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Improvement in Durability and Service of Asphalt Pavements through Regionalization Methods: A Case Study in Baja California, Mexico

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Abstract: The objective of this research is to develop a pavement design procedure that allows calibrating the design variables of asphalt pavements using regionalized conditions, to obtain efficient pavement performance for developing countries with limited resources and data. This study analyzes the roads of the state of Baja California, Mexico; where type structures are determined and the performance grade of the binder used in the manufacture of asphalt concrete is regionalized according to the weather conditions altitude, traffic, and quality of the available materials. In a complementary way, the economic incidence of pavements during its service life is analyzed, projecting the analysis with different pavement structures and damage coefficients. The results show that this approach favors the asphalt pavements that comply with the projected in its service life, reducing maintenance interventions and costs.

Keywords: asphalt pavement; infrastructure planning; durability

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1. Introduction

A pavement is durable if it maintains its structural and functional integrity to a satisfactory level throughout its nominal design life; this, when exposed to the environmental effects and traffic loads [1]. The deterioration in the pavements, overwhelmingly, is attributed to the poor quality of the materials, inefficiency of construction processes, or designs that underestimate the real traffic, subsequently, the design is inadequate regarding the structure of the pavement and the asphalt layer [2]. It is important to mention that pavement is doomed to fail because the materials that constitute it obey to the fatigue laws, that is, a certain number of admitted loads that make the pavement weaker and fail [3]. Therefore, it is necessary to correctly establish design variables, which contribute to the pavement achieving optimum serviceability during the life which they were designed for [4]. According to Andersen [5], one of the key components for the analysis of pavement structural behavior is the response model used to estimate the stresses, deformations, and displacements of the pavement structure subjected to existing traffic, taking into account the properties of the material and predominant environmental conditions. Based on these considerations, the optimum pavement structure must be defined by a design that provides a satisfactory level of performance to the user, an acceptable level of reliability, sustainability in using natural resources, environmental care, and a minimum total cost [6–8].

To achieve the above, the mechanistic pavement design method and mechanistic-empirical design method contemplate all the components mentioned. In this sense, current literature has shown that they are the most suitable for maintaining pavements structural and functional integrity [9–12].

These design methods are powerful tools, but their main problem lies in their eminently empirical nature. The import of the methods into other countries is quite difficult, because it requires a solid database, which is normally not available in most of the developing countries [13,14]. According to Das [15], each region, state, county, and country may be following a particular pavement design guideline, somewhat different than the rest others. The input parameters, the equations, the design recommendations, and thickness values provided in these guidelines may vary widely. For example, the different design methods between counties in the United States of America, the adaptations of these methods in some Latin American countries, and the development of the South African mechanistic pavement design method, the French method, United Kingdom and Shell methods currently in use in Europe, to mention a few.

In Mexico, examples of these tools are the Structural Pavement Sections Catalog for Roads of the Mexican Republic supported by the Ministry of Communications and Transport (SCT for its acronym in Spanish) and a design program promoted by the National Autonomous University of Mexico (UNAM) and funded by the SCT, named as Dispav-5; however, these tools were developed under specific load and climate conditions of the central region of the country, leaving some territorial areas out of reach. Likewise, regarding the already mentioned catalog, it is a document focused on Mexican highways, mostly under federal jurisdiction, where the generalized weight and calculations of the traffic are reflected and also, where the regional temperature is involved [16].

This research aims to develop a procedure that allows calibrating asphalt pavements design variables through regionalized conditions, to obtain type structural sections that achieve economic viability in projects; without diminishing the durability and service of roads. Additionally, this study proposes criteria for the calibration of traffic variables, damage coefficients, resistance characteristics of materials, preparation of pavement-type structures with data that can be obtained through simple laboratory tests, fieldwork or existing information. Thus, it is relevant for developing countries with limited resources and data to design asphalt pavements, where the design lays on experience and empirical knowledge.

After this introduction, a background review of the determining factors in pavements structural and functional conditions is presented in Section 2. Then, the study area and the methodology applied for this study are described in Section 3. The results of the applied procedure and its discussion are exposed in Section 4, finally, a summary and conclusions in Section 5.

2. Background

According to the Federal Highway Administration [17], a balanced and comprehensive pavement condition rating system should be based on two types of pavement conditions, structural and functional. The first one is the pavement's capacity to receive the traffic and the environmental conditions. The second is the functional condition that is based on ride quality and safety rated by its users.

Various factors influence asphalt pavements durability built on roads; this is because construction processes, quality of materials, design aspects, weather conditions as well as operating conditions directly contribute to asphalt pavements durability [18]. It is important to mention that the present research focuses on highways and roads, mainly in the design stage.

Most of the studies where factors that impact asphalt pavements durability are identified, mainly focus on (1) traffic effects and vehicular loads, (2) characteristics and properties of the materials that make up the structure of the pavements, and (3) weather and road operation effects.

In the first one of these, various studies have analyzed the traffic effects on pavement surface deterioration and the loss of its structural capacity [19–22]. It is important to mention that vehicular traffic and its solicitations directly affect the structure that constitutes the pavement, for this reason, it is essential to quantify loads magnitude by distributing the different types of vehicles, contact areas, and distribution of tire inflation pressures on the pavement [23].

For existing traffic sizing, AASHTO implements the concept of equivalent single axle load (ESAL) in order to provide a more precise and rational point of view regarding the structural capacity of a pavement [18]. This concept represents the predicted damage unit induced by repetitions of a single axis of 8.2 tons with an inflation pressure of 5.8 kg/cm^2 in a time frame [24,25]. According to Lavin [26], the number of equivalent axles is a key aspect in estimating the useful life and design of pavement. As mentioned above, requesting traffic is a contributing factor in predicting damage the pavement will suffer over a time frame. Nevertheless, the characterization of solicitations produced by the traffic on the pavements is quite complex, due not only to the variability and periodicity of the vehicles that drive on them but also to the vehicle-pavement interactions and driving speeds [3].

In the second one of them, several studies point out the importance of the characteristics of the materials that make up pavement structures, since mechanistic methods involve the analysis of stresses and deformations in an elastic multilayer system [27–31].

Regarding the above, asphalt pavements are a system of layers built with different mechanical properties. Usually, upper layers of pavements have the best quality and, with this, decreases with depth until reaching the natural ground [32]. According to Rengifo and Vargas [33], asphalt pavement stability, in order to withstand loads and to resist stresses, depends directly on the internal friction and cohesion of the aggregates used. If those values are adequate, the movement of aggregates is prevented due to the forces exerted by traffic. The determination of the properties and performance of the materials is achieved from a set of established tests or trials, to verify that these materials work correctly according to ranges, limits, and/or standard values for similar or equivalent conditions [34].

Regarding the third factor, studies have analyzed the climatic variable as an aspect in consideration since this directly affects the behavior of the design and evaluation of asphalt pavement durability [35–39]. This condition modifies pavement stiffness due to the thermoplastic properties of the material that constitutes the asphalt layers [40]. Asphalt pavement surfaces progressively deteriorate when exposed to repeated loads caused by traffic and environmental conditions, such as heat, wind, rain, and separation of the asphalt layer by moisture or ultraviolet radiation. All of these factors lead to the cracking of asphalt surfaces in the pavement structure, which leads to failure [41]. In accordance with the above, there is ample evidence that the presence of different climatic phenomena significantly contributes to the deterioration of road pavements. Therefore, the consideration of these events is essential in the planning of design projects.

Besides durability, it is necessary to provide road infrastructure that offers quality, safety, and comfort [42]. The functional quality is rated by users, primarily for surface smoothness, safety, comfort, and infrastructure overall appearance [43]. Furthermore, the elapsed time of failure impacts the pavement life cycle, giving rise to a behavior curve reflecting the service level provided to the user, which in turn has significant economic implications [44].

Due to the above, AASTHO developed a test in 1959. This test establishes serviceability based on the average of the evaluations of the users participating in the study [4,45]. The evaluation of this parameter defines the concept of the Present Serviceability Index (PSI), which qualifies the pavement surface according to a scale of values from 0 to 5 [24]. This index has been used in various studies to optimize the useful life of the pavement through models and decision-making procedures that consider multiple objectives, such as reducing maintenance and rehabilitation costs, preserving the quality of the pavement surface during its useful life, optimal resource allocation, pavement management, as well as equip users with safer and more comfortable roads [46–49]. Thus, the serviceability evaluation is fundamental for maintenance and rehabilitation decision-making, as well as providing a quality transportation system, optimizing resources, and reducing the costs of road infrastructure during its useful life.

Therefore, a pavement with good performance can reduce costs and risks through the whole life cycle of road infrastructure while keeping users safe. However, the inaccessibility of some countries to apply mechanistic and empirical mechanistic methods, the designer could modify variables in favor of the structure design with lower construction costs, which do not include maintenance work on the pavement [13]. For this reason, generating regionalized pavement structures for road construction is considered essential, eliminating the possibility of manipulating the design variables. Additionally, the Marshall design is widely used in Latin American countries asphalt pavements design. This procedure has substantial drawbacks with respect to replicating the real or actual behavior of asphalt during construction and in actual in-service conditions [50].

That is why several authors have made proposals for the regionalization of variables to design pavements. In this sense, Yang et al. [51] developed an asphalt pavement regionalization multi-index method in China. They conclude that the method's accuracy and reliability help in ensuring asphalt pavement life service and adequate performance.

Guerrero & Albitres [52] concluded that weather and operating conditions directly influence asphalt pavements' durability. Therefore, it is necessary to develop techniques that improve the design processes of asphalt pavements and be resilient to the area's requirements. In fact, since the implementation of the design method Superior Performing Asphalt Pavement (SUPERPAVE), many studies worldwide focus on calibration climatic zones for the PG for asphalt binders, significantly improving the behavior of this material to the environmental conditions of the analysis regions [50,53–56].

On the other hand, Villacorta et al. [57] carried out a study in Mexico using aging asphalt modeling, concluding that the omission of regionalized factors in predicting asphalt pavements' mechanical properties presents numerous errors compared to the actual performance. Finally, it is important to mention that in several Latin American countries, pavement design is performed by using adaptations of the AASHTO-93 empirical design method obtaining reliable results [15].

3. Materials and Methods

3.1. Study Area

The state of Baja California has an area of 71,446 km^2 that corresponds to 3.6% of the total surface of the country. To the north, Baja California borders the states of California and Arizona in the United States, to the south the state of Baja California Sur, on the east the state of Sonora and west by the Pacific Ocean [58]. Baja California has 5 municipalities connected through a road network that reaches more than 11 thousand kilometers, between 4 and 2 lane roads, coated roads, gaps, and dirt roads (Figure 1). It should be noted that the physical condition of most of these roads is considered in good and satisfactory condition, presenting good conditions for users [59]. Furthermore, the state has project and construction technical standards for road infrastructure works that regulate the quality of materials. However, its deterioration occurs prematurely, which has led to constant maintenance and conservation interventions to keep roads in good condition.

According to the above, roads in the state of Baja California, Mexico are not complying with the estimated time of service, in other words, pavement deterioration is occurring prematurely, being less than 20 years as recommended by the American Association of State Highway Transportation Officials (AASHTO) for road design. Therefore, the need to carry out a more specific analysis of mobilized traffic in the area to be built is foreseen, in order to establish suitable asphalt pavement structures for the region.

3.2. Methodological Description

This research is developed in three fundamental phases. The first one corresponds to the type structures determination for asphalt pavements (1); it consists of designing pavements layers using materials critical resistance parameters according to regional technological limitations and traffic demands. The second phase is the performance grade regionalization of asphalt cement (2), which consists of elaborating a regionalized map according to region temperature and altitude. The final phase is the economic impact analysis of durability regarding asphalt pavements (3); this is an economic analysis of the pavement durability during its service life. In Figure 2, the procedure structure and the input data used in the present investigation are presented.

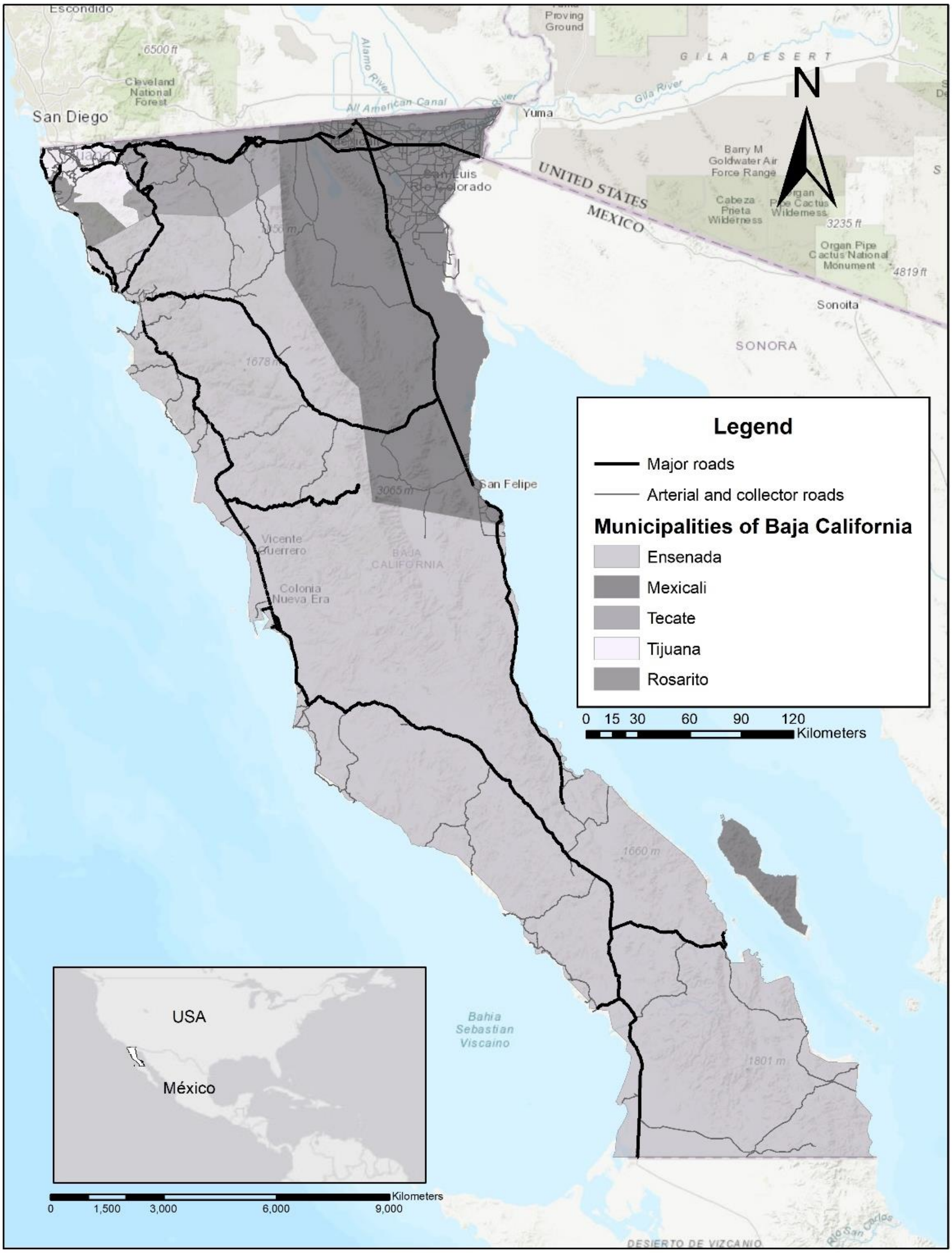

Figure 1. Baja California municipal boundary and road network.

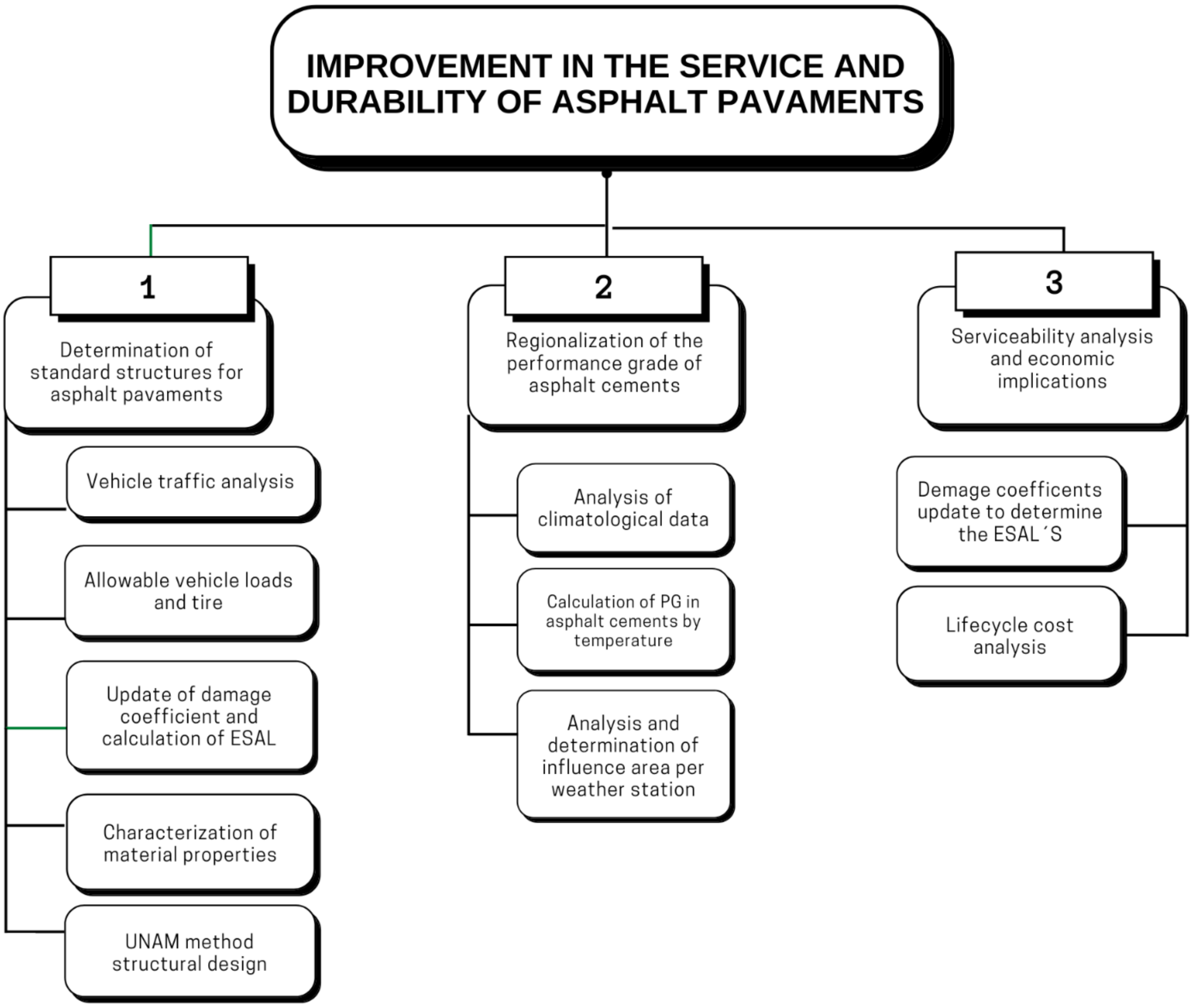

Figure 2. Research methodology.

3.2.1. Type Structures Determination for Asphalt Pavements

In order to calculate thicknesses in asphalt pavement structures, the design meth-od of the interactive computer program Dispav-5 version 3.0 has been used, developed by the UNAM Engineering Institute in 2014, the foundation of this program is theoretical-experimental and for its application concepts and methods of mechanistic calculation are used [60]. Likewise, it was necessary to quantify the magnitude of the loads by distributing the different types of vehicles and representative axles according to its vehicle composition, the contact area, and tire pressure distribution on the pavement. These calculations are made according to the procedure established in report 325 and 444 in the UNAM Engineering Institute series [61].

It is important to mention that for this research, eight traffic ranges are considered, in units of equivalent axles, to cover in a better way the demands of real traffic.

Traffic effects on pavement conditions can be estimated by means of the annual average daily traffic (AADT) and design traffic (DT). The calculation of the equivalent axis corresponding to the traffic through the Equations (1) and (2):

$$DT = AADT_{present} \times GR = AADT_{apresent} \times 365\left[\frac{(1+GR)^{n}-1}{GR}\right] \quad (1)$$

where DT is the design traffic; AADT is the average daily traffic; GR is the vehicle growth rate which is obtained by least squares technique from an initial AADT and a final AADT.

$$\Sigma \mathrm{L} = (\mathrm{DT}) \times (\mathrm{CD}) \times \sum \mathrm{i} = 1\mathrm{PCi}\ (\mathrm{wi} \sum \mathrm{Cdm} + (1 - \mathrm{wi}) \sum \mathrm{Cdv}) \quad (2)$$

where ΣL is the sum of equivalent axis of 8.2 tons expected at the end of the project; DT design traffic; CD is the distribution coefficient per lane in decimals, that is 0.5 for two lane roads, 0.4 to 0.5 on four lane roads and 0.3 to 0.4 on six or more lanes; Cdm is the damage coefficient of cargo vehicles (loaded) and Cdv is the damage coefficient of empty vehicles to calculate this coefficient refer to Corro et al. [60]; Ci is the directional distribution coefficient for each type of vehicle (i); and wi is the proportion of cargo vehicles (loaded) for each type of vehicle (i).

To determine the distribution of loads per axis, analysis by means of the concept of load spectrum is carried out, which is calculated from the quotient between the number of a type of axis for a certain level of load and the total number of axes. For this work, in which an overdesigned pavement structure is sought, the maximum loads allowed and established in current regulations were used; in addition to obtaining the inflation pressures in tires of transport trucks in loaded condition, observing typical values ranging from 98 to 110 pounds per square inch (PSI). Moreover, the update of the damage coefficients of loaded vehicles was carried out using the mathematical model of the engineering institute of the UNAM [61], that is the coefficient of damage produced by any axis (single, tandem and tridem) of weight d_iP in tons and inflation pressure p in $\frac{\mathrm{kg}}{\mathrm{cm}^2}$ relation to the equivalent axis.

Furthermore, for thicknesses calculation, the physical properties established by the current regulations for materials that make up the different layers are considered [16].

$$E = 130(CBR)^{0.7} \quad (3)$$

where CBR represents the minimum California Bearing Ratio established in current regulations and E is the stiffness modulus for non-stabilized layers.

To obtain the design thicknesses, Dispav 5 uses as a resistance parameter, the concept of critical support value $C\hat{B}R = \overline{CBR}(1 - 0.84\mathrm{V})$ where $\overline{CBR}$ it is the average value in the field and V is the coefficient of variation, that is a value between 0.2 and 0.3 depending on the homogeneity of the material. Finally, the method includes a simple procedure to obtain the equivalent design thicknesses Z_N of the structural section of the pavement, this procedure adapts four nomograms from the Thickness Design-Asphalt Pavements for Highways and Streets of the Asphalt institute that works with the critical support of each layer CBR, Qu confidence level, and the accumulated equivalent traffic in the project lane. With these nomograms, the equivalent thicknesses Z_N for each layer are obtained at a depth N. The equivalent thickness allows to obtain the structural thicknesses D_i for each layer by means of the following equation:

$$Z_N = a_1 D_1 + a_2 D_2 + a_3 D_3 \quad (4)$$

where Z_N is the design thickness, a_1 is the equivalence factor (≤2 for hot mix asphalt); a_2 is the equivalence factor (=1 for mechanically stabilized layers).

3.2.2. Performance Grade Regionalization (PG, for Its Acronym in English) of Asphalt Cement

For PG grade regionalization, an analysis of the weather conditions of the five municipalities that make up the entity is necessary, using the weather stations network of the National Water Commission (CONAGUA for its acronym in Spanish). This network has 122 stations distributed in Baja California, of which only 57 fulfilled the criteria established in the N-CMT-4-05-004/18 standard of the SCT necessary to calculate the PG grade; this, due to lack of data in some stations. The already mentioned calculations are performed considering high temperatures, through the following equation:

$$T_{(pav)} = 54.32 + 0.78T_{(air)} - 0.0025Lat^2 - 15.14log_{10}(H + 25) \\ + Z\left(9 + 0.61\sigma_{air}{}^2\right)^{1/2} \quad (5)$$

where: $T_{(pav)}$ represents the pavement temperature below the surface in °C, $T_{(air)}$ is the average air temperature of the seven consecutive hottest days in °C, H is the depth from the surface in mm, σ_{air} is the standard deviation of the seven consecutive hottest days in °C, and Z from the normal distribution table, Z = 2.055 for 98% reliability.

On the other hand, for low temperature, the following equation is used:

$$T_{(pav)} = -1.56 + 0.72T_{(air)} - 0.004Lat^2 6.26log_{10}(H + 25) \\ - Z\left(4.4052\sigma_{air}{}^2\right)^{1/2} \quad (6)$$

where: $T_{(pav)}$ represents the pavement temperature below the surface in °C, $T_{(air)}$ is the lowest air temperature (average of the coldest days of the year) in °C, H is the depth from the surface in mm, σ_{air} is the standard deviation of the lowest temperature in °C, Z from the normal distribution table, Z = 2.055 for 98% reliability.

By obtaining the value of $T_{(pav)}$ from the already mentioned equations, the area of influence of each one of the climatic stations is determined by means of the Thiessen Polygon method. This methodology is used to study the spatial and temporal distribution of hydrological variables (temperature, precipitation, infiltration) and in engineering applications [62], through a Geographic Information Systems (GIS), in which the zonification maps are generated. However, the Thiessen Polygon method does not consider the elevation of the climatic station; thus, when a difference in elevations of more than 500 m was identified in the same polygon, its area of influence was adjusted (Figure 3).

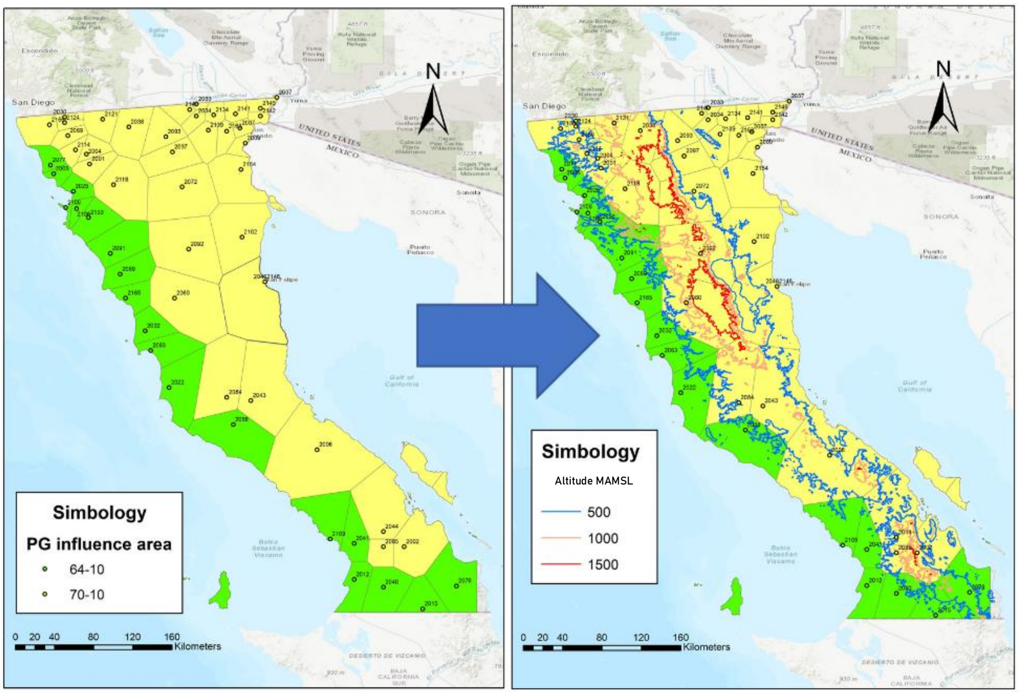

Figure 3. Areas of influence determination in the state of Baja California.

3.2.3. Economic Impact of Durability on Asphalt Pavements

For the economic impact analysis of asphalt pavements durability, a costs analysis is carried out to build and maintain a road for 20 years; starting the intervention on the pavement surface when regular surface condition is present, in accordance with the pavement serviceability diagram of the AASHTO pavement structure design guide (Figure 4).

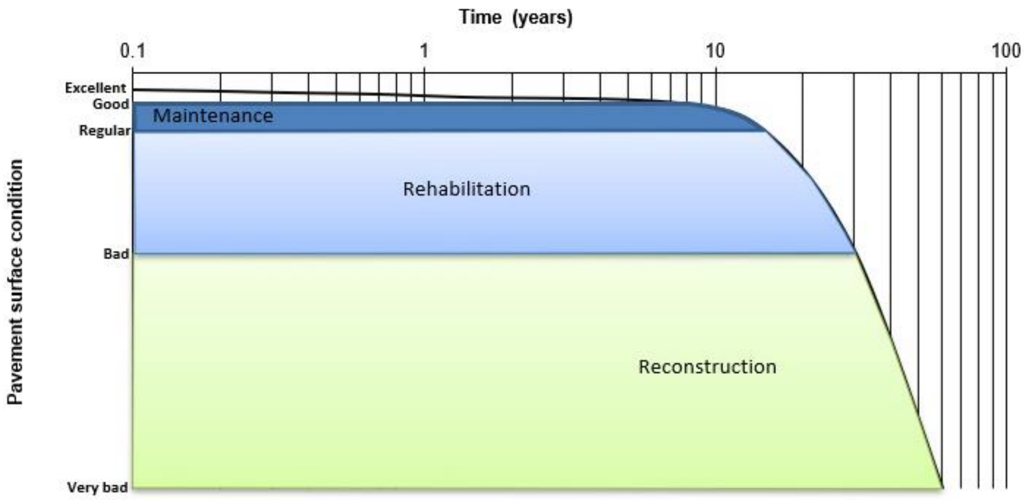

Figure 4. Functional capacity loss of a pavement over time. Adapted from ref [24].

For this analysis, road data are used from a random monitoring station from some of the roads in Baja California, and data were provided by the SCT. Likewise, two types of structures are used: one is proposed by this research (type 1), and the other one refers to a conventional structure recommended in federal regulations (type 2), as well as three different damage coefficients (DC):

(1) New DCs, these are calculated through maximum permissible axles loads conditions, stipulated in the NOM-012-SCT-2-2014 regulation and by the common tires inflation pressures in Baja California.
(2) DC 1978, these are established in appendix E of publication no. 444, by the UNAM Engineering Institute.
(3) Default DC, these are used by default in the Dispav-5 design program, when the designer does not have information on tire inflation pressure and actual project loads. The AASTHO serviceability diagram was adjusted according to the damage coefficients obtained, using the projected life. Once the pavements' life was established, the serviceability curves were adjusted, using the equation obtained from the trend for each of the damage coefficients analyzed. The intervention curves were constructed using the same trend equation obtained for each graph, an example can be found in Figure 5.

In order to establish the differences in the previously mentioned scenarios in the equivalent axles obtained and to determine, approximately, the lifetime of the projected pavement, construction and maintenance costs are estimated based on a road with a 3.65-m lane width, a single lane and a length of one kilometer for a pavement consisting of a structure with different layers that includes the subgrade, sub-base, hydraulic base, and hot asphalt mix layer (HMA). As for maintenance work, the milling of 5 cm of the asphalt layer is established and incorporates a hot-made overlayer, being the most common in the region.

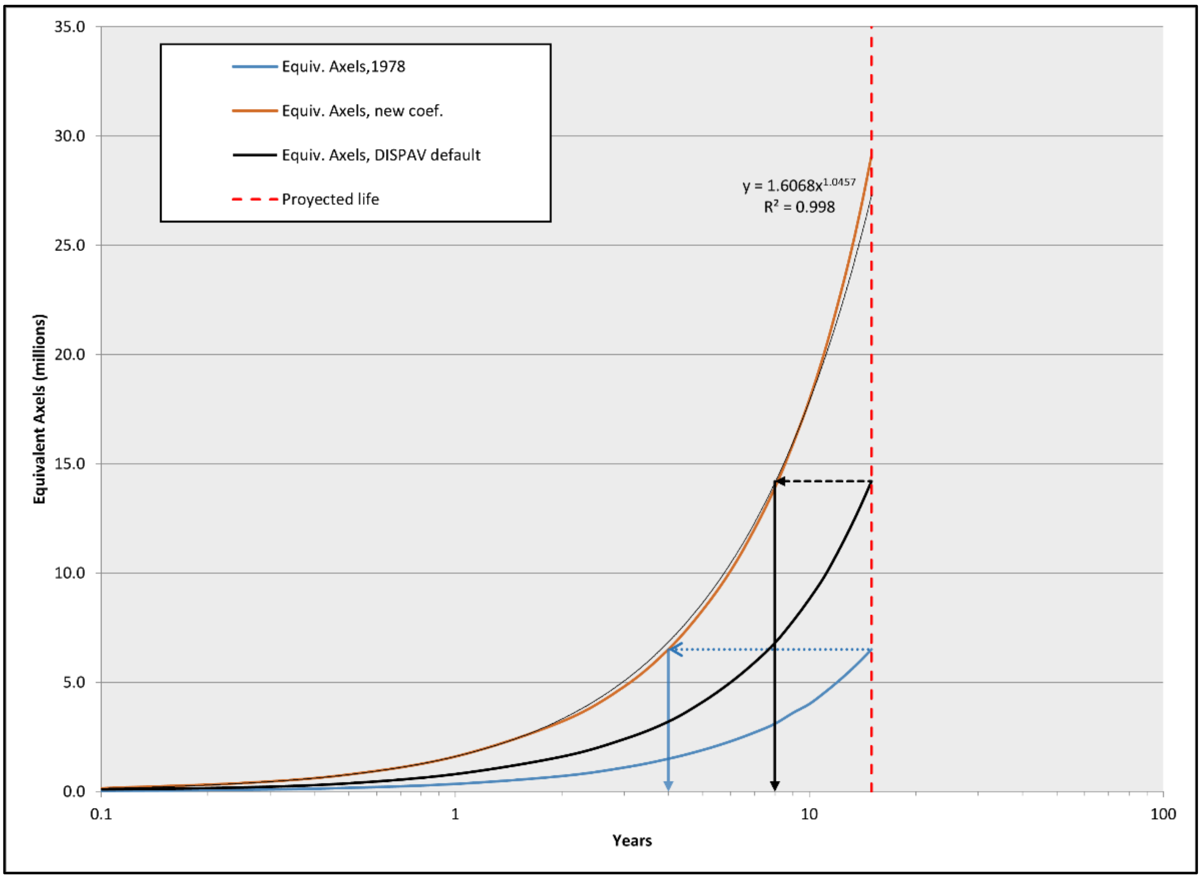

Figure 5. Graph of equivalent axes with different damage coefficients and pavement projected life.

4. Results and Discussion

4.1. Asphalt Pavement Structures

The first step of the proposed method considers the analysis of traffic, which is usually dynamic even in the same region, so this method considers existing databases. For this study area the SCT traffic data for Baja California state is used. Figure 6 shows the proposed type structures made with asphalt pavement for the study area. It is important to mention that these sections are classified according to the number of equivalent axles obtained, so it must start from the vehicular gauging generated through existing pavements or from an estimated traffic study for new pavements, with the objective of choosing the most suitable option.

The application of the method in the case study allowed to characterize the traffic in eight representative ranges. A variation in the pavement structures of each one is observed, starting from 50 cm in the case of less traffic and reaching structures of 177 cm when the traffic exceeds 100,000,000 equivalent axes. This is in contrast to the National Catalog of Structural Sections, which establishes five ranges, which can cause pavement oversizing in some regions and higher investment costs. Additionally, the procedure established for this research work allows the establishment of specific structures for any traffic intensity.

4.2. Asphalt Binder Performance Grade (PG)

For asphalt binder selection, an analysis is generated to prepare the map with the zonification of the state of Baja California, where asphalt cements PG grade are established by temperature and elevation (Figure 7). This tool allows managing agencies, designers, or builders to determine the PG grade of the asphalt binder, based on the geographical coordinates of the road to build or to maintain.

ESAL's	CONVENTIONAL STRUCTURE Layer	Thickness	BINDER BASE STRUCTURE Layer	Thickness
< 100,000	Surface Course (*HMA) Base Course Compacted Subgrade	5 cm 20 cm 25 cm	Does not apply	
> 100,000 ≤ 1,000,000	Surface Course (*HMA) Base Course Compacted Subgrade Subjacent Course	9 cm 25 cm 45 cm 30 cm ---	Does not apply	
> 1,000,000 ≤ 3,000,000	Surface Course (*HMA) Base Course Compacted Subgrade Subjacent Course	12 cm 30 cm 40 cm 70 cm	Does not apply	
> 3,000,000 ≤ 10,000,000	Surface Course (*HMA) Base Course Subbase Course Compacted Subgrade Subjacent Course	16 cm 20 cm 20 cm 35 cm 70 cm	Surface Course (*HMA) Binder Base Course Subbase Course Compacted Subgrade Subjacent Course	5 cm 15 cm 20 cm 45 cm 70 cm
> 10,000,000 ≤ 30,000,000	Surface Course (*HMA) Base Course Subbase Course Compacted Subgrade Subjacent Course	20 cm 20 cm 20 cm 35 cm 70 cm	Surface Course (*HMA) Binder Base Course Subbase Course Compacted Subgrade Subjacent Course	8 cm 15 cm 30 cm 40 cm 70 cm
> 30,000,000 ≤ 50,000,000	Surface Course (*HMA) Base Course Subbase Course Compacted Subgrade Subjacent Course	22 cm 20 cm 20 cm 40 cm 70 cm	Surface Course (*HMA) Binder Base Course Subbase Course Compacted Subgrade Subjacent Course	6 cm 20 cm 30 cm 40 cm 70 cm
> 50,000,000 ≤ 100,000,000	Surface Course (*HMA) Base Course Subbase Course Compacted Subgrade Subjacent Course	25 cm 20 cm 25 cm 35 cm 70 cm	Surface Course (*HMA) Binder Base Course Subbase Course Compacted Subgrade Subjacent Course	6 cm 22 cm 30 cm 45 cm 70 cm
> 100,000,000 ≤ 150,000,000	Surface Course (*HMA) Base Course Subbase Course Compacted Subgrade Subjacent Course	27 cm 20 cm 20 cm 40 cm 70 cm	Surface Course (*HMA) Binder Base Course Subbase Course Compacted Subgrade Subjacent Course	8 cm 22 cm 30 cm 45 cm 70 cm

* Hot Mix Asphalt

Figure 6. Type sections for asphalt pavements in Baja California.

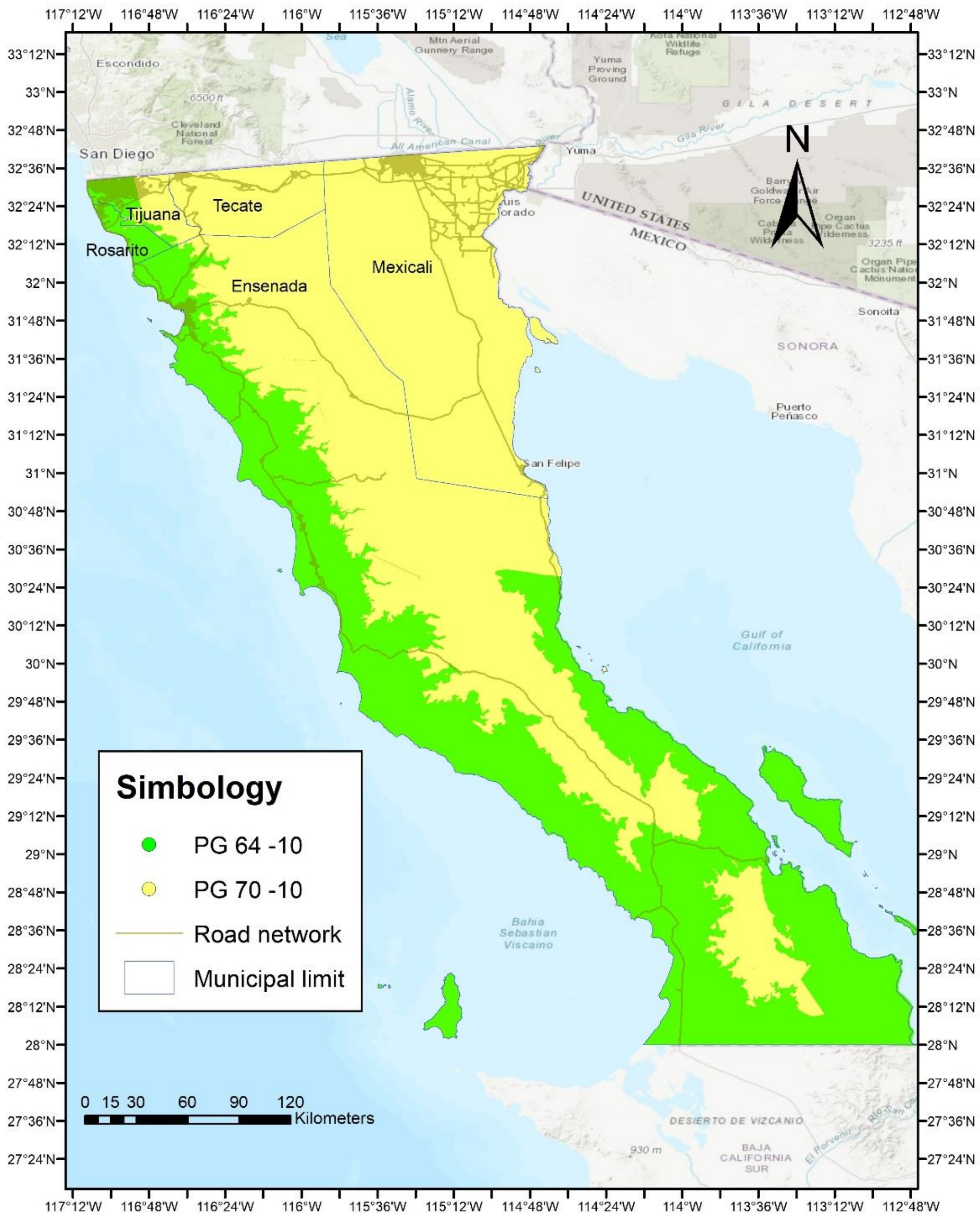

Figure 7. Performance grade (PG) selection map of asphalt binder.

In the case study, two PG were found, characterized mainly by the proximity to the oceans, the presence of mountain ranges, and desert areas. It is important to mention that the PG can be adjusted based on the non-recovered deformation of the J_{nr} binder so that the asphalt adapts better to traffic intensity and speed. However, it is advisable to carry out the above in a specific area once the road to be built has been defined. In this sense, in the present analysis, regionalization of the PG had to be carried out only from the area of influence of the climatological stations.

4.3. Serviceability Analysis and Economic Implications

The results of the evaluation of interventions through the serviceability curve for different damage coefficients, show the need to increase maintenance interventions to maintain a road in good working conditions, over a 20-year useful life (Figure 8).

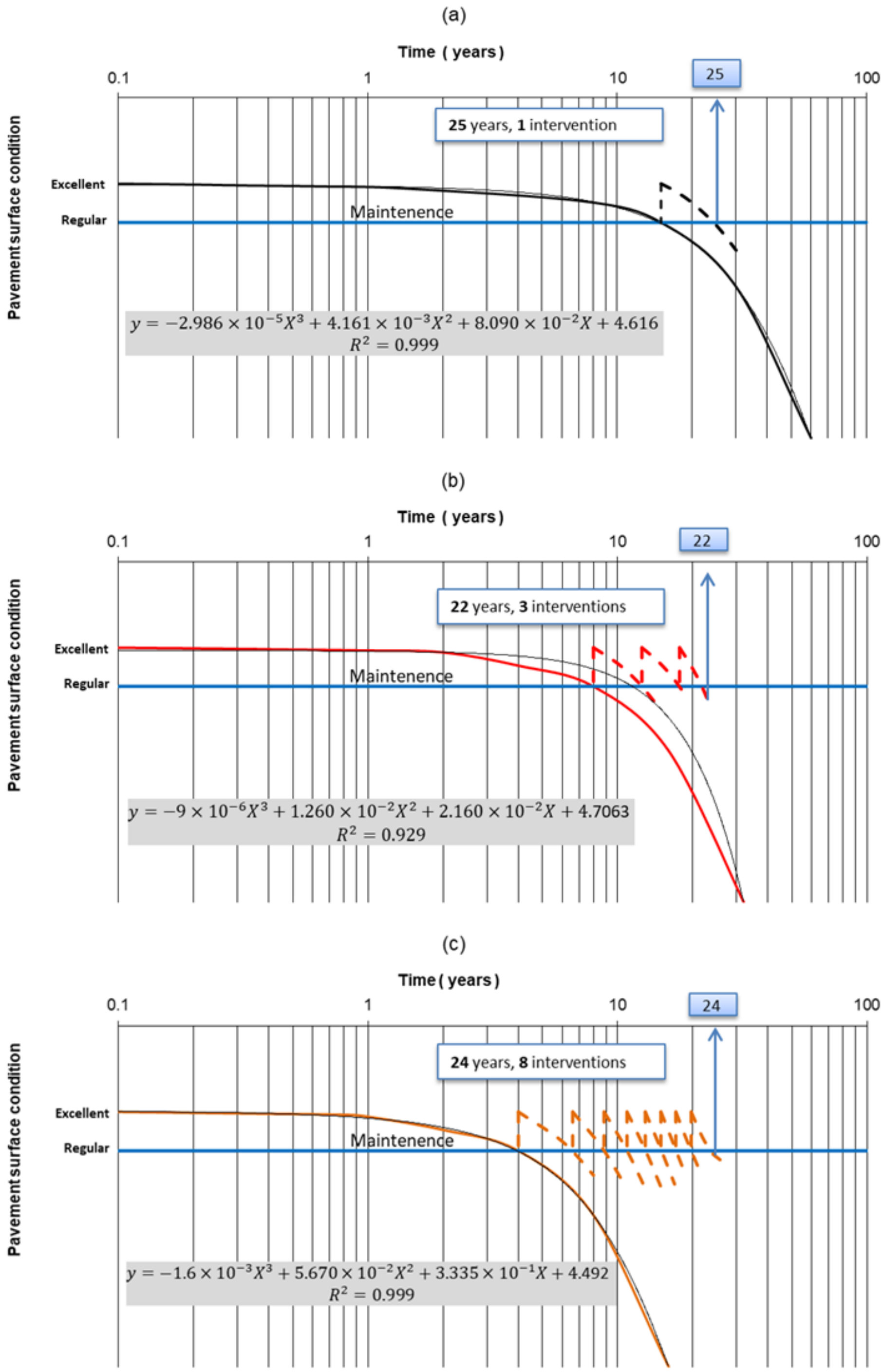

Figure 8. Number of maintenance operations required through the serviceability curve for different damage coefficients. (**a**) serviceability new coefficients; (**b**) serviceability with default coefficients; (**c**) serviceability with 1978 coefficients.

In this regard, the total cost of a road built with the proposed structure represents a higher construction cost than the one proposed by the current regulations. However, according to the results obtained, when using the proposed structure, a 20-year useful life is achieved with a single intervention. Unlike conventional structures that are supported by publication no. 444 of the UNAM Engineering Institute and in the Dispav-5 program, which require, respectively, eight and three interventions. It is for this reason that the proposal presented by this research considerably reduces the integral cost of the road to build and to preserve, as shown in Figure 9.

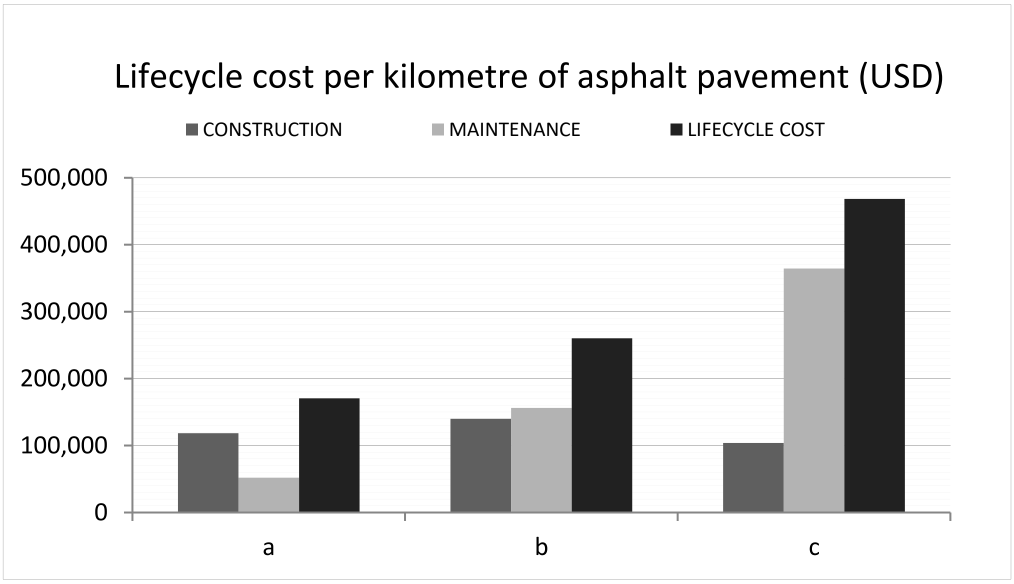

Figure 9. Comprehensive cost in 1 km of asphalt pavement. (**a**) serviceability new coefficients; (**b**) serviceability with default coefficients; (**c**) serviceability with 1978 coefficients.

5. Summary and Conclusions

In this research, a regionalized pavement design procedure is proposed, suitable for developing countries with limited resources and data to design with mechanical or mechanical-empirical approaches.

This procedure is based on calibrating asphalt pavements design variables through regionalized conditions. It was applied in the state of Baja California, México, highlighting these findings:

- Allows using available traffic data or fieldwork to estimate the damage received by the asphalt pavement.
- The resistance parameters of the materials that make up the pavement structure can be obtained through simple laboratory tests with reliable results.
- Proposes a simple procedure to establish the PG of asphalt cement, adjusting the information from the meteorological stations based on its temperature and altitude.
- The procedure develops a map that helps decision-making by the correct selection of asphalt cement.
- It sets a benchmark for pavement designers by allowing their designs to be compared with standard structures.
- Designing with this approach can considerably reduce the integral cost of the road to build and to preserve.
- The procedure can support the planning and decision-making regarding investment in asphalt pavements in different territorial scales, considering urban areas, regions, or even an entire country.

The proposed method allows obtaining reliable results. However, an improvement opportunity is to integrate all processes into a single pavement design tool to facilitate the pavement design task.

Thus, roads construction with asphalt pavements extends beyond the pavement design stage since construction processes, quality of materials, and weather and operating conditions contribute significantly to the durability. However, the use of regionalized methods reduces uncertainty in the design stage, contributing to the vision of improving the durability and service conditions of the road infrastructure.

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References

1. Nicholls, J.; McHale, M.; Griffiths, R. *Best Practice Guide for Durability of Asphalt Pavements*; Transport Research Laboratory Wokingham: Wokingham, UK, 2008.
2. Miranda Rebolledo, J.R. *Deterioros en Pavimentos Flexibles y Rígidos*; Universidad Austral de Chile: Valdivia, Chile, 2010.
3. Valdés, G.; Pérez-Jiménez, F.; Martinez, A. Influencia de la temperatura y tipo de mezcla asfáltica en el comportamiento a fatiga de los pavimentos flexibles. *Rev. Constr.* **2012**, *11*, 87–100. [CrossRef]
4. Montoya, J. Implementación del Sistema de Gestión de Pavimentos con Herramienta HDM-4 para la Red Vial Nro. 5 Tramo Ancón–Huacho–Pativilca. In *Tesis (Ingeniero Civil) Lima*; Universidad Ricardo Palma: Lima, Peru, 2007; p. 397.
5. Andersen, S.; Levenberg, E.; Andersen, M.B. Efficient reevaluation of surface displacements in a layered elastic half-space. *Int. J. Pavement Eng.* **2020**, *21*, 408–415. [CrossRef]
6. Darter, M.I.; Hudson, W.R.; Haas, R.C. Selection of Optimal Pavement Designs Considering Reliability Performance and Costs. *Transp. Res. Rec.* **1974**, 67–79. Available online: https://onlinepubs.trb.org/Onlinepubs/trr/1974/485/485-006.pdf (accessed on 12 March 2022).
7. Darter, M.; Khazanovich, L.; Yu, T.; Mallela, J. Reliability analysis of cracking and faulting prediction in the new mechanistic–empirical pavement design procedure. *Transp. Res. Rec.* **2005**, *1936*, 150–160. [CrossRef]
8. Moreno, M.A.R.; Navarro, T.E.; Zeballos, G.T. Including reliability in the AASHTO-93 flexible pavement design method integrating pavement deterioration models. *Rev. Constr.* **2017**, *16*, 284–294.
9. Vásquez-Varela, L.R.; García-Orozco, F.J. An overview of asphalt pavement design for streets and roads. *Rev. Fac. Ing. Univ. Antioq.* **2021**, *98*, 10–26. [CrossRef]
10. El-Ashwah, A.S.; El-Badawy, S.M.; Gabr, A.R. A Simplified Mechanistic-Empirical Flexible Pavement Design Method for Moderate to Hot Climate Regions. *Sustainability* **2021**, *13*, 10760. [CrossRef]
11. Islam, M.R.; Tarefder, R.A. *Pavement Design: Materials, Analysis, and Highways*; McGraw-Hill Education: New York, NY, USA, 2020.
12. Li, Q.; Xiao, D.X.; Wang, K.C.; Hall, K.D.; Qiu, Y. Mechanistic-empirical pavement design guide (MEPDG): A bird's-eye view. *J. Mod. Transp.* **2011**, *19*, 114–133. [CrossRef]
13. Martínez Díaz, M.; Pérez, I. Mechanistic-empirical pavement design guide: Características y elementos distintivos. *Rev. Constr.* **2015**, *14*, 32–40.
14. Chehab, G.R.; Chehade, R.H.; Houssami, L.; Mrad, R. Implementation initiatives of the mechanistic-empirical pavement design guide in countries with insufficient design input data–the case of lebanon. In Proceedings of the International Congress and Exhibition "Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology", Sharm Elsheikh, Egypt, 15–19 July 2017; pp. 147–167.
15. Das, A.J. Structural design of asphalt pavements: Principles and practices in various design guidelines. *Transp. Dev. Econ.* **2015**, *1*, 25–32. [CrossRef]
16. SCT. *CMT Características De Los Materiales*; Instituto Mexicano del Transporte: Pedro Escobedo, Mexico, 2013.
17. Baladi, G.Y.; Prohaska, M.; Thomas, K.; Dawson, T.; Musunuru, G. *Pavement Performance Measures and Forecasting and the Effects of Maintenance and Rehabilitation Strategy on Treatment Effectiveness*; Federal Highway Administration: Washington, DC, USA, 2017.
18. Rico Rodríguez, A.; Téllez Gutiérrez, R.; Garnica Anguas, P. *Pavimentos flexibles. Problemática, Metodologías de Diseño y Tendencias*; SCT: Lagos de Moreno, Mexico, 1998.
19. Walubita, L.F.; Faruk, A.N.; Lee, S.I.; Nguyen, D.; Hassan, R.; Scullion, T. *HMA Shear Resistance, permanent Deformation, and Rutting Tests for Texas Mixes: Final Year-2 Report*; Texas A&M Transportation Institute: College Station, TX, USA, 2014.
20. Bo, L.; Kundwa, M.J.; Jiao, C.Y.; Wei, Z.X. Pavement performance evaluation and maintenance decision-making in Rwanda. *Int. J. Pavement Res. Technol.* **2019**, *12*, 443–447. [CrossRef]
21. Jia, Y.; Yang, Y.; Liu, G.; Gao, Y.; Yang, T.; Hu, D. Reliability assessment of flexural fatigue failure of asphalt mixture: A new perspective. *Constr. Build. Mater.* **2020**, *257*, 119553. [CrossRef]

22. Lv, Q.; Huang, W.; Sadek, H.; Xiao, F.; Yan, C. Investigation of the rutting performance of various modified asphalt mixtures using the Hamburg Wheel-Tracking Device test and Multiple Stress Creep Recovery test. *Constr. Build. Mater.* **2019**, *206*, 62–70. [CrossRef]
23. Garnica Anguas, P.; Correa, Á. Conceptos Mecanicistas en Pavimentos. 2004. Available online: https://trid.trb.org/view/1100428 (accessed on 12 March 2022).
24. AASHTO, Group; Transportation Officials. *Guide for Design of Pavement Structures*; AASHTO: Washington, DC, USA, 1993.
25. Transportation Federal Highway Administration. *Comprehensive Truck Size and Weight Study*; US Department of Transportation: Washington, DC, USA, 1995.
26. Lavin, P. *Asphalt Pavements: A Practical Guide to Design, Production and Maintenance for Engineers and Architects*; CRC Press: Boca Raton, FL, USA, 2003.
27. Rahman, M.M.; Gassman, S.L. Permanent Deformation Characteristics of Coarse Grained Subgrade Soils Using Repeated Load Triaxial Tests. In Proceedings of the Eighth International Conference on Case Histories in Geotechnical Engineering (Geo-Congress 2019) American Society of Civil Engineers, Philadelphia, PA, USA, 24–27 March 2019.
28. Ramos, A.; Correia, A.G.; Indraratna, B.; Ngo, T.; Calçada, R.; Costa, P.A. Mechanistic-empirical permanent deformation models: Laboratory testing, modelling and ranking. *Transp. Geotech.* **2020**, *23*, 100326. [CrossRef]
29. Xiao, Y.; Tutumluer, E.; Mishra, D. Performance evaluations of unbound aggregate permanent deformation models for various aggregate physical properties. *Transp. Res. Rec.* **2015**, *2525*, 20–30. [CrossRef]
30. Xiao, Y.; Mishra, D.; Tutumluer, E.J.T.R.R. Framework to improve the pavement ME design unbound aggregate rutting model by using field data. *Res. Artic.* **2016**, *2591*, 57–69. [CrossRef]
31. Al-Mohammedawi, A.; Mollenhauer, K. Current Research and Challenges in Bitumen Emulsion Manufacturing and Its Properties. *Materials* **2022**, *15*, 2026. [CrossRef] [PubMed]
32. Huang, Y.H. *Pavement Analysis and Design*; Pearson Prentice Hall: Hoboken, NJ, USA, 2004.
33. Rengifo Gonzales, J.A.; Vargas Villaca, M.A. Análisis comparativo entre pavimento flexible convencional y pavimento flexible reciclado en las cuadras 1-29 de la avenida La Paz San Miguel-Lima. 2017. Available online: https://alicia.concytec.gob.pe/vufind/Record/USMP_05c2b60640365902e605d787b74e06fc/Description (accessed on 12 March 2022).
34. Calderón, A.U. Guía de pruebas de laboratorio y muestreo en campo para la verificación de calidad en materiales de un pavimento asfáltico. *Métodos Y Mater.* **2011**, *1*, 39–50. [CrossRef]
35. Lukanen, E.O.; Stubstad, R.; Briggs, R.C.; Intertec, B. *Temperature Predictions and Adjustment Factors for Asphalt Pavement*; Turner-Fairbank Highway Research Center: McLean, VA, USA, 2000.
36. Bairgi, B.K.; Tarefder, R.A. Effect of foaming water contents on high-temperature rheological characteristics of foamed asphalt binder. In Proceedings of the International Conference on Transportation and Development 2018, Reston, VA, USA, 11 July 2018.
37. Rondón Quintana, H.A.; Ruge Cárdenas, J.C.; Moreno Anselmi, L.Á. Efecto del agua sobre el asfalto y su posible influencia en el daño por humedad en una mezcla asfáltica porosa. *Ingeniare. Rev. Chil. Ing.* **2016**, *24*, 558–569. [CrossRef]
38. Li, X.; Marasteanu, M. Evaluation of the low temperature fracture resistance of asphalt mixtures using the semi circular bend test. In Proceedings of the Association of Asphalt Paving Technologists-Proceedings of the Technology Sessions, AAPT 2004, Lino Lakes, MN, USA, 7–9 June 2004; pp. 401–426.
39. Wei, J.; Chen, Q.; Du, J.; Liu, K.; Jiang, K. Study on the Durability of Acid Rain Erosion-Resistant Asphalt Mixtures. *Materials* **2022**, *15*, 1849. [CrossRef] [PubMed]
40. Infante, A.S.F.; Lozano, F.A.R.; Barrera, D.H.; Jiménez, C.; Bohórquez, N. Análisis de un asfalto modificado con icopor y su incidencia en una mezcla asfáltica densa en caliente. *Ing. E Investig.* **2007**, *27*, 5–15.
41. Zhu, G.J.; Wu, S.P.; Liu, R.; Zhou, L. Study on the fatigue property for aged asphalt mixtures by using four point bending tests. In *Materials Science Forum*; Trans Tech Publications LtD.: Stafa-Zurich, Switzerland, 2009; pp. 289–294.
42. Sandoval, C.H.H.; Fonseca, A.M.P.; León, Y.F. Factibilidad de mezclas asfálticas de alto módulo con agregados del área de influencia de Tunja. *Rev. Fac. Ing.* **2013**, *22*, 9–20. [CrossRef]
43. Pradena, M. Análisis del Índice de Regularidad Internacional de Construcción en Superficies Asfalticas Utilizando el Software HDM-4. *Rev. Constr.* **2008**, *7*, 72–83.
44. Vázquez, R. Proyecto geométrico ejecutivo de la rehabilitación estructural del pavimento incluye obras menores y señalamiento, del subtramo km. In *132 + 800 al km. 147 + 915, Tramo Tepalcapa-Palmillas, de la Autopista México—Querétaro*; Instituto Politécnico Nacional: Mexico City, Mexico, 2006.
45. Miquel, M.P. Análisis de Regularidad Superficial en caminos pavimentados. *Rev. Constr.* **2006**, *5*, 16–22.
46. Meneses, S.; Ferreira, A. Flexible pavement maintenance programming considering the minimisation of maintenance and rehabilitation costs and the maximisation of the residual value of pavements. *Int. J. Pavement Eng.* **2015**, *16*, 571–586. [CrossRef]
47. Santos, J.; Ferreira, A. Pavement design optimization considering costs and preventive interventions. *J. Transp. Eng.* **2012**, *138*, 911–923. [CrossRef]
48. Augeri, M.G.; Greco, S.; Nicolosi, V. Planning urban pavement maintenance by a new interactive multiobjective optimization approach. *Eur. Transp. Res. Rev.* **2019**, *11*, 17. [CrossRef]
49. de Bortoli, A.; Féraille, A.; Leurent, F. Towards Road Sustainability—Part I: Principles and Holistic Assessment Method for Pavement Maintenance Policies. *Sustainability* **2022**, *14*, 1513. [CrossRef]

50. Jitsangiam, P.; Chindaprasirt, P.; Nikraz, H. An evaluation of the suitability of SUPERPAVE and Marshall asphalt mix designs as they relate to Thailand's climatic conditions. *Constr. Build. Mater.* **2013**, *40*, 961–970. [CrossRef]
51. Yang, Y.; Qian, B.; Xu, Q.; Yang, Y. Climate regionalization of asphalt pavement based on the K-means clustering algorithm. *Adv. Civ. Eng.* **2020**, *2020*, 6917243. [CrossRef]
52. Guerrero, N.H.; Albitres, C.M.C. La deformación permanente en las mezclas asfálticas y el consecuente deterioro de los pavimentos asfálticos en el Perú. *Perf. Ing.* **2015**, *11*, 11.
53. Leonovich, I.; Melnikova, I. Influence of temperature on the formation of damages in asphalt concrete pavements under climatic conditions of the Republic of Belarus. *Balt. J. Road Bridge Eng.* **2012**, *7*, 42–47. [CrossRef]
54. Bandara, N.; Henson, S.; Klieber, K. Creating a climate zone map for mechanistic empirical pavement designs. In Proceedings of the T&DI Congress 2014: Planes, Trains, and Automobiles, Orlando, FL, USA, 8–11 June 2014; pp. 682–691.
55. Pszczoła, M.; Ryś, D.; Jaskuła, P.; Drogi, M. Analysis of climatic zones in Poland with regard to asphalt performance grading. *Roads Bridges* **2017**, *16*, 245–264.
56. Hussain, G.M.A.; Abdulaziz, M.A.G.; Xiang, Z.N.; Al-Hammadi, M.A. Climate zones of the asphalt binder performance for the highway pavement design. *Civ. Eng. J.* **2020**, *6*, 2220–2230. [CrossRef]
57. Leiva Villacorta, F.; Camacho Garita, E.; Aguiar Moya, J.P. Simulación de variables climáticas en ensayos de daño acelerado de pavimentos a escala natural. *Infraestruct. Vial* **2016**, *18*, 20–29. [CrossRef]
58. INEGI. *Anuario de Estadísticas por Entidad Federativa 2011*; Instituto Nacional de Estadistica y Geografia: Mexico City, Mexico, 2011.
59. García, L.; Mungaray-Moctezuma, A.; Calderón, J.; Sánchez-Atondo, A.; Gutiérrez-Moreno, J. Impacto de la accesibilidad carretera en la calidad de vida de las localidades urbanas y suburbanas de Baja California, México. *EURE* **2019**, *45*, 99–122. [CrossRef]
60. Corro, S.; Castillo, G.; Ossa, A.; Hernández, A.; Mandujano, D.; Hernández, F.; Arizaga, S.J. Incluyendo carreteras de altas especificaciones. In *Manual: Dispav-5, Versión 3.0*; UNAM: Mexico City, Mexico, 2014.
61. Corro, S.; Prado, G.; Rangel, A.J. *Diseño Estructural de Pavimentos Asfálticos, Incluyendo Carreteras de Altas Especificaciones*; UNAM: Mexico City, Mexico, 1999.
62. Cuza-Sorolla, A.; Hernández-Aguilar, M.L.; Barrera-Rojas, M.Á. Aplicación de polígonos Thiessen para la definición y análisis de áreas de influencia del sistema de salud en ciudades costeras del estado de Quintana Roo. *Quivera Rev. Estud. Territ.* **2021**, *23*, 49–71. [CrossRef]