Volumetric Strain Reliability Analysis Modeling of Pavement Structures under Multi-Lane Loading

Curtis Berthelot, Ph.D., P.Eng.
Chief Technical Officer, PSI Technologies Inc.

Roberto Soares, Ph.D., P.Eng.
Chief Software Systems Engineer, PSI Technologies Inc.

Jody Berthelot, E.I.T.
General Manager, PSI Technologies Inc.

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ABSTRACT

Pavement engineers use strain calculations to estimate road structural layer thickness requirements for design, load equivalency analysis and life cycle performance prediction of flexible pavements. The primary strain calculations traditionally used have been peak tensile horizontal orthogonal strain at the bottom of the hot mix layer and vertical compressive orthogonal strain at the top of the subgrade. These idealized peak orthogonal strains have been used to correlate to the primary structural pavement failure modes of fatigue cracking and rutting, respectively.

Over recent years heavy commercial trucks have evolved in larger configurations that apply higher strain states within pavement structures. The objective of this study was to use non-linear 3-D pavement numerical modeling to quantify volumetric strain responses within typical flexible pavement structures under modern commercial heavy truck multi-lane loadings.

This study evaluated volumetric strain distributions in two pavement structures across four truck configurations under single and multi-truck/multi-lane field state loading scenarios. Trucks evaluated in this study included a 5-axle semi, 7-axle semi, 8-axle b-train, and a 9-axle semi. All trucks were modeled at maximum allowable legal load limits representative of typical highway jurisdiction heavy haul load limits.

Based on the 3-D pavement analysis conducted, larger heavy truck configurations as well as multi-lane/multi-truck field state loading can significantly increase primary responses within a pavement structure. Vertical deflection profile and volumetric shear strain in the subgrade were found to be more sensitive under larger trucks and multi-truck/multi-lane pavement loading. Volumetric strain calculations provide the added ability to perform reliability analysis across specific pavement primary responses. This study shows how pavement engineers can use 3-D volumetric primary pavement response profiles across different material layer types under any field state load condition for structural pavement design, life cycle performance predictions, and improved life cycle asset structural performance prediction.

INTRODUCTION

Pavement engineers have used idealized orthogonal strain calculations to estimate structural thickness design requirements, load equivalencies and life cycle performance prediction of pavements for decades. The two primary strains typically used for flexible pavement engineering purposes are peak tensile horizontal orthogonal strain at the bottom of the hot mix layer and vertical compressive orthogonal strain at the top of the subgrade. These idealized linear elastic strains are empirically calibrated to structural pavement failure modes of fatigue cracking and rutting, respectively. A significant limitation to using idealized peak strain calculations is their calibration of pavement structural performance to individual axles or axle groups of traditional smaller trucks applied in individual lane loading scenarios.

Modern advances in 3-D non-linear pavement modeling capabilities now provide pavement engineers with improved numerical computational capabilities for directly modeling volumetric primary responses of road structures under larger heavy truck configurations, diverse tire types, lane loading position, pavement deterioration state, climatic conditions, *et cetera* [1] [2]. As well, modern 3-D pavement modeling enables pavement engineers to quantify actual field state primary responses under heavily loaded multi-lane pavement structures as shown in Figure 1.

Figure 1. Typical Multi-Lane Loading Field State Conditions

STUDY OBJECTIVE

The objective of this study was to use non-linear 3-D pavement numerical modeling to quantify volumetric strain responses within typical flexible pavement structures under modern commercial heavy truck multi-lane loadings.

PAVEMENT STRUCTURE AND MATERIAL PROPERTIES

A benefit to 3-D numerical pavement modeling systems is the ability to encode user-definable pavement structural geometry and more complex material constitutive relations specific to the individual material layers. For purposes of this study, two conventional flexible pavement structures representative of typical primary pavements of AASHTO Structural Number 125 and 162 were considered in this analysis [3]. Table 1 summarizes the road geometric cross-sections modeled in the analysis, and Table 2 summarizes the pavement structural layer thickness used in the analysis.

Table 1. Pavement Geometric Cross-Sectional Geometry

Lane Width (m)	3.75
Shoulder Width (m)	2.50
Side Slope	4:1
Ditch Depth (m)	1.80
Surface Cross Slope (%)	2
Subgrade Cross Slope (%)	4

As seen in Table 2, an overall road structural depth of 5m for fixed bottom boundary condition was selected because at that depth the stress state is primarily a function of overburden materials and not by applied truck loadings.

Table 2. Pavement Structure Layer Thickness

Main Lane Layer	**Minimum Driving Lane Layer Thickness (mm)**	**Minimum Passing Lane Layer Thickness (mm)**
HMAC	200	150
Granular Base	300	250
Granular Subbase	400	300
Prepared Subgrade	600	300
In Situ Subgrade	3500	4000
Total Model Thickness	**5000**	**5000**
AASHTO Structural Number (Metric/Imperial)	**162/6.4**	**125/4.9**

The range of non-linear material constitutive properties used in the analysis are summarized in Table 3. The non-linear material properties were based on triaxial stress dependent frequency load characterization of the pavement materials used in this analysis at highway speed, 20°C, and 3-D *in situ* stress states under the specified truck loadings [4] [5] [6] [7].

Table 3. Non-Linear Pavement Structure Layer Material Constitutive Property Range

Main Lane Layer	**Non-Linear Range of Layer Specific Dynamic Modulus (MPa)**		**Non-Linear Range of Layer Specific Poissons Ratio**	
	Min	**Max**	**Min**	**Max**
HMAC	1764	2610	.28	.36
Granular Base	412	554	.32	.39
Granular Subbase	209	270	.37	.42
Prepared Subgrade (USCS CL)	75	125	.30	.45
In Situ Subgrade (USCS CL)	75	75	.35	.45

Figure 2 illustrates the pavement cross sections by lane used in the numerical modeling analysis. Shoulders were assumed to be surfaced with 75mm of HMAC layer with continuous substructure layer interface profiles with the base and subbase shimmed to meet surface elevation profiles and structural drainage with subgrade cross slopes fixed.

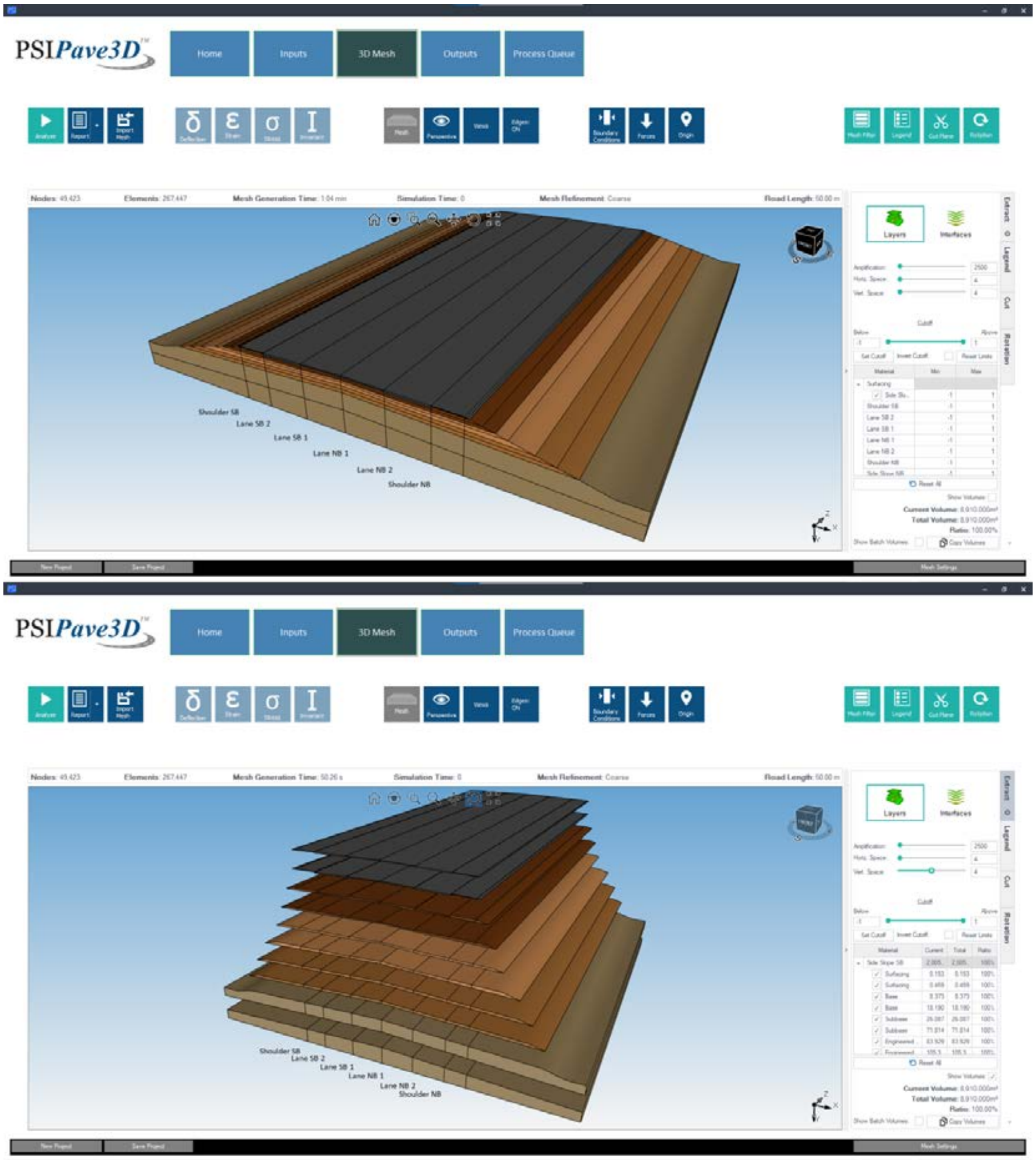


Figure 2. PSIPave3D™ Pavement Structure Cross Section Input Screens

HEAVY TRUCK LOADING SCENARIOS

One of the advantages modern 3-D non-linear numerical pavement modeling systems is they provide the ability to encode specific truck configurations, tire types, tire pressures, tire loadings, vehicle speeds, vehicle turning movements, etc. This study encoded common heavy trucks: 5-axle semi, 8-axle B-train double, 7-axle semi and 9-axle semi configurations, as shown in Figure 3 and Figure 4. Table 4 summarizes the maximum allowable load limits by axle group by truck type used in the modeling, with gross allowable weights ranging from 40.0 to 73.3 metric tonnes. The applied axle weight limits selected in this analysis were for illustrative purposes and estimated based on typical maximum allowable weight limits across Canadian jurisdictions in heavy haul scenarios [8] [9].

5-Axle Semi

7-Axle Semi

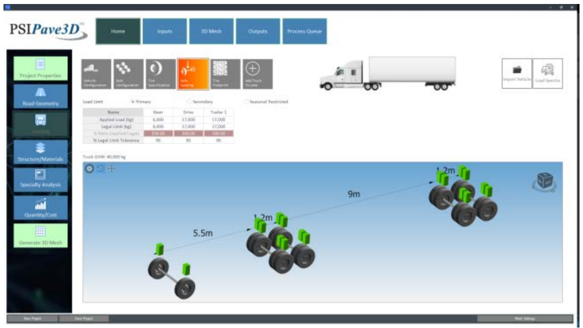
8-Axle B-Train

9-Axle Semi

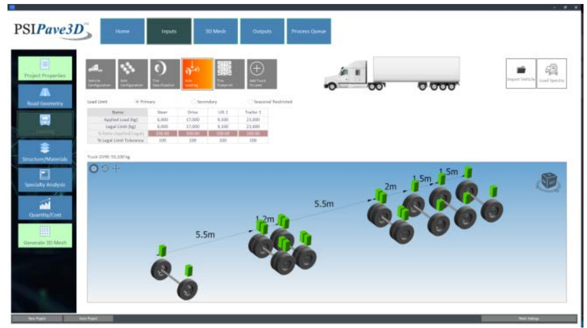
Figure 3. Typical Canadian Heavy Truck Configurations

Table 4. Heavy Truck Configuration and Gross Vehicle Weight Summary

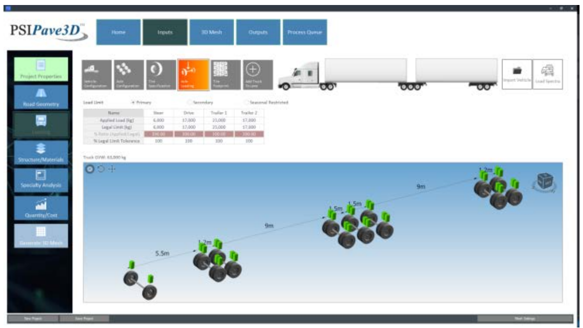
Truck Type	Vehicle Configuration	Steering Axle (kg)	Drive Tandem Axle (kg)	Trailer Single Axle (kg)	Trailer Tandem Axle (kg)	Trailer Tridem Axle Group (kg)	Gross Vehicle Weight (kg)
5-Axle	Semi-Truck	6,000	17,000	--	17,000	--	40,000
8-Axle	B-Train Double	6,000	17,000	--	17,000	23,000	63,000
7-Axle	Semi-Truck	6,000	17,000	9,100	--	23,000	55,100
9-Axle	Semi-Truck	6,000	17,000	9,100 (3)	--	23,000	73,300



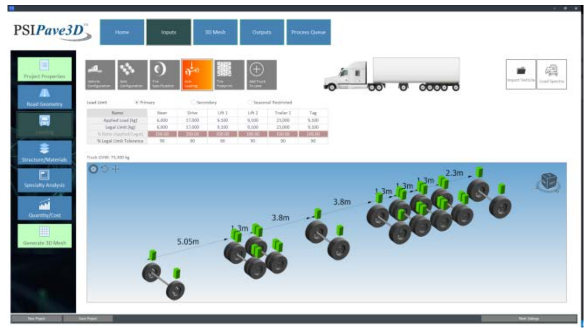
5-Axle Semi



7-Axle Semi



8-Axle B-Train



9-Axle Semi

Figure 4. PSIPave3D™ Heavy Truck Weights and Dimensions Input Screens

Table 5 summarizes the tire specifications by truck by individual axle used in the modeling. As seen in Table 5, PSIPave3D™ has all standard truck tires encoded within the model for construction of any combination of tire configurations representative of typical heavy trucks operating globally [10] [11].

Table 5. PSIPave3D™ Truck Tire Specifications Input Summary

Truck Type	**Vehicle Configuration**	**Steering Axle**	**Drive Axle Group**	**Trailer Single Axle Group**	**Trailer Tandem Axle Group**	**Trailer Tridem Axle Group**
5-Axle	Semi-Truck	29.5/ 75R22.5	29.5/ 75R22.5	--	29.5/ 75R22.5	--
8-Axle	B-Train Double	29.5/ 75R22.5	29.5/ 75R22.5	29.5/ 75R22.5	29.5/ 75R22.5	29.5/ 75R22.5
7-Axle	Semi-Truck	29.5/ 5R22.5	--	29.5/ 75R22.5	29.5/ 75R22.5	385/ 65R22.5
9-Axle	Semi-Truck	29.5/7 5R22.5	29.5/ 75R22.5	445/ 65R22.5	--	295/ 75R22.5

Table 6 summarizes and Figure 5 illustrates the pavement structure and truck placement as encoded into PSIPave3D™ road model. As seen in Figure 5, the trucks were placed on adjacent lanes of a 4-lane road structure and slightly staggered to capture the critical load state of impacted strains in the pavement.

Table 6. Heavy Truck Lane Placement

Truck Type	Vehicle Configuration	Lane
5-Axle	Semi-Truck	SB1
8-Axle	B-Train Double	SB2
7-Axle	Semi-Truck	NB1
9-Axle	Semi-Truck	NB2

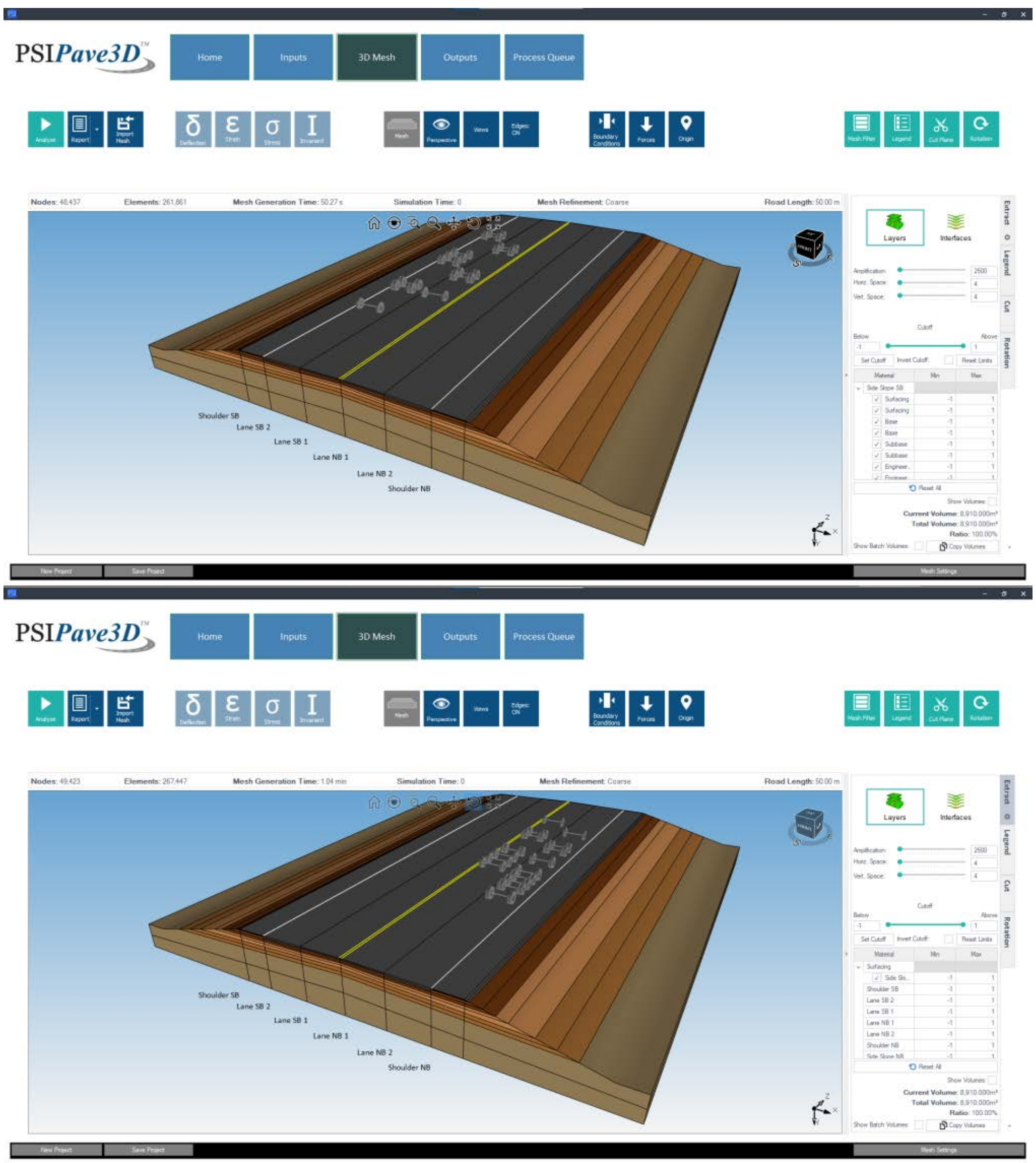


Figure 5. PSIPave3D™ Numerical Model Truck Load Positioning on Lanes

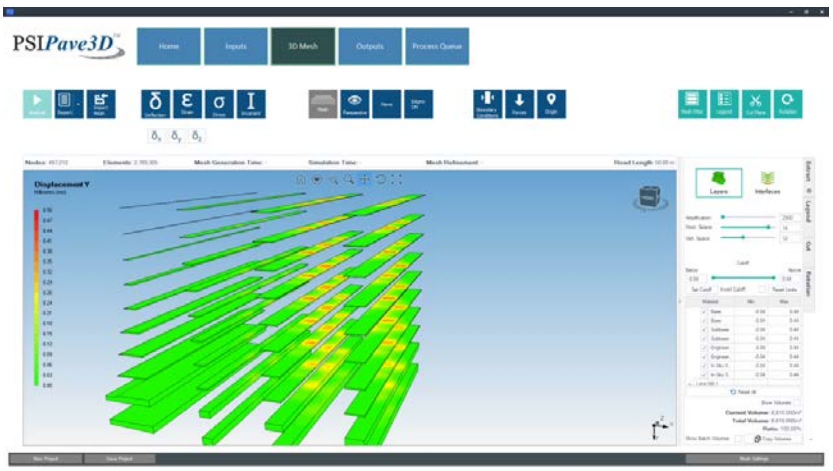
ROAD STRUCTURAL PRIMARY RESPONSE MODELING

For purposes of this study, two primary loading scenarios were modeled: 1) each truck individually on their individual lane; and 2) two trucks with adjacent lane loading in the same direction. Four primary 3-D pavement responses were evaluated in the structural evaluation.

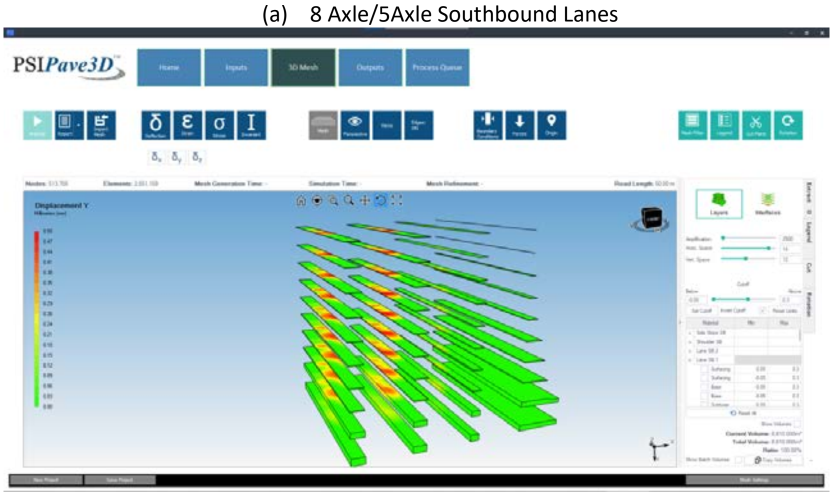
1 - Vertical Displacement Profile.
2 - Horizontal Tensile Strain Profile.
3 - Vertical Compressive Strain Profile.
4 - Shear Strain Profile in Peak Plane.

VERTICAL DISPLACEMENT PROFILE

Vertical deflection is a common pavement structural primary response that is measured in the field using non-destructive methods as a ground truth measure to estimate in-service pavement structural integrity as an operational system. PSIPave3D™ has the ability to provide an exploded discretized view of the primary responses within pavement structures by lane by layer. These illustrations help the pavement engineer to visualize primary response concentrations as well as dissipation of primary responses within the road structure as shown in Figure 6 for vertical deflection.



(a) 8 Axle/5Axle Southbound Lanes



(b) 7Axle/9Axle Northbound Lanes

Figure 6. Deflection Contour with Depth of Pavement

Based on the numerical results from the PSIPave3D™ vertical deformation calculations, Figure 7 and Figure 8 illustrate the HMAC surface peak deflection profiles with and without adjacent lane truck loading at 84 and 98 percent reliability.

The reliability analysis performed in this paper were chosen to illustrate how volumetric primary response analysis of pavements can be used to quantify the risk of potential overloading pavements with respect to individual pavement response directly related to specific performance indicators. The reliability thresholds were chosen to illustrate the possible range in reliability threshold possible for unique field state conditions. The analysis herein shows how the design engineer can select a wide range of pavement reliability representative of any influencing factor(s) that may contribute to the field state conditions driving specific primary responses. In this paper the effect of adjacent multi-lane loading was but one of many factors that contribute to the decision criterion of selection of pavement performance reliability.

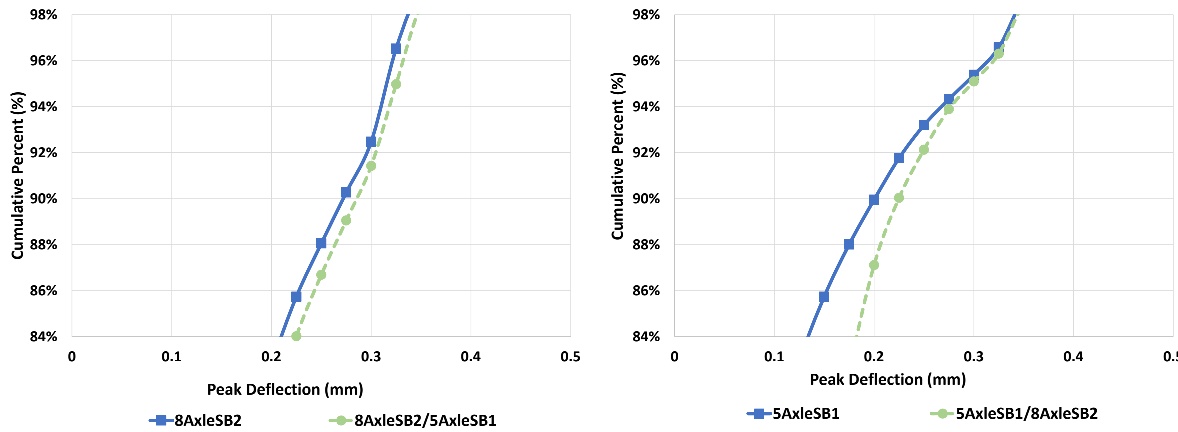


Figure 7. Volumetric Deflection Profile in HMAC Surface (Southbound Lanes)

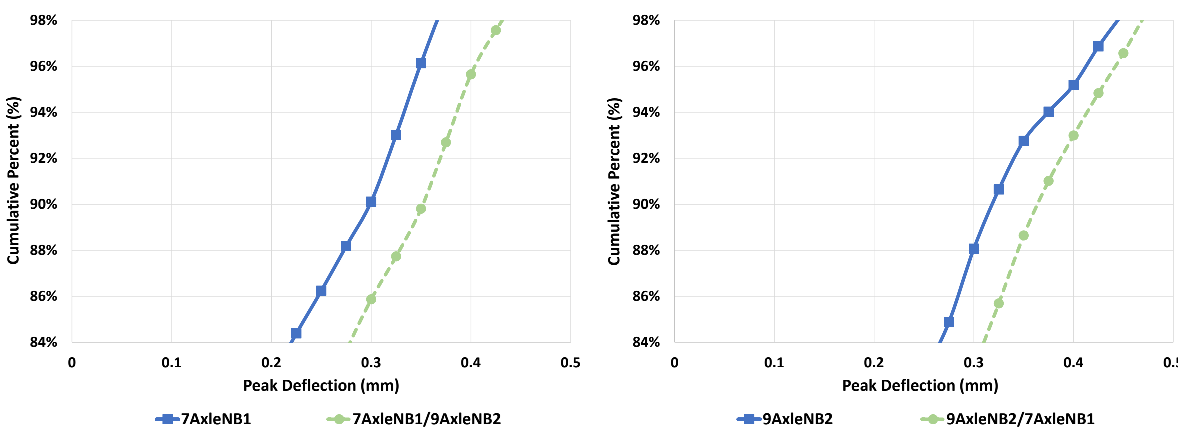


Figure 8. Volumetric Deflection Profile in HMAC Surface (Northbound Lanes)

Table 7 summarizes and Figure 9 illustrates the peak surface deflection values. It should be noted these peak surface deflections concur with those observed in the field for similar pavements under similar loadings. Peak surface deflection at 84 percent reliability ranged between 0.13 mm and 0.27 mm for single lane truck loadings and 0.18 mm and 0.31 mm for multi-lane truck loadings. This resulted in an increase in surface deflection ranging from 10 to 27 percent between single and multi-lane loading scenarios.

Peak surface deflection at 98 percent reliability ranged between 0.33 mm and 0.44 mm for single lane truck loadings and 0.34 mm and 0.46 mm for multi-lane truck loadings. The resulting increase in surface deflection ranged from 0 to 16 percent between single and multi-lane loading scenarios.

In summary, the peak surface deflection within the HMAC was observed to increase between 84 and 98 percent reliability. However, there was minimal increase in peak surface deflection with multi-lane loading relative to single lane loading.

Table 7. Peak Surface Deflection in HMAC Surface Layer under Single and Multi-Lane Loading

Truck/Lane	84% Reliability			98% Reliability		
	Single Lane Loading Peak Vertical Deflection	Multi-Lane Loading Peak Vertical Deflection and Percent Difference		Single Lane Loading Peak Vertical Deflection	Multi-Lane Loading Peak Vertical Deflection and Percent Difference	
	(mm)	(mm)	(%)	(mm)	(mm)	(%)
8-Axle SB2/ 5-Axle SB1	0.21	0.23	10	0.33	0.34	3
5-Axle SB1/ 8-Axle SB2	0.13	0.18	18	0.34	0.34	0
7-Axle NB1/ 9-Axle NB2	0.22	0.28	27	0.37	0.43	16
9-Axle NB2/ 7-Axle NB1	0.27	0.31	15	0.44	0.46	5

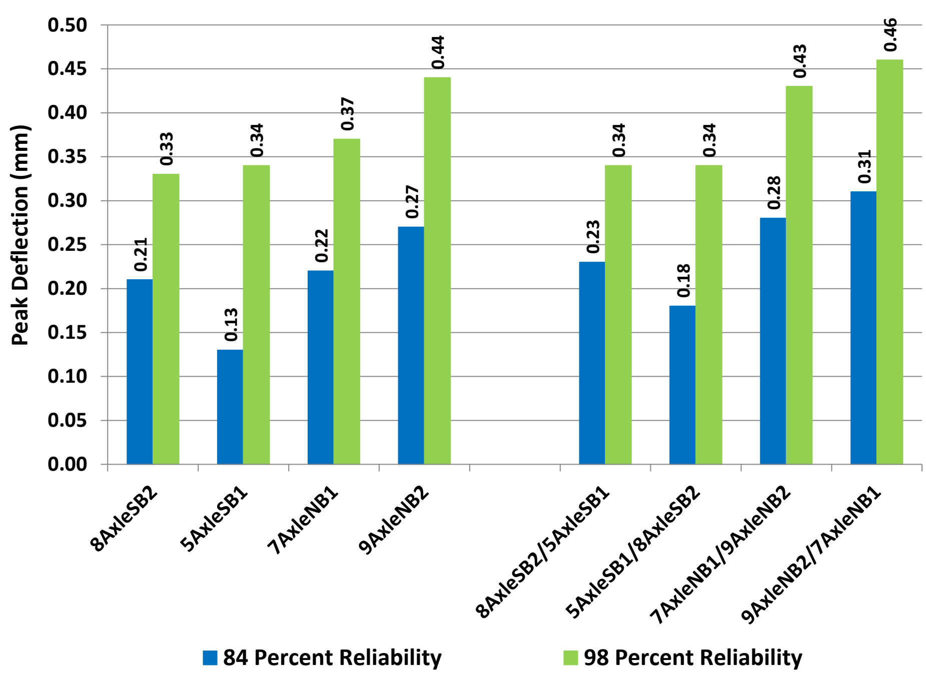


Figure 9. Peak Surface Deflection in HMAC under Single and Multi-Lane Loading

HORIZONTAL TENSILE STRAIN PROFILE IN HMAC

Peak tensile strain at the bottom of the HMAC layer has been a traditional measure of primary pavement response used to empirically correlate to fatigue cracking performance of pavements. Figure 10 and Figure 11 illustrate the peak orthogonal horizontal tensile strain profile within the HMAC layer in the southbound and northbound lanes at 84 and 98 percent reliability, respectively.

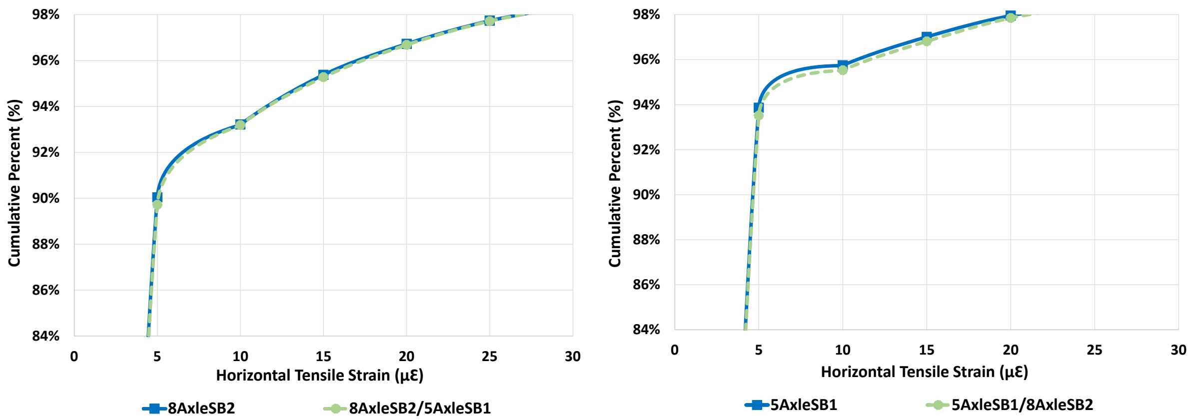


Figure 10. Volumetric Horizontal Tensile Strain in HMAC (Southbound Lanes)

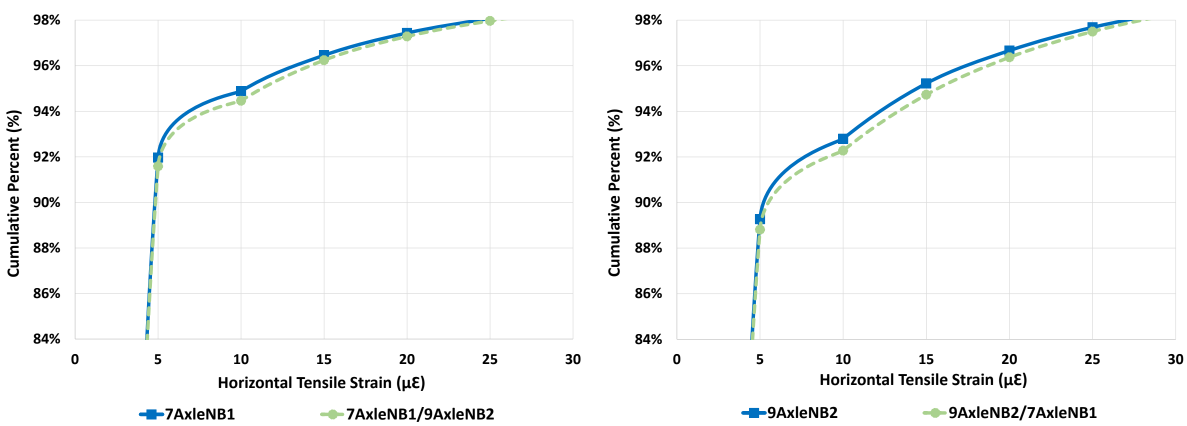


Figure 11. Volumetric Horizontal Tensile Strain in HMAC (Northbound Lanes)

Table 8 summarizes and Figure 12 illustrates the peak horizontal tensile strain values for the pavement and loading scenarios considered at 84 and 98 percent reliability. Peak horizontal tensile strain ranged between 4 με and 4 με for single lane truck loadings and 4 με and 4 με for multi-lane truck loadings resulting in an increase of 0 percent between single and multi-lane loading scenarios at 84% reliability. At 98 percent reliability, peak horizontal tensile strain ranged between 20 με and 27 με for single lane truck loadings and 21 με and 28 με for multi-lane truck loadings, resulting in an increase of 4 to 5 percent between single and multi-lane loading scenarios.

In summary, the peak horizontal strain within the HMAC layer was observed to significantly increase between 84 and 98 percent primary response reliability. However, there was a minimal increase in peak horizontal strain with multi-lane loading relative to single lane loading.

Table 8. Peak Horizontal Tensile Strain in HMAC Layer under Single and Multi-Lane Loading

Truck/Lane	84% Reliability			98% Reliability		
	Single Lane Loading Peak Horizontal Tensile Strain	Multi-Lane Loading Peak Horizontal Tensile Strain and Percent Difference		Single Lane Loading Peak Horizontal Tensile Strain	Multi-Lane Loading Peak Horizontal Tensile Strain and Percent Difference	
	(µε)	(µε)	(%)	(µε)	(µε)	(%)
8-Axle SB2/ 5-Axle SB1	4	4	0	26	27	4
5-Axle SB1/ 8-Axle SB2	4	4	0	20	21	5
7-Axle NB1/ 9-Axle NB2	4	4	0	24	25	4
9-Axle NB2/ 7-Axle NB1	4	4	0	27	28	4

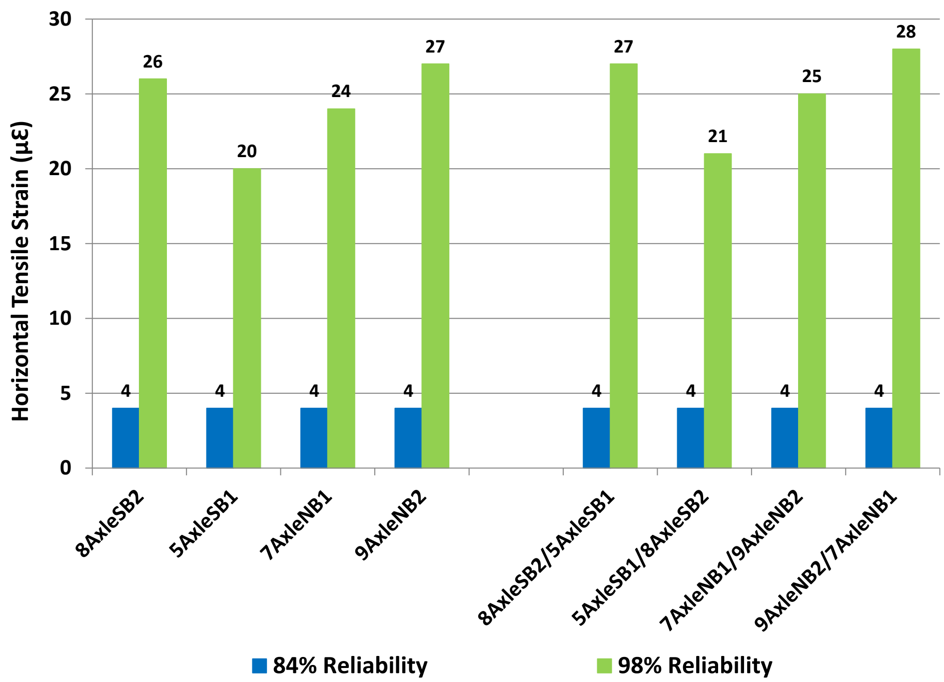


Figure 12. Peak Horizontal Tensile Strain under Single and Multi-Lane Loading

VERTICAL COMPRESSIVE STRAIN PROFILE IN SUBGRADE

Peak vertical compressive strain within the top of subgrade has been a traditional measure used to empirically predict structural rutting within a flexible pavement. Figure 13 and Figure 14 illustrate the peak vertical compressive strain profiles within the prepared subgrade layers in the southbound and northbound lanes at 84 percent and 98 percent reliability, respectively.

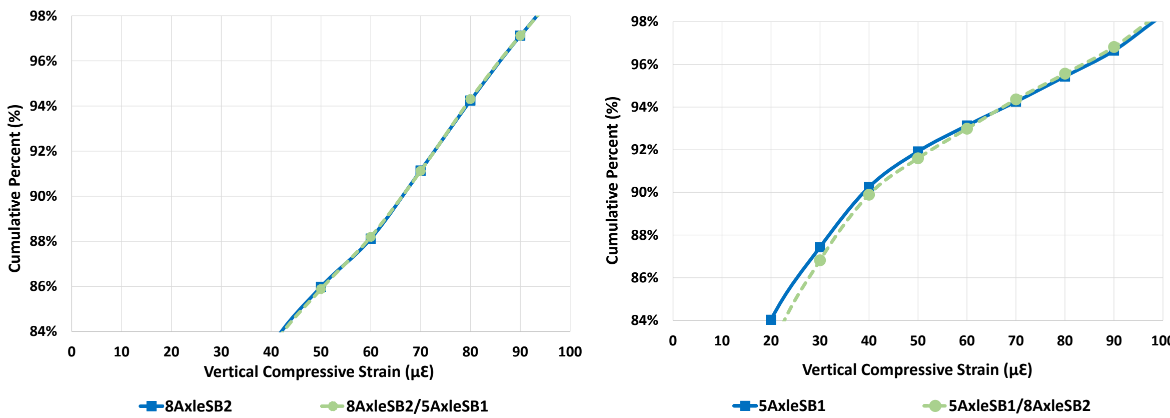


Figure 13. Volumetric Vertical Compressive Strain Profile in Top of Subgrade (Southbound Lanes)

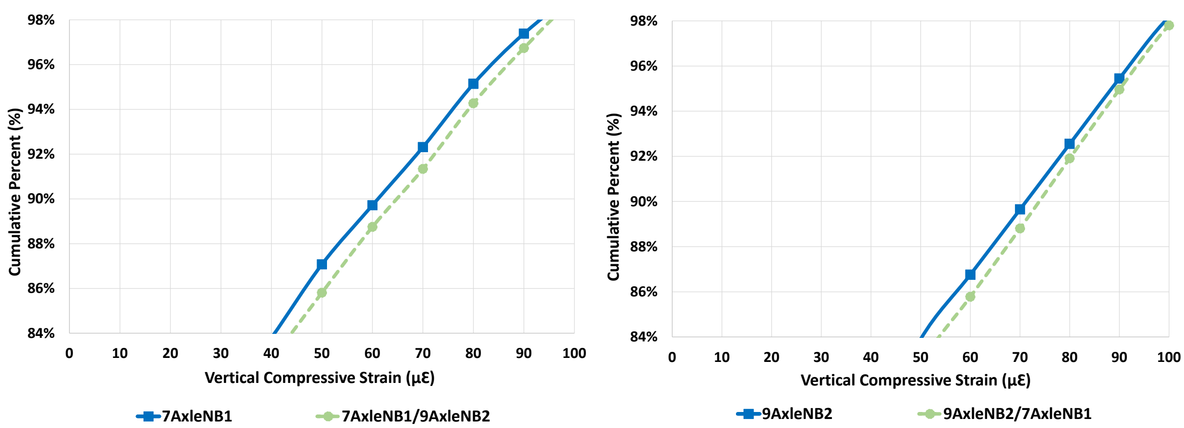


Figure 14. Volumetric Vertical Compressive Strain Profile in Top of Subgrade (Northbound Lanes)

Table 9 summarizes and Figure 15 illustrates the peak vertical compressive strain values on top of the subgrade. At 84 percent reliability, peak vertical compressive strain in top of subgrade ranged between 20 με and 50 με for single lane truck loadings and 22 με and 53 με for multi-lane truck loadings, resulting in an increase of 0 to 10 percent between single and multi-lane loading scenarios. At 98 percent reliability, peak vertical compressive strain in top of subgrade ranged between 92 με and 99 με for single lane truck loadings and 93 με and 100 με for multi-lane truck loadings, resulting in an increase in vertical compressive strain within the subgrade of 0 to 14 percent between single and multi-lane loading scenarios.

In summary, the peak vertical compressive strain within the subgrade was observed to significantly increase between 84 and 98 percent reliability. However, there was a minimal increase in peak vertical compressive strain with multi-lane loading relative to single lane loading.

Table 9. Peak Vertical Compressive Strain in Subgrade Layer under Single and Multi-Lane Loading

Truck/Lane	84% Reliability			98% Reliability		
	Single Lane Loading Peak Vertical Compressive Strain	Multi-Lane Loading Peak Vertical Compressive Strain and Percent Difference		Single Lane Loading Peak Vertical Compressive Strain	Multi-Lane Loading Peak Vertical Compressive Strain and Percent Difference	
	(με)	(με)	(%)	(με)	(με)	(%)
8-Axle SB2/ 5-Axle SB1	42	42	0	93	93	0
5-Axle SB1/ 8-Axle SB2	20	22	10	96	96	0
7-Axle NB1/ 9-Axle NB2	41	44	7	92	95	14
9-Axle NB2/ 7-Axle NB1	50	53	6	99	100	1

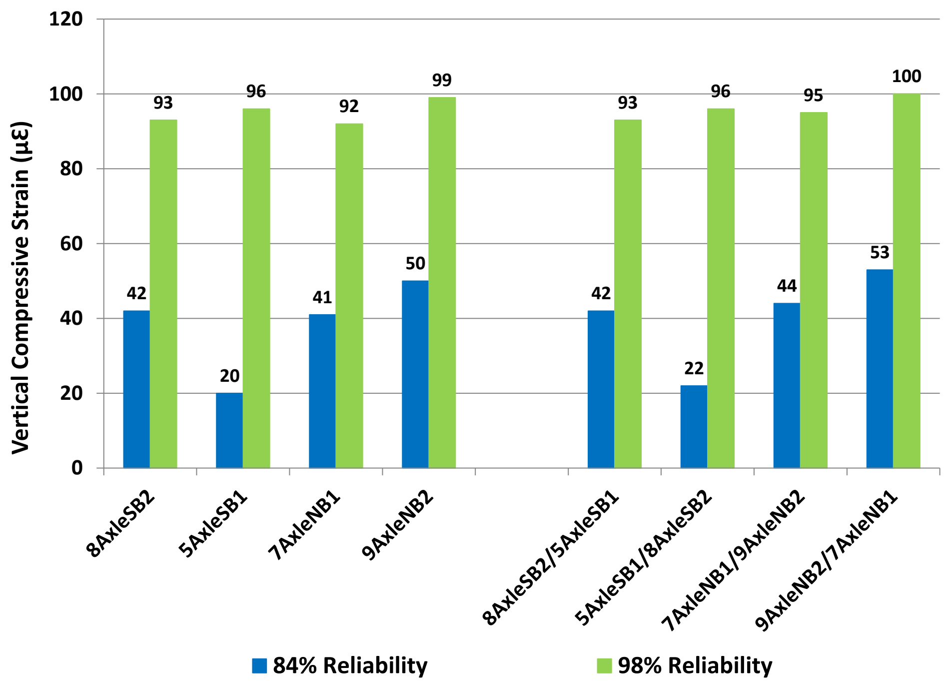
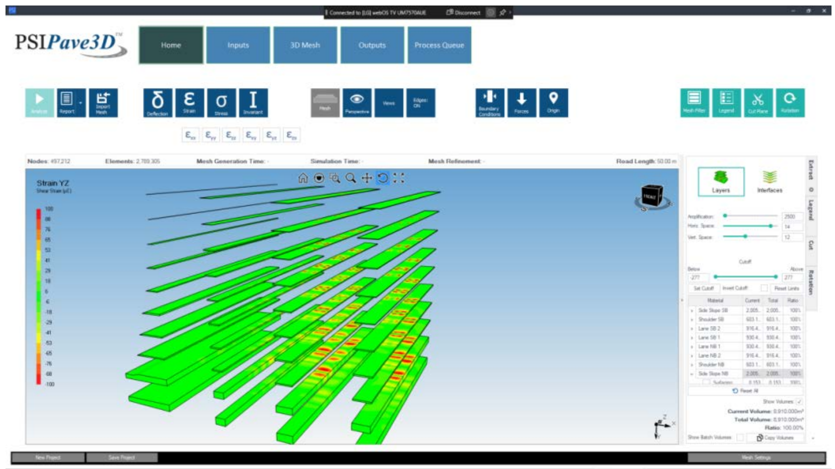


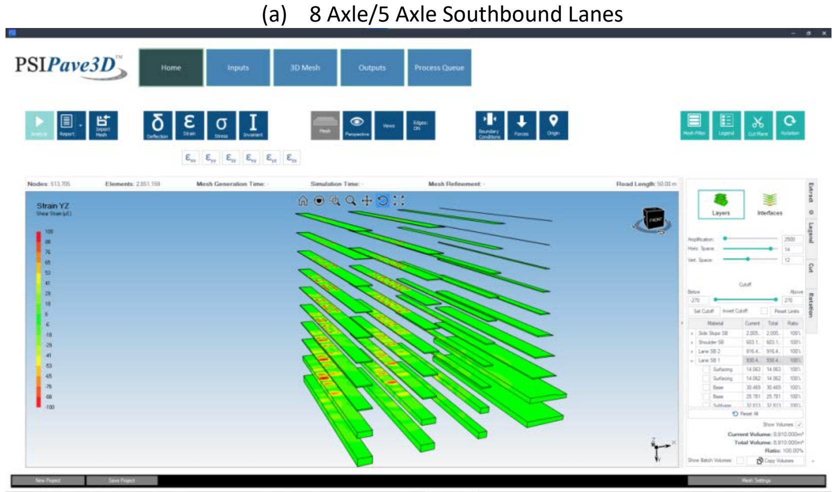
Figure 15. Peak Vertical Compressive Strain in Subgrade Layer under Single and Multi-Lane Loading

SHEAR STRAIN PROFILE

Shear failures are often observed in flexible pavements in all pavement layers. However, shear strain is a complex primary response to accurately calculate in engineered systems such as flexible pavement structures under heavy truck loading. PSIPave3D™ being a full 3-D numerical model with advanced material constitutive theory and load field state capabilities has the ability to provide accurate shear strain calculations throughout the road structure. Figure 16 illustrates PSIPave3D™ visualization of shear strain with an exploded view by lane by layer to help visualize primary response concentration and dissipation of shear strain within the road structure.



(a) 8 Axle/5 Axle Southbound Lanes



(b) 7 Axle/9 Axle Northbound Lanes

Figure 16. Shear Strain Profile with Depth of Pavement

Figure 17 and Figure 18 illustrate the volumetric shear strain profiles within the prepared subgrade layers at 84 percent and 98 percent reliability, respectively.

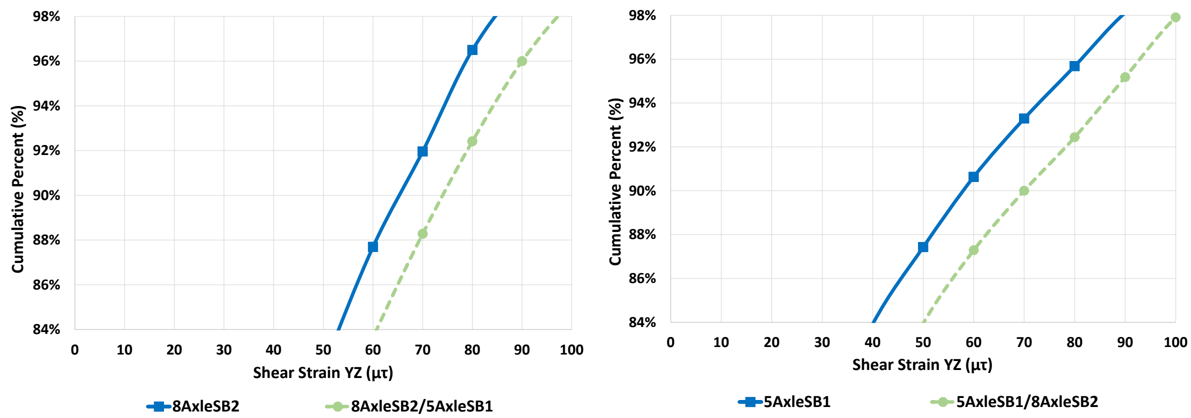


Figure 17. Volumetric Shear Strain Profile in Subgrade (Southbound Lanes)

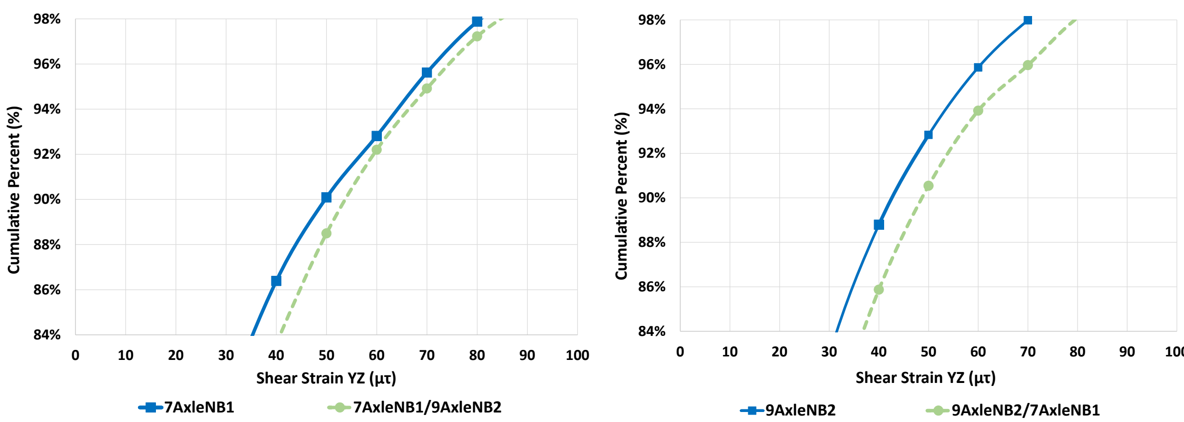


Figure 18. Volumetric Shear Strain Profile in Subgrade (Northbound Lanes)

Table 10 summarizes and Figure 19 illustrates the peak volumetric shear strain values within the subgrade at 84 and 98 percent reliability, respectively. At 84 percent reliability, volumetric shear strain ranged between 33 µτ and 53 µτ for single lane truck loadings and 38 µτ and 61 µτ for multi-lane truck loadings, resulting in an increase of 15 to 25 percent between single lane and multi-lane loading. At 98 percent reliability, volumetric shear strain ranged between 70 µτ and 89 µτ for single lane truck loadings and 79 µτ and 100 µτ for multi-lane truck loadings, resulting in an increase of 5 to 15 percent lane loading.

Based on the shear strain analysis performed, there was a significant increase in the level of shear strain in the subgrade from 84 to 98 percent reliability. As well there was a significant increase in subgrade shear strain state under multi-lane loading as compared to single lane loading.

Table 10. Volumetric Shear in Subgrade Layer under Single and Multi-Lane Loading

Truck/Lane	84% Reliability			98% Reliability		
	Single Lane Loading Volumetric Shear Strain	Multi-Lane Loading Volumetric Shear Strain and Percent Difference		Single Lane Loading Volumetric Shear Strain	Multi-Lane Loading Volumetric Shear Strain and Percent Difference	
	($\mu\tau_{yz}$)	($\mu\tau_{yz}$)	(%)	($\mu\tau_{yz}$)	($\mu\tau_{yz}$)	(%)
8-Axle SB2/ 5-Axle SB1	53	61	15	84	97	15
5-Axle SB1/ 8-Axle SB2	40	50	25	89	100	12
7-Axle NB1/ 9-Axle NB2	35	41	17	80	84	5
9-Axle NB2/ 7-Axle NB1	33	38	15	70	79	13

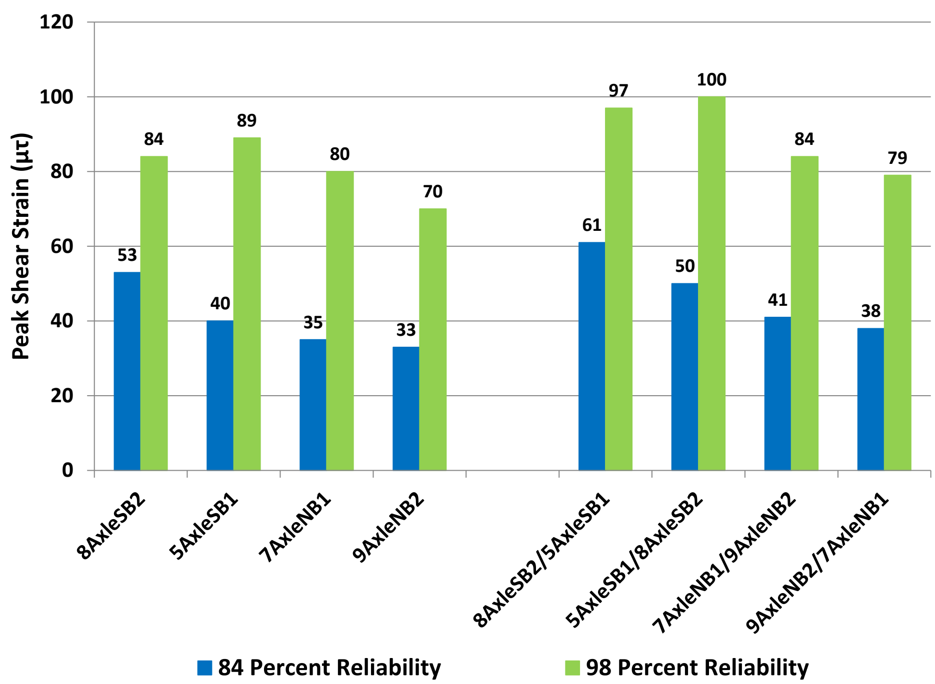


Figure 19. Peak Shear Strain in Subgrade under Single and Multi-Lane Loading

CONCLUSIONS

Pavement engineers use strain calculations to estimate pavement damage thresholds to design road structural layer thickness, load equivalencies and predict the life cycle performance of flexible pavements. The primary strain calculations traditionally used have been peak tensile horizontal orthogonal strain at the bottom of the hot mix layer and vertical compressive orthogonal strain at the top of the subgrade. These idealized peak orthogonal strains have been used to correlate to the primary structural pavement failure modes of fatigue cracking and rutting, respectively.

A challenge to relying on traditional measures of pavement performance is that there is significant economic efficiency and environmental justification globally for larger heavy commercial trucks. Given the significant growth in the number of heavy trucks on multi-lane corridors, there is an increasing probability of heavily loaded trucks to be travelling on adjacent lanes of multi-lane roads at the same time.

Traditional pavement design and performance prediction methods commonly used by pavement design engineers have been based on smaller commercial trucks and do not incorporate the effects of pavement cross loading within the pavement structure due to multiple truck loading of the pavement at the same time.

Over recent years larger but more efficient trucks being used in the trucking industry apply higher strain states within pavement structures. The objective of this study was to use 3-D pavement numerical modeling to quantify volumetric strain states within two typical pavement structures under four modern commercial heavy trucks. This study used 3-D numerical modeling to quantify the effects of both larger heavy trucks and large commercial trucks operating on adjacent lanes.

Based on the findings of this study, the level of reliability of pavement design selected by the pavement engineer can significantly influence the primary response target level used to engineer the primary response limit of the pavement.

Based on the primary pavement response modeling conducted in this research, it was found that the volumetric shear strain in the subgrade and surface deflection primary responses can increase by up to 27 percent with adjacent truck lane loading scenarios. It was found that the traditional orthogonal primary strain responses used in pavement engineering were less sensitive under adjacent multi-lane loading.

Based on this analysis, for heavily loaded multi-lane road corridors, it is recommended that pavement design engineers consider the effect of multi-heavy truck lane loadings effects within surface deflection profile as well as shear strain state within the road structure when engineering the design and/or life cycle performance of pavement structures. This paper shows how multi-lane loading may have a significant incremental impact on pavement primary responses. As an example, for multi-lane heavily loaded pavements, pavement engineers could utilize accurate traffic models and/or data collection systems to increase the cumulative loading projections on individual lanes of multi-lane facilities either in the original design phase and/or midlife rehabilitation design and analysis.

REFERENCES

1. Alimohammadi, H., Zheng, J., Buss, A., Schaefer, V. R., Williams, C., & Zheng, G. (2021). Finite element viscoelastic simulations of rutting behavior of hot mix and warm mix asphalt overlay on flexible pavements. International Journal of Pavement Research and Technology, 14(6), 708-719.https://doi.org/10.1007/s42947-020-0057-5
2. Gungor, O. E., Al-Qadi, I. L., Gamez, A., & Hernandez, J. A. (2017). Development of adjustment factors for MEPDG pavement responses utilizing finite-element analysis. Journal of Transportation Engineering, Part A: Systems, 143(7), 04017022.
3. AASHTO. (2008). Mechanistic-empirical pavement design guide: A manual of practice, Washington, DC.
4. Berthelot, C. (1999). Mechanistic Modeling of Saskatchewan Specific Pavement Studies-9A Asphalt Concrete Pavements, Volume I (Doctor of Philosophy Dissertation, Texas A&M University).
5. Haichert, R., Berthelot, J., Soares, R., & Berthelot, C. (2021). Structural Modelling of Recycled Materials for Rehabilitating Urban Heavy Haul Arterial Roadways (No. TRBAM-21-03849).
6. Berthelot, C., Haichert, R., Soares, R., Podborochynski, D., Guenther, D. 2011. City of Saskatoon Mechanistic Pavement Structure Modeling. 2011 Transportation Association of Canada (TAC) Annual Conference. Edmonton, AB.
7. Allen, D. H., Little, D. N., Soares, R. F., & Berthelot, C. (2017). Multi-scale computational model for design of flexible pavement–part I: expanding multi-scaling. International Journal of Pavement Engineering, 18(4), 309-320.
8. Saskatchewan Truck Weight Classifications and Restrictions, The Vehicle Weight and Dimension Regulations, 2010. https://publications.saskatchewan.ca/api/v1/products/31363/formats/38391/download.
9. Ontario Regulation 413/05: Vehicle Weights and Dimensions - For Safe, Productive and Infrastructure-Friendly Vehicles (Ontario.Ca), under Highway Traffic Act, R.S.O. 1990, c. H.8, March 2021, https://www.ontario.ca/laws/regulation/050413.
10. Soares, R., Eng, P. D., Haichert, R., Eng, P., Berthelot, C., & Hanson, R. (2019). The Effect of Tire Under Inflation and Tire Anomaly on Pavement Structural Layers. In Transportation Association of Canada and ITS Canada 2019 Joint Conference and Exhibition.
11. Sizes & Specifications for Goodyear Tires, https://www.goodyeartrucktires.com/tires/sizes-specs-page.html?prodline=160631.