



## SENSITIVITY ANALYSIS OF THE EFFECTS OF LOAD MAGNITUDE ON PAVEMENT STRAINS USING LOAD SPECTRA

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### ARTICLE INFORMATION ABSTRACT

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The purpose of this study is to evaluate the effect of wheel loads on linear responses by sensitivity analysis on an elastic linear analysis. Sensitivity analysis of traffic factors was carried out on the failure parameters, where the impact of each of the wheel load magnitude for each axle type and its relationship with the pavement response outputs was evaluated. The reference central value (mean) of the ALS on both the southbound axis and northbound axis of the selected route, Kaduna-Zaria roadway, were either increased or reduced by 0% to 50%, and also, 100% and 500%, to see how the pavement will respond to a constant pavement configuration and material properties applied to all cases. The results obtained from KENLAYER runs were used to determine the relationship between the axle load groups and the pavement responses. The effect of load magnitude on pavement responses, was evaluated in respect of the tensile strains and compressive strains. The findings of the study revealed that: Development of comprehensive data base was accomplished from the local traffic data that meets the requirements of M-E design procedure. Wheel load group relationship for each axle type to vertical strains on top of the subgrade soils are linear, while the tensile strain at the bottom of the asphalt concrete is about 50%.

### 1.0 Introduction

Sensitivity analysis is the apportionment of output variability from a model to its various inputs. Sensitivity analysis draws upon many of the same concepts as the design of experiments. A rich and powerful set of formal and rigorous techniques for performing sensitivity analysis has been developed over recent years (Cacuci, 2003). These can be categorized in a variety of ways, for the purposes of the present study; the most used categorizations are LSA and GSA methods.

LSA provides an economical approach for identifying the subset of inputs that have the largest impact on the outputs. Only the sensitivities and the reference input values for the baseline cases are evaluated-i.e., the evaluation is only for very small regions of the overall solution space. This provides only a "local" as opposed to a "global" sensitivity evaluation. The one-at-time (OAT) method is the most common type of LSA. In standard OAT applications, one or more baseline scenarios are exercised by varying each independently in turn.

In this study, the software program used is KENLAYER, to obtain the resulting pavement reactions, with the elimination of all the data from the AASHO Road test, sensitivity analysis was made on five-layer systems to illustrate the effect of various axle(wheel) load magnitudes with different configurations on pavement responses. The approach utilized is to fix all pavement configurations and material properties, contact pressure, constant default wheel spacing, and calculating various contact radius from the variations of the increment to the reference median axle load magnitude of the considered configuration, to show its effect. Comparison of the effect (output) in respect of the resulting pavement reactions (strains) was achieved by utilizing the OAT standard in the sensitivity analysis

The empirical - mechanistic (E-M) based method of pavement design is based on the mechanics of materials, which relates input such as a wheel loads to output such as pavement response. (Huang, 2007; Mathew and Rao, 2007). According to Huang (2007), with the use of KENLAYER, sensitivity analyses were made on five-layer Systems to illustrate the effect of various parameters on pavement responses in this study. The complex interactions among the large number of parameters make it difficult to present a concise, but accurate, picture on the effect of a given parameter, because the effect depends not only on the parameter itself, but also on all other parameters. Conclusions based on a set of parameters could be invalid if some of the other parameters are changed. The best approach is to fix all other parameters at their most reasonable values while varying the parameter in question, to show its effect.

The core concern here-in is evaluation of effect of load magnitude from collected axle load spectra on pavement responses. The key input is the arithmetic average axle load magnitude determined from the captured from the actual axle load groups from the site -specific information by WIM system is used subjected to increment variation of the mean axle load magnitude by axle configuration, but the layer properties for the M-E analysis, remained fixed, all through the sensitivity process.

## 2. Materials and Methods

The required materials in this study consist of pavement configuration that includes the number of layers, the thickness of each layer, and the type of materials. The basic material properties for the structural models are the resilient moduli of HMA, base, subbase, and subgrade. Traffic should be divided into a number of load groups, each with different load magnitudes and configurations. The methods adopted in this research includes the disaggregation of traffic information incorporated into a truly mechanistic analysis for an accurate pavement response. In this study, the computer program KENLAYER is used and the impact of varied axle load magnitudes was evaluated on the obtained pavement responses.

### 2.1 Data Collection and Gathering of Materials

The inputs required for carrying out a sensitivity analysis of elastic multilayer systems using load spectra are presented as follows:

- (a) Secondary data for the study: (i) Comprehensive site-specific truck traffic information on Kaduna-Zaria roadway, (ii) Pavement configuration and material properties
- (b) Traffic information obtained from literature review.

#### 2.1.1 Primary data

The Nigerian overlay design methodology research results were used as a primary data for the material properties and pavement geometry. In addition, Load stress for typical Nigerian Roads was adopted as (PSI/KPA) (80/552) for single axle with dual tires for Nigerian Roads from the same source. The details are given in Table I, for layer properties for the M-E analysis.

**Table I:** Layer properties for the M-E analysis

Layer	Material	Elastic Modulus Psi/Kpa	Poissons'ratio	Thickness in/cm
1	WEARING COURSE	70,000 / 4,830,000.0	0.30	2.000 / 5.08
2	BINDER'S COURSE	200,000 / 1,380,000.0	0.35	2.800 / 7.112
3	STONE BASE	65,000 / 448,500.0	0.40	8.100 / 20.574
4	SUB-BASE	45,000 / 310,000.0	0.45	5.200 / 13.208
5	SUB-GRADE	42,000 / 289,000.0	0.45	SEMI-INFINITE

SOURCE: Claros *et al.*, (1986).

### 2.1.2 Secondary data

Truck traffic information were collected from the Secondary data were obtained by collecting truck traffic information from the Scott Stewart International work in 2007. Portable Weigh-in-Motion (WIM) system was used for the measurement of vehicle classification and truck axle weights to compute the traffic loading inputs needed for Kaduna-Zaria roadway network. The vehicle classification included five categories of truck and transit vehicle types by axle classification (2-, 3-, 4-,5-, and 6-axles). Additional information obtained were axle configurations (Steering, Single, Tandem and Tridem), axle loads, all for Kaduna-Zaria Roadway.

### 2.1.3 Traffic information from literatures:

Dual wheel spacing and axle-axle distance for each load group was obtained from literatures. The details are given in Table 2, for dual wheel spacing and axle -axle distance for each load group

**Table 2:** Dual wheel spacing and axle -axle distance for each load group.

Group	No of Axles in the Outer Wheel Path	Dual Wheel Spacing (yw) vm	Axle-Axle Distance (xw) cm
SAST	1	0	0
SADT	2	34	0
TADT	4	34	137
TRDT	6	34	137

Source: Timm et al. (1999); Huang (2007).

## 2.2 Methods

Sensitivity analysis was carried on the failure parameters with respect to changes in the tensile and compressive strains at the bottom of the Asphaltic Concrete and at the top of the subgrade respectively. This was done by increasing and decreasing the determined arithmetic average axle load magnitude of the captured ALS.

For the 5 layers under consideration, the parameters considered in the layer properties for the M-E analysis were kept fixed at each time the increment average axle load magnitude of interest varied. Under a given contact radius, the stresses, strains, and deflections in a linear system are proportional to the contact pressure or the magnitude of the total vertical load. The strains induced in pavement layers by the respective loading groups were computed from KENLAYER runs. This study shows a five-layer system subjected to a total vertical load, which is applied by a single tire and a set of dual tires were the loading groups of interest for the sensitivity analyses.

The determined average axle load magnitude for each of the considered axle configurations were either increased or reduced by -50% to +50% and between -500% and +500%, to see how the pavement will respond to a constant Layer property for the M-E analysis applied to all cases. The impact of the varied axle load magnitude of the four considered axle configurations were determined respectively. The effect due to variation in the arithmetic average axle load groups on the pavement responses were determined as it affects the compressive strains in the subgrade and the tensile strains under the HMA leading to permanent damage of the pavement.

**Contact Pressure:** An average contact pressure 80Psi (552KPA) (Secondary data) was adopted for all the four different axle configurations from the work of Claros et al. (1986), for this study. SAST: Single Axle with Single Tire; SADT: Single Axle with Dual Tires; TADT: Tandem Axle with Dual Tires; TRDT: Tridem Axle with Dual Tires.

### 2.2.1 Reference axle mean load for Kaduna–Zaria roadway:

This is the arithmetic average axle load magnitude of the captured ALS data from the secondary data from SSI (2007) for each axle configuration.

### 2.2.2 Increment variation in reference axle mean loads

Increment variation in reference axle mean loads for each of the four considered axle configurations was done by increasing and decreasing the determined the arithmetic average axle load magnitude for each axle configuration. The arithmetic average axle load magnitudes were either increased or reduced by -50% to +50%, and also, between -500% and +500%.

**2.2.5: Wheel Load Magnitude:** In this study, the usual practice that the wheel load is equal to the axle load divided by the number of wheels on the axle, is not done because results from other researchers shows that this is not true. Molenaar (2009) shows that camber of the pavement surface results in an unequal sharing of the axle load over both wheel groups of the axle. The wheel group on the verge side of the road carries 52% of the load while the wheel group near the centre line of the road carries 47%. The number of tires in the outer path which is essential in the layer theory was considered and the camber analysis that relates the pavement roughness and the vehicle camber was also considered, for the distribution of axle load magnitude as contained in the camber analysis. Therefore, using the axle load ranges as obtained in the developed axle load distribution for each of the four different axle configuration, wheel load is calculated as follows:

$$P = \frac{\text{Axle gross load (KN)} \times 0.52}{\text{Number of wheels on the outer wheel path}} \quad (1)$$

Number of wheels on the outer wheel path as contained in column 3 of Table 2.

**2.2.6: Contact Area between Tire and Pavement (Contact Radius):** In this study, the principle of superposition for a realistic wheel load configuration was utilized, with all the four considered axle configurations, with the assumption that the tire imprint has a circular shape and carries uniformly distributed vertical stress that is equal to the tire inflation pressure, (that is, it is assumed that the tires are treadles and that the tire walls carry no load). The assumed approach by the NCHRP I-37A whereby it accepts a single tire inflation as input and utilizes it for all axle configurations was employed. The contact pressure in this study is  $5.52 \text{ kg/cm}^2$  i.e., 552kpa and contact radius is calculated as follows:

$$a = \sqrt{\frac{P}{i \pi}} \quad (2)$$

Where a = Contact radius, P = (Wheel load): Total load on the tire as determined in Equation 1 above, i = tire pressure. Papagiannakis and Massad (2008); Oguara (2004); and Huang (2007)

## 2.4 M-E methods for flexible pavement analysis output

The mechanistic resulting pavement reactions for each axle load and each axle type was computed by using the KENLAYER Software in which the stresses and strains were analyzed due to each axle-load group. The stress under specific loading conditions without relying on equivalency factor was obtained.

### 2.2.9 Sensitivity analysis of elastic multilayer systems

Impact /Influence of Axle Load on Tensile Strain & Vertical strain

The influence was determined in this study by fixing all other pavement parameters at their most reasonable values while varying the axle load increment to compute the influence of axle

load on the computed pavement strains, utilizing this influence value as described below at the Southbound/Northbound:

$$\text{Impact Value on Tensile Strain} = \frac{T_i - T_{\text{default}}}{T_{\text{default}}} \times 100 \quad (3)$$

$T_i$  = Tensile strain value at the axle load increment magnitude

$T_{\text{default}}$  = Tensile strain value at the axle load default value. (Awosanya et al., 2023)

$$\text{Impact Value on Vertical Strain} = \frac{V_i - V_{\text{default}}}{V_{\text{default}}} \times 100 \quad (4)$$

$V_i$  = Vertical compressive strain value at the axle load increment magnitude

$V_{\text{default}}$  = Vertical compressive strain value at the axle load default value. (Awosanya et al., 2023)

### 3. Results and discussions

Multilayer elastic analysis is performed using the KENLAYER Software. The different variables discussed section are considered. The effect of load magnitude on the resulting pavement strains under an increment of the magnitude of the total load, for single tire and a set of dual tires are investigated, with the pavement configurations and material properties were all fixed. The following sections discuss the outcomes of these results.

#### 3.1 Default axle load distribution

From the captured axle load magnitudes for each axle types on the four axle types on the Kaduna-Zaria roadway. The axle load magnitude was obtained in tonnage (ton), but was converted to KiloNewtons. That is 1ton= 9.86KN. For each of the axis, that is, Southbound (SB-Axis) and Northbound (NB-Axis), arithmetic mean axle load magnitude for each axle configuration are determined as contained in Table 3.1.

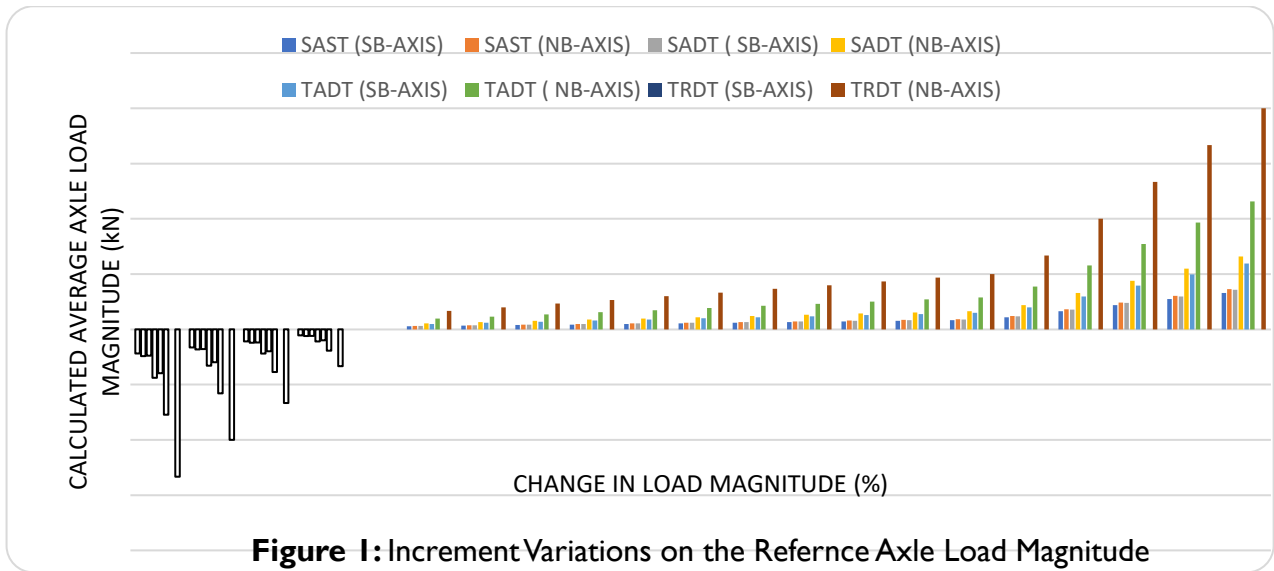
**Table 3:** Arithmetic mean axle load magnitude (default axle load (kN)) for each axle configuration

Axle configuration	Default value k N (Southbound)	Default value k N (Northbound)
Single axle with single tire	54.84	60.32
Single axle with dual tire	59.91	109.38
Tandem axle with dual tire	99.75	196.09
Tridem axle with dual tire	Nil	321.88

From the table 3, northbound axis has very high axle load magnitude while southbound axis has the lowest values. The main reason was that industrial and construction commodities came from the Apapa wharf into the country, while agricultural materials were transported towards the southern part of the country.

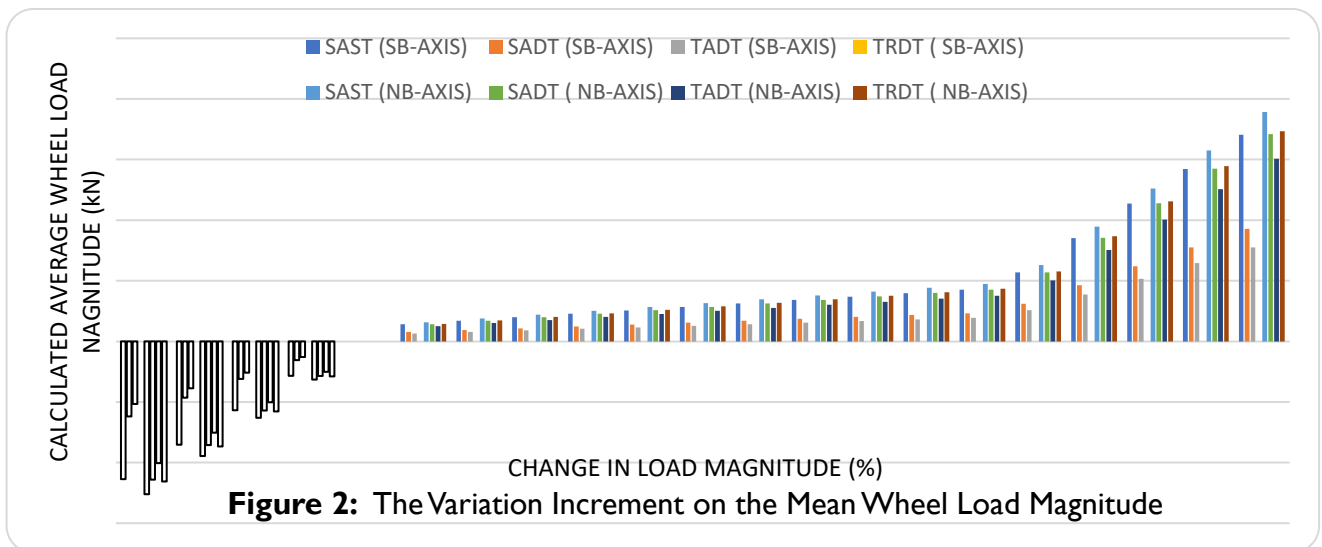
#### 3.2 Axle load default

The magnitude of default axle load for each group was subjected to incremental variations between -500% and +500%. Figure 1 represents the increment variations on the default axle load magnitude for the four different axle types. The same trend of the output obtained above was achieved.



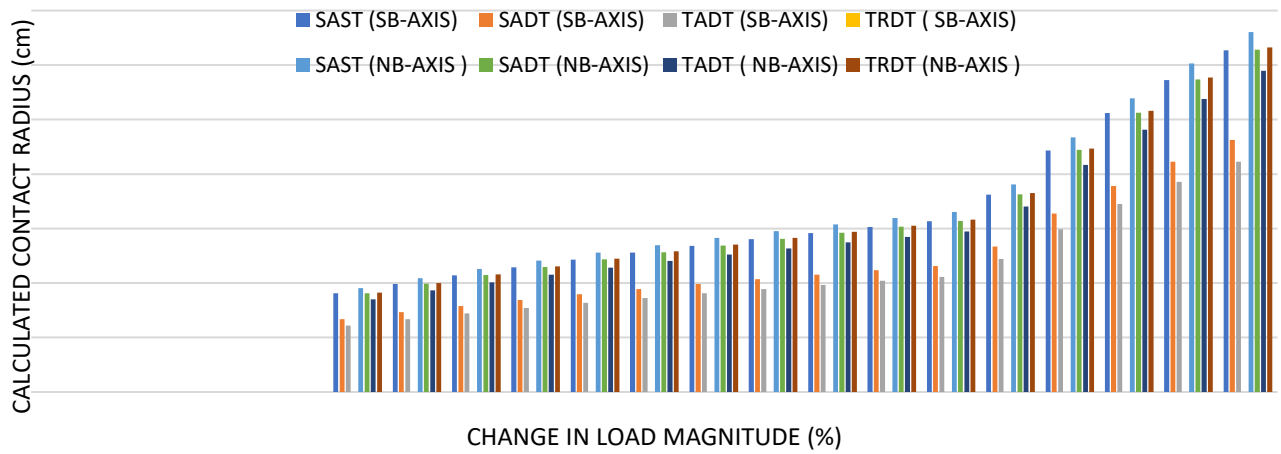
### 3.3 Wheel Loads

Wheel load from each axle type are calculated according to Equation 1. Figure 2 represents the wheel loads on the four different wheel configurations considered in this study. This table indicates that as the axle load magnitude increases, the wheel load for each group is increasing.



### 3.4 Contact radius (cm)

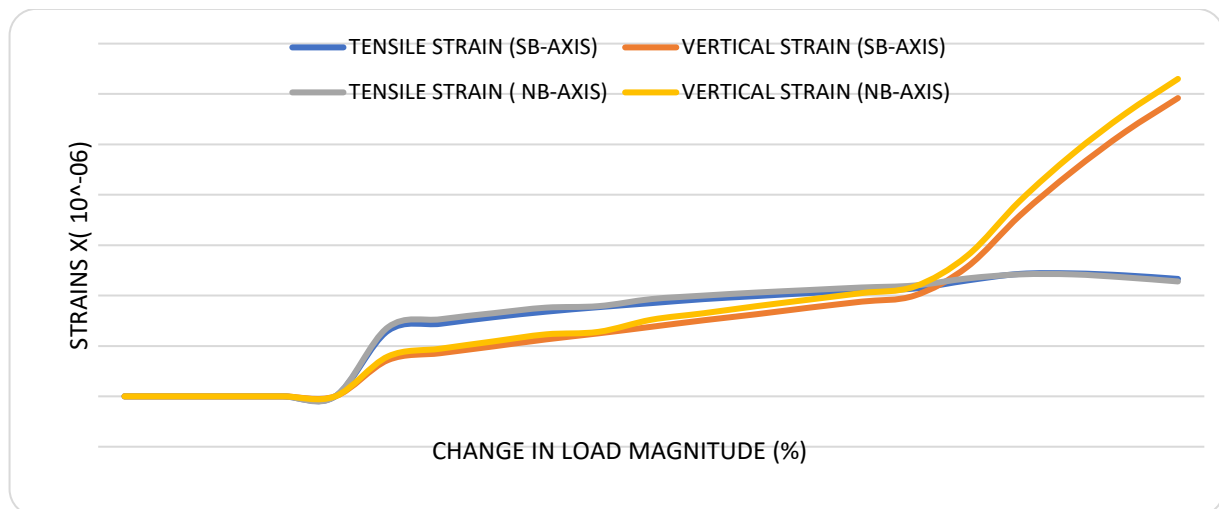
The contact radius for each determined wheel load for each axle type, are calculated according to Equation 2. Figure 3 present the resulting contact radius (cm) for each axle load for each axle type. The observed trend is that the contact radius increases as the axle load magnitude for each axle type with increasing axle load magnitude, with the significance of the number of axles sharing the same suspension system and the number of tires in each axle



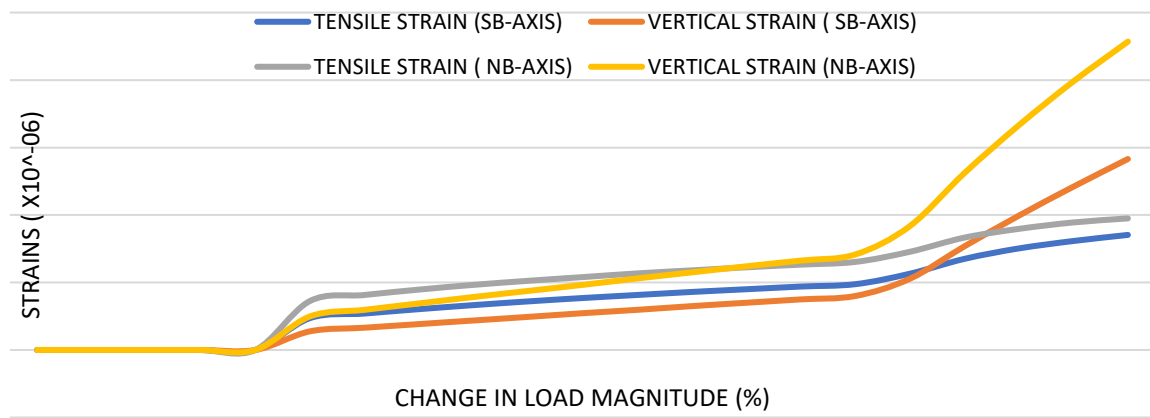
**Figure 3:** Contact Radius (cm) for the Variations Increment on the Mean Wheel Magnitude

### 3.5 Pavement Responses on Kaduna Zaria Roadway from increment variation on Load Spectra Default Value

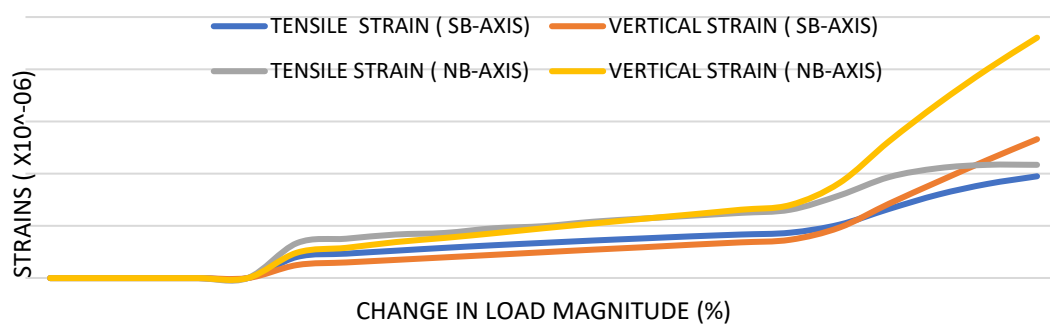
Figures 4 to 7 present the relationship between tensile strains on the bottom of asphalt layer and the compressive strain on the top of subgrade soils versus axle load by each axle type. The figures show that the tensile and compressive strains increase with increasing the axle load. The flexible pavement is subjected to a combination of single, tandem, tridem- axle loads. The pavement is loaded with one or more identical uniform circular loads normal to the surface. The program superimposes the various loads and computes the strains at locations specified. The principal tensile strains at the bottom of the asphalt layer and the vertical compressive strains on top of the subgrade under the specified locations were determined by KENLAYER.



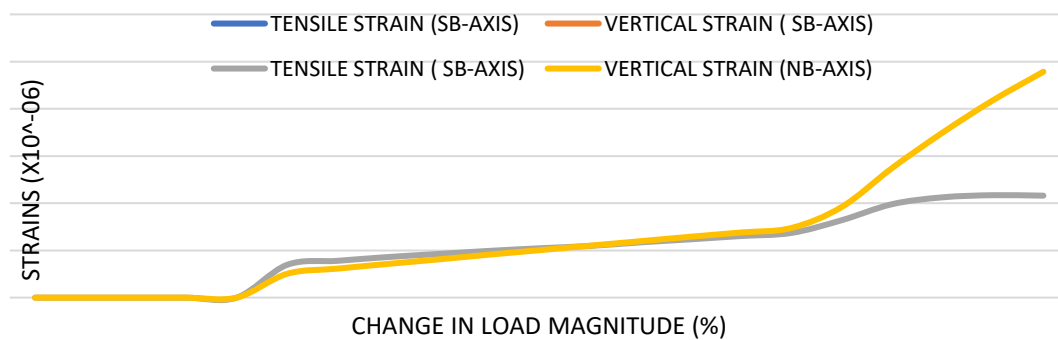
**Figure 4:** Results of Sensitivity Analysis on Load Magnitude for Single Axle with Single Tire for Kaduna-Zaria Roadway



**Figure 5:** Results of Sensitivity Analysis on Load Magnitude for Single Axle with Dual Tires for Kaduna-Zaria Roadway



**Figure 6:** Results of Sensitivity Analysis on Load Magnitude for Tandem Axle with Dual Tires for Kaduna-Zaria Roadway



**Figure 7:** Results of Sensitivity Analysis on Load Magnitudes for Tridem Axle with Dual Tires for Kaduna-Zaria Roadway.

### 3.36 Effect of Load Magnitude on Pavement Responses.

The impact value of tensile strain is calculated according to Equation 3 and the impact value of vertical strain is calculated according to Equation 4. Figure 8 through to 11 illustrate the effect of wheel load from the four considered wheel configurations on tensile strains and compressive strains, in which an approach is to fix all other parameters at their most reasonable values were employed while varying the increment variation of the default magnitude of each axle type, which was used to show its effect.

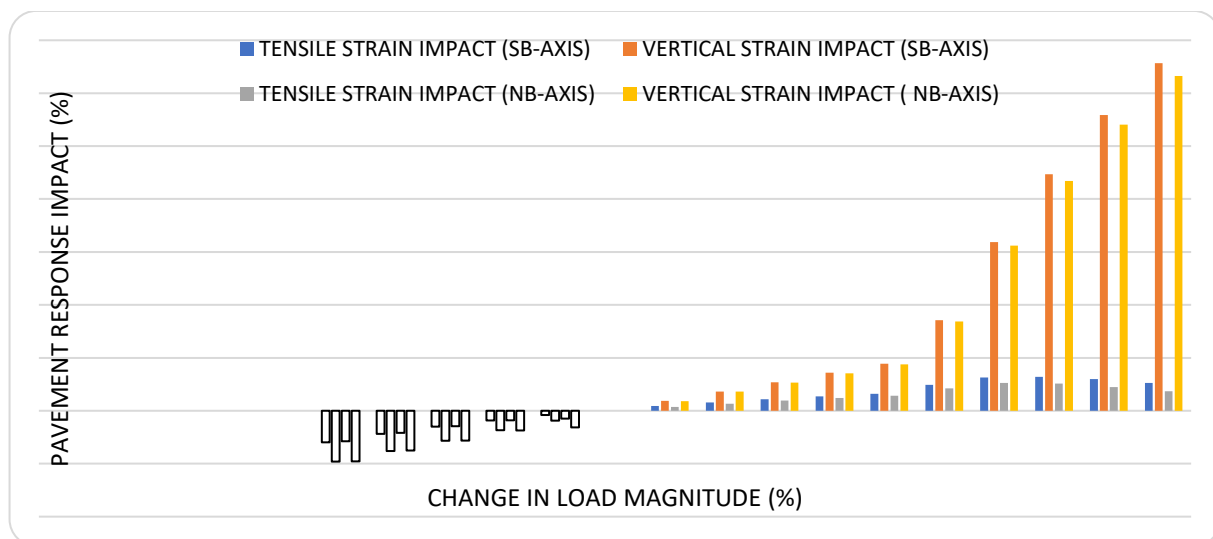
Linear analysis was employed, which was integrated into NEMPADS by the researcher that developed the computer software, (Olowosulu, 2005). According to Huang (2007), linear



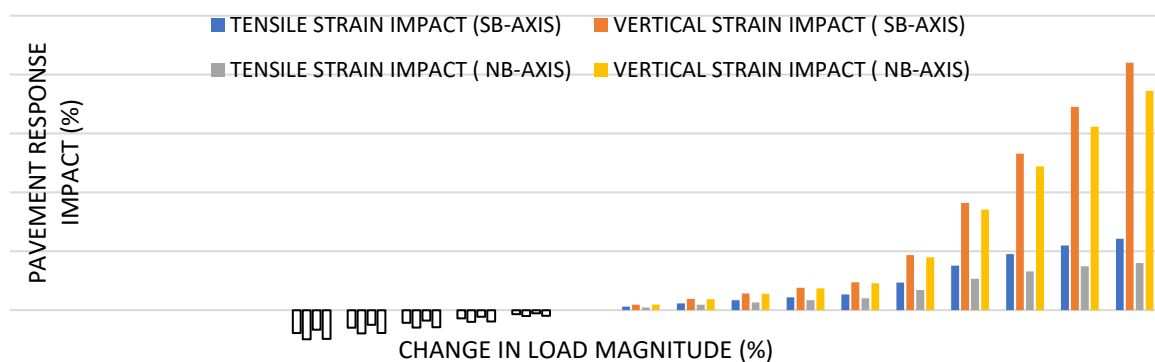
analysis is based on the assumption that all layers which are linear elastic. Although HMA layers are viscoelastic and granular layers are nonlinear elastic, an approximate procedure is to assume them to be linear by selecting appropriate moduli for HMA, based on vehicle speeds and pavement temperatures, and for granular materials, based on the level of loading. (Huang, 2007). The purpose herein is to find the effect of load magnitude on pavement responses.

This study serves an important role of solving the problem of overloading on the roadways, because heavier axle loads with greater effect on the pavement response, will incur a greater destructive capability on the pavement, reducing the pavement life.

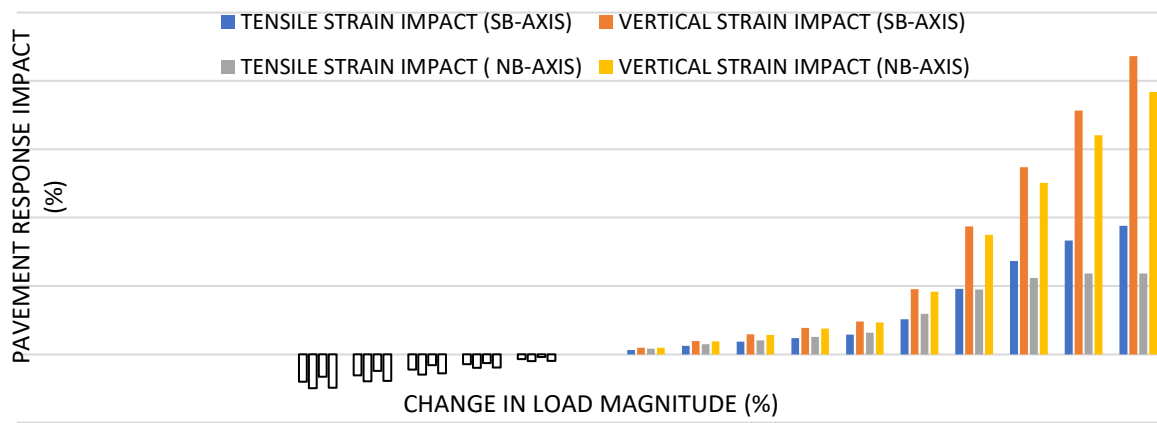
An effective and efficient axle load groups threshold and management will be established in this study, by connecting an approved maximum axle load magnitude for each different axle types on each roadway, with a commensurate penalty for violating the established traffic instructions. Additionally, mode of transportation for carrying heavy goods and commodities instead of employing trucks on our roadway, for the purpose of reducing or eliminating cumulative damage ratio, therefore, increasing the pavement life of the roadway.



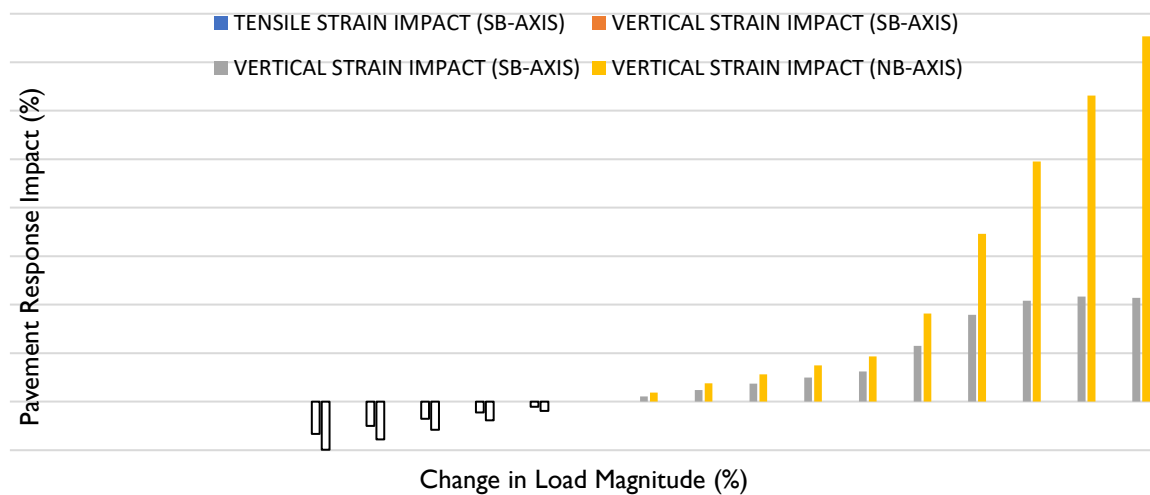
**Figure 8:** Summary of Sensitivity Analysis for Load Magnitude for Single Axle with Single Tires (Sast)



**Figure 9:** Summary of Sensitivity Analysis for Load Magnitude for Single Axle with Dual Tires (SADT)



**Figure 10:** Summary of Sensitivity Analysis for Load Magnitude for Tandem Axle with Dual Tires (TADT)



**Figure 11:** Summary of Sensitivity Analysis for Load Magnitude for Tridem Axle with Dual Tires (TRDT).

The default magnitude in the northbound axis is greater than the obtained magnitude in the southbound axis on all the four different axle types considered. For the lighter default axle loads on the southbound axis, the impact per axle load groups is greater on the four axle types compared for the heavier axle load groups in the northbound. For the five-layered elastic pavement system under the multiple circular loaded areas for the determined wheel loads considered for the four different axle types on the Kaduna-Zaria Roadway, the following deductions are made:

1. The corresponding effects of each of the axle type on the elastic pavement between the increment variation on the default axle load magnitude between 10% and 100% are more rational averagely, because the relationship between the increment variation of the default axle load magnitude is nearly an-half (about 50%) to the effect of the pavement response (tensile strains) of each accomplished tensile strains for SADT Loads, TADT Loads and TRDT Loads while for the SAST Loads, it is about 25% response.
2. The corresponding pavement response effects shows that the TRDT Loads has the greatest range of effects and followed by TADT Loads, third in ranking is the SADT Loads and the least in impart is the SAST.

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1. The corresponding effects of each of the axle type on the elastic pavement between the increment variation on the default axle load magnitude between 10% and 100% are more rational averagely, because the relationship between the increment variation of the default axle load magnitude is nearly linearly (about 100%) to the effect of the pavement response (vertical strains) of each accomplished vertical strain for SAST Loads, SADT Loads, TADT Loads and TRDT Loads.
2. The corresponding pavement response effects shows that the TADT Loads has the greatest range of effects and followed by TRDT Loads, third in ranking is the SADT Loads and the least in impart is the SAST.

#### **4.0 Conclusion**

The Following conclusions were drawn from this study

- 1) The linear effect, as indicated in this section of the study by the curvilinear relationship between tensile strain and wheel load magnitudes, is more pronounced for thinner HMA than for thicker HMA as adopted in this study, and the relationship is about 50% of the tensile strain to the varied wheel load.
- 2) The relationship between vertical strains and wheel load is nearly linear.
- 3) The magnitude in responses between single and dual wheels are more significant when the HMA is thin and become less significant as the HMA thickness increases.
- 4) This study concluded that the impact due to variation in the mean axle load magnitude by each axle type is more significant under heavy traffic loads compared to light loads and this affects the compressive strains in the subgrade more than the tensile strains under the HMA leading to permanent damage of the pavement.

This recommendation is made for future research for Nigerian environment: The use of load spectra in the M-E design process should be adopted in the design of pavements as it provides more friendly analysis of the impact of changes in future traffic on the road infrastructure

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