ASSESSING THE IMPACTS OF PROPOSED HIGH-EFFICIENCY LOG TRUCK CONFIGURATIONS ON ONTARIO PAVEMENTS

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Abstract

Although Ontario has among the most generous and flexible commercial truck weight and dimension regulations, its truck-based industries must compete with those in other Canadian provinces that have instituted designated route or corridor-type transportation programs. Notably, British Columbia, Alberta, and Saskatchewan permit B-train trucks with 70.5-88.0 tonnes combined gross vehicle weight (GCVW) under these programs. FPInnovations, on behalf of Resolute Forest Products, is pursuing a similar opportunity in Ontario. Specifically, two 9-axle B-train configurations have been proposed for use in a log hauling corridor near Thunder Bay. If successful, the initiative will not only benefit the (northwest) Ontario forest industry through log hauling savings and improved competitiveness but also will reduce truck traffic, pavement maintenance, and GHG emissions.

In this study, the loading and dimensions of the proposed configurations were optimized to maximize payloads while ensuring safe vehicle dynamic performance, adequate bridge and culvert capacities, and acceptable pavement impacts. This paper emphasizes the development of a novel and flexible methodology for assessing the pavement impacts of the proposed 9-axle B-train configurations. Given that the tridem-drive 9-axle log B-train is still under consideration by the Ministry of Transportation of Ontario (MTO), discussion in this paper was limited to the tandem-drive 9-axle log B-train.

The first step of this analysis was to compare the load equivalency of the proposed 9-axle B-train configurations with a baseline 8-axle B-train reference truck. To do so, the original MTO terms of reference for pavement evaluations recommended the use of the AASHTO ESAL method. To compliment and validate the results, the load equivalency analysis was repeated using the Transportation Association of Canada (TAC)'s Load Equivalency Factors (LEF). Using these approaches both of the proposed 9-axle B-train configurations generated less impact per tonne payload than the reference configuration. The second step of the pavement impact analysis consisted of conducting advanced pavement modeling to quantify instantaneous and long-term impacts to the pavements. This analysis compared impacts from the proposed trucks and from current log trucks and considered a range of representative King's and Secondary Highway pavement structures, and ranges of material properties, that were identified through analyses of MTO pavement data, FWD results, and other data sources.

Introduction

In most Canadian provinces, there is a need to improve transportation efficiency to ensure provincial competitiveness of industries such as mining, oil & gas, and the forest industry without accelerating the damage rate on provincial infrastructure, such as bridges and roads. There are numerous approaches used to improve transportation efficiency.

This project, which targets the Ontario forest industry, is aimed at increasing the productivity of the forest product supply chain by improving transportation efficiency. This project also aims at decreasing transportation cost to expand the range of feedstock availability. Typically, this can be done by either implementing or improving transport programs, such Winter Weight Premiums (WWP) and heavy haul corridors, elaborating transportation partnership programs, or by introducing newer and higher efficiency truck configurations.

In this perspective, FPInnovations, in collaboration with Ontario's forest industry members and the Ministry of Transportation in Ontario (MTO), proposed the implementation of a higher productivity configuration, with significant payload improvements, for use within a defined hauling corridor under special permit as has been done elsewhere in Canada and the world. From a regulator's view, a key incentive for considering a new trucking configuration is that they offer improved public safety and are infrastructure friendly. This paper, therefore, highlights the scientific approach used to quantify the theoretical structural impacts from the new truck configurations within the proposed hauling corridor. Although the study involved analyzing the truck impacts on pavements and bridges, the focus of this paper is on the pavement analysis.

Vehicle configurations and hauling corridor

Proposed truck configuration

FPInnovations conducted formal safety and infrastructure impact assessments of 9-axle B-train log hauling configurations proposed prior to implementation in British Columbia (Parker et al. 2014). Similar 9-axle log hauling B-trains have been operating in Alberta and Saskatchewan since 2009. The current proposal is based on FPInnovations' experience and specific expertise in conducting this type of analysis. FPInnovations is proposing both tandem-drive and tridem-drive 9-axle log hauling B-train configurations, with wide-spread axle groups on both trailers. Given that the tridem-drive 9-axle log B-train is still under consideration by MTO, therefore, discussion in this paper was limited to the tandem-drive 9-axle log B-train.

The steering axle carries 5,500 kg, and the tandem-axle drive group carries a maximum of 17,800 kg. Maximum loading of 24,600 kg is carried on both the lead and rear trailer tridem-axle groups, respectively. The configuration's Allowable Gross Vehicle Weight (AGVW) is 72,500 kg (711 kN) and the maximum payload is estimated to be 51,000 kg. Unlike current log hauling trucks, this new truck is not assumed to receive a WWP. Figures 1 and 2 show a picture and a summary of the proposed weights and dimensions of this configuration, respectively.

In addition to offering a higher AGVW, this configuration can be easily and relatively cheaply built from existing 8-axle log B-train configurations by switching the rear trailers to tridem-axle B-train trailers.

Figure 1. Example of tandem-drive 9 axle B-train.

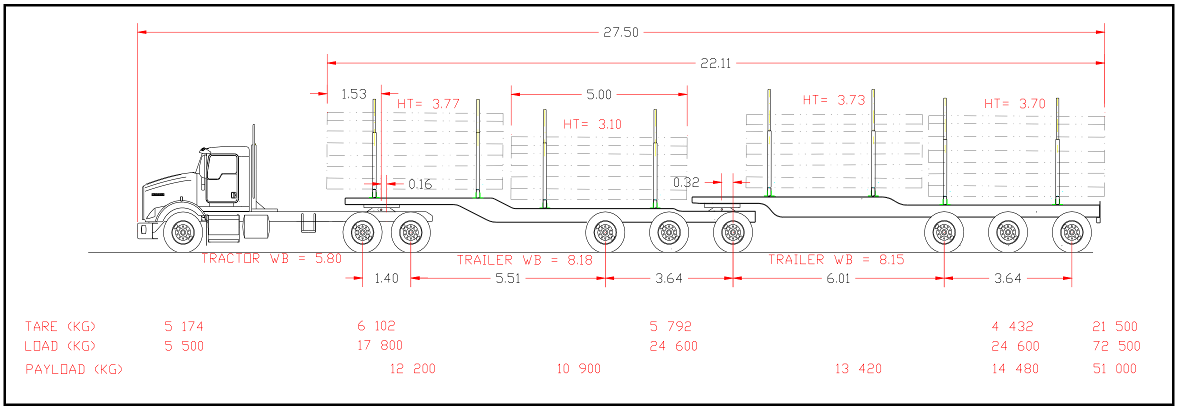

Figure 2. Proposed 72.5-tonne tandem-drive 9-axle configuration (dimensions in meters).

Reference configurations

Two reference truck configurations were employed for the purpose of putting into context the projected impacts of 9-axle log B-trains on highway infrastructure. Both reference vehicles are representative of log hauling vehicles that are used in the region currently and for the foreseeable future. The first configuration is a tandem-drive 8-axle log B-train (Figure 3). The second reference log truck is a 7-axle tractor/4-axle semi-trailer (Figure 4). These reference vehicles were evaluated with the Northwestern Ontario Log Transportation Association (NOLTA) Agreement weights which allow for an increase of 5% in truck loading during summer and fall. Winter weight premiums allow for an increase in truck loading of 10%; however, wintertime loads were not considered for this analysis because frozen pavements experience little, if any, damage when compared to summertime conditions. The impact of the proposed 9-axle B-train configuration on Ontario pavements was compared to that of both reference trucks.

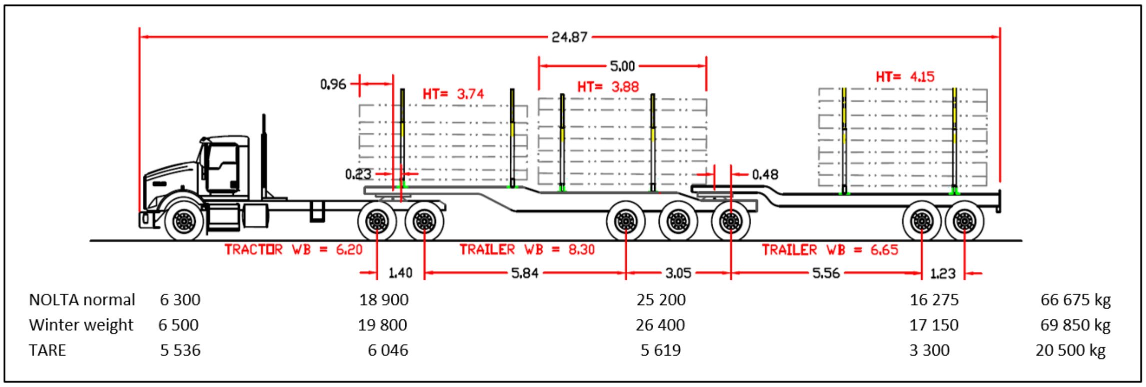

Figure 3. Reference vehicle: 8-axle log B-train.

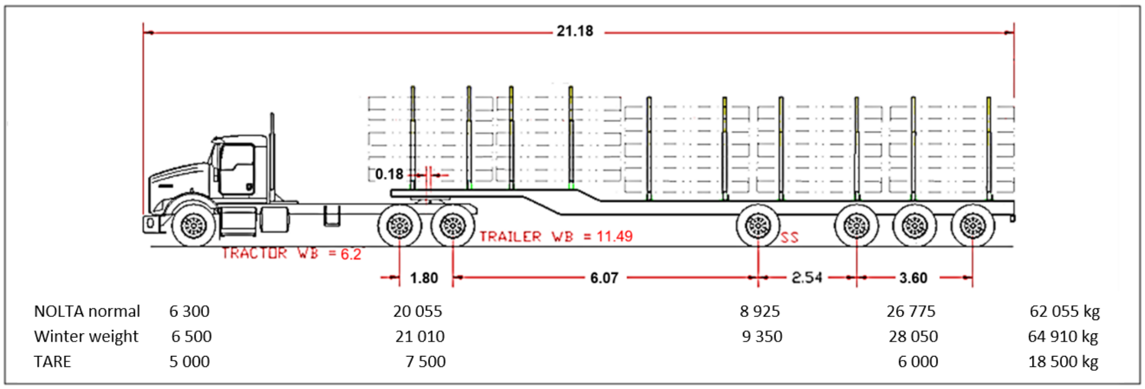

Figure 4. Reference vehicle: 7-axle tractor/4-axle semi-trailer.

The log hauling fleet in Ontario consists of about 90% 7-axle tractor/4-axle semi-trailers, about 5% 8-axle tandem-drive B-trains, and about 5% 8-axle tractor/5-axle semi-trailers. However, use of the 8-axle tractor/5-axle semi-trailer, which does not meet SPIF-specifications, was grandfathered into legislation but this ends in 2021.

<u>Hauling corridor</u>

The proposed hauling corridor for use with the two 9-axle log B-trains contains a total of 753 km of Ontario public highway and is comprised of the following segments:

- Highway 17 from Highway 61 to Highway 72 (at Dinorwic) (321 km)
- Highway 61 from Highway 17/Harbour Expressway to Highway 130 (21 km)
- Highway 130 from Highway 17 to Highway 61 (15.5 km)
- Highway 61B/Chippewa Road from Highway 61 to City Road (6.5 km)
- Highway 599 from Highway 17 to approximately 40 km north of Savant Lake (166 km)
- Highway 642 from Highway 599 to approximately 4 km east of Alcona (56 km)
- Highway 516 from Highway 599 to approximately 45 km west of Highway 599 (45 km)
- Highway 622 from Highway 17 to the Sapawe mill connector road (119 km)
- Highway 623 from the Sapawe mill connector road to the mill entrance road (3 km)

The proposed 9-axle B-trains will travel from forest to mill via resource roads and the public highway network. The 9-axle log B-trains will be used on a series of routes that lead to their Ignace, Sapawe, and Thunder Bay sawmills. The main haul route would be Highway 17 to the destination sawmills at Ignace and at lakeside in Thunder Bay. Four secondary highways will also be used: Hwy 599 from about 40 km north of Savant Lake to Hwy 17; Highway 642 from about 4 km east of Alcona to Hwy 599; and Hwy 516 from about 45 km west of Hwy 599 to Hwy 599. Logs would also be transported to the Sapawe sawmill from Hwy 17 southwards on Hwy 622 to about 45 km north of Atikokan where the trucks would turn onto a connector resource road taking them to Hwy 623 (for 3 km) and the Sapawe sawmill.

Figure 5 illustrates the entire hauling corridor proposed for use with the 9-axle B-trains.

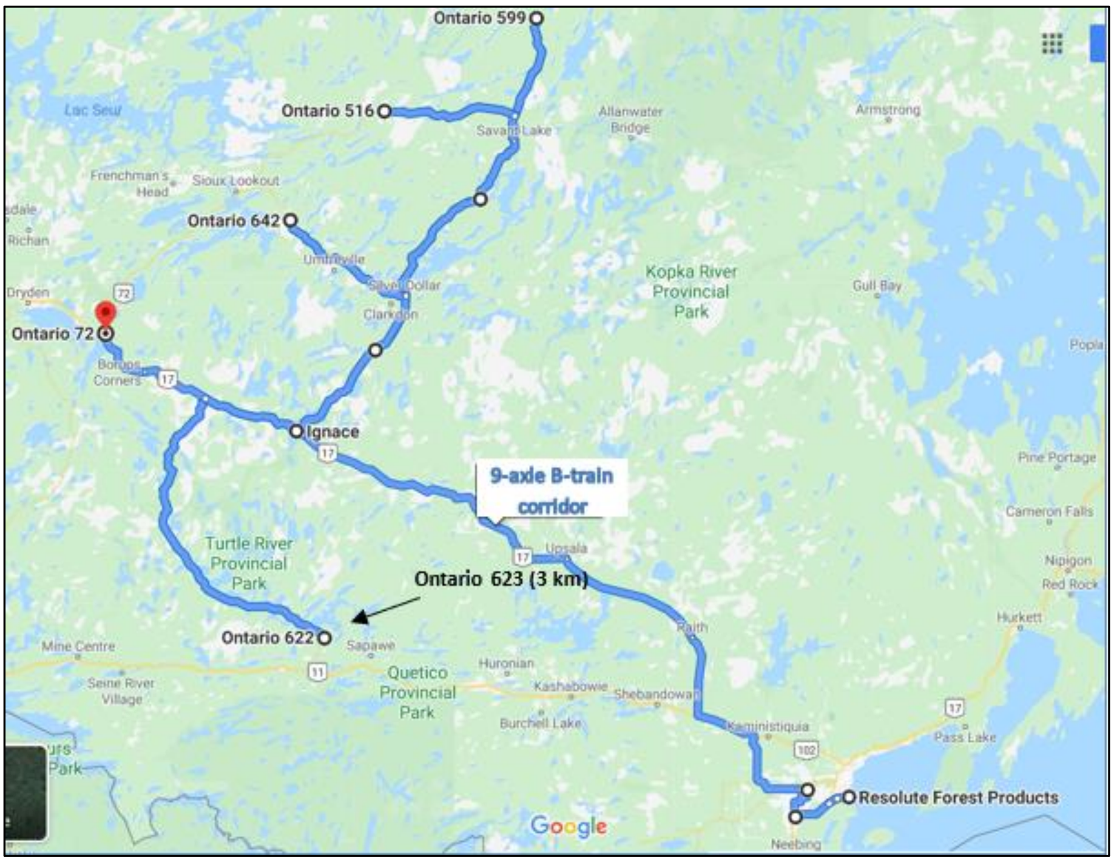

Figure 5. Preferred and alternative 9-axle log B-train routes to Resolute's sawmill.

Methodology for pavement impact analysis

Two requirements for the pavement impact analysis were provided by the MTO.

- Provide estimates for the axle LEF from each of the proposed baseline configurations.
- Determine the estimated total impact by route or portion of route according to the expected traffic and existing conditions (bearing capacity) of the road.

To address these two points, the methodology for the pavement impact analysis was structured in two parts. The first part consisted in a comparative analysis of the LEFs between each of the proposed configuration and the baseline (reference) configurations; LEFs are expressed in units of Equivalent Single Axle Loads (ESALs). The second part consisted of advanced pavement modeling to compare the pavement impact of the reference vehicles and that of the 9-axle configuration on representative highway sections. A comparative analysis of short-term and long-term pavement damages, as well as a sensitivity analysis with additional structures, was performed to assess the total corridor impact comprehensively and conservatively. The following sections describe the analysis methodology in detail.

Load equivalency factor analysis

This analysis compared the load equivalency of the proposed 72.5-tonne 9-axle B-train versus that of the two reference trucks. Per the project Terms of Reference, the American Association of State Highway Officials (AASHTO 1993) equations were used for making LEF comparisons. In addition to the AASHTO LEF calculation method, FPInnovations conducted an analysis based upon the Transportation Association of Canada (TAC) LEF equations to better account for the impacts from different axle configurations.

The AASHTO formula is as follows:

- $LEF\ (ESALs) = \ (0.01169 * L\ +\ 0.064)^{(4+8.9/L)}$

Where, L represents the load carried by a given axle within an axle group in kN. The total LEF of a truck is the sum of the LEFs from each of its axle groups. This equation does not distinguish between differences in pavement impact due to axle group configuration.

TAC has developed equations for four different axle configurations as opposed to the single AASHTO formula.

- single steering axle: $LEF\ (ESALs) = 0.004836 \times (L)^{2.9093}$
- dual tire single axle: $LEF\ (ESALs) = 0.002418 \times (L)^{2.9093}$
- dual tire tandem axle: $LEF\ (ESALs) = 0.001515 \times (L)^{2.5430}$
- dual tire tridem axle: $LEF\ (ESALs) = 0.002363 \times (L)^{2.1130}$

Where, L is the axle group load, in tonnes. These widely used equations account for variations in axle configuration and are, therefore, believed to be more accurate than the AASHTO LEF equations. In addition, the TAC LEF equations were developed from testing of 14 representative Canadian pavements, three of which were from Ontario. For these reasons, the TAC LEF analysis were included in addition to the analysis based on the AASHTO formula.

Recently FPInnovations published supplemental formulae to be used with the standard TAC formulae (Thiam and Bradley, 2020). These formulae were developed to account for different tire sizes – notably widebase single tires – used on truck steering axles. FPInnovations applied these formulae to the two reference vehicles to analyze their steering axle LEF with both conventional 11R22.5 tires and 385/65R22.5 widebase tires. Table 1 below summarizes the FPInnovations widebase single tire formulae.

Table 1. FPInnovations' widebase single tire formulae (Thiam and Bradley, 2020)

Tire size	Single-axle/single-tire ESAL equation
295/60R22.5	$ESAL = 4.05 - 0.82(L) + 0.081(L)^2 - 6.76/L$
11R22.5	$ESAL = 5.31 - 1.03(L) + 0.091(L)^2 - 9.23/L$
11R24.5	$ESAL = 5.77 - 1.10(L) + 0.094(L)^2 - 10.16/L$
315/80R22.5	$ESAL = 4.24 - 0.86(L) + 0.082(L)^2 - 7.08/L$
385/65R22.5	$ESAL = 6.03 - 1.15(L) + 0.096(L)^2 - 10.66/L$
455/55R22.5	$ESAL = 5.81 - 1.12(L) + 0.094(L)^2 - 10.20/L$
425/65R22.5	$ESAL = 5.98 - 1.15(L) + 0.095(L)^2 - 10.57/L$
445/65R22.5	$ESAL = 5.88 - 1.14(L) + 0.094(L)^2 - 10.30/L$

Note. L = axle group load, in tonnes.

The LEF estimates provide a relative comparison of theoretical damage between the proposed configuration and the reference configurations. LEF estimates cannot account for the specific road structures of interest and their existing conditions, however, so an advanced pavement analysis was undertaken as well.

<u>Advanced pavement modeling</u>

The methodology for the advanced pavement modeling consisted of determining the short-term and long-term impacts of the proposed configuration relative to the reference vehicles.

The first step of the analysis was to define the pavement structures. Based on the data provided by MTO, a total of four pavement structures were selected to represent the range of pavements found in the corridor— two structures to represent the King's highways (K-type pavements) and two structures to represent the secondary highways (S-type pavements). Within the corridor, only Highway 17 and Highway 61 are King's highways; the remaining segments are S-type highways. Of the corridor's 753 km total length, the MTO was able to provide pavement structure data from its Asset Management System (AMS) for 95% (720 kms). It was assumed, therefore, that although some segments were missing from the dataset, the available data was sufficient to perform the analysis and draw conclusions.

The highways within the corridor were sorted and filtered based on highway class, surface type, and granular base equivalency (GBE), given in the AMS dataset. This preliminary analysis revealed that almost all S-type highways in the corridor are bituminous surface-treatments (ST), while a select few have hot mix asphalt (HMA) surfaces. All S-type structures have granular base equivalent thicknesses of 600 - 625 mm. In addition, a large proportion of the S-type highways have a very thin (e.g., 20 mm) surface thickness. Conversely, all K-type highways in the corridor have thicker surfaces and granular base equivalent thicknesses of 600 - 625 mm or 700 - 870 mm.

Based on these preliminary findings the corridor pavements were arranged in the following four groupings:

1. S-type structures with thin (20 mm) ST surfaces and GBE of 600 mm.
2. S-type structures with thicker (> 20 mm) ST surfaces and GBE of 600–625 mm.
3. S-type and K-type structures with HMA surfaces and GBE of 600–625 mm.
4. K-type structures with HMA surfaces and GBE of 700–870 mm.

Table 2 summarizes the 4 groups of pavements in the corridor and additional important specifications used for subsequent secondary filtering.

Table 2. Summary of key AMS structure data for four corridor pavement structure groupings

Highway	Total length (km)	Year constructed	AMS rating	Subgrade type	Subbase thickness (mm)	Base thickness (mm)	Pavement type	Surface thickness (mm)	GBE equivalent thickness (mm)
642, 599	89	1997	Fair - good	Gran, sandy silt	710 - 715	80-85	ST	20	600
622, 599, 516	316	1974 - 2009	Fair - good	Gran, sandy silt	260 - 740	22 - 240	ST	30-92	600-625
623, 622, 130, 61, 17	80	1969 - 2018	Fair - good	Sandy silt	110 - 130	165 - 235	HMA	50 - 145	600-625
130, 61, 17	236	1969 - 1976	Good	Sandy silt	170 - 575	50 - 310	HMA	130 - 190	700-870

Note. ST = bituminous surface-treated pavement; HMA = hot mix asphalt pavement.

Table 3 summarizes the four (4) ***most critical pavement structures*** in each grouping of pavements, that were taken to represent the weakest (most conservative) structures found in each of the four pavement groups. The AMS data indicates that the majority of corridor structures are built over sandy-silt subgrades. Approximately 89 km of Highways 642 and 599 consists of the thin ST pavement described by “Structure 1”; approximately 315 km of Highways 622, 599, and 516 consists of the thicker surface-treated pavements described by “Structure 2”; approximately 80 km of Highways 623, 622, 130, 61, and 17 consist of HMA-surfaced highways with a GBE of 600-625 mm described by “Structure 3”; and, finally, about 236 km of Highways 130, 61, and 17 consists of HMA with a GBE of 700-870 mm described by “Structure 4”.

The selection of these four groupings representing the most vulnerable and representative pavements was made by considering pavement age, time since last rehabilitation, rehabilitation type, current pavement condition, subgrade type and modulus, granular base equivalent thickness, etc. These assumptions were verified in the sensitivity analysis.

Table 3. Representative conservative pavement structures chosen for analysis

Structure	Length of representative sections (Km)	Subgrade modulus (MPa)	Subbase thickness (mm)	Base thickness (mm)	Pavement type	Surface thickness (mm)	GBE equivalent thickness (mm)	Governing failure mode
1	52	41	710	85	ST	20	600	Rutting
2	45	41	743	22	ST	40	600	Rutting
3	19	35	112	235	HMA	145	600	Fatigue cracking
4	19	35	567	50	HMA	135	700	Fatigue cracking

Note – ST = bituminous surface-treated pavement; AC = hot mix asphalt pavement.

Figure 6 shows the total length of each structure group as well as the length associated with each of the representative and conservative sections within each group. For example, thin surfaced pavements (group 1) comprise 89 km in total of which 52 km consists of the representative pavement structure (structure 1).

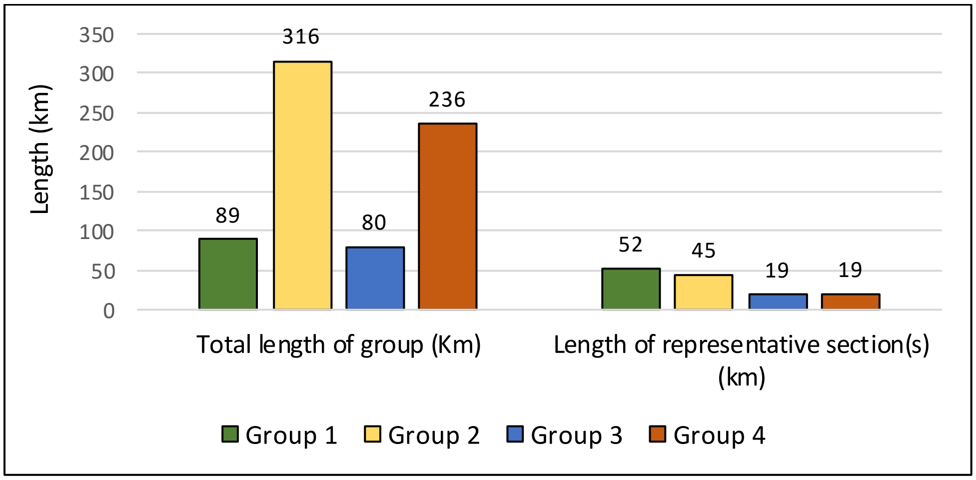

Figure 6. Total length of the pavement groups and of sections having the representative structures.

The representative and conservative structures corresponded to, at most, 7% (group 1) of the total corridor length (720 km). The total length of highway sections with the four conservative representative structures accounted for just 19% of the total corridor length. As was demonstrated in the sensitivity analysis, the remaining 81% of corridor length was composed of thicker and stronger pavement structures.

The second step of the analysis was to estimate material properties to reflect existing pavement conditions. As detailed in the documents provided by the MTO, the corridor pavement surfaces consist of thin or thicker HMA or ST layers. Some pavement structures have been reconstructed or surface-treated several times. The base and subbase pavement layers consist of granular A and granular B (type I or II), respectively. The subgrade soils vary across the province, however, most of the highway subgrades in the corridor are silty and sandy soils with very low bearing capacity. Material properties needed for the advanced modelling are the Poisson's ratio, which is specific to each soil and material, and the resilient modulus. These values were selected in consideration of the AMS data, MTO studies, and other published data. The following table summarizes the resilient modulus and Poison's ratio values that were used for the advanced pavement modeling:

Table 4. Material properties used in analysis

Material Layer	Resilient modulus (MPa)	Poisson's ratio
Hot mix asphalt	2000	0.35
Bituminous surface treatment	1200	0.35
Granular base course	150	0.35
Granular subbase course	100	0.35
Subgrade	Variable (see table 5)	0.4

The first part of the analysis was to estimate strain-based spontaneous responses. Strains in response to vehicle loading were estimated at key depths in the highway structures using WinJULEA, a multi-layer linear elastic software. The input data used in the analysis were:

- Pavement material mechanical properties (resilient modulus (Mr) and Poisson's ratio).
- Pavement material layer thicknesses.
- Axle loads, tire sizes and arrangements, tire contact pressure.

WinJULEA allows the prediction of spontaneous strains in a pavement in response to static wheel loads. The loads on the pavement surface produce two strains that are believed to be critical for design purposes. One is the horizontal tensile strain at the bottom of the surface layer and this strain is associated with bottom-up fatigue cracking failure. The other is the vertical compressive strain at the top of the subgrade layer and this strain is associated with rutting failure. These two critical strains were modeled in each pavement structure.

Following the estimation of spontaneous strains, a long-term damage analysis was performed to estimate the number of truck passes for the pavement structure to reach a failed condition starting from an uncracked and unrutted condition. This analysis was conducted using the Asphalt Institute's transform equations (Huang 2004) and focused on two performance parameters:

1. Horizontal tensile strain at the bottom of the HMA surface (maximum bottom-up fatigue cracking criteria).
2. Vertical compressive strain at the top of the subgrade layer (maximum rutting criteria).

Asphalt Institute's surface rutting equation is:

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

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

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

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

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 asphalt (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)

For each axle group of a truck configuration, long-term rutting and cracking damage rates were calculated. Using Miner's Law, the axle group damage rates were accumulated to estimate the truck's damage rate:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} \quad (4)$$

k = number of different stresses

n_i = number of cycles accumulated at the i^{th} stress, S_i

N_i = numbers of cycle to failure at S_i

The governing failure mode was taken to be either rutting or bottom-up fatigue cracking – whichever failed condition was generated by the fewest number of truck passes (number of loading cycles) to failure. In this study, HMA pavements consistently failed first in fatigue cracking rather than in rutting unlike ST surfaced pavements which consistently failed first in rutting.

A detailed analysis was made of theoretical pavement damage from the 72.5-tonne 9-axle tandem-drive B-train, and this was compared with the theoretical damage generated by the reference configurations.

Following the analysis of the four, representative, most conservative structures, a sensitivity analysis was performed on additional structures from each grouping. This was conducted to confirm that the selected representative structures were, in fact, the weakest sections within their respective groups. Table 5 summarizes the 12 additional structures analyzed.

Table 5. Additional pavement structures considered in the sensitivity analysis, by group

Pavement group	Structure number	Highway	Function class	Pavement type	AMS rating	Subgrade modulus (MPa)	Subbase thickness (mm)	Base thickness (mm)	Surface thickness (mm)
1	1.1	599	COL	ST	Fair	41	709	85	20
1	1.2	642	LOC	ST	Good	41	716	80	20
2	2.1	622	COL	ST	Good	41	743	22	40
2	2.2	599	COL	ST	Fair	35	478	160	60
2	2.3	622	COL	ST	Fair	41	701	50	40
2	2.4	599	COL	ST	Fair	35	263	240	92
2	2.5	599	COL	ST	Fair	41	582	150	30
3	3.1	17	ART	AC	Good	35	112	235	145
4	4.1	17	ART	AC	Good	35	567	50	135
4	4.2	17	ART	AC	Good	41	176	310	140
4	4.3	17	ART	AC	Good	41	575	180	145
4	4.4	17	ART	AC	Good	37	478	250	150

Note. LOC = Local highway; COL=collector highway; ART = arterial highway. AMS rating is assessed surface condition.

The sensitivity analysis involved a single verification. For each group of structures, the initial representative conservative structure was taken to be the baseline (100%) and the number of 9-

axle B-train passes to cause failure for each of the additional structures was compared to this to make sure that the baseline structure would fail faster (i.e., was the weakest structure).

Results

The following section details the results of the comparative analysis of pavement impacts from the proposed 9-axle tandem-drive B-train and the 8-axle tandem-drive B-train and 7-axle quad/semi-trailer reference configurations.

Load equivalency factor

Table 6 summarizes the results of the LEF analysis using the AASHTO and the TAC methods. It can be seen that the 9-axle configuration was the least damaging configuration regardless of LEF method used.

Table 6. AASHTO and TAC LEF analysis summary.

AASHTO Method						
Truck configuration	**GVW (tonne)**	**Payload (tonne)**	**LEF (ESAL)**	**ESAL/tonne payload**	**Trips to transport 18,000 t of logs**	**ESAL to transport 18,000 t of logs**
9-axle tandem-drive B-train	72.500	50.90	9.1	0.18	354	3225
8-axle tandem-drive B-train (reference)	66.675	46.18	9.2	0.20	390	3692
7-axle tandem-drive quad/semi-trailer (reference)	62.055	43.56	10.4	0.24	413	4311
TAC Method						
Truck configuration	**GVW (tonne)**	**Payload (tonne)**	**LEF (ESAL)**	**ESAL/tonne payload**	**Trips to transport 18,000 t of logs**	**ESAL to transport 18,000 t of logs**
9-axle tandem-drive B-train	72.50	50.90	7.1	0.14	354	2507
8-axle tandem-drive B-train (reference)	66.68	46.18	7.7	0.17	390	2993
7-axle tandem-drive/ quad semi- trailer (reference)	62.05	43.56	8.0	0.18	413	3303
8-axle tandem-drive B-train (reference) – with 385/65R22.5 steering tires	66.68	46.18	7.6	0.16	390	2947
7-axle tandem-drive/ quad semi-trailer (reference) – with 385/65R22.5 steering tires	62.05	43.56	7.9	0.18	413	3254

Using the AASHTO method, the 9-axle B-train was estimated to have a total load equivalency per pass of 9.1 ESALs. The reference configurations both had higher load equivalencies per pass (9.2 and 10.4 ESALs). Considering the amount of payload transported per trip, the 9-axle configuration also had the lowest impact (0.18 ESAL/ tonne payload). Assuming a typical log hauling truck is able to transport around 18,000 tonnes payload per year, the 9-axle B-train would require only 354 trips to do so and this would generate only 3,225 ESALs of theoretically pavement impact. In comparison, the reference vehicles would not only require 36-59 more trips to move the same log tonnage but also would generate 467-1,086 ESALs more pavement damage. When comparing incremental road impacts of trucking configurations, it is typical to express their pavement impacts in terms of ESALs per loaded truck pass. Notably, in the case of the 72.5-t tandem-drive 9-axle B-train, the configuration had both a smaller ESALs per tonne payload and also a smaller total LEF per pass than either of the lighter reference vehicles.

As for the TAC method supplemented with FPInnovations' widebase single tire formulae, the 8-axle tandem-drive B-train and 7-axle quad/semi-trailer were evaluated with regular 11R22.5 steering tires and with widebase 385/65R22.5 steering tires and compared to the 9-axle B-train equipped with conventional 11R22.5 tires only. As shown in Table 6, the reference configurations with widebase steering tires produced slightly less impact than those with regular steering tires. Although the TAC and FPInnovations equations produced lower LEF estimates than the AASHTO formula, the resulting trends were similar. Once again, the 9-axle configuration was found to have the smallest LEF (7.1 ESALs), as compared to 7.6 and 7.9 ESALs for the 8-axle and 7-axle reference trucks, respectively, equipped with widebase steer tires. As with the AASHTO LEF equation, the TAC method predicted that the 9-axle B-train would generate the fewest ESALs per tonne payload and, therefore, was the most efficient transport configuration.

<u>Advanced pavement modeling</u>

As discussed in the methodology, spontaneous strains were evaluated at the bottom of the surfacing layer and at the top of the subgrade, respectively.

Figure 7 shows the maximum horizontal tensile strains for the two HMA structures (structures 3 and 4) in response to steering axle loading. As anticipated, and consistent with the LEF results, the 9-axle B-train steering axle generated smaller horizontal tensile strains in the HMA pavements than did the steering axle of either reference truck. The tensile strains were slightly higher in structure 4 than in structure 3 because it has a slightly thinner asphalt surface. Similar trends were also observed for the other axle configurations of each truck on both these structures.

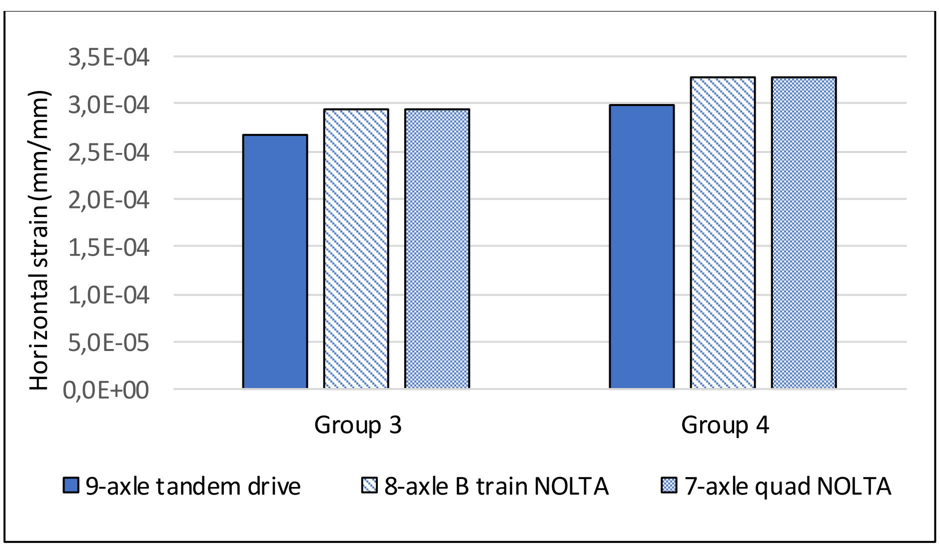

Figure 7. Comparison of HMA horizontal strains from 3 truck steering axle loadings.

Figure 8 shows the maximum vertical compressive strains at the top of the subgrade of all four representative structures in response to 3 steering axle loads. In all four structures, the 9-axle configuration produced the lowest compressive strain, and the 7-axle reference produced the highest strain. Structures 2 and 3 had the highest subgrade strains because they have the lowest total overall thicknesses (see Figure 8).

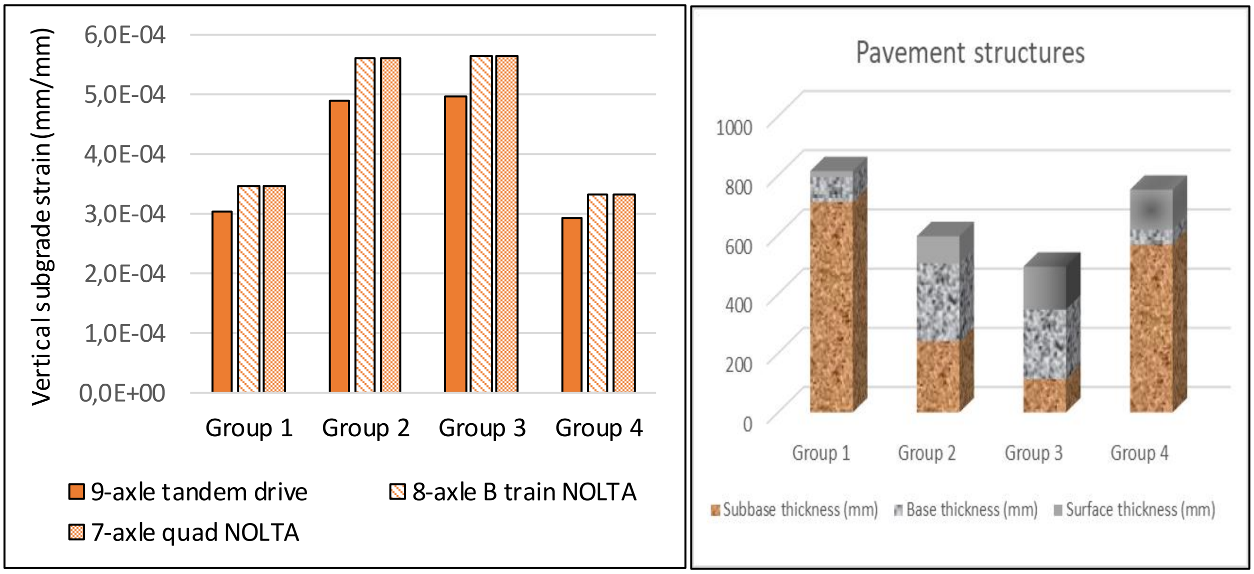

Figure 8. Comparison of vertical subgrade strains in four representative pavements (left) and graphic illustration of the representative pavement structures (right).

Following the evaluation of spontaneous responses, the comparative analysis of long-term damage estimates was conducted for the proposed 72.5-t 9-axle configuration and the two reference vehicles loaded to their NOLTA Agreement loadings (66.7 t for the 8-axle B-train and 62.1 t for the 7-axle quad semi-trailer).

Figure 9 compares predictions of truck passes to cause a failed rutting condition in structure 1. The 8-axle and 7-axle reference log trucks were estimated to fail structure 1 pavements 20% and 28% faster, respectively, than the 9-axle B-train.

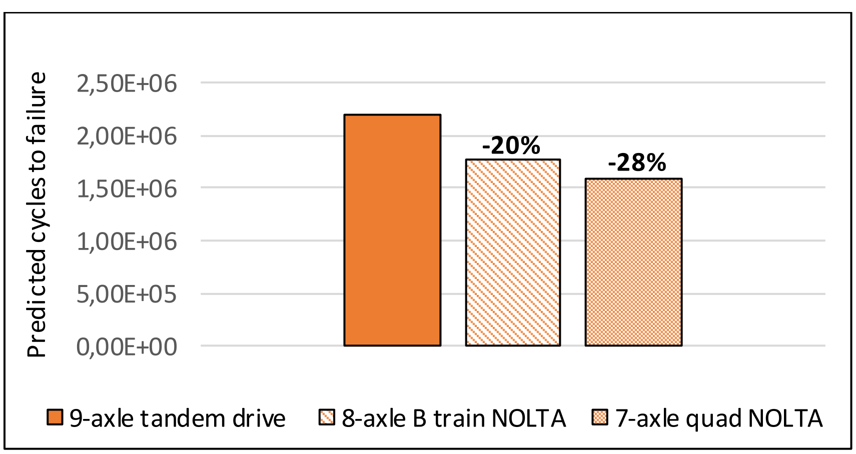

Figure 9. Long-term damage predictions for structure 1.

Figure 10 compares predictions of truck passes to cause a failed rutting condition in structure 2. Similar trends were observed as for structure 1. The 8-axle and 7-axle reference log trucks were estimated to fail structure 2 pavements 20% and 27% faster, respectively, than the 9-axle B-train.

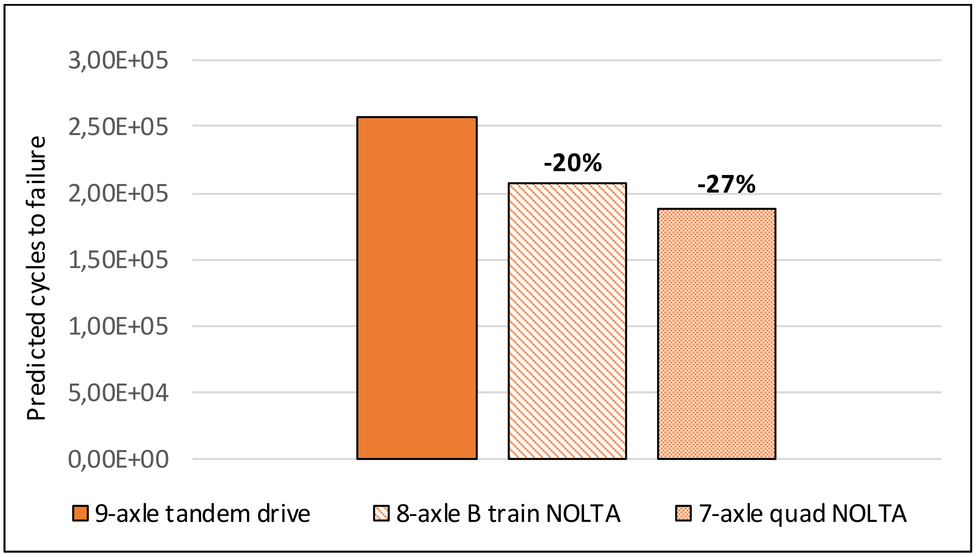

Figure 10. Long-term damage predictions for structure 2.

Since HMA surfaces can fail in both fatigue cracking and rutting, both modes were evaluated for structures 3 and 4. Results for both failure modes are presented in Appendix B. The governing failure mode for these pavement structures was found to be bottom-up fatigue cracking. Figure 11 displays the truck passes to cause a failed condition in fatigue cracking in structures 3 and 4. Trends were similar for both structures with them failing slightly slower when subjected to 9-axle B-train traffic than when subjected to either of the reference truck configurations.

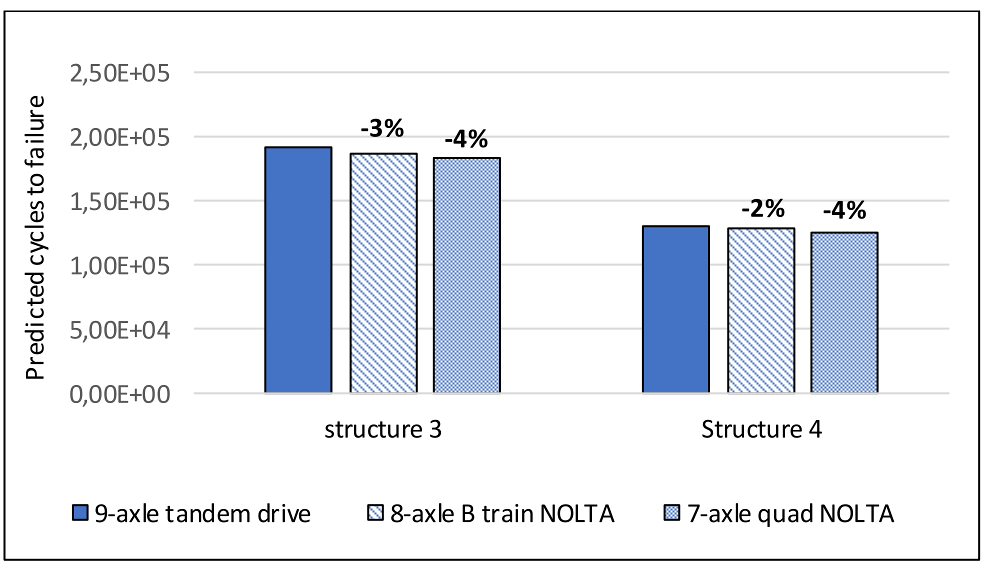

Figure 11. Long-term damage results for structures 3 and 4.

Sensitivity analysis results

The sensitivity analysis was conducted to verify that the representative conservative structure of each grouping was the weakest structure (i.e., all other structures in the grouping would have a higher number of predicted cycles to failure). This analysis evaluated the cycles to failure for each of the "non-representative" pavement structures in each group; the predicted cycles to failure were expressed relative to the predicted cycles to failure of the group's representative conservative structure.

Figure 12 presents the results of the sensitivity analysis for group 1 pavements in the corridor. As seen in the chart, the two additional pavements (1.1 and 1.2) had the same or slightly more predicted service life than the representative pavement for group 1 (pavement 1). Figure 13 shows the sensitivity analysis performed on group 2 pavements in the corridor. This is the group with the most structure variability. The representative conservative structure (structure 2) was much weaker and more vulnerable than any of the other group 2 pavements (2.1 – 2.5). This confirms that structure 2 represented the weakest, most conservative structure from group 2. Figure 14 shows the sensitivity analysis performed on group 4. Four additional structures were analyzed, all of which, were predicted to perform equal to or better than the representative pavement (structure 4). This confirmed the choice of structure 4 as the most conservative structure in group 4.

The same approach was not possible for group 3 pavement structures because the AMS database was missing base course or surface thickness information for the additional structures. Instead, verification of the representative pavement was carried out by comparing other attributes of the pavement structures in the group. The representative structure for group 3 had the weakest subgrade modulus (35 MPa), was relatively old (constructed in 1969), and had not been rehabilitated for some time (last rehabilitated 23 years ago). All other structures in the group had similar layer thicknesses but were newer and had been rehabilitated within the last 10 years (except for one structure of unknown construction date and last rehabilitated 26 years ago).

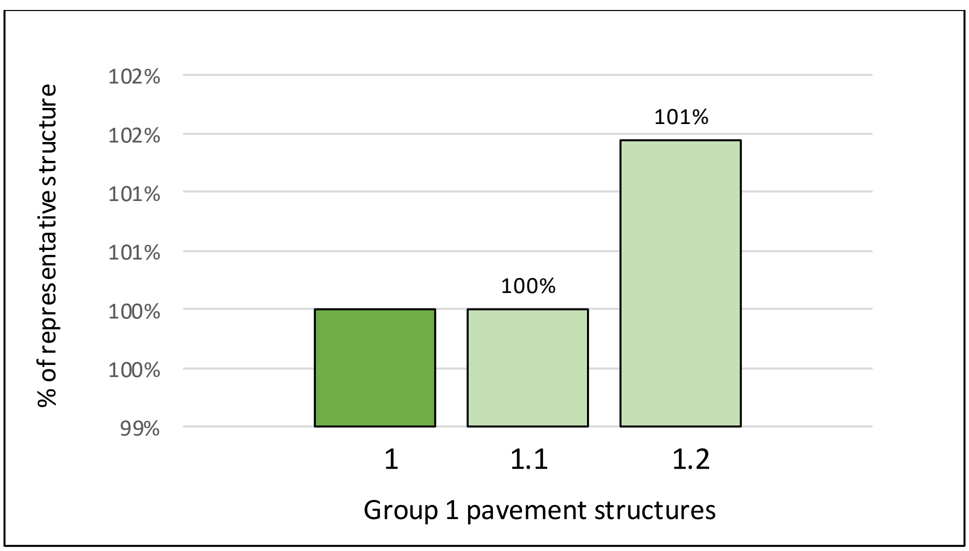

Figure 12. Comparison of predicted service life of group 1 pavements relative to structure 1.

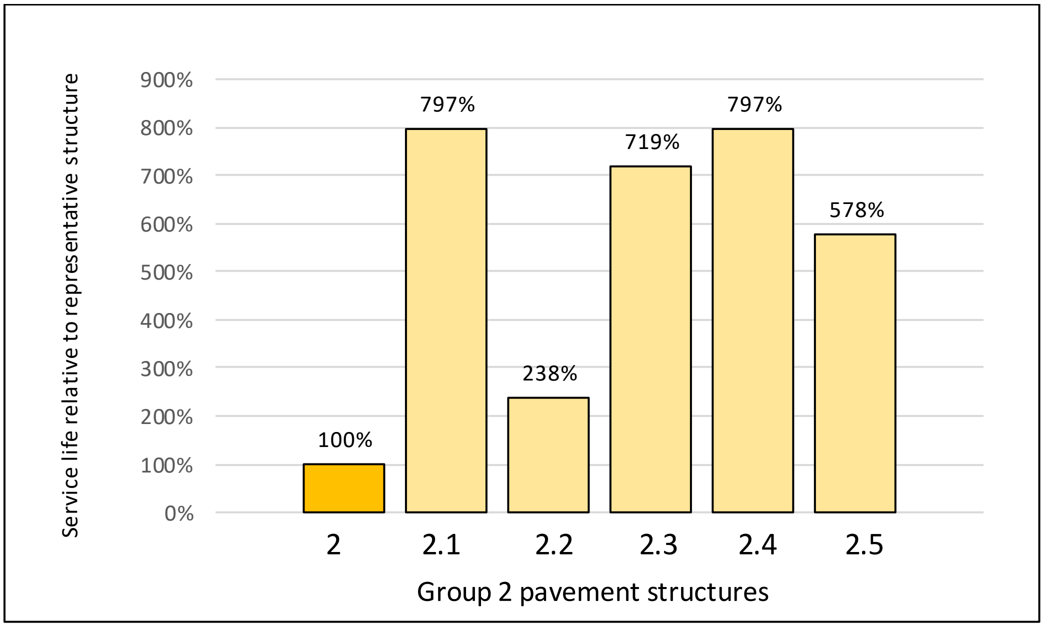

Figure 13. Comparison of predicted service life of group 2 pavements relative to structure 2.

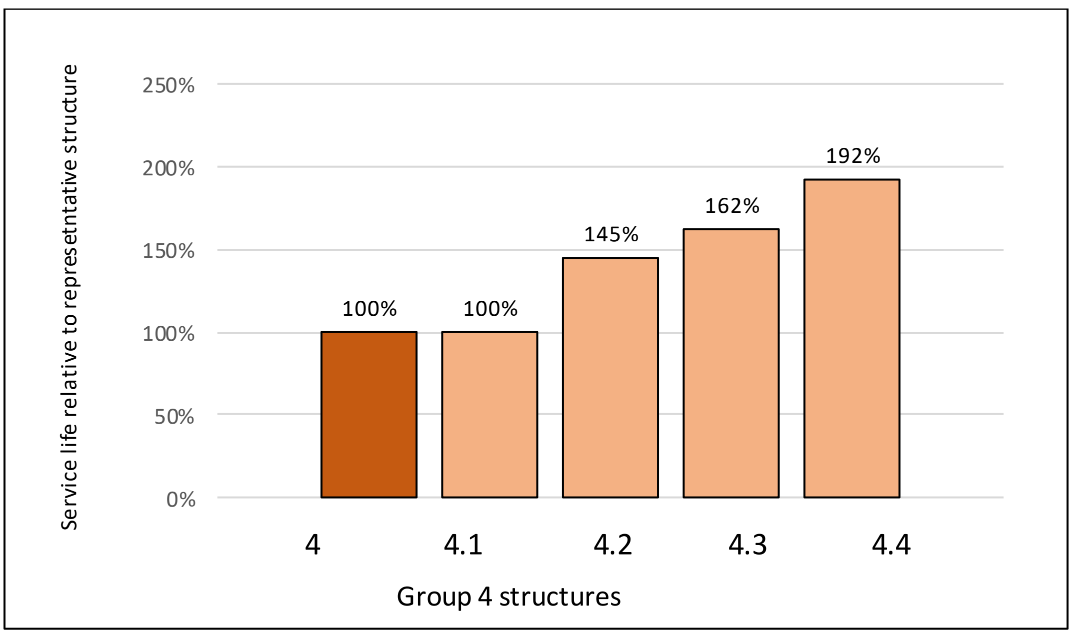

Figure 14. Comparison of predicted service life of additional group 4 pavements relative to structure 4.

Conclusions

This paper summarizes the analysis of pavement impacts within a proposed hauling corridor near Thunder Bay by a proposed, new, 72.5-tonne 9-axle tandem-drive log B-train. Pavement impacts from log hauling configurations currently operating in the corridor were used as a baseline against which to compare the impacts of the 9-axle configuration.

This configuration would be relatively easy to assemble from existing 8-axle log B-trains and so represents a relatively low-cost opportunity to improve industry competitiveness and transport safety. 9-axle B-train log hauling configurations already have been operating in BC, AB, and SK for many years and have a safe operating record. Additional benefits of this high-efficiency configuration include a substantial reduction in fuel use and greenhouse gas emissions.

A load equivalency analysis was conducted using both the AASHTO equation and TAC equations supplemented with recently developed widebase LEF. Both analyses found the same trends:

- The load equivalency per trip was lowest for the 72.5-t 9-axle tandem-drive B-train and highest for the 62.1-t 7-axle tractor/ quad semi-trailer.
- The ESALs per tonne payload also were lowest for the 72.5-t 9-axle tandem-drive B-trains and highest for the 62.06-t 7-axle tractor/ quad semi-trailer. The reference vehicles generated between 11% and 34% more impact to pavements per tonne payload.
- The number of trips required and associated ESALs to move the same annual tonnage of logs was lowest for the 72.5-t 9-axle tandem-drive B-train and highest for the 62.06-t 7-axle tractor/ quad semi-trailer.

A long-term damage analysis was conducted with conservative (weak) pavement structure representing each of four distinct pavement types in the corridor. The analysis estimated the number of truck passes by each of the subject trucks to cause a failed condition in each pavement. Both rutting and bottom-up fatigue cracking were considered, and the governing failure mode was identified as the mode that would occur first. In all cases, the reference vehicles failed the pavements faster (in fewer passes) than the 9-axle tandem-drive log B-train—indicating that the 9-axle B-train was more road friendly and replacing the current log trucks with the 9-axle configuration will reduce pavement impacts and increase maintenance intervals of the corridor pavements.

A sensitivity analysis also was conducted in which the other (non-representative) pavement structures within each grouping of pavement types were evaluated for rutting and cracking rates to ensure that the weakest pavement structure in the group was, indeed, the one used as the representative conservative structure. Based on estimates of number of passes to reach the governing failure condition, the sensitivity analysis confirmed that each of the four representative pavement structures were the weakest and, hence, most conservative structures with which to model 9-axle B-train impacts.

Given the above, from a pavement perspective, there appears to be a strong argument for accepting the use of the 9-axle tandem-drive B-train at 72.5 tonne AGVW within the defined corridor.

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