

Investigation of Flexible Pavements' Edge Failure Distress

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ABSTRACT: From practical observation, it was noted that failure near pavement edges is quite common in New Zealand. This failure mode is associated with the mountainous topography that makes constructing wide pavements expensive. The main objective of this research work is to investigate the different factors affecting this type of distress. A three dimensional finite elements model was designed to study different loading and shoulder conditions. A half fractional factorial experimental design was made to study five factors: shoulder width, shoulder stiffness, axle load, tire pressure and pavement thickness. The finite elements model solution was compared with multilayer analysis and actual field measurements carried out at the Transit New Zealand accelerated test track to ensure accurate predictions. None of the solutions provided a perfect match between the measured and predicted vertical strains. The multilayer linear elastic solution and the three dimensional finite elements solutions were reasonably close. The order of importance of the different factors affecting pavement response in the outer wheel path relies on the type of response. The shoulder thickness was the most important factor affecting the maximum surface deflection under the outer wheel followed by the axle load, tire pressure, and shoulder width. For the compressive strain on the top of the subgrade and the maximum shear strain in the base course, the order of importance of factors was different. The shoulder stiffness, width and thickness played a significant role in distributing the stresses and strains on the top of the subgrade thus controlling the edge failure.

KEYWORDS

Edge failure, tire pressure, axle load, finite elements, experimental design.

1 INTRODUCTION

From practical observation, it is apparent that pavement failure near the edges of the pavement is more common compared to the compressive failure in the wheel path in many of the New Zealand roads. This failure mode is associated with narrow roads which are common in New Zealand because of the mountainous topography that makes constructing wide pavements expensive. When these relatively narrow pavements are subjected to heavy vehicles trafficking, the edges tend to crumble due to lack of lateral support. Heavy traffic volumes and axle loads are increasing and will continue to do so because of the predicted rapid growth in the forestry and dairy industries. In particular there is a large volume of timber currently coming on stream in New Zealand which will be frequently transported over narrow roads. As each section of the

forest is milled there is a large increase in traffic for a relatively short period of time. The costs of increasing the width of shoulders on these narrow roads cannot be justified because the higher traffic volume is only for a short period of time. The damage caused by this traffic is often associated with edge failure (lack of pavement support) rather than the classic failure mechanisms of rutting or roughness.

The aim of the research is to obtain an improved understanding of the role of lateral pavement support on pavement performance and to develop cost-effective methods to reduce or prevent pavement edge failure especially where pavement widening is not an option.

Ball and Patrick (2005) carried out an investigation of the edge failure on New Zealand state highways and local authority roads utilizing data extracted from the Road Asset Maintenance Management system (RAMM) database. The data covered approximately 3,000 km of state highway and 3,000 km of local sealed roads. Besides basic data such as location, surface type, length of inspection site, traffic and heavy traffic levels, etc., the following factors were particularly selected for statistical analysis: lane width, number of lanes, length of unpatched edge breaks, length of patched edge breaks, terrain type, and radius of curvature of both lanes. They found that the principal factors affecting the occurrence of edge breaks are lane width, seal age and total traffic per lane. Seal age in itself made a significant contribution to the amount of edge breaks occurring. They concluded that because of the strong dependence of the probability of edge break on lane width, research to improve the strength of the pavement edge would have a significant potential to improve rural road performance. The hypothesis forming the basis of the current research is that by providing support to the sides of the pavement using trenches containing high-strength material failure will be minimized or prevented. As the strength, width and depth requirements of the lateral support are not known, the first stage of the research is to model and measure the stresses and strains generated by heavy traffic outside the wheel track.

A Finite Elements (FE) analysis of pavement stresses and strains is conducted at the University of Canterbury using general-purpose finite elements software. The results of the modelling are compared with the measured strains using the Transit NZ CAPTIF accelerated testing facility located in Christchurch. Only limited amount of vertical strains measurements were used to validate the three-dimensional finite elements model and the results of this validation are shown in this paper.

2 FINITE ELEMENTS MODEL

2.1 Model Geometry

ABAQUS (Hibbit Et. Al., 2003), a general-purpose finite elements code, was used to simulate the loading of a fully instrumented section in the accelerated test track, CAPTIF. The structural composition of this section is mainly made of chip seal applied on an unbound base course that overlays the subgrade; this type of construction is common in New Zealand. A half model was developed to reduce the computational effort by making use of the symmetry in the geometry and the loading. To carry out the experimental factorial design, different model geometries were considered. For example, two thicknesses for the base course were considered, 300 mm and 500 mm. The thickness of the subgrade is the difference between the CAPTIF tank depth (1500 mm) and the thickness of the base course. The 300 and 500 mm base course thicknesses were modelled using two and four elements, respectively. The thickness of the subgrade layer that

ranges from 1000 to 1200 mm was modelled using eight and nine elements, respectively. The length of the finite elements section is 2000 mm. Figure 1 shows the three-dimensional finite elements model (3DFEM). The loaded area is composed of eight elements, four elements in each half of the model. The loaded area is modelled based on tire imprints measurements carried out at the accelerated test track. It was found that the tire imprint width is 225 mm and the length of the tire imprint is 125 mm. However, these dimensions will vary based on the applied axle load and tire inflation pressure. In this analysis, the tire imprint width was maintained at 225 mm and the length of the tire imprint was calculated according to the applied load and tire pressure as shown below in Equation 1.

$$A = \frac{P}{q} \quad \text{Equation 1}$$

A = Loaded area, m²

P= Total load per tire, kN

q = Tire Pressure, kPa

For example, for a dual tire-single axle load of 80 kN and a tire inflation pressure of 400 kPa,

$$\text{the loaded area under each tire} = A = \frac{20}{400} = 0.05 \text{ m}^2$$

X = 225 mm from actual measurements of the tire imprints at CAPTIF

A = 2 * X * Y (Because this is half model), see Figure 1.

Y=111.1 mm

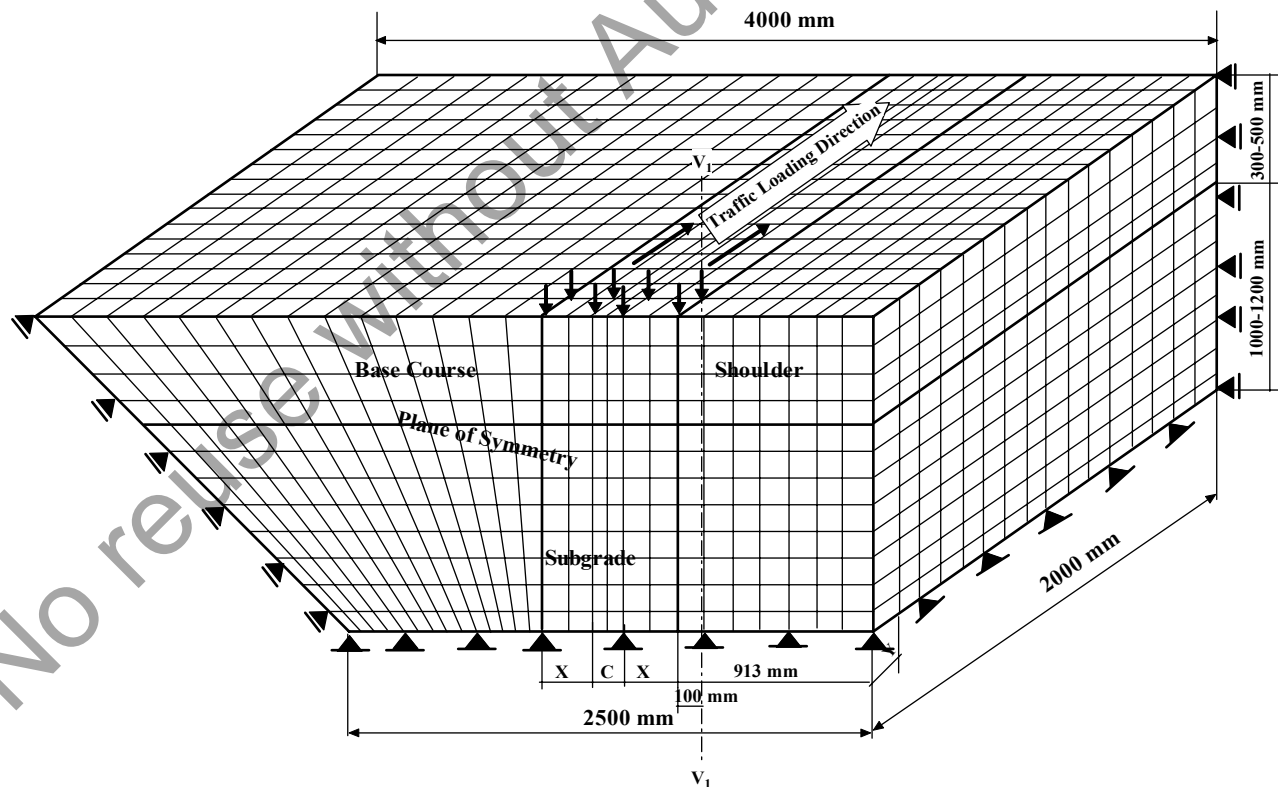


Figure 1: Three dimensional finite elements model.

Where X is the width and Y is length of the loaded area in each half of the 3DFEM. The clearance (C) between the two loaded areas is 125 mm. The length of the loaded area varies for different axle loads and tire pressures and it can be calculated as shown above. For each run in the experimental factorial design, a separate 3DFEM model was developed to simulate the tire pressure, axle load, pavement thickness, and shoulder properties.

The aspect ratio is defined as the ratio of maximum to minimum characteristic dimensions in the element. This ratio affects the distortion of the elements during analysis, and it should not exceed 4.0. In addition, a good practice is to choose corner angles in the range of 30° to 120° (Chandrupatla and Belegundu, 1996). The average aspect ratio for all models is 1.34 and the worst aspect ratio is 2.45. The average minimum and maximum corner angles are 75.95° and 104.06°, respectively.

2.3 Boundary Conditions

The rigid boundaries of the concrete tank in the accelerated test track, CAPTIF, were simulated in the finite elements model so that the bottom base of the subgrade is prevented from axial movements in the three directions. The sides of the model are only allowed to slide in the plane of the wall and are prevented from any movement perpendicular to the concrete wall. At the plane of symmetry, elements are only allowed to move vertically without any lateral displacement.

3 MULTILAYER ELASTIC ANALYSIS

The pavement structure was modelled as three layers subjected to dual load of 20 kN per tyre and tyre pressure of 750 kPa. The distance from center to center of the dual is 350 mm (350 mm = C+X = 125+225mm). The top layer was modeled as a granular material of thickness 300 mm, and resilient modulus and Poisson ratio as 288MPa, and 0.35, respectively. The subgrade was modeled as 1200 mm layer with resilient modulus and Poisson ratio of 24MPa, and 0.4, respectively. The third layer was considered as PCC layer with 28 GPa modulus and 0.15 Poisson' ratio. These properties were used in the verification analysis of the finite elements model.

4 MATERIAL PROPERTIES

The data from the repeated triaxial test for both the base course and the subgrade was used to determine the resilient modulus and the stress dependency of these materials. For the base course the k-θ model shown by Equation 2 showed excellent fit for the triaxial data with a coefficient of determination (R²) value of 99.3%.

$$M_r = 108.91 * \left(\frac{\theta}{P_a} \right)^{0.723} \quad \text{Equation 2}$$

M_r = Resilient Modulus (MPa)

θ = Bulk stress (kPa)

P_a = atmospheric pressure (101.3 kPa)

For linear elastic analysis, an average value of the resilient modulus of the base course and subgrade was calculated. The average resilient modulus for the base course is 288 MPa and that for subgrade is 24 MPa.

5 VERIFICATION OF THE 3DFEM

The pavement response predicted from the three dimensional finite elements (3DFEM) was compared with the multilayer elastic system solution. Linear and nonlinear elastic solutions were considered. Everstress software (1999) was used to carry out the nonlinear and linear isotropic elastic solution. The solution shown here is for a tire pressure of 750 kPa and standard axle load of 80 kN and the material properties as discussed before. The vertical compressive strains were determined at different depths under the centerline of the dual and compared with the measured strains in the accelerated test track facility (CAPTIF) as shown in Figure 2. Figure 2 shows that none of the above mentioned methods perfectly matched the measured strains. The nonlinear analysis provided a slightly better match compared to the linear analysis. The linear elastic solution by 3DFEM and the multilayer analysis perfectly matched each other and reasonably compared with the measured strains. The linear elastic solution predictions of the 3DFEM were considered acceptable and will suffice the purpose of this study.

6 EXPERIMENTAL FRACTIONAL FACTORIAL DESIGN

In the factorial experimental design, five factors; shoulder width, shoulder stiffness, axle load, tire pressure, and pavement thickness were examined. Table 1 shows the different factors and the level of each factor. Each factor was set at two extreme levels in order to span a wide range of each factor. For example, tire pressure was set at low value of 400 kPa and high value of 900 kPa while axle load spans a range from standard axle load (80 kN) to heavy axle load (120 kN). The shoulder stiffness varies from very weak material, which is similar to the subgrade soil with resilient modulus 30 MPa to strong material, which is similar to good quality base course with resilient modulus of 450 MPa. The width of the shoulder was measured from the outside edge of the outer tire and ranges from 100 mm, which represent extremely narrow shoulder with extreme encroachment from traffic, to 913 mm which is the maximum shoulder width in the Canterbury accelerated test track (CAPTIF) and that represents a relatively wide shoulder for a rough terrain rural highway. The thickness of the base course ranges from 300 mm to about 500 mm. For full factorial experimental design, a five-factor experiment each at two levels requires $2^5 = 32$ runs. This is somehow large number of computations, therefore, a half fractional factorial design was utilized and this reduced the number of runs to 16 runs.

The pavement responses examined in this analysis are the maximum surface deflection, the compressive stain on the top of the subgrade, and the maximum shear strain in the base course. All responses are calculated in the vertical plane directly under the center of the outer tire.

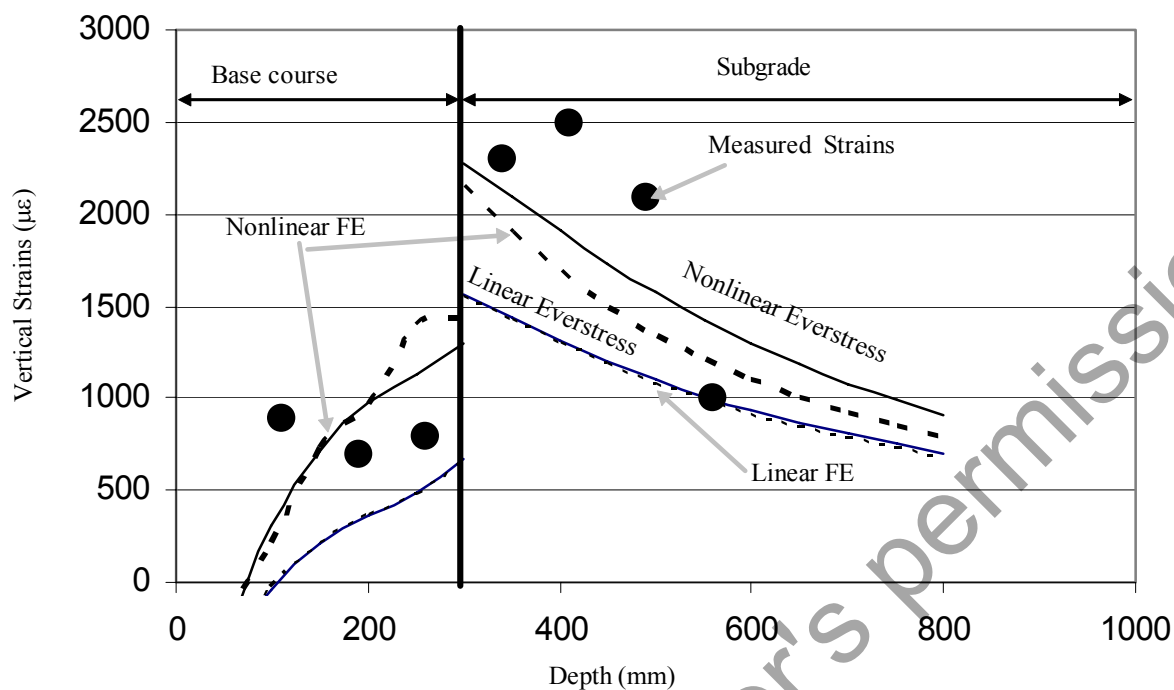


Figure 2: Comparisons between measured and predicted strains using different analytical methods.

Table 1: The factors and levels studied in the factorial analysis

Factors	Units	Levels	
		Low Level	High Level
Shoulder Width	mm	100	913
Shoulder Stiffness	MPa	30	450
Axle Load	kN	80	120
Tire Pressure	kPa	400	900
Pavement Thickness	mm	300	500

7 RESULTS AND ANALYSIS

Table 2 shows the results of the 16 runs of the experimental design for three pavement responses, maximum surface deflection under the center of the outer wheel (Δ_o), the compressive strain on the top of the subgrade (ϵ_{zz}), and the maximum shear strain in the base course (ϵ_{zx}). In Table 2, a coded system was used to represent the low and high levels of each factor. In this system, code 1 is used to indicate the high level of the factor while -1 is to indicate the low level of this factor. The actual values of each factor are shown in Table 1.

Table 2: Experimental design results

Run	A	B	C	D	E	Δ_0	ε_{zz}	ε_{zx}
1	-1	-1	-1	-1	1	799	870	311
2	1	-1	-1	-1	-1	1024	1211	303
3	-1	1	-1	-1	-1	994	930	266
4	1	1	-1	-1	1	531	430	277
5	-1	-1	1	-1	-1	1525	1879	457
6	1	-1	1	-1	1	974	1097	342
7	-1	1	1	-1	1	996	907	295
8	1	1	1	-1	-1	1137	1156	294
9	-1	-1	-1	1	-1	1260	1146	495
10	1	-1	-1	1	1	834	724	594
11	-1	1	-1	1	1	846	586	573
12	1	1	-1	1	-1	1000	608	461
13	-1	-1	1	1	1	1290	1305	660
14	1	-1	1	1	-1	1657	1753	579
15	-1	1	1	1	-1	1608	1312	528
16	1	1	1	1	1	889	634	609

W = shoulder width (mm)

E= shoulder stiffness (MPa)

P = Axle load (kN)

q= Tire pressure (kPa)

h = Pavement thickness (mm) (the same as shoulder thickness)

Δ_0 = Maximum surface deflection under the center of the outer tire (μm)

ε_{zz} = compressive strain on the top of the subgrade under the center of the outer tire ($\mu\varepsilon$).

ε_{zx} = maximum shear strain in the base course under the center of the outer tyre ($\mu\varepsilon$).

The Design Expert software was used to carry out the analysis of the factorial design (2004). Figure 3 shows the normal probability plot of effects for the maximum surface deflection under the center of the outer wheel. Effects which lie on the straight line are the insignificant effects, whereas the significant effects are far from the line (Douglas, 2003). Figure 3 shows that pavement thickness is the most significant factor affecting the maximum surface deflection under the center of the outer tire followed by the axle load, tire pressure, shoulder stiffness and shoulder width. Table 3 shows the analysis of variance (ANOVA) for the different factors. The Model F-value of 55.57 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0100 indicate model terms are significant. In this case W, E, P, q, h are significant model terms.

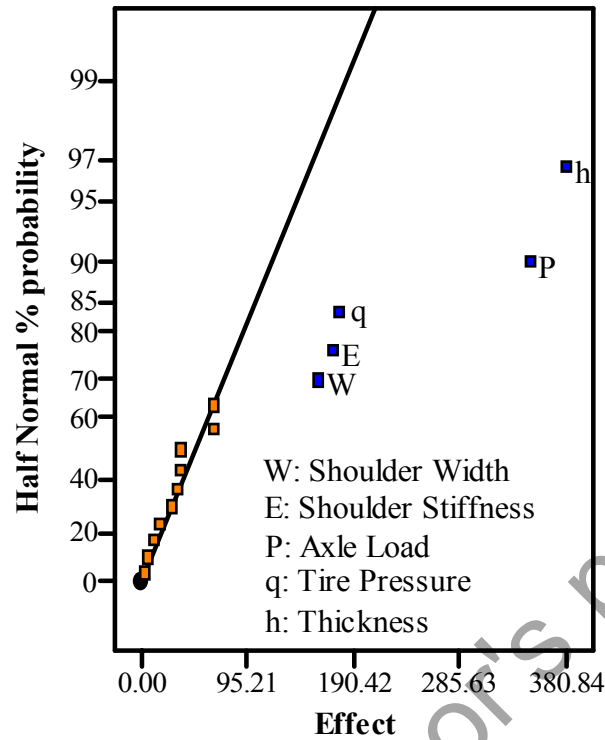


Figure 3: Significant factors affecting the maximum deflection under the center of the outer tire.

Equation 3 represents the relationship between the predicted maximum surface deflection under the outer tire and the significant parameters. The coefficient of determination of this model (R^2) is 96.5.

$$\Delta_o = 943.87 - 0.1957 * W - 0.405 * E + 8.711 * P + 0.3514 * q - 1.904 * h \quad \text{Equation 3}$$

$$R^2 = 96.5$$

Table 3: Analysis of variance (ANOVA) for selected factorial model for surface deflection under the center of the outer tire response.

Source	Sum Squares	of DF	Mean Square	F Value	Prob>F
Model	1.406E+006	5	2.813E+005	55.57	< 0.0001
W	1.013E+005	1	1.013E+005	20.01	0.0012
E	1.159E+005	1	1.159E+005	22.89	0.0007
P	4.856E+005	1	4.856E+005	95.95	< 0.0001
q	1.235E+005	1	1.235E+005	24.40	0.0006
h	5.802E+005	1	5.802E+005	114.62	< 0.0001

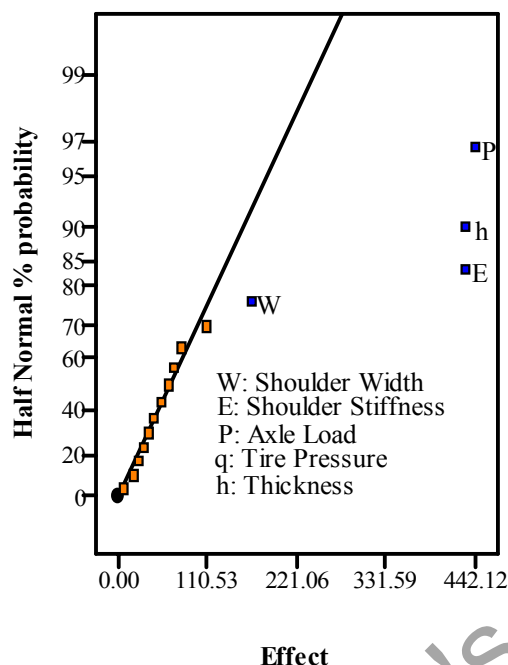


Figure 4: Significant factors affecting compressive strain on the top of the subgrade under the center of the outer tire.

Figure 4 shows the order of importance of the factors affecting the compressive strain on the top of the subgrade under the outer wheel load. Axle load, pavement thickness, shoulder stiffness, and shoulder width played the most significant role affecting the compressive strain on the top of the subgrade. The ANOVA shows that the model F-value is 47.27 which implies that the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Equation 4 represents the relationship between the compressive strain on the top of the subgrade under the outer wheel load as a function of the significant factors. The coefficient of determination is 94.5.

$$\varepsilon_{zz} = 1136.95 - 0.2033 * W - 1.01821 * E + 11.023 * P - 2.152 * h$$

$$R^2 = 94.5$$

Equation 4

In a similar manner, the design expert analysis shows that the significant factors affecting the maximum shear strain in the base course are as follows. The tire pressure is the most significant factor affecting the shear strain in the base course followed by axle load, the interaction between the tire pressure and pavement thickness and the shoulder stiffness. The ANOVA shows that the Model F-value of 59.42 implies the model is significant. The relationship between the maximum shear strain in the base course and the significant factors is given by Equation 5. The coefficient of determination of this model is reasonably high ($R^2=96.7$).

$$\varepsilon_{zx} = 238.19 - 0.1301 * E + 1.507 * P + 0.0198 * q - 0.588 * h + 1.172 * q * h$$

$$R^2 = 96.7$$

Equation 5

By investigating different shoulder conditions showed that pavement responses differ for each shoulder geometry and material conditions. The analysis shows that for the same axle load (120 kN) and tire pressure (900 kPa), the deflection under the outer wheel load for the very weak shoulder is about three times that of the relatively strong shoulder and about 1.8 times the medium shoulder. This clearly emphasizes the importance of the shoulder stiffness represented by its width, thickness, and resilient modulus on the pavement response.

It was obvious that the weak short shoulder does not provide a good distribution of the load around the pavement edge and this causes the compressive strains and compressive stresses on the top of the subgrade to peak at a distance 287.5 mm from the center of the dual exactly under the outside edge of outer wheel. This high concentration of stresses and strains will lead to the edge failure. In the meanwhile, relatively strong shoulder provides a good spread of the loads, therefore, reducing deflections, stresses and strains in the pavement layers.

8 CONCLUSIONS

From the factorial design, it is obvious that shoulder rigidity (i.e. stiffness) which is a function of the width, thickness and resilient modulus of the shoulder material, is a significant factor affecting the lateral support and therefore pavement response in the outer wheel path. Axle load is a significant factor for all responses affecting the edge damage of the pavement while the tire pressure is only significant for responses close to the pavement surface. Using stiff shoulders will help reducing the concentration of deflections, stresses, strains on the top of the subgrade, and will likely reduce the edge damage of the pavement. The order of importance of factors differs based on the pavement response under consideration.

REFERECES

Ball G.F. and Patrick, J. E. (2005) "A Study of Seal Edge Break Using RAMM Databases" Central Laboratories Report: 05-521068.00

Chandrupatla and Belegundu, Introduction to Finite Elements in Engineering, Prentice-Hall, ISBN 0-13-061591-9, 1996.

Design Expert version 6, 2004, State-Ease Inc.2021 East Hennpin Ave., Suite 480, Minneapolis, MN 55413

Douglas C. M., Design and Analysis of Experiments, John Wiley & Sons, Inc, 2001

Everstress version 5 for Windows software, Layered Elastic Analysis, Washington State Department of Transportation, March 1999

HIBBIT, KARLSSON and SORENSEN, INC., Getting Started with ABAQUS Standard, 2003.