

# CONSIDERATION OF PAVEMENT ROUGHNESS EFFECTS ON VEHICLE-PAVEMENT INTERACTION

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## ABSTRACT

Current mechanistic pavement design and analysis techniques use several simplifications to enable the process to be practical and cost-effective. These include equivalent vehicle loads, linear elastic analysis and static vehicle load and pavement response analysis. These simplifications allow the process of pavement design and analysis to be applied by the majority of engineers, but cause the process to be less related to real life. In a project performed at CSIR Transportek an investigation was done to establish the effects of incorporation of moving dynamic traffic loads in pavement design and analysis. The objective of this study was to identify parameters to be included in vehicle-pavement interaction analyses and to establish the expected effects of such analyses.

In previous papers the background and major findings of this study were reported. In this paper the focus is on quantification of the pavement roughness effects on the calculated structural pavement life and the effects of surfacing maintenance on the moving dynamic tyre loads generated by vehicles. A simplified method for calculating the moving dynamic tyre load population is used together with standard pavement response analysis methods to quantify the effects of pavement surfacing maintenance on roughness and structural pavement life. This method can be used as a pavement management system tool to enable quantified decisions regarding different surfacing maintenance options.

The aim of this paper is to present some of the results of the vehicle-pavement interaction project, mainly in terms of the expected effects of pavement roughness on the moving dynamic effects in pavement analysis and design. Background is provided of the study and previous reported results. This is followed by a summary of the important vehicle and pavement parameters to be included in the analysis. Examples of the model where these parameters are included are provided. Finally, conclusions and recommendations around the effects of pavement roughness on moving dynamic load effects in pavement analysis and design are provided.

## INTRODUCTION

Current mechanistic pavement design and analysis techniques use several simplifications to enable the process to be practical and cost-effective. These include equivalent vehicle loads, linear elastic analysis and static vehicle load and pavement response analysis. These simplifications allow the process of pavement design and analysis to be applied by the majority of engineers, but cause the process to be less related to real life. In recent years attempts were made to incorporate more realistic effects into pavement design and analysis. In a project performed at CSIR Transportek an investigation was done to establish the effects of incorporation of moving dynamic traffic loads in pavement design and analysis. The objective of this study was to identify those parameters that are important to be included in a more realistic analysis model, and to establish the expected effects of such an analysis model.

The aim of this paper is to present some of the results of the vehicle-pavement interaction project, mainly in terms of the expected effects of pavement roughness on the moving dynamic effects in pavement analysis and design. Background is provided of the study and previous reported results. This is followed by a summary of the important vehicle and pavement parameters to be included in the analysis. Examples of the model where these parameters are included are provided. Finally, conclusions around the effects of pavement roughness on moving dynamic load effects in pavement analysis and design are provided.

Previously the main results of the Vehicle-Pavement Interaction (V-PI) investigation were presented in various formats (Steyn and Visser, 2000; Steyn and Visser, 2001; Steyn et al, 2001). In this paper the focus fall on some further application of the findings in the project. The paper focuses on the effects of varying pavement surface roughness on the population of Moving Dynamic tyre Loads (MDL). The importance of this topic lies mainly in the fact that surface roughness is a parameter specified during the quality control of pavements, it deteriorates during use of the pavement and it is a typical maintenance option that can be applied to a pavement. The typical effect of surface roughness maintenance on the applied tyre loads and expected life for a nominal pavement is illustrated. No detailed pavement response analyses are provided, as the focus is on the changes in load definition due to roughness changes. However, the method can equally be used for more complicated pavement structures than that shown in this paper.

Vehicle-Pavement Interaction (V-PI) can be defined as the relationship between pavements and the vehicles that use these pavements. Traditionally pavement engineers focussed more on the pavement structure and its response to simplified load cases in an attempt to understand the pavement's life better. It has, however, always been known that these simplifications (i.e. uniform circular contact stresses, static load cases and linear elastic material response) are not reality. Through the advent of faster computers and user-friendly software the ability to incorporate more of reality into pavement designs and analysis become possible. Although major gaps still exist regarding many of the data required for detailed V-PI analysis, steps are being made in a positive direction.

## **BACKGROUND**

CSIR Transportek started to focus on investigations regarding V-PI in more detail since the early 1990s with initial work on tyre-pavement contact stresses (De Beer et al, 1997) and more detailed V-PI investigations later on (Steyn, 1997). The objective of this work was to obtain a better understanding and definition of the issues of V-PI and provide a knowledge base of V-PI analysis in southern African conditions.

The Stress-In-Motion (SIM) developments provided a detailed basis for understanding tyre-pavement contact stresses, and more refinements are made in this field.

The V-PI investigation culminated into a simplified method for incorporation of MDL into current pavement analysis methods (Steyn, 2001). This method is based on an empirical relationship between vehicle parameters and pavement roughness. The main conclusions (relevant to this paper) from the initial work on V-PI are:

- Pavement roughness is the main cause for dynamic loads;
- The static tyre load component is directly related to the Gross Vehicle Mass of the vehicles that use the pavement, while the dynamic load component is directly related to and dependent on the vehicle speed, vehicle type, GVM, load and pavement roughness;

- The control of tyre load levels on roads is the joint responsibility of the road authority (through control of pavement roughness and vehicle speed) and the vehicle owner (through control of GVM and vehicle speed), and
- The use of percentile values of the dynamic tyre load population rather than an equivalent static 80 kN axle load in pavement response analyses cause significantly different pavement responses.

### **VEHICLE AND PAVEMENT PARAMETERS**

The main parameters affecting V-PI specifically are the tyres, suspension, vehicle dimensions, configuration, load, and speed (vehicular components), and pavement roughness (pavement component). The vehicle owner has control over the vehicular parameters while the road owner control the pavement parameter. Parameters such as the vehicle load and speed can easily be changed, while parameters such as the tyre and suspension types are only changed when new parts are fitted, or when maintenance are performed on these parts. The pavement roughness is controlled during construction and thereafter deteriorates depending on factors such as the pavement type, material type, environment, maintenance actions and traffic loading applied to the pavement.

Typical parameter details for heavy vehicles on South African roads (Table 1) were obtained during a survey in 1997. This survey consisted of observations at weighbridges, comments from industry leaders, surveys done by tyre manufacturers and data collected at weigh-in-motion sites. A total number of more than 115 000 vehicles and more than 500 000 tyres were included in the survey data. Data on vehicle speed were collected from 40 weigh-in-motion stations located on national, provincial and urban routes. It is important to realise that although laws and regulations regulate parameters such as the vehicle speed and load, these laws and regulations and changes thereof also indirectly influence parameters such as vehicle configurations. Often a change in the legal loads that may be carried by a vehicle may result in a different configuration being more cost-effective to operate. The indirect effect of laws and regulations thus also affect the V-PI analysis.

### **SIMPLIFIED ANALYSIS METHOD**

It was shown during the V-PI project that a full finite element analysis of the V-PI phenomenon is a complicated, labour and knowledge intensive process that is not necessarily available to all pavement engineers. Good hardware, software, input data on various material and vehicle components and knowledge and experience of the whole system are needed to enable an accurate model of the V-PI to be constructed and analysed. A simplified and practical analysis method was thus developed to incorporate the effects of MDL into day-to-day pavement analyses. This method utilises existing analysis methods (i.e. the South African Mechanistic Design Method) and focuses on providing a better defined tyre load model that allows incorporation of the effects of pavement roughness and traffic properties into the pavement analysis. A complete description and examples of the simplified analysis process are provided in Steyn (2001) and Steyn and Visser (2001).

**Table 1: Typical vehicular component information for heavy vehicles (Gross Vehicle Mass > 7 000 kg) in South Africa (Barnard, 1997; Bosman et al, 1995; Campbell, 1997; SATMC, 1997; Steyn and Fisher, 1997).**

COMPONENT	VALUE
Tyre type	Radial – 50 % to 70 %
Tyre size	12R22.5 – 50 % to 59 % 315/80R22.5 – 19 % to 27 %
Tyre inflation pressure [kPa]	150 kPa to 1 000 kPa
Suspension type	Steel – 80 % Air – 5 to 20 %
Vehicle configuration	40 % Rigid – 2 axles (11) 30 % Articulated – 6 axles (123) 20 % Interlink – 7 axles (1222)
Average speed (speed limit of 80 km/h)	79.9 km/h (standard deviation 10.2 km/h)

The simplified method essentially contains the following steps. The tyre load population is determined using equations 1 and 2 and the knowledge that this population is normally distributed. The expected vehicle types, loads, speeds and pavement roughness on the road to be evaluated are used as input to Equations 1 and 2.

$$\text{Average Load} = 12,6 + 1,003 * (\text{GVM}/\text{Number of tyres on vehicle})$$

Average Load [N]

GVM [N]

$R^2 = 99,9 \%$

Correlation Coefficient = 0,999

Standard error of y – estimate = 97,1

**Equation 1: Relationships between Gross Vehicle Mass, vehicle type and Average tyre load.**

$$\text{CoV Load} = 0,39 - 4,0E - 7 * \text{GVM} - 0,003 * \text{Load} + 0,01 * \text{number of tyres} + 0,03 * \text{roughness} + 0,001 * \text{speed}$$

CoV Load [%]

GVM [N]

Load [%]

roughness [HRI]

speed [km/h]

$R^2 = 94,9\%$

Standard error of y – estimate = 0,055

**Equation 2: Relationship between Coefficient of Variation of tyre loads (CoV Load) and vehicle speed, pavement roughness and vehicle type.**

The tyre load population can be modified with age of the pavement as the pavement roughness deteriorates with use, or for cases where the pavement roughness improves due to maintenance of the pavement surfacing. In this way an annual tyre load population can be developed over the expected life of the pavement. From this tyre load population a specific percentile tyre load level is selected for use in pavement life calculations. The selected percentile value will depend on issues such as the importance of the road. Calculations for the expected life of the pavement are then made either for the complete life of the pavement, but preferably on an annual basis using the specific pavement roughness for the pavement for each year. During this process, the expected traffic for the year is used to calculate a new roughness level and the structural life of the pavement for the following year calculated using the new tyre load percentile from the tyre load distribution. This procedure is repeated until the design period for the pavement has been covered.

Whenever pavement surfacing maintenance is planned for a year the pavement roughness is improved, and the expected tyre load population calculated for the new pavement roughness level. Pavement rehabilitation may cause both a new tyre load population (due to better pavement roughness) and increase in expected pavement life due to improved material properties.

In the development of the simplified method several assumptions had to be made. The main assumptions when using equations 1 and 2 are that:

- steel suspension is used by the vehicles;
- tyre inflation pressures are at manufacturers recommended levels;
- rigid, articulated and interlink vehicles are used on the road, and
- the speed spectrum (40 – 100 km/h), load spectrum (empty, full and 10 per cent overloaded) and roughness spectrum (HRI = 1,2; 3,1 and 5,3) used for development of the equations.

The main limitation of the method is that it is an empirical method for determining the tyre load population. Although the results of the analysis should thus be viewed in this light, it is important to realise that the output quantifies the effect of roughness changes on tyre loads and pavement life in a cost-effective way. The method should thus be used with caution and as an *indication* of expected tyre loads and pavement lives, and not as a definite value for these parameters.

## **PAVEMENT ROUGHNESS AND LIFE**

One of the main conclusions from the work on V-PI was that management of tyre loads (and overloading) on a road network is the joint responsibility of vehicle owners and road owners. The role of the vehicle owners (through vehicle load levels) is obvious in this responsibility, but the role of the road owner deserves attention. It was shown (equation 2) that the pavement roughness plays a definite role in the Coefficient of Variation (CoV) of the tyre load population, with higher pavement roughness levels causing a higher percentage of impact loads on the pavement.

To illustrate the effect of pavement roughness deterioration and surface maintenance on the tyre load population and expected life of a pavement, two simple examples are provided. In the examples a few assumptions are made regarding the expected traffic on the pavement, the pavement structure, initial pavement roughness and pavement roughness deterioration as a function of traffic loads. The roughness deterioration should ideally, for more practical applications, be sourced from pavement management system records. Using these assumptions, the annual tyre load population is calculated over a period of 10 years and the effects of no maintenance and maintenance after 5 years illustrated.

The assumptions made for the two examples are the following:

Gross Vehicle Mass (GVM)	16,5 kN
Number of tyres per vehicle	6 (rigid vehicles - for simplicity it is assumed that only rigid vehicles use the road)
Percentage load	100 per cent
Initial pavement roughness (Half-Car Roughness Index - HRI)	1,5 m/km
Terminal pavement roughness (HRI)	4 m/km
Roughness deterioration	Exponential with increased traffic
Average vehicle speed	100 km/h
Pavement structure (class ES3)	Thinly surfaced, granular base structure
Pavement class	Rural class B pavement
Traffic volume (first example)	1000 vehicles per day with 10 % heavy vehicles (rigid design vehicles)
Traffic volume (second example)	14 500 vehicles per day with 10 % heavy vehicles (rigid design vehicles)

The average and coefficient of variation of the tyre load population for each year has been calculated, and the 90<sup>th</sup> percentile tyre load been used to calculate the pavement life at the end of that year. The annual number of standard axle loads (80 kN single axles) has been calculated for each year, and the following year's pavement roughness calculated based on the number of standard axle loads that have already used the road since construction. In the first case no maintenance was allowed on the pavement. In the second case the pavement roughness was returned to the initial value through maintenance after 5 years of trafficking. No growth in traffic volume was allowed to simplify the specific example, and the increase in standard axles on the pavement is thus purely due to deteriorating pavement roughness.

The cumulative tyre load population for the example is shown in Figure 1. It indicates the dynamic tyre loads expected on the pavement at a vehicle speed of 100 km/h. For clarity only the initial (year 0) and final (year 10) tyre load populations are shown. The effect of the change in pavement roughness (from HRI 1,5 m/km to HRI 4 m/km) over the 10 year period can be observed. These two extremes give rise to 90<sup>th</sup> percentile tyre loads of 35 kN (year 0) and 38 kN (year 10) respectively (8,6 per cent increase).

The results of the tyre load and pavement life analyses for the first example are shown in Figures 2 and 3. In Figure 2 the deterioration in remaining pavement life from 1,6 million standard axles to 1,1 million standard axles can be seen on the example where no maintenance was performed. On the example with maintenance the effect of returning the pavement roughness to the original level after 5 years is visible as a final structural life of 1,45 million standard axles. The difference in pavement remaining structural life after 10 years in the example is thus approximately 0,35 million standard axles (21,9 per cent).

In Figure 3 the phenomenon is illustrated through the number of standard axle loads applied to the pavement per year. The case without any maintenance indicates a growth of approximately 6 500 standard axles applied per year over the 10 year analysis period, while the case with maintenance only grew by approximately 1 500 standard axles. This translates to a difference of approximately 5 per cent in standard axles per year at year 10.

In the second example a pavement with a nominal life of 14 million standard axles (ES30) has been analysed with similar data input (although a traffic volume of 14 500 vehicles per day with 10 per cent heavy vehicles and an appropriately stronger pavement structure have been used). Similar pavement roughness deterioration has been used and the difference in pavement remaining structural life after 10 years was 1,1 million standard axles (8,4 per cent). The growth in standard axles applied per year similar to the first example with 5 per cent.

Analysis of the two examples indicates that the percentage increase in standard axles per year due to increasing pavement roughness (for similar roughness deterioration curves) remained constant between the two examples. However, the effect of pavement roughness deterioration difference on pavement structural life was more severe on the lighter (ES3) pavement than on the stronger (ES30) pavement. It starts to indicate that the effect of lack of surfacing maintenance on lighter pavements (for similar traffic and all the other assumptions made in the examples) may be more detrimental than on heavier pavements.

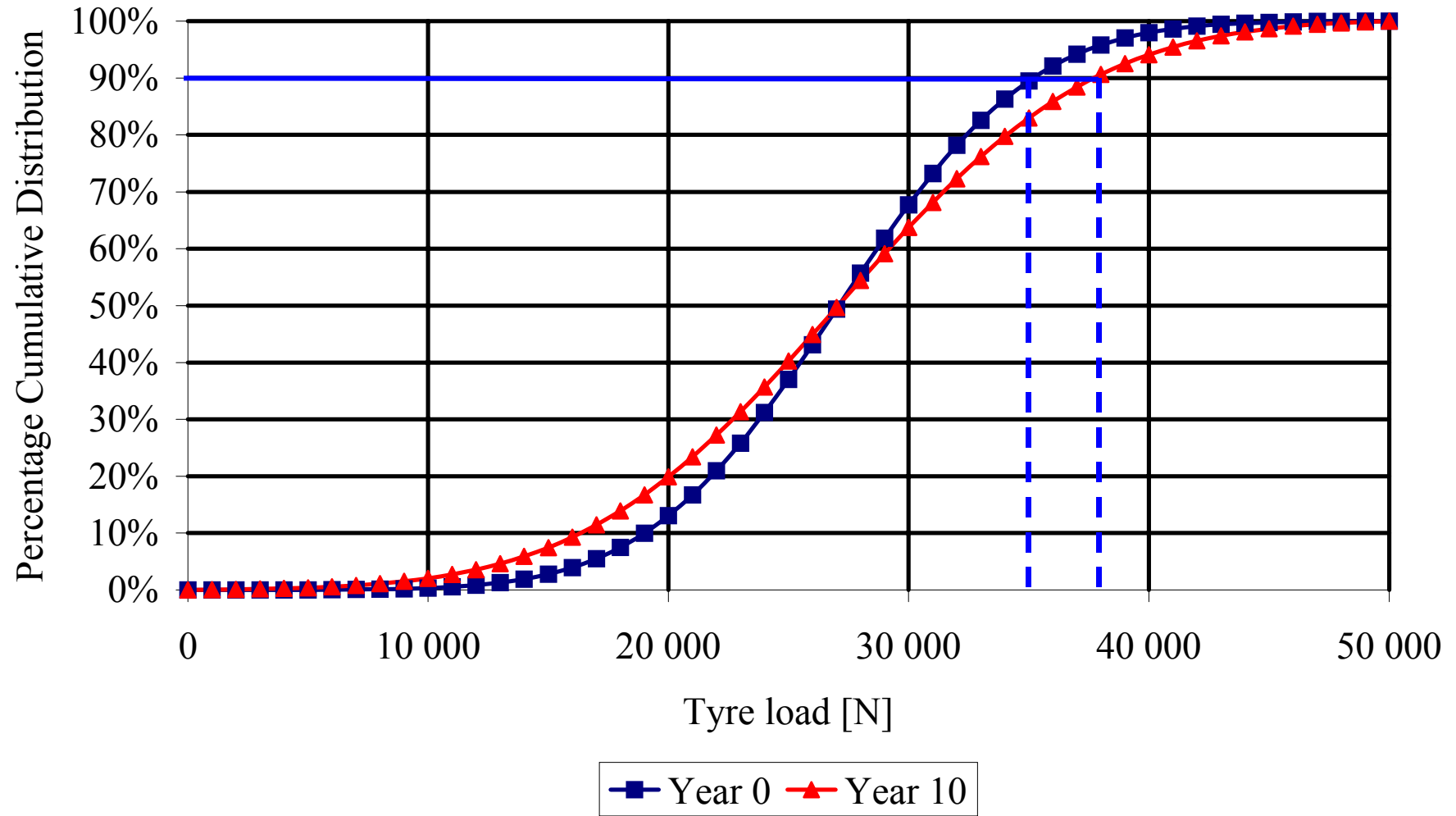
A word of caution is necessary. The above two examples are based on various assumptions (as indicated earlier in the paper). Further, the pavement roughness deterioration used and the selection of a maintenance procedure after 5 years that changes the pavement roughness back to the initial value may be criticised. However, the value of the examples (and related analyses) lies mainly in the quantification of the effect of pavement roughness and moving dynamic tyre loads on pavement deterioration. Previously, the fact that traffic cause pavement roughness to deteriorate was known, but not quantified. With the tools available a relative comparison can be made to determine the sensitivity to surfacing maintenance for different pavement structures.

Further, the values of the 90<sup>th</sup> percentile tyre loads used in this analysis are the 90<sup>th</sup> percentile moving dynamic tyre load applied at a speed of 100 km/h. The typical elastic deflection at this load and speed (incorporating mass and inertia effects of the pavement structure) may be in the region of 30 per cent of the elastic deflection when a standard 80 kN axle load is applied statically to the pavement structure.

Essentially these examples indicates the nominal value of performing a surface maintenance action during the life of the pavement, in terms of the structural pavement condition (pavement life) after 10 years of service and the difference in number of standard axle loads caused by moving dynamic loads per year after 10 years of trafficking.

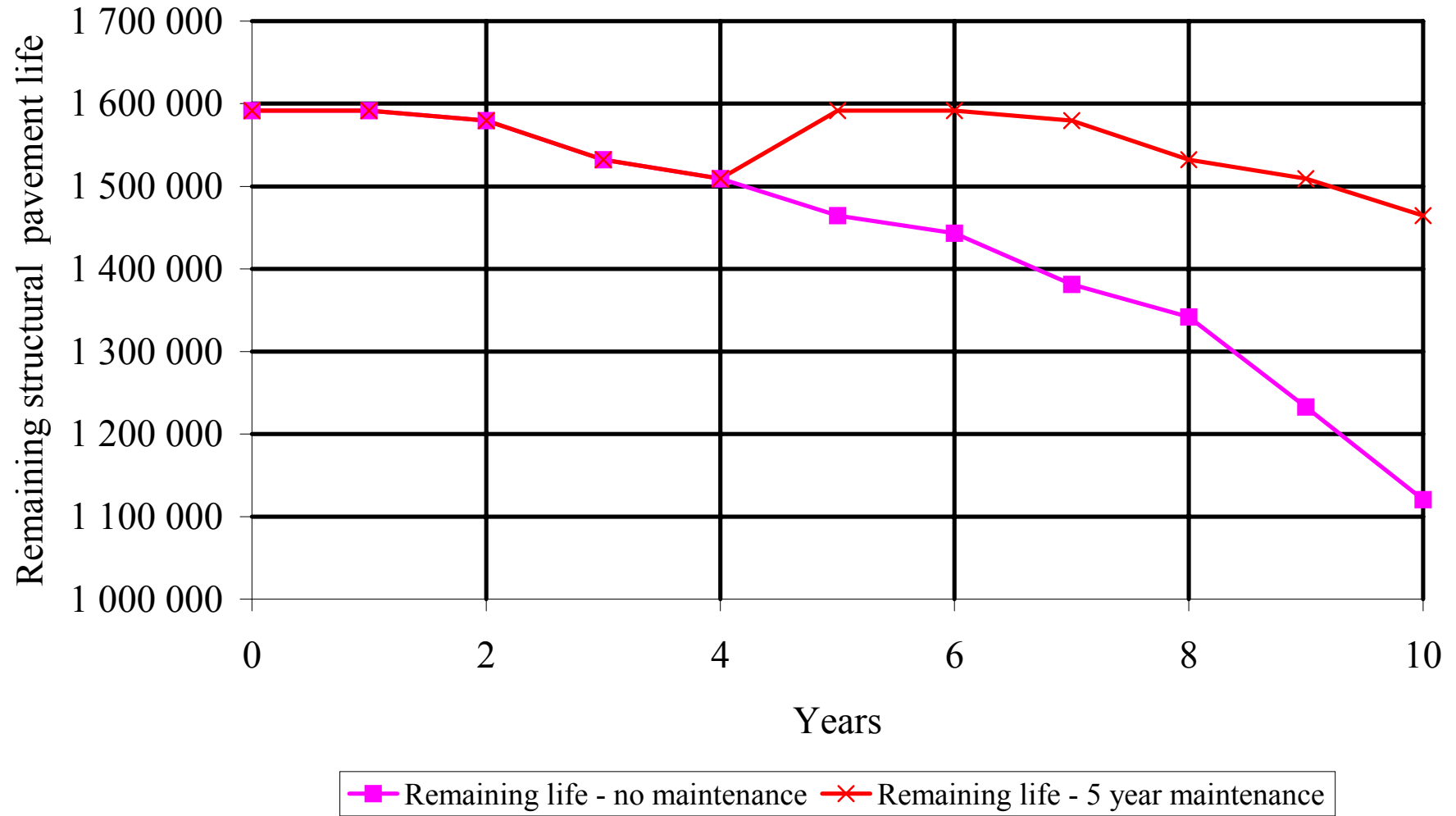
It further indicates that for the assumptions made the lighter pavement structure was more sensitive to pavement roughness deterioration than the heavier pavement structure.

The effects of different maintenance schedules and actions on these parameters can be quantified using this process, leading to more reliable estimates of the sensitivity of pavement networks to maintenance and the lack thereof.

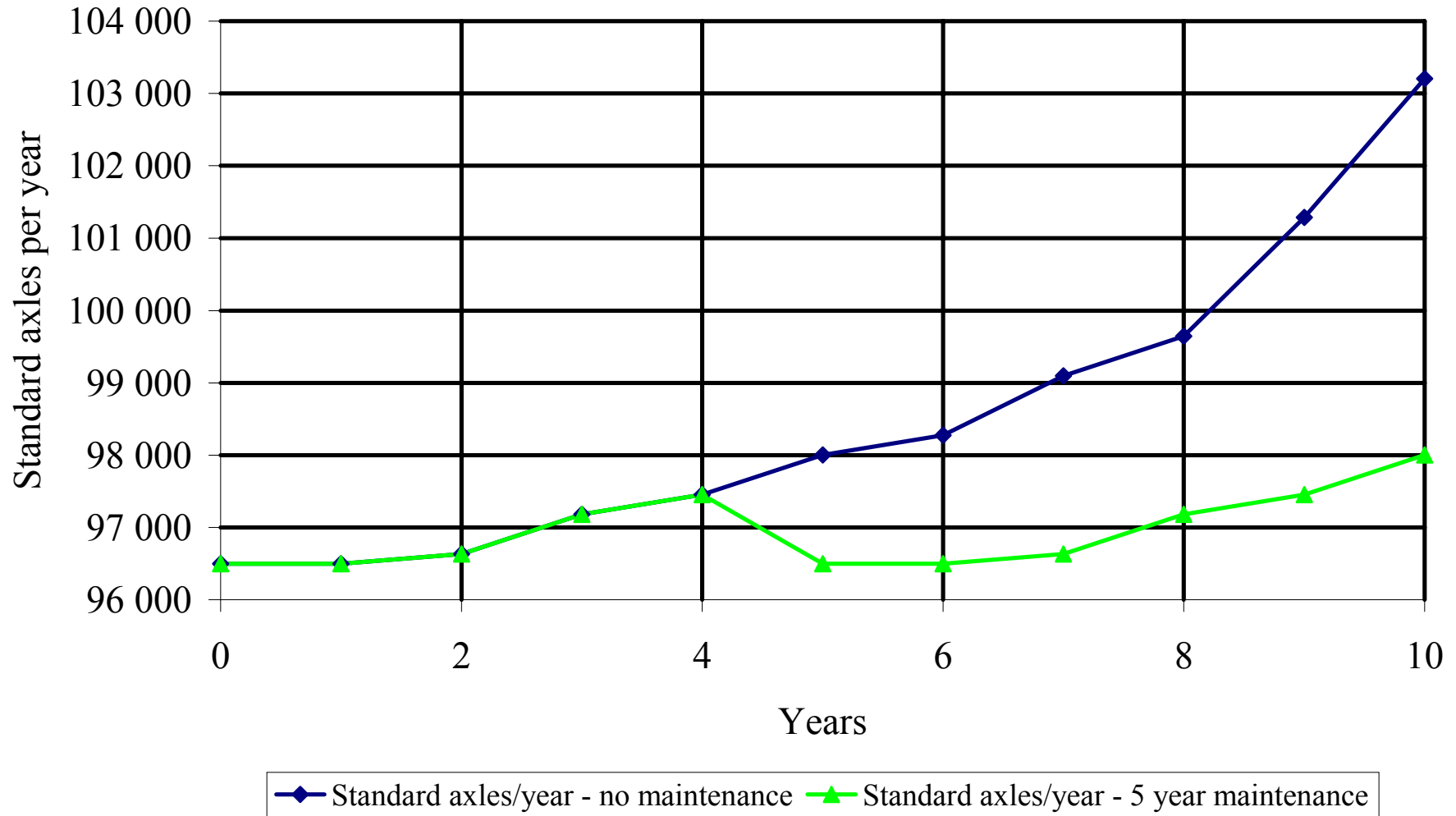


**Figure 1:** Cumulative tyre load distribution for example used in paper.





**Figure 2: Change in pavement life due to pavement roughness deterioration.**



**Figure 3: Change in standard axles per year due to pavement roughness deterioration.**

## CONCLUSIONS

In this paper the nominal effects of pavement roughness on vehicle-pavement interaction are demonstrated. Pavement roughness is the primary cause for moving dynamic tyre loads on pavements. Control and management of pavement roughness can aid in limiting the magnitude of moving dynamic tyre loads on a pavement.

Although it has been known for long that pavement roughness deteriorates with traffic and time, the effect on moving dynamic tyre loads and structural pavement lives could not easily be quantified. In the paper a simplified and practical method is demonstrated that can be used to obtain an initial quantification of the effects of pavement roughness on these parameters, based on input data from the vehicle population and pavement roughness.

Further, the effect of surface maintenance actions on the moving dynamic tyre loads and expected structural pavement life can be estimated using the method. The benefits of pavement surfacing maintenance actions in terms of lower moving dynamic loads applied to the pavement, and subsequent longer structural lives of the pavements, are quantified for two specific examples.

The proposed method can be used as a simplified tool to enable decision makers to make more reliable decisions regarding maintenance actions designed for pavement roughness maintenance. Although much more detailed analyses are possible (and under specific conditions desirable) the simplified method can be used as a cost-effective preliminary tool.

## RECOMMENDATIONS

Based on the information provided in this paper it is recommended that the principles discussed in this paper regarding minimising road roughness be adhered to during road construction, rehabilitation and maintenance. Although the method proposed in the paper may still be empirical, it provides a first level indication of the effects of various road roughness levels on tyre loading and pavement deterioration. Pavement engineers may use it to determine an initial indication of acceptable road roughness levels for different vehicle and road conditions.

It is further recommended that refinements in the range of vehicle components incorporated into the current model (i.e. air suspension and different tyre types) be developed. Verification of the increased pavement deterioration caused by changing moving dynamic tyre load populations should be verified through long-term pavement performance studies.

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