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Analysis of Yukon highways pavement damage caused by permitted overload trucks

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INTRODUCTION

In 2019, the Yukon Department of Highways and Public Works contracted FPInnovations to provide a theoretical analysis, of limited scope, of highway damage caused by heavy trucks operating with permitted overloads.

Project objective

The objective of the analysis was to provide the Department with recommendations regarding maximum permitted truck loads on Yukon Highways.

METHODOLOGY

Analysis of Permitted Overload Traffic (2016-2018)

The department provided FPInnovations with the policies and regulations regarding truck overloads in the Yukon territory. In addition, they provided a summary of permit load data from 2016 to 2018 as well as all related truck configurations. As a first step, FPInnovations reviewed and analyzed 12 truck configurations (Figure 1) and the permit load data pertaining to them in the 2016-18 permit load dataset. FPInnovations also calculated the theoretical pavement impacts of each truck trip. For this preliminary analysis, equivalent single axle loads (ESALs) were used to estimate the pavement impacts. ESALs of each configuration were calculated using Transportation Association of Canada (TAC) formulae. Axle loadings were taken to be the worst case allowed under Yukon overweight policy. Gross combined vehicle weight (GCVW) was constrained to either the mean or maximum permitted overload weight for that vehicle combination.

Configuration		
Axle types	Description	Schematic
1-2-3	Tractor/ tridem semi-trailer	
1-2-1-3	Tractor/ jeep/ tridem semi-trailer	
1-2-3-2	Tractor/ tridem semi-trailer with tandem-booster	
1-2-2-3	Tractor/ tandem jeep/ tridem semi-trailer	
1-3-3-1	Tridem-tractor/ tridem semi-trailer with booster axle	
1-3-2-3-1	Tridem-tractor/ tandem-jeep/ tridem semi-trailer with booster axle	
1-2-1-3-1	Tractor/ jeep/ tridem semi-trailer with booster axle	
1-3-2-3-2	Tridem-tractor/ tandem-jeep/ tridem semi-trailer with tandem-booster	
1-2-3-3-2	Tractor/ tridem semi-trailer/ tridem semi-trailer with tandem-booster	
1-2-2-3-1	Tractor/ tandem-jeep/ tridem semi-trailer with booster axle	
1-2-2-3-2	Tractor/ tandem-jeep/ tridem semi-trailer with tandem-booster	
1-2-2-2-2	Tractor/ tandem-jeep/ tandem semi-trailer with tandem-booster	

Figure 1. Truck configurations receiving Yukon overload permits.

Table 1 summarizes the pavement impacts estimated in the preliminary analysis. The total impact from each truck configuration was taken to be the number of trips during the three-year period multiplied by the average ESAL count for its configuration. Representative tire sizes, axle spreads and interaxle distances were estimated for each configuration based upon applicable weights and dimensions regulations from British Columbia and the Yukon.

Table 1. Preliminary analysis of pavement impacts from permit overloads (2016-18)

Truck configuration	No. of trips (2016-2018)	ESALs per trip[1]		Relative impact	
		(Mean weight)	(Max weight)	(Mean weight)	(Max weight)
1-2-3	64	4.8	7.8	**6%**	**7%**
1-2-1-3	33	6.5	10.9	4%	5%
1-2-3-2	34	6.6	7.2	5%	3%
1-2-2-3	27	6.8	9.0	4%	3%
1-3-3-1	19	6.4	9.0	3%	2%
1-3-2-3-1	26	8.3	10.6	4%	4%
1-2-1-3-1	52	8.6	14.7	**9%**	**11%**
1-3-2-3-2	13	8.0	11.4	2%	2%
1-2-3-3-2	32	8.9	11.0	6%	5%
1-2-2-3-1	166	9.9	15.3	**34%**	**36%**
1-2-2-3-2	76	11.0	15.1	**17%**	**16%**
1-2-2-2-2	18	12.0	21.5	5%	5%
All configurations	**560**			**100%**	**100%**

NOTE: ESALs of each configuration were calculated using Transportation Association of Canada formulae. The sum of axle loads was constrained to either the mean or maximum permitted overload GCVW for that configuration.

A total of 4799 ESALs resulted from summing the number of permitted overload trips by each configuration in the 3-year period multiplied by its mean permitted weight. Just four truck configurations accounted for 2/3 (67%) of the total theoretical pavement damage generated by all permitted overload weights. A similar result was obtained when ESALs were calculated using the vehicles' maximum approved permit weights (7132 ESALs in total with the four configurations accounting for 69%).

Based on this preliminary analysis, it was agreed to focus the analysis on the following four truck configurations:

- 1-2-3 (single-steer, tandem-drive tractor/ tridem semi-trailer)
- 1-2-1-3-1 (single-steer, tandem-drive tractor/ jeep/ tridem semi-trailer/ single-axle booster)
- 1-2-2-3-1 (single-steer, tandem-drive tractor/ tandem-jeep/ tridem semi-trailer/ single-axle booster)
- 1-2-2-3-2 (single-steer, tandem-drive tractor/ tandem-jeep/ tridem semi-trailer/ tandem-axle booster)

Reference truck configurations

Given that objective of the project is to quantify the incremental pavement impacts arising from the Department's overweight policy, it was agreed to use the above configurations loaded with maximum legal axle weights as the non-permit pavement impact reference vehicles. Although

Yukon Highway Regulation 13 (HR 13) specifies different legal limits for tandem-axle groups with different axle spacing, this was simplified by conservatively assuming a maximum tandem-axle legal weight (19,100 kg). Also, assuming the above configurations use tractors rather than full trucks, it was agreed to use the HR 13-specified maximum legal steering axle weight of 6000 kg for the analysis. Table 2 summarizes the reference truck configurations proposed for use in the detailed pavement damage assessments as well as their max legal gross combined vehicle weights (GCVW). The reference vehicle GCVW and their theoretical ESALs are comparable, albeit slightly greater, than the corresponding mean permit GVW and ESALs given by the 2016-18 population of approved permits. Modeling with these configurations at maximum legal loadings, therefore, will produce a fair and conservative representation of non-permit loads and their pavement impacts

Table 2. Proposed reference configurations for the detailed pavement analysis

Configuration		No. of axles	REFERENCE (Max Legal GCVW (kg))
1-2-3	Tractor/ tridem semi-trailer	6	49,100
1-2-1-3-1	Tractor/ jeep/ tridem semi-trailer with booster axle	8	69,100
1-2-2-3-1	Tractor/ tandem-jeep/ tridem semi-trailer with booster axle	9	78,200
1-2-2-3-2	Tractor/ tandem-jeep/ tridem semi-trailer with tandem-booster	10	87,300

Permitted overload “challenge” truck configurations

The Department’s Carrier Compliance Policy stipulates that permitted axle weights can exceed legal limits by as much as 25% for single axles, 20% for tandem axles, and 15% for tridem axles. These tolerances allow the four subject trucks an increase of payload of 8.9 to 16.6 tonnes, and an increase in GCVW of 18% to 20%. In some cases, exceptional loads that exceed these limits receive approval, but this occurs rarely and only a case by case basis, as stated in the 2010 overweight permit policy that was provided FPInnovations. In the case of the four configurations, the maximum approved permit GVW during 2016-18 never exceeded the legal plus tolerance limits. It was decided, therefore, to use the above configurations loaded with maximum legal axle weights plus the axle weight tolerances as pavement impact “challenge” vehicles (Table 3).

Table 3. Permit overload “challenge” configurations for the detailed pavement analysis

Configuration		No. of axles	Permitted GCVW (kg)	Increase over legal
1-2-3	Tractor/ tridem semi-trailer	6	58,020	18%
1-2-1-3-1	Tractor/ jeep/ tridem semi-trailer with booster axle	8	83,020	20%
1-2-2-3-1	Tractor/ tandem-jeep/ tridem semi-trailer with booster axle	9	93,440	19%
1-2-2-3-2	Tractor/ tandem-jeep/ tridem semi-trailer with tandem-booster	10	103,860	19%

The proposed challenge loads and the corresponding theoretical pavement impacts (ESALs) are similar but slightly greater than the corresponding maximum permit GCVW given in the 2016-18 population of approved permitted overloads (Figures 2 and 3). It should be noted that, for all four configurations, the legal plus full permit overload tolerance GCVW was greater than the corresponding max permit GCVW; and, the legal plus full permit overload tolerance ESALs was greater than the corresponding max permit ESALs given by the 2016-18 population of approved permits (Figures 2 and 3). Modeling with these configurations at legal plus tolerance permit loadings, therefore, produced a fair but conservative representation of permitted loads and their pavement impacts.

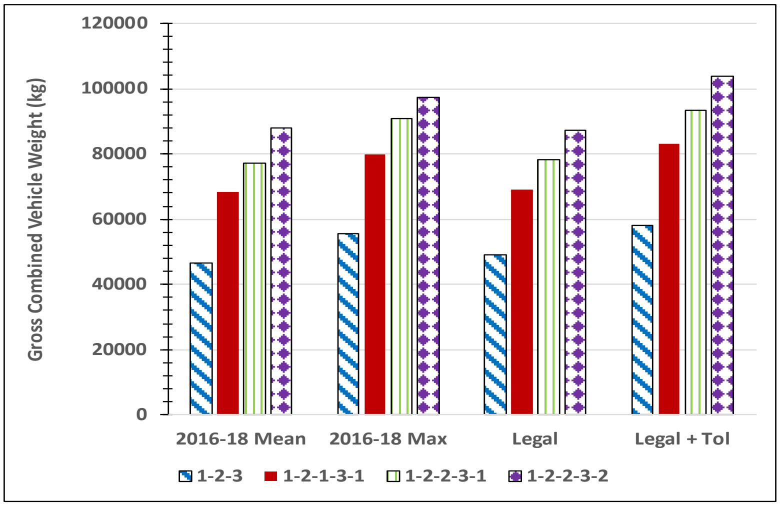

Figure 2. Comparison of the mean and maximum permitted overload GCVW from 2016 to 2018, legal highway loads, and legal highway loads plus full permit overload tolerances for 4 truck configurations.

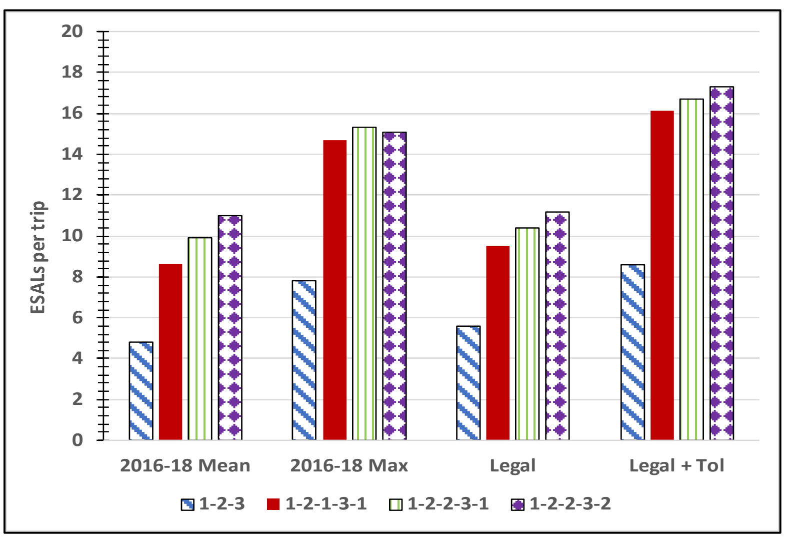

Figure 3. Comparison of ESALs for the mean and maximum permitted overload from 2016 to 2018, legal highway loads, and legal highway loads plus full permit overload tolerances for 4 truck configurations.

Truck axle and tire configurations and loads

Table 4 summarizes the axles, tires, and axle loads defined for the four truck configurations modeled in this analysis. More detail about these configurations (e.g., wheel spacing, tire contact areas) are given in Appendix 1 and Appendix 2. A cold inflation pressure of 690 kPa (100 psi) was assumed for all sizes and tire loads, as per typical industry practice. The tire contact areas were estimated based upon tire volume, inflation, and load using formulae from the Tire & Rim Association (Tire & Rim 2009).

Table 4. Truck axle and tire arrangements, tire sizes, and axle group loadings

Axle group	Tire size	Tire arrangement	Legal load (kg)	Maximum permit load (kg)	Overload tolerance (%)
Steering axle	385/65R22.5	Single	6,000	7,500	25%
Drive - tandem	11R24.5	Dual assembly	19,100	22,920	20%
Single jeep or booster axle	11R22.5	Dual assembly	10,000	12,500	25%
Tandem jeep or booster axle	11R22.5	Dual assembly	19,100	22,920	20%
Trailer - tridem	11R22.5	Dual assembly	24,000	27,600	15%

Representative Highway Sections and Seasonal Material Properties

In order to cover a wide range of pavements in the Yukon territory, the department provided FPInnovations with four distinct highway sections that are representative. The range of structures includes bitumen surface treatment (BST) sections with and without a subbase course, a relatively strong asphaltic concrete pavement, and relatively weak gravel-surfaced roadway.

The four low volume highway types selected for analysis are:

1) Bitumen Surface Treatment (BST) pavement typical of the Alaska Highway (Highway 1) between Watson Lake and Whitehorse;
2) BST pavement typical of the Klondike Highway (Highway 2) between Carmacks and Dawson City;
3) Gravel-surfaced road typical of the middle portion of the Campbell Highway (Highway 4);
4) Hot mix asphalt (HMA) pavement within Whitehorse Corridor and Watson Lake town.

A single thickness or, in some cases, a range of thicknesses was specified for each layer of the highways. It is important to mention that initially, 2 similar BST sections without subbase were proposed by the department (Klondike and Tagish). After discussion, FPinnovations and the department came to an agreement to replace the Tagish highway section with the HMA pavement to increase variability of the pavement structures.

The typical profiles (thicknesses) proposed in this study for each of the four roads were validated by data collected by Golder and associates in the FWD study they conducted in 2017 for the department (Golder & Associates, 2017).

Table 5 summarizes the layer thicknesses of the analyzed structures, what highway they are representative of, and any additional remarks about the structure.

Table 5. Representative Yukon highway structures

Highway	Segment	Location	Layer thickness (mm)				Remarks
			BST	AC	Base	Subbase	
Alaska Highway	Watson Lake to Whitehorse	KM 1209 to 1266	25	0	120	380	Base course varies from 80 to 160 mm. Total thickness of base plus subbase does not exceed 500 mm. Subgrade is poor (silty, clayey).
Alaska Highway	Watson Lake to Whitehorse	KM 1209 to 1266	0	45	225	480	Used with GP subgrade
Klondike Highway North	Carmacks to Dawson City	KM 358 to 700	25	0	90	0	Base course thickness varies from negligible to 150 mm.
Campbell Highway	Middle	KM 115 to 360	0	0	75	0	Gravel-surfaced roads commonly have 50-100 mm of surfacing aggregate over the subgrade.

The influence of seasonal variation was considered in this study. Three representative seasonal conditions were defined for each road presented in table 5. This was accomplished by defining the material properties representative of well drained, unfrozen conditions (i.e., typical of summer-fall), and frozen to a depth of 75 cm (i.e., typical of early winter conditions). Late spring conditions were modeled using 80% recovery strength values estimated from FWD testing – this corresponded to the upper portion of granular materials being well drained and the lower portion (plus the underlying subgrade) being partially saturated. Pavement materials' properties for all four highways and three seasonal conditions, such as conservative values of resilient moduli (Mr) were drawn from on-line sources (e.g., on-line databases owned by Alberta Transportation, University of Laval, *Ministere des Transports du Quebec*) and from FPInnovations' own database of pavement material properties. These data base provide values of Mr for pavement materials comparable to the ones used in the Yukon territory. When available, these properties were determined in reference to the Department's material test data. These values were validated by comparing them to values found in the literature, including the Level 3 analysis values in the Mechanistic Empirical Pavement Design Guide (MEPDG) and the results from FWD testing conducted by Golder and Associates in the Yukon territory in 2017 (Golder and Associates, 2017). These materials mechanical properties (resilient modulus and Poisson Ratio are critical for the analysis.

As for the subgrade for each road structure, it was assumed that they can vary tremendously due to Yukon geological context. Therefore, in order to be conservative, the weakest subgrades in the territory were chosen for this analysis.

Table 6 summarizes the seasonal variation of material properties used in the analysis.

Table 6. Pavement material properties representative of 4 highways and 3 seasonal conditions

Season	Pavement material modeling parameters						Remarks
	Resilient modulus (MPa) and Poisson's ratio [ ]						
	AC	BST	Surfacing aggregate	Granular Base	Granular Subbase	Subgrade	
Summer	2200 [0.35]	1250 [0.35]	225 [0.35]	200 [0.35]	100 [0.35]	60 (Hwy 1 BST); 125 (Hwy 4); 185 (Hwy 2); 80 (Hwy 1 ACP) [0.40]	Granular A 20 mm crushed Base close to OMC. Granular E 200 mm pit run Subbase near OMC. Subgrade ML/ MH/ CL/ CH soils partly saturated.
Late spring	2200 [0.35]	1250 [0.35]	225 (upper) 155 (lower) [0.35]	200 (upper) 140 (lower) [0.35]	80 (only AC pavement) 100 (upper) 65 (lower) [0.35]	35 (Hwy 1 BST); 70 (Hwy 4); 110 (Hwy 2); 60 (Hwy 1 ACP) [0.40]	Surfacing aggregate on Campbell Highway split (upper 70 mm drained; lower 30 mm plus subgrade partly saturated corresponding to FWD-test values for 80% recovered condition). Granular Base layer in Klondike BST Highway split (upper 65 mm drained; lower 25 mm plus subgrade partly saturated corresponding to FWD-test values for 80% recovered condition). Granular Subbase in Alaska AC structure assigned resilient modulus = 80 MPa (entire 480 mm plus subgrade assumed partly saturated corresponding to FWD-test values for 80% recovered condition). Alaska BST structure: Granular Base not split (all is considered "upper"). Granular Subbase layer is split (upper 260 mm drained; lower 120 mm plus subgrade partly saturated corresponding to FWD-test values for 80% recovered condition).
Winter	21000 [0.10]	16000 [0.20]	950 [0.15]	850 [0.15]	600 [0.15]	400 (upper Hwy 1 BST, Hwy 2, and Hwy 4). 60 (lower Hwy 1 BST); 160 (lower Hwy 2); 120 (lower Hwy 4). 100 (Hwy 1 ACP) [0.15] (upper - frozen) [0.40] (lower - unfrozen)	Assumed well frozen to 750 mm depth. Subgrade in Alaska BST Highway split (upper 225 mm frozen and below this unfrozen and undrained). At frost depth = 750 mm, GP subgrade in Alaska AC Highway is unfrozen and undrained (Mr = 100 MPa; Poisson's ratio = 0.4). Subgrade in Klondike BST Highway is split (upper 635 mm frozen and below this unfrozen and undrained). Subgrade in Campbell gravel Highway is split (upper 650 mm frozen and below this unfrozen and undrained).

Note (1): Modulus of subgrade varied depending on estimates of maintenance interval (i.e., minimum truck passes to a failed condition in rutting).

Analysis Approach

The methodology of the advanced pavement modeling consists of determining the short term and long-term impacts of each of the truck loads. This analysis was accomplished by estimating the spontaneous strain and stress responses under loading. The test matrix involved analysis of 4 truck configurations (with 3 to 5 types of axles each), 4 highway structures, 3 seasons, and 2 loading conditions. This resulted in the evaluation of 432 unique pavement response combinations.

Strains in response to vehicle loading 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 (ERDC). 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 were:

- Pavement material mechanical properties (resilient modulus (Mr) and Poisson's ratio);
- Pavement material thicknesses; and,
- Axle loading, tire size, tire type, tire contact pressure.

These input data were previously defined in this report.

Following the pavement modeling to assess the spontaneous response of each load, a long-term damage analysis also was performed using the spontaneous strain results to estimate the number of load repetitions to reach a failed condition. This analysis was performed using Asphalt Institute's transform equations (Huang 2004) and focused on two performance parameters:

- Horizontal tensile strain at the bottom of the asphaltic concrete mat (maximum bottom-up fatigue cracking criteria) in the case of hot mix asphalt pavements;
- Vertical compressive strain at the top of the subgrade layer (maximum rutting criteria).

Asphalt Institute's surface rutting equation:

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

Where,
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:

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

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 asphaltic concrete mat
E = resilient modulus of the asphaltic concrete (psi)

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

V_{beff} = effective bitumen content [1]
V_v = voids content [2]

For each combination of loading, season, and pavement, the rates of damage caused by each axle type were aggregated using Miners' Law to estimate the rate of pavement damage from each truck configuration.

A detailed analysis was made of theoretical pavement damage from the subject truck configurations loaded to maximum permitted overload weights. The resulting damage rates were compared with those generated by the same configurations loaded to legal highway axle weights.

A sensitivity analysis was performed to select representative values for resilient modulus in order that predicted service life agreed with expected service life (Appendix 3). The Alaska Highway BST section was defined as having a range of base course thicknesses (i.e., 80 to 160 mm). Therefore, an additional sensitivity of results from thin or thick granular base layers was conducted and is included in Appendix 4.

Finally, a sensitivity analysis was conducted of pavement damage for several levels of permitted overloading, with results arranged by axle type, configuration, season, and highway structure.

[1] In consultation with Yukon H&PW, the effective bitumen content was estimated to be 11% for this analysis.
[2] In consultation with Yukon H&PW, the voids content was estimated to be 5% for this analysis.

RESULTS

Comparisons of Spontaneous Strain

As explained in the methodology section, WinJULEA allows the prediction of spontaneous strains in a pavement in response to static wheel loads. While these strains typically are greater than strains developed in response to moving loads, the values are useful for making relative comparisons of impacts due to axle and tire configurations and due to the level of overloading. For the purposes of this comparison, spontaneous strains were reported at the top of the subgrade where the vertical compressive strain is correlated to surface rut development.

Alaska Highway BST structure

Figure 4 illustrates the predicted spontaneous subgrade strains in a representative BST pavement on the Alaska Highway due to five legally loaded axle configurations.

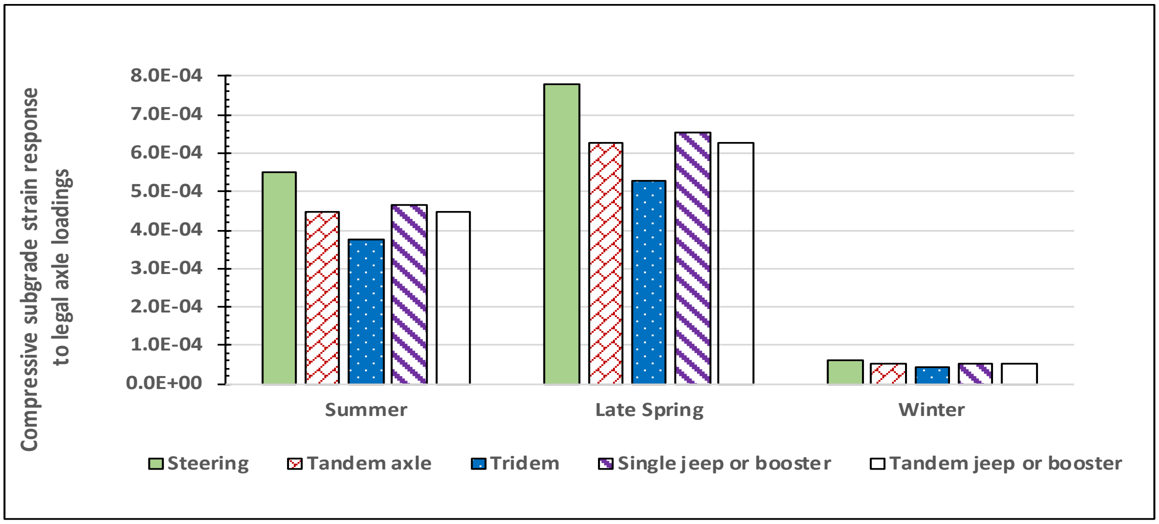

Figure 4. Subgrade strain in BST pavement sections of the Alaska Highway at legal highway loadings, by axle type and season.

Steering axles at a legal 6,000 kg loading were found to generate the highest spontaneous strains. These were 24% higher than tandem axle drive group at the 19,100 kg legal loading. The tandem drives and tandem jeep or tandem booster generated about the same spontaneous subgrade strains. A single jeep or booster axle loaded to 10,000 kg generated only about 5% more strain than the legally loaded tandem axles while the legally loaded (24-tonne) tridem axle generated 16% less rutting strain than a legally loaded tandem axle. These proportions remained the same regardless of season.

Per typical industry practice, tandem axle drive groups were modeled with 11R24.5 tires whereas trailer tandem axle groups were modeled with 11R22.5 tires. At the two tandem axle loadings, use of differently sized tires resulted in the 11R24.5 tires having 4-5 cm^2 more contact area per tire than the 11R22.5 tires; the difference in predicted spontaneous strains, however, was negligible.

As anticipated, strains in the spring were the highest during the year and strains in the winter were the lowest. For corresponding axles, instantaneous strains in the late spring (at an 80% recovered condition) were estimated to be 41% higher than in the late summer. In contrast, those same axles generated only 11% of summer levels in the early winter (with a 75 cm frost depth).

Figure 5 illustrates the relative increase in predicted subgrade strains for the same highway at maximum permit loads.

As illustrated in Figure 5, a direct correlation was observed between the percentage increase in permit overload and the predicted increase in spontaneous strain. That is, single axles permitted 25% higher loads generated 24% higher strains; tandem axles permitted 20% higher loads generated 19% higher strains; and, tridem axles permitted 15% higher loads generated 14% higher strains.

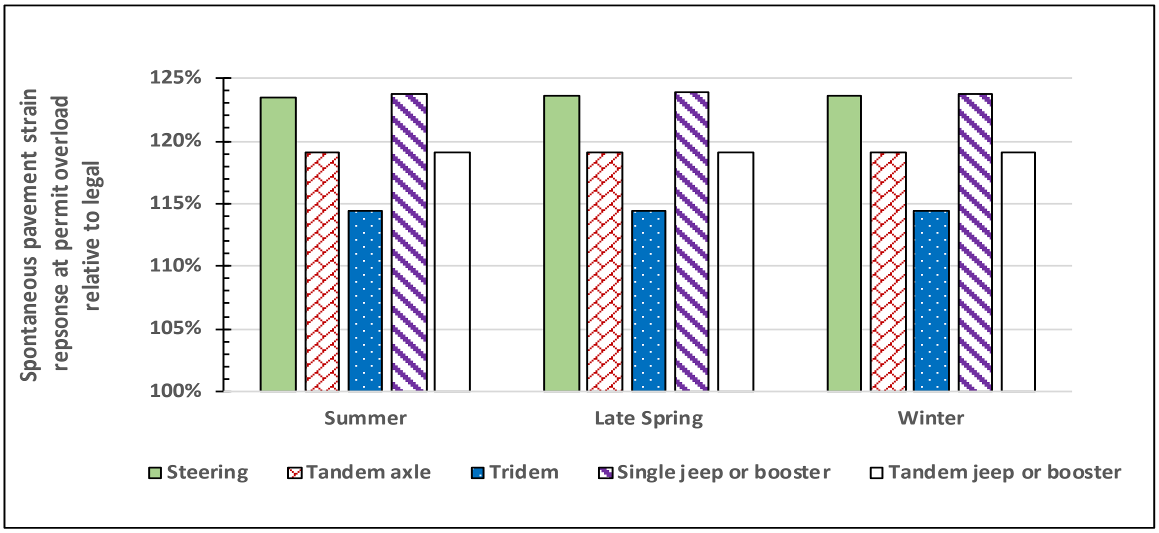

Figure 5. Effect of permit overloading, axle type, and season on subgrade strain in BST pavement sections of the Alaska Highway.

As noted in Figure 4, single axles (steering or single jeep or single booster axles) at legal loads had the highest pavement impacts (i.e., 24% higher strains than tandem axles at legal loads). When overloaded by 25% (under permit) the strains of these already highly impactful axles are increased dramatically. The spontaneous strains from 25% overloaded single axles were 53% higher than tandem axles at legal loads. This effect held for single and tridem axle types but to a lesser degree because their overloading percentage was less.

While the use of widebase single steering tires is expected to reduce strains near the surface of pavements, BST pavements fail primarily by primary rutting and this tends to be governed by wheel load rather than tire contact area.

Klondike Highway North BST structure

Figures 6 and 7 illustrate the predicted spontaneous subgrade strains in a weaker BST pavement, such as found on the Klondike Highway North, in response to legal weights and permitted overloads. This pavement structure differs from the Alaska Highway BST structure in that it has 25% less granular A (base) and no subbase.

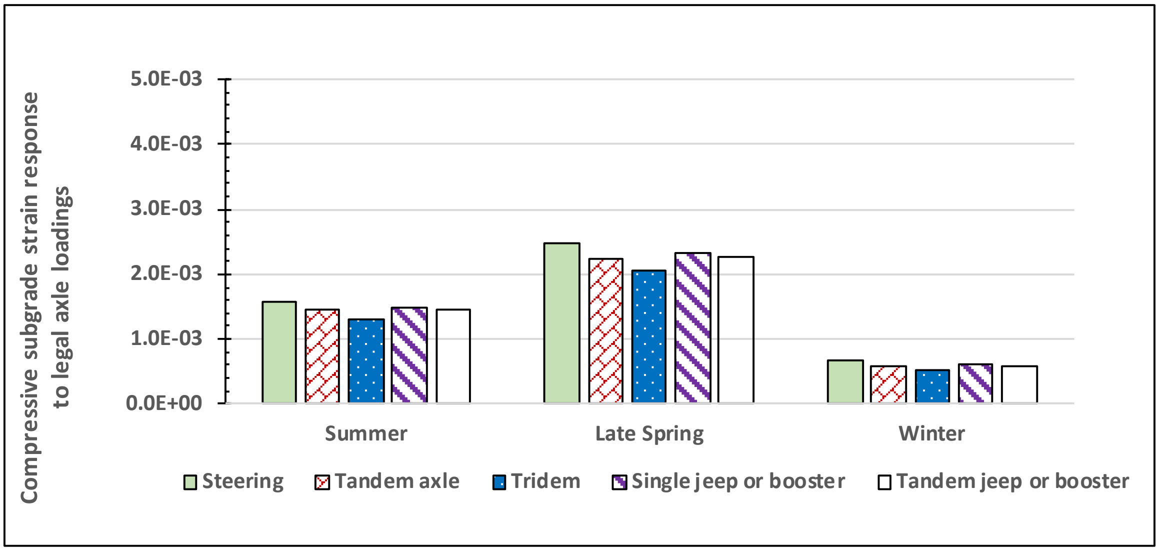

Figure 6. Subgrade strain in BST pavement sections of the Klondike Highway North at legal highway loadings, by axle type and season.

As would be anticipated with this thinner structure the Klondike Highway North BST structure was more sensitive to axle loading than was the Alaska Highway BST structure. In response to legal axle loads, spontaneous strains in the Klondike Highway North BST structure in the late spring were between 6.4 and 7.5 times more than in the Alaska Highway BST structure. Perhaps of more concern given the length of time that summer-fall conditions exist, spontaneous strains in the Klondike Highway North in summer conditions were between 6 and 7 times more than in the Alaska Highway BST structure. During early winter and in response to legal loads, spontaneous strains in the Klondike Highway North were between 9.5 and 11 times more than in the Alaska Highway BST structure, however, given the relatively small absolute values of these strains this is not anticipated to be of concern for pavement damage.

The differences in spontaneous strain resulting from axle type were less pronounced in the Klondike Highway North BST structure than was observed in the Alaska Highway BST structure; however, the pattern of relative strain differences was similar. Legally loaded (6-t) steering axles generated the highest spontaneous strains, and these were 12%-14% higher than strains from legally loaded (19.1-t) tandem axles. Legally loaded (10-t) single jeeps or booster axles generated 3%-4% more strain than legally loaded tandem axles. Legally loaded (24-t) tridem axles generated 11% less strain than legally loaded tandem axles. The small range in strain increases noted above (1% to 2%) was caused by seasonal variation of material properties.

Strains in the spring were the highest during the year and strains in the winter were the lowest. For corresponding axles, instantaneous strains in the late spring (at an 80% recovered condition) were estimated to be about 45% higher than summer-fall levels. In contrast, those same axles generated only 17% of summer-fall levels in the early winter (with a 75 cm frost depth).

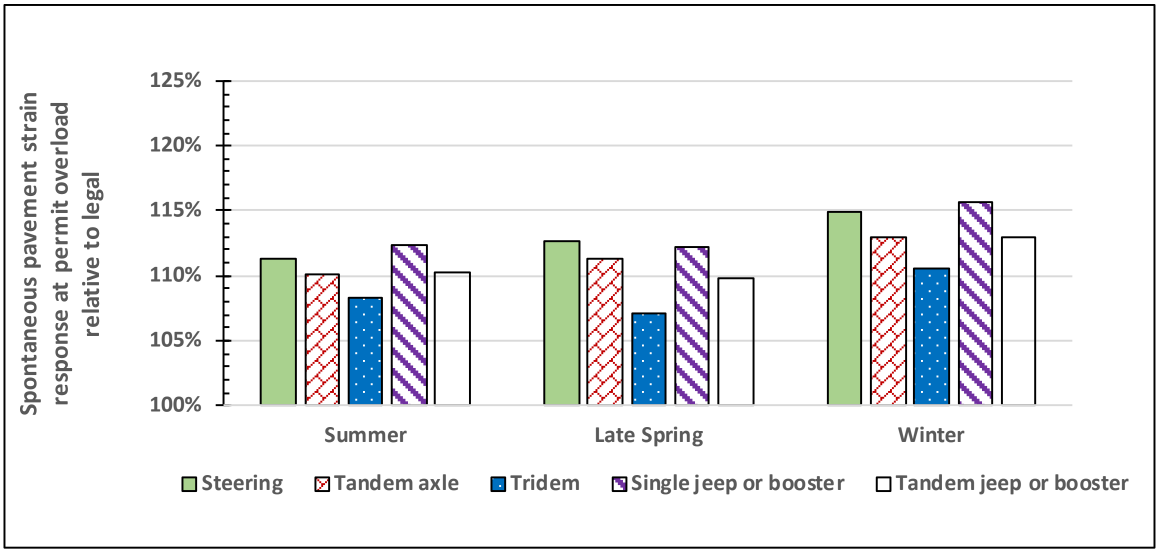

Figure 7. Effect of permit overloading, axle type, and season on subgrade strain in BST pavement sections of the Klondike Highway North.

Given the thinner structure and resulting high levels of strains at legal loads there was no longer a direct correlation between the percentage increase in permit overload and the predicted increase in spontaneous strain. Instead, single axles that are currently permitted 25% higher loads generated only 11%-16% higher strains; tandem axles which are currently permitted 20% higher loads generated only 10%-13% higher strains; and, tridem axles which are currently permitted 15% higher loads generated only 7%-11% higher strains.

As illustrated in Figure 5, single axles (steering or single jeep or single booster axles) at legal loads had the highest pavement impacts, and these were 12%-14% higher, depending on season, than strains from legally loaded tandem axles. When overloaded by 25% (under permit) the strains of these already highly impactful axles were increased to 27%-31% higher than the strains from legally loaded tandem axles, depending on seasonal conditions. This effect held for other axle types but to a lesser degree because of their reduced overload tolerances and their reduced strain levels relative to legally loaded tandem axle strains.

Campbell Highway gravel structure

Given their structural similarity and given that a thin BST coating acts fundamentally like an equivalent depth of gravel, the Campbell Highway and the Klondike Highway North BST structures were expected to have similar spontaneous strain results.

Figure 8 illustrates the predicted spontaneous subgrade strains in the gravel-surfaced highway structure due to 5 legally loaded axle configurations. Figure 9 illustrates the relative increase in predicted spontaneous subgrade strains for the same highway at maximum permit loads.

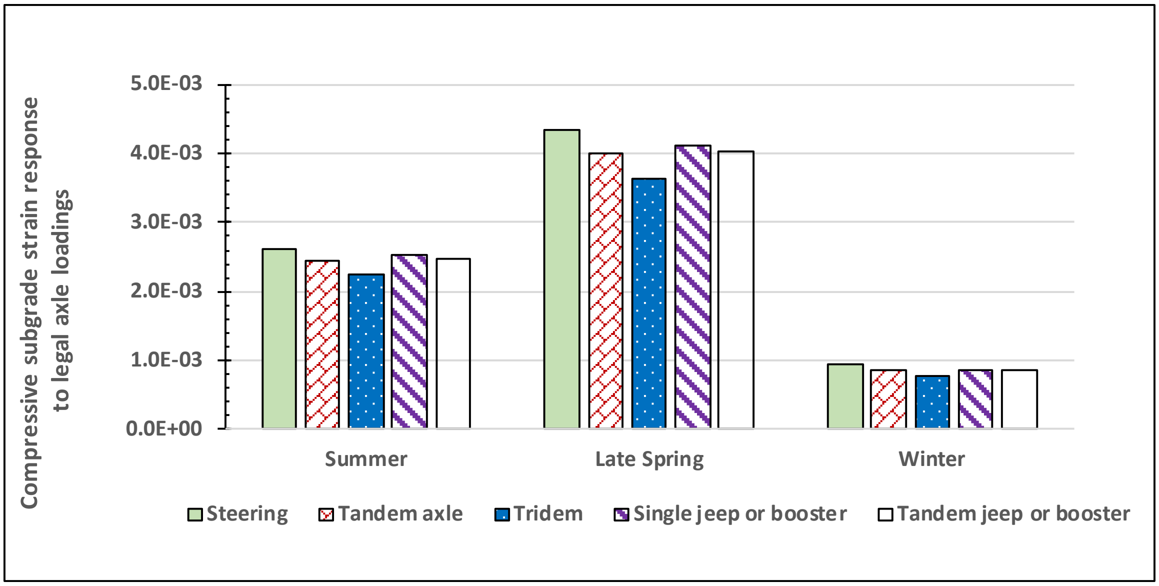

Figure 8. Subgrade strain in gravel-surfaced sections of the Campbell Highway at legal highway loadings, by axle type and season.

The Campbell Highway gravel-surfaced structure is slightly weaker than the Klondike Highway North BST structure. As a result, summertime strains due to legal axle loadings were about 18%-20% higher, depending on axle type, than in the Klondike Highway BST structure. In late spring conditions, the Campbell Highway gravel highway had 26%-31% higher strains than the Klondike BST structure. In early winter conditions, the Campbell Highway gravel highway had 38%- 47% higher strains than the Klondike BST structure.

The differences in spontaneous strain resulting from axle type were less pronounced in the Campbell Highway gravel structure than were observed in the Klondike Highway North BST structure; however, the pattern of relative strain differences was similar. Legally loaded (6-t) steering axles generated the highest spontaneous strains; these steering axle strains were 12%-14% higher than strains from legally loaded (19.1-tonne) tandem axles. Legally loaded (10-t) single jeeps or booster axles generated 3%-4% higher strains than legally loaded tandem axles. Legally loaded (24-t) tridem axles generated 11% lower strains than legally loaded tandem axles. The small range in strain increases (1% to 2%) that are noted for the various axle types are the result of seasonal variation of material properties.

Strains in the spring were the highest during the year and strains in the winter were the lowest. For corresponding axles, instantaneous strains in late spring conditions were estimated to be about 52%-56% higher than summer-fall levels, depending on axle type. In contrast, those same axles generated only 20% of summer-fall levels in the early winter conditions.

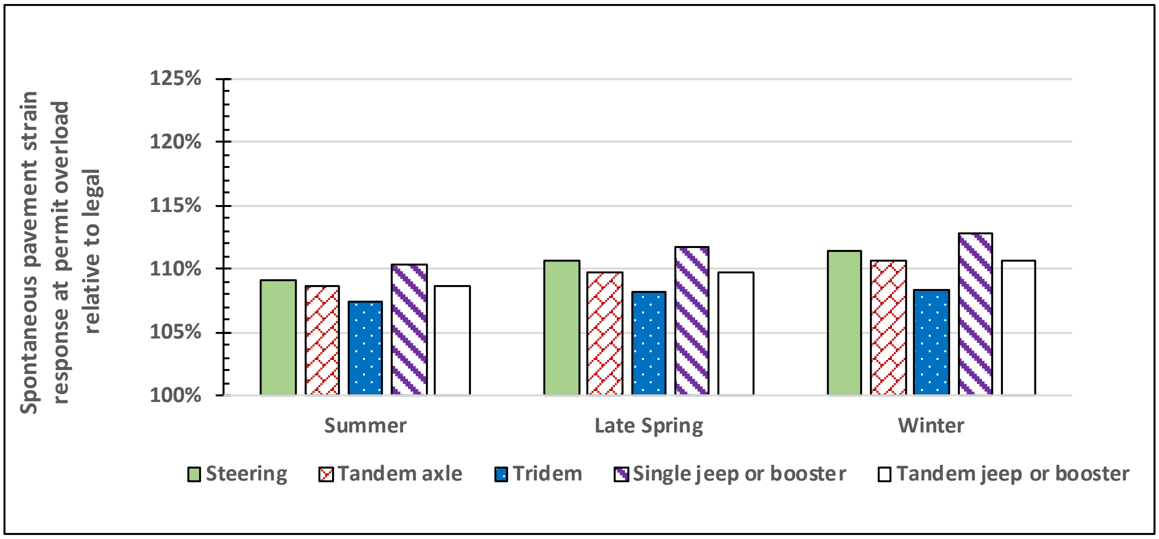

Figure 9. Effect of permit overloading, axle type, and season on subgrade strain in gravel-surfaced highway sections of the Campbell Highway.

As with the weak BST structure of the Klondike Highway North the gravel-surfaced highway structure had relatively high strains at legal axle loadings and did not have a direct correlation between the percentage increase in permit overload and the percentage increase in spontaneous strain. Instead, single axles with 25% overloads generated 11%-14% higher strains; tandem axles with 20% overloads generated 8%-11% higher strains; and, tridem axles with 15% overloads generated 8%-9% higher strains. The small range in strain increases (1% to 3%) that are noted for the various axle types are the result of seasonal variation of material properties.

As illustrated in Figure 8, single steering axles at legal loads had the highest strains, and these were 9%-11% higher, depending on season, than from legally loaded tandem axles. When overloaded by 25% (under permit) the strains of these already highly impactful axles were increased to 22%-25% higher, depending on season, than strains from legally loaded tandem axles. This effect held for other axle types but to a lesser degree because of their reduced overload tolerance and their reduced strain levels relative to legally loaded tandem axle strains.

Alaska Highway AC structure

Asphaltic concrete (AC) pavements are used relatively infrequently in the Yukon, however, they were included in the analysis for completeness and they provide an opportunity to examine pavement wear trends in a stronger pavement structure. In contrast to BST pavements, it is necessary to consider both surface rutting and fatigue cracking of the asphalt mat in AC pavements. It was found that fatigue cracking rather than surface rutting was the governing failure mode for the Alaska Highway AC structure. The spontaneous strains results, therefore, are for horizontal tensile strains at the bottom of the AC mat and are indicated to be tensile strain with a negative sign.

Figure 10 illustrates the predicted spontaneous subgrade strains in a representative AC pavement on the Alaska Highway due to 5 legally loaded axle configurations. Figure 11 illustrates the relative increase in predicted spontaneous AC mat strains for the same highway at maximum permit loads.

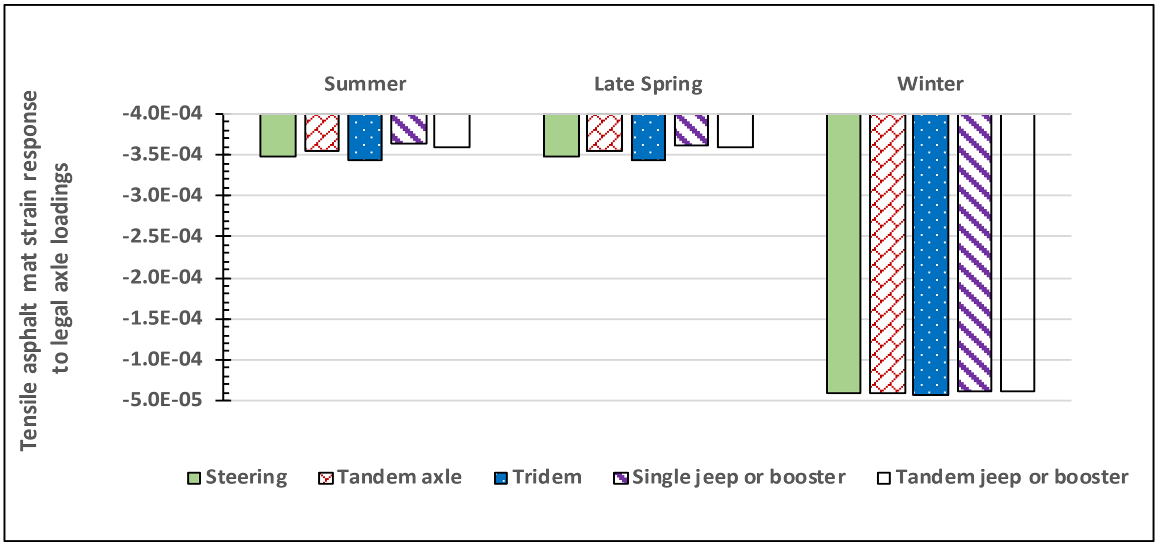

Figure 10. Tensile strain in the AC mat of pavement sections of the Alaska Highway at legal highway loadings, by axle type and season.

The largest tensile strains at legal axle loads were generated by single axle jeeps and single booster axles, under summer and late spring conditions. These single axles generated about 2% more strain than legally loaded drive tandem axles. Steering axles and tridem axles at legal loadings were found to generate the least spontaneous tensile strain. These were 2%-4% less than the strain generated by legally loaded drive or trailer tandem axles. Under winter conditions the AC tensile strains became very small and the differences due to axle type negligible.

On an axle-by-axle basis, tensile strains in the AC mat were predicted to be about the same in the summer as in the late spring, but about only 17% of these strain levels in the winter.

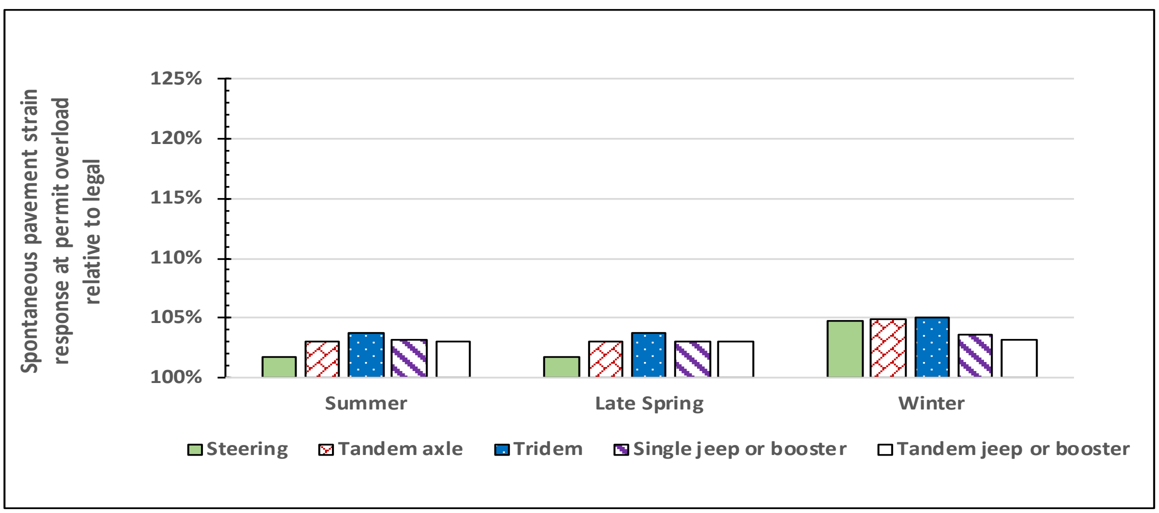

Figure 11. Effect of permit overloading, axle type, and season on subgrade strain in AC pavement sections of the Alaska Highway.

The Alaska Highway AC pavement is relatively insensitive to load when compared to weaker BST pavements. Increasing the axle loads from legal to permitted overload levels created no more than 2%-4% increase in AC mat strains in the spring and summer. In the winter a similar increase in load created 3%-5% higher strains, however, pavements become relatively load insensitive at this time so a small increase to the small absolute strain levels is of little consequence.

Summary of Spontaneous Strain Results

The following discussion summarizes the learnings from the comparison of key strains (compressive vertical subgrade strain and horizontal tensile asphalt mat strain) from the four axle types and four pavement structures. Figure 12 and Figure 13 illustrate the spontaneous strains for the governing failure modes resulting from steering axles and tridem axles, respectively, under summer conditions. The other axle types (single trailer axles and tandem axles) displayed identical trends but with strain values between those from the steering axles and the tridem axles.

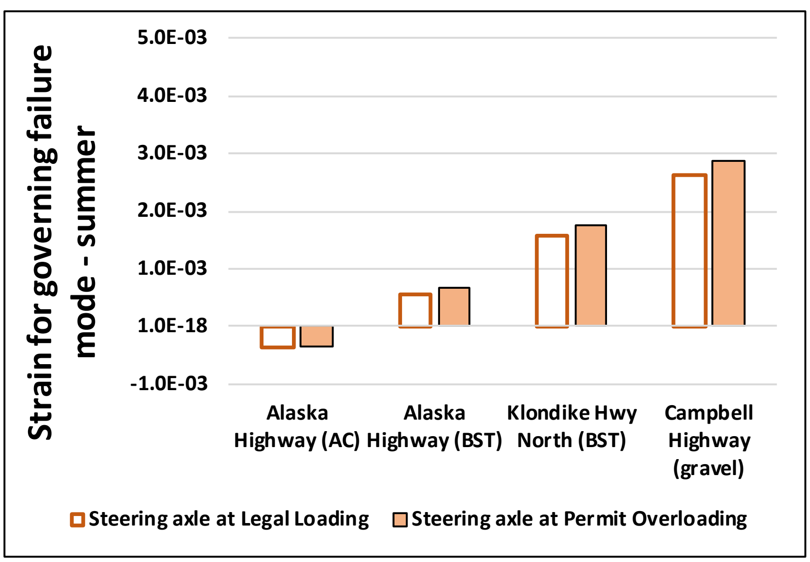

Figure 12. Strains governing failure in 4 highway structures due to steering axle loads under summer conditions.

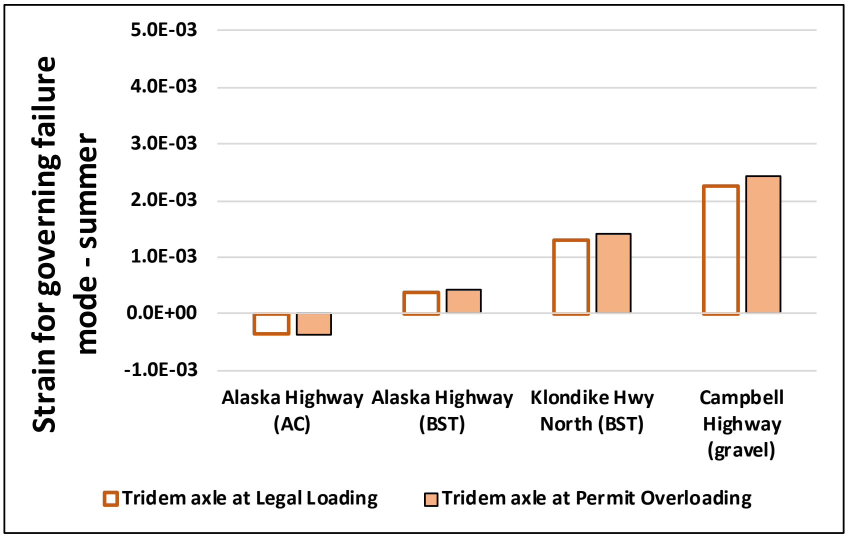

Figure 13. Strains governing failure in 4 highway structures due to tridem axle loads under summer conditions.

Under summer conditions, the highest strains were found in the weakest pavements (i.e., the Klondike North BST and Campbell gravel-surfaced highway). Unlike the rutting failures of the BST and gravel structures, the governing failure mode for the Alaska Highway asphaltic concrete sections was bottom-up fatigue cracking. The predicted fatigue cracking strains were tensile (-ve in the chart) and much smaller in value than the other pavements despite them being from much closer to the pavement surface.

Steering axles had the smallest axle mass (6000 to 7500 kg) but their single tires tended to concentrate the axle load - resulting in the largest rutting and cracking strains. Conversely, tridem axles, which had the highest axle mass (24000 to 27600 kg), have 12 dispersed loads and this resulted in the smallest cracking and rutting strains. Tire contact pressure was comparable for all tires despite the widebase steering tires being larger than the conventional-sized tires used in drive and trailer dual tire assemblies; tire contact pressure increased by 4%-6% with the increase in loading from legal to permit overload.

The spontaneous strains for the governing failure modes under late spring conditions were higher than in the summer but followed a trend in relative size by axle and highway structure. Charts illustrating the results under late spring conditions are presented in Appendix 5. As with the summer conditions, the single and tandem axles displayed strain values between those from the steering and tridem axles.

The BST and gravel highway structures experienced thaw-weakening in the late spring when thaw water concentrated in the subgrade and subbase. Subgrade strains were much higher in these structures at this time of year as compared with summer levels. Conversely, strains associated with fatigue cracking (the governing failure mode in Highway 1 asphaltic concrete (AC) sections) remained unchanged from summer levels because the upper layers of the pavement were relatively drained and strong at this time of year.

The trends identified under summer conditions for strains and axle types also were found to hold under winter conditions. Charts illustrating the results under winter conditions are presented in Appendix 5.

While analysis of spontaneous strains does highlight important trends, it is necessary to transform the strains into predictions of long-term damage in order to understand the pavement implications of the increased strains that resulted with permit overloading.

Long-term Damage Caused by Current Levels of Permit Overloads

Long-term damage estimates for common failure modes of highway pavements can be derived using strain-based transformations, as explained in the methodology section. When comparing multiple failure modes, it is enough to report the lowest number of passes to create a failed condition by either rutting or cracking (whichever failure occurs first is considered the 'governing' failure mode). The following provides a comparison of pavement life subject to the four studied heavy truck configurations and seasonal conditions.

Resilient modulus values used in the modeling were originally set to relatively conservative levels. In the cases of the Klondike and Campbell Highway sections, however, use of these values appeared to result in unreasonably small predictions of pavement service life. When modeling long-term damage for these highways, therefore the resilient moduli values were increased, within validated ranges, to generate predictions of number of truck passes to failure (service life) that were met maintenance interval expectations. In order to establish which of the pavement material properties to vary, a sensitivity analysis (Appendix 3) of long-term service life was conducted; and, this found that subgrade resilient modulus had the largest impact on rutting rate (the prevalent failure mode for Yukon's BST and gravel highways). Given the relatively wide range of stiffness found in CL/ML/CH/MH soils (as compared to that of controlled materials like highway aggregates), it was judged appropriate to vary just the subgrade resilient modulus when trying to increase the predicted number of truck passes to create a failed rutting state.

Winter conditions

Table 7 summarizes the estimated service lives of the four Yukon low volume highway types if subjected to trafficking by four truck configurations with legal and with permit loads, under winter conditions.

Table 7. Predicted service life when subject to overloaded trucks – winter conditions

	Pavement life – winter conditions							
	Alaska Highway BST structure		Klondike Highway BST structure		Campbell Highway gravel structure		Alaska Highway AC structure	
Vehicle	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload
1-2-3	3,688M	1,620M	69,040	40,229	13,934	9,043	3.318M	2.834M
1-2-1-3-1	2,623M	1,107M	48,457	27,261	9,817	6,164	2.369M	2.048M
1-2-2-3-1	2,401M	1,044M	43,654	24,998	8,796	5,595	2.097M	1.824M
1-2-2-3-2	2,214M	988M	39,718	23,082	7,966	5,122	1.881M	1.645M

M = Million. For example, 3,687M = 3,687,000,000 truck passes.

The governing failure mode for the BST and gravel-surfaced highways was surface rutting. The governing failure mode in the AC pavement sections of the Alaska Highway was bottom-up fatigue cracking. The relative insensitivity of frozen pavements to loading is reflected in the service life predictions in Table 7. Under frozen winter conditions all highway structures are predicted to meet appropriate service lives when subject to current levels of permit overloading. The large number of predicted cycles to failure under winter conditions for all highway structures suggests that, in frozen conditions, the current overload tolerances appear to be suitable. Given the relative insensitivity of frozen pavements to overloading, permit overloading tolerances for the winter should be set according to truck safety performance and bridge capacity rather than to highway structural capacity.

Late spring conditions

Table 8 summarizes the estimated service lives of the four Yukon low volume highway types if subjected to trafficking by four truck configurations with legal and with permit loads, under late spring seasonal conditions. This period of high vulnerability is expected to last only about 30 days. Like in winter, the governing failure mode was rutting for the BST and gravel-surfaced highways and fatigue cracking for the AC pavement sections of the Alaska Highway.

Table 8. Predicted service life when subject to overloaded trucks – late spring conditions

	Pavement life – late spring conditions							
	Alaska Highway BST structure		Klondike Highway BST structure		Campbell Highway gravel structure		Alaska Highway AC structure	
Vehicle	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload
1-2-3	49,063	21,517	179	116	14	9	63,968	57,773
1-2-1-3-1	34,915	14,705	123	79	10	6	46,317	41,863
1-2-2-3-1	31,964	13,873	110	72	9	6	41,020	37,109
1-2-2-3-2	29,473	13,131	100	66	8	5	36,810	33,325

As in the winter conditions, the 1-2-3 truck configuration was the least damaging of the four configurations modeled under late spring conditions, whereas the 1-2-2-3-2 configuration was the most damaging. The same pattern also was observed with the summer results (Table 9).

The results from the long-term damage estimates for late spring conditions indicate that the Campbell Highway and Klondike Highway North are not all-season highways and they become very vulnerable to damage from heavy trucks at this time of year. Both legal loads and permit overloads are predicted to rapidly rut the highway surfaces to a failed condition. Ruts in a gravel surface are a typical wear pattern and are easily rectified with grading before the ruts become deep; however, rutting and the subsequent break-up of the BST surface of the Klondike Highway would create a safety hazard (intermittent gravel patches) and the BST re-surfacing cannot be done until warmer weather arrives in the summer. It would be advisable to consider spring load restrictions (extending the SLR period from early spring?) for both highway types because of the high damage rates from even legally loaded trucks. In contrast, the Alaska Highway BST and AC structures appeared to be sufficiently strong to support a *limited number* of permitted overloads during the late spring.

The rates of deterioration of the Alaska BST pavement by permit overloads was the highest of any of the highway structures analyzed under late spring conditions (Figure 14). The rate of damage of the Alaska BST pavement from permit overloads was 228% to 237% of the damage rates at legal loadings. This type of BST pavement offers an opportunity to capture large gains in serviceability with a modest change in permitted loading. Additional sensitivity analyses of the impact of reduced axle tolerances for permit overloading under summer conditions was investigated and the results could equally well be applied to the short period of late spring.

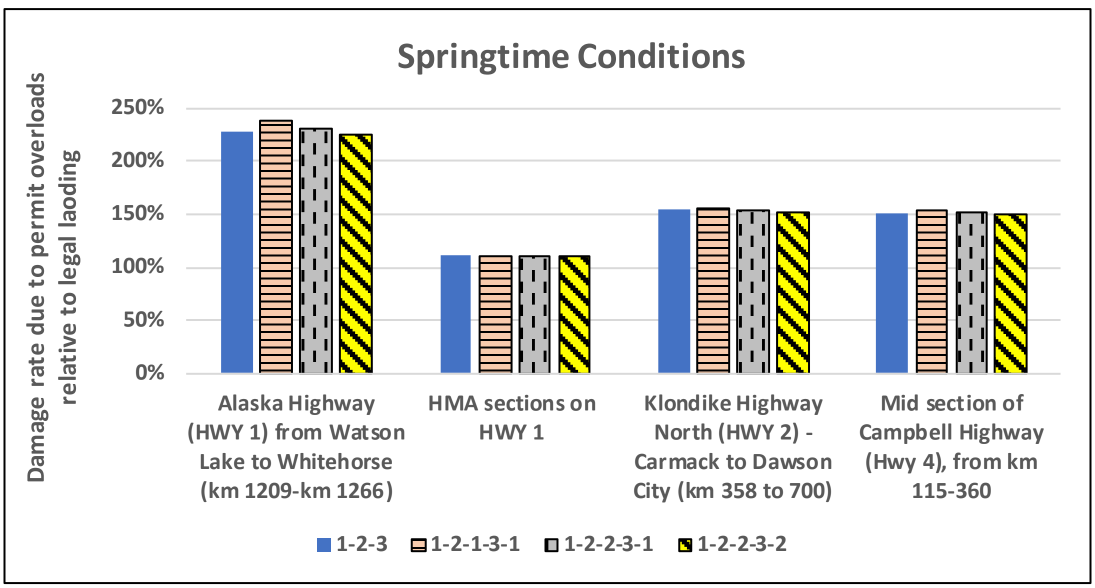

Figure 14. Rate of damage due to permit overloads, relative to at legal loading, for four Yukon highway structures under late spring conditions.

Summer conditions

Table 9 summarizes the estimated service lives of the four Yukon low volume highway types if subjected to trafficking by four truck configurations with legal and with permit loads, under summer seasonal conditions. Summer pavement conditions last approximately 100 days (compared with only 30 days for late spring conditions), and the weaker highway structures are moderately vulnerable to overloaded vehicles during this period.

Table 9. Predicted service life when subject to overloaded trucks – summer conditions

	Service life – summer conditions							
	Alaska Highway BST structure		Klondike Highway BST structure		Campbell Highway gravel structure		Alaska Highway AC structure	
Vehicle	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload	At legal loading	At permit overload
1-2-3	226,824	99,789	1293	852	122	85	63,578	57,357
1-2-1-3-1	161,368	68,175	919	581	86	59	46,031	41,552
1-2-2-3-1	147,707	64,300	823	527	77	53	40,768	36,837
1-2-2-3-2	136,178	60,843	745	483	69	48	36,585	33,083

The 1-2-3 truck configuration was the least damaging of the four configurations modeled under summer conditions, whereas the 1-2-2-3-2 configuration was the most damaging. As in the other seasons, the governing failure mode was rutting for the BST and gravel-surfaced highways and fatigue cracking for the AC pavement sections of the Alaska Highway.

The absolute number of truck passes, as well as the relative number of passes, are both important to consider when establishing highway overload policy. As can be seen in Table 9, the Klondike Highway BST and the Campbell Highway gravel-surfaced highways can withstand few of these heavy truck configurations in the summer/fall—regardless of whether at legal or permit loading. Recalling the 2016-18 traffic summary from Table 1, there were, on average, 109 permitted overload trips per year on Yukon highways by the 4 subject truck configurations. This volume of permitted overload traffic is expected to rapidly deteriorate the Campbell Highway and the Klondike Highway North BST (under permit overload traffic alone they would reach a failed condition in rutting within 1 summer and 5 years, respectively).

The Alaska Highway BST structure had the longest predicted service lives under summer conditions and these varied from almost 99,800 permit trips by a 1-2-3 truck to about 60,800 permit trips by a 1-2-2-3-2 truck. The rates of deterioration of the Alaska BST pavement by permit overloads was the highest of any of the highway structures analyzed under summer conditions. The rate of damage of the Alaska BST pavement from permit overloads was 224% to 237% of the damage rates at legal loadings (Figure 15). This type of BST pavement offers an opportunity to capture large gains in serviceability with a modest change in permitted loading.

The results from long-term damage analysis of the studied truck configurations under summer conditions were not enough to recommend or discourage permit overload changes. Additional sensitivity analyses of the impact of reduced axle tolerances for permit overloading under summer conditions, therefore, were investigated and are presented in the next section of the report.

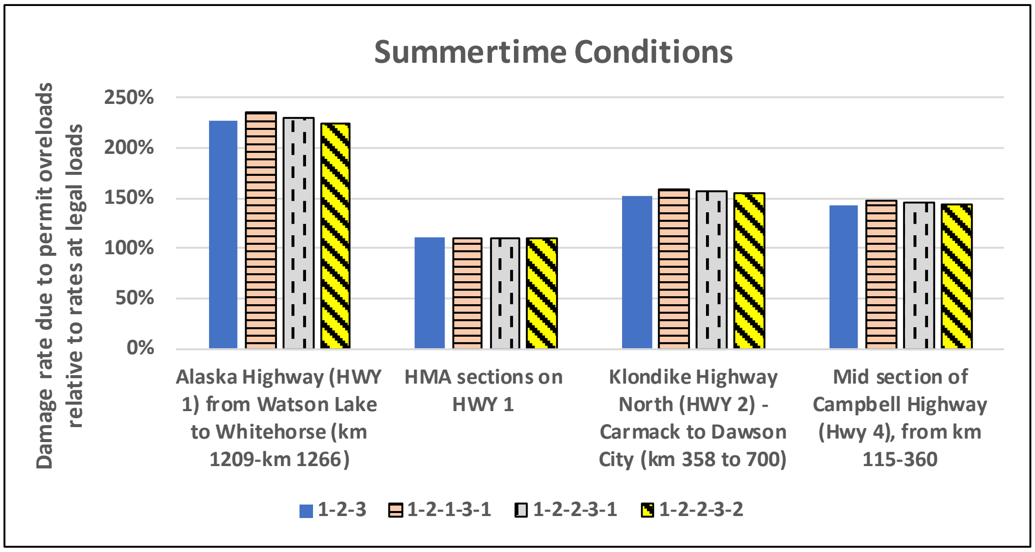

Figure 15. Rate of damage due to permit overloads, relative to at legal loading, for four Yukon highway structures under summer conditions.

Long-term Damage Caused by Reduced Permit Overloads in the Summer

Alaska Highway BST sections

An analysis was undertaken of the impact of permitted axle overloading on the BST structure of the Alaska Highway in order to evaluate how overloading tolerance policy might be better aligned with Yukon pavement performance. Table 10 summarizes the axle loading variation specified for this sensitivity analysis. 90% and 120% of currently permitted overloading were evaluated. 90% of the overloading tolerance was taken to be the lower limit for the sensitivity analysis because any less and the resulting loadings would approach legal axle limits 120% of the overloading tolerance was taken to be the upper limit for the sensitivity analysis because any more and the resulting axle loads start to exceed manufacturer-ratings for key truck components (tires, rims, suspensions, etc.)

Table 10. Axle loading used for sensitivity analysis

	Axle load (kg)			
Axle / tire arrangement	At legal loading	At 90% of permit overload	At 100% of permit overload	At 120% of permit overload
Single steer axle / single tires	6000	6750	7500	9000
Tandem axle/ dual tires	19100	21488	23875	28650
Tridem axle/ dual tires	24000	27000	30000	36000
Single jeep or booster axle/ dual tires	10000	11250	12500	15000

As discussed in the previous section of the report, summer conditions appear to provide a good opportunity to improve highway service life by refining permitted axle overloading tolerances. The first part of the analysis examined the impact on service life of each of the subject pavements from lighter permit overloading. Table 11 provides an example of the analysis and results summary, and Figure 16 illustrates these results graphically. The relative damage rate of the 4 configurations was the same as that detailed in Tables 7, 8, and 9 so, for simplicity, the results in Table 11, 12 and 13 (and Figure 16) have been aggregated and expressed as the average of all 4 truck configurations.

Table 11. Relative sensitivity to axle overloading of BST Alaska Highway in summer conditions

	Number of passes to a failed condition (average of the 4 studied truck configurations)			
10% reduction in permitted load applied to:	At legal loading	At 90% of permitted load	At 100% of permitted load	Difference between 90% and 100% of permitted load
All axles	168,019	114,875	73,277	41,598
Steering axle	168,019	84,949	73,277	11,673
Steering & single axles	168,019	89,044	73,277	15,767
Tandem axles	168,019	84,971	73,277	11,694
Tridem axles	168,019	77,366	73,277	4,090

The results for the Alaska Highway BST indicate that a general reduction in permitted loading by 10% in the summer would extend service life by over 41,500 permitted overload trips, on average. A reduction in the tolerance for only single axles with dual tires and single steering axles would have the greatest impact on pavement rutting and is estimated to be over 15,700 permitted overload trips, on average. Such a policy change would capture about 38% of the improvement estimated from if all permit axle loads were reduced by 10%. A reduction in the tolerance for only single steering axles would mitigate less of the pavement rutting and is estimated to increase pavement serviceability by over 11,600 permitted overload trips, on average. A 10% reduction in permitted tandem axle loads is predicted to generate almost the same pavement serviceability benefit. Reducing tridem permitted loads by 10% would extend service life modestly (by only 4090 trips, on average) and, thus, has relatively little impact on the Alaska Highway BST serviceability.

For comparison, an analysis was conducted for the Alaska Highway BST section under late spring conditions. A general reduction in permitted loading by 10% in the late spring would extend service life by over 9,000 permitted overload trips, on average. A reduction in the tolerance for only single axles with dual tires and single steering axles would have the greatest impact on pavement rutting and is estimated to extend service life by 3,425 permitted overload trips, on average. As with the summer, this change would capture about 38% of the improvement estimated from if all permit axle loads were reduced by 10%. A reduction in the tolerance for only single steering axles would mitigate less of the pavement rutting and is estimated to increase pavement serviceability by over 2,500 permitted overload trips, on average.

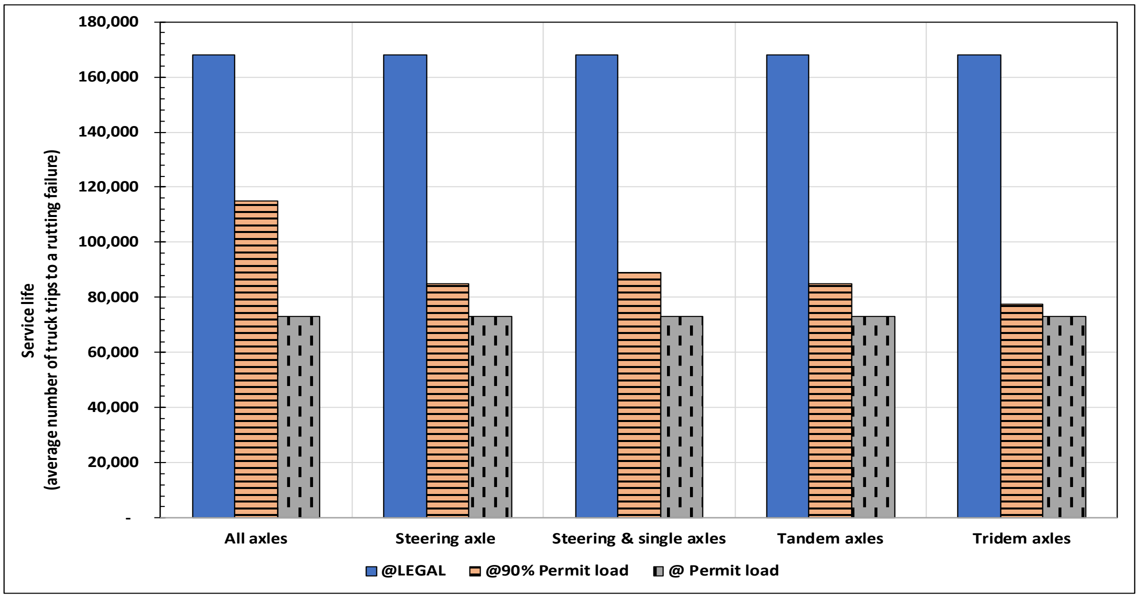

Figure 16. Relative sensitivity to permitted axle overloading of Alaska Highway BST in summer conditions.

Alaska AC, Klondike BST, and Campbell gravel highway structures

An analysis was conducted on the sensitivity of highway service life, in summer conditions, to permitted loading for the Alaska AC, Klondike BST, and Campbell gravel highway structures. Tables 12, 13, and 14 summarize the results.

Table 12. Relative sensitivity to axle overloading of AC Alaska Highway in summer conditions

	Number of passes to a failed condition (averaged for the 4 subject truck configurations)			
10% reduction in permitted load applied to:	At legal loading	At 90% of permitted load	At 100% of permitted load	Difference between 90% and 100% of permitted load
All axles	46,741	45,100	42,207	2,893
Steering axle	46,741	42,473	42,207	266
Steering & single axles	46,741	42,640	42,207	433
Tandem axles	46,741	43,344	42,207	1,137
Tridem axles	46,741	43,799	42,207	1,592

The results for the Alaska Highway AC sections indicate that relatively little improvement in pavement life (to a fatigue cracking failure) can be obtained by a 10% reduction in permitted load for all axle types together or for individual axle types. Interestingly, a 10% reduction in permitted loads for tridem axles was predicted to generate the greatest improvement in pavement serviceability. These sections of AC pavement are interspersed with BST sections and, therefore, an overload policy change to benefit the BST sections should also be considered for these sections.

Table 13. Relative sensitivity to axle overloading of BST Klondike Highway in summer conditions

	Number of passes to a failed condition (averaged for the 4 subject truck configurations)			
10% reduction in permitted load applied to:	At legal loading	At 90% of permitted load	At 100% of permitted load	Difference between 90% and 100% of permitted load
All axles	945	756	611	145
Steering axle	945	634	611	23
Steering & single axles	945	647	611	37
Tandem axles	945	666	611	56
Tridem axles	945	649	611	38

Table 14. Relative sensitivity to axle overloading of gravel-surfaced Campbell Highway in summer conditions

	Number of passes to a failed condition (averaged for the 4 subject truck configurations)			
10% reduction in permitted load applied to:	At legal loading	At 90% of permitted load	At 100% of permitted load	Difference between 90% and 100% of permitted load
All axles	89	74	61	13
Steering axle	89	63	61	2
Steering & single axles	89	64	61	3
Tandem axles	89	66	61	5
Tridem axles	89	65	61	4

The results shown in Tables 13 and 14 highlight the fact that these highway structures are relatively weak and vulnerable in the summer. Decreasing the level of permit overload to 90% on the Klondike BST structure would have little impact on pavement life but would impact the transport industry. In fact, reducing truck loading to legal levels may be required to achieve desirable levels of maintenance. Decreasing the level of permit overload to 90% on the gravel-surfaced Campbell highway structure also would have little impact on pavement life but would impact the transport industry. In the case of this key mine haul route, the accelerated rutting from 100% permit overloads may be necessary to support this important Yukon industry.

Summary of Long-Term Damage Results

The use of permitted overloads increases the damage rate of trucks and shortens the pavement service life. The four truck configurations evaluated (1-2-3, 1-2-1-3-1, 1-2-2-3-1, and 1-2-2-3-2) are estimated to generate, on an ESAL basis, 2/3 of the damage of Yukon's permit overloads and so are a good representation of the population of Yukon permit overloads. The 1-2-3 truck configuration was consistently found to be the least damaging of the 4 configurations while the 1-2-2-3-2 configuration was consistently the most damaging.

The stronger pavements (Alaska Highway AC and BST structures) had the longest predicted service lives (i.e., passes to reach a failed condition) and the weakest pavement (gravel-surfaced Campbell Highway) had the shortest predicted service life. Rutting was the governing failure mode for the BST and gravel-surfaced highways while bottom-up fatigue cracking governed failure of the AC pavement. The consequences of repairing a failed condition in a highway surface vary with the pavement structure and can be quite minor (i.e., for a rutted gravel surface) or involving considerable cost and effort (i.e., alligator-cracked AC surfaces).

The four truck configurations with permit loading generated approximately 220% of their damage rates at legal loads on the Alaska BST Highway structure in the summer. A general reduction in permitted loading by 10% in the summer was predicted to slow the deterioration due to overloads and extend service life by over 41,500 permit overload trips, on average. Currently the overload tolerance for single axles (including steering axles) is 25% all year. A reduction in this tolerance alone (and not the tandem or tridem axle tolerances) would increase pavement service life by over 15,700 permit overload trips, on average, in the summer and by 3,425 permit overload trips, on average, in the late spring. Such a change would capture about 38% of the improvement estimated from if all permit axle loads were reduced by 10%. A reduction in the tolerance for just single steering axles would capture about 28% of the improvement estimated from applying a 10% reduction to all permit loads. This is estimated to increase summertime service life by over 11,600 permitted overload trips, on average, and by about 2,500 permitted overload trips, on average, in the late spring.

The Klondike Highway North BST section and the gravel-surfaced Campbell Highway section were found to be very weak and vulnerable to rutting damage under both late spring and summer conditions. Given the relatively few passes by either legally loaded or permit overload trucks needed to create a failed condition on the Klondike Highway North BST section, it was recommended that spring load restrictions be considered for this highway for late spring if current damage levels are unacceptable. As for summer, reducing truck loading to legal levels may be required to achieve desirable levels of maintenance on the Klondike Highway North BST section. Conversely, shallow rutting of the Campbell Highway may be less of a priority and could be actively managed with grading and with enough permit fees to recover grading costs.

Table 15 summarizes long-term damage analysis recommendations that flow from the preceding results and discussion.

Table 15. Recommended loading levels for use on Yukon Highways

Highway structure	Spring Load Restrictions	Legal loading	90% of permitted single axle load	100% of permitted load	Comment
Highway 1 BST	x	Late spring, winter, summer	Late spring, summer	x	Winter permit levels not governed by pavement capacity
Highway 1 HMA	x	Late spring, winter, summer	Late spring, summer	x	
Highway 2 BST	Late spring?	Winter, summer	x	x	
Highway 4 gravel	x	Late spring, winter, summer	x	Late spring, summer	

Note: X indicates “not recommended”

CONCLUSIONS AND RECOMMENDATIONS

In 2019, the Yukon Department of Highways and Public Works contracted FPInnovations to provide a theoretical analysis, of limited scope, of highway damage caused by heavy trucks operating with permitted overloads. The objective of the analysis was to provide the Department with recommendations regarding maximum permitted truck loads on Yukon Highways.

Permit overload traffic from 2016-18 was used to estimate which 4 to 5 truck configurations should be used to model permit overload vehicles in the analyses. About 2/3 of the pavement impacts from all permit overload trips, however, was found to be generated by only four of the truck configurations (1-2-3, 1-2-1-3-1, 1-2-2-3-1, and 1-2-2-3-2). Use of these truck configurations for pavement impact modeling, therefore, is believed to be representative of current permit overload traffic.

Four types of low volume highway structure were used for the analyses. Representative pavement material thicknesses for these highway structures were defined by the Department. Pavement material mechanical properties for winter, late spring, and summer conditions were selected from the literature and validated by FPInnovations. The ‘winter conditions’ attempted to replicate an early winter condition of well frozen to a frost depth of 75 cm; and, the ‘late spring conditions’ attempted to replicate an 80% recovered strength condition with thawed but saturated subgrade.

Spontaneous critical strains in response to single, tandem, and tridem axles were modeled for each highway structure under each seasonal condition. Critical strains under frozen (winter) conditions were found to be minimal. Critical strains under saturated subgrade conditions (late spring) were higher than in the winter or summer. Single steering axles consistently created the highest critical strains, followed by single axles (dual-tired), tandem axles, and tridem axles.

Estimates of long-term damage can be made using strain-based transform equations for common failure modes and the critical strains estimated by modeling. These estimates of number of passes to a failed condition also allowed the aggregation of axle impacts to form estimates of pavement impacts for the 4 studied truck configurations. Rutting was found to be the governing failure mode for the BST and gravel-surfaced highways while bottom-up fatigue cracking governed failure in the AC pavement.

The four highway structures were found to be relatively insensitive to long-term damage at any loading when well frozen. Permit loads in the winter could be increased with only minimal impacts to highways. **It is recommended, therefore, that the levels of permit overloading used in the winter in the Yukon should be governed by truck safety and bridge load limits rather than by pavement capacity.**

The gravel-surfaced Campbell Highway and the BST Klondike Highway North were found to become extremely vulnerable to truck impacts under late spring conditions. The number of passes to create a failed condition (service life) were predicted to be no more than 9 and 116 permitted trips, respectively. Limiting truck loading to legal weights made little difference and the number of passes to failure increased to no more than 14 and 179 legally loaded trips, respectively. **Given its extreme vulnerability and the difficulty of repairing damaged BST under late spring conditions, permit overloading at this time of year should be discouraged for the BST Klondike**

Highway North. Consideration also should be given to protecting the Klondike BST by applying spring load restrictions in the late spring. Permit overload application fees should adequately cover maintenance activities required to address incremental damage on the Campbell Highway due to permit overloads.

The BST and AC Alaska Highway pavements were found to be the strongest of the structures analyzed. This is believed to be mostly due to them having relatively thick base courses. An analysis of the Alaska Hwy BST structure found that damage rate trends were unchanged when base course was varied from 80 to 160 mm-thick. Under both late spring and summer conditions, the predicted number of passes to failure of the Alaska BST pavement was more sensitive to loading than with any other pavement, and the use of current permit loads was predicted to reduce its service life by 55% to 58%, depending on truck configuration. Conversely, under both late spring and summer conditions, the AC Alaska Highway structure showed very little sensitivity (e.g., 10%) to legal vs. permit loading.

The sensitivity of the BST Alaska Highway structure to loading creates an opportunity to influence pavement serviceability with a relatively modest change in permit load level. Currently, the overload tolerance for single axles (including steering axles) is 25% all year. A reduction in this tolerance alone (and not the tandem or tridem axle tolerances) would increase pavement service life by over 15,700 permit overload trips, on average, in the summer and by 3,425 permit overload trips, on average, in the late spring. Such a change would capture about 38% of the improvement estimated from if all permit axle loads were reduced by 10%. A reduction in the tolerance for just single steering axles would capture about 28% of the improvement estimated from applying a 10% reduction to all permit loads. This is estimated to increase summertime service life by over 11,600 permitted overload trips, on average, and by about 2,500 permitted overload trips, on average, in the late spring. Additional but smaller benefits also would accrue to the AC pavement sections of the Alaska Highway. **It is recommended that the Department consider reducing the single axle permit loads from current levels during the late spring and summer/fall. A reduction of 10% (e.g., permitted steering axle loads reduced by 10% from 7500 kg to 6750 kg) is anticipated to generate considerable benefit to this key gateway route to the Yukon.**

The analysis did not evaluate the influence of steering tire size on steering axle-caused pavement damage. Nor was the reduction in permit loading optimized – only a 10% reduction was evaluated. In addition, the subgrade resilient moduli selected for the Klondike BST structural model could not be validated using the method of comparing modeled service life to truck traffic volumes in actual maintenance intervals. **It is recommended that the Department consider further modeling to refine the report's recommendations.**

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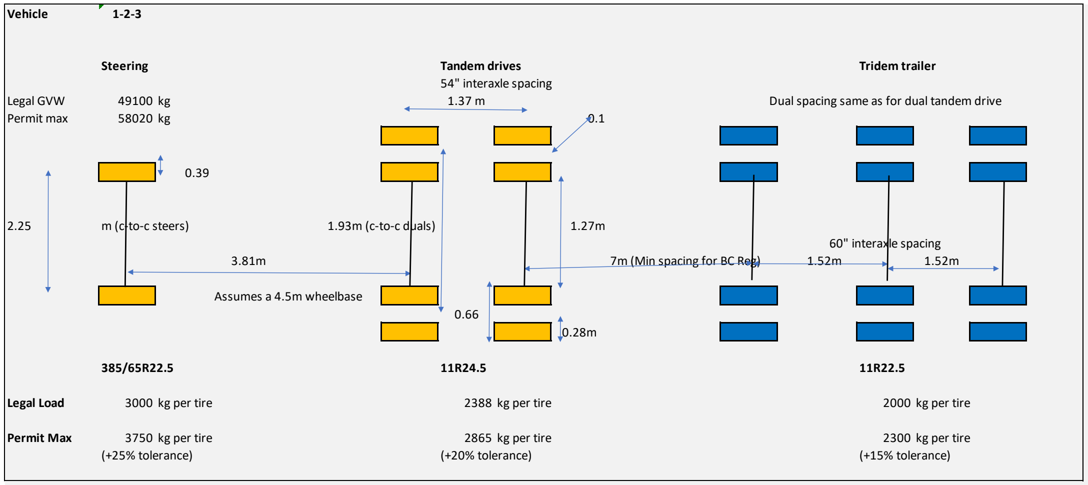
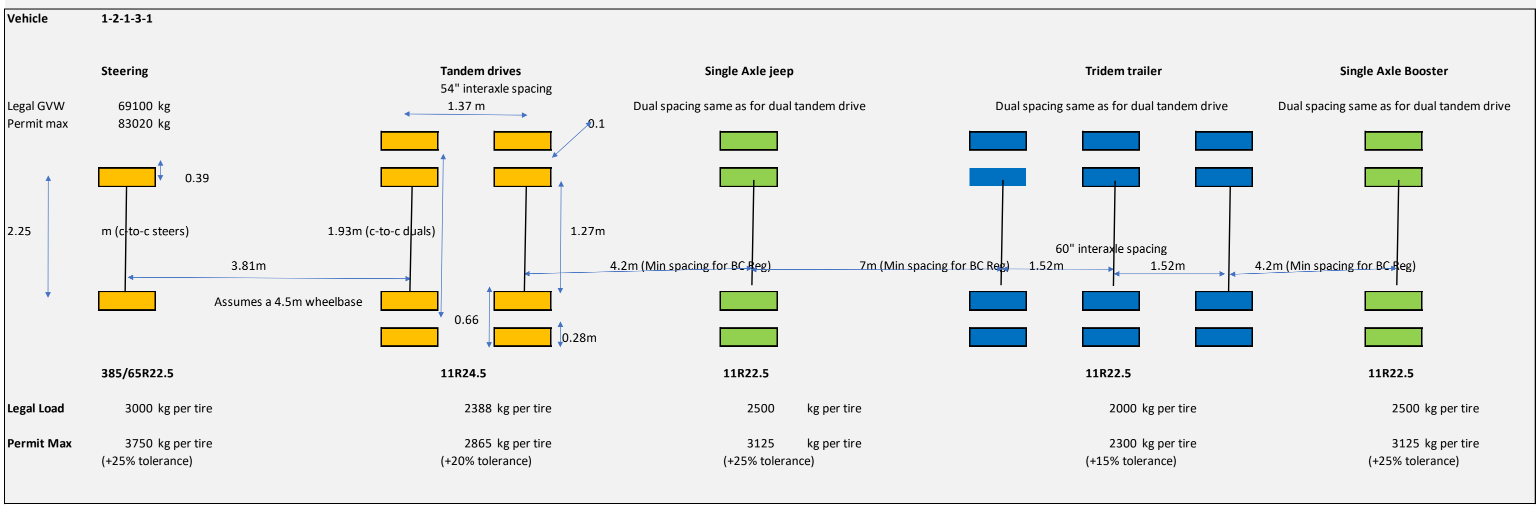
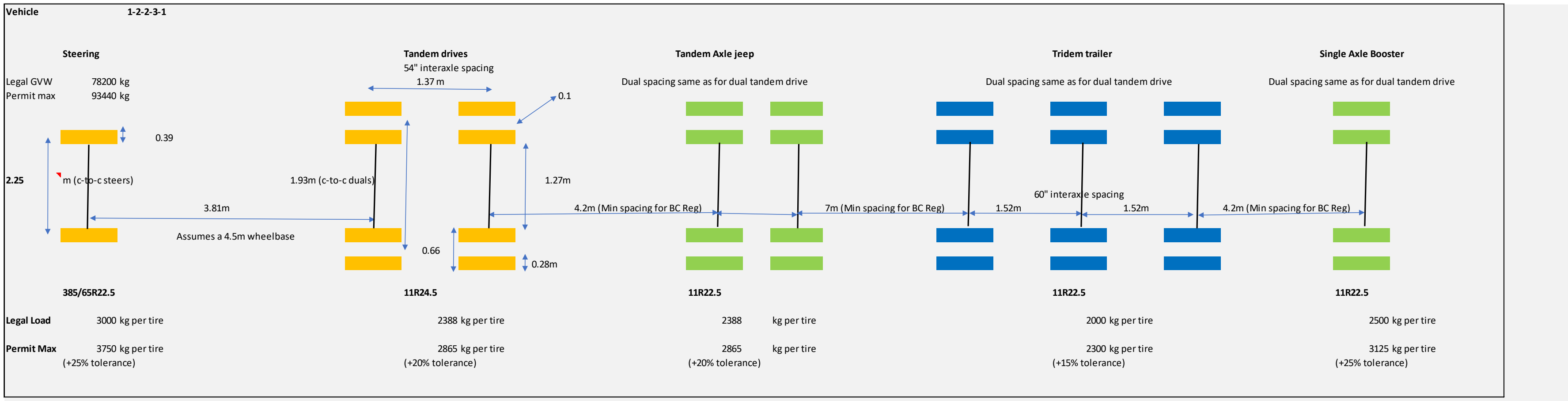
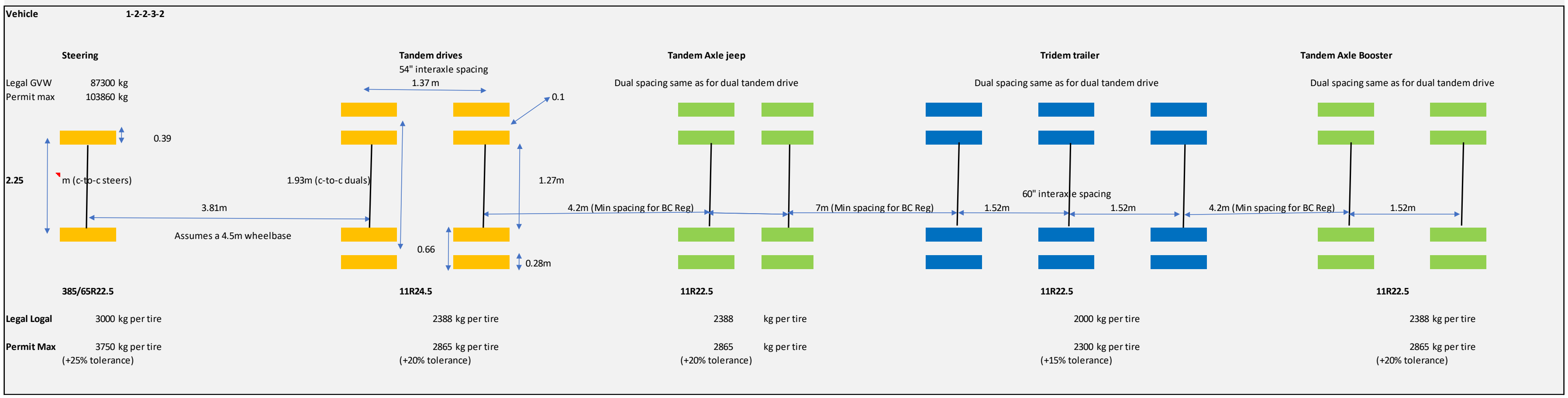
APPENDIX 1. TRUCK DIMENSIONS






Vehicle 1-2-2-3-1
Steering
Legal GVW 78200 kg
Permit max 93440 kg
0.39
2.25 m (c-to-c steers)
3.81m
Assumes a 4.5m wheelbase
385/65R22.5
Legal Load 3000 kg per tire
Permit Max 3750 kg per tire
(+25% tolerance)
Tandem drives
54" interaxle spacing
1.37 m
0.1
1.93m (c-to-c duals)
1.27m
0.66
0.28m
11R24.5
2388 kg per tire
2865 kg per tire
(+20% tolerance)
Tandem Axle jeep
Dual spacing same as for dual tandem drive
4.2m (Min spacing for BC Reg)
7m (Min spacing for BC Reg)
11R22.5
2388 kg per tire
2865 kg per tire
(+20% tolerance)
Tridem trailer
Dual spacing same as for dual tandem drive
60" interaxle spacing
1.52m
1.52m
11R22.5
2000 kg per tire
2300 kg per tire
(+15% tolerance)
Single Axle Booster
Dual spacing same as for dual tandem drive
4.2m (Min spacing for BC Reg)
11R22.5
2500 kg per tire
3125 kg per tire
(+25% tolerance)


Vehicle 1-2-2-3-2
Steering
Legal GVW 87300 kg
Permit max 103860 kg
0.39
2.25 m (c-to-c steers)
3.81m
Assumes a 4.5m wheelbase
385/65R22.5
Legal Logal 3000 kg per tire
Permit Max 3750 kg per tire
(+25% tolerance)
Tandem drives
54" interaxle spacing
1.37 m
0.1
1.93m (c-to-c duals)
1.27m
0.66
0.28m
11R24.5
2388 kg per tire
2865 kg per tire
(+20% tolerance)
Tandem Axle jeep
Dual spacing same as for dual tandem drive
4.2m (Min spacing for BC Reg)
7m (Min spacing for BC Reg)
11R22.5
2388 kg per tire
2865 kg per tire
(+20% tolerance)
Tridem trailer
Dual spacing same as for dual tandem drive
60" interaxle spacing
1.52m
1.52m
11R22.5
2000 kg per tire
2300 kg per tire
(+15% tolerance)
Tandem Axle Booster
Dual spacing same as for dual tandem drive
4.2m (Min spacing for BC Reg)
1.52m
11R22.5
2388 kg per tire
2865 kg per tire
(+20% tolerance)

APPENDIX 2. TIRE PARAMETERS

Table. Tire parameters used in modeling

Vehicle	Tire location	Tire size	Cold inflation pressure (psi)	Maximum tire load (kg)		Tire contact area (cm^2)	
				At Legal loading	At Max. Permit loading	At Legal loading	At Max. Permit loading
1-2-3							
	Steering	385/65R22.5	100	3000	3750	523	617
	Drive	11R24.5	100	2388	2865	421	482
	Trailer	11R22.5	100	2000	2300	369	406
1-2-1-3-1							
	Steering	385/65R22.5	100	3000	3750	523	617
	Drive	11R24.5	100	2388	2865	421	482
	Jeep	11R22.5	100	2500	3125	432	510
	Trailer	11R22.5	100	2000	2300	369	406
	Booster	11R22.5	100	2500	3125	432	510
1-2-2-3-1							
	Steering	385/65R22.5	100	3000	3750	523	617
	Drive	11R24.5	100	2388	2865	421	482
	Jeep	11R22.5	100	2388	2865	417	477
	Trailer	11R22.5	100	2000	2300	369	406
	Booster	11R22.5	100	2500	3125	432	510
1-2-2-3-2							
	Steering	385/65R22.5	100	3000	3750	523	617
	Drive	11R24.5	100	2388	2865	421	482
	Jeep	11R22.5	100	2388	2865	417	477
	Trailer	11R22.5	100	2000	2300	369	406
	Booster	11R22.5	100	2388	2865	417	477

APPENDIX 3. VALIDATION OF MATERIAL PROPERTIES FOR MODELING

An analysis of the service life estimates (predicted number of truck passes to a failed condition) for the Alaska Highway and Klondike North BST sections and Campbell Highway was made to validate the material properties specified for modeling these structures. Provided that the predicted pavement service life exceeded the actual maintenance interval then the material properties used for the modeling were assumed to be appropriate.

Yukon H&PW advised that the assumed maintenance intervals were as follows: Alaska BST highway resurfacing interval is typically at least 13 years; Klondike Highway North BST highway resurfacing interval is typically at least 9 years; and, gravel-surfaced highways are shaped in the late spring and sometimes in the late summer before it freezes.

Data from a 2011 traffic study of Yukon traffic (Yukon 2011), supplemented with traffic data collected in 2016-2018, was utilized to estimate traffic volume and growth on the two sections. The distribution of truck configurations found in the mixture of traffic on the Campbell Highway was not measured in the survey and so this was assumed to be comparable to that measured for the Alaska Highway near the Carcross Cutoff South (i.e., at KM 1392).

Modeling was used to predict the number of passes by a legally loaded 1-2-3 truck needed to cause a failed rutting condition in each pavement. A 1-2-3 truck configuration at legal loading was used as the reference vehicle because this type of truck was specifically counted in the traffic study (i.e., #10 traffic survey vehicle classification) and it was one of the four modeled trucks. In real life, however, pavements typically experience a mixture of truck types and so a relation was sought to convert rutting damage from a mixture of traffic types into damage from the 1-2-3 configuration. A relation for each of the pavements was developed using modeled damage rates for that pavement in late spring and summer for each of the traffic survey truck configurations at legal loadings. The ratio of the summertime damage from 1-2-3 trucks divided by the average truck damage was 102%, on average, for the Klondike Highway North BST and 110%, on average, for the Campbell Highway gravel-surfaced sections. In late spring conditions, the ratio of the damage from 1-2-3 trucks divided by the average truck damage was 99%, on average, for the Klondike Highway North BST and 111%, on average, for the Campbell Highway gravel-surfaced sections.

The following table illustrates the process used to validate material properties used in the models by comparing the predicted number of passes to create a failed condition to the actual truck traffic volumes that occurs between maintenance activities.

As can be seen, the estimated 1-2-3 truck passes to create a failed condition were more than experienced in practice and so the model inputs were judged to be appropriate. Predictions with the originally specified resilient moduli in the Klondike North and Campbell Highway sections were smaller than experienced in real life so the ML/CL/MH/CH subgrade values were incrementally increased until predictions comparable to real life were achieved. The properties of granular base and subbase materials is better understood and, therefore, was not varied from originally specified. As can be seen, the model successfully matched real life for the Campbell Highway but, even with the highest subgrade moduli possible, the model for Highway 2 BST (Klondike Highway North) predicted much shorter service life than experienced. The reason for this is unclear and should be investigated; however, this investigation was not within the scope of this project.

Table. Validation of resilient modulus estimates for the BST and gravel highway granular materials

Structure	Seasonal conditions	Duration (days)	Traffic vol. (vpd)	Truck traffic (%)	Daily truck trips per direction	Truck trips per mnte. interval	Equivalent trips by 1-2-3 trucks in grading interval	Modeled 1-2-3 trips to failure	Adjust subgrade resilient modulus?
Hwy 1 BST	Summer	100 x 13	800	5.5%	22.0	28,600	29,172	226,824	NO
	Late spring	30 x 13	500	5.5%	13.8	5,363	5,470	49,034	NO
Hwy 2 BST	Summer	100 x 9	493	9.9%	24.4	21,963	22,402	1,293	YES
	Late spring	30 x 9	708	5.5%	19.5	5,257	5,204	179	YES
Hwy 4 gravel	Summer	90	30	6%	0.9	81	89	122	NO
	Late spring	30	12	6%	0.4	11	12	14	NO

APPENDIX 4. SENSITIVITY OF ALASKA HIGHWAY BST PAVEMENT RESULTS TO GRANULAR BASE THICKNESS

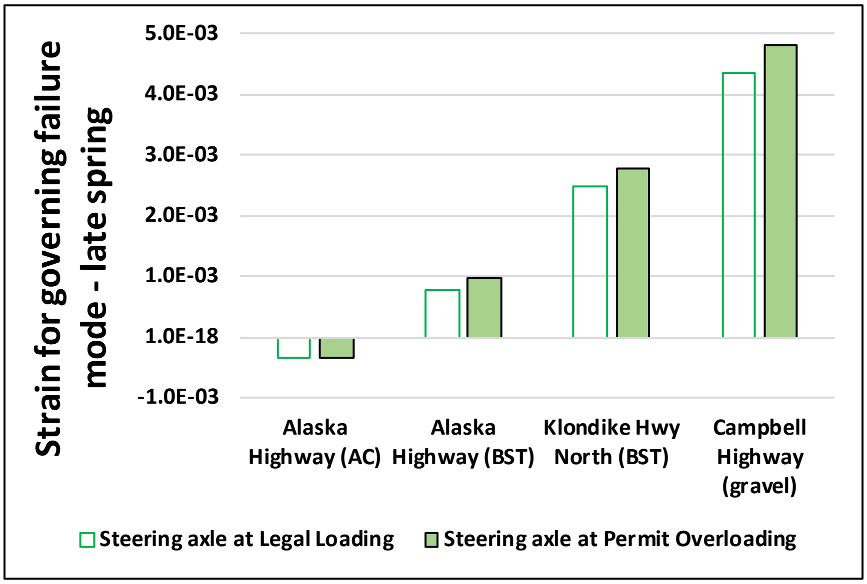
Considerable variability in granular base course thickness exists in Yukon BST pavements containing subbase courses. The Alaska Highway BST structure originally was defined as having a base course between 80 and 160 mm thick and a combined thickness of granular base and subbase of no more than 500 mm. Given the important role in BST pavement load bearing provided by the base course an analysis was conducted to investigate the sensitivity of predicted service life to base course thickness. The table below summarizes the impact on the service life estimates of the Alaska Highway BST pavement with granular base course thicknesses of 80, 120, and 160 mm under summer conditions.

Table. Sensitivity of service life estimates of the Alaska Highway BST pavement with three different granular base course thicknesses under summer seasonal conditions

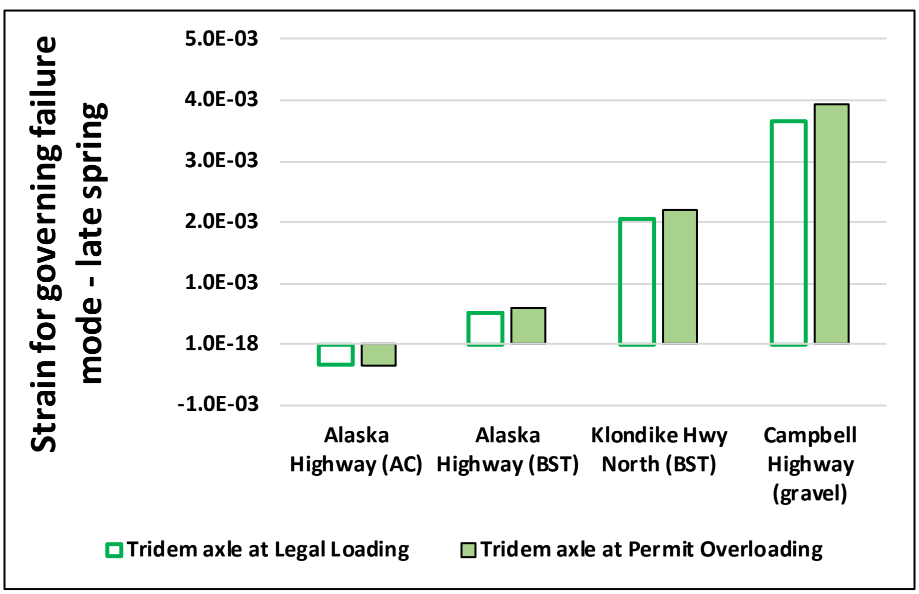
	Estimated number of truck passes to reach a rutting failure. Alaska Highway BST. Summer conditions					
	80 mm base		120 mm base		160 mm base	
Vehicle	at legal loading	at permit overload	at legal loading	at permit overload	at legal loading	at permit overload
1-2-3	106,064	47,036	226,824	99,789	453,417	198,245
1-2-1-3-1	75,413	32,111	161,368	68,175	322,734	135,522
1-2-2-3-1	68,997	30,264	147,707	64,300	295,507	127,893
1-2-2-3-2	63,587	28,617	136,178	60,843	272,515	121,078

The service life of the Alaska Highway BST pavement was affected by the choice of granular base course thickness; however, the relative decrease in service life due to permitted overloads was about 56% regardless of base thickness. It is concluded, therefore, that the use of 120 mm granular base course for modeling the impacts of overloading on the service life of the Alaska Highway BST pavement is appropriate.

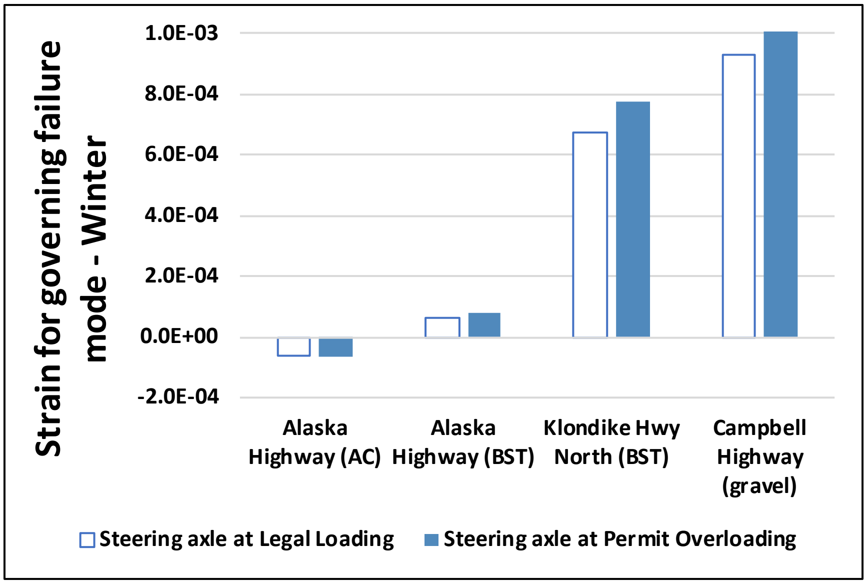
APPENDIX 5. SPONTANEOUS STRAIN RESULTS FOR LATE SPRING AND WINTER CONDITIONS



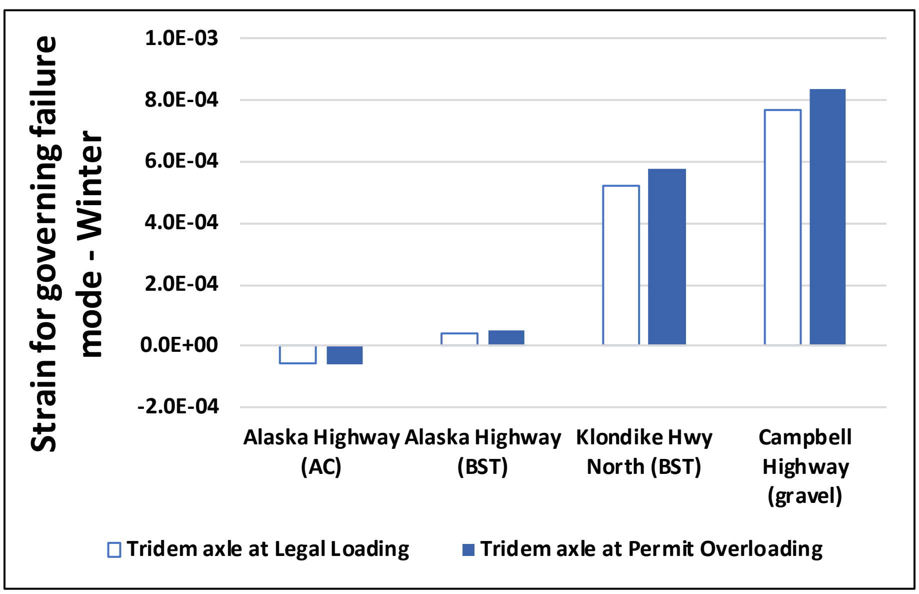
Strains governing failure in 4 highway structures due to steering axle loads under late spring conditions.



Strains governing failure in 4 highway structures due to tridem axle loads under late spring conditions.



Strains governing failure in 4 highway structures due to steering axle loads under winter conditions.



Strains governing failure in 4 highway structures due to tridem axle loads under winter conditions.

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