**Quantifying the Impact of Truck Axle Groups on Rural and Urban Pavement Structure Performance**

Prepared by:

Roberto Soares, Ph.D., PSI Technologies Inc.
221 Jessop Avenue, Saskatoon, SK, Canada, S7N 1Y3
Phone: (306) 477-4090, Fax: (306) 477-4190, rsoares@pavesci.com

Curtis Berthelot, Ph.D., P. Eng.
Professor and Director of Transportation and Infrastructure Centre of Excellence,
University of Saskatchewan, 57 Campus Drive, Saskatoon, SK
Ph: (306) 966-7009, Fax: (306) 966-5427.

Diana Podborochynski, PSI Technologies Inc.
221 Jessop Avenue, Saskatoon, SK, Canada, S7N1Y3
Phone: (306) 477-4090, Fax: (306) 477-4190, dpodborochynski@pavesci.com

Rielle Haichert, PSI Technologies Inc.
221 Jessop Avenue, Saskatoon, SK, Canada, S7N 1Y3
Phone: (306) 477-4090, Fax: (306) 477-4190, rhaichert@pavesci.com

Paper prepared for presentation
at the Pavement Performance Case Studies Session
of the 2012 Annual Conference of the
Transportation Association of Canada
New Brunswick

**ABSTRACT**
In recent years, many City of Saskatoon (COS) roads have experienced premature failures and pavement distresses. High water tables, increased precipitation, and poor surface drainage have led to more moisture infiltration within road structures. Further deterioration of these aged pavements is due to heavy loadings year round in urban traffic. Significant increases in commercial truck loadings across the Saskatchewan road network have resulted in accelerated damage to the provincial highway system, as well as urban roads.

This paper quantifies the predicted strains and peak deflection in pavement structure layers due to different truck axle configurations. Single and tridem axle loads are examined across primary weight limits, on typical rural and urban cross sections. Typical rural and urban cross sections examined include dry and wet subgrades. Mechanistic primary response is predicted using a three dimensional non-linear orthotropic computational mechanics road model. Mechanistic analysis was used to model peak surface deflections and normal and shear strains within each pavement structure, for each load type and load spectra.

The results of this research showed that a tridem axle load induced higher peak strains within the pavement structure, compared to a single axle load. Modeling results showed urban pavement structures constructed on a wet subgrade performed poorly and had strains and high peak surface deflections, especially with tandem axle loads. When a truck load is applied on the pavement edge, the model revealed a significant increase in shear strains at the edge of the "clay-box" (urban) or side slope edge (rural). Both areas are subject to lower confinement and are therefore more susceptible to strain failure, which materializes in the field as edge and side slope failures. Further analysis of the "clay-box" effect revealed significant shear strains within the subgrade due to effects at the edge of the urban road structure

## INTRODUCTION

Typically, the pavement structure of Saskatchewan's roadways are constructed with a hot mix asphalt concrete (HMAC) surface, granular base layer, with or without a granular subbase layer placed as an integrated surfacing structure on the *in situ* subgrade. The pavement structure varies depending on location and use. For example, thicker structures may be used for roadways with heavier and frequent truck traffic. In Saskatchewan, rural and urban roads differ in the way they mitigate drainage. Rural roads are constructed with a drainage ditch and a sideslope. The sideslope, extending from the shoulder edge of the roadway, allows surface moisture to drain down the sideslope and into the ditch. Urban roads are constructed with curb and gutter. Urban road structural layers are surrounded by subgrade material. Rural roads have subgrade material at the bottom of the road structure, but the sides of the road structure are open to the sideslope.

This study investigates the primary deflections and strains in both rural and urban pavement structures, under two subgrade conditions and two types of axle loadings. A 3D non-linear orthotropic computational mechanics road model is used to analyze the behaviour of each structure type and case. The model used is PSIPave3D™.

### Background

Saskatchewan's economy is dependent on bulk commodity export including agriculture, livestock, oil, and mined mineral resources. Over the years, the shift from rail transportation to road transportation has increased truck traffic on Saskatchewan highways (*1,2*). Saskatchewan's economy predominantly depends on interprovincial and international trucking transportation, relying on Saskatchewan highways which are vital to the movement of goods.

Saskatchewan's urban and rural roadways were designed based on the Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures, using the Saskatchewan Highways modified CBR Shell Design Curves. The CBR Shell Curves determine hot mix asphalt concrete (HMAC), granular base, and subbase layer thicknesses based on the *in situ* CBR of the subgrade (*3*). Consequently, Saskatchewan road structural designs are highly dependent on subgrade type and subgrade condition (*4*). There are several limitations to this design method. The CBR Shell Curve method does not determine stresses and strains within the pavement structure. The design method relies heavily on subgrade type; pavement layer thicknesses are determined based on subgrade type (*4*). The design method uses CBR as the material property to assess the subgrade; the CBR test is an empirical test (*4*). The design method does not provide insight into the variance of pavement structural primary response depending on material type, field condition state, or frequency, type, or weight of loading (*4,5*).

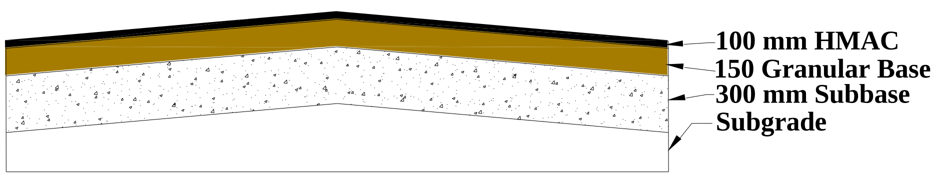
PSIPave3D™ is a finite element model that is encoded into a user-friendly software package created for routine and advanced road designs. It has been used in research and development studies to assess the primary response of urban pavement structure drainage systems, recycled pavement structures, and typical road designs. The deflection as well as 3D-strain behaviour 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 (*4,6*). For example, in a study comparing City of Saskatoon drainage layers, peak surface deflections measured in the field using a heavy weight deflectometer corresponded to deflections predicted using the model (*4*). The road model outputs not just 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.

## Objective

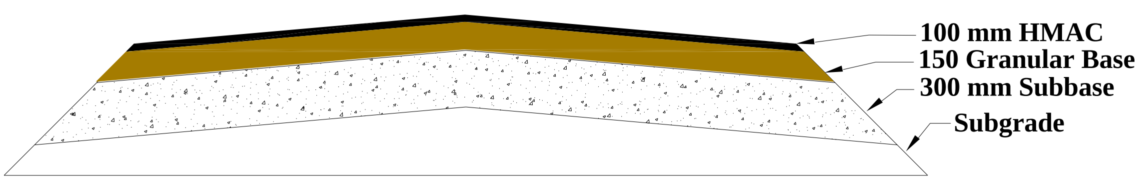
Although pavement deterioration over years of service is unpredictable, it is known to be primarily a factor of traffic loading, pavement structure thickness, material quality, and environmental and climatic conditions (*1*,*2*,*7*). The objective of this study was to examine the primary response of urban and rural roadways in varying subgrade condition states, under primary weight limits for single and tridem axle configurations. This objective was to be met using a 3D non-linear orthotropic computational mechanics road model capable of predicting primary deflections, strains, and stresses, within each pavement structure.

## SCOPE AND METHODOLOGY

Saskatchewan's roadways are constructed from flexible pavement structures typically comprised of a hot mix asphalt concrete (HMAC) surface, granular base layer, with or without a granular subbase layer placed as an integrated surfacing structure on the *in situ* subgrade. Although the pavement structure varies depending on location and use, for purposes of this study, one pavement structure is used for both rural and urban cross sections. Using the same cross section for both urban and rural cases allows for a direct comparison of the primary response of both cases. Figure 1 illustrates both the urban and rural cross sections.




**a) Urban cross section**




**b) Rural cross section**

**Figure 1 Cross sections used in this study**

For purposes of this study, one type of subgrade soil was examined, a silty-clayey sand, under two moisture conditions states, below optimum moisture condition, and above optimum moisture condition. For simplicity, the subgrade conditions states in this study are referred to as 'dry' and 'wet'. A dry subgrade is considered most favorable in the field. A wet subgrade is less favorable, as a wet subgrade can cause swelling on the subgrade, structural failures, and retains moisture.

This study examined the loading effects of a single axle and a tridem axle load with dual tires, both under primary weight limits for both urban and rural cross sections, under both wet and dry subgrade conditions. The single axle dual tire loads was 89 kN and the tridem axle load was 225 kN.

In addition to the above mentioned cases, the effect of edge loads was examined by placing the primary weight limit loads (single axle only) on the edge of the roadway surface for wet subgrade cases. The purpose of this case study was to examine the effects of heavy truck loads applied to the edge of both an urban and a rural cross section. Urban and rural cross sections are constructed differently, with one confined in a "clay box" area and the other with a side slope or a "free edge." Heavy loads on both types of pavement edges can significantly increase premature pavement failures. With the exception of the rural cross section side slope, the remaining geometric parameters were constant.

For the purposes of direct comparison between urban and rural cross sections, the same materials and cross section layer depths were used for each case study. This study limited truck load to primary weight limits applied through either a single or tridem axle. The only material property variation was in the subgrade moisture content, dry or wet.

**STUDY RESULTS**

Figure 2 illustrates the peak surface deflection modeled under primary weight limits for single and tridem axle loads, under dry and wet subgrade conditions, for both urban and rural pavement structures. The truck load is considered in the driving lane. When comparing single and tridem axles, the tridem axles have higher peak surface deflections compared to the single axles, under both dry and wet subgrade conditions, for both urban and rural cross sections.

When comparing wet and dry subgrade conditions, the peak surface deflection of pavement structures with a wet subgrade is greater than that on a dry subgrade. This is expected, as wet subgrade offers poorer performance. A wet subgrade occurs during spring thaw or excessive precipitation, during which the subgrade is at its weakest. There is little difference in peak surface deflection between the urban and rural cross sections, no matter what the subgrade condition is. For example, under a wet subgrade condition state, the urban and rural cross sections have model peak surface deflection of 1.18 mm and 1.22 mm for single axles, respectively. This is a difference of 0.04 mm, which may be considered minimal.

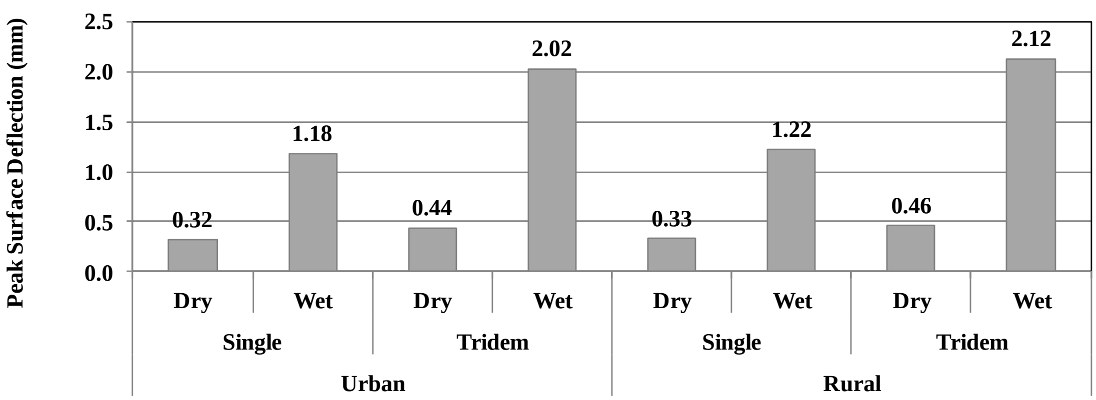



**Figure 2 Peak surface deflection (lane loading)**

The model is capable of determining the vertical compressive strain and the shear strain at the top of the subgrade layer. Figure 3 illustrates both peak vertical compressive and peak shear strain at the top of subgrade, for the urban and rural cases, under primary weight limits. The wet subgrade has significantly higher strains at the top of subgrade compared to the dry subgrade. This is no surprise – roadways are often more susceptible to structural failure due to poor subgrades during spring thaw, when road structures can be the wettest. The rural roadway had similar strains at the top of subgrade compared to the urban cross section, because when loads are applied at the lane, away from the edges, little difference should be observed if the structure and load magnitudes are the same.

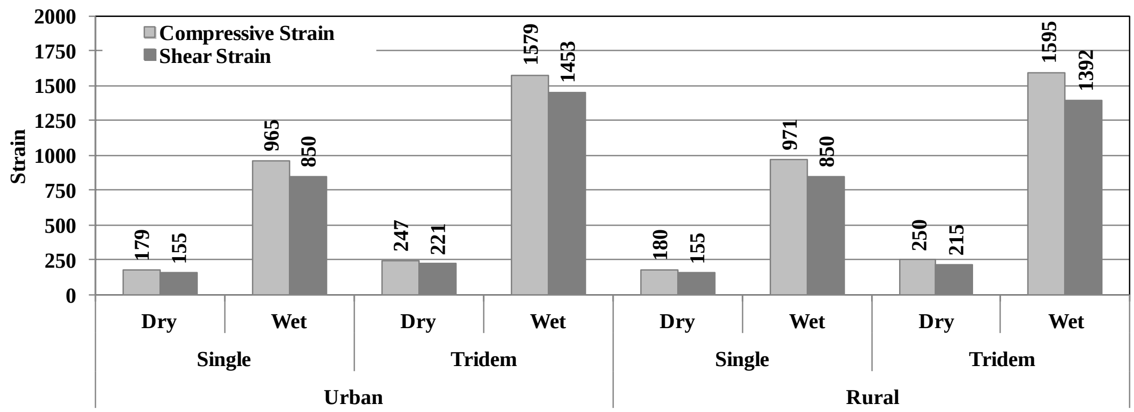



**Figure 3 Peak compressive and shear strain (lane loading)**

However, when comparing axle configurations, there is a significant difference in strain magnitudes. A tridem induces higher strains on the pavement – both vertical compressive and shear strain at the top of subgrade. It can also be observed that in a dry subgrade condition, there is an increase of 38% in vertical compressive strain at the top of subgrade and 43% in the shear strain component. Furthermore, in a wet subgrade scenario, these percentages increase by almost a factor of two. By applying a tridem load in a wet subgrade condition, vertical compressive strain increased by 64% when compared to a single axle load. The shear strain increased by 71%. These numbers are indicative of a non-linear relationship between load magnitude and subgrade material properties.

The model can also determine peak horizontal tensile strain and peak shear strain at the bottom of the HMAC layer, as illustrated in Figure 4. In this case, the urban and rural roadways had the same strain behaviour at the bottom of the HMAC layer, independent of the subgrade condition.
When comparing single and tridem axles, the tridem axle grouping resulted in smaller strains at the bottom of the HMAC layer, compared to single axles, at primary weight limits. This reduction in horizontal strain can be explained by the way the loads are distributed on a single versus tridem axle. A truck load of 89 kN is spread over 4 tires on a single axle, whereas 225 kN is carried by 12 tires in a tridem. If an equal load distribution is assumed for both cases, one tire in a single axle configuration carried 22.3 kN and one tire in a tridem configuration carried 18.8 kN or 16% less. This causes higher strains at the top of the pavement by the single axle; however, the higher overall load magnitude of a tridem has a greater impact on the subgrade.

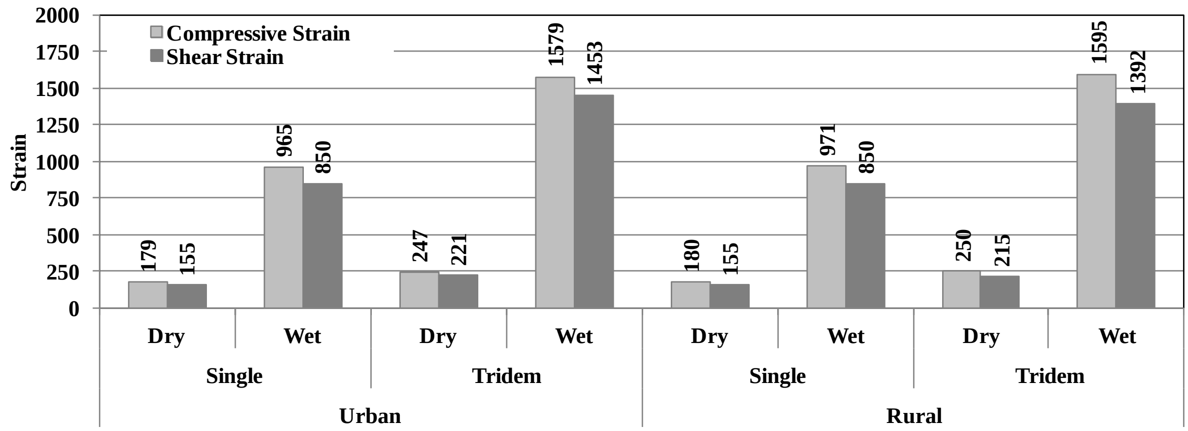
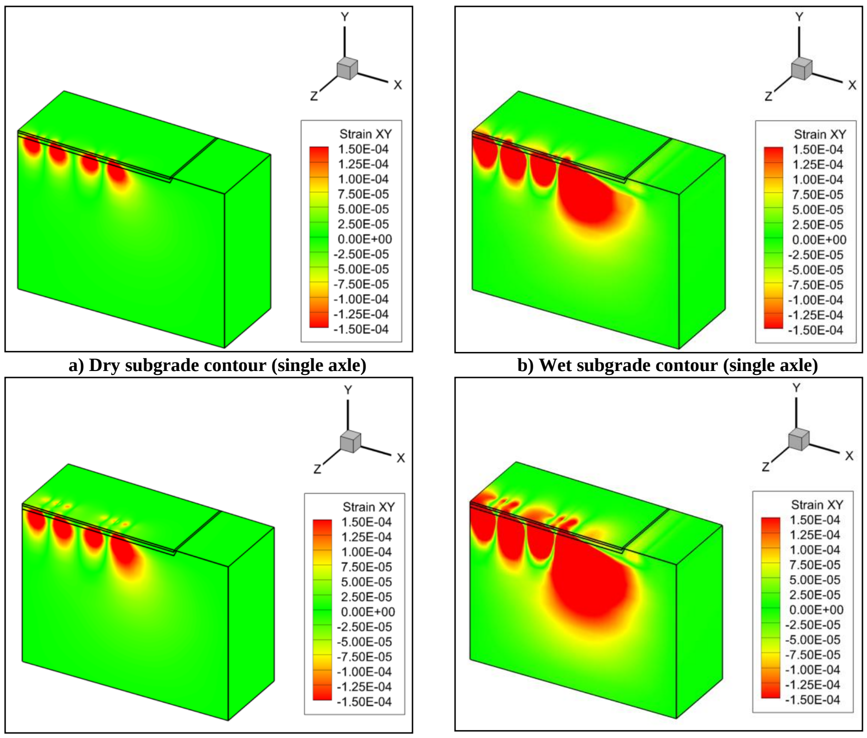



**Figure 4 Peak horizontal and shear strain (lane loading)**

Even though strains are higher in the HMAC, they are not reduced by a significant amount. In the worst case scenario of a wet subgrade, the horizontal strain is reduced by 26% and shear by 29%. This may lead to conclusions of tridem being more beneficial than single axles. However, for thin structures that are highly dependent on subgrade conditions, the benefits turn into more pavement damage. This is illustrated in Figure 3 by how tridem axles induce significantly higher strains at the top of subgrade than single axles.

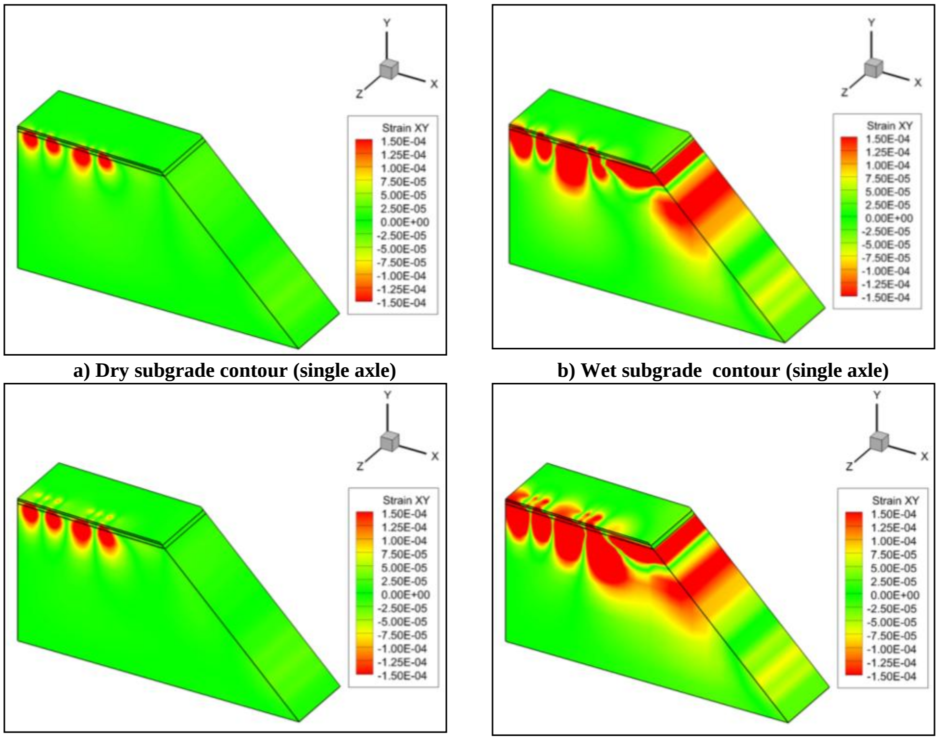
Figure 5 and Figure 6 illustrate the contour profiles of shear strain for both urban and rural cases, respectively.




a) Dry subgrade contour (single axle)
b) Wet subgrade contour (single axle)
c) Dry subgrade contour (tridem axle)
d) Wet subgrade contour (tridem axle)

**Figure 5 Shear strain contours (lane loading) – Urban Case**

These figures provide visual indices of the distribution of shear strains in the pavement structure. As seen in Figures 5 and 6, the shear strains are more severe in the wet subgrade conditions for both urban and rural conditions.




**a) Dry subgrade contour (single axle)** **b) Wet subgrade contour (single axle)**

**c) Dry subgrade contour (tridem axle)** **d) Wet subgrade contour (tridem axle)**

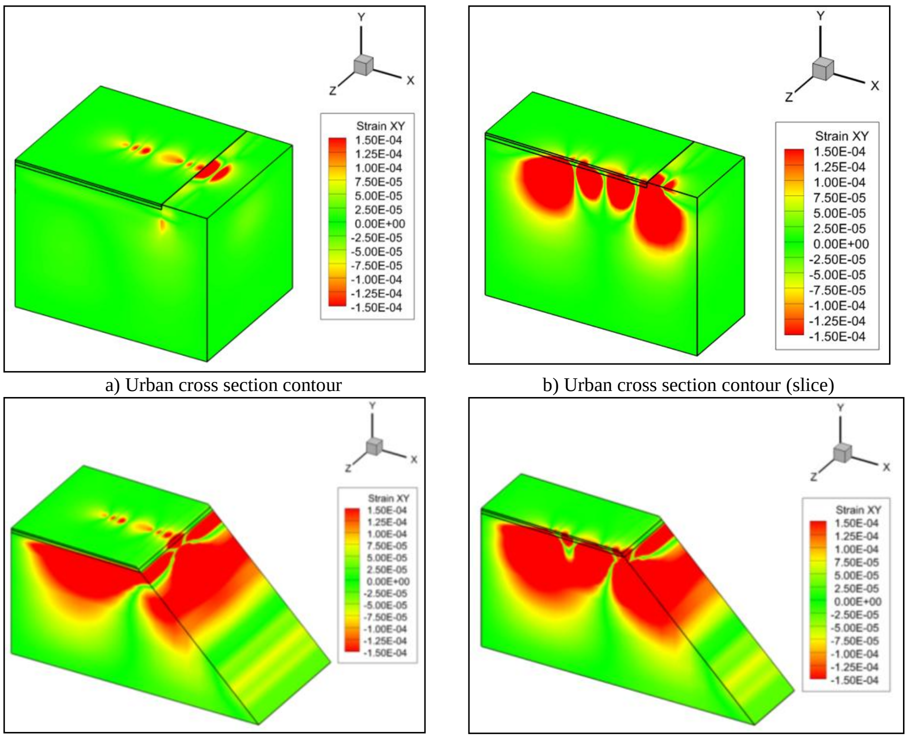
**Figure 6 Shear strain contours (lane loading) – Rural Case**

Urban and rural cross sections performed similarly because loads, geometry and material were assumed to be to be the same in both cases. Even though urban roads and rural highways are designed for different purposes, they may have structural similarities. Therefore, our model indicates that for similar design and regular truck load on the designed lanes, both cross sections behave similarly.

## CASE STUDY: URBAN VS. RURAL EDGE LOAD EFFECTS

One aspect of these simulations that is interesting, is the effect of edge loading. Even though strains observed on the side slope and clay box are not much higher than the ones observed in lane load, they may be considered too high for the location in which they occur. Urban roads can be considered to be constructed in a “clay box”, with clay subgrade below the road structure and surrounding the sides of the road structure. An urban “clay box” in often constructed with marginal subgrade material and can have a tendency, particularly when the subgrade material is highly plastic, to be susceptible to freeze-thaw and moisture issues, making it more susceptible to failure. These materials typically cannot sustain strains (both normal and shear) as high as the ones observed within this study. The same holds true for the side slope edge on the rural cross section. The strains observed might be higher than in a lane load case, but the edge is a free edge and prone to shear failures.

Figure 7 presents contour profiles of shear strain for both urban and rural cross sections with a wet subgrade. The contours on the right are slices of the road structures illustrated on the left. The loading is a single axle, loaded near the edge of the pavement structure; near the sidewalk for the urban cross section and on the shoulder for the rural cross section. The urban cross section show high shear strains in the wet subgrade, especially at the edge of the cross sections. This is because the subgrade surrounds an urban cross section and is present directly below the sidewalk. The rural cross section shows high shear strains in the wet subgrade. As seen in Figure 7 d), the shear strains are dissipated in the sideslope of the rural cross section.




a) Urban cross section contour

b) Urban cross section contour (slice)

c) Rural cross section contour

d) rural cross section contour (slice)

**Figure 7 Shear strain contours on wet subgrade (single axle edge loading)**

## CONCLUSIONS AND RECOMMENDATIONS

This paper quantified the predicted strains and peak deflection in pavement structure layers due to single and tridem axle loads across primary weight limits, on typical rural and urban cross sections. Typical rural and urban cross sections examined include dry and wet subgrades. Mechanistic primary response was predicted using a three dimensional non-linear orthotropic computational mechanics road model. Mechanistic analysis was used to model peak surface deflections and normal and shear strains within each pavement structure, for each load type and load spectra.

Tridem axles have the tendency to cause more damage to pavements, especially in Saskatchewan pavement conditions, where the structures are very subgrade dependent. When a tridem axle passes through a thin pavement structure, it can be seen that the subgrade still carries significant strain levels. These high strain levels cause two additional effects. First, subgrade materials are intrinsically weak, and experience strains higher than their failure limits, including both normal and shear limits. Second, high strain levels coupled with moisture conditions and freeze-thaw cycles make subgrades even more susceptible to premature failures. These scenarios are all common in Saskatchewan highways.

By adopting a mechanistic design approach like the one illustrated here, different scenarios and case studies can be evaluated, allowing the province or the City to make weight restrictions or axle restrictions based on current road conditions. These scenarios cannot be evaluated by CBR curves.

**REFERENCES**


1) Liu, A., Bell L., Stamatinos G. 2007. Provincial Highway Vehicle Weight Management Review and New Policy Development in Saskatchewan. Annual Conference of the Transportation Association of Canada. Saskatoon, SK.
2) Berthelot, C., Stuber, E., Podborochynski, D., Fair, J., Marjerison, B. 2008. Use of Non-Destructive Testing to Establish Mechanistic-Based Seasonal Load-Carrying Capacity of Thin-Paved Highways in Saskatchewan. Canadian Journal of Civil Engineering. Vol.35 No.7, pp.708-715.
3) Saskatchewan Ministry of Highways and Infrastructure (SMHI). (2009). *Surfacing Manual*. SMHI internal document, Saskatchewan.
4) Berthelot, C., Soares, R., Haichert, R., Podborochynski, D., Guenther, D., Kelln, R. 2012. Modeling the Structural Response of Urban Sub-Surface Drainage Systems. Presented at the Transportation Research Board 91st Annual Meeting. Washington, D.C.
5) AASHTO. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Structures*. Washington, D.C., 2002.
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) Thomas, L. 2008. Mechanistic-Empirical Equivalent Single Axle Loads for Urban Pavements. Masters of Science Thesis, Department of Civil Engineering, University of Saskatchewan. Saskatoon, SK.