SINAI International Scientific Journal (SISJ)
Volume 1, Issue 3, January 2025

Effect of Axle Spacing on Rigid Pavement Performance in Egypt

*Abdallah Wahda[1], Mohamed Zakaria[2], Mahmoud Gobara[3, *]*
[1]Civil Engineering Department, Al Azhar University, Cairo, Egypt
[2]Civil Engineering Department, Al Azhar University, Cairo, Egypt
[3]Department of civil, Faculty of Engineering, Sinai University - Arish Branch, Arish, Egypt
**Corresponding author*

Correspondence:
Mahmoud Gobara
Mahmoud.gobara@su.edu.eg

Citation:
Wahda, A., Zakaria, M., and Gobara, M., "Effect of Axle Spacing on Rigid Pavement Performance in Egypt", SINAI International Scientific Journal (SISJ),vol.1 issue.3, pp. 21-38, 2025

Received: 15 May 2024

Accepted: 21 July 2024

ABSTRACT

Many factors influence the rigid pavement's fatigue life. The most important of these factors are axle loading, the spacing between axles in the one-axle group, and the type of used tires. This study showed the influence of various rear axle spacings on the life of fatigue damage and identified the performance of the rigid pavement. The Finite Element software program DYNA-SLAB was used to calculate the stresses under the various axles. The fatigue life was assessed by the Mechanistic-Empirical Design Guide (M-EPDG) equation depending on the result of stresses from the DYNA-SLAB program, then the Axle Factor for each axle type was calculated. The results indicated that by increasing axle spacing in the one-axle group up to 2.20m for tandem and tridem axle, the Axle Factor decreased, giving the best performance of the rigid pavement. But for quad axles, if the spacing is more than 2 m, the Axle Factor increased and gives the worst performance of the rigid pavement.

KEYWORDS: Axle spacing, rigid pavement, Fatigue, Load Factor, Axle Factor (AF).

1. INTRODUCTION

Two cases of rigid pavement will be analyzed to investigate the pavement life [10-12] for different axle configurations, including the influence of different axle spacing [13, 14] and the influence of tire type. To evaluate, compare and determine the pavement response [15-17] the pavement life for different axle configurations, the following analysis will proceed. The Ref. [1] displayed that the fatigue life of a plain concrete mixture under different truck axle configurations was found to be directly defined from a repeated four-point beam test [18,19] in addition to evaluating the S-N curves for each axle configuration by using load pluses that were equivalent to the transition of an entire axle group. According to laboratory research [10, 20, 21], for a given stress ratio, the fatigue damage resulting from different axle configurations within an axle group increased with the number of axles; nevertheless, the damage per axle was lower when there were multiple axles in the same stress ratio than when there was just one axle. The Ref[2] determined the vehicle SF31904's physical road structure sample while it was traveling on the cement concrete pavement. Tensile stress was calculated and analyzed in a variety of scenarios using the finite element program ABAQUS. The relative curve for slab and maximum tensile stress [22, 24] were also proven to have a role in the equation. The findings showed that using the basic structure and earthen foundation module under SF31904 heavy mineral resulted in a lowered maximum stress of less than 30 MPa. Swati Roy Maitra and others [3] provided a finite element model method for estimating the stress in concrete pavement caused by the composite of tire load and positive temperature gradient [22,25,26]. A comparison with IRC: 58 showed that using the IRC approach overstated stress, particularly temperature stress. In order to assess the curling stress on concrete pavement [27, 30], a modification of Bradbury's temperature stress coefficient was proposed. Ref. [4] compare

Online ISSN: 3009-7800
Print ISSN: 3009-6324

between the effects of different tire designs on the stress, strain, and deflections that arise from loading huge Michigan trucks with many axles (11 axles) and a typical semi-trailer with five axles. ISLAB2000, a finite element computer software application, has been employed. The standard truck has a higher potential for fatigue damage during the day under a positive temperature gradient across the slab. According to the results, the Michigan trucks have a bigger potential for fatigue damage during the night under a negative temperature gradient. Ref. [5] displayed an estimate of the new fatigue models of the Mechanistic-Empirical Pavement Design Guide [31, 33, 35] for both types of pavements, flexible and rigid, for multiple axles loads and to determine the validity of using this method of design in the Arab Republic of Egypt. The comparison between the results of the Mechanistic-Empirical Pavement Design Guide and of Michigan Department of Transportation's laboratory tests indicate that the average overall error was +20%.

2. OBJECTIVS

This study's primary goal is to assess the way rigid pavement performs in response to different axle spacing by calculating the number of cycles to fatigue failure for rigid pavement and the Axle Factor (AF) to make a comparison between the different values of the Axle Factor for each axle spacing.

Table 1: List of the previous fatigue model

Equation	Reference
$N = 10^{2.13\left(\frac{MR}{\sigma}\right)^{1.2}}$	Darter (1990)
$N = 10^{11.81-12.1765\left(\frac{\sigma}{MR}\right)} \quad for\ 0.5 \le \left(\frac{\sigma}{MR}\right) \le 1$	Portland Cement Association (1963)
$N = 10^{17.61-17.61\left(\frac{\sigma}{MR}\right)}$	Zero-Maintenance (1977)
$N = 10^{-1.736\left(\frac{\sigma}{MR}\right)+4.284} \quad for\ \frac{\sigma}{MR} \ge 1.25 Log\ N$ $= 10^{2.8127\left(\frac{\sigma}{MR}\right)^{-1.2214}} \quad for\ \frac{\sigma}{MR} \le 1.25$	NCHRP (1992)
$Log\ N = 1.323\left(\frac{MR}{\sigma}\right) + 0.588$	Foxworthy (1985)
$N_f = \left[\frac{1.2968}{\frac{\sigma}{MR}}\right]^{32.57}$	Roesler (1998)
$N_f = \left[\frac{2.689}{\frac{\sigma}{MR}}\right]^{21.79}$	Roesler (2004)
$Log\ N = \frac{1-(0.465\ SR + 0.088\ log\ log\ T\ )}{0.153\ (1-0.297\ R)}$	Rao (2005)
$N = \left[\frac{4.2577}{SR-0.4325}\right]^{3.268} \quad W\ en\ 0.45 \le SR \le 0.55 Log\ N$ $= \frac{0.9718-SR}{0.0828} \quad for\ SR > 0.55$	Portland Cement Association (1980)

$\frac{\sigma_{max}}{MOR} = 1 - \beta(1 - R) log_{10}N$	Tepfers and Kutti 1979
$Log\ N = \left[\frac{-SR^{-10.24} \log \log (1 - p)}{0.0112}\right]^{-0.217}$	American Concrete Pavement Association

3. BACKGROUND ABOUT FATIGUE DAMAGE OF RIGID PAVEMENT

The fatigue damage is the most dangerous and most frequent collapse of the concrete pavement, which attracted researchers to more attention and more studies to evaluate the age of fatigue failure in the rigid pavement. There are a lot of methods that were used to evaluate the fatigue life of rigid pavement, such as the medium stress process, the dispersive energy method, and the maximum stress method.

3.1. Previous Concrete Fatigue Models

Table 1 shows the most fatigue models as they are listed in the Michigan Department of Transportation in MDOT's study [1] and other different research.

3.2. M-EPDG Fatigue Model

One technique for estimating the rigid pavement's fatigue life is to use the Mechanistic-Empirical Design Guide (M-EPDG). The pavement response to the number of permitted load repetitions before failure for distinct types of axles (single, tandem and tridem) was assessed using the empirical function. The M-EPDG uses the following calibrated equation to establish the fatigue life of concrete pavement [6].

$$Log\,(N_{i.j.k.l.m.n}) = C_1 \left(\frac{MR_i}{\sigma_{i.l.k.m.n}}\right)^{C_2} + 0.437 \quad (1)$$

Where:

$N_{i,j,k,l,m,n}$	=	Permissible number of load applications at specifications i,j,k,l,m,n
i	=	Age (reports for PCC rupture modulus adjustment, layer bond quality, shoulder deterioration LTE)
j	=	Month (accounts for base shift and effective subgrade reaction dynamic modulus).
k	=	Axle configuration (single, tandem, and bottom-up cracking tridem; short, medium, and long top-down cracker)
l	=	load level (incremental load for each axle type)
m	=	temperature difference
n	=	traffic path
MRi	=	Modulus of rupture of PCC at age "i" (Psi)

Online ISSN: 3009-7800
Print ISSN: 3009-6324

C_1 & C_2 = Calibration constant (2.0, 1.22).

$\sigma_{i,j,k,l,m,n}$ = The used stress at condition (i, j, k, l, m, n).

4. RESEARCH METHODOLOGY

To estimate the operation of concrete pavement below different rear axle spacing, the following steps were proceeded with:

- The horizontal tensile stresses were calculated due to different axle configurations [tandem, tridem and quad], using conventional tires.
- The fatigue life was calculated using the M-E PDG procedure for concrete pavement.
- Axle loads for various groups of axles were computed.
- A comparison was made between the calculated Axle Factors for different rear axle spacing.

Fig 1. demonstrates descriptions of research methodology used to assess concrete pavement efficiency.

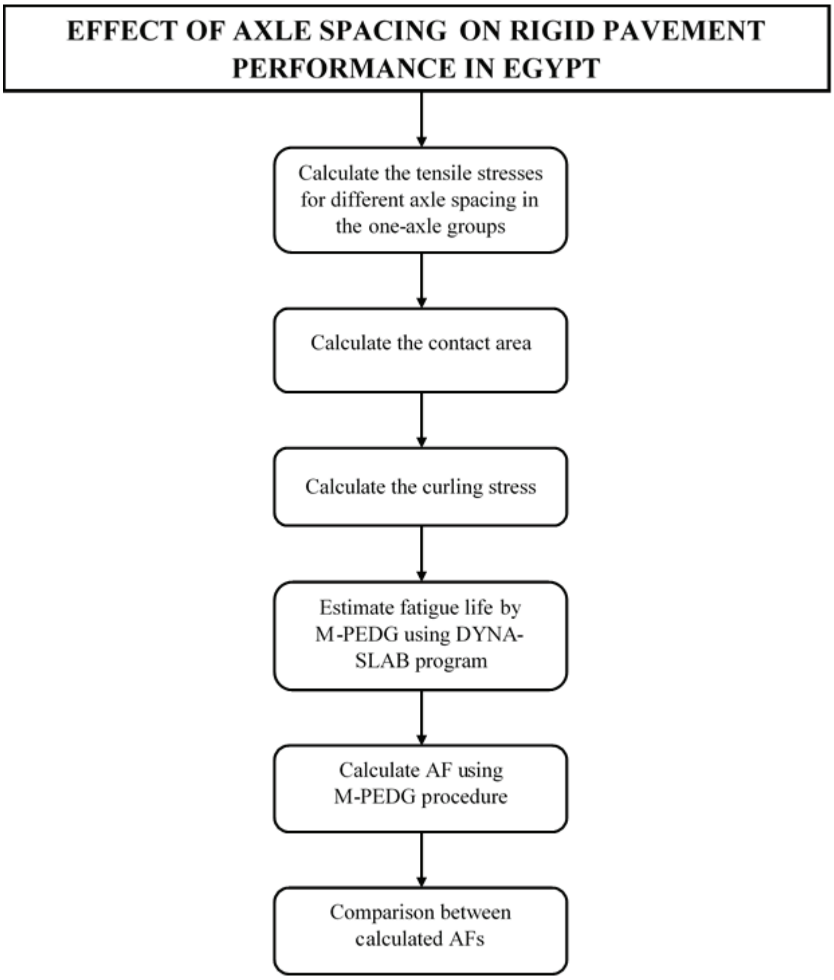


Fig. 1: Flow chart of the research methodology.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

Table 2: The Selected axle spacing

Axle type	Axle load (Ib)	Tire load (Ib)	Axle spacing (in)
Tandem Axle	44092 [20 ton]	5512	51 (1.30m)
			59 (1.50m)
			71 (1.80m)
			83 (2.10m)
			87 (2.20m)
			91 (2.30m)
Tridem Axle	66138 [30 ton]	5512	51 (1.30m)
			59 (1.50m)
			71 (1.80m)
			83 (2.10m)
			87 (2.20m)
			91 (2.30m)
Quad Axle	88185 [40 ton]	5512	51 (1.30m)
			59 (1.50m)
			71 (1.80m)
			83 (2.10m)
			87 (2.20m)
			91 (2.30m)

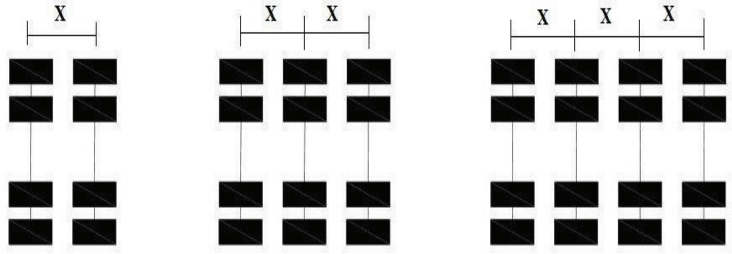
5. *DATA COLLECTION*

The truck traffic counts were conducted to determine the percentage of axle spacing in the one-axle group within the truck traffic volume on some of the Egyptian road networks. The number of trucks that counted was 130 trucks (50 tandem, 50 tridem and 30 quad). The data collection was selected from five roads (Arish – Rafah, Arish – Kantara, Cairo – Ismailia desert, Katamia - AL Ain AL Sokhna and Ring Road). Table 2 shows the selected axle spacing in the one-axle group.

5.1. Axle Configurations

This research analyzes the main different axle configurations that are existing over the Egyptian road network. The axle configurations are tandem axle, tridem axle, and quad-axle, as shown in Fig. 2.

Online ISSN: 3009-7800
Print ISSN: 3009-6324



TADT TRDT QADT

44 Kip 66 Kip 88 Kip

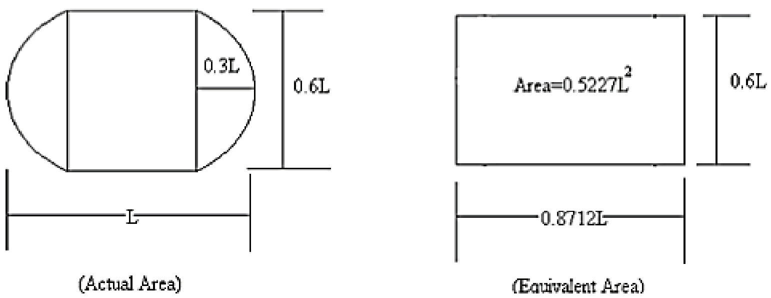
X = From 1.30 m (51-inch) to 2.30m (91-inch), and Y = 41.7 cm (16.42-inch)

Fig. 2: Conventional tire and Axle configuration with loads

5.2. Calculation of Contact Area

Due to the difference in tire loads, the contact area is changed. But in the case of different axle spacing, the tire load is 5512 on all axle configuration types. So, the tire's contact area is 8.2 inches in length and 5.7 inches in width. For conventional tires, the truck tire type used in the analysis is 295/80R22.5. The following formula is used to get the contact area for a dual tire [7]:

$$A_c = \pi\,(0.3L)^2 + (0.4L)\,(0.6L) = 0.5227L^2 \qquad \text{or} \qquad L = (A_c / 0.5227)^{0.5} \tag{2}$$



Where: Ac = equivalent contact area.

L = Length of contact area

5.3. Curling Stress

The curling stress due to alteration in temperature between the upper and lower parts of the PCC was added to the calculated stress derived from the DYNA-SLAB program. The following equation shows the edge curling stress due to a 1 C change between the top and bottom of the slab [8].

$$\sigma_t = \frac{C_x \quad E \quad e \quad (\Delta t)}{2} \tag{3}$$

Online ISSN: 3009-7800
Print ISSN: 3009-6324

To calculate the coefficient in the direction of calculated stress, we should determine the radius of relative stiffness:

$$l = \sqrt[4]{\frac{E \quad 3}{12(1-\mu^2)k}} \tag{4}$$

Where:

Σ	=	Slab (Edge or Interior or Corner) warping stress
E	=	Modulus of elasticity of PCC (4.0E+06) psi
E	=	Thermal Coefficient of PCC ($5\ x\ 10^{-6}/$)
Δt	=	temperature differential between the top and bottom of the slab (1.5° C= 52)
Cx	=	coefficient in direction of calculated stress
I	=	Radius of relative stiffness
H	=	Slab thickness (13-inch)
K	=	Modulus of subgrade reaction (150 psi)
μ	=	Poisson’s ratio for PCC (0.15)

$$l = \sqrt[4]{\frac{E\ h^3}{12(1-\mu^2)k}} = \sqrt[4]{\frac{4.0\ x\ 10^6\ \ 13^3}{12(1-0.15^2)150}} = 47.3\ inc \tag{5}$$

$$\frac{L}{l} = \frac{15\ x\ 12}{47.3} = 3.8$$

From Fig. 3 get C_x = 0.40

$$\sigma_x = \frac{0.40 \quad 4.0\ x\ 10^6\ x\ 5\ x\ 10^{-6}\ x\ 52}{2} = 208\ psi \tag{6}$$

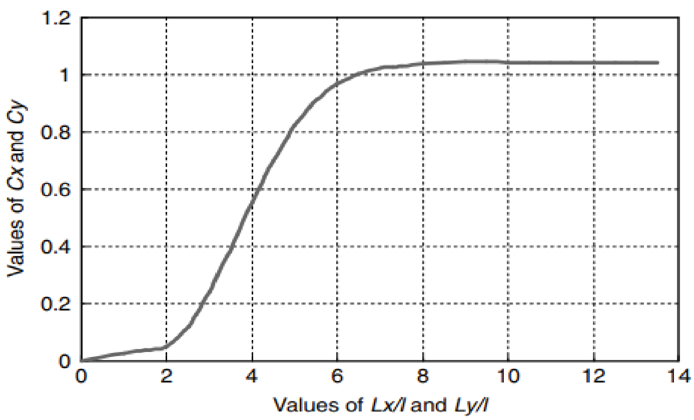


Fig. 3: warping stress coefficient

Online ISSN: 3009-7800
Print ISSN: 3009-6324

5.4. *Estimate the Cycle Number to Fatigue Failure Using M-EPDG*

To estimate the number of cycles to fatigue failure, the DYNA-SLAB finite element program was used to determine the tensile stress under various axle configurations (tandem, tridem and quad). The assumptions that were taken in the program and a constant in all cases are:

- Modulus of elasticity = 4.0 E+06 Psi.
- Poisson ratio = 0.15.
- Slab thickness = 13 inches.
- Dual spacing = 16.4 inches.
- Modulus of subgrade reaction = 150 p.
- Load transfer in the x direction is by the dowel bars only.
- Dowel and concrete interaction = 1.52E+06.
- The average contact area of a dual tire is 8.20 in length and 5.70- in width inch.
- Dimension of slabs = 12-inch wide * 15-inch long.

6. RESULTS

6.1. *Influence of various rear axle spacing on the fatigue life of rigid pavement*

The distances between truck axles in the one-axle group differ depending on the truck's type and purpose. According to the Egyptian Code, there are two types of spacing between the axles in the one-axle group, which are less than 2 m. In distances greater than 2 m, the contact area of a conventional tire is 10.7 inches in length and 7.4 inches in width due to a 5512 lb tire load. The Axle Factors for each axle group were determined based on [1]:

$$AF = \frac{Damage\ of\ t\ \ e\ axle\ group}{Damage\ of\ single\ axle} = \frac{\frac{1}{Nf\ of\ axle\ group}}{\frac{1}{Nf\ of\ single\ axle}} = \frac{N_f\ standard\ axle(18\ Kip)}{N_f\ of\ axles} \quad (7)$$

6.1.1. Tandem Axle

The tandem axle load is 20 t (44 Kip) with a conventional tire type. The axle spacing in the one-axle group is (1.30 m, 1.50 m, 1.80 m, 2.10 m, 2.20 m and 2.30 m). Fig. 4 displays the stress-time curve due to axle load using the Finite Element software DYNA-SLAB.

6.1.2. Tridem Axle

The tridem axle load is 30 t (66 Kip) with a conventional tire type. The spaces between axles in the one-axle group are (1.30 m, 1.50 m, 1.80 m, 2.10 m, 2.20 m and 2.30 m). Fig. 5 displays the stress-time curve due to axle load using the Finite Element software DYNA-SLAB.

6.1.3. Quad Axle

The quad axle load is 40 t (88 Kip) with a conventional tire type. The spaces between axles in the one-axle group are (1.30 m, 1.50 m, 1.80 m, 2.10 m, 2.20 m and 2.30 m). Fig. 6 displays the stress-time curve due to axle load using the Finite Element software DYNA-SLAB.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

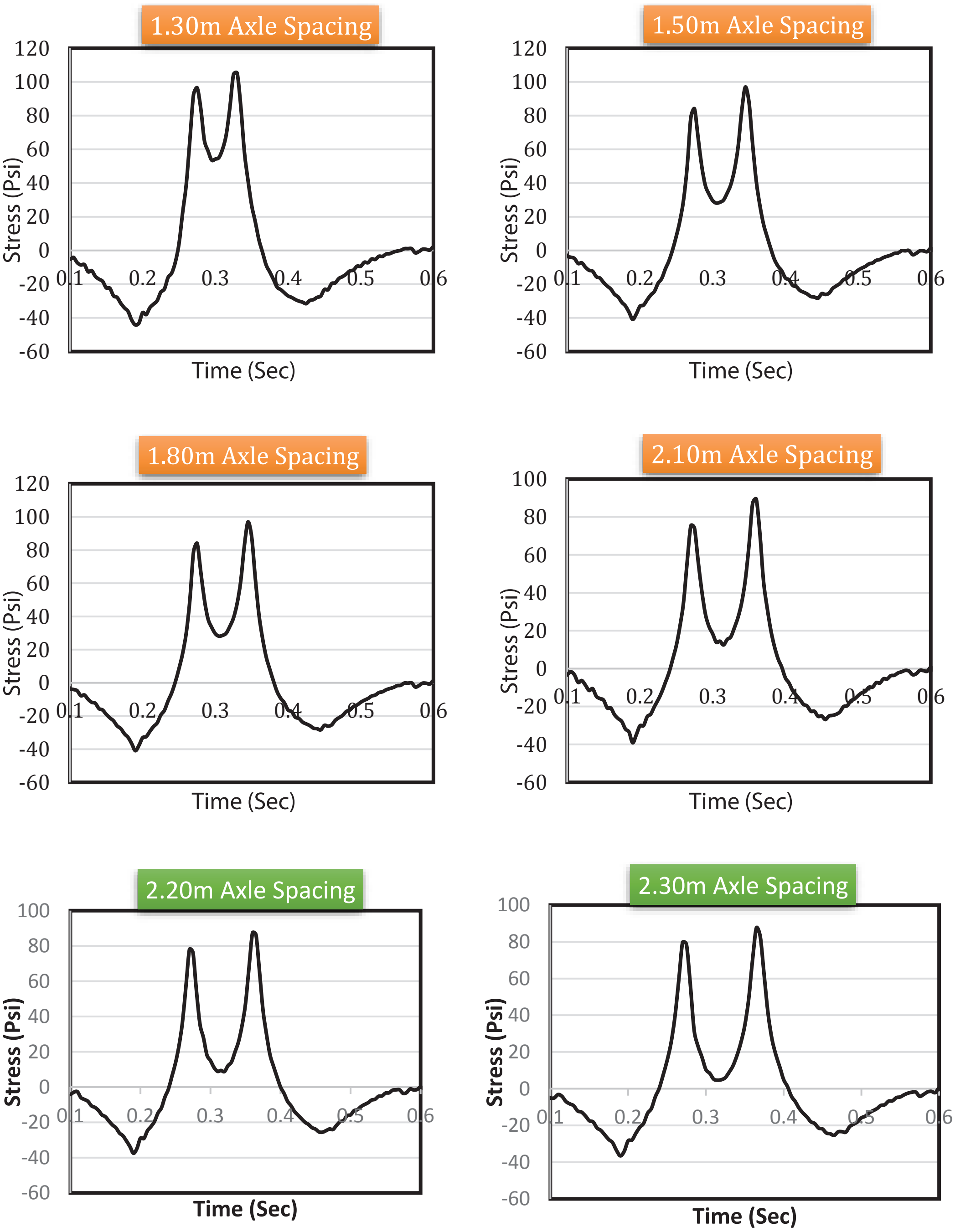


Figure [4-4] Stress-time curve for different spacing for TADT

Fig. 4: DYNA-SLAB tensile stress of tandem axle for different axle spacing.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

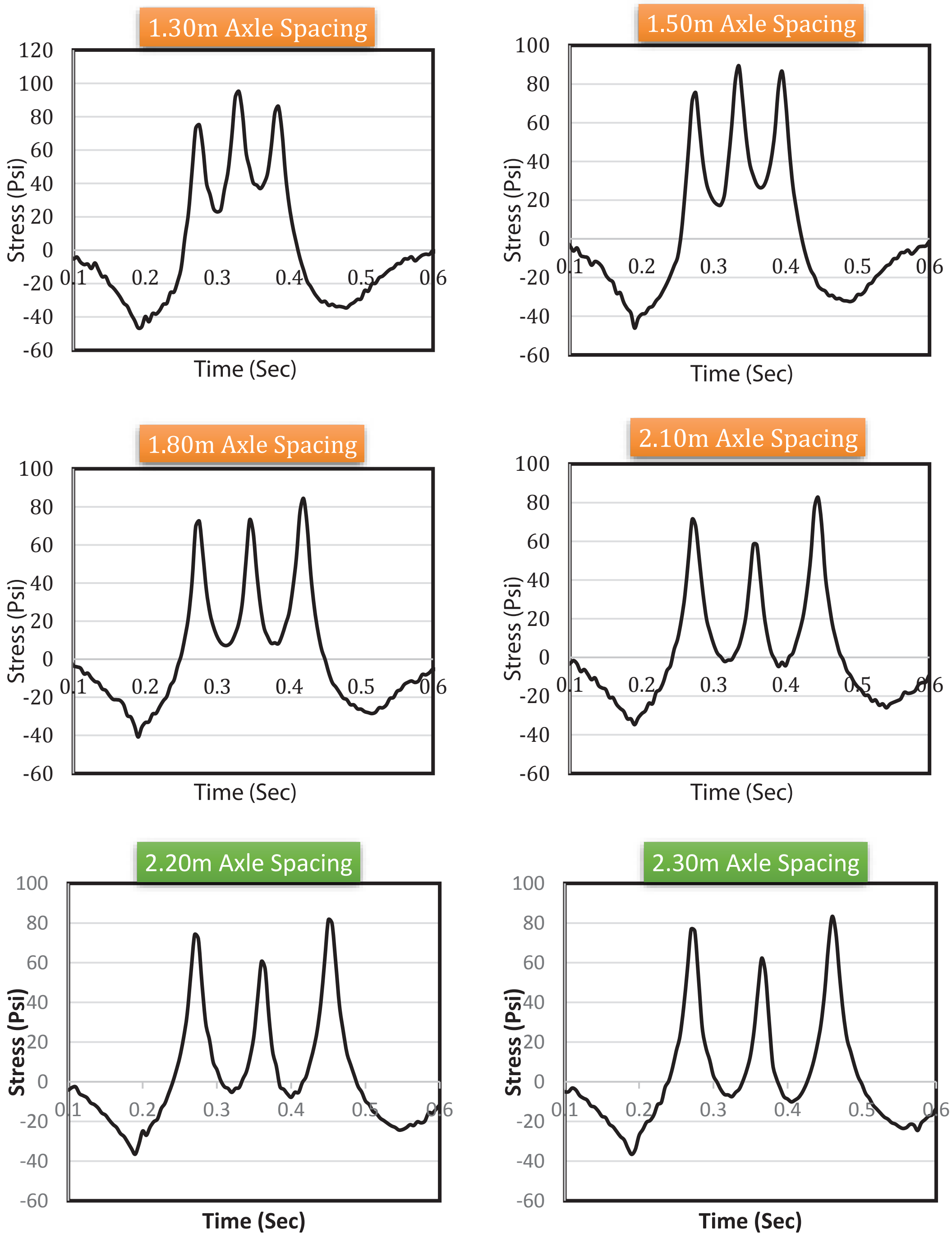


Fig. 5: DYNA-SLAB tensile stress of tridem axle for different axle spacing

Online ISSN: 3009-7800
Print ISSN: 3009-6324

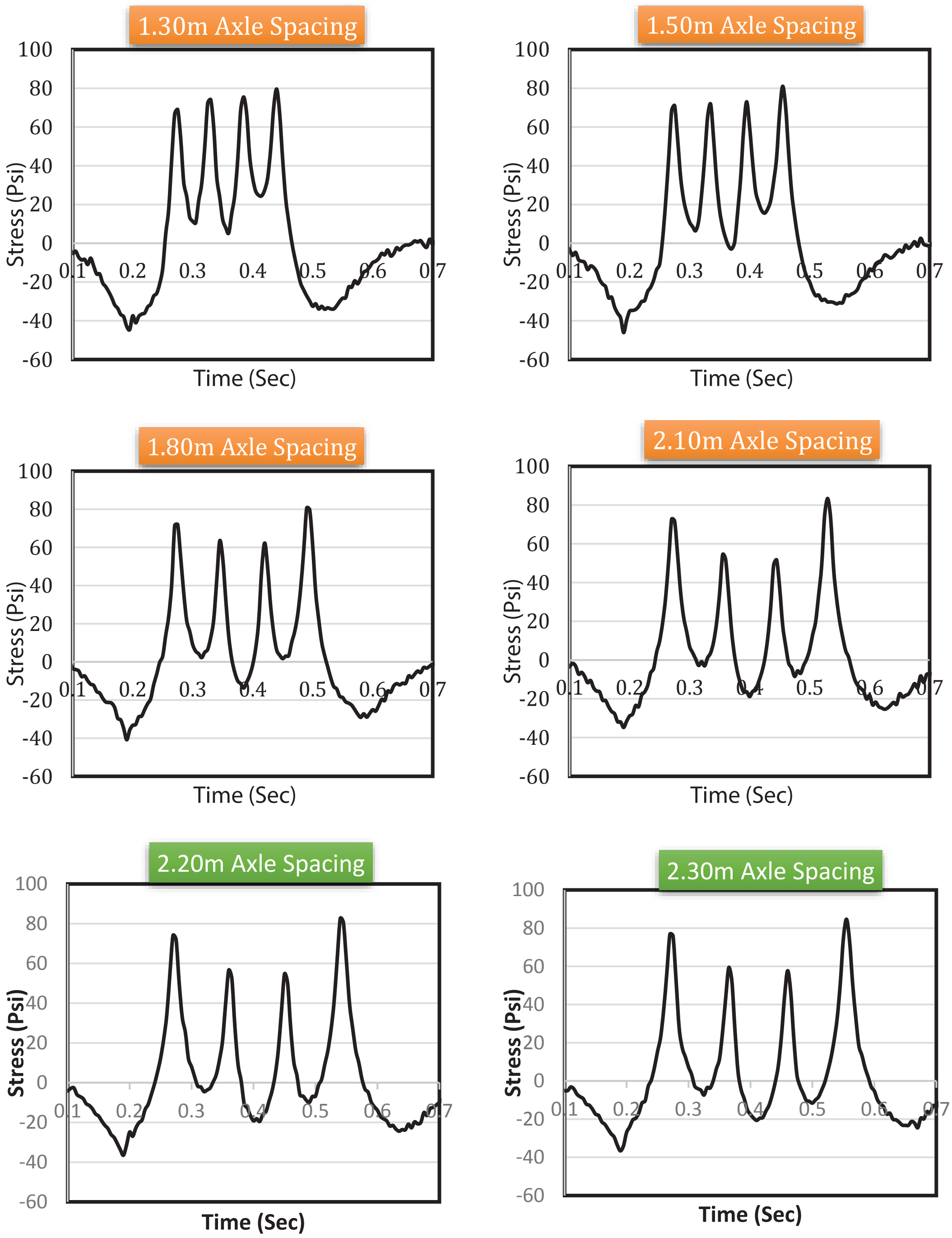


Fig. 6: DYNA-SLAB tensile stress of quad axle for different axle spacing

Online ISSN: 3009-7800
Print ISSN: 3009-6324

Table 3 displays the total tensile stress for various axle spacing due to axle load using the Finite Element software DYNA-SLAB. Additionally,

Table 4 shows the number of cycles to fatigue failure [NF] for each axle by using M-EPDG equation. The Axle Factors were calculated to compare the different axle spacing and the effect on the performance of rigid pavement under axle load. Table 5 shows that Axle Factors for each axle group depends on the standard axle of 18 kip.

Table 3: Total stress due to longitudinal stress plus curling stress

Axle group	Axle Spacing (m)	Stress (Psi)			
		Axle [1]	**Axle [2]**	**Axle [3]**	**Axle [4]**
Tandem axle (20 ton) (44 Kip)	1.30	313	312		
	1.50	310	308		
	1.80	305	296		
	2.10	297	295		
	2.20	295	294		
	2.30	296	291		
Tridem axle (30 ton) (66 Kip)	1.30	294	300	303	
	1.50	290	297	295	
	1.80	285	281	292	
	2.10	285	279	291	
	2.20	288	282	290	
	2.30	285	284	291	
Quad Axle (30 ton) (88 Kip)	1.30	288	284	282	280
	1.50	262	280	279	289
	1.80	256	280	279	289
	2.10	257	281	281	291
	2.20	258	282	280	291
	2.30	259	284	283	293

Online ISSN: 3009-7800
Print ISSN: 3009-6324

Table 4: Number of cycle load to fatigue failure

Axle group	Axle Spacing (m)	N_f			
		Axle [1]	**Axle [2]**	**Axle [3]**	**Axle [4]**
Tandem axle (20 ton) (44 Kip)	1.30	204582	212164		
	1.50	231503	261311		
	1.80	296619	457367		
	2.10	426014	475218		
	2.20	469803	496859		
	2.30	465384	594312		
Tridem axle (30 ton) (66 Kip)	1.30	498609	321564	383142	
	1.50	631770	425596	488216	
	1.80	792294	997919	546408	
	2.10	800868	1105597	593393	
	2.20	693884	940528	631770	
	2.30	811737	854603	577431	
Quad Axle (30 ton) (88 Kip)	1.30	701620	872946	941047	1044030
	1.50	3216139	1070096	1119413	650829
	1.80	4579359	1059938	1090746	663903
	2.10	4505084	988539	1021531	575065
	2.20	4054135	942085	1058750	597385
	2.30	3912694	855068	912001	538954

SINAI International Scientific Journal (SISJ), 2025, 1(3)
Online ISSN: 3009-7800
Print ISSN: 3009-6324

Table 5: Axle Factor using M-EPDG equation.

Axle group	Axle Spacing(m)	Total AF
Tandem axle (20 ton) (44 Kip)	1.30	4.69
	1.50	3.98
	1.80	2.72
	2.10	2.18
	2.20	2.02
	2.30	1.87
Tridem axle (30 ton) (66 Kip)	1.30	3.78
	1.50	2.92
	1.80	2.00
	2.10	1.88
	2.20	2.00
	2.30	2.02
Quad Axle (30 ton) (88 Kip)	1.30	2.24
	1.50	1.80
	1.80	1.75
	2.10	1.93
	2.20	1.94
	2.30	2.14

7. DISCUSSION

Fig. 7 shows that if the spacing between axles in the one-axle group increases, the Axle Factor decreases with a rise in the number of cycles to fatigue failure, and that gives the best performance of rigid pavement. It is allowed to increase the axle spacing to 2.20 m with the same axle load for tandem and tridem axles. But when the axle spacing increases to more than 2.20 m, the Axle Factor increases because there is no overlap between axles in the one-axle group. For quad axles, the AF increases if the spacing between axles was raised to 2 m, leading to the worst performance of rigid pavement and not allowing the axle spacing to increase more than 2.0 m.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

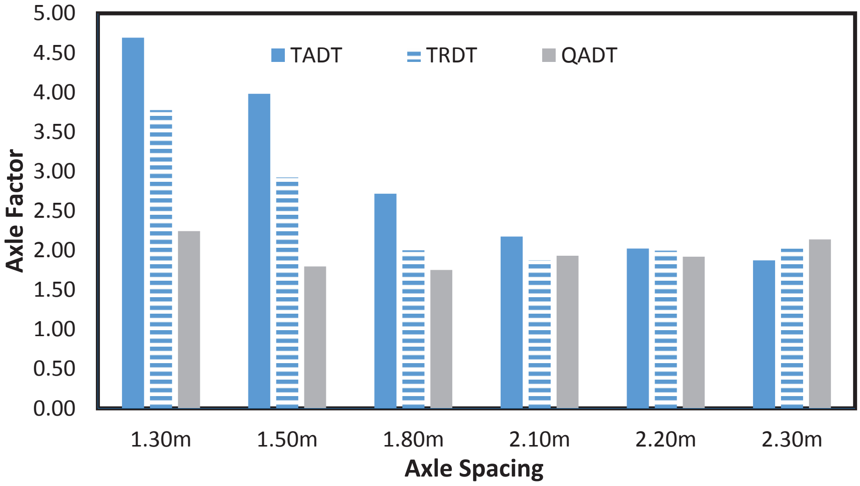


Fig. 7: Comparison between Axle Factor due to different axle spacing

8. CONCLUSION

This research studies the influence of different axle spacings (1.30, 1.50, 1.80, 2.0, 2.1, 2.2, and 2.3 m) on the performance of rigid pavement using DYNA-SLAB program. The aim of this analysis is to calculate the stress and determine the Nf, which is used to calculate the Axle Factor (AF) for each axle an to make a comparison between them. The following points summarize the results of this research:

- By increasing the number of axles in the one-axle group, the performance of rigid pavement increases with a decrease in Axle Factor.
- According to analysis for tandem and tridem axles, it is allowed to increase in the axle spacing to 2.20 m with the same axle load. But when the axle spacing increases to more than 2.20 m, the Axle Factor increases because there is no overlap between axles in the one-axle group.
- For quad axles, if the spacing between axles is raised to 2m, the AF increases.

CONFLICT OF INTEREST

[1] All authors declare that they have no conflicts of interest.

REFERENCES

[1] Chatti, K. et al., "Effect of Michigan Multi-Axle Trucks on Pavement Distress.", Volume III-Rigid Pavement, Project RC-1504, 2009.

[2] Su, Y., Xin, S., Shi J., and Zhang, Z., " Stress Analysis of Cement Concrete Pavement with Special Heavy Mine Vehicle" International Conference on Future Energy, Environment, and Materials Volume 16, Part B, 2012, Pages 722-729.

[3] Maitra, S. R., Reddy, K. S., and Ramachandra, L. S., " Estimation of Critical Stress in Jointed Concrete Pavement" The 2nd Conference of Transportation Research Group of India (2nd CTRG) Volume 104, 2 December 2013, Pages 208-217.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

[4] Kabir, R., "Numerical Study of Structural Response of Rigid and Flexible Pavements Under Heavy Vehicles Loading " Open Access Master's Thesis, Michigan Technological University, 2015 https://digitalcommons.mtu.edu/etdr/23/.
[5] El Refaey, M., Solyman, M., Salama, H., and Zakaria, M., " Evaluation of the New Mechanistic-Empirical Pavement Design Guide Fatigue Models for Multiple Axle Loads", 2013.
[6] ARA Inc. “Guide for Mechanistic-Empirical Pavement Design Guide of New and Rehabilitated pavement structure”. Final report for project No. 1-37A. National Cooperative Highway Research Project. (NCHRP). Washington, DC, 2004.
[7] Abbas, D. S. *et al*. "Measured and calculated area of contact under different tire types" AIP Conference Proceeding Vol. 2775. No. 1. AIP Publishing, 2023.
[8] Bradbury R. D., Reinforced concrete Pavement. Wire Reinforcement Institute, Washington, DC, 1938.
[9] American Association of State Highway and Transportation Officials, “The AASHO Road Test’’ Highway Research Board of the NAS-NRC Division of Engineering and Industrial Research, Report 5, Special Report 61E, Washington D. C., USA, 1962.
[10] Li, S., Liu, X., and Liu, Z., Interlaminar shear fatigue and damage characteristics of asphalt layer for asphalt overlay on rigid pavement. Construction and Building Materials, 68, 341-347., 2014.
[11] Abbass, M., and Singh, G., Fatigue analysis of rice husk ash and basalt fibre-based sustainable geopolymer concrete in rigid pavements. Materials Today: Proceedings, 45, 5014-5022, 2021.
[12] Zarei, B., and Shafabakhsh, G. A., Dynamic analysis of composite pavement using finite element method and prediction of fatigue life. Computational Research Progress in Applied Science & Engineering (CRPASE), 4(2), 2018.
[13] Gillmann, R., Axle spacing and load equivalency factors. Transportation research record, 1655(1), 227-232, 1999.
[14] Basar, G., Cetin, M., and Nichols, A. P., Comparison of vehicle re-identification models for trucks based on axle spacing measurements. Journal of Intelligent Transportation Systems, 22(6), 517-529, 2018.
[15] Mallela, J., and George, K. P., Three-dimensional dynamic response model for rigid pavements. Lateral, 3(5), 7, 1994.
[16] Vepa, T. S., and George, K. P. (1997). Deflection response models for cracked rigid pavements. Journal of Transportation Engineering, 123(5), 377-384, 1997.
[17] Taghavi, G. A., Aguirre, N., Carrasco, C. J., Vrtis, M., and Garg, N., Evaluation of the response from the rigid pavement analysis system (RPAS) program for the characterisation of jointed concrete pavements. Road Materials and Pavement Design, 22(10), 2212-2231., 2021.
[18] Guzmán, C., Torres, D., Hucailuk, C., and Filipussi, D., Analysis of the acoustic emission in a reinforced concrete beam using a four points bending test. Procedia Materials Science, 8, 148-154, 2015.
[19] Weinberger, R., Reches, Z., Eidelman, A., and Scott, T., Tensile properties of rocks in four-point beam tests under confining pressure. In ARMA North America Rock Mechanics Symposium (pp. ARMA-1994). ARMA, 1994.
[20] Hiller, J. E., and Roesler, J. R., Determination of critical concrete pavement fatigue damage locations using influence lines. Journal of Transportation Engineering, 131(8), 599-607, 2005.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

[21] Cheng, H., Liu, J., Sun, L., & Liu, L., Critical position of fatigue damage within asphalt pavement considering temperature and strain distribution. International Journal of Pavement Engineering, 22(14), 1773-1784, 2021.
[22] Choubane, B., and Tia, M., Nonlinear temperature gradient effect on maximum warping stresses in rigid pavements. Transportation Research Record, 1370(1), 11., 1992.
[23] Chatti, K., Manik, A., Salama, H., Haider, S., Brake, N., and El Mohtar, N., "Effect of Michigan Multi-Axle Trucks On Pavement Distress" Michigan State University, Final Report, Project RC-1504, 2009.
[24] Setyawan, A., Yusep, M. P., Setiawan, B., Muandululman, F., Setiawan, A. G., and Prabowo, G. A., The Evaluation of Deflection and Tensile Stress in Jointed Plain Concrete Pavement for a Damaged Road. In Journal of Physics: Conference Series (Vol. 1912, No. 1, p. 012057). IOP Publishing., 2021.
[25] Assogba, C., Tan, Y., Zhou, X., Zhang, C., and Anato, J. N., Numerical investigation of the mechanical response of semi-rigid base asphalt pavement under traffic load and nonlinear temperature gradient effect. Construction and Building Materials, 235, 117406., 2020.
[26] Mohamed, A. R., & Hansen, W., Effect of nonlinear temperature gradient on curling stress in concrete pavements. Transportation Research Record, 1568(1), 65-71, 1997.
[27] Zokaei-Ashtiani, A., Tirado, C., Carrasco, C., and Nazarian, S. Impact of different approaches to modelling rigid pavement base layers on slab curling stresses. International Journal of Pavement Engineering, 17(10), 861-869, 2016.
[28] Smith, K., Wilson, T., Darter, M., and Okamoto, P., " Analysis of Concrete Pavements Subjected to Early Loading" Transportation Research Record No.1370, Transportation Research Board p. 1-10, 1992.
[29] Chatti, K., Lysmer, J., and Monismith, C., " Dynamic Finite-Element Analysis of Jointed Concrete Pavements" Transportation Research Record No.1449, Transportation Research Board Vol. 1449, pp. 79-90, 1994.
[30] Ioannides, A. M., and Salsilli-Murua, R. A., Temperature curling in rigid pavements: an application of dimensional analysis. Transportation Research Record, 1227, 1-11, 1989.
[31] Baus, R. L., and Stires, N. R., Mechanistic-empirical pavement design guide implementation (No. FHWA-SC-10-01). University of South Carolina. Dept. of Civil & Environmental Engineering, 2010.
[32] Chatti, K., Manik, A. and Brake, N., " Effect of Axle Configuration on Fatigue and Faulting of Concrete Pavements " International Conference on Heavy Vehicles, 2008, Paris, France 10.1002/9781118557464.ch13.
[33] Mallela, J., Titus-Glover, L., et al., Implementation of the AASHTO mechanistic-empirical pavement design guide for Colorado (No. CDOT-2013-4). Colorado. Dept. of Transportation. Research Branch, 2000.
[34] Chatti, K., Brake, N., Haier, S., and Salama, H., "The Effect of Different Axle Configurations on the Fatigue Life of Plain Cement Concrete" Pavement Cracking: Mechanisms, Modeling, Detection, Testing and Case Histories. 155-165. 10.1201/9780203882191.ch16, 2008.
[35] Pierce, L. M., & McGovern, G., Implementation of the AASHTO mechanistic-empirical pavement design guide and software (No. Project 20-05, Topic 44-06), 2014.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

[36] Setyawan, S.E. Zoorob and Hasan, K., "Investigating and Comparing Traffic Induced and Restrained Temperature Stresses in a Conventional Rigid Pavement and Semi-Rigid Layers" The 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering (ICRMCE) Volume 54, 2013, Pages 875-884.
[37] ROADEX Network, "Effect of Axle and Tyre Configurations on Pavement Durability" Summary of Pajala Mine Road Impact Analysis – ROADEX implementation. ROADEX summary report. www.roadex.org, 2014.
[38] Dhawale, A. and Vishwanath "Comparative Study of Wheel Load Stress and Warping Stress on Concrete Pavements " International Journal of Civil, Structural, Environmental and Infrastructure Engineering, Research and Development (IJCSEIERD) ISSN(P): 2249-6866; ISSN(E): 2249-7978, Vol. 4, Issue 1, Feb 2014, 9-14.
[39] Shafabakhsh, A. G., *et al.,* " Dynamic Effects of Moving Loads on the Jointed Plain Concrete Pavement Responses" Engineering Journal vol. 21, no. 5, pp. 137-144, Sep. 2017.
[40] Walubita, L. F., Nyamuhokya, T., P., *et al*. " A Mechanistic-Empirical Impact Analysis of Different Truck Configurations on A Jointed Plain Concrete Pavement (JPCP)" Civil Engineering Journal. 26. 507-529. 10.14311/CEJ.2017.04.0041, 2017.
[41] Tepfers, R., and Kutti, T., "Fatigue strength of plain, ordinary, and lightweight concrete." J. Am. Concr. Inst., 76, 635–652, 1979.
[42] Titus-Glover, L., "Enhanced Portland Cement Concrete Fatigue Model for StreetPave" Transportation Research Record: Journal of the Transportation Research Board, No. 1919, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 29–37.
[43] Kurt, D. S., Thomas P. W., Darter, M., and Okamoto, P., "Analysis of Concrete Pavements Subjected to Early Loading" Transportation Research Record No.1370, Transportation Research Board p. 1-10. 1992.
[44] "Goodyear Truck Tires Service Manual", Section 11, Retreading, p107" 2013.
[45] Salgado, R., "EFFECTS OF HEAVIER TRUCK LOADINGS AND SUPER-SINGLE TIRES ON SUBGRADES" Transportation Research Program, Project No: C-36-52R, File No: 6-20-17, FHWA/IN/JTRP-2002/20.
[46] North American Council for Freight Efficiency (NACFE) "Annual Fleet Fuel Efficiency Study," http://nacfe.org/wp- content/uploads/2015/05/NACFE--2015 Annual--Fleet--Fuel- Study --Report-- 050115.pdf , 2015.
[47] Walker, D., "PASER Asphalt Pavement Manual", Transportation Information Center, University of Wisconsin-Madison. 2002. http://tic.engr.wisc.edu.
[48] Kurt D. Smith 2004 "Review of Fatigue Models for Concrete Airfield Pavement Design" Airfields Pavements 2003.
[49] IRC: 58-(2002) "GUIDELINE FOR THE DESIGN OF PLAIN JOINTED RIGID PAVEMENT FOR HIGHWAYS" Second Revision, The Indian Road Congress, Jamnagar House, Shahjahan Road, New Delhi-110011.
[50] Al-Qadi, I., Loulizi, A., Janajreh, I., and Freeman, T. (2002). "Pavement Response to Dual Tires and New Wide-Base Tires at Same Tire Pressure," Journal of Transportation Research Board, Issue Number 1806, pp 38-47.

Online ISSN: 3009-7800
Print ISSN: 3009-6324