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PREDICTED PAVEMENT DAMAGE FROM WIDEBASE STEERING TIRES

A METHODOLOGY TO ESTIMATE WIDEBASE STEERING TIRE LOAD EQUIVALENCY

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ABSTRACT:

Canadian regulators utilize the ESAL concept for vehicle impact evaluations and(or) pavement design. Unfortunately, TAC's ESAL equations do not account for tire size and, consequently, overestimate steering axle impacts when those axles are equipped with widebase steering tires. Many new vehicles proposed for use in Canada feature tridem-drive tractors and heavily loaded steering axles—these heavy loads necessitate the use of widebase steering tires. In order to optimize high efficiency truck configurations in Canada, therefore, accurate estimates of widebase steering tire ESALs are needed. This work describes a methodology to estimate ESALs for widebase steering tires. These ESAL equations were used to justify an increase in steering axle weights for B.C. 9-axle log B-trains.

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INTRODUCTION

The equivalent single axle load concept (ESAL) concept is utilized by various regulators, researchers, and designers to evaluate relative vehicle impacts to pavements and(or) to design pavements. This concept estimates the theoretical pavement damage from a truck with any configuration of axles in terms of number of passes by a single axle equipped with dual tires and loaded to 8181 kg (18,000 lbs). ESAL equations have been created for single axle-single tire axles, single axle-dual tire axles, tandem axle-dual tire axles, and tridem axle-dual tire groups. By applying the appropriate equation to each of a truck's axle groups, the ESAL equivalency for the entire truck can be estimated. The ESAL concept is by far the most widely accepted pavement concept in the world (TRB Circular E-C118).

ESALs are not transferable from one jurisdiction to another because climate, soils, pavements, and trucks can vary. Some Canadian provinces have their own way to calculate ESALs based on their structures, climates, and their preferred weighting of damage mechanisms. The Transportation Association of Canada (TAC, formerly RTAC) and the American Association of Highway Transportation Officials (AASHTO, formerly AASHO) have produced generalized formulae based on average highway conditions (AASHTO, 1993; TAC, 1991). The Canadian ESAL equations were developed through field testing of 14 Canadian pavements in the Heavy Vehicle Weights and Dimensions Study (RTAC, 1986).

A limitation of the ESAL concept is that the field testing was conducted with trucks equipped with conventional-sized tires and, therefore, the data do not support evaluations of pavement damage for unconventional tire sizes. Recently, this has become an issue because of the widespread use of widebase steering tires on Canadian heavy trucks with steering axle loads in excess of 5500 kg (e.g., trucks with tridem-drive axles which are required to carry 24%-27% of the drive group load on their steering axles). Use of TAC's single axle-single tire ESAL equation to estimate the equivalency of heavily loaded steering axles equipped with widebase tires overestimates their pavement impacts and may result in unfair or inaccurate vehicle evaluations.

This project was created to develop a methodology for accurately estimating ESALs for widebase steering tire sizes, and to develop single axle-single tire ESAL equations for the most popular Canadian widebase steering tires. Regulators and others may adopt the new ESAL equations for widebase steering tires or may calculate their own using the proposed methodology.

Forest industry proponents of a new log hauling truck configuration in B.C. requested that FPInnovations' work with the BC Ministry of Transportation and Infrastructure (TRAN) to incorporate the new ESAL equations into the government's methodology for assessing new vehicle pavement damage rates. The 9-axle tridem-drive log B-train was originally introduced in B.C. with a steering axle weight of 6900 kg because the truck failed to meet the pavement damage performance criteria with full, legal (7300 kg), steering axle weights. It was hoped that a more accurate assessment of steering axles equipped with widebase steering tires might result in a load increase to full steering axle weights. Apart from the increase in payload, it was expected that the use of full steering axle weights would result in improved steerability under low friction conditions and a reduction in out-of-compliance infractions due to steering axle overloads.

Objectives

The objectives of this project were:

1. Conduct a literature review to have a better understanding of the evolution of widebase tires and their various impacts according to research.
2. Develop a methodology to assess the equivalent single axle load values of widebase steering tires on flexible Canadian pavements.
3. Develop equations to estimate ESALs for popular Canadian sizes and loads of widebase steering tires.
4. Use the new methodology to assess the pavement impacts of B.C. 9-axle log B-trains.

BACKGROUND

Literature review

An extensive review of the literature (over 100 papers) was conducted in 2018 to summarize the state of knowledge about widebase single tires (Thiam, 2018). Select excerpts are included as supporting information in Appendix 1.

Historically, widebase tires have evolved considerably since their introduction in the early 1980s. Over the years, widebase tires have become increasingly wider, with larger contact areas, and better able to develop uniform contact pressures. These technological improvements have reduced the potential pavement damage (i.e., pavement cracking) of these tires.

It has been reported that widebase tires improve fuel efficiency, reduce emissions, increase payload, exhibit superior braking and comfort, and reduce tire repair, maintenance, and recycling costs (Ang-Olson and Schroeer, 2002; Al-Qadi and Elsefi, 2007). As for their impacts on pavements, most studies have focused on comparing them to dual-tire assemblies (i.e., few studies have looked at their use on steering axles). Although widebase single tires have been the subject of many studies to compare their potential pavement damage to that from regular dual-tire assemblies, almost no significant study was found analyzing widebase steering tires to conventionally sized steering tires.

Implementation

The trucking industry, of late, has been using widebase tires as an alternative to conventional dual-tire assemblies. This trend is anticipated to continue as more and more jurisdictions approve the use of widebase single tires at weights equivalent to that allowed for conventional dual-tire assemblies. Widebase single tires have been used successfully on trucks in Europe and Canada since the early 1980s. In 1997, around 65% of trailers and semi-trailers in Germany were equipped with widebase single tires (COST 334, 2001). Although current widebase tires are wider than earlier models and are legal in many countries, the market share of widebase tires does not exceed 5% of truck applications (Ang-Olson and Schroeer, 2002) in the USA and Canada. Moreover, most of the trucks using widebase single tires were found to be carrying lightweight commodities or were traveling empty (Bell et al., 1996). Although the use of the widebase single tires is expected to increase in the future, some government DOTs are still concerned about their impacts on infrastructure (Bonaquist, 1992; Ang-Olson and Schroeer, 2002).

Tire designation code

The nomenclature of tires includes three tire dimensions and the type of tire designated in the form of AAA/BBXCC.C. The first number (AAA) is the nominal or undeflected width from wall-to-wall in millimeters, the second number (BB) is the side wall height given as a percentage of the tire width, the letter (X) indicates the type of tire (e.g., R = radial), and the third number (CC.C) is the approved tire rim diameter, in inches. For example, a tire with designation 275/80R22.5 is a radial tire with a nominal width of 275 mm, a sidewall height of 220 mm (=275 mm x 80%), and a rim diameter of 22.5 in. The naming scheme is standardized and uniformly adopted among tire manufacturers.

ANALYSIS

General methodology

The methodology of the advanced pavement modeling consisted of estimating the long-term impacts of steering tires on 14 representative Provincial pavements, and then calibrating these impacts to the TAC single axle-single tire ESAL equation. This analysis started with estimating the spontaneous strain responses to various steering axle loads and tire sizes. Strains were estimated at key depths in the highway structures using WinJULEA, a multi-layer, linear elastic software based on the Burmister theory. The Burmister theory is an extension to multilayer systems of Boussinesq's theory on linearity and elasticity of homogeneous structures. The Burmister model is mainly characterized by flexible pavement responses to external loadings. WinJULEA was developed at the Geotechnical and Structural Laboratory of the US Army Corps of Engineers' Engineering Research and Development Center. WinJULEA is a widely known and used software in the pavement engineering community. It has been chosen in this study because it is user friendly and it allows modeling multiple layer pavement structures (up to 100 layers) unlike most known pavement models (ElSym5, KenPave, etc.) which have a limited number of layers for the pavement structure.

The input data needed to perform the analysis of steering axle impacts were:

- Pavement material mechanical properties (resilient modulus and Poisson's ratio);
- Pavement material layer thicknesses; and,
- Tire size, tire load, and the resulting tire contact area.

These input data are defined in Table 1, Table 2, and Table 3 and Figure 1, respectively. In addition to these, the location coordinates for reporting maximum strain must be defined. Two evaluation locations were specified for the analysis:

1. under the tire centre in the HMA mat near its interface with the granular base course.
2. under the tire centre at the top of the subgrade.

Two strain responses found in these locations in a flexible pavement can be used to predict long-term pavement performance. They are:

1. horizontal tensile strain at the bottom of the HMA mat.
2. vertical compressive strain at the top of the subgrade layer.

These two key strains were calculated for all 896 combinations of pavement structure, tire size, and tire load.

The long-term damage analysis was performed using the Asphalt Institute's strain-based transform equations (Yuan 2004), and focused on the two most common, traffic-related, failure modes for Canadian pavements:

Asphalt Institute's surface rutting equation is:

$$N_R = 1.365 * 10^{-9} * \varepsilon_v^{-4.477} \quad (1)$$

Where,
N_R = number of passes to cause a 0.5 inch (12.5 mm) -deep surface rut
ε_V = vertical compressive strain at the top of the subgrade

Asphalt Institute's bottom-up fatigue cracking equation is:

$$N_F = 18.4 * 0.004325 * k_{F1} * |\varepsilon|^{-3.291} * E^{-0.854} \quad (2)$$

Where,

N_F = number of passes to cause alligator cracking over 10% of the wheel lanes
ε = horizontal tensile strain at the bottom of the HMA mat
E = resilient modulus of the asphaltic concrete (psi)

$$k_{F1} = 10^{\left(4.84*\left(\frac{Vbeff}{Vv+Vbeff}-0.69\right)\right)} = 1.0 \quad (3)$$

V_{beff} = effective bitumen content (estimated to be 11% for this analysis)
V_v = voids content (estimated to be 5% for this analysis)

The pavement damage rates are calculated using Miner's law (i.e., n/N_R and n/N_C). The pavement's governing mode of failure corresponds to smallest number of passes predicted to generate a failed condition (i.e., the lesser of N_R or N_C).

The long-term damage rate results for the 14 representative Provincial pavements tested in the RTAC-86 study were calculated, and then the governing failure mode and its associated damage rate were identified. These governing damage rates then were normalized to general damage rates for a representative Canadian flexible pavement by averaging the 14 Provincial damage rates, for each combination of tire load and size. This approach is identical to that used in the RTAC-86 study.

Estimates of equivalent single axle load (ESAL) for each tire size were calibrated to the RTAC-86 ESAL estimate for a 11R22.5 tire with a 2750 kg loading and 690 kPa cold inflation. This calibration was done my multiplying the predicted number of subject tire passes to failure (for a given load, and 690 kPa inflation) by the ratio of the TAC ESALs (0.69 ESALs at 2750 kg, 690 kPa) divided by the predicted number of 11R22.5 tire passes to failure (at 2750 kg, 690 kPa). Equation 4 illustrates the calibration calculation used to estimate the ESAL value for a subject tire size with a tire load of P and cold inflation of 690 kPa (100 psi):

$$ESALs = Passes\ to\ failure\ by\ subject\ tire\ (load\ P\ \&\ 690\ kPa) x \frac{0.69\ ESALs}{Passes\ to\ failure\ by\ 11R22.5\ tire\ (2750\ kg\ \&\ 690\ kPa)} \quad (4)$$

ESAL equations were developed for each size tire with a least-squares regression of ESAL values calculated for nine discrete tire loads ranging from 2000 kg to 5000 kg. The best fit was found to occur with a power form of equation.

Pavement structures

Two material properties are utilized for calculating pavement performance with layered elastic models—resilient modulus and Poisson's ratio. Values for these parameters were taken to be the same as specified in RTAC-86 (Table 1).

Table 1. RTAC-86 material properties considered in this analysis

Material	Resilient modulus (MPa)	Poisson's ratio	Comment
Hot mix asphalt	2200	0.35	all types
Granular base course	150	0.35	all types
Granular subbase course	100	0.35	all types
Subgrade	70	0.40	silty sand, gravelly clay, granitic gravel
Subgrade (Clay)	40	0.40	Clay

Pavement layer thickness is another key parameter used for modeling pavement performance with layered elastic models. Table 2 summarizes the layer thicknesses and material types found in each of the 14 RTAC-86 test pavements. RTAC-86 based its ESAL derivations on field measurements gathered at these 14 test pavements. In order to build on the RTAC-86 results, the performance of these same 14 pavements were modeled.

Table 2. RTAC-86 test pavement structures considered in the analysis

Pavement structure	HMA mat (mm)	Granular base course (mm)		Granular subbase course (mm)		Subgrade material
NB	225	76	Crushed rock	460	Crushed stone	Silty sand
NS	160	275	Granular	200	Granular	Gravelly clay
QC 1	135	200	Crushed limestone	625	Granitic sand	Granitic gravel
QC 2	130	375	Crushed limestone	450	Granitic sand	Granitic gravel
QC 3	56	150	Granitic gneiss	450	Granitic sand	Clay
QC 4	56	200	Granitic gneiss	550	Granitic sand	Clay
ON 1	110	150	Granular A	350	Granular C	Silty sand
ON 2	170	200	Granular A	250	Granular B	Sand
ON 3	190	300	Granular A	90	Old road	Clay
AB 1	136	170	2-20 Gravel	-	-	Clay
AB 2	136	250	2-20 Gravel	-	-	Clay
BC 1	75	200	Granular	610	Granular crushed rock	Silty sand
BC 2	85	210	Granular	610	Silty gravel	Silty sand
BC 3	100	454	Granular	50	Mixed clay and sand	Clay

The same HMA, granular base, and granular subbase stiffnesses (resilient moduli) and Poisson's ratio values were specified for all structures and, as a result, modeled strain differences were largely attributable to layer thickness differences and to subgrade modulus. The thinnest, weakest, pavements were the Alberta structures (AB 1, AB 2) and one Quebec structure (QC 3). The New Brunswick structure (NB) and two Ontario structures (ON 2, ON 3) were the thickest, strongest pavements.

Steering tires

Steering tires were evaluated over a range of loads corresponding to maximum legal axle limits used by various Provinces across Canada. Lighter tire loads also were evaluated in order to improve the accuracy of the least-squares regression equations for ESALs. All tires were evaluated at all loads regardless of whether the loading exceeded the manufacturer's maximum load rating shown in Table 3.

Tire (gross) contact area is the total footprint area of a tire (including the spaces between tread blocks) and is an important consideration for modeling tire-pavement interaction. In practice, contact area varies with numerous factors, including tire size, load, inflation, carcass design, wheel width, tread pattern, and tread wear; however, it can be approximated using a general formula (equation 5) that is based only upon tire load, cold tire inflation, and tire volume (Tire & Rim Association, 2009):

$$Contact\ Area\ (in^2) = 39.8 - (Inflation \times 0.315) + (Load \times 0.00887) + (Volume \times 0.000938) \quad (5)$$

Where:

Inflation = cold tire inflation (psi)

Load = tire load (kips)

and $Tire\ Volume\ (in^3) = (H + D_r)\ x\ S\ x\ H$ (6)

The design tire dimensions used to estimate tire volume are defined in Appendix 2. These values are listed in (Tire & Rim Association, 2009) for conventional tire sizes. Volumes of metric tire sizes with aspect ratios (e.g., 315/80R22.5) were estimated using (BND TechSource Tire Calculator), and the resulting contact area estimates verified by comparing with values derived using (Tire & Rim Association, 2009) dimensions. Good agreement (0% - 3% difference) was found between the contact area estimates derived using the two methods (Appendix 2).

Table 3. Design tire dimensions used to estimate tire contact area

Tire size	Design section height (H) (inch)	Rim diameter code (D_r) (inch)	Design new tire section width on design rim width (S) (inch)
295/60R22.5	7.0	22.5	11.6
11R22.5	9.49	22.5	11.0
11R24.5	9.49	24.5	11.0
315/80R22.5	9.9	22.5	12.4
385/65R22.5	9.9	22.5	15.2
455/55R22.5	9.9	22.5	17.9
425/65R22.5	10.9	22.5	16.7
445/65R22.5	11.4	22.5	17.5

Table 4 summarizes the steering tires considered in this analysis. These tires were identified as the most popular sizes of widebase single tires used in steering axle positions and were selected in consultation with TRAN.

Table 4. Popular North American truck steering tire sizes considered in the analysis

Tire size	Estimated contact area at 2750 kg load (mm^2) *	Maximum axle load capacity (kg) *	Comment
295/60R22.5	43743	5430	Not popular for forestry
11R22.5	46325	5400	Typical on eastern Canadian log trucks and on-highway trucks
315/80R22.5	46553	6520	Not popular for forestry
11R24.5	46722	5780	Typical on western Canadian log trucks
385/65R22.5	47986	7480	Common on tridem-drive log trucks
455/55R22.5	49482	8560	Not popular for forestry
425/65R22.5	50161	8880	Common on tridem-drive log trucks
445/65R22.5	51373	9640	Used on tridem-drive log hauling trucks

* at a cold inflation pressure of 690 kPa (100 psi)

Figure 1 presents the estimated contact areas generated for each steering tire size over the range of tire loading at a cold inflation of 690 kPa (100 psi). All strain evaluations were conducted assuming a cold tire inflation pressure of 690 kPa because this reflects typical industry practice and was the standard used for the RTAC-86 study also.

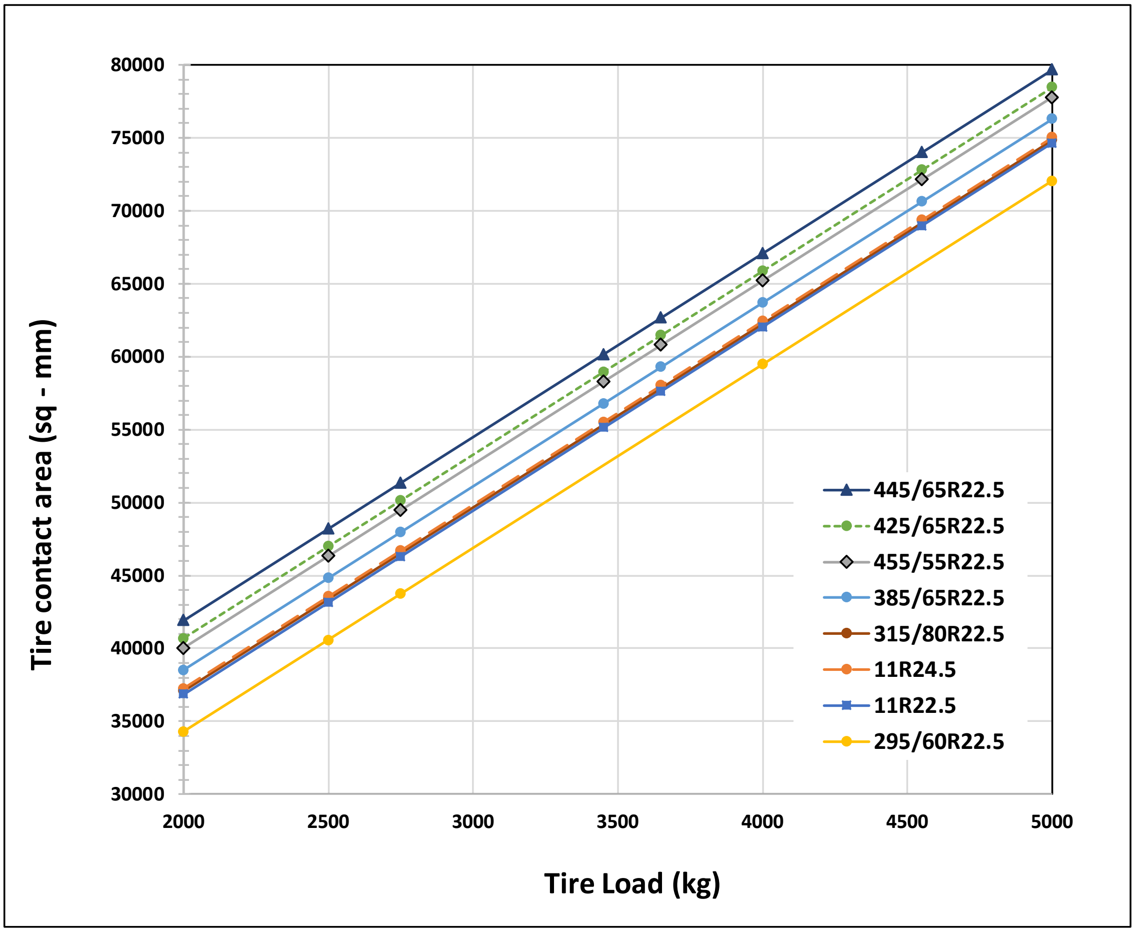

Figure 1. Tire contact area vs tire load for 8 truck steering tire sizes inflated to 690 kPa.

The Tire & Rim Association estimates tire contact area as a function of tire inflation, tire load, and tire volume, and Figure 1 illustrates the resulting linear relation for tire contact area described by Equation 5. The slopes of the tire contact lines are the same for all tire sizes because tire volume is the only variable to change with tire size (inflation pressure is held constant as discussed). The tire volumes of the subject steering tires vary in the order shown in the legend of Figure 1, with 445/65R22.5 tires having the largest volume and 295/60R22.5 having the smallest volume. The height of metric tire sizes is calculated with the tire's aspect ratio (e.g., the height of a 455/55R22.5 tire = 250 mm = 455 mm x 55%). Although 455/55R22.5 tires have the largest width (455 mm), their height is smaller than that of the 425/65R22.5 and 445/65R22.5 tires, and this makes for a smaller tire volume.

As can be seen, the widebase steering tires have considerably larger contact areas than the 11R22.5 tire. The difference in contact area varies from 1661 mm^2 (385/65R22.5 tires) to 5048 mm^2 (445/65R22.5 tires).

Modeling & analyses

The use of WinJULEA to estimate instantaneous pavement responses to widebase tire loading was validated by comparing strain predictions from WinJULEA with values estimated using the ICT WIDE tool (Al-Qadi et al., 2014). This comparison is described in the validation section of the report.

A sensitivity analysis was undertaken with the representative New Brunswick pavement to identify general trends related to tire size, load, and inflation pressure, and pavement structure. This sensitivity analysis compared damage rates for various tire sizes and tire loads when the structure's asphaltic concrete mat or granular base course layers were thickened or thinned by 50 mm. This analysis assessed how modeled pavement impacts varied relative to structure differences and informed the rationale for normalization of the results from all 14 representative Provincial pavements.

The key instantaneous strains were calculated for eight tire sizes and eight tire loads for each of the 14 representative Provincial pavements specified in RTAC-86, for a total of 896 distinct combinations. For each combination, long-term rutting and cracking damage rates were calculated, and then the governing failure mode and its associated damage rate were identified. The damage rates from the 14 pavement structures were averaged, for each tire size and load, to create general damage rates for Canadian pavements. Estimates of equivalent single axle load (ESAL) for each tire size were calibrated to the TAC single axle-single tire ESAL value for a 11R22.5 tire with a 2750 kg loading and 690 kPa cold inflation.

ESAL equations were developed for each tire size by doing a least squares regression of the ESALs for each discrete tire load (2000 kg, 2500 kg, 2750 kg, 3450 kg, 3650 kg, 4000 kg, 4550 kg, and 5500 kg). A backward stepwise multiple regression analysis was used to identify the significant variables to use for predicting ESALs. A standard form of the ESAL equation was determined [$ESAL = a + b(Load) + c(Load)^2 + d(1/Load)$], and then the coefficients for each tire size were derived using Excel's regression analysis.

An evaluation of pavement impacts for a tridem-drive 9-axle B-train was undertaken using TAC ESAL equations and then using a combination of the new widebase ESAL estimates and TAC ESAL equations for non-steering axles. In both cases, the results were compared to results for a reference vehicle, to see whether the 9-axle B-train generated at least 5% less pavement impact than the reference vehicle.

RESULTS

Validation of WinJULEA

ICT WIDE is a specialized software program developed in an FHWA study by the University of Illinois, in collaboration with New Brunswick Transportation and Infrastructure. ICT WIDE is modeled on pavement responses from 445/50R22.5 and 455/55R22.5 widebase single tires. Its limited number of tire sizes precluded the use of the ICT WIDE software for this project's ESAL assessments; however, it was useful for validating the use of WinJULEA software to predict pavement responses to tires larger than conventional steering tire sizes (i.e., 11R22.5 and 11R24.5). Table 5 summarizes the comparison of horizontal tensile strain values from WinJULEA and ICT WIDE for a 455/55R22.5 tire at a 2750 kg load and a 690 kPa cold inflation.

Table 5. Comparison of bottom-up fatigue cracking strains predicted by WinJULEA and ICT WIDE

Pavement	Maximum tensile strain at bottom of AC mat 455/55R22.5 *		
	WinJULEA	ICT WIDE	Difference
NB	1.40E-04	1.28E-04	9%
NS	2.10E-04	1.97E-04	6%
QC 1	2.55E-04	2.46E-04	4%
QC 2	2.59E-04	2.48E-04	4%
QC 3	4.52E-04	4.28E-04	5%
QC 4	4.44E-04	4.41E-04	1%
ON 1	3.16E-04	2.93E-04	7%
ON 2	1.98E-04	1.87E-04	6%
ON 3	1.76E-04	1.71E-04	3%
AB 1	2.85E-04	2.69E-04	6%
AB 2	2.69E-04	2.55E-04	5%
BC 1	4.06E-04	4.01E-04	1%
BC 2	3.77E-04	3.71E-04	2%
BC 3	3.30E-04	3.21E-04	3%
Average			4%

* tire load of 2750 kg and cold inflation of 690 kPa

As can be seen, WinJULEA and ICT WIDE predictions of tensile AC mat strain closely agreed for all 14 different pavement structures. WinJULEA predicted strains were, on average, 4% higher than those from ICT WIDE, and never more than 9%. Based on this close agreement, it was judged that WinJULEA could accurately, albeit slightly conservatively, estimate pavement strains for widebase steering tires.

Modeled instantaneous pavement responses

Using WinJULEA, the maximum horizontal tensile strain at the bottom of the HMA mat and the maximum vertical compressive strain at the top of the subgrade were predicted for all combinations of pavement structure, tire size, and tire load. Table 6 presents the modeled strain results arranged from top to bottom in the order of increasing horizontal tensile strain in the HMA mat. Table 7 presents the modeled strain results arranged from top to bottom in the order of increasing vertical compressive subgrade strain.

Table 6. Summary of predicted bottom-up fatigue cracking strains in 14 pavement structures *

Pavement structure	HMA mat thickness (mm)	Maximum horizontal tensile asphalt strain	Aggregate thickness (mm)		Subgrade modulus (MPa)	Maximum vertical compressive subgrade strain
			Granular base	Granular subbase		
NB	225	1.42E-04	76	460	70	1.40E-04
ON3	190	1.79E-04	300	90	40	3.04E-04
ON2	170	2.02E-04	200	250	70	2.18E-04
NS	160	2.15E-04	275	200	70	2.18E-04
QC1	135	2.62E-04	200	625	70	1.26E-04
QC2	130	2.67E-04	375	450	70	1.26E-04
AB2	136	2.76E-04	250	-	40	6.14E-04
AB1	136	2.92E-04	170	-	40	7.95E-04
ON1	110	3.27E-04	150	350	70	2.79E-04
BC3	100	3.42E-04	454	50	40	3.88E-04
BC2	85	3.93E-04	210	610	70	1.55E-04
BC1	75	4.25E-04	200	610	70	1.64E-04
QC4	56	4.69E-04	200	550	40	2.79E-04
QC3	56	4.77E-04	150	450	40	4.09E-04

* 11R22.5 tires loaded to 2750 kg, and cold inflation of 690 kPa

As anticipated, the horizontal tensile strains were directly correlated to the thickness of the HMA mat. Those structures with the thickest HMA mats had, for the given loading condition, the smallest strains and vice versa.

As anticipated, the subgrade rutting strains were predominantly correlated to total aggregate thickness and subgrade modulus. Asphalt thickness also played a minor role. As can be seen, QC1, which had the smallest subgrade strain, also had the greatest total aggregate depth (825 mm) and a high subgrade modulus. An exception to this pattern for subgrade strains was the ON3 structure which, because of its thick HMA mat, performed more strongly than indicated by its total aggregate thickness.

The predictable and logical patterns of strains observed with the 14 Provincial structures provided modellers good confidence in the WinJULEA predictions.

Table 7. Summary of predicted rutting strains in 14 pavement structures *

Pavement structure	HMA mat thickness (mm)	Maximum horizontal tensile asphalt strain	Aggregate thickness (mm)			Subgrade modulus (MPa)	Maximum vertical compressive subgrade strain
			Granular base	Granular subbase	Total		
QC1	135	2.62E-04	200	625	825	70	1.26E-04
QC2	130	2.67E-04	375	450	825	70	1.26E-04
NB	225	1.42E-04	76	460	536	70	1.40E-04
BC2	85	3.93E-04	210	610	820	70	1.55E-04
BC1	75	4.25E-04	200	610	810	70	1.64E-04
ON2	170	2.02E-04	200	250	450	70	2.18E-04
NS	160	2.15E-04	275	200	475	70	2.18E-04
ON1	110	3.27E-04	150	350	500	70	2.79E-04
QC4	56	4.69E-04	200	550	750	40	2.79E-04
ON3	190	1.79E-04	300	90	390	40	3.04E-04
BC3	100	3.42E-04	454	50	504	40	3.88E-04
QC3	56	4.77E-04	150	450	600	40	4.09E-04
AB2	136	2.76E-04	250	-	250	40	6.14E-04
AB1	136	2.92E-04	170	-	170	40	7.95E-04

* 11R22.5 tires loaded to 2750 kg, and cold inflation of 690 kPa

Long-term pavement damage estimates

The fatigue-cracking strains and the rutting strains were transformed using the Asphalt Institute equations (equations 1 and 2) to estimate long-term pavement damage from the steering axle wheels. The smaller of the two estimates of passes to failure (service life) was taken to be the governing failure mode because it would, theoretically, happen first. Table 8 presents the long-term damage predictions for two representative tire sizes; the long-term damage predictions for the pavements are listed from top to bottom in the order of decreasing predicted service life. These values were normalized and used to represent a typical Canadian flexible pavement's average service life with which to calculate ESALs.

Table 8. Pavement life comparison of 14 pavements for a conventional and a widebase steering tire *

Pavement	11R22.5 steering tire		385/65R22.5 steering tire	
	Predicted passes to a failed condition	Governing failure mode	Predicted passes to a failed condition	Governing failure mode
NB	7,294,436	Fatigue cracking (bottom up)	7,479,970	Fatigue cracking (bottom up)
ON3	3,413,308	Fatigue cracking (bottom up)	3,522,906	Fatigue cracking (bottom up)
ON2	2,276,618	Fatigue cracking (bottom up)	2,305,363	Fatigue cracking (bottom up)
NS	1,859,907	Fatigue cracking (bottom up)	1,939,730	Fatigue cracking (bottom up)
QC1	969,437	Fatigue cracking (bottom up)	1,019,470	Fatigue cracking (bottom up)
QC2	914,171	Fatigue cracking (bottom up)	964,104	Fatigue cracking (bottom up)
ON1	450,508	Fatigue cracking (bottom up)	499,539	Fatigue cracking (bottom up)
BC3	403,398	Fatigue cracking (bottom up)	430,805	Fatigue cracking (bottom up)
AB2	327,730	Rutting	330,808	Rutting
BC2	256,880	Fatigue cracking (bottom up)	276,371	Fatigue cracking (bottom up)
BC1	198,222	Fatigue cracking (bottom up)	214,658	Fatigue cracking (bottom up)
QC4	143,339	Fatigue cracking (bottom up)	157,374	Fatigue cracking (bottom up)
QC3	135,277	Fatigue cracking (bottom up)	148,329	Fatigue cracking (bottom up)
AB1	102,684	Rutting	104,071	Rutting
Average	1,338,994		1,385,250	

* tire load of 2750 kg and cold tire inflation of 690 kPa

As anticipated, the long-term damage predictions were correlated with HMA mat thickness because, for all but two structures, the governing failure mode was bottom up fatigue cracking. As can be seen, the order of passes to failure was very similar to that shown in Table 6.

The results are given for both a conventionally sized steering tire and a widebase steering tire size. The widebase tire results were, on average, 3.5% more than for the conventional tire; however, the difference varied from 0.9% to 10.9%. The use of a widebase steering tire made little difference to pavement service life for those pavements governed by rutting failure (the benefit of a larger tire contact area has little affect on subgrade strains). The strongest pavements (NB, ON3, ON2) also showed little improvement (1.3% - 3.2%) from the use of a widebase tire size.

Sensitivity analysis of pavement structure differences

The sensitivity analysis compared pavement responses to various tire sizes and loads in stronger and weaker variants of the NB pavement structure. Referring to Table 2, the NB structure had a hot mix asphalt mat thickness of 225 mm, a 76 mm-thick granular base course, a 460 mm-thick subbase course, and a silty sand subgrade. Four variants were created from the NB structure by changing the HMA mat and base course thickness by ±50 mm. Table 9 summarizes the results of the sensitivity analysis.

Table 9. Sensitivity of relative impacts to pavement structure variation

Tire size	Axle Load (kg)	Damage rate					Change in reference structure damage rate			
		NB structure	+50 mm HMA	-50 mm HMA	+ 50 mm Base	-50 mm Base	+50 mm HMA	-50 mm HMA	+ 50 mm Base	-50 mm Base
11R22.5 (RTAC)	5500	1.4E-07	1.1E-08	3.0E-07	1.3E-07	1.5E-07	-92%	122%	-6%	10%
11R22.5	5500	1.4E-07	1.1E-08	3.1E-07	1.3E-07	1.5E-07	-92%	121%	-6%	10%
11R24.5	5500	1.4E-07	1.1E-08	3.0E-07	1.3E-07	1.5E-07	-92%	122%	-6%	11%
295/60R22.5	5500	1.4E-07	1.1E-08	3.2E-07	1.4E-07	1.6E-07	-92%	120%	-6%	10%
315/80R22.5	5500	1.4E-07	1.1E-08	3.0E-07	1.3E-07	1.5E-07	-92%	122%	-6%	10%
385/65R22.5	5500	1.3E-07	1.0E-08	3.0E-07	1.3E-07	1.5E-07	-92%	122%	-6%	11%
	6900	2.5E-07	2.0E-08	5.6E-07	2.3E-07	2.7E-07	-92%	126%	-6%	11%
	7300	2.9E-07	2.3E-08	6.5E-07	2.7E-07	3.2E-07	-92%	127%	-6%	11%
425/65R22.5	5500	1.3E-07	1.0E-08	2.9E-07	1.2E-07	1.4E-07	-92%	123%	-6%	11%
	6900	2.4E-07	1.9E-08	5.4E-07	2.3E-07	2.7E-07	-92%	126%	-6%	11%
	7300	2.8E-07	2.2E-08	6.4E-07	2.6E-07	3.1E-07	-92%	127%	-6%	11%
Average for 5500 kg load							-92%	122%	-6%	10%

The governing failure mode for the NB pavement structure under all tire sizes and tire loads was bottom up fatigue cracking—this did not change with any of the structural changes. As anticipated, strains and resulting damage rates grew smaller as tire size increased. A 50 mm increase in the HMA mat thickness generated a 92% reduction in all damage rates. Conversely, a 50 mm decrease in HMA mat thickness resulted in a 122% increase in all damage rates for 5500 kg axle loads and slightly greater increases for higher axle loads. Given that fatigue cracking was the governing failure mode it was not surprising that largest changes in damage rate occurred with changes in HMA mat thickness. Increasing the base course thickness resulted in a 6% reduction in all damage rates while decreasing the granular base course thickness by 50 mm resulted in a 11% increase in all damage rates.

The consistency of relative results between the weaker and stronger structures above supports the conclusion that the 14 Provincial structures also can be expected to reflect similar relative responses to variations in tire size and load. This supports the conclusion that the damage rates from all 14 pavement structures can be normalized (averaged) and represented by a single general damage rate.

Validation of modeled ESAL values

The proposed methodology for deriving ESAL values was validated by comparing results for conventionally sized tires (11R22.5) with ESALs derived using two well accepted methods: the TAC single axle-single tire ESAL equation and the AASHTO Table D.4. of ESAL values for flexible pavements, single axles and terminal serviceability (P_T) of 2.5 (AASHTO, 1993). Close agreement with the TAC equation was anticipated because the TAC method was derived from field testing with steering axles equipped with 11R22.5 tires. Conversely, poorer agreement with the AASHTO ESAL values was anticipated because the AASHTO values were derived from field testing by trucks equipped with 10.00-22.5 bias ply tires (i.e., less damaging than radial tires) and the ESAL values are applicable to single axles equipped with either single- or dual-tire assemblies (dual-tired assemblies are less damaging than single tires). Figure 2 illustrates the comparison of ESAL values derived by the three methods.

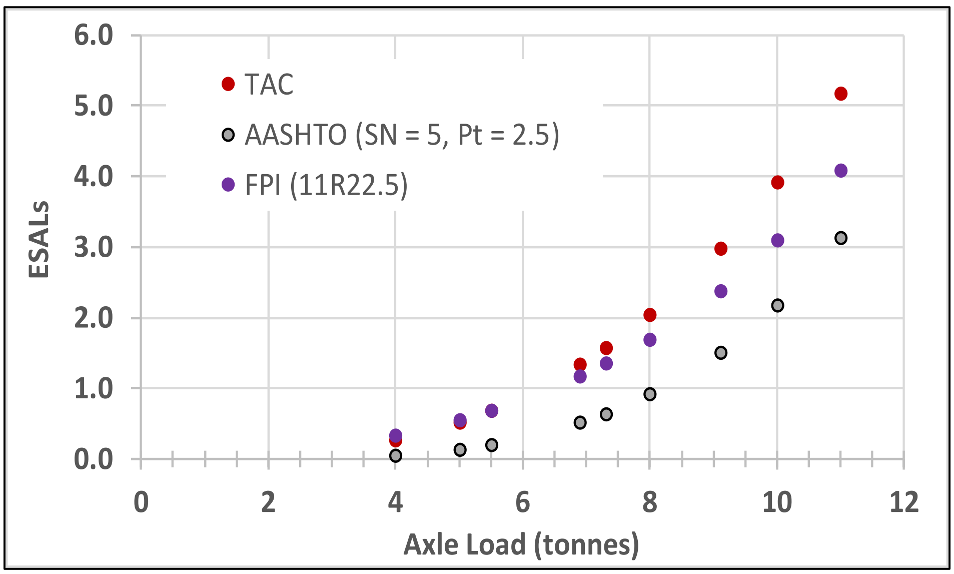

Figure 2. Comparison of three methods to estimate single axle-single tire ESALs.

In general, the values and trend agreed with both well accepted ESAL calculation methods. Very close agreement was observed between the TAC ESAL single axle-single tire equation, especially for the range of loads up to the manufacturer-specified load limit of these tires (5400 kg axle load). As expected, the ESAL values derived using the proposed methodology were higher than the AASHTO values.

ESAL values for various steering tires

Using the proposed methodology ESAL values for discrete axle loads (tire loads) were calculated for all eight tire sizes (Table 10). The values followed consistent and expected trends of ESAL value increasing with axle load and decreasing with increasing tire size. The metric size tires 295/60R22.5 and 315/80R22.5 were included for completeness but these were of less significance to the project and so fewer discrete loads were included in their analyses.

Table 10. Estimated equivalent single axle loads for various steering tire sizes and loads

Tire size	Equivalent Single Axle Loads								
	Axle load (tonnes)								
	4.0	5.0	5.5	6.9	7.3	8.0	9.1	10.0	11.0
295/60R22.5	0.37	0.61	0.75			1.80		3.23	
11R22.5	0.33	0.55	0.68	1.18	1.35	1.70	2.38	3.10	4.09
315/80R22.5	0.33	0.55	0.69			1.69		3.09	
11R24.5	0.32	0.55	0.68	1.15	1.34	1.68	2.36	3.08	4.07
385/65R22.5	0.31	0.53	0.66	1.13	1.30	1.63	2.31	3.02	4.01
455/55R22.5	0.29	0.49	0.63	1.09	1.25	1.58	2.25	2.95	3.93
425/65R22.5	0.28	0.49	0.61	1.07	1.24	1.56	2.22	2.92	3.90
445/65R22.5	0.27	0.47	0.59	1.04	1.20	1.52	2.18	2.87	3.84

ESAL equations for various steering tires

A backwards stepwise multiple regression analysis resulted in a consistent form of equation for predicting ESALs based on steering axle load. The equation took the form:

$$ESAL = a + b(axle\ load) + c(axle\ load)^2 + d(\frac{1}{axle\ load}) \quad (7)$$

A regression analysis with this standard form of equation produced coefficient values for each size of tire. As can be seen in Table 11 the fit of these equations was excellent with coefficient of multiple determination (R^2) values of 0.9997 or better, and root mean square errors (RMSE) of 0.02 ESALs or better. The two metric-sized tires (295/60R22.5 and 315/80R22.5) were evaluated at only 5 discrete tire loads and when these were regressed the resulting equations had very high R^2 values and very low RMSE values.

Table 11. ESAL equations for 8 sizes of heavy truck steering tires

Tire size	Single tire-single axle ESAL equation	R^2	RMSE (ESAL)
295/60R22.5	ESAL = 4.05-0.82(Load)+0.081(Load)^2-6.76/Load	1.0000	0.003
11R22.5	ESAL = 5.31-1.03(Load)+0.091(Load)^2-9.23/Load	0.9997	0.021
11R24.5	ESAL = 5.77-1.10(Load)+0.094(Load)^2-10.16/Load	0.9998	0.018
315/80R22.5	ESAL = 4.24-0.86(Load)+0.082(Load)^2-7.08/Load	0.9999	0.009
385/65R22.5	ESAL = 6.03-1.15(Load)+0.096(Load)^2-10.66/Load	0.9998	0.019
455/55R22.5	ESAL = 5.81-1.12(Load)+0.094(Load)^2-10.20/Load	0.9997	0.021
425/65R22.5	ESAL = 5.98-1.15(Load)+0.095(Load)^2-10.57/Load	0.9997	0.022
445/65R22.5	ESAL = 5.88-1.14(Load)+0.094(Load)^2-10.30/Load	0.9997	0.020

Figure 3 illustrates the ESAL equations for the conventional steering tire sizes (11R22.5 and 11R24.5) as compared to that of the widebase steering tire sizes (385/65R22.5, 445/55R22.5, 425/65R22.5, and 445/65R22.5).

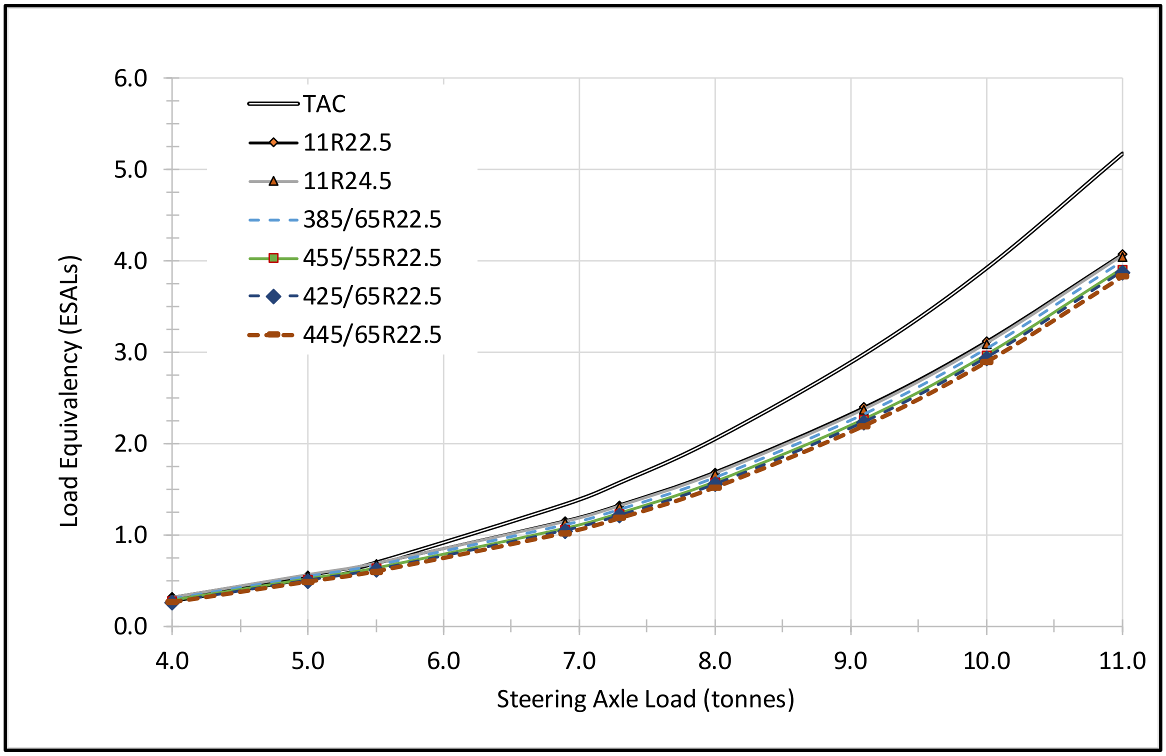

Figure 3. ESAL equations for conventional and widebase truck steering tires.

Because they spread load over a larger contact area, widebase steering tires generate smaller pavement strains and damage rates than conventional sized tires. This is illustrated by how tires with larger contact areas have flatter ESAL curves. The ESAL equations have the same general shape as the TAC (11R22.5) ESAL equation and do not cross for the range of loads considered.

The difference in predicted ESAL values are relatively small for lighter axle loads but are as much as 0.25 ESALs for the largest axle loads. Compared with estimates using the TAC equation, widebase tire ESALs are predicted to be 0.90 to 1.05 ESALs less at a 10,000 kg axle load. TAC single axle-single tire ESALs were assumed to be double that of single axle-dual tire ESALs (for a given axle load). For this reason, the TAC steering axle ESALs were extrapolated to much higher steering axle loads than were used in testing or that the 11R22.5 tires are rated for (refer to Table 4). As a result, the TAC load equivalencies for steering loads in excess of about 5500 kg are believed to overestimate actual pavement impacts as predicted using pavement modeling. The load equivalencies for conventional tire sizes loaded up to their maximum load rating (e.g., 5.5 tonnes), however, closely agree with predictions using pavement modeling.

Pavement impact comparison of new B.C. log truck

Under the reducible load overweight policy of TRAN, non-regulation configurations can be permitted to use public highways. The authorization of overweight or over-dimension log truck configurations requires that they meet specific safety and performance criteria. In order that new B.C. truck configurations evolve to become less damaging to pavements, one of the criteria is that the damage from new truck configurations must be at least 5% less than from a reference vehicle. ESALs are estimated using TAC ESAL equations for each axle and the theoretical pavement damage, which is compared to that of a reference truck, is calculated as the total ESALs divided by payload (tonnes).

In B.C., trucks with tridem-drive axles are required by regulation to have a steering axle load of, at least, 27% of the drive load. These high steering axle loads exceed the carrying capacity of conventional-sized tires (see Table 3) and necessitate the use of widebase steering tires. Many new truck configurations feature these tridem-drive axles.

Tandem- and tridem-drive variants of 9-axle log B-train configurations were authorized by TRAN for use in B.C. in 2017 after extensive theoretical and field evaluations. When the pavement impacts of the tridem-drive variant were assessed it was found that it could not meet the 5% reduction criterion at full legal axle weights. To allow the configuration to meet the 5% threshold, therefore, the permitted maximum steering axle load was limited to 6900 kg. At the same time, FPInnovations undertook an evaluation of widebase tire ESALs to ascertain how the current method for new vehicle evaluations could be modified to account for widebase steering tires. Table 12 illustrates the original comparison of pavement impacts that led to a 400 kg reduction in steering axle load (from a full B.C. legal steering axle load of 7300 kg).

Table 12. Pavement impact performance of 9-axle tridem-drive B-train, using TAC ESAL equations

Configuration		Steer axle	Drive axle	Lead trailer axle	Rear trailer axle	Total	Payload	ESALs/ payload	Difference from reference
8-axle tandem-drive B-train	Load (t)	5.5	17.0	24.0	17.0	63.5	43.89		
	ESALs	0.69	2.04	1.95	2.04	6.72		0.153	
9-axle tridem-drive B-train	Load (t)	6.9	24.0	24.0	17.0	71.9	50.07		
	ESALs	1.33	1.95	1.95	2.04	7.27		0.145	- 5.1%

Table 13 illustrates the same pavement performance evaluation using an estimate of 385/65R22.5 tire ESALs for the steering axle and TAC ESAL equations for all other axles. The reference B-train is assumed to be equipped with 11R22.5 steering tires, however, virtually the same ESAL outcome results if the reference truck were equipped with 11R24.5, 12R22.5, 12R24.5, or 315/80R22.5 size tires and their ESALs were estimated using the FPInnovations-generated ESAL equations.

Table 13. Pavement impact performance of 9-axle tridem-drive B-train, using TAC ESAL equations

Configuration		Steer axle	Drive axle	Lead trailer axle	Rear trailer axle	Total	Payload	ESALs/ payload	Difference from reference
8-axle tandem-drive B-train (reference)	Load (t)	5.5	17.0	24.0	17.0	63.5	43.89		
	ESALs	0.69	2.04	1.95	2.04	6.72		0.153	
9-axle tridem-drive B-train	Load (t)	7.3	24.0	24.0	17.0	72.3	50.47		
	ESALs	1.30	1.95	1.95	2.04	7.24		0.143	- 6.3%

385/65R22.5 tires are estimated to generate 1.30 ESALs at a steering axle load of 7300 kg. The reduction in ESALs from the original TAC ESAL estimate and the increase in payload were enough for the truck, with a full legal steering axle load, to meet the pavement performance criteria of at least 5% reduction in ESALs per tonnes payload. This result substantiates a 400 kg increase in authorized steering axle loads for the B.C. 9-axle tridem-drive log B-trains.

CONCLUSIONS AND RECOMMENDATIONS

Spontaneous pavement strain response was sensitive to tire contact area and tire load. Widebase steering tires had 2% - 8% more contact area, depending on tire load, than conventional North American (i.e., 11R22.5 or 11R24.5) steering tires. This increase in tire contact area resulted in reduced pavement strains, especially near the pavement surface (e.g., up to 2.7% less for tensile strain at the bottom of the AC mat). Most of the pavements were found to have a governing failure mode of bottom-up fatigue cracking and so the larger contact areas of widebase steering tires had important implications for pavement service life.

Tensile AC strain was predicted in 14 pavement structures under 455/55R22.5 widebase single tires using ICT WIDE (a specialized software for estimating pavement impacts of 445/50R22.5 and 455/55R22.5 widebase single tires) and WinJULEA (a layered elastic pavement design software). It was found that WinJULEA predicted 4% higher strains, on average. The close agreement in predicted strain values verified the accuracy of WinJULEA's predictions of pavement strains for widebase steering tire sizes and validated the use of this software for estimating pavement responses.

The proposed methodology allows ESALs to be estimated for all popular North American steering tire sizes at typical Canadian regulated axle loadings. The methodology was validated by comparing ESAL values for conventional tire sizes (e.g., 11R22.5 and 11R24.5) with values estimated using ESAL equations published by the Transportation Association of Canada (TAC) and by the American Association of State Highway and Transportation Officials (AASHTO). This validation found good agreement between the ESAL estimates derived with these three methods.

A backwards stepwise regression analysis produced tire size specific ESAL equations for the range of applicable steering axle loads. These equations took a consistent form of:

$$ESAL = a + b(\text{axle load}) + c(\text{axle load})2 + d/(\text{axle load})$$

The fit of these equations to the estimated ESAL for discrete axle loads was excellent with coefficient of multiple determination (R2) values of 0.9997 or better, and root mean square errors (RMSE) of 0.02 ESALs or better.

The ESAL concept is used by various stakeholders in Canada for evaluating relative impacts from vehicles and(or) designing pavements. These tire size specific ESAL equations offer stakeholders improved accuracy for long-term pavement impact comparisons.

Many new truck configurations in Canada feature tridem-drive groups and widebase steering tires. Having a method to accurately assess ESALs for these configurations will help to optimize their loading. An analysis of steering tire impacts for 9-axle tridem-drive log B-trains used in British Columbia found that use of widebase steering tires allowed these trucks to meet a pavement impact performance threshold for new configurations when their steering axles were fully loaded (to 7300 kg). It is recommended that the B.C. Ministry of Transportation and Infrastructure increase the permitted steering axle weight for these new truck configurations to reflect the new estimates of ESALs for widebase steering tire sizes.

REFERENCES

AASHTO (1993). AASHTO Guide for design of pavement structures. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

ABAQUS (2007). ABAQUS/Standard User’s Manual Version 6.7, Hibbitt, Karlsson & Sorenson, Inc., Pawtucket, RI.

Akram T., Scullion T., Smith R. E., and Fernando E. G. (1992). Estimating Damage Effects of Dual versus Wide Base Tires with Multidepth Deflectometers. Transportation Research Record 1355-59.

Al-Qadi, I.L., Loulizi, A., Elseifi, M.A, and Lahouar, S. (2000). Effect of tire type on flexible pavements response to truck loading. Final Report submitted to Michelin Americas Research and Development Corporation, 515 Michelin Road, South Carolina.

Al-Qadi, I. L., M. Elseifi and P. J. Yoo. (2004). Pavement Damage Due to Different Tires and Vehicle Configuration. Final report. Virginia Tech Transportation Institute, Blacksburg, VA.

Al-Qadi, I.L., P.J. Yoo, M.A. Elseifi, and I. Janajreh (2005). Effects of Tire Configurations on Pavement Damage, Journal of the Association of Asphalt Paving Technologists, Vol. 74, pp.921-962.

Al-Qadi, I.L. and M.A. Elseifi (2007). State-of-the-Practice of the New Generation of Widebase Tire and its Impact on Trucking Operations, Transportation Research Record, 2008, TRB, Washington, D.C., pp. 100-109.

Al-Qadi, I.L., E. Tutumluer, S.H. Dessouky, and J. Kwon (2007). Effectiveness of Geogrid-Reinforcement in Flexible Pavements: A Full-Scale Testing, Final Report to Tensar Earth Technologies, Inc., University of Illinois at Urbana-Champaign, IL.

Al-Qadi I.L., H. Wang, P.J. Yoo, and S.H. Dessouky (2008). Dynamic Analysis and In-situ Validation of Perpetual Pavement Response to Vehicular Loading, Transportation Research Record 2087, pp. 29-39. Transportation Research Board. Washington, D.C.

Al-Qadi, I.L., and H. Wang (2009). Full-depth Pavement Responses under Various Tire Configurations: Accelerated Pavement Testing and Finite Element Modeling, accepted by the Journal of the Association of Asphalt Paving Technologists, Vol. 78, pp. 645-680.

Al-Qadi. (2014). ICT WIDE tool.

Ang-Olsen, J., and Schroeer, W. (2002). Energy efficiency strategies for freight trucking: potential impact on fuel use and greenhouse gas emissions. Transportation Research Record 1815. Transportation Research Board. Washington, D.C. pp. 11-18.

ARA, Inc., ERES Consultants Division. (2004). Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures. Final report, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C. http://www.trb.org/mepdg/guide.htm.

Asphalt Institute (1982). Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1), Research report 82-1, 9th ed., College Park, MD.

Bathe, K.J. (1982). Finite Element Procedures in Engineering Analysis, Prentice-Hall, NJ.

Bell, C.A. et al. (1996) Synthesis of Practice for Out-of-Service Criteria for Commercial Vehicles, Part A; Vehicle Criteria, Transportation Research Report FHWAMC-96-036. Transportation Research Institute, Oregon State University, Corvallis, OR, 1996.

Bonaquist, R. (1992). An assessment of the increased damage potential of widebase single tires. Proc. of the 7th International Conference on Asphalt Pavements, Nottingham, UK, pp. 1-16.

BND TechSource Tire_Calculator, accessed January 2020 at http://bndtechsource.ucoz.com/index/tire_data_calculator/0-20

Bridgestone 2018 tire data book.(2018). Medium & light truck. Version 18.1.

Chopra, A.K. (2001). Dynamics of Structures, 2nd ed., Prentice Hall, Upper Saddle River, NJ.

COST 334 (2001). Effects of Wide Single Tires and Dual Tires, Final report of the action, European Cooperation in the Field of Scientific and Technical Research, Brussels, Belgium.

CVSE. (2019). Commercial Transport Procedures Manual. BC Ministry of Transportation and Infrastructure. Victoria, B.C. October 2019, accessed January 2020 at https://www2.gov.bc.ca/assets/gov/driving-and-transportation/cvse/commercial-transportation-manual/chapter-4.pdf

Deacon, J. A., J. T. Harvey, I. Guada, L. Popescu, and C. L. Monismith. (2002). Analytically Based Approach to Rutting Prediction. In Transportation Research Record: Journal of the Transportation Research Board, No. 1806, Transportation Research Board of the National Academies, Washington, D.C. pp. 9–18.

Doré G., Grellet D. and J.-P. Bilodeau. (2002). Strains at Shallow Depth in Bound Surfacing Materials. Proc., 10th International Conference on Asphalt Pavement, Vol. 2, Quebec City, Quebec. pp. 1491–1503.

Doré, G., G. Duplain, and P. Pierre. (2007) Monitoring Mechanical Response of In-service Pavements Using Retrofitted Fiber Optic Sensors. Proc., International Conference on the Advanced Characteristics of Pavement and Soil Engineering Materials, Athens, Greece. pp. 883–891.

Deacon J.A., J.T. Harvey, I. Guada, L. Popescu, and C.L. Monismith, (2002). Analytically Based Approach to Rutting Prediction, Transportation Research Record, 1806, pp. 9-18.

Green, J., U. Toros, S. Kim, T. Byron, and B. Choubane. (2009). Impact of Widebase Single Tires on Pavement Damage. FL/DOT/SMO/09-528. Florida Department of Transportation. Tallahassee, FL.

Grellet, D., G. Doré, and J.-P. Bilodeau. (2012). Comparative Study on the Impact of Wide Base Tires and Dual Tires on the Strains Occurring Within Flexible Pavements Asphalt Concrete Surface Course. Canadian Journal of Civil Engineering, Vol. 39, No. 5. pp. 526–535.

Grellet, D., G. Doré, and J.-P. Bilodeau.(2010). Effect of Tire Type on Strains Occurring in Asphalt Concrete Layers. Proc., 11th International Conference on Asphalt Pavements, Vol. 2, Nagoya, Japan. pp. 985–994.

Huang, Yang. (2004). Pavement analysis and design. Pearson. ISBN 10: 0131424734

Huhtala, M., Pihlajamäki, J. (1989). Strain and stress measurements in pavements; Proceedings of the conference: Road and Airport Pavement Response Monitoring Systems; West Lebanon, New Hampshire, U.S.A., September 12-16; pp. pp 229-243.

Kilcarr, S. (2001). Single Life May Be Best for Linehaul Tires. FleetOwner (Online), PRIMEDIA, Inc, 2001, Available at: http://fleetowner.com/news/fleet_single_life_may/, Accessed 9 February 2005.

Kim, Y.R., Baek, C., Underwood, B.S., Subramanian, V., Guddati, M., Lee, K. (2005). Application of viscoelastic continuum damage model based finite element analysis to predict the fatigue performance of asphalt pavements. KSCE Journal of Civil Engineering 12, pp. 109-120. 10.1007/s12205-008-0109-x

MnPAVE. (2011). 6.100 User's Guide: Mn/DOT Flexible Pavement Design, Mechanistic–Empirical Method. Minnesota Department of Transportation, Minneapolis, MN.

Monismith, C. L., L. Popescu, and J. T. Harvey.(2006). Rut Depth Estimation for Mechanistic–Empirical Pavement Design Using Simple Shear Test Results. Journal of Association of Asphalt Paving Technologists, Vol. 75. pp. 1294–1338.

Monismith C.L., R.G. Hicks, F.N. Finn, J. Sousa, J. Harvey, S. Weissman, J. Deacon, J. Coplantz, and G. Paulsen (1994). Permanent Deformation Response of Asphalt Aggregate Mix, SHRP-A-415 Report, Strategic Highway Research Program, National Research Council, Washington, D.C.

Monismith C.L., L. Popescu, and J.T. Harvey (2006). Rut Depth Estimation for Mechanistic-Empirical Pavement Design Using Simple Shear Test Results, Journal of Association of Asphalt Paving Technologists, Vol.75.

Myers, L., Roque, R., Ruth, B.E. (1999). Mechanisms of surface-initiated longitudinal wheel path cracks in high-type bituminous pavements. Asphalt Paving Technology, Vol. 67, pp.401-432.

Organization for Economic Co-Operation and Development (1992). Dynamic Loading of Pavements, OECD report, OECD, Paris, France.

Perdomo, D. and B. Nokes (1993). Theoretical Analysis of the Effects of Wide-Base Tires on Flexible Pavements Using Circly. Transportation Research Record, No. 1388, TRB, National Research Council, Washington, DC, pp. 108-119.

Priest, A.L., D.H. Timm, and W.E. Barrett (2005). Mechanistic Comparison of Widebase Single vs. Standard Dual Tire Configurations, Final Report, National Center for Asphalt Technology (NCAT), Auburn, AL.

Prophete, F. (2003). Effect of Different Types of Tires on Pavements. Proc., 10th International Conference on Asphalt Pavement, Quebec City, Quebec, Canada, Vol. 2. pp. 1186–1197.

Roads and Transportation Association of Canada. (1986). Pavement Management Guide. Ottawa, ON

Siddharthan, R.V., Yao, J., and Sebaaly, P.E., (2002). Pavement strain from moving dynamic 3D load distribution. Journal of Transportation Engineering, American Society of Civil Engineers, 557–566.

Theyse, H.L., M. De Beer, and F.C. Rust (1996). Overview of the South African Mechanistic Pavement Design Analysis Method, Transportation Research Record, 1539, pp. 6-17.

Thiam, Papa-Masseck. (2018). WBST literature review. Report 12112. FPInnovations. Montreal, QC.

Tire & Rim Association. (2009). Yearbook. Akron, Ohio.

Transportation Association of Canada. (1997). Pavement Design and Management Guide.

Transportation Association of Canada. (2003). Pavement Design and Management Guide.

Transportation Research Board. (2007). Pavement Lessons Learned from the AASHO Road Test and Performance of the Interstate Highway System. Transportation Research Circular E-C118. TRB, Washington, DC.

Van Gurp, C. and A.J. Van Leest. (2002). Thin Asphalt Pavements on Soft Soil, Proc. 9th International Conference on Asphalt Pavements, International Society for Asphalt Pavements, Copenhagen, Denmark.

Wang, H. and I.L. Al-Qadi. (2009). Combined Effect of Moving Wheel Loading and Three-Dimensional Contact Stresses on Perpetual Pavement Responses, Transportation Research Record, 2095, pp. 53-61.

Yoo, P.J. and I.L. Al-Qadi. (2008). Truth and Myth of Fatigue Cracking Potential in Hot-Mix Asphalt: Numerical Analysis and Validation, Journal of Association of Asphalt Paving Technologists, vol. 77, pp. 549-590.

APPENDIX 1: EXCERPTS FROM THE LITERATURE

Evolution of widebase single tires

According to Priest et al. (2005), the trucking industry is continually developing new and innovative ideas to increase efficiency through tire, suspension, and engine developments. This section focuses on the evolution of tire development. Since their first appearance in the early 1980s, widebase tires have been extensively studied and undergone considerable changes. The first models had a width of 295 mm (11.6”), compared to sizes up to 455 mm wide currently in America and up to 495 mm wide in Europe (Al-Qadi et al., 2004). The first generations of widebase tires (e.g. 385/65R22.5 and 425/65R22.5) were found to cause a significant increase in pavement damage compared to dual-tire assemblies (Huhtala et al., 1989; Bonaquist, 1992; Akram et al., 1992; Perdomo and Nokes, 1993; Myers et al., 1999; Siddharthan et al., 2002; Kim et al., 2005). This led many transportation agencies to discourage their use. A new generation of widebase tires (445/50R22.5 and 455/55R22.5) were introduced in the 2000s to address the pavement damage concerns and to provide other safety and cost-saving advantages. Moreover, in addition to offering wider tires, tire manufacturers (Michelin, Goodyear, Bridgestone) also have improved the shape and composition of the first generations of tires to modify footprints and reduce tire impacts on pavements. As a result, the new generations of widebase tires provide 15%–18% larger footprints and less pavement impact than the previous generations (Al-Qadi et al., 2005). Figure 4 illustrates the evolution in size of widebase tires.

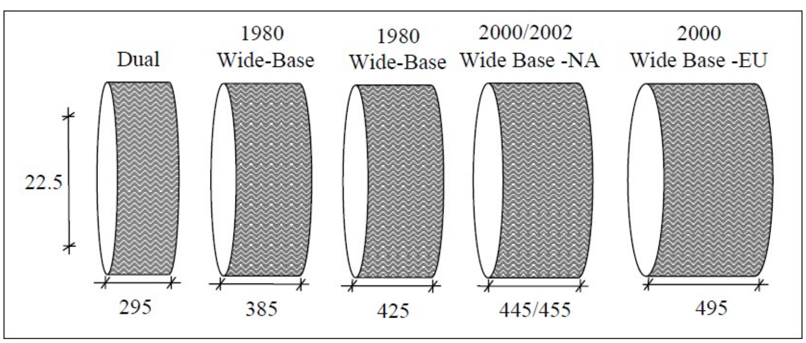

Figure 4. Widebase steering tires have increased in width and resulting footprint size.

Research summary on the impacts of widebase tires

Although studies have shown that widebase tires, especially the latest generation, have the potential to provide tremendous impacts, including improved fuel economy, increased payload capacity, lower tire and wheel cost, reduced maintenance, and improved safety and comfort because of improved ride and handling in all weather conditions, the most extensive research has been performed on widebase tire impacts on pavements and on the environment. This section focuses on these two aspects.

Research summary on environmental impacts of widebase tires

According to Al Qadi, in 2008, the transportation sector produced 33% of the total greenhouse gas (GHG) emissions in the United States, second only to that produced by the electrical power generation industry. Factors related to pavements that contribute directly to vehicle operating costs and GHG emissions include the rolling resistance due to tire–pavement interaction and pavement roughness. Improvements in tire technology to reduce rolling resistance, therefore, could result in reduced operating costs and GHG emissions. Tire rolling resistance accounts for approximately 35% of the energy supplied by a vehicle's engine. The new generation of widebase tires may reduce the rolling resistance by as much as 12%; and, the result is a significant reduction in fuel consumption. In a recent survey conducted in Canada, truck fleet companies using widebase tires reported a significant reduction in fuel consumption varying between 3.5% and 12%. Considering the reduction in fuel consumption, using the new widebase tires would help reduce GHG emissions and the associated damage to the environment. Recent studies suggest that the consumption of a liter of fuel results in the emission of 68 g of carbon monoxide, 2,730 g of carbon dioxide, and 9.6 g of nitrogen oxide. Using the new widebase tires, therefore, could reduce carbon dioxide emissions by more than 4 metric tons annually with an average fuel saving of 1,500 L per truck (Bachman et al., 2008).

Research summary on impact of widebase tires on pavements

Evolution of research on the impact of widebase tires on pavements

Although widebase tires provide many benefits, a general concern has been raised by transportation agencies regarding their impact on pavement performance. This concern was raised because the first generations of widebase tires lowered the total contact area, increasing the stress applied to the roadway. Further, they commonly were inflated to higher pressures, which may have caused more surface damage. The Federal Highway Administration (FHWA) initiated a study in 1989 to investigate the effect of widebase single tires, specifically the 425/65R22.5, on flexible pavement response and performance using accelerated pavement testing (APT) at the Accelerated Loading Facility at the Turner-Fairbanks Research Center. This study found that measured pavement strains and stresses significantly were increased under widebase single tires, and both the fatigue and rutting life of the pavement decreased dramatically (Bonaquist, 1992). Other studies using computer models found similar results. For example, a study conducted by Siddharthan et al. (1998) used a newly developed continuum-based finite-layer model with dynamic loading to investigate the effect of widebase tires. This study found that the widebase tire (the same tire that was used at FHWA) caused a 33% and 16 % increase in calculated strain under a 150 mm and 254 mm (6" and 10")-thick asphalt layer, respectively. Both studies focused on the induced tensile strain at the bottom of the asphalt layer because that pavement response is linked to bottom-up fatigue cracking damage. Based on conclusions of such studies, many agencies placed restrictions on the use of widebase single tires (in lieu of dual-tire assemblies) to preserve the integrity of their highway infrastructure (Al-Qadi et al., 2005). To address this concern, manufacturers introduced new sizes and modified the first-generation tires. The latest widebase tire models have a much wider tread width and a lower profile than those developed in the 1980s. Further, they carry the load differently than their predecessors and are designed to be run at higher speeds and lower inflation pressures (Kilcarr, 2001). The new tires are designed to reduce pavement cracking by decreasing the tire-pavement surface stress through a more uniform surface contact pressure (Al-Qadi et al., 2005). More recent studies have shown that there is little difference in pavement response at the surface or within the layers from a standard dual-tire assembly versus a widebase single tire. In 2004, a study was conducted using both finite-element modeling and instrumented field test sections at the Virginia Smart Road on two new generation widebase tires, the 445/50R22.5 and 455/55R22.5 (Al-Qadi et al., 2005). Fatigue cracking, top-down cracking, and rutting failure mechanisms were considered. The study concluded that the larger of the two, the 455/55R22.5, induced approximately the same instantaneous pavement responses (and predicted long-term damage) as the standard dual assembly tested (275/80R22.5), at the same tire load. The other widebase tire tested (445/50R22.5) was found to slightly decrease the induced pavement responses.

In 2000, Al-Qadi et al. investigated pavement responses to conventional dual-tire assemblies and widebase tires at the heavily instrumented Virginia Smart Road (Al-Qadi et al., 2000). The tested widebase single tire (MICHELIN 445/50R22.5) had a wider tread than the dual tires combined. The widebase single tire had greater load-carrying capacity than the conventional dual-tire assembly. In addition, the widebase single tire developed a relatively uniform contact pressure that was less than the conventional tires. In 2003, Prophète investigated the relative pavement damage of four different tire assemblies using instrumentation at Laval University (Prophète, 2003). The investigated tires were conventional 11R22.5 and 12R22.5 tires in dual-tire assemblies, and 385/65R22.5 and 455/55R22.5 widebase single tires. Three failure mechanisms were considered: bottom-up fatigue cracking of the asphaltic concrete mat, rutting of the subgrade (secondary rutting), and rutting of the asphaltic concrete mat (primary rutting). The vertical strain measurements at the top of the subgrade were very small, indicating that tire type and inflation pressure has diminished effect at this depth in the pavement. The 455/55R22.5 widebase tire, however, resulted in significantly less strain near the pavement surface than the standard widebase tire 385/65R22.5, especially during spring.

The COST Action 334

The effects of widebase tires, as compared to conventional dual-tire assemblies, was extensively investigated in Europe prior to the adoption of these tires (COST 334, 2001). The main objective of this study was to identify possible advantages and disadvantages of different tire assemblies with respect to road pavement damage, vehicle operating costs, vehicle safety and comfort, and environment. The results of the study were used to establish load limit regulations for different axle configurations commonly used in Europe. Seventeen different tire types were evaluated (8 conventional dual-assemblies and 9 widebase single tires). The study included measurements of contact stress and tire footprint; full-scale accelerated pavement testing of selected tire types; measurement of pavement response to different axle configurations; finite element simulation of primary rutting; and, development of regression models to determine the relative damage of different tires and axle configurations.

The COST Action 334 resulted in significant advances in the understanding of the aggressiveness of different tire sizes and configurations. Unfortunately, the results of this study are not directly applicable to North America because of differences in tire sizes and pavement structures.

Because of the continued development of new and improved tires, it should not be concluded that all widebase tires will increase pavement distress. Rather, continued research and investigation into the immediate and prolonged effects of tires as they are developed is needed. This includes analysis through mechanical models, measured pavement response, and field performance.

Impact of widebase tires on thin pavements

Wang et al. (2011) studied the impact of widebase tires on low volume thin pavements. To do so, a three-dimensional (3D) finite-element (FE) model was built to simulate the realistic tire loading on secondary road pavements. The model allows for predicting pavement responses to loading applied by various tire configurations. A 455/55R22.5 tire type was used for this study. The analyzed pavement structures comprised a 76-mm HMA layer and an aggregate base layer with various thicknesses (203, 305, and 457 mm). The impact of a widebase tire on secondary road pavement damage was analyzed using available damage models and was compared to that resulting from conventional dual-tire assemblies. It was found that the new widebase tire (455/55R22.5) caused greater fatigue damage but less HMA rutting and base shear failure compared to the conventional dual-tire assembly when carrying the same load. The findings indicate that widebase tires' impact on secondary road a pavement depends on the roads' predominant failure mechanisms. In this case, rutting was the governing failure mode.

Al Qadi and Wang also studied the effect of widebase tire on the same thin pavement using accelerated pavement testing, to validate FEM modeling conducted by Wang et al. and presented above. FEM results from Wang study were validated.

Impact of widebase tires on full depth flexible pavements

Al Qadi and Wang studied the effect of widebase tire on a full depth pavement. Accelerated pavement testing was used for the analysis. The full-depth pavement sections used for accelerated testing were built as part of an extended-life pavement project. These sections were composed of asphalt layers with three different thicknesses (152, 254, and 420 mm) directly over a 305-mm lime-stabilized subgrade. This has shown that, on average, the strain ratios between widebase tires and the dual-tire assembly decrease as the asphalt layer thickness increases from 254 mm to 420 mm. This finding indicates that the wider tires result in less fatigue cracking potential.

Akram et al. (2006) used Multi-Depth Deflectometers (MDDs) to assess the relative damage of dual and widebase single tires. In this study MDDs were installed in two in-service asphaltic concrete highways (one thick, one thin) to measure the pavement response to vehicle loading. Deflections measured at several depths within the pavement by MDD under dual and widebase single tires were used to calculate average vertical compressive strains. The Asphalt Institute subgrade limiting strain criteria were used to estimate the reduction in pavement life that will occur by using the widebase single tires in place of duals. Widebase single tires were found to be more damaging on both tandem-drive and tandem-trailer axle positions.

APPENDIX 2: TIRE SPECIFICATIONS

Table 14. Tire volumes and contact areas and results verification

								Verification (TRA)	Verification (TRA)	Verification
Tire Size	Maximum Speed (km/h)	Axle Load (kg)	Tire Load (kg)	Tire Load (lbs)	Tire Volume (in^3)	Estimated Footprint Area (mm^2)	Contact Load N	Tire Volume (in^3)	Estimated Footprint Area (mm^2)	% difference TRA vs Estimate
11R22.5	100	4000	2000	4400	10491	36883	19620	10491	36883	0%
	100	5000	2500	5500	10491	43178	24525	10491	43178	0%
	100	5500	2750	6050	10491	46325	26978	10491	46325	0%
11R24.5	100	4000	2000	4400	11147	37280	19620	11147	37280	0%
	100	5000	2500	5500	11147	43575	24525	11147	43575	0%
	100	5500	2750	6050	11147	46722	26978	11147	46722	0%
385/65R22.5	100	4000	2000	4400	13236	38544	19620	15178	39719	3%
	100	5000	2500	5500	13236	44839	24525	15178	46014	3%
	100	5500	2750	6050	13236	47986	26978	15178	49162	2%
	100	6900	3450	7590	13236	56799	33845	15178	57974	2%
	100	7300	3650	8030	13236	59317	35807	15178	60492	2%
	100	8000	4000	8800	13236	63723	39240	15178	64899	2%
	100	9100	4550	10010	13236	70648	44636	15178	71823	2%
455/55R22.5	100	4000	2000	4400	15708	40040	19620	17938	41389	3%
	100	5000	2500	5500	15708	46335	24525	17938	47684	3%
	100	5500	2750	6050	15708	49482	26978	17938	50832	3%
	100	6900	3450	7590	15708	58295	33845	17938	59644	2%
	100	7300	3650	8030	15708	60813	35807	17938	62162	2%
	100	8000	4000	8800	15708	65219	39240	17938	66569	2%
	100	9100	4550	10010	15708	72143	44636	17938	73493	2%
425/65R22.5	100	4000	2000	4400	16830	40719	19620	19081	42081	3%
	100	5000	2500	5500	16830	47014	24525	19081	48376	3%
	100	5500	2750	6050	16830	50161	26978	19081	51524	3%
	100	6900	3450	7590	16830	58974	33845	19081	60336	2%
	100	7300	3650	8030	16830	61492	35807	19081	62854	2%
	100	8000	4000	8800	16830	65898	39240	19081	67261	2%
	100	9100	4550	10010	16830	72823	44636	19081	74185	2%
445/65R22.5	100	4000	2000	4400	18832	41930	19620	21240	43388	3%
	100	5000	2500	5500	18832	48225	24525	21240	49683	3%
	100	5500	2750	6050	18832	51373	26978	21240	52830	3%
	100	6900	3450	7590	18832	60185	33845	21240	61643	2%
	100	7300	3650	8030	18832	62703	35807	21240	64161	2%
	100	8000	4000	8800	18832	67110	39240	21240	68567	2%
	100	9100	4550	10010	18832	74034	44636	21240	75491	2%

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