measurement of flexible pavements. The IRI was developed by the World Bank in 1986 [10, 11] with the intention of establishing the overall use of an index to measure surface roughness on roads worldwide and define a standard roughness measurement technique for the quality control of the projects financed by this institution. The IRI is obtained from measured longitudinal profiles [12], where a quarter-car (QC) model [13] rides along a 100 m profile interval at constant speed (80 km/h). In this work, we generate the road profiles using the Road Profile Simulation Model, where the ride of the QC is analyzed. The IRI is also being widely used to other purposes, such as a user's comfort indicator and in economic studies concerning fuel consumption cost per kilometer in roads.

The PDM selected for this project simulates time evolution of the IRI. This evolution is produced by the deterioration of the upper bituminous layer of a flexible paved road. The PDM selected is based on HDM-III (Highway Design and Maintenance standards model III) and was named the "D.0" model by Paterson in 1992 [14]. It takes into account the weather conditions of the region where the analyzed road is located, the initial conditions of the road (roughness and structural properties), traffic, and also previous rehabilitation or maintenance actions. The equation of this PDM reads

$$IRI_T = 1.04e^{mT}\left[IRI_0 + 263\,(1+SNC)^{-5}\,NE_T\right] \quad (1)$$

where IRI_T is roughness at pavement age T (m/km), IRI_0 is initial roughness (m/km), NE_T is cumulative ESALs at age T (million ESAL/lane), T is pavement age since rehabilitation or reconstruction (years), m is an environmental coefficient, and SNC is the Structural Number modified Coefficient for subgrade strength.

4. Dynamic Load Amplification Factor

Once the PDM is defined, the superficial deterioration of the pavement during its lifetime can be simulated. The dynamic effects exerted to the pavement by the traffic will increase as the pavement deteriorates. Navarrina et al. [7] have developed a model for the computation of the fatigue damage, for a given road, along its lifetime, which takes into account the contribution of dynamic axle loads. The dynamic effects are introduced in the formulation by means of the so-called "Dynamic Load Amplification" (DLA) factor, which is the relation between the magnitude of the vertical load transmitted to the pavement associated with the dynamic case and the one associated with the static case. Equation (2) presents the vertical load $V_d(t)$ exerted by the wheel on the pavement along the ride. It is important to note the distinction between global time T and local time t in the following equations. The global time T is used to track the condition of the road over its lifetime and is measured in years, starting from the date placed in service of the road studied. On the other hand, the local time t is measured very likely in seconds (starting at the moment T in which the QHV simulation is initiated) and is used to track the dynamic response of the QHV model along a short interval of time:

$$V_d(t) = V\left(1+\eta(t)\right) \quad (2)$$

where V is the static vertical load and $\eta(t)$ is the dynamic amplification function.

For a complete description of the DLA factor and its computation, we refer to [7]. The DLA factor can be calculated using the following equation:

$$\begin{aligned}\Phi(T)^{1/\alpha} &\approx \frac{1}{t_{max}}\int_{t=0}^{t=t_{max}}\left(1+\eta(t)\right)^{1/\alpha}dt \\ &= \frac{1}{L}\int_{x=0}^{x=L}\left(1+\eta(x)\right)^{1/\alpha}dx\end{aligned} \quad (3)$$

where t_{max} is the time that takes the heavy vehicle to reach the end of the interval studied, α is a constant coefficient depending on the hot-mix asphalt type, and L is the length of the road profile.

Since the model needs the road profile $p(x)$ to compute the ride, to calculate the DLA factor and in order to achieve acceptable and realistic results, it would be necessary to provide frequent measures of the profile for each road being analyzed. In order to avoid these measures, which it is not practical, we make use of a virtual ride, where artificial road profiles are generated for a given value of IRI. The fundamentals of this model are presented below.

4.1. Road Profile Simulation Model. It is possible to generate an artificial road profile from a stochastic representation. This stochastic process can be described in terms of the Power Spectral Density of vertical displacements obtained through the Fourier Transform of the autocorrelation function.

The road profile $p(x)$ is introduced in the dynamic model by means of its Laplace transform $P(\xi)$:

$$P(\xi) = \mathscr{L}\{p(x)\}(\xi) = \int_{x=0}^{x=\infty} e^{-\xi x}p(x)\,dx \quad (4)$$

which can be expressed in the polar form

$$P(\xi) = \left|P(\xi)\right| e^{i\,arg(P(\xi))}. \quad (5)$$

The modulus of the Laplace Transform can be written in relation to the Power Spectral Density (PSD) function, denoted as $G_d(n)$, as

$$\left|P(\xi)\right| = \left(G_d(n)\big|_{n=-i\xi/2\pi}\right)^{1/2}. \quad (6)$$

The geometry of the road profile can be simulated if the PSD is known. Several power spectral density approximations of longitudinal road profiles can be found in the literature [15]. In this work, we have used the "displacement Power Spectral Density." For this PSD, the ISO 8608:2016 [16] recommends the use of the so-called straight line fitting, which uses a two-parameter spectrum to describe a road profile, and reads

$$G_d(n) = G_d(n_0)\cdot\left(\frac{n}{n_0}\right)^{-2} \quad (7)$$

where G_d is the PSD of vertical displacements, n is the spatial frequency, while n_0 and $G_d(n_0)$ are the parameters and their values are established in the standard ISO 8608 in order to facilitate the comparison between different road roughness profiles.

The value of the Power Spectral Density function, assuming a continuous road profile, for a defined value of spatial frequency n and within a frequency band Δn is defined as

$$G_d(n) = \lim_{\Delta n \longrightarrow 0} \frac{\Upsilon_x^2}{\Delta n} \quad (8)$$

where Υ_x^2 is the mean square value of the component of the signal for the spatial frequency n, cantered within a frequency band Δn [17].

Following [18], the road profile can be simulated from a simple harmonic function:

$$p(x) = \sum_{j=0}^{N} \sqrt{\Delta n 2 G_d(n_0)} \left(\frac{n_0}{j\Delta n}\right) \cos\left(2\pi j \Delta n x + \varphi_j\right) \quad (9)$$

where N is number of samples (L/B), L is length of road profile, B is sampling interval of the length, Δn is discretized frequency interval $(1/L)$, n_0 is reference spatial frequency (0.1 cycles/m) [16], x is spatial variable for the ride ranging from 0 to L, and φ_j is random phase angle uniformly distributed within the 0-2π range.

Equations relating the PSD with the IRI value of a road profile can be found in the literature [19]. However, in order to achieve more accurate and consistent results, we have developed our own expression. For this reason, we have performed a number of simulations (2.500) followed by a function fitting. As a result, the following expression was obtained:

$$G_d(n_0) = 2^{(3.236496516\sqrt{IRI}-1)} \quad (10)$$

5. Accumulated Fatigue Damage Indicator

Once the previous models are defined, we need to determine the fatigue failure of the pavement. For this purpose, the accumulated fatigue damage indicator is presented.

Miner [20] expressed mathematically the concept of fatigue damage by means of the formula

$$D = \sum_i \left(\frac{n_i}{N_i}\right) \quad (11)$$

which quantifies the total accumulated fatigue damage D that is reached when different loads are repeatedly applied in different proportions, where n_i is the actual number of cycles of each load and N_i is the total number of cycles needed to reach the fatigue failure when only load i is applied.

The ratio between the actual number of cycles and the total number of cycles that produces failure can be used as an indicator of the accumulated fatigue damage caused by one single load repeatedly applied.

For a given type of hot-mix asphalt, as well as a given load, the maximum number of cycles can be obtained using a strain-based fatigue law. The strain-based fatigue law of a hot-mix asphalt pavement can be expressed as

$$\epsilon_r = K \cdot N^{-\alpha} \Longleftrightarrow N = \left(\frac{K}{\epsilon_r}\right)^{1/\alpha} \quad (12)$$

where N is the number of load cycles to failure, ϵ_r is the reference strain, which quantifies the structural elastic deformation caused by one single load, and K and α are coefficients that depend on the hot-mix asphalt type.

According to [7], the accumulated fatigue damage indicator $(\Psi(\tau))$ and its dynamic counterpart $(\Psi_d(\tau))$ can be written as

$$\Psi(\tau) = \frac{E(T)|_{T=\tau T_p}}{N} \quad (13)$$

$$\Psi_d(\tau) = \frac{E_d(T)|_{T=\tau T_p}}{N} \quad (14)$$

where T is the time, T_p is the project lifetime, τ is the nondimensional time $(\tau = T/T_p)$, and E_d is the dynamic loading counterpart of the equivalent project traffic E.

In order to calculate the accumulated fatigue damage indicator, taking into account the dynamic loads, the reference strain (ϵ_r) of the asphaltic layers must be determined. A Multilayer Elastic Model based on Burmister's theory [9] was developed for this purpose. As an example, the reference strain of the pavement section T3121, taken from the Spanish standard 6.1-IC [21], was calculated with a dual axle configuration. Figure 1 presents the distribution of the reference strain using the dual axle defined in Figure 2.

6. The DMSA Software

DMSA is an acronym for Dynamic & Maintenance Simulation App. This is a tool that was designed and implemented by the authors in the context of the project entitled Impact of Preventive Maintenance on Flexible Pavement Service Life, financed by the European Investment Bank Institute (EIB Institute) under the STAREBEI Programme in 2017. This software was developed at the request of the European Investment Bank (EIB), whose engineering department wanted a specific tool to evaluate the sustainability of the projects submitted in applications for financing.

The formulation is based on some theoretical concepts that were presented by the authors in previous papers [7] and on the research work developed during the realization of the above-mentioned STAREBEI project. A comprehensive description of the rationale and the details of the mathematical model underlying the software implementation can be found in [22].

DMSA was designed to calculate the time evolution of both the roughness of the road profile and the accumulated fatigue damage of the asphalt along the project lifetime. These indicators are essential to assess how the comfort and safety of the road and the structural integrity of the asphalt evolution over time. The simulation can take into account a maintenance scenario defined by the user. This feature allows for comparing different options at the time of designing or selecting the most convenient conservation strategy for a pavement. Obviously, this helps to take more rational and well-founded decisions at this level, considering both the technical and the economic effects in the long term.

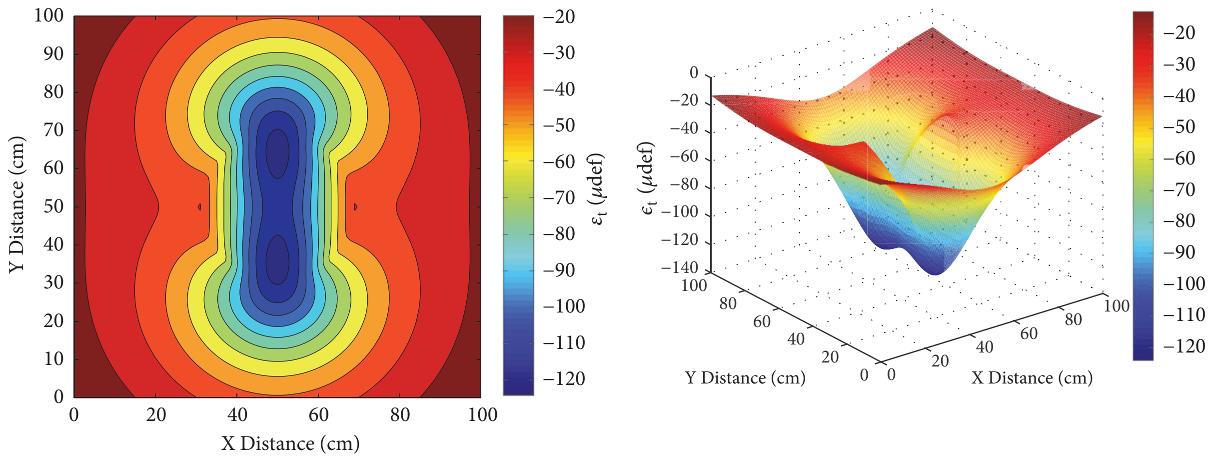

Figure 1: Dual axle distribution of the reference strain (2D and 3D representation).

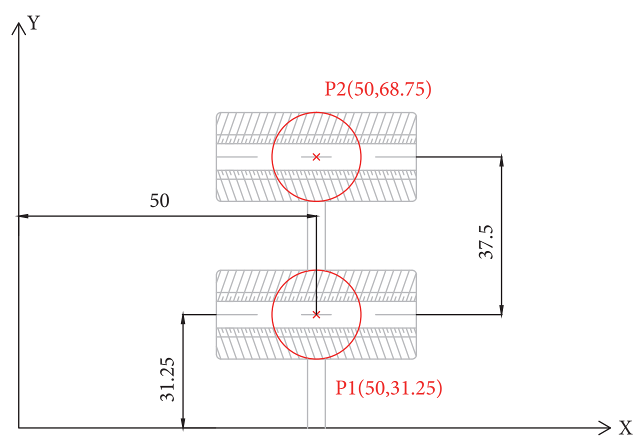

Figure 2: Schematic definition of the dual axle.

The main DMSA window is shown in Figure 3. The application is very user-friendly, what makes the introduction of the required data and the launching of the simulation process almost self-explanatory. The required data can be introduced interactively at the execution time or loaded from a plain text file. Most of the required data are parameters commonly used in road engineering to define the pavement characteristics (number of upper asphalt layers and lower granular layers on top of the subgrade, alongside with their corresponding thicknesses, Young's moduli, and Poisson's ratios), the static loads exerted by the vehicles (pressure of the wheels of the standard axle and radius of their corresponding footprints), and the fatigue deterioration model of the asphalt. On the other hand, the model requires the predicted evolution of the traffic intensity over time (in number of equivalent axles per year). And, finally, it is optional to define a maintenance scenario. In this case, the user can choose the dates throughout the project lifetime when renewal actions are set to be carried out in order to reduce the IRI to suitable values. Alternatively, the user can enable an automatic mode in which the surface renewal actions are set to be performed whenever the IRI exceeds a certain threshold.

7. Application Example

Finally, an application example is analyzed with DMSA to evaluate the impact of preventive maintenance in the pavement service life. In this sample case, the authors analyzed a pavement section from catalog of the Spanish Standard 6.1-IC [21]. More details of the section and the different parameters needed for the computation are presented in Appendix A.

First, we analyzed the behavior of the section in a scenario without any maintenance along the pavement lifetime.

In Figure 4, the time evolution of the IRI is shown. As can be observed, when the pavement section reaches its end of project lifetime, the IRI value is close to 15 m/km. At this level of roughness, user comfort and safety can be compromised [23].

Figure 5 plots the evolution in time of the accumulated fatigue damage taking into account the dynamic axle load effects. It is clear that this pavement section, under the traffic and weather conditions considered, reaches the fatigue failure before the project lifetime if no maintenance strategy is defined. Therefore, a complete rehabilitation of the pavement must be carried out at time t=28 years.

Figure 3: Main window of DMSA.

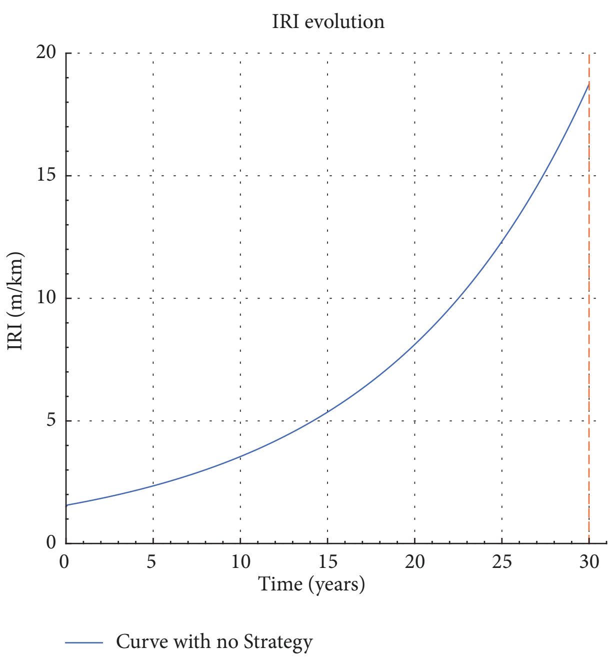

Figure 4: Sample case–time evolution of the IRI without actions.

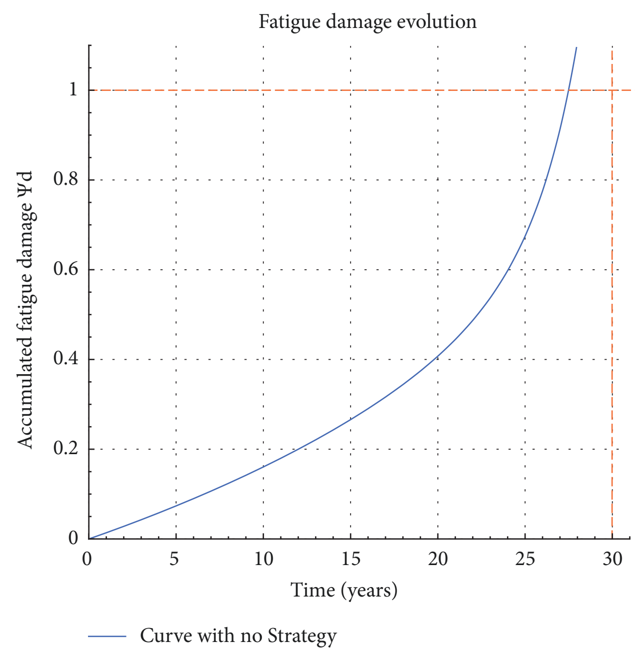

Figure 5: Sample case–time evolution of the fatigue damage without actions.

As the road surface profile deteriorates over time, the IRI increases, as seen in Figure 4. An increase in the pavement roughness will lead to an increase of the dynamic effects and this will lead to a dramatic fall in the service life of the pavement. In order to avoid this scenario, a maintenance strategy can be defined. Maintenance should focus on keeping the roughness, measured with the IRI, below a suitable value. This will decrease the dynamic effects and therefore the pavement lifetime will be increased.

DMSA allows the user to choose between a manual and an automatic maintenance strategy mode. In the latter, the user must define a threshold value of the IRI at which the maintenance needs to be applied. In the manual maintenance strategy, the user defines the date (year and month) at which each action takes place. These two modes let the user simulate and analyze different maintenance scenarios, such us unplanned actions. Moreover, it is possible to make a combination of manual and automatic strategies. In both modes, the user needs to set the IRI value after the maintenance action is applied, and DMSA lets the user compare the effects that the maintenance has on the pavement lifetime compared with the scenario without maintenance.

In this example, two different maintenance strategies are carried out: Maintenance 1 and 2. In Maintenance 1, an automatic maintenance mode is chosen, while in Maintenance 2, the manual mode is selected.

Maintenance Strategy 1. This strategy consists of keeping the IRI value below the threshold of 4.5m/km. A priori, the number of renewal actions is unknown. DMSA will set automatically an action when the IRI value reaches a value

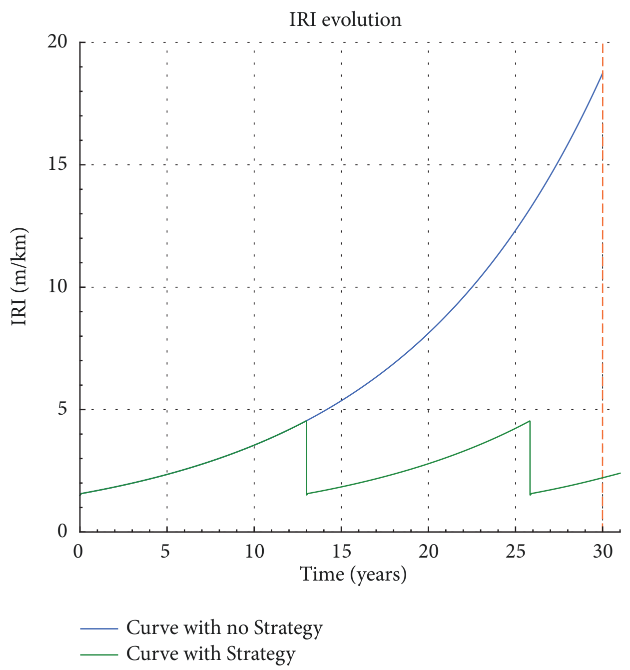

Figure 6: Sample case–time evolution of the IRI for Maintenance Strategy 1.

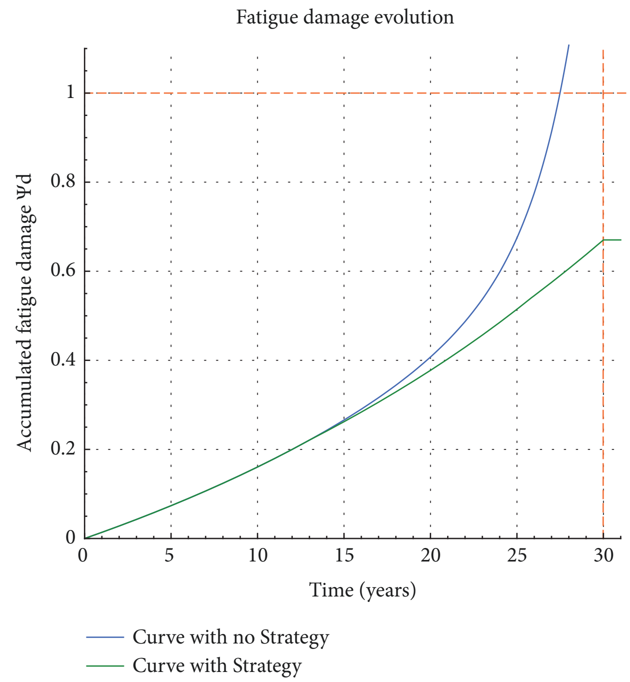

Figure 7: Sample case–time evolution of the fatigue damage for Maintenance Strategy 1.

higher than 4.5 m/km. After each action, the IRI after the renewal action is set to 1.5m/km. In this kind of strategy, the user wants to limit the IRI and therefore the dynamic effects. After running DMSA, the user obtains Figures 6 and 7 and the following two renewal actions:

(i) First Action: year 12, month 12 with an IRI after the renewal action of 1.5 m/km

(ii) Second Action: year 25, month 10 with an IRI value after the renewal action of 1.5 m/km.

In Figure 7, the time evolution of the accumulated fatigue damage along its lifetime is plotted. If we compare it with the scenario without maintenance, the reader can note that the maintenance strategy significantly increases the pavement lifetime, as the fatigue failure is not reached in the project lifetime. This is motivated to the acceptable range of IRI over time, since the user defines the maximum value that it can reach.

Figure 6 plots the evolution in time of IRI. Note the effect that the two renewal actions have on the IRI.

Maintenance Strategy 2. In this maintenance strategy, three punctual renewal actions are manually chosen to be performed along the pavement service life. This kind of strategy can be more proper of a scenario in which the user knows a priori the number of renewal actions and wants to distribute them along the pavement service life. In this example, we have decided to apply three maintenance actions. Since the project service lifetime is 30 years, we have located each action every approximately 7 years, which seems to be more rational than to choose more unbalanced periods. The actions are

(i) First Action: year 7, month 7 with an IRI after the renewal action of 1.5 m/km

(ii) Second Action: year 15, month 6 with an IRI after the renewal action of 1.5 m/km

(iii) Third Action: year 22, month 8 with an IRI value after actuation of 1.5 m/km.

In Figure 9, the time evolution of the accumulated fatigue damage is plotted along its lifetime. Again, the fatigue failure is reached after the project service lifetime. Figure 8 shows the evolution in time of the IRI. Note that now we have three actions and the maximum value of IRI is not limited.

This strategy keeps the IRI in lower values in comparison to the previous maintenance strategy; however, one more maintenance renewal action is required. Table 1 presents a comparison between the results for the three scenarios. The fatigue damage reached at the end of the service lifetime (30 years) and the maximum IRI obtained are shown.

Note that Maintenance Strategy 2 obtains better results in terms of fatigue damage and maximum IRI. Also, a lower value of IRI will increase user comfort and safety. On the other hand, it requires one more action, which may lead to traffic interruption and other user costs.

In this example case, the user should select the strategy that fits better with the maintenance policy; that is, in this case, choose between one that keeps the pavement in lower condition with less maintenance actions and other that improves the pavement condition executing one more renewal action.

8. Conclusions

The results obtained in this work confirm the need of taking into account the dynamic loads in pavement design and the importance of carrying out adequate preventive conservation

TABLE 1: Sample case–maximum values of fatigue damage and IRI.

	No Maintenance Strategy	Maintenance Strategy 1	Maintenance Strategy 2
$\Psi_d(30)$	181,83 %	66,48 %	65,43 %
max IRI	18,74 m/km	4,5 m/km	3 m/km

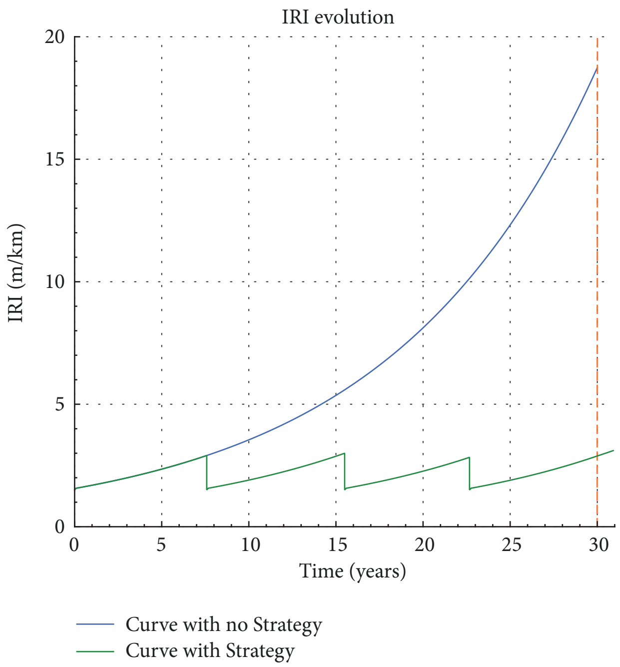

FIGURE 8: Sample case–time evolution of the IRI for Maintenance Strategy 2.

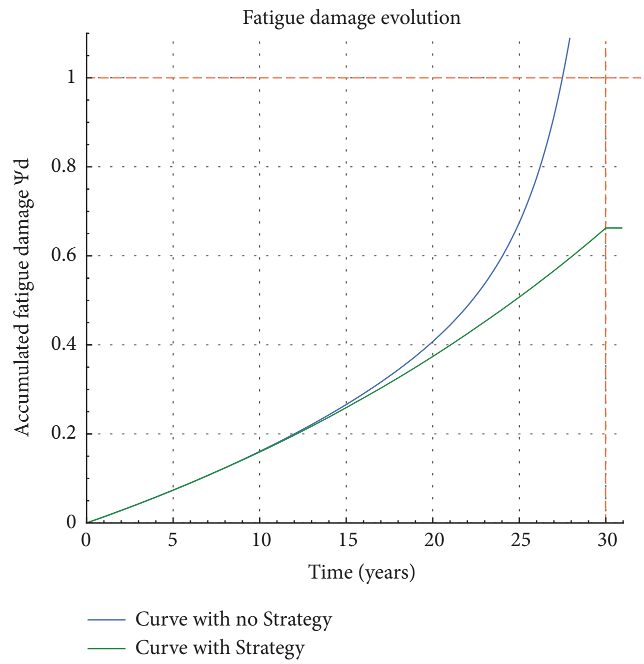

FIGURE 9: Sample case–time evolution of the fatigue damage for Maintenance Strategy 2.

strategies. These actions keep the IRI, and consequently the DLA, at low values, thus increasing the lifetime of the road.

In this work, an expression modeling the relationship between IRI and the PSD of an artificial road profile is presented.

Real maintenance strategies can be simulated with DMSA. Also, the effects of these maintenance strategies on the pavement's ride quality and structural integrity can be analyzed. This study shows that there could be substantial differences in the service lifetime of a flexible pavement depending on the maintenance strategy being applied. Our simulations show that a decrease of the IRI implies a decrease of the DLA factor, what increases the pavement lifetime. The DMSA software was developed for being used by the EIB as an evaluation tool for projects. The DMSA software will be public release in the near future. DMSA can be used as a design, evaluation, and maintenance planning tool for road promoters.

Appendix

A. Sample Case Data

This appendix contains all the input data used to run in DMSA the sample case.

A.1. Layer Characteristics. A T3121 pavement section from the Spanish standard 6.1-IC [21] was used for this sample case. This section is recommended for traffic up to 200 heavy vehicles per day. The properties of each layer conforming section T3121 are

(i) Asphaltic layer:
  (a) Layer thickness = 16 cm
  (b) Young's modulus = 6000 MPa
  (c) Poisson's ratio = 0.33

(ii) Granular unbound layer:
  (a) Layer thickness = 15 cm
  (b) Young's modulus = 500 MPa
  (c) Poisson's ratio = 0.35

(iii) Granular unbound layer:
  (a) Layer thickness = 25 cm
  (b) Young's modulus = 300 MPa
  (c) Poisson's ratio = 0.35

(iv) Subgrade:
  (a) Layer thickness = ∞
  (b) Young's modulus = 200 MPa
  (c) Poisson's ratio = 0.35.

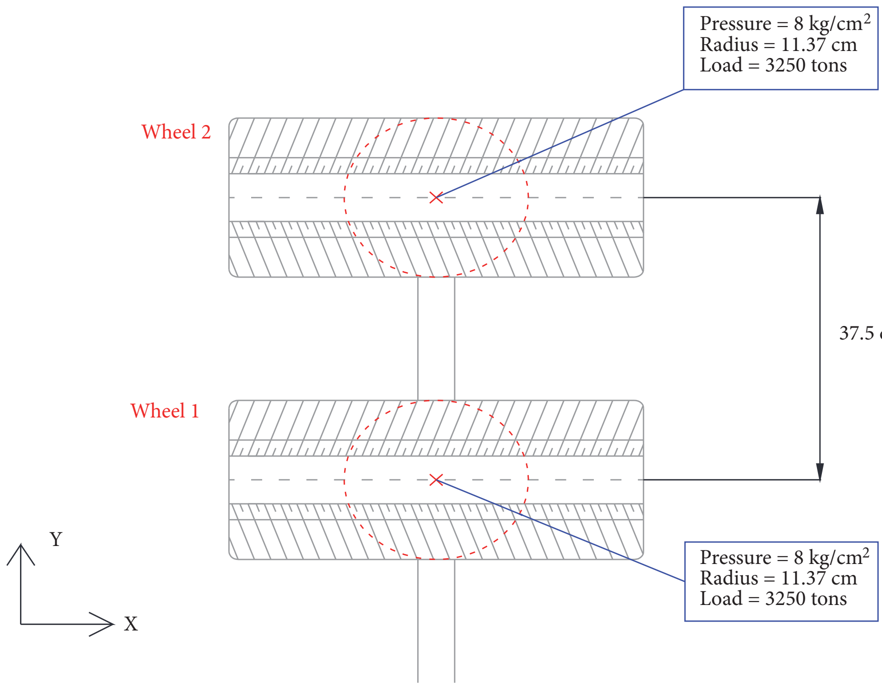

FIGURE 10: Sample case–load and axle characteristics.

TABLE 2: Sample case–traffic data.

YEAR	TRAFFIC	YEAR	TRAFFIC
1	34,952	16	54,455
2	36,001	17	56,088
3	37,081	18	57,771
4	38,193	19	59,504
5	39,339	20	61,289
6	40,519	21	63,128
7	41,735	22	65,022
8	42,987	23	66,972
9	44,277	24	68,982
10	45,605	25	71,051
11	46,973	26	73,183
12	48,382	27	75,378
13	49,834	28	77,639
14	51,329	29	79,969
15	52,869	30	82,368

The strain-based fatigue model of the hot-mix asphalt layers of this pavement follows equation (12) with $\alpha = 0.27243$ and $K = 0.006925$.

A.2. Heavy Vehicle Characteristics. The heavy axle used for the sample case is a dual axle, with a 3.25 tons ($\equiv 8kg/cm^2$) load per wheel modeled as a uniform circular load of radius 11.37 cm. Figure 10 presents all these data, adding the wheel separation of this axle.

With respect to the suspension type, the parameters of the QHV-AS (Quarter Heavy Vehicle with Air Spring suspension) has been used for the sample case. This model and its respective parameter values can be consulted in [7].

A.3. Pavement Deterioration Model Parameters. The Pavement Deterioration Model parameters of the sample case are

(i) Environmental coefficient, $m = 0.08$

(ii) Structural Number modified Coefficient for subgrade strength, $SNC = 6.1978$

(iii) Initial roughness, $IRI_0 = 1.5$ m/km

(iv) Project design life period, $T_p = 30$ years.

A.4. Traffic. DMSA application has been designed for operating with number of axles per year of service as measure of traffic during the service lifetime of the studied pavement. For the sample case, the traffic is presented in Table 2.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

In this paper, we present the final results of the research project "Impact of Preventive Maintenance on Flexible Pavement Service Life," submitted to the STAREBEI Programme of the EIB Institute by the end of 2016. The objectives and some preliminary results of this project were presented (oral communication only) in the Knowledge Programme 2017 event that took place on March 7, 2017, at the headquarters of the EIB Institute in Luxembourg, alongside other proposals that were approved in the same call.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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