The Effect of Tire Under Inflation and Tire Anomaly on Pavement Structural Layers.

Roberto Soares, Ph.D. P.Eng.
PSI Technologies Inc.
221 Jessop Ave, Saskatoon, SK, S7N 1Y3

Rielle Haichert, P.Eng.
PSI Technologies Inc.
221 Jessop Ave, Saskatoon, SK, S7N 1Y3

Curtis Berthelot, Ph.D., P.Eng.
PSI Technologies Inc.
221 Jessop Ave, Saskatoon, SK, S7N 1Y3

Randy Hanson, P.Eng.
International Road Dynamics
702-43rd Street East, Saskatoon, SK, S7K 3T9

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ABSTRACT

Truck loading is an important factor in pavement design and road asset preservation. In addition to load weight spectra, roads are often subjected to uneven axle loading, lateral lane position wander, variable tire pressures and variable tire types. An important consideration in determining load impact is how the load traction state is distributed within a single vehicle and the impact on road primary response profiles. This paper is a study of the structural effects on the pavement layers caused by uneven tire load tractions as compared to a non-uniformly distributed loading which is often assumed for pavement design, asset management and performance prediction purposes.

Tire load distribution measurements were collected from sensors installed on traffic data collection sites. Based on the real world traffic stream data collected, the frequency of tires with low contact pressures was established.

A nonlinear stress-dependent three-dimensional finite element analysis was performed on a typical rural road structure under various climatic field state conditions. Shear strain profiles were analyzed by various heavy truck loadings within the road structure. These findings show shear strain increases of up to 30 percent around the underinflated tire cases when compared to a uniformly distributed loading across all field state climatic conditions and traffic speeds. Based on these results, it is recommended load enforcement; pavement management and design of roads consider load distribution among tires within axle groupings, tire footprint distribution and lane distribution in addition to total axle group weights.

INTRODUCTION

There are three primary inputs required when designing a pavement: truck loads, pavement geometry and material properties within each layer. Climatic conditions and current damage state of the road structure also influence primary response profiles and performance of roads. Pavement geometry refers to layer thickness, surface profile, lane width, side slopes, and others geometric considerations. Material properties are the selection of materials within each layer and are generally selected to dissipate the load applied at the surface to protect the subgrade. How heavy the truck loads are distributed over its axles and individual tires can significantly influence the load traction state applied to a pavement structure.

This paper evaluated how an underinflated tire influenced the structural primary response profile of a typical pavement structure. A three-dimensional computational road model (PSIPave3D™) was developed and used to calculate the fundamental mechanistic pavement response profiles across road materials, structures, and field state conditions (1, 2, 3). The strain behavior within the road structure was spatially calculated by the model incorporating road layer thicknesses, load spectra, climatic conditions and material constitutive properties. In particular, this paper presents shear strain profiles to compare the alternates

Field data was collected using International Road Dynamics (IRD) sensor technology (VectorSense™) across five sites. The number of trucks with underinflated tires was quantified and documented.

Objective

The objective of this study was to investigate the effects of a single underinflated tire on the structural primary response of a typical pavement structure across different field state conditions.

Scope

In this study, two baseline road field climatic conditions were modeled including:

- Dry road structure
- Wetted up structure with wet subgrade

These road structures were subject to loading of two tridem axle groups passing with the following two loading conditions analyzed:

- 24,000 kg tridem axle group loadings, all tires properly inflated
- 24,000 kg tridem axle group loadings, one tire underinflated to the point of not effectively carrying load.

Field data was collected to investigate the frequency of trucks with underinflated tire through the use of field data collection sites across North America and Europe

ROAD GEOMETRY

For the analysis presented herein, the pavement geometry consists of a two lane rural road with 3.75m wide lanes (8.4 m total pavement top width) and 3:1 side slope on a rural cross section. Layer thicknesses are 40 mm of new hot mix asphalt concrete (HMAC), 60 mm of old HMAC, 200 mm of base, 300 mm of subbase and 500 mm of prepared subgrade on top of low plastic clay-till *in situ* subgrade an illustrated in Figure 1.

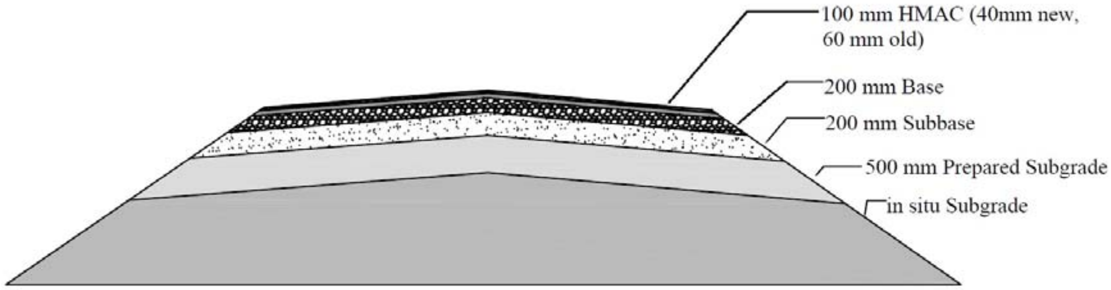


Figure 1 Case Study Road Cross Section

LABORATORY MATERIALS CHARACTERIZATION

Laboratory characterization was conducted on subgrade, subbase, base and HMAC materials. Subgrade material was classified by the Unified Soils Classification System (USCS) as a Low Plastic Clay (CL).

The samples were subjected to different stress states and characterized according to a nonlinear stress-dependency behavior under typical field state load conditions. The material characterization results were then encoded into the model material constitutive stress and frequency dependent material properties.

Triaxial frequency sweep testing was performed on continuum samples prepared at optimum moisture and density as well as dry/optimum density and wet/low density conditions representative of the observed in situ range of each material within typical road structures (*4, 5, 6, 7, 8, 9*). Mechanistic characterization was performed across field stress states and load frequencies as directed by the three dimensional model. Test loading frequencies ranged from 0.1 Hz to 25 Hz to characterize the materials across common vehicle speeds.

Table 1 Non-Linear Dynamic Modulus Range

Material Type	Material Condition Description	Range of Dynamic Modulus (MPa) Across Stress State and Slow Traffic Speed (30 km/h)		Range of Dynamic Modulus (MPa) Across Stress State and Highway Traffic Speed (100 km/h)	
		Min	Max	Min	Max
HMAC	MHI Type 71, New Pavement	1230	3112	1602	4053
	MHI Type 71, Old Pavement	615	1556	801	2027
Base	MHI Type 33, Optimum Moisture	116	571	117	576
	MHI Type 33, Wet of Optimum Moisture	61	344	62	346
Subbase	MHI Type 6, Optimum Moisture	121	417	122	418
	MHI Type 6, Wet of Optimum Moisture	61	208	61	209
Subgrade	Clay Till at Optimum Moisture and Density	92	155	97	163
	Clay Till at Wet of Optimum Moisture	39	73	41	76

Non-linear Poisson's ratio was characterized across the full range of field stress states and load frequencies representative of the design field state conditions, as seen in Table 2 below. Poisson's ratio is a ratio of the vertical to lateral strain. Poisson's ratio is a critical input into three-dimensional numerical modeling simulations when evaluating shear strain conditions and exhibits non-linear behavior as a function of stress state and load rate.

Table 2 Non-Linear Poisson's Ratio Range

Material Type	Material Condition Description	Range of Poisson's Ratio Across Stress State and Slow Traffic Speed (30 km/h)		Range of Poisson's Ratio Across Stress State and Highway Traffic Speed (100 km/h)	
		Min	Max	Min	Max
HMAC	MHI Type 71, New Pavement	0.24	0.38	0.23	0.36
	MHI Type 71, Old Pavement	0.30	0.45	0.28	0.43
Base	MHI Type 33, Optimum Moisture	0.28	0.45	0.27	0.45
	MHI Type 33, Wet of Optimum Moisture	0.45	0.45	0.45	0.45
Subbase	MHI Type 6, Optimum Moisture	0.45	0.45	0.45	0.45
	MHI Type 6, Wet of Optimum Moisture	0.45	0.45	0.45	0.45
Subgrade	Clay Till at Optimum Moisture and Density	0.29	0.38	0.29	0.38
	Clay Till at Wet of Optimum Moisture	0.45	0.45	0.45	0.45

FIELD LOADING VALIDATION

IRD employs in road sensors, VectorSense™, to collect vehicle and traffic data including lane position information, single/dual and super single tire measurement and identification of low pressure tires, all at highway speed. IRD currently has several sites collecting data from their VectorSense™ sensors installed on roads across North America and Europe as illustrated in Figure 2.

Figure 2 IRD VectorSense™ Sensors Installed on Road

As illustrated in Figure 3 and summarized in Table 3, across IRD's current VectorSense™ data collection sites, on average, approximately two percent of trucks (Class 5 and higher) exhibit at least tire with a pressure anomaly (ie. low road contact pressure due to low tire pressure or excessive tire wear). At locations where this data is used for traffic enforcement, the rate of trucks with low pressure tires has been observed to be reduced relative to the site prior to enforcement. Figure 3 shows the outputs of VectorSense for examples of trucks with anomalous tires; the first three trucks with one tire anomaly each and the last truck with two tire anomalies as highlighted in.

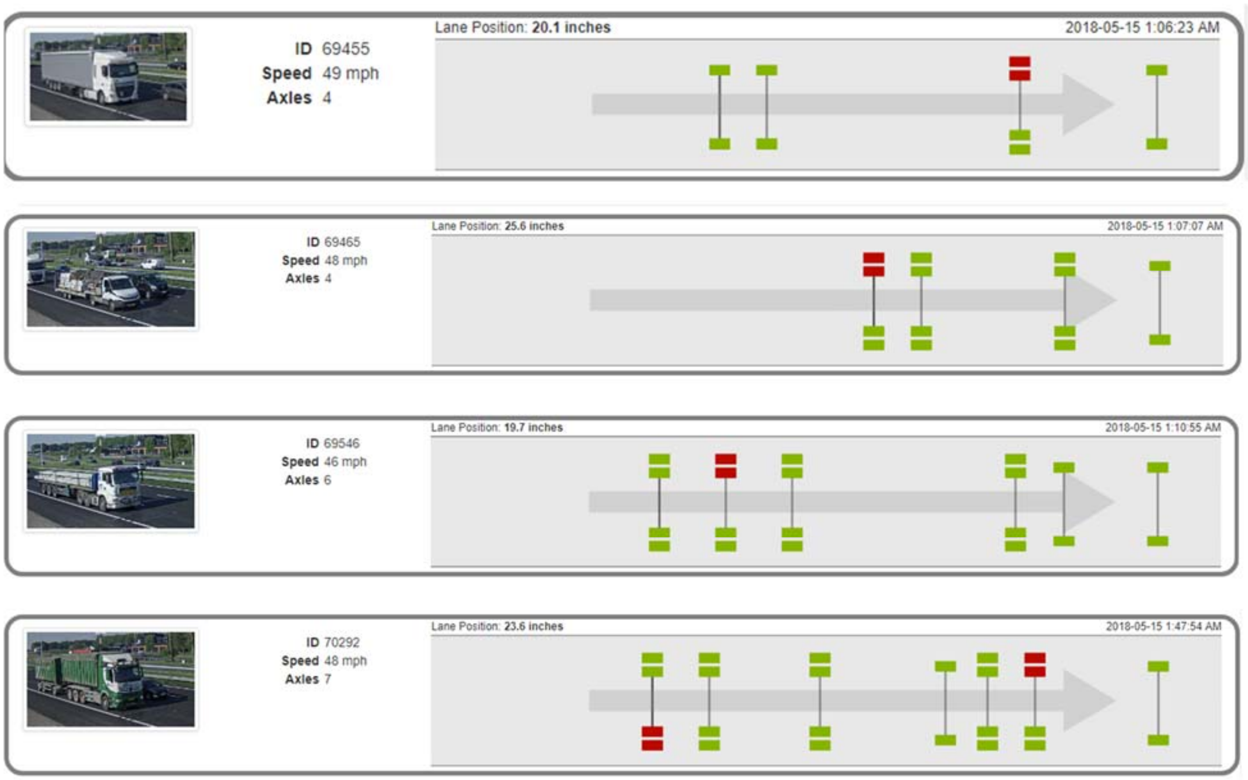


Figure 3 Traffic Data Interface with a Flagged Tire Anomaly

Table 3 IRD VectorSense™ Tire Pressure Field Data Collection Summary

Location	Average Daily Truck Count	Average Daily Trucks with Tire Anomaly	% of Trucks with Tire Anomaly
South West USA	1990	37	1.9%
North West USA	1425	18	1.3%
Midwest USA	1100	18	1.6%
Western Canada	835	18	2.2%
Western Europe	6102	67	1.1%

Based on actual field data, there is reason to model the impact of variable tire pressure loading on roads. Figure 4 shows the non-uniform tire contact distribution as applied in the finite element model (FEM). The load distribution follows similar studies by (*10, 11, 12*).

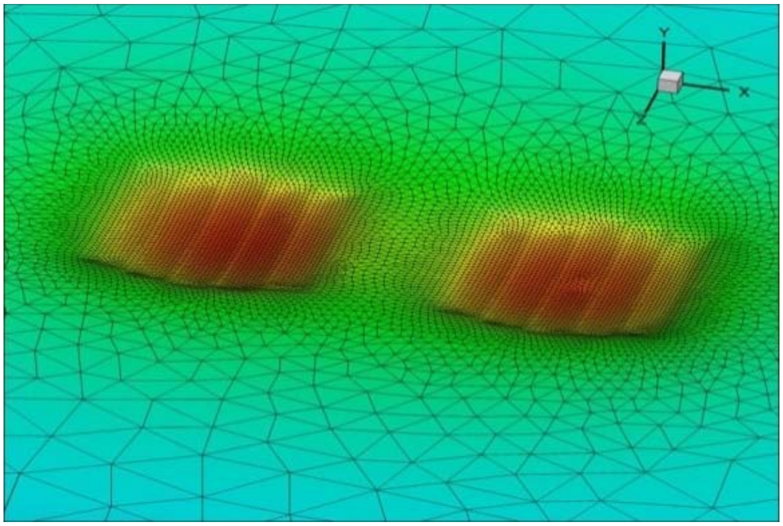


Figure 4 PSIPave3D™ Finite Element Model Dual Tire Pressure Distribution

ROAD STRUCTURAL MODELING

PSIPave3D™ is a three dimensional non-linear computational road model developed to calculate the fundamental mechanistic pavement response across road materials, structures, and field state conditions for both road analysis and design (*2, 3*). This model is used in this study to calculate the peak shear strains around the applied truck loads on the pavement structures.

The model is built into a user-friendly software package created for routine road analysis and design. The deflection as well as three dimensional strain behavior of a road structure is spatially calculated by the model incorporating road layer thicknesses, load spectra, climatic conditions and material constitutive properties into the design and analysis of any given road structure. Past studies have demonstrated validity of the model (*2, 3*). The road model outputs orthogonal strains, which conventional road design methodologies typically calculate and empirically correlate to field performance, but also shear strains, which truly dictate the structural performance and failure criterion for road materials.

The load distribution across the two cases were as follows: for the properly inflated case, a primary load truck weight of a tridem axle (24,000 kg) was applied uniformly across all twelve tires of a typical 1.85 m spread tridem groups (dual tire configurations) on the driving lane. In the flat tire case, the total load was the same, however the distribution across was unevenly distributed with a few tires carrying more loads than others. In addition, there was a second tridem axle on the passing lane. This second tridem axle was kept at a constant load of 24,000kg. The two tridems and the one million elements FEM mesh can be seen in Figure 5.

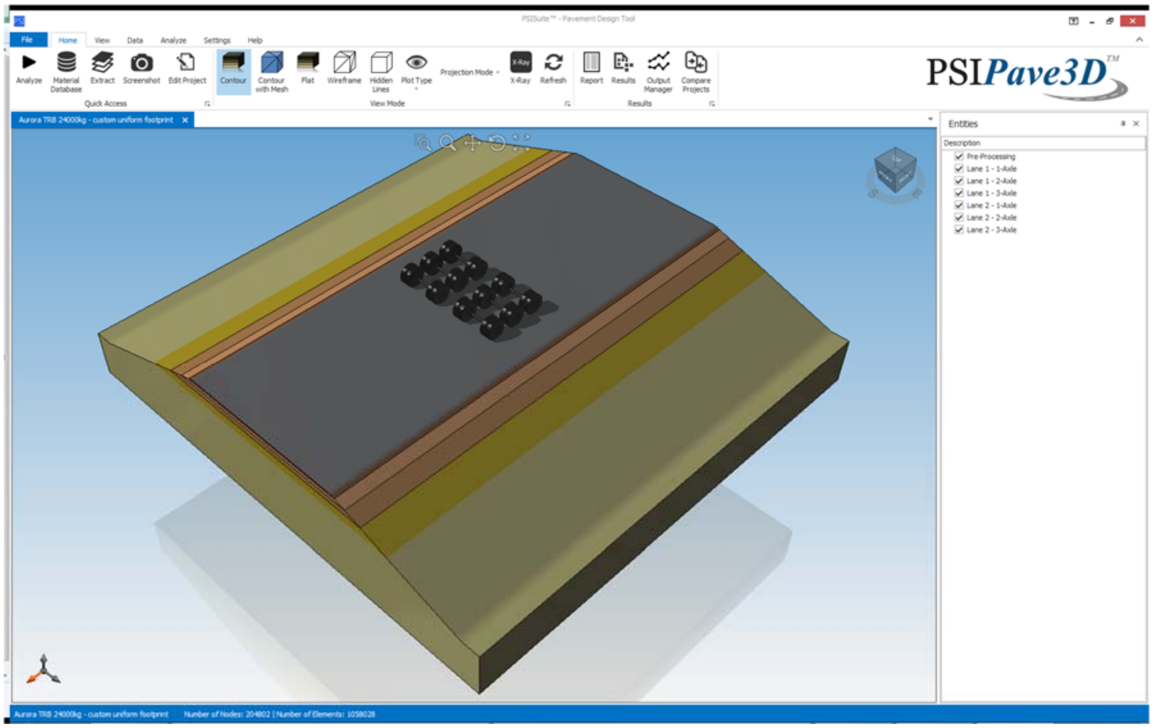


Figure 5 Tridem Axle Load Configuration of Two B-Trains Passing

COMPUTATIONAL MODELING RESULTS

Pavement Cross Sections – Deflection Profiles

The results obtained from the nonlinear material properties and stress dependent simulations show and a localized increase in deflection when a flat tire is present when compared to all tires properly inflated. Figure 6 to Figure 9 illustrate a three-dimensional cross section of the deformed pavement shape magnified 1,000 times and with a shear strain contour across four different cases. The slice passes through the flat tire where a higher peak can be seen in each figure. Figure 6 and Figure 7 compare a dry case with uniform and flat tires respectively. Figure 8 and Figure 9 compare a wet structure with uniform and flat tires respectively. It can be seen the effect on both flat tire cases where the redistribution of the load induces higher strains.

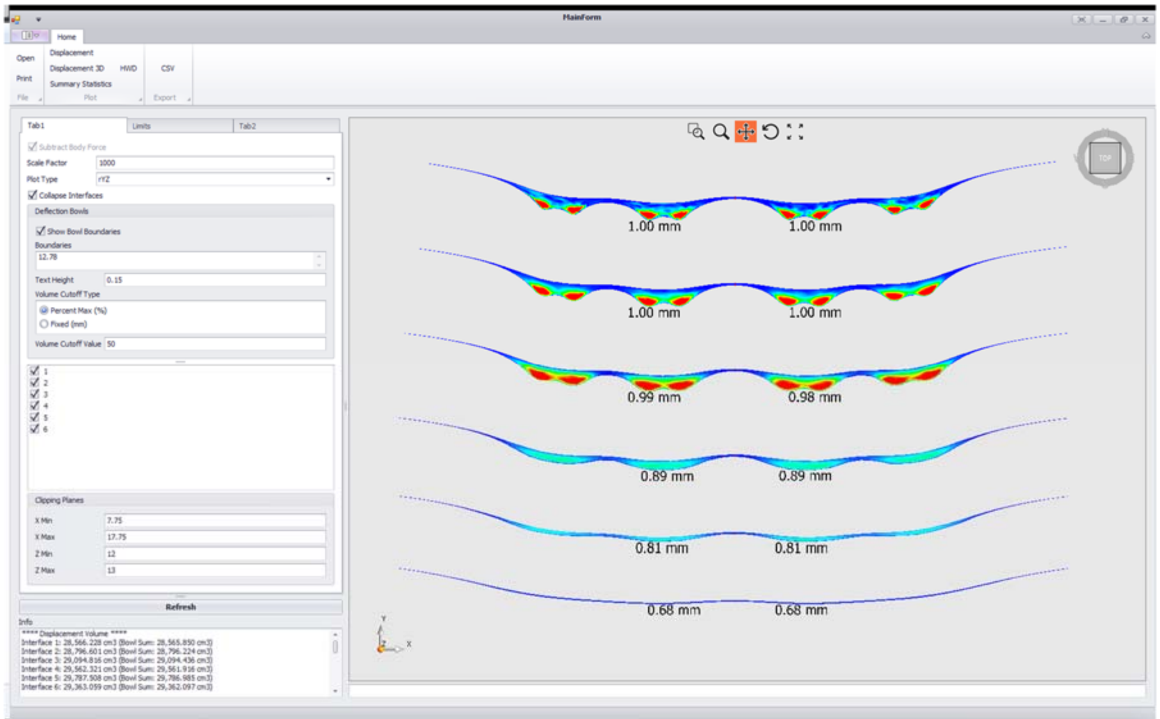


Figure 6: Deflection Profile and Shear Strain Contour – Uniform Tire Inflation – Dry Structure – 100 km/h

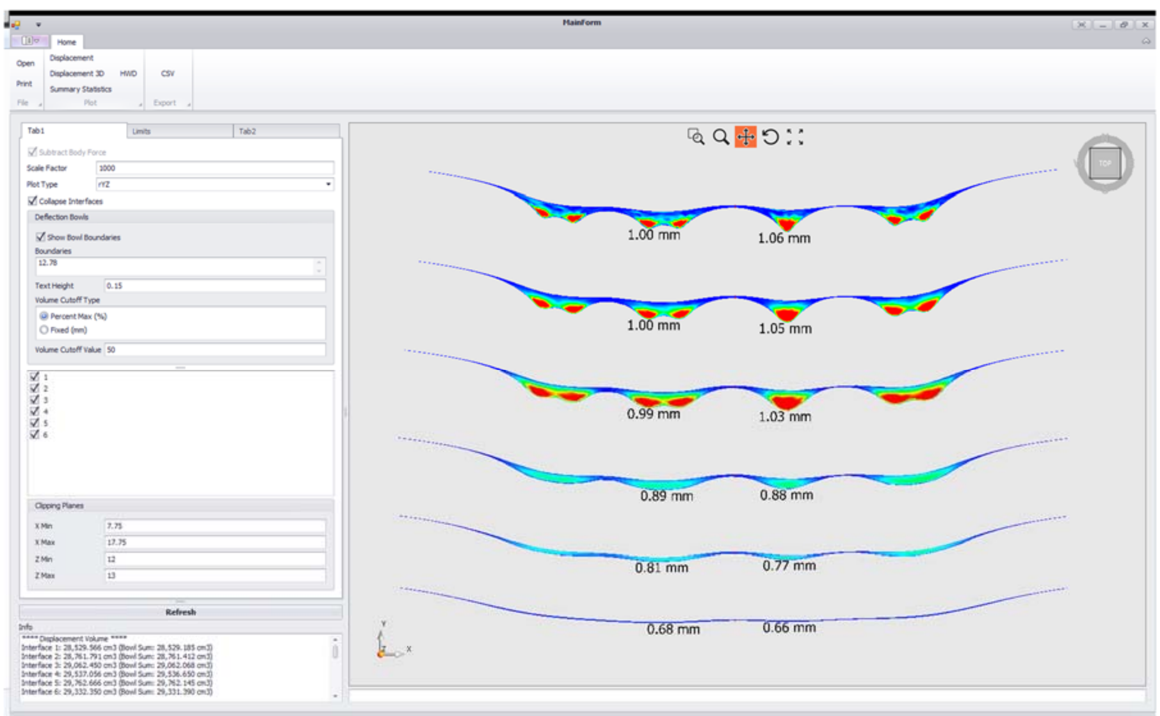


Figure 7: Deflection Profile and Shear Strain Contour – Single Flat Tire – Dry Structure – 100 km/h

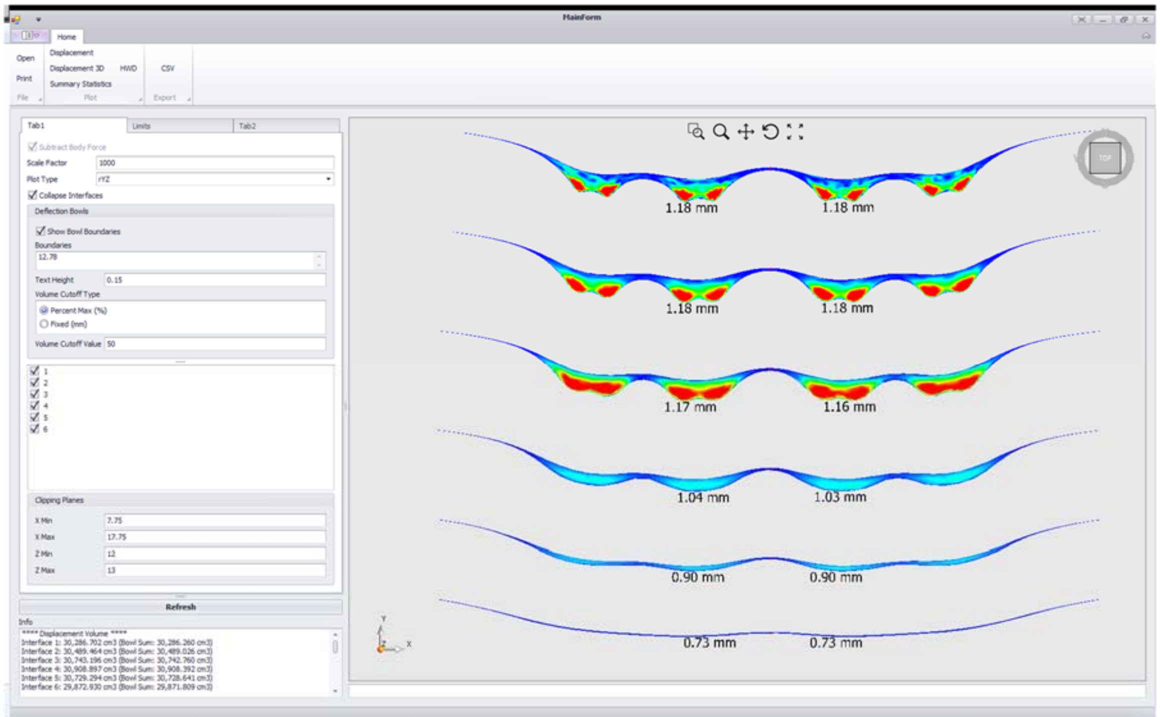


Figure 8: Deflection Profile and Shear Strain Contour – Uniform Tire Inflation – Wet Structure – 30 km/h

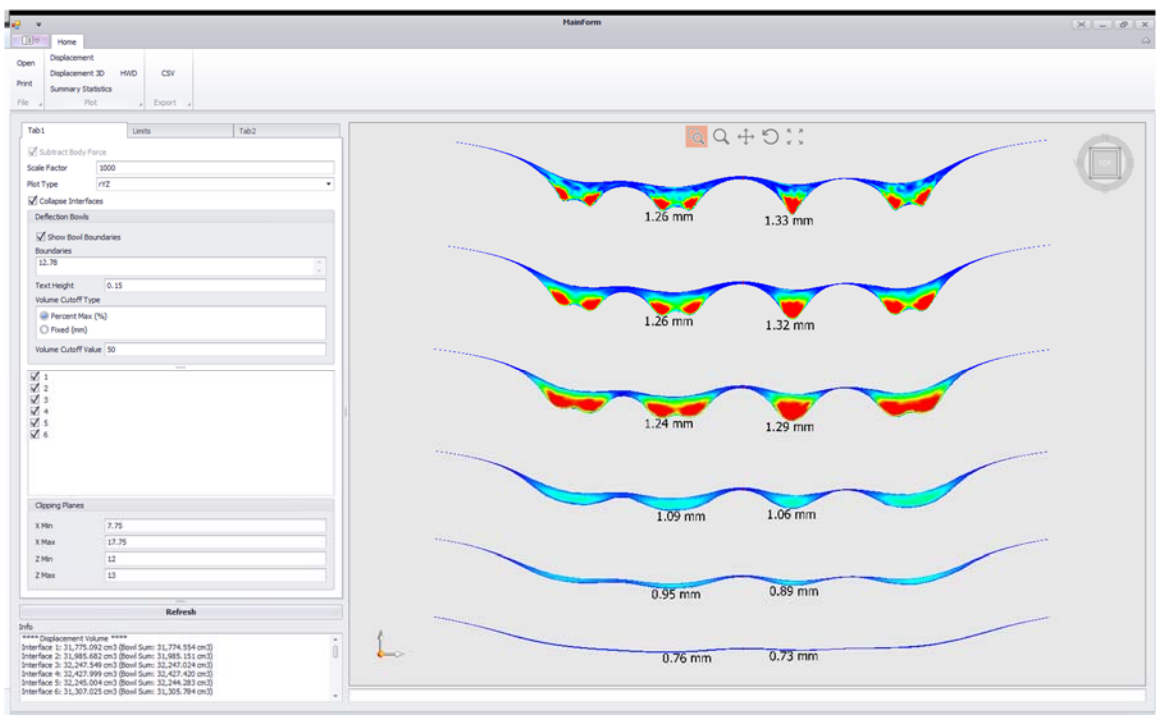
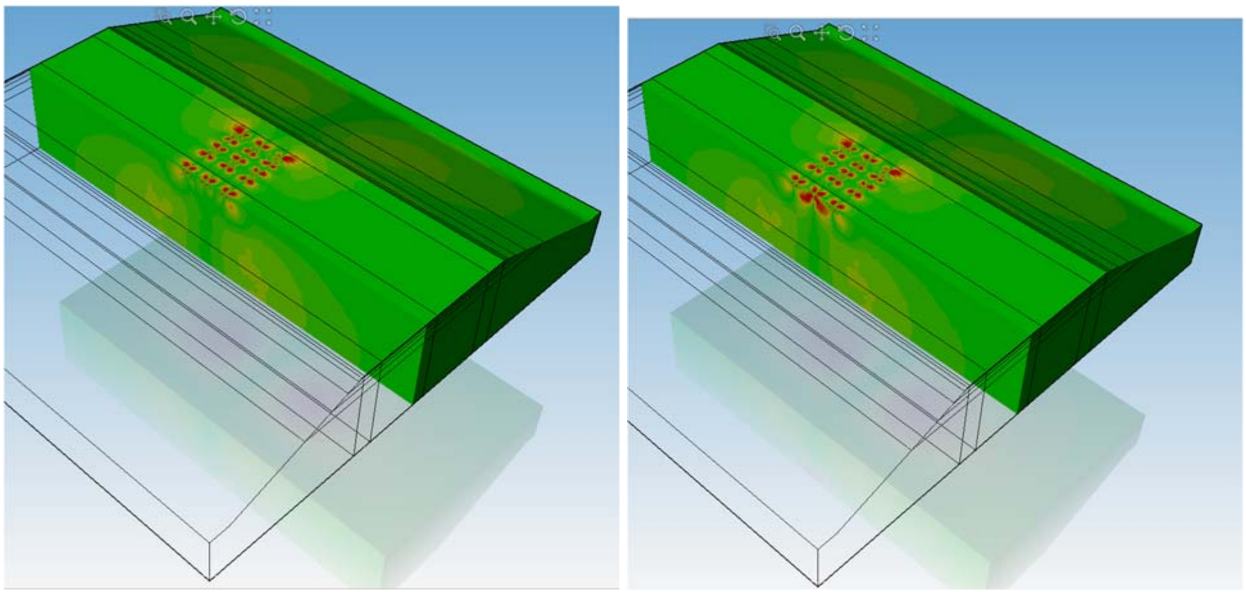


Figure 9: Deflection Profile and Shear Strain Contour – Single Flat Tire – Wet Structure – 30 km/h

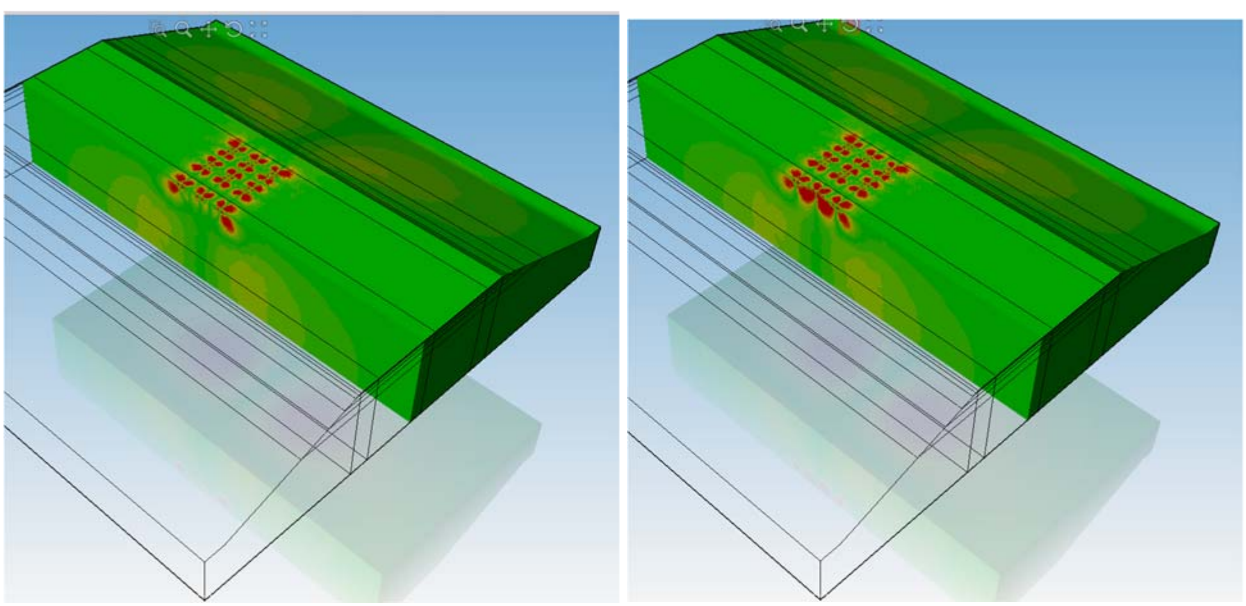
Pavement Shear Strain Results

Shear strains are a reliable mechanistic indicator of pavement performance and given that geomaterials are generally weak in shear, Figure 10 and Figure 11 present shear strain distribution across depth for the four different simulations. Figure 10 and Figure 11shows a uniform shear strain distribution across the uniform inflated tires on the tridem axle on the right side of the figures. On the left side the, cases differ from the right as they contains one anomaly (missing/severely underinflated tire) and it shows a large volumetric concentration of shear strain where the single tire is missing. This is caused by the redistribution of the axle load.



Uniform Tire Inflation **Flat Tire**

Figure 10: Shear Strain Profile – Uniform Tire Inflation – Dry Structure – 100 km/h



Uniform Tire Inflation **Flat Tire**

Figure 11: Shear Strain Profile –Wet Structure – 30 km/h

Figure 12 through Figure 14 illustrate the shear strain results of the cases with uniform tires loading and with one flat tire. As seen in Figure 12 through, the peak shear was increased for the cases with one flat tire for the new HMAC, old HMAC, Base and Subgrade by 0 percent, 21 percent, 10 percent and 0 percent, respectively. Therefore, across the cases modeled, the increase in strain due to the flat tire was mostly exhibited in the lower asphalt layer, and to a lower extent, in the base layer. Note that subbase results are omitted to keep results concise.

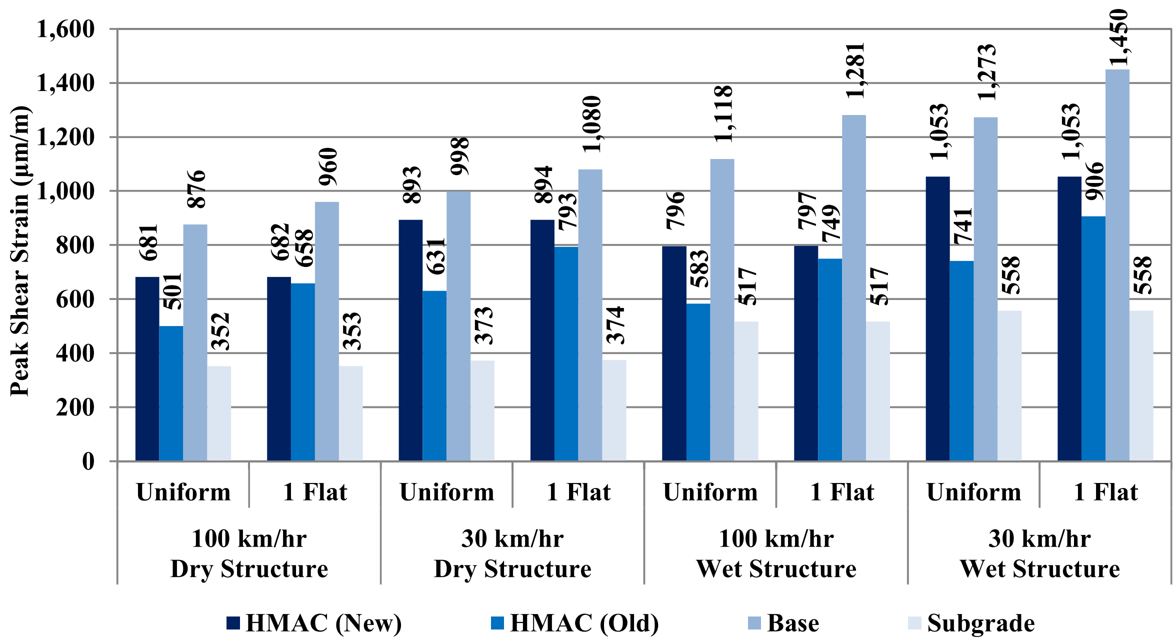


Figure 12: Peak Shear Strains across Material Layers

Figure 13 illustrates a volumetric distribution of shear strains, essentially highlighting the physical amount of HMAC under a given strain level. This measurement is used to quantify the magnitude of HMAC that is subjected to strain states higher than a certain threshold and it allows for the analysis to be focused on the areas of interest. Figure 14 contains the volume of the old HMAC layer subject to shear strains greater than 400 µm/m.

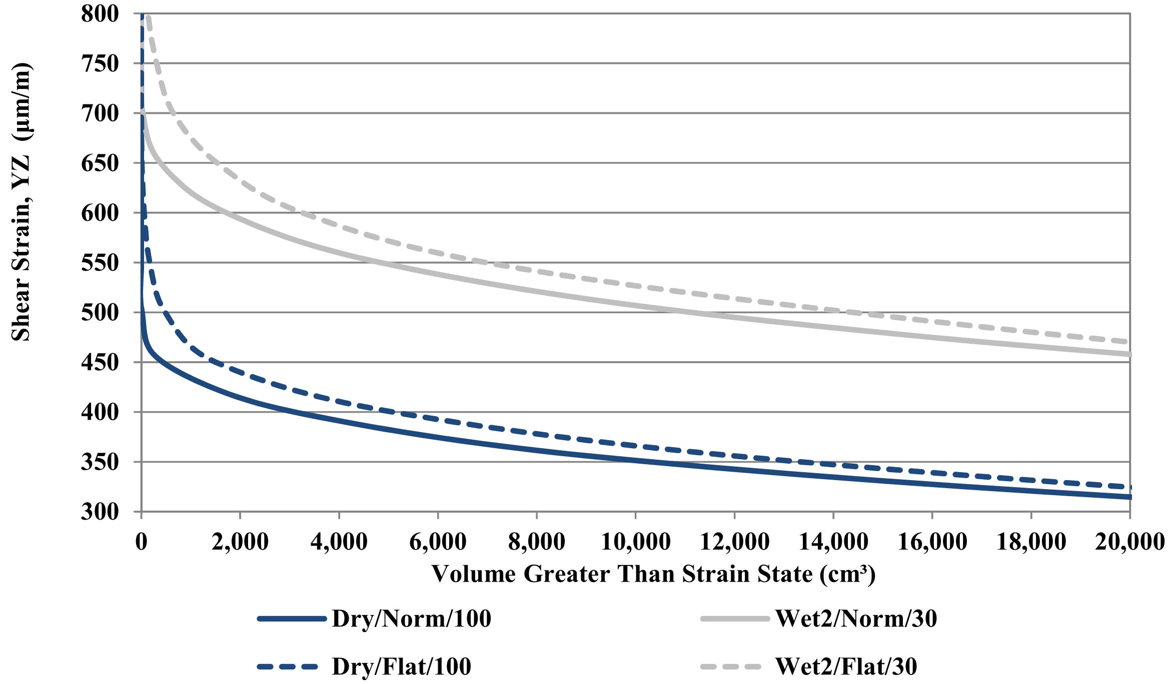


Figure 13 Volumetric Shear Strain in HMAC old

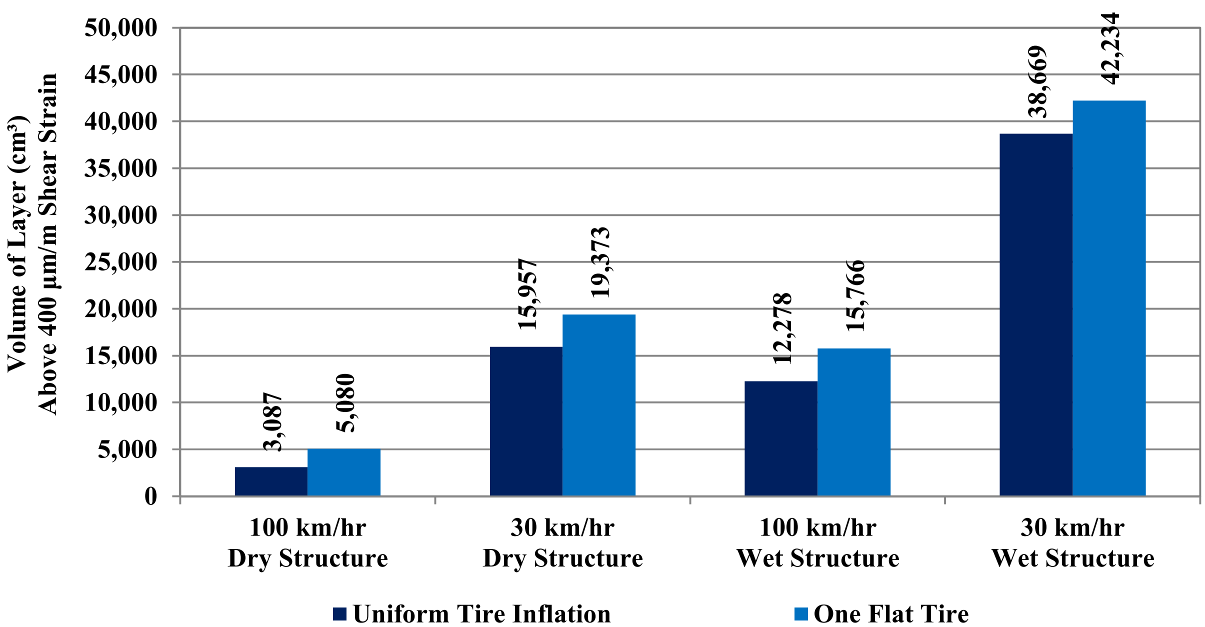


Figure 14 Volumetric Shear Strain in HMAC old

As seen in Figure 13 and Figure 14, the dry structure with a truck speed of 100 km/h exhibited the lowest volume of old HMAC that exceeded 400 µm/m shear strain. The volume of old HMAC subject to

shear strain increased from 3,087 cm^3 for uniform tire inflation case to 5,080 cm^3 for the one flat tire case, which is an increase of 65%.
The wet structure with a truck speed of 30 km/h exhibited the highest volume of old HMAC that exceeded 400 µm/m shear strain. The volume of old HMAC subject to shear strain increased from 38,669 cm^3 for uniform tire inflation case to 42,234 cm^3 for the one flat tire case, which is an increase of 9%.
Therefore, it can be seen that a truck with a flat tire causes an increase in volume of material subject to higher shear strain states than a truck with uniform tire loading across all modeled pavement conditions. The relative level influence of flat tires on a pavement was greater in the case of lower overall pavement shear strain volumetric influence.

CONCLUSIONS

This study investigated the effects of underinflated tires on roadway structural performance of a typical rural paved road. The structural design input data obtained was validated using sensors field-modeling validation, and finite element modeling using PSIPave3D™.

The modeled peak shear strain in the HMAC of a properly inflated tire configuration was reduced by up to 21 percent, compared to the case of flat tire peak shear strain. The shear strains are dissipated uniformly in the properly inflated case due to the total load distribution equally across all tires. The cases with a flat tire show a greater difference in the peak strains and overall volumetric analysis; however this difference is greatly reduced through depth, indicating more vulnerability on the top layers.

The combined efforts of FEM simulation and load management through traffic data analysis are a powerful tool for identifying and quantifying the effects and damages caused by tire anomalies and underinflated tires in pavement management and design.

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