Research Paper

International Journal of Research and Review
Volume 11 ; Issue : 10 ; October 2024
Website: www.ijrrjournal.com
E-ISSN : 2349-9788 ; P-ISSN : 2454-2237

Study of the Influence of the Variability of Traffic-Related Parameters on the Service Life of Flexible Pavement Structures in Senegal by a Mechanistic-Empirical Approach

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DOI : https://doi.org/10.52403/ijrr.20241007

ABSTRACT

The results of the study showed that exceeding the axle load and axle configuration are indisputably among the most damaging factors for flexible pavement structures in Senegal, made of local materials (Diack basalt, Sindia laterite). The regulatory axle load recommended by UEMOA for users is set at 11.5 tons and 12 tons for a single and twin axle respectively. For calculation purposes, this load is set at 13 tons. However, in Senegal, this axle load is often exceeded, and given the diversity of heavy goods vehicles in traffic, single axles, whose effects, according to several authors, are more detrimental to flexible pavement structures, are increasingly observed in road traffic. Differences in fatigue cracking and rutting damage between single and dual wheels, as well as load overruns, show the need to take axle configuration and possible overloads into account when dimensioning flexible pavement structures in Senegal, and when planning their maintenance, the costs of which are excessively high, according to Senegal's Autonomous Road Maintenance Fund (FERA).

Keywords: Single wheel, dual wheel, damage, fatigue cracking, rutting, traffic

INTRODUCTION

In Senegal, the transport sector is an essential factor in the economy. It contributes to the growth and improvement of people's living conditions through their mobility and the opening up of certain areas. Therefore, the construction of durable road structures is essential. However, significant deterioration and ruins are observed prematurely on road structures and maintenance needs are estimated according to the Autonomous Road Maintenance Fund (FERA) at one hundred and seventy-one (171) billion FCFA for the three fiscal years 2015 to 2017. Faced with such a network, which requires so many funds for its maintenance, the estimation of the life of these structures is fundamental in order to forecast the costs for future maintenance and rehabilitation.

The main objective of this article is the determination by a Mechanistic-Empirical design approach of the service life of pavement structures in terms of the number of permissible cycles by fatigue cracking and rutting. This design method has been widely applied in the dimensioning of flexible pavement structures. It is based on the mechanics of materials, which links an input, such as wheel load, to an output or pavement response, such as stress or strain. The approach consists in calculating the response of the pavement materials to the applied loading and then predicting the performance of the pavement from the response. To do this, the responses of the pavement are calculated using the calculation codes Kenlayer and Alizé LCPC, then the performance of the pavement is deduced from transfer functions proposed by the organizations namely, Asphalt Institute, Shell Oil and the University of Nottingham.

REVIEW OF LITERATURE

An important method frequently used in pavement performance analysis is the failure criterion, sometimes referred to as the transfer function, an equation used to predict pavement life in terms of the number of repetitions or loading cycles until failure, designated by equations $[Eq1]$ and $[Eq2]$. The most common transfer functions associate pavement responses to structural rutting, as opposed to surface rutting, and fatigue cracking. The deformation criterion of the platform, the transfer function for the number of load cycles to failure in the structural rutting (permanent deformation), is related to the vertical strain at the top of the platform layer. Different agencies have developed their own models, some of which contain tensile strain at the base of the bearing layer (ε_t), others use vertical deformation at the top of the platform (ε_z). Shell Petroleum International and Asphalt Institute have adopted two criteria in their empirical mechanistic design methods, namely fatigue cracking and rutting [1].

Fatigue cracking is related to tensile deformation at the base of the bearing layer $[Eq1]$.

$$N_f = f_1 \varepsilon_t^{-f_2} E_1^{-f_3} \qquad [Eq1]$$

N_f: Number of loading cycles before fatigue failure

ε_t: Tensile strain at the base of asphalt layer

E_1 : Young's modulus of asphalt layer

f_1, f_2 and f_3 are parameters of the wearing course material (Table 1). They are determined from laboratory fatigue tests [2].

A check against the permanent deformations on the pavement surface (rutting) is also made, that is, the permanent deformations in the unrelated granular materials and in the platform, do not lead to the appearance on the surface of excessive deformations, producing unacceptable ruts or uni defects.

$$N_d = 10^6 f_4 \varepsilon_z^{-f_5} \qquad [Eq2]$$

N_d represents the number of loading cycles before failure due to cumulative plastic deformation

ε_z is the vertical deformation at the top of the platform

f_4 and f_5 are parameters related to the untreated gravel (Table 1). They are determined by road tests [2].

Table 1 Summary of parameters

Model parameters f_i	Asphalt institute	Shell Oil	University of Nottingham
f_1	0,0796	0,0685	-
f_2	3,291	5,671	-
f_3	0,854	2,363	-
f_4	$1,36.10^{-9}$	$6,15.10^{-7}$	$1,13.10^{-6}$
f_5	4,477	4,0	3,571

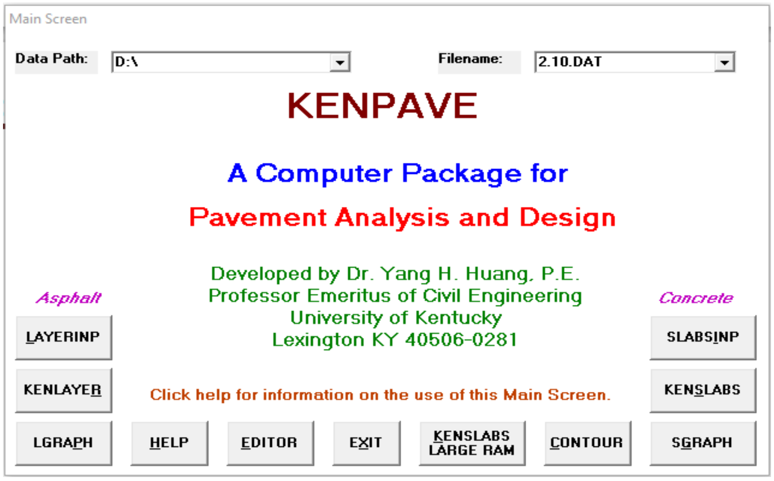
It should be noted that the sometimes significant variation between the f_i regression constants in table 1 is largely attributable to the test procedures used and the units employed [3].

Exceeding the axle load is one of the most damaging factors for flexible pavement structures. UEMOA (West African Economic and Monetary Union) regulation no. 14/2005/CM/UEMOA of December 16, 2005 on the harmonization of standards and procedures for the control of the weight gauge and axle load of heavy goods vehicles in the member states of the Union, sets the axle load at 12 tons for a single intermediate or rear axle with dual wheels [4]. However, recent studies have shown that this load is far from being respected. In fact, it is estimated that 60 to 70% of heavy goods vehicles are overloaded, contributing to the premature deterioration of roadways. The State of Senegal has therefore decided to implement a gradual control system to achieve a tolerance of 5% [5]. High loads cause permanent deformation, leading to rutting in the pavement. [6] have shown that longitudinal permanent deformation at the base of the wearing course increases by 200% to 400% when increasing the load from 42 to 86 kN. [7] observed a linear variation between tire load intensity and rutting. They reported that the damage caused depends not only on the weight of the vehicle, but also on the pattern of loads transmitted to the pavement. [8] show that the stresses caused by the tire load of a heavy vehicle are the major factor reducing the life of flexible pavements.

The mechanical loads taken into account in the dimensioning of the pavements come from the traffic loads which are applied on the surface of the bearing layer by the intermediaries of the tires. These tires can be made of single or dual wheels. [7] pointed out that the stresses and strains caused depend not only on the weight of the vehicle, but also on the axle configuration (single axles, tandem, tridem). The increase in the number of axles reduces the load transmitted to the pavement surface [9]. Indeed, a tandem axle produces less damage than a single axle [10]. Similarly, a tridem axle produces less damage than a tandem axle. [11] points out that there is a very large difference between the different types of wheels. They argue that single wheels cause more damage because of the increased contact pressures they cause. [12] and [13] confirm this, they indicate that this damage is related to tire width and contact pressure. The work of [14] on the response of various types of flexible pavements shows that the deformations obtained under single wheel loading are much higher than the deformations obtained under dual wheel loading.

Description of the Kenlayer calculation code

Kenlayer is a computer program developed at the University of Kentucky and used for the solution of a multilayer elastic system under a loaded circular region. The principle of the calculation of this software is based on the Burmister theory of an elastic multilayer system like other programs based on the analytical method. Kenlayer's superiority over other programs using Burmister's multilayer elastic theory is its ability to solve linear-elastic, nonlinear-elastic or viscoelastic systems. The program also performs damage analysis to assess design life given damage caused by fatigue cracking or permanent deformations, using basic expressions given by performance models such as those given by the Asphalt Institute [1]. In its present dimension, it can be applied to a maximum of 19 layers with output at 25 different radial coordinates and 19 different vertical coordinates, or a total of 475 points. To facilitate data entry and editing, a program called LAYERINP, distributed in the same package, is used. The program uses menus and forms for data entry in order to create and edit the data file. Figure 1 shows the main Kenlayer screen.



Main Screen

Data Path: D:\

Filename: 2.10.DAT

KENPAVE

A Computer Package for

Pavement Analysis and Design

Developed by Dr. Yang H. Huang, P.E.
Professor Emeritus of Civil Engineering
University of Kentucky
Lexington KY 40506-0281

Click help for information on the use of this Main Screen.

Figure 1 KENPAVE main screen

MATERIALS AND METHODS

The method consists of using the Kenlayer calculation code to determine the vertical strain at the top of the platform and the tensile strain below the wearing course, and deducing from the transfer functions the number of cycles permissible for fatigue cracking and rutting.

For the purposes of this model, the pavement will be studied on the assumption of linear behavior for all the materials making up the various layers. Each layer is characterized by a Young's modulus (E) and a Poisson's ratio (υ). The Young's moduli of the surface layer and the subgrade are 1300 MPa and 30 MPa respectively. The choice of modulus for the wearing course is not arbitrary. [15] studied different types of pavement with moduli of 2300 MPa and 1300 MPa in the wearing course. The first modulus is not the one usually used in Senegal. 1300 MPa represents the minimum modulus to avoid pavement failure [15]. The 2300 MPa modulus is obtained by iteration. In fact, several moduli were tested, starting with 1300 MPa. Gradually increasing this modulus up to 2200 MPa leads to pavement failure [15]. Still according to the researcher, failure disappears once a value of 2300 MPa is reached for a flexible pavement with an untreated gravel base layer and an 8 cm asphalt concrete. However, 1300 MPa represents a reference modulus for an wearing course, as the use of very high moduli results in the use of low thicknesses and hence undersizing [16]. Hence the choice of an asphalt concrete thickness of 8 cm throughout the rest of the modelling. Where necessary, this thickness is varied in order to assess the behavior of the pavement with respect to these variations.

To determine the Young's modulus (E) of subgrade materials, triaxial tests with repeated loading to study reversible behavior were carried out by [17] at the University of Wisconsin-Madison in the USA and [18] at the Université Gustave Eiffel in Nantes on untreated gravel from various locations in Senegal (Diack, Bakel, Bandia and Sindia). The non-linear elasticity model K-ϴ $[Eq3]$ was calibrated on the results of these tests to determine the parameters k1 and k2. These are used to calculate a reference value for Young's modulus in accordance with standard NF P 98-235-1 (q= 600 kPa, P= 300kPa). The mean values of elasticity parameters calculated in this way are 400 MPa and 274 MPa for Diack basalt and Sindia laterite respectively (Table 2). Poisson's ratio values are chosen with reference to the work of [16].

$$M_r = k_1 \left(\frac{\theta}{P_a}\right)^{k_2} \qquad [Eq3]$$

ϴ is the sum of the principal stresses;
k1 and k2 are the model parameters;
Pa is the normalizing atmospheric pressure.

Table 2 Material parameters for the structure studied

Pavement layers	Type of Layer	Thickness (m)	E(MPa)	Poisson's ratio v
Surface	Asphalt concrete	0,08	1300	0,35
Base	Diack's basalt	0,25	400	0,25
Sub-base	Laterite of Sindia	0,25	274	0,25
Subgrade	PF1	∞	30	0,25

Loading the structure

Traffic loads are applied to the pavement by tires, which exert forces on the tire-pavement contact surface. In Senegal, the reference load taken into account is that of 130 kN made up of two dual wheels (Figure 2). The loading considered in the simulation is that of a dual wheel half-axle and a 65 kN single wheel, in order to assess the impact of axle configuration on flexible pavement structures. The loading will be distributed and applied to one and two indentations in the surface layer. The reference load used for the design is 130 kN. It is shown in figure 2. Two cases will be studied, that of a single wheel and a dual wheel, in order to see which would create the most damage.

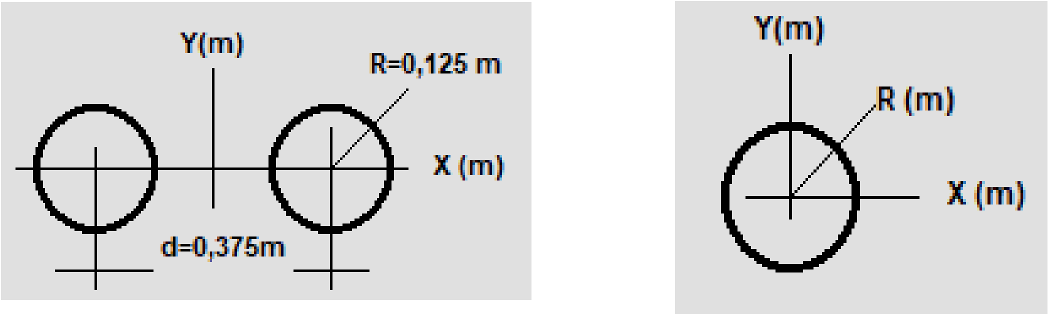
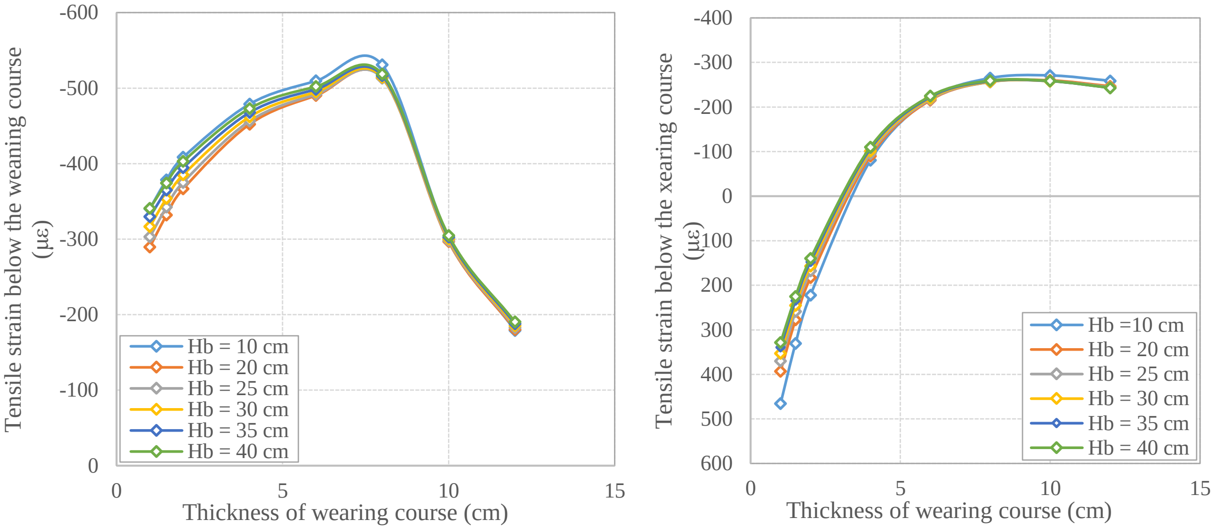


Figure 2 Standard axle load of 65 kN [19]

RESULTS AND DISCUSSIONS

Sensitivity analysis of fatigue and rutting cracking as a function of wearing course thickness and with regard to exceeding the regulatory load and axle configuration is studied. Variations in pavement response as a function of asphalt concrete thickness are shown in figure 3.

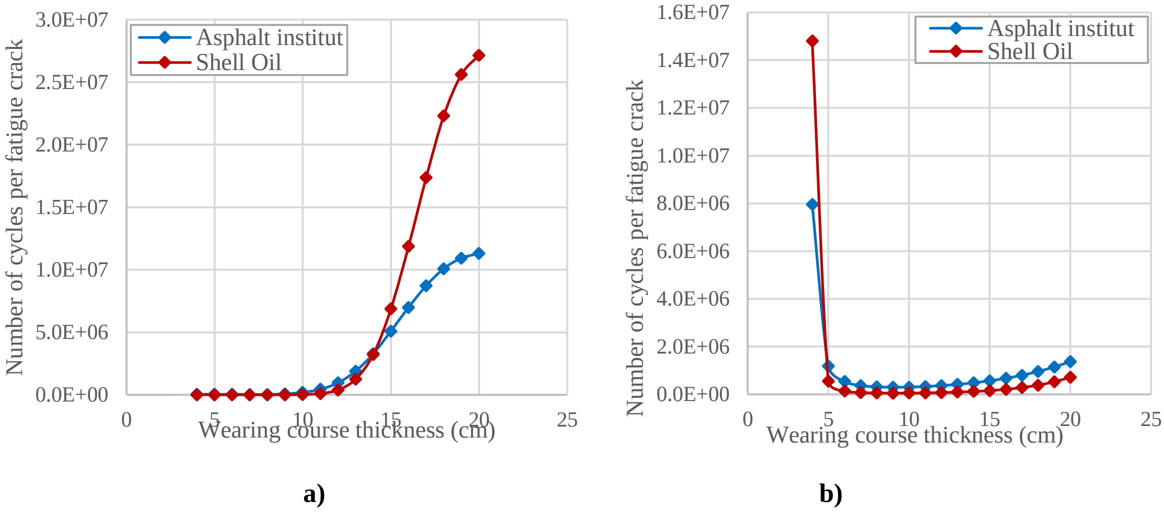
It can be seen that, whatever the thickness of the base layer, the tensile strain increases when the thickness of the wearing course is in the range from 1 cm to around 8 cm. From 8 cm upwards, the strain decreases with increasing layer thickness (Figure 3). It is at this point that the asphalt layer begins to act structurally and distribute the load to the lower layers. A maximum level of deformation was reached at 7.5 cm, confirming what is indicated in the literature, which is between 4 cm and 8 cm for road traffic loads [20]. A further increase in the thickness of the bearing layer reduces the bending of the structure and therefore the resulting deformation. We also note that with Alizé, when the thickness of the bearing layer is low, the horizontal deformation is compressive, that is, it is positive.



a) **b)**

Figure 3 Variation of tensile deformation below the bearing layer for a given H_b base layer thickness: a) Kenlayer b) Alizé

With Kenlayer, the number of permissible fatigue cracking cycles decreases between 4 cm and 8 cm. This decrease in the number of fatigue cracking cycles in the 4 cm to 8 cm range, while the thickness of the wearing course increases, could lead to premature damage to flexible pavement structures, especially as the catalog of new pavement structures and guide to pavement design in Senegal recommends a wearing course thickness of around 1 cm. From 8 cm upwards, this number starts to increase. In the thickness range from 4 to 9 cm, the number of cycles permissible for fatigue cracking is not very sensitive to variations in wearing course thickness (Figure 4a). However, from 9 cm up to 20 cm, there is a significant variation in this number of cycles, and this variation becomes more pronounced as the wearing course thickness approaches 20 cm. In fact, with Asphalt Institute, when the layer thickness is increased from 4 cm to 6 cm, that's to say a variation of 2 cm, the number of permissible fatigue cycles varies by 28% in relative variation. If the thickness is increased from 10 cm to 12 cm, that's to say a 2 cm variation, the number of cycles varies by 401%. These differences could be explained by the wide stress diffusion that increases with layer thickness. With Alizé, the number of cycles starts to increase from 9 cm bearing thickness. In contrast to Kenlayer, the number of cycles is highly sensitive between 4 cm and 5 cm. We find an absolute difference of $6{,}7 \times 10^6$ cycles, or 574% in relative variation with Asphalt Institute and 1.4×10^7cycles and 2561% with Shell Oil in absolute and relative values respectively (Figure 4b). Between 4 cm and 6 cm, the number of fatigue cycles with Asphalt Institute varies by 1372% in relative value. Between 10 cm and 12 cm, it varies by 20%. Comparing the differences between Alizé and Kenlayer, we see that in the wearing course thickness range from 4 cm to 10 cm, the number of permissible cycles to fatigue failure obtained with Alizé is higher than that obtained with Kenlayer. From 11 cm to 20 cm, the number of cycles is greater than with Kenlayer (Figure 5). But the problem is that the number of fatigue cracking cycles in the 4 cm to 9 cm range decreases as the thickness of the wearing course increases.



a) b)

Figure 4 Variation in the number of permissible cycles per fatigue: a) Kenlayer b) Alizé

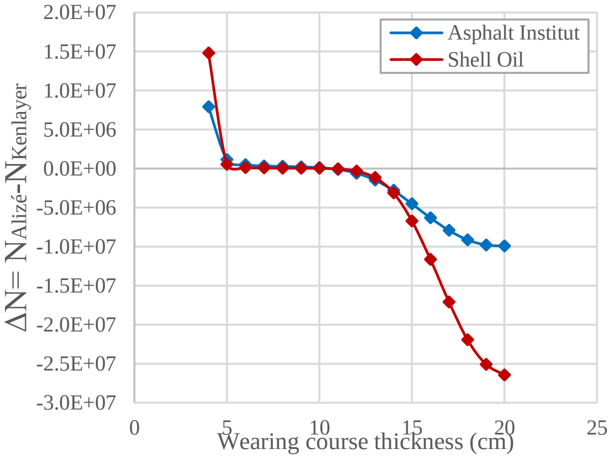
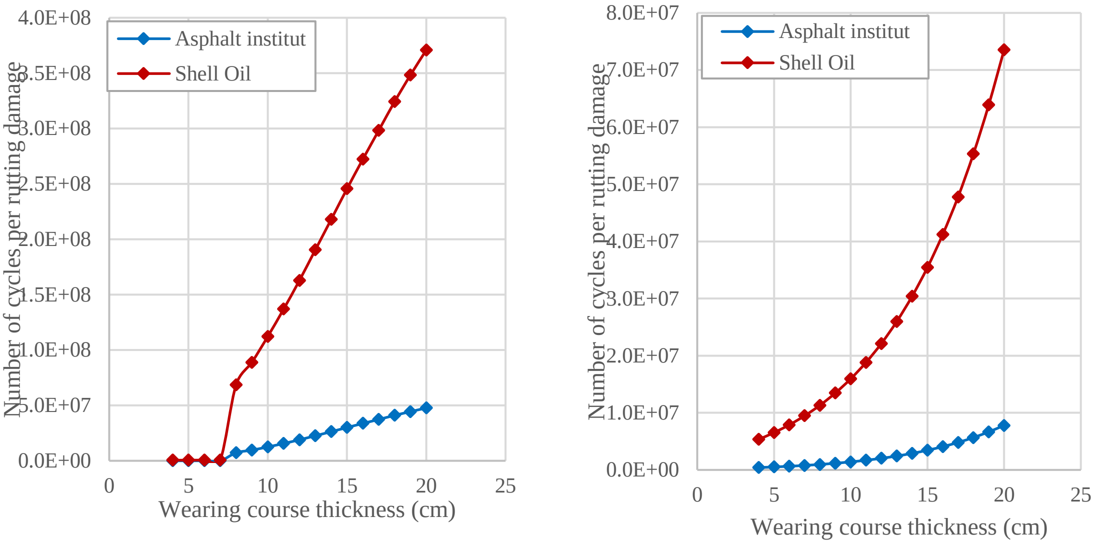


Figure 5 Variation in number of fatigue cycles as a function of wearing course thickness

In the study of the number of permissible cycles before rutting failure, we first note that the number of cycles increases with increasing wearing course thickness (Figure 6). However, the number of cycles is low in the 4 cm to 7 cm range, compared with values above 7 cm wearing course thickness. With Kenlayer, It is of the order of 10^4 cycles with Asphalt Institute and 10^5 cycles with Shell Oil. Whereas above 7 cm, this number reaches the order of 10^7cycles with Asphalt Institute and 10^8 cycles with Shell Oil. From 8 cm upwards, the model tends to overestimate the number of permissible cycles. From 4 cm to 6 cm, with Asphalt Institute, the number of cycles varies by 6×10^3 cycles, or 19.4% in relative terms. If the thickness is increased from 10 cm to 12 cm, a difference of 2 cm, the number of cycles varies by 52%. Whereas with Alizé, when the thickness goes from 4 cm to 6 cm, it varies by 2.27×10^5 cycles and 55% in absolute and relative variation respectively. Between 10 cm and 12 cm wearing course thickness, the number of cycles varies by 6.2×10^5 and 44% in relative variation.

Given the differences in terms of relative variation, the number of permissible cycles for fatigue cracking seems to be more sensitive to variations in wearing course thickness than the number of cycles for rutting damage. In fact, with Asphalt Institute, for values of 4 cm and 6 cm wearing course thickness, the relative difference is 28% and 19.4% for fatigue cracking and rutting respectively. And between 10 cm and 12 cm, the difference is 401% for fatigue cracking and 52% for rutting. This greater susceptibility to fatigue cracking could be explained by the fact that the wearing course is subjected to the most severe traffic aggression, being in direct contact with traffic loads.

In general, the rutting allowable load repetitions obtained by the Asphalt Institute is very low compared to those obtained by Shell Oil (Figure 6). These very high Shell Oil allowable repetitions can lead to poor design, that’s to say the choice of low pavement layer thicknesses.



a) **b)**

Figure 6 Variation in the number of permissible cycles per rut: a) Kenlayer b) Alizé

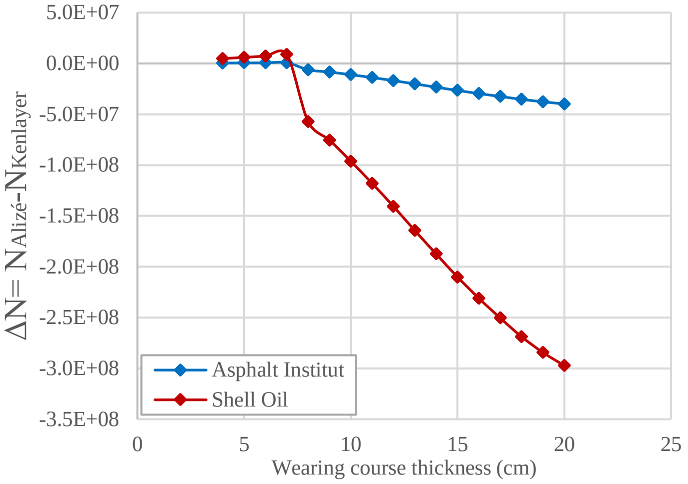


Figure 7 Variation in the number of permissible cycles per rut as a function of wearing course thickness

With the Alizé calculation code, for a wearing course thickness of between 4 cm and 7 cm, a 1 cm variation in thickness results in a variation of the order of 10^5 cycles and 10^6 cycles at rutting failure with Asphalt Institute and Shell Oil respectively. Between 7 cm and 20 cm, still with a variation of 1 cm, this number of cycles rises to around 10^6 with Asphalt Institute and 10^7 with Shell Oil. Compared with the number of cycles for rutting failure, that for fatigue cracking obtained for a variation of 1 cm in wearing course thickness shows the greater sensitivity of fatigue cracking compared with rutting damage for a variation in wearing course thickness. In addition, this significant variation in the number of cycles to rutting and more or less significant variation in the number of cycles to fatigue failure for a variation of 1 cm in thickness could lead to premature deterioration of pavement structures calculated with the Alizé design code. This greater sensitivity to fatigue cracking is illustrated in figure 8.

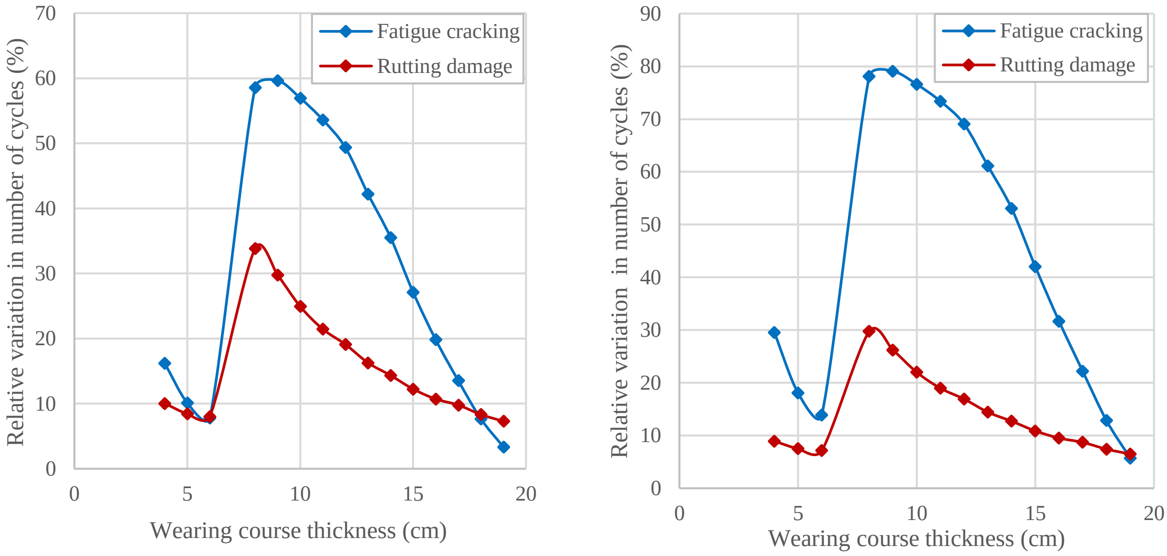


Figure 8 Evolution of relative variation as a function of wearing course thickness with Alizé: a) Asphalt Institute b) Shell Oil

Effect of exceeding regulatory loads

The results of this study show that the vertical deformation at the top of the platform and that below the wearing course vary linearly with increasing load. However, the variation is much greater with vertical deformation, with a slope of 48.014 compared with 16.318 for tensile deformation (Figure 9). The results also show that it is possible to predict the effect of overloading on pavement response. It can be seen that, as axle load increases, the number of permissible cycles to fatigue and rutting failure decreases (Figure 10). This is due to the increase in tensile deformation below the wearing course and vertical deformation at the top of the subgrade.

For flexible pavement structures, fatigue cracking would appear to be more sensitive to exceeding the reference load than rutting. This could be explained by the high repeated bending stresses beneath the asphalt concrete layer, which can reach permissible values prematurely.

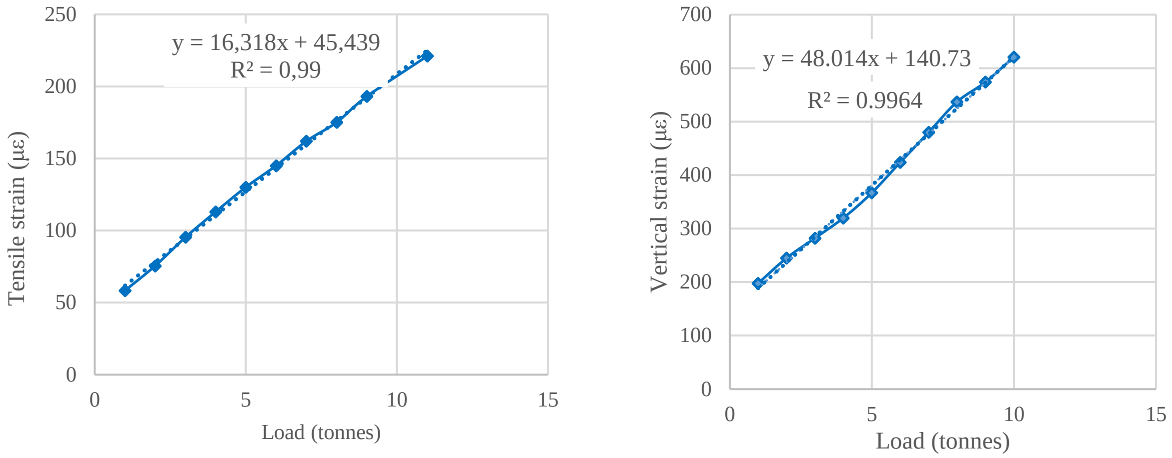


Figure 9 Pavement response as a function of axle load

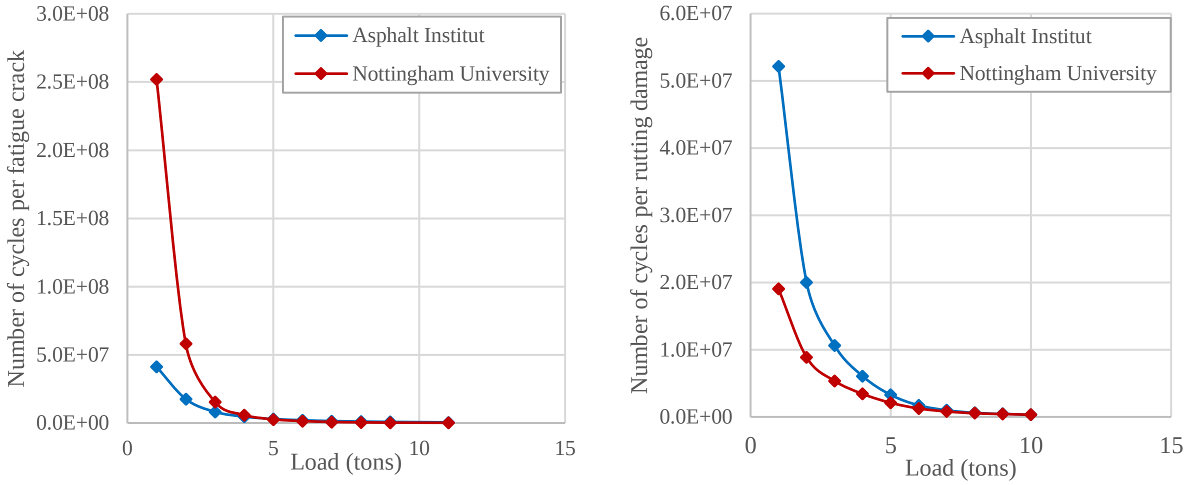


Figure 10 Number of permissible cycles as a function of axle load

The almost linear evolution ($R^2 = 0.99$) of the number of cycles as a function of axle overload is illustrated in figure 11. It shows the high sensitivity of flexible pavement structures in relation to their service life in the event of overloads, but also the prediction of a reduction in this service life.

For an overload of 12.5 tons, that’s to say 1 ton more than the regulation axle (11.5 tons), the number of fatigue cracking cycles is reduced by 0.62 million cycles with the Asphalt Institute and 0.67 million with the University of Nottingham respectively. The number of rutting cycles is reduced by 0.74 million and 0.45 million with Asphalt Institute and Nottingham University respectively.

For a variation of 4 tons in relation to the regulation axle, the number of fatigue cracking cycles decreases by 1.5 million cycles with Asphalt Institute and 1.6 million with the University of Nottingham respectively. The number of rutting cycles was reduced by 1.7 million and 1.3 million with the Asphalt Institute and the University of Nottingham respectively.

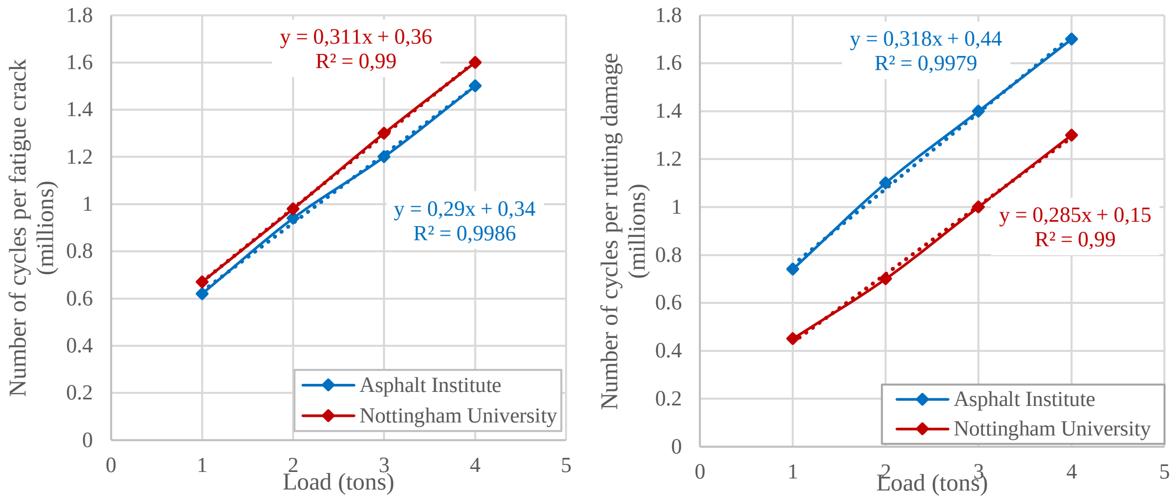


Figure 11 Evolution of the overload in relation to the legal axle as a function of the number of admissible cycles

Effect of axle configuration

A comparative study of the effect of axle configuration on pavement response is shown in figures 12 and 13. It can be seen that the deformations generated by the single wheel are higher than those obtained with the dual wheel. It can also be seen that this difference decreases with depth and even tends to cancel out towards the subgrade layer (Figure 12). The more unfavorable effect of the single wheel compared to the dual wheel could be explained by the fact that the single wheel tends to puncture the structure. With regard to variations in tensile deformation below the wearing course and vertical deformation at the top of the platform, these pavement responses are higher with the single wheel than with the dual wheel. However, the greatest difference is noted for wearing course thicknesses in the 4 cm and 8 cm range (Figure 13). Indeed, for a 4 cm thickness, the tensile strain deviation is 265.4 με and 269.9 με for an 8 cm thickness. However, for a thickness of 15 cm, for example, the deviation is 76.9 με. Hence the need to take into account the effect of the single wheel in the design of flexible pavement structures, given the diversity of axle configurations in Senegalese road traffic.

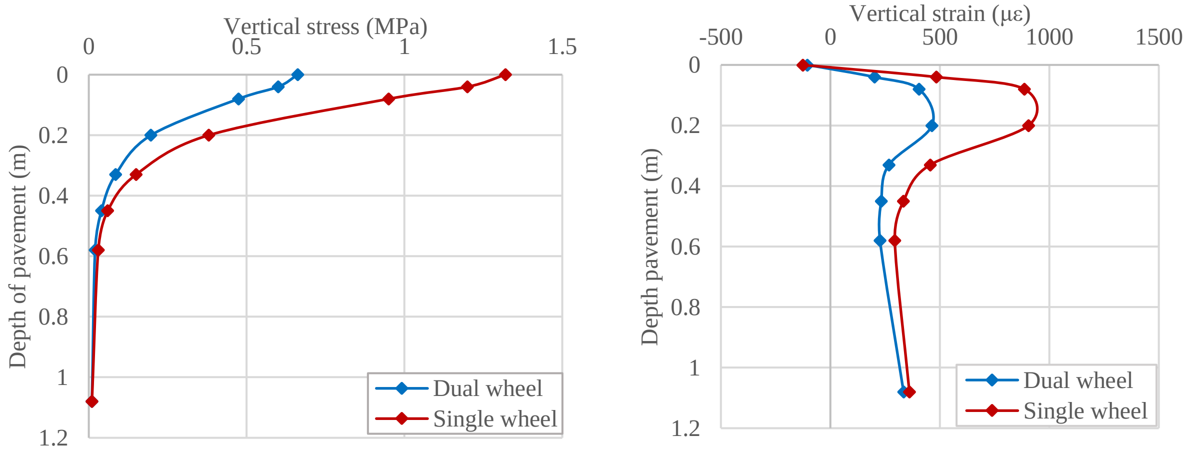


Figure 12 Stress and vertical strain as a function of pavement depth

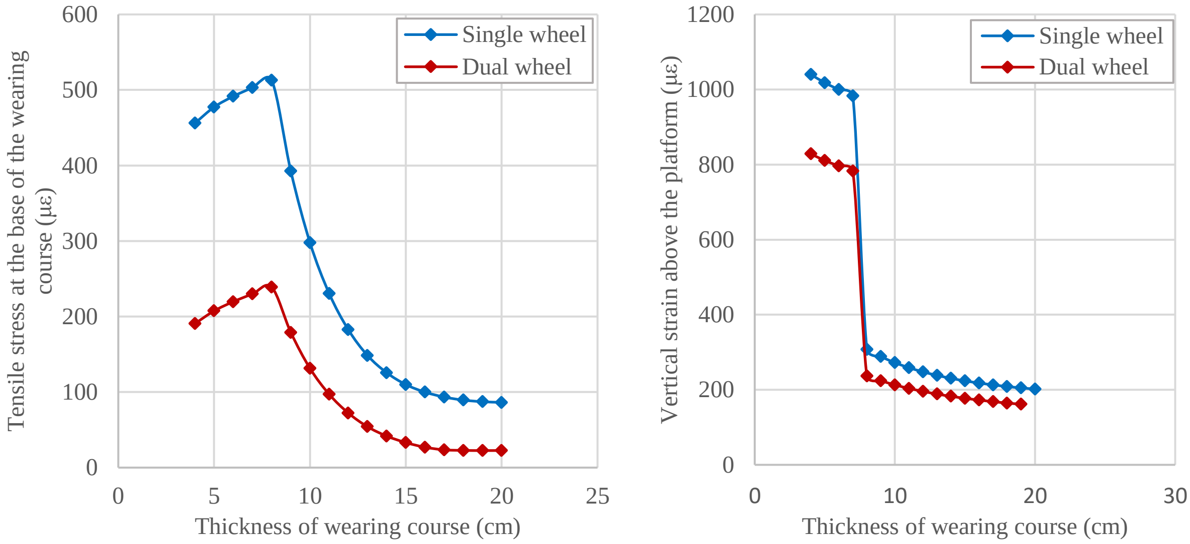


Figure 13 Evolution of pavement response as a function of wearing course thickness and axle configuration

By the same token, the number of permissible cycles is lower with all models in the case of a single wheel. In fact, the higher the tensile deformation below the wearing course or the vertical deformation at the top of the subgrade, the lower the number of permissible cycles at failure or rutting. This sharp increase in the number of cycles could be explained in part by the wearing course's ability to act structurally from a certain thickness and distribute the load to the lower layers. This results in a sharp reduction in tensile deformation below the wearing course and vertical deformation above the subgrade, leading to a rapid increase in the number of cycles from a given wearing course thickness.

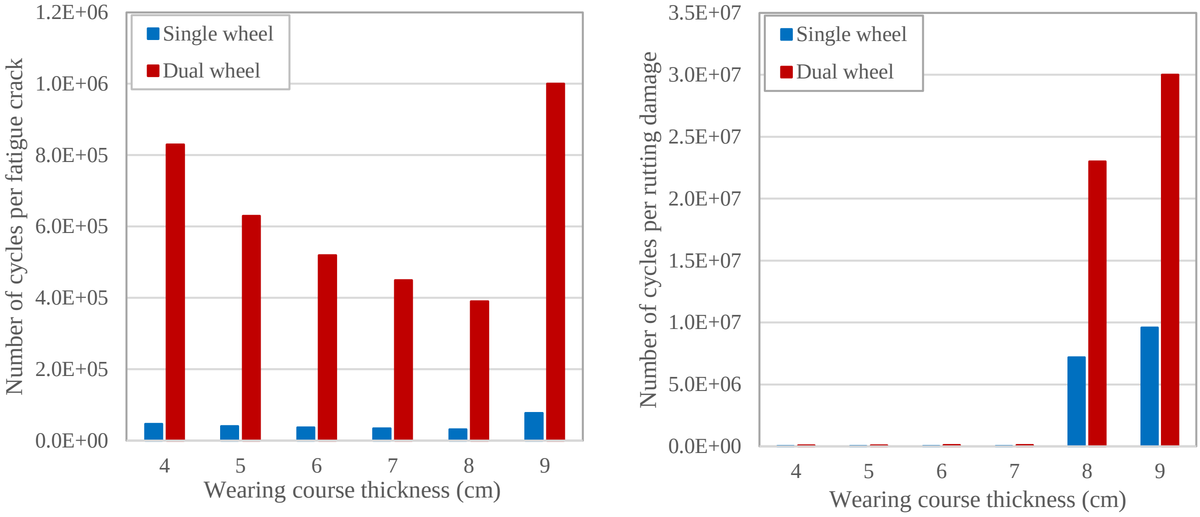
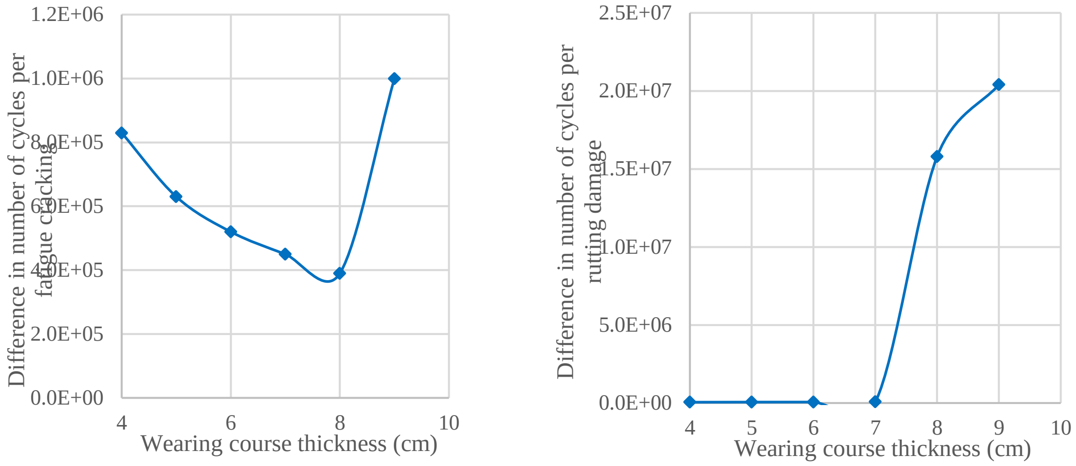


Figure 14 Influence of axle configuration on service life as a function of wearing course thickness (Asphalt Institute)



a) **b)**

Figure 15 Difference in number of cycles between dual wheel and single wheel (Asphalt Institute): a) fatigue cracking b) rutting damage

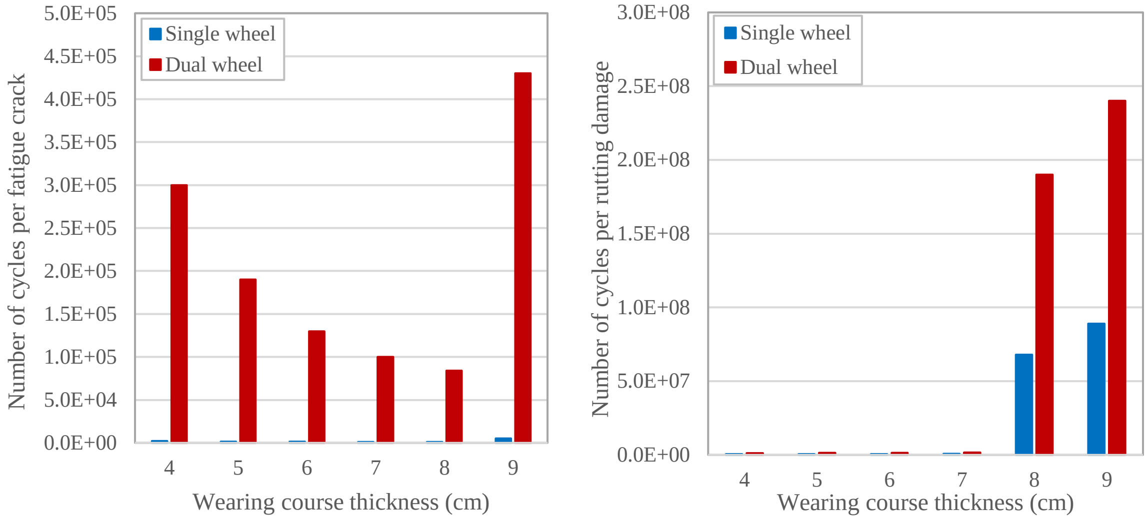
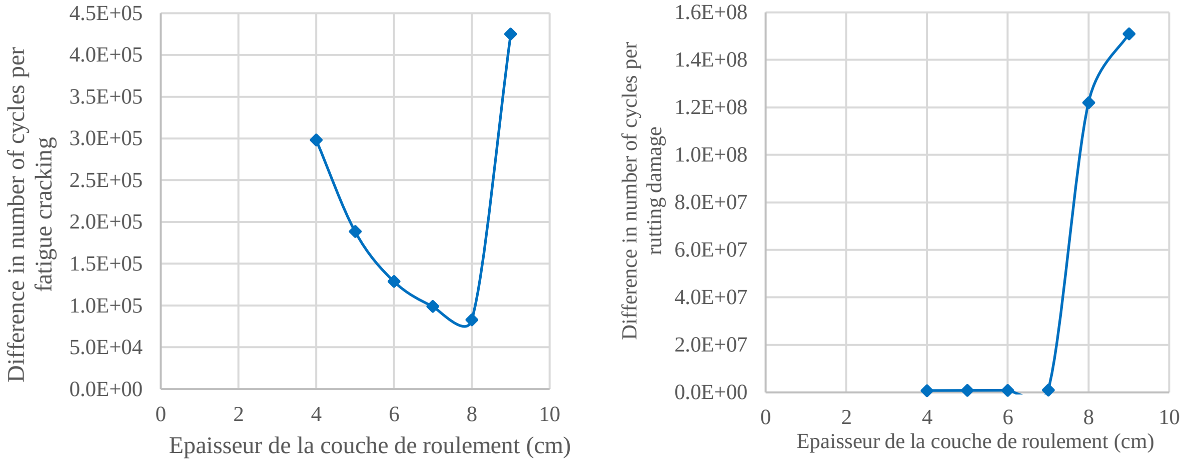


Figure 16 Sensitivity of permissible number of cycles to wearing course thickness (Shell Oil)



a) **b)**

Figure 17 Difference in number of cycles between dual wheel and single wheel (Shell Oil): a) fatigue cracking b) rutting damage

CONCLUSION

This paper focuses on the effect of traffic, particularly overloads and axle configuration, on the performance of flexible pavement structures. Its main objective is to determine pavement responses at critical points. Vertical deformation above the subgrade and tensile strain below the wearing course are determined using the Kenlayer calculation code. Pavement performance is then assessed using transfer functions such as Asphalt Institute and Shell Oil, and the number of cycles corresponding to fatigue cracking and rutting are deduced. The study is of vital importance in predicting the service life of flexible pavement structures, in order to plan for their future maintenance or rehabilitation. The results show that deformations in the pavement are greater in the case of single wheel than dual wheel loading. However, this variation is cancelled out as we approach the platform. As for the effect of exceeding the regulatory load, the latter varies linearly with the tensile strain below the wearing course and the vertical strain at the top of the platform, and consequently, for a given overload, these pavement responses can be predicted. The significant differences in damage between single and dual wheels, and in load overshoot, show the need to take axle configuration and possible overloads into account when dimensioning flexible pavement structures and predicting their maintenance.

Declaration by Authors

Acknowledgement: None
Source of Funding: None
Conflict of Interest: The authors declare no conflict of interest.

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How to cite this article: Babacar Diouf, Makhaly Ba, Mory Coulibaly. Study of the influence of the variability of traffic-related parameters on the service life of flexible pavement structures in Senegal by a Mechanistic-Empirical approach. *International Journal of Research and Review*. 2024; 11(10): 59-72. DOI: *https://doi.org/10.52403/ijrr.20241007*

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