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Re: In Situ Performance Comparison of Geogrid-Stabilized Aggregate Layer and Unstabilized Aggregate Layer Using Automated Plate Load Testing (APLT)
Loss of Support Evaluation on West Roadways Test Bed adjacent to WCR47, Weld County, CO
Finite Element (FE) Analysis to Characterize the Impact of Loss of Support on Pavement Stresses – Comparison between TX130S and Control Section

Dear Dr. Wayne,

This transmittal summarizes the results of FE analysis characterizing the impact of loss of support (LOS) on stresses in the rigid pavement layer, using cyclic APLT results obtained from the Control and TX130S sections on the West Roadways test bed adjacent to WCR47 in Weld County, CO.

Background – How Does Loss of Support (LOS) relate to permanent deformation of the foundation?

An inherent assumption in rigid pavement design procedures is that the subgrade support is uniform and continuous. It is widely known that this assumption only holds true if there is no loss of support (LOS) under loading. LOS results from differential vertical deformation due to repeated loading that causes irrecoverable deformation and from material pumping and erosion beneath the pavement (material and drainage related). Previous research on LOS indicates that a void ≥ 0.05 in. beneath the pavement can be defined as a LOS condition (Birkhoff and McCullough 1979[1]).

Ingios designed an APLT testing program at the project site to directly measure LOS based on permanent deformation characteristics under vertical loading. When LOS develops beneath a slab, the result is localized stress concentration within the pavement layer and higher stresses on the foundation support layers. With increased stresses in the pavement layer, fatigue life of the pavement is reduced and a progressive failure mechanism (with water filled voids accelerating erosion) is initiated in the foundation layers. (Note: curling/warping is also a factor that contributes to LOS, but is addressed through joint spacing design.)

[1] Birkhoff, J.W. and McCullogh, B. F. "Detection of voids underneath continuously reinforced concrete pavements," FHWA/TX-79/24+177-18, Texas State Dept. of Highways and Public Transportation, Austin, TX, 1979.

The AASHTO (1986[2]) rigid pavement design procedure addresses LOS by defining the void as a percentage of area relative to the slab size and using a LOS factor to apply a reduction to the modulus of subgrade reaction value used in the design. LOS factor = 1 corresponds to a void size of 1.59%; LOS factor = 2 corresponds to a void size of 4.59%; and LOS factor = 3 corresponds to a void size of 8.16%.

Because direct measurement of void size (i.e., 0.05 inches of vertical differential movement) has not been incorporated into pavement foundation verification or stabilization design practices, AASHTO (1993) and modern ME design provides suggested LOS and erosion index factors based only on material type such as listed in Table 1. No substantiated design values have been provided for geogrid stabilized materials.

Table 1. Typical ranges of LOS factors for different types of materials (AASHTO 1993[3])

Type of Material	Range of Modulus (psi)	LS Factor
Cement treated granular base	1,000,000 to 2,000,000	0.0 to 1.0
Cement aggregate mixtures	500,000 to 1,000,000	
Asphalt treated base	350,000 to 1,000,000	
Bituminous stabilized mixtures	40,000 to 300,000	
Lime Stabilized Materials	20,000 to 70,000	1.0 to 3.0
Unbound Granular Materials	15,000 to 45,000	
Fine Grained Subgrade Materials	3,000 to 40,000	2.0 to 3.0
Geogrid Stabilized Pavement Foundations	**Not provided**	**Not provided**

In this study, the APLT testing technology and analysis was used to field verify differential permanent deformations. Then the impact of the permanent deformation on the fatigue life was quantified using finite element analysis of the pavement system.

Summary of Field Testing on the West Roadways Test Bed

Field testing was conducted on the West Roadways test bed on April 20, 2017. Results from the testing were summarized in two separate memos submitted earlier on May 8 and August 22, 2017. In brief, the test sections consisted of a 50 ft long control section (no geogrid) and an adjoining 100 ft long TX130S geogrid stabilized section. The control section consisted of nominal 8 in. of crushed aggregate base coarse (ABC) over subgrade, while the geogrid section consisted of nominal 4 in. of crushed ABC stabilized with TX130S geogrid positioned at the aggregate/subgrade interface. In situ testing included cyclic APLTs using a 30-in. diameter loading plate on the ABC layer to determine composite resilient modulus ($M_{r\text{-comp (30in.)}}$) and permanent deformation (δ_p). In addition, cyclic APLTs using a 12-in. diameter load plate were conducted to determine composite resilient modulus ($M_{r\text{-Comp(12in.)}}$) and layered M_r values for the aggregate base and subgrade ($M_{r\text{-Base (12in.)}}$ and $M_{r\text{-SG (12in.)}}$). The aggregate base

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[2] *AASHTO design guide for design of pavement structures*. American Association of State Highway and Transportation Officials, Washington D.C., 1986

[3] *AASHTO Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

material comprised of 0.75-in. passing crushed aggregate base per Colorado DOT Class 6 requirements and the TX130S geogrid is a multi-axial geogrid with hexagonal structure and triangular apertures.

The average $M_{r\text{-Comp (30in.)}}$ and δ_p results from accelerated 30 in. cyclic APLTs obtained from the two sections were used to characterize the impact of LOS on pavement layer stresses. The average $M_{r\text{-Comp(30in.)}}$ in the control section was 15,481 psi and in the TX130S section was 13,728 psi. The average δ_p after 500 cycles in the control section was 0.069 in. and the TX130S section was 0.033 in.

FE Model Setup and Analysis Results

The pavement layer stresses were determined using KENSLABS 2D FE software. The software is based on thin plate theory wherein a slab is divided into rectangular finite elements and stresses at each connecting nodes are determined (Huang 2004). The foundation can be modeled as liquid, solid, and layered system. The liquid model involves using a static modulus of subgrade reaction (*k*-value), the solid model involves using a composite single layer resilient modulus values (i.e., $M_{r\text{-Comp}}$), and the layered model involves using individual layer moduli values and their thicknesses. In this study, the solid model using $M_{r\text{-Comp}}$ value was utilized.

KENSLABS was selected over other pavement analysis software programs because of its unique ability to model LOS with a defined magnitude of "gap" (i.e., δ_p) at each node. The different LOS factors were modeled with an area of void that is equivalent to the area defined in the AASHTO (1993).

The FE model setup along with the results are included in the attached. Analysis was conducted assuming 8 in. and 10 in. thick concrete pavement that is 20 ft long and 12 ft wide. An 18-kip single axle loading with two sets of dual tires were used for loading near the pavement edge. The maximum major and minor principal stresses for each LOS condition, pavement thickness, and foundation support condition (Control vs. TX130S) were captured and summarized in a table. Stress ratio (SR) was calculated as the ratio of the maximum stress in the pavement layer and the modulus of rupture of the concrete (assumed as 660 psi). Based on the SR values, the number of load repetitions for fatigue failure (*N*) were calculated using the PCA (1984[4]) fatigue model. For reference, SR < 0.45 results in *N* that is >100,000,000 cycles ("unlimited"). In addition, color-coded spatial plots of major and minor principal stresses in the pavement for 10 in. concrete pavement case are also presented in the attached to visualize the impact of LOS and Control versus TX130S foundation support on the stresses developed in the pavement layer due to loading.

Following are the key findings from the FEA results:

- For LOS = 0 condition (i.e., no permanent deformation), the SR values were relatively low (< 0.45) for both Control and TX130S foundation support condition cases.
- Both the magnitude of δ_p and the area of void has a significant impact on the stresses developed in the pavement layer.
- For 10 in. pavement, using the average δ_p = 0.033 in the TX130S section, the pavement stresses increased by about 4 times for LOS = 1 case compared to LOS = 0 case. However, the SR values

[4] *Thickness Design for Concrete Highway and Street Pavements*. Portland Cement Association (PCA), 1984.

remained < 0.45. Analysis on 8 in. pavement showed the SR = 0.52 for the LOS = 1 case and thereby reducing *N* to about 336k cycles.

- For 10 in. pavement, using the average δ_p = 0.069 in the Control section, the pavement stresses increased by about 8 times for the LOS = 1 case compared to LOS = 0 case. This resulted in SR = 0.77, reducing *N* to about 4k cycles. Analysis on 8 in. pavement showed SR = 1.02 and thereby reducing *N* to about 650 cycles.
- The SR values decreased slightly with increase in the LOS from 1 to 3. This trend does not hold true if the shape of the void area is oriented differently than what is setup in this study, and must be explored in future studies. In short, it matters where the load is positioned relative to the void.

The results presented herein demonstrate the impact of permanent deformation related LOS on PCC pavement stresses and thereby the fatigue life of the pavement. Minimizing development of voids by controlling permanent deformation is a direct approach for minimizing bending stresses in the pavement layer and therefore extending pavement fatigue life. Further, our analysis suggests that relying on LOS without consideration of the magnitude of future permanent deformation (void depth) introduces uncertainty in design performance predictions.

We recommend that future studies include testing to quantify δ_p with extended cycle APLTs for a range of geosynthetic stabilized foundation layers. The influence of the orientation of the area of void, jointed pavement with different joint stiffness conditions, and liquid and layered model versus solid model on FE analysis results should also be assessed in future evaluations.

If you have any questions about the results or analysis, please do not hesitate to contact us.

Sincerely,

David White, Ph.D., P.E. (IA, MN, KY)
President and Chief Engineer

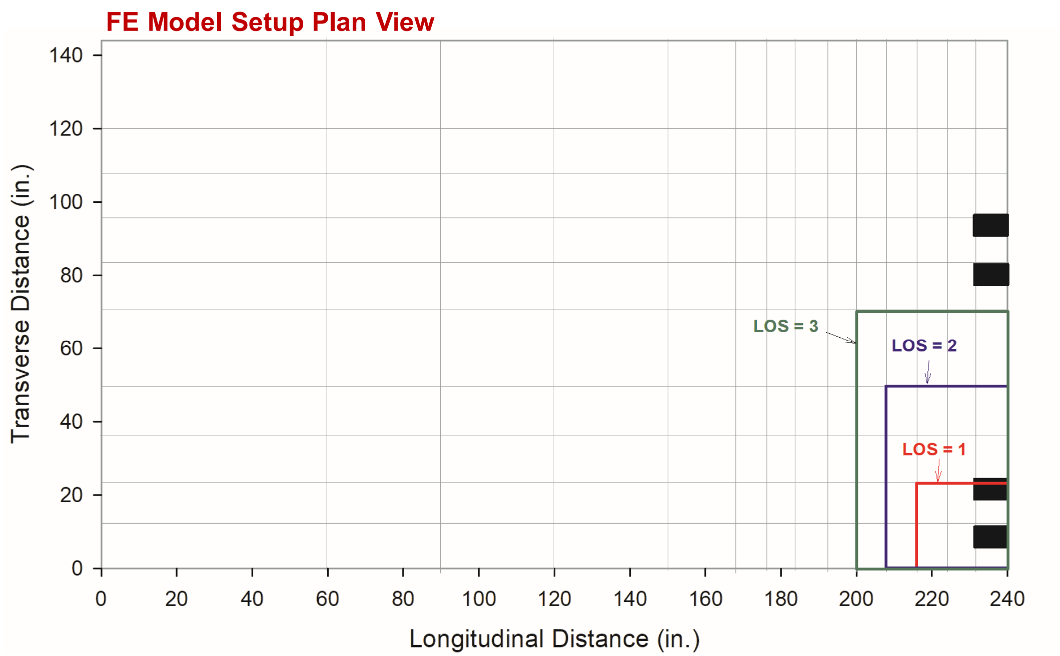
Pavana Vennapusa, Ph.D., P.E. (IA, TX)
Lead Engineer

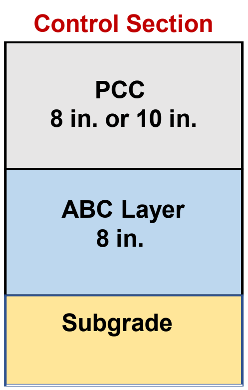
<u>Attachments:</u>
Finite Element Analysis Results

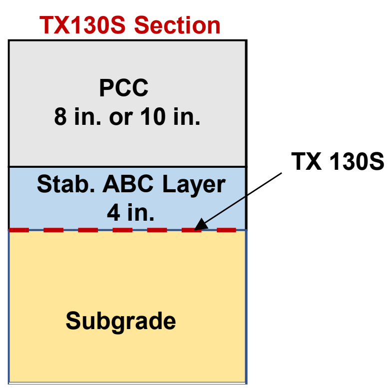
Impact of Loss of Support (LOS) due to permanent deformation on pavement stresses

CR49 West Roadways Project
Finite Element Analysis Results

2D FE model setup in Kenslabs pavement analysis software.







Slab Properties

Length	20	ft
Width	12	ft
Thickness	10 & 8	in.
Elastic Modulus	4,000,000	psi
Poisson's Ratio	0.15	
Modulus of Rupture, MR	660	psi

Foundation Properties [One Layer]

30 in. PLT $M_{r\text{-Comp}}$	15,481	psi [Control]
30 in. PLT $\delta_{p\text{-}500}$	0.069	in. [Control]
30 in. PLT $\delta_{p\text{-}500}$-C	0.031	in. [Control]
30 in. PLT $M_{r\text{-Comp}}$	13,728	psi (TX130S]
30 in. PLT $\delta_{p\text{-}500}$	0.033	in. [TX130S]
30 in. PLT $\delta_{p\text{-}500}$-C	0.017	in. [TX130S]

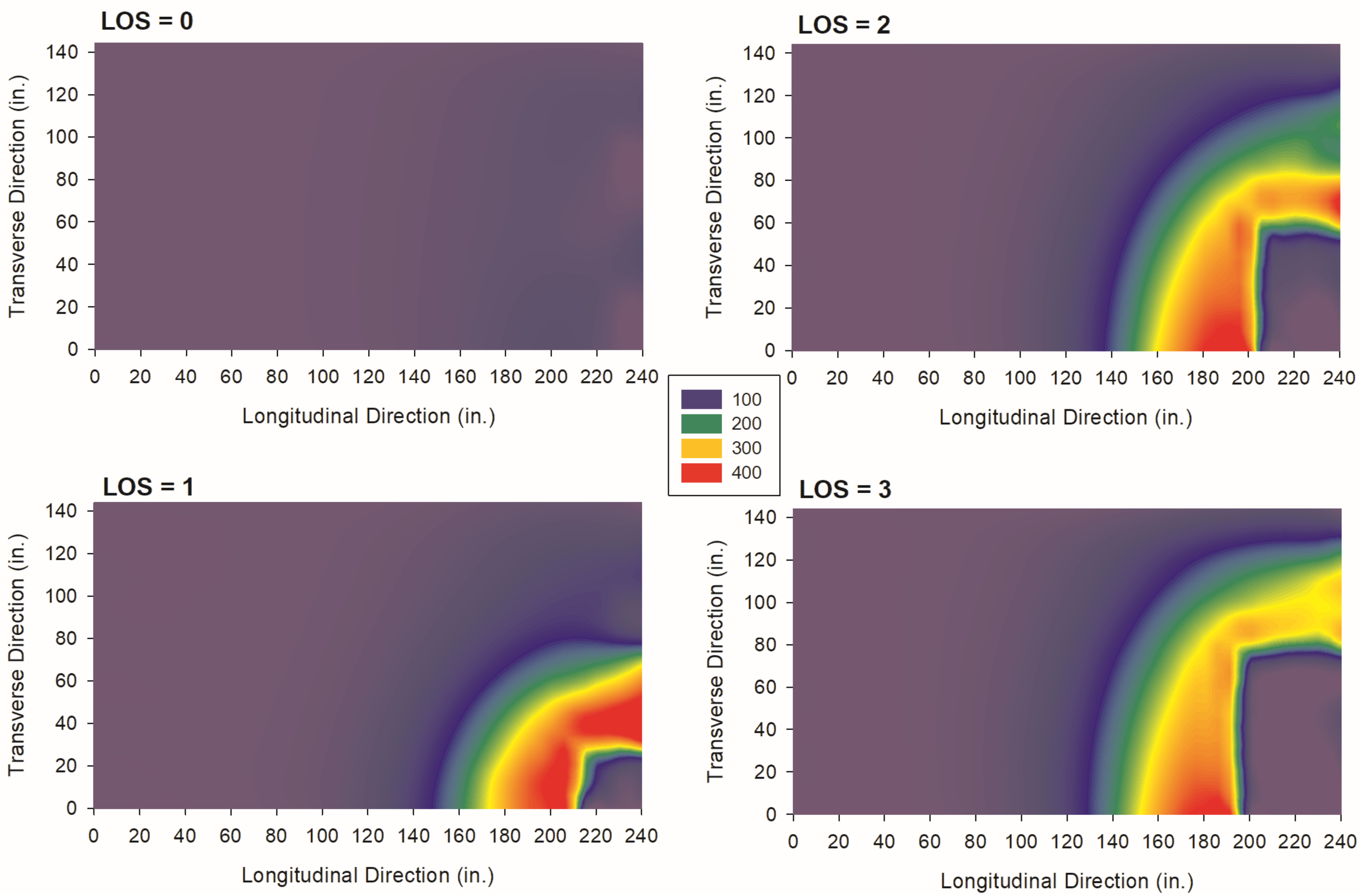
LOS Modeling

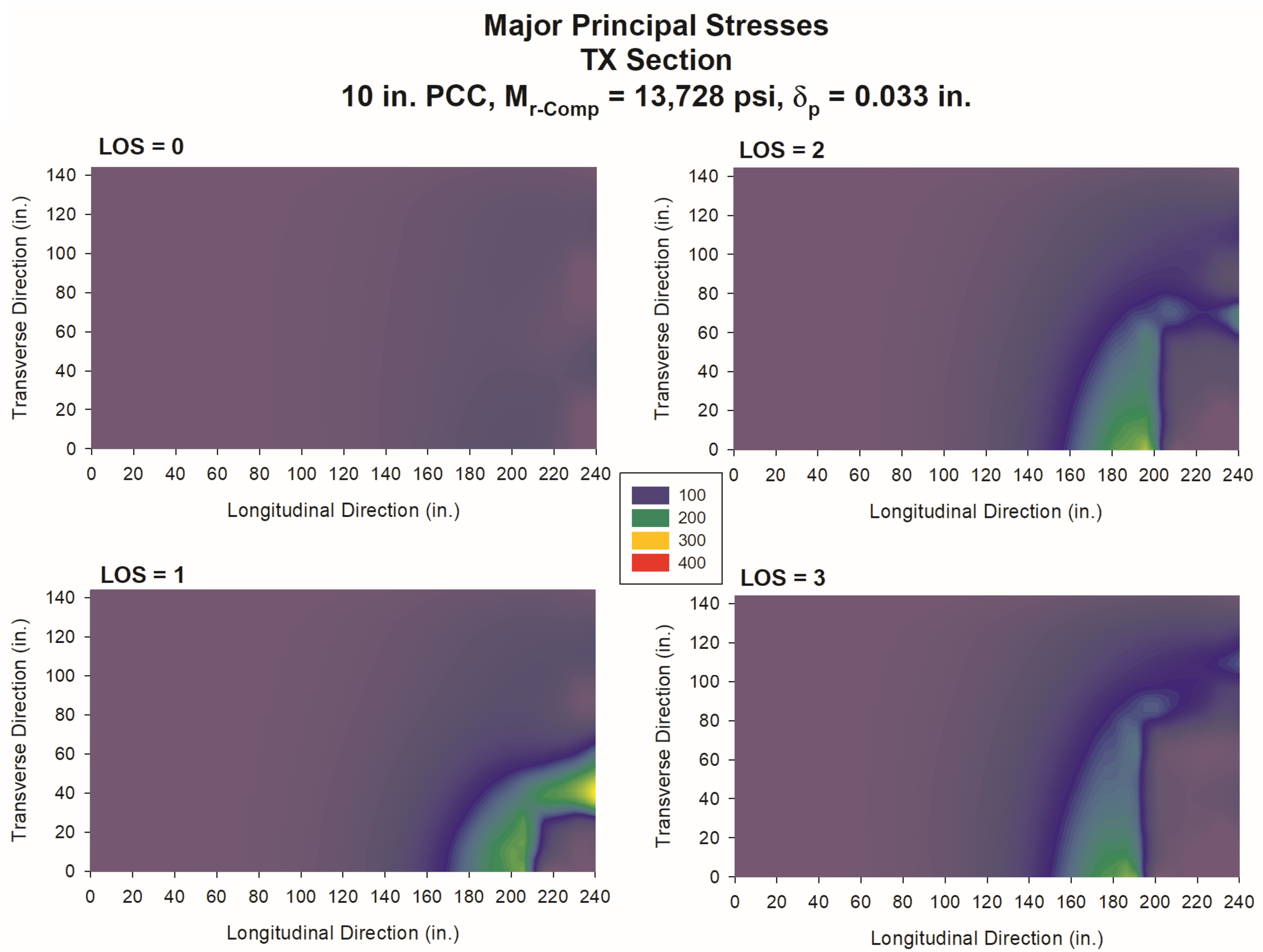
Target % Void Area, per AASHTO (1993)			**Target Void Area**	
LOS = 0	0.00	%	0	in^2
LOS = 1	1.59	%	550	in^2
LOS = 2	4.59	%	1,586	in^2
LOS = 3	8.16	%	2,820	in^2
Actual % Void Area used in FEM Analysis			**Actual Void Area**	
LOS = 0	**0.00**	%	**0**	in^2
LOS = 1	**1.67**	%	**576**	in^2
LOS = 2	**4.63**	%	**1,600**	in^2
LOS = 3	**8.22**	%	**2,840**	in^2

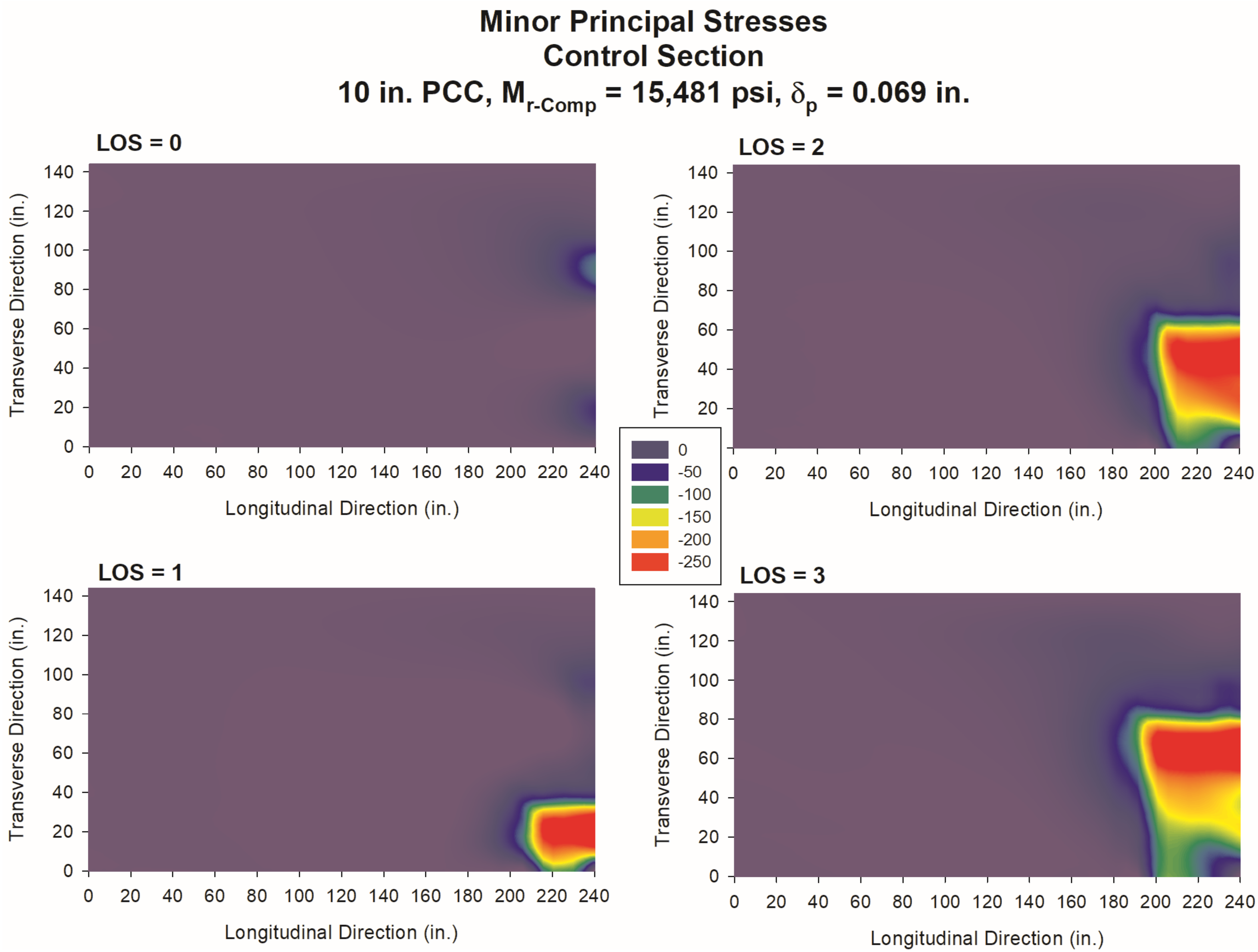
Loading, 18 kip single axile - two sets of dual tires

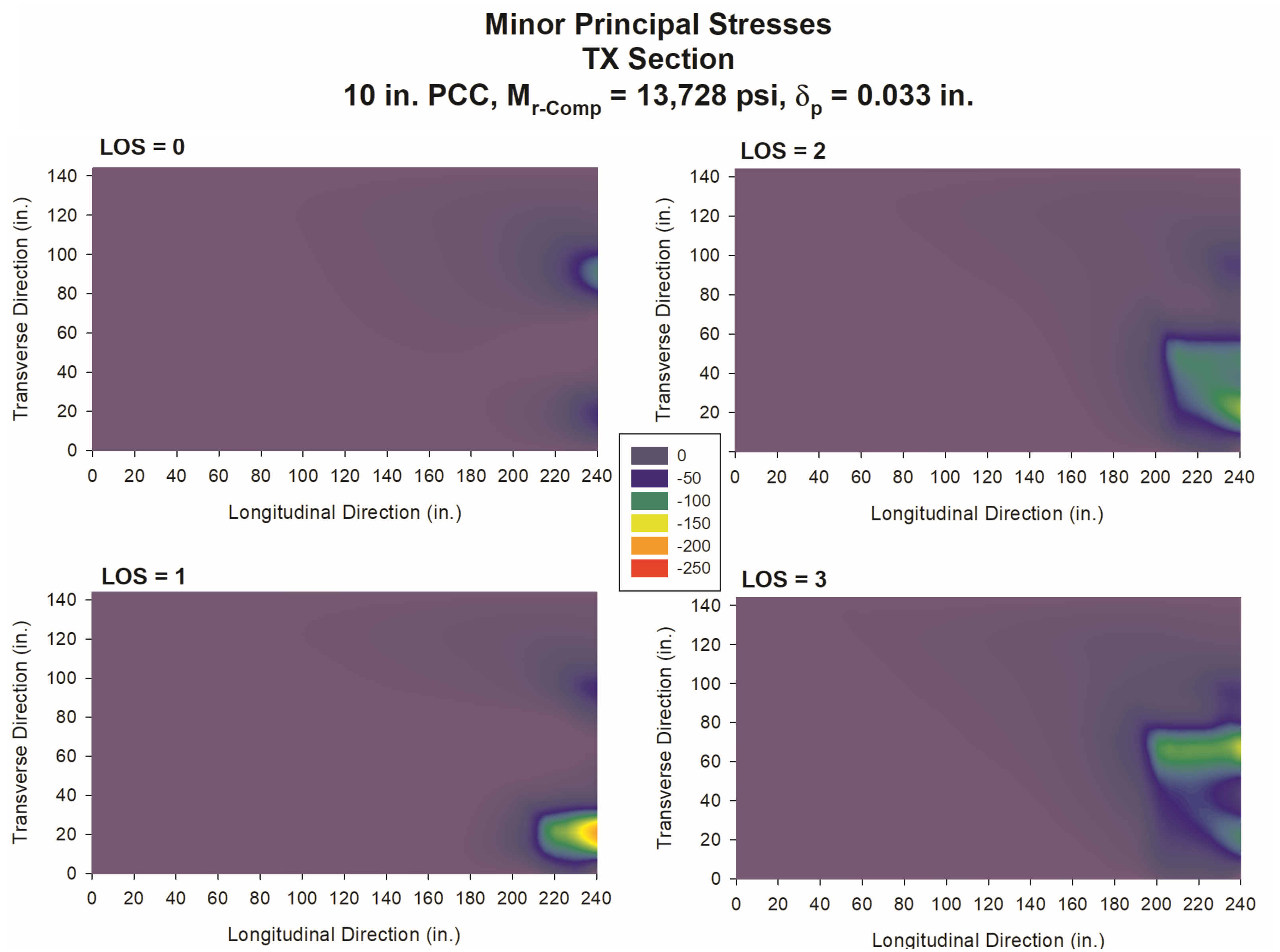
Tire Contact Stress	100	psi
Tire Contact Width	5.53	in.
Tire Contact Length	8.13	in.
Max load on each tire	4,500	lbs
Gap between dual tires	7.702	in.

Major Principal Stresses
Control Section
10 in. PCC, $M_{r\text{-}Comp}$ = 15,481 psi, δ_p = 0.069 in.




Major Principal Stresses
TX Section
10 in. PCC, $M_{r\text{-}Comp}$ = 13,728 psi, δ_p = 0.033 in.
LOS = 0
LOS = 1
LOS = 2
LOS = 3
Transverse Direction (in.)
Longitudinal Direction (in.)
0
20
40
60
80
100
120
140
160
180
200
220
240
100
200
300
400


Minor Principal Stresses
Control Section
10 in. PCC, $M_{r\text{-}Comp}$ = 15,481 psi, δ_p = 0.069 in.
LOS = 0
LOS = 1
LOS = 2
LOS = 3
Transverse Direction (in.)
Longitudinal Direction (in.)
0
-50
-100
-150
-200
-250


Minor Principal Stresses
TX Section
10 in. PCC, $M_{r\text{-}Comp}$ = 13,728 psi, δ_p = 0.033 in.
LOS = 0
LOS = 1
LOS = 2
LOS = 3
Transverse Direction (in.)
Longitudinal Direction (in.)
0
-50
-100
-150
-200
-250

Summary of stress results

SR = stress ratio calculated using the maximum value of major (+ve) and minor (-ve) principal stresses divided by the modulus of rupture (MR) of concrete.

N = No. of load repetitions for fatigue failure per PCA (1984) for PCC pavements.

δ_p assumed for gap is based on average δ_p measured at the end of 500 cycles from 30 in. cyclic APLTs from each section.

TX or Control	LOS	Slab Thick., H (in.)	$M_{r\text{-}Comp}$ (psi)	Gap, δ_p (in.)	Max. Major Principal Stress ($\sigma_{max\text{-}Major}$), psi	Max. Minor Principal Stress ($\sigma_{max\text{-}Minor}$), psi	Stress Ratio, *SR* (σ_{max}/MR)	*N* for fatigue failure
TX	0	10	13,728	0	61.5	-126.3	0.19	>100,000,000
	1	10	13,728	0.033	252.2	-230.1	0.38	>100,000,000
	2	10	13,728	0.033	224.8	-173.1	0.34	>100,000,000
	3	10	13,728	0.033	216.4	-155.8	0.33	>100,000,000
Control	0	10	15,481	0.069	62.2	-123.4	0.19	>100,000,000
	1	10	15,481	0.069	505.9	-424.8	0.77	4,097
	2	10	15,481	0.069	433.2	-360.4	0.66	15,135
	3	10	15,481	0.069	419.2	-408.5	0.64	20,998
TX	0	8	13,728	0	99.3	-171.5	0.26	>100,000,000
	1	8	13,728	0.033	342.7	-316.9	0.52	336,181
	2	8	13,728	0.033	276.3	-213.9	0.42	>100,000,000
	3	8	13,728	0.033	258.9	-222.2	0.39	>100,000,000
Control	0	8	15,481	0.069	99.0	-66.8	0.15	>100,000,000
	1	8	15,481	0.069	672.5	-580.1	1.02	651
	2	8	15,481	0.069	537.3	-446.1	0.81	2,651
	3	8	15,481	0.069	382.7	-529.5	0.80	2,939