info@fpinnovations.ca
www.fpinnovations.ca

9-AXLE B-TRAINS FOR LOG HAULING ON B.C. RESOURCE ROAD

(Version 2.1)

PROJECT NUMBER: 301011441

Allan Bradley, RPF, P.Eng

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Version Number (Release Date)	Scope of Revisions
Version 1.0 (October 2016)	Full report.
Version 2.0 (January 2017)	CL-625 bridge evaluation results added. Bridge capacity and curve width tables revised for approved ranges of axle dimensions.
Version 2.1 (December 2020)	Seven common B.C. forestry trucks added as reference vehicles to the curve width and gradeability tables. Bridge capacity tables revised with QuickBridge V 1.3 software using closer axle spacings for 9-axle B-trains, and a dynamic load allowance of 0.25 for the BCL-625, CL-625 bridge design vehicles and the 9-axle B-trains.

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APPROVER CONTACT INFORMATION
James Sinnett
Manager, Transportation and Infrastructure
james.sinnett@fpinnovations.ca

REVIEWERS
Brian Chow, P.Eng., Chief Engineer, Engineering Branch, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development

Matt Campbell, P.Eng. R.P.F.
FPInnovations Coordinator,
CANFOR

AUTHOR CONTACT INFORMATION
Allan Bradley, RPF, P.Eng
Research Lead
Transportation and Infrastructure
(604) 222-5667

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EXECUTIVE SUMMARY

Substantial benefits can be realized by forest companies in British Columbia through implementation of new 9-axle log-hauling configurations. At the request of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, FPInnovations undertook analyses to assess the potential impacts of the new trucks on resource roads and bridges. The analyses considered forestry bridge capacity (up to 80 m spans); vehicle fit to the road geometry; gradeability and road impacts. The vehicle weights and dimensions authorized for designated provincial highways were the basis for the analyses.

Those planning to implement 9-axle configurations on B.C. resource roads are advised to review the capacity of the infrastructure and adequacy of road geometry on their networks in light of the findings of this analysis. This document provides analysis that can be used, by qualified persons, to assess bridge infrastructure and road geometry for suitability to 9-axle B-train traffic.

The bridge analysis consisted of evaluating force effects of the 9-axle B-train in comparison to those of the typical, historic, design vehicle configurations (e.g., BCFS L-45, L-75, CL-625, BCL-625). The analysis found that bridges with less capacity than L-75 bridges were found to have length restrictions. L-45, L-60, CL-625, and BCL-625 bridges with lengths exceeding the maximum lengths identified in this report should be load evaluated by a professional bridge engineer for use with the 9-axle B-trains.

A note of caution. Logging truck design vehicle configurations and loads have increased over time. Some bridges that were designed for lower design vehicle configurations have been evaluated for upgrading to higher allowable loads (e.g., L-45 upgraded to L-75) based on a bridge-specific evaluation for a specific higher load configuration. **Any structures that have been upgraded in such a manner, for the purposes of 9-axle evaluation captured by the analysis in this document, must be evaluated based on their original design vehicle configuration**. It is recommended that any structure that is suspect for having been upgraded in load capacity be reviewed to confirm its original design vehicle configuration prior to application of the guidance in this document.

In consideration of horizontal road geometry, swept path requirements of 9-axle B-trains were compared to those of 7 common log haul vehicles (reference vehicles). When compared to an 8-axle tridem-drive lowbed with single booster axle or a tridem-drive 8-axle B-train, only minor differences were predicted for most FSR curves. On tight radius, slow speed, curves the 9-axle B-trains have greater curve width requirements than all but the 8-axle tridem-drive lowbed with single booster axle; however, these curves are not found on FSRs and any difficulties negotiating these curves are expected to cause minor operational issues rather than safety issues.

The swept path requirements of 9-axle B-trains were found to be met by FLNR (2018)-recommended curve criteria. Provided that curves are, at least, as wide as the FLNR design criteria no additional curve widening will be needed to accommodate 9-axle B-trains.

Provided the operation currently uses 8-axle tridem-drive B-trains or 7-axle tridem-drive hayracks, no changes to vertical curves (crest or dip curves) were indicated by the analysis of K values and stopping sight distances.

To gauge performance on road grades, a theoretical analysis of 9-axle B-Trains on road grades was evaluated. The results indicated that 9-axle B-trains are well suited to flat or gently rolling terrain, with adverse grades of no more than 9% (winter routes) or 13% (summer routes). Given their gradeability limitations and swept path requirements 9-axle B-trains are not appropriate for use on steep, tightly curving roads. Accordingly, 9-axle B-trains are suitable for replacing log hauling configurations commonly used in flat or rolling terrain, such as 8-axle super B-trains. Given their limitations, 9-axle B-trains do not appear to be suitable for replacing log hauling configurations commonly used in steep terrain, such as 8-axle tridem-drive tractor/ quad wagon trailers.

Proponents can evaluate the use of 9-axle B-Trains "screening" based on log haul vehicle configurations that they are currently using, and comparing known geometric aspects of proposed roads against performance information provided in this document. **The as-built geometry of network roads should be reviewed in light of the findings of this report**.

Provided the operation currently uses 8-axle B-trains or 7-axle hayracks, no changes to vertical curves (crest or dip curves) were indicated by the analysis of K values and stopping sight distances.

The guidance in this report can be used by qualified professional's to document their assessment for use by their client. The resulting documentation would also support meeting expectations for professional practice for members of ABCFP and EGBC.

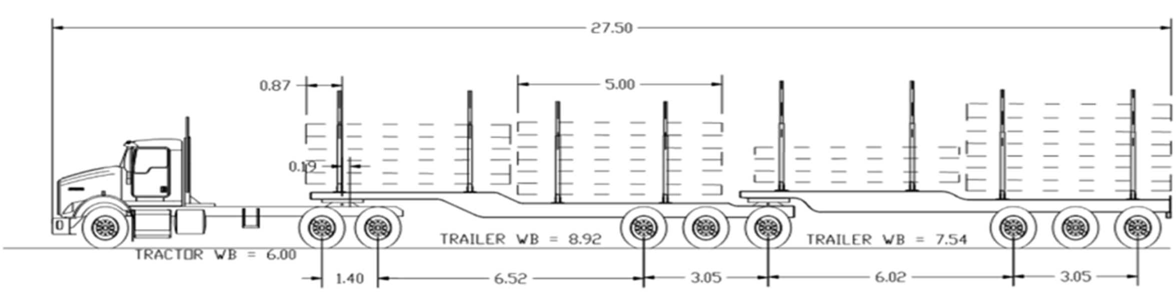
1 INTRODUCTION

The 9-axle B-train, a new more efficient log hauling truck, has been accepted for implementation in B.C. The B.C. forest industry can realize substantial benefits by implementing new 9-axle log-hauling configurations. Moving large volumes of goods with higher payload trucks is inherently more efficient. These 9-axle B-trains carry about 18% more payload than 8-axle B-trains. The efficiency gain in payload will help protect the B.C. forest industry by making local companies more competitive, and by increasing the supply of fibre to mills by increasing the distance that low value wood can be economically transported. Another important benefit of more efficient (larger) truck configurations is the reduced fuel consumption and resulting reduction in greenhouse gas emissions.

Increasing the size of commercial truck configurations is not a matter of just adding another axle to an existing configuration. The increased weights and dimensions, and dynamic performance, of the new configuration must be carefully considered to ensure road user safety and infrastructure service life are not compromised. The gross vehicle weights of the 9-axle log B-trains are 7 to 8.4 tonnes heavier than the maximum regulated Gross Vehicle Weight (GVW) of 63.5 tonnes. In 2013, all new truck configurations were required to have a static rollover threshold of 0.40 – up from 0.35. This more stringent safety requirement constrains allowable load heights of new configurations more than truck configurations that were in regulation prior to 2013.

2 BACKGROUND

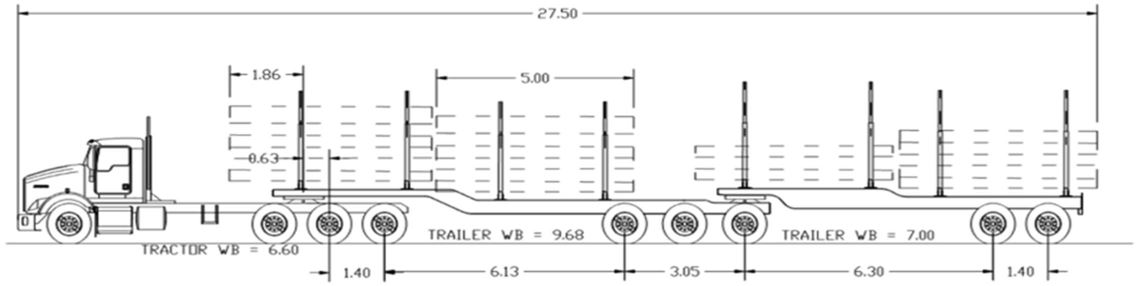
In 2014, FPInnovations evaluated the dynamic performance of the 9-axle B-trains and their effects on road pavements (Parker, Bradley, & Sinnett, 2014) (Figure 1 and Figure 2). In 2017-18, at the request of the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNR), FPInnovations analyzed the impacts of the 9-axle B-trains on resource roads and bridges. The analyses considered bridge capacity, horizontal road alignment, road and bridge vertical alignment, and road impacts. The vehicle weights and dimensions authorized for designated provincial highways were the basis for the analyses. This report summarizes the results of this work on resource roads and bridges.



Axle group	Steering	Drives	Lead trailer	Rear trailer	Total
Axle load (kg)	5 500	17 000	24 000	24 000	70 500
Axle width (m)	2.50	2.50	2.60	2.60	

Bunk width (m)	2.90	2.90	2.90

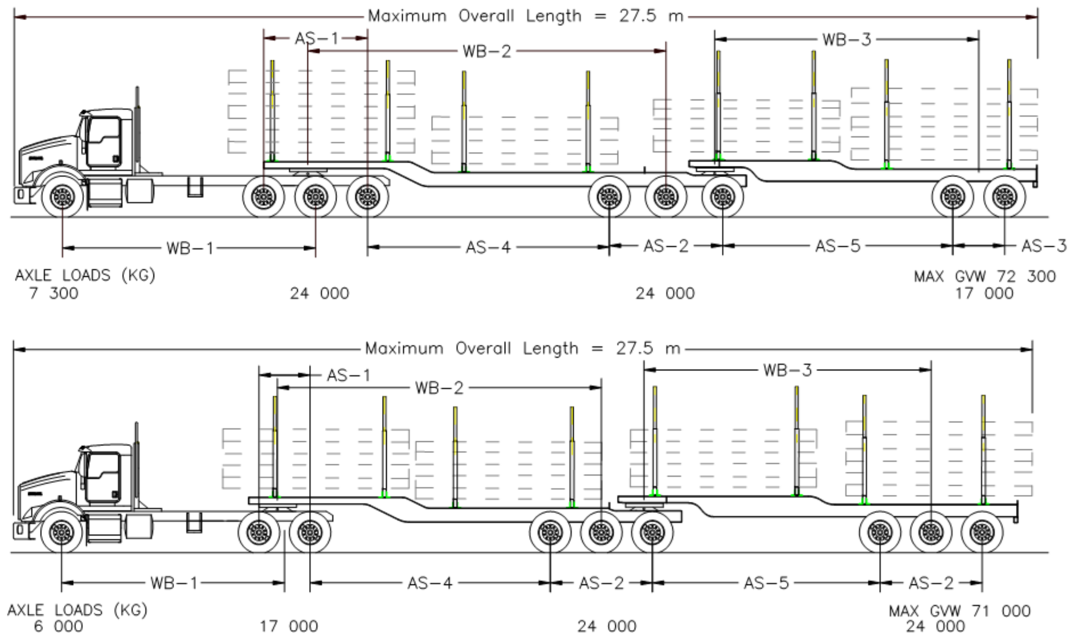
Figure 1. New 9-axle tandem-drive B-train log-hauling configuration for B.C.



Axle group	Steering	Drives	Lead trailer	Rear trailer	Total
Axle load (kg)	7 300	24 000	24 000	17 000	72 300
Axle width (m)	2.50	2.50	2.60	2.60	
Bunk width (m)		2.90	2.90	2.90	

Figure 2. New 9-axle tridem-drive B-train log-hauling configuration for B.C.

In October 2016, the forest industry stakeholders specified ranges of wheelbases and axle group spreads for both configurations that would reflect the variation in truck axle dimensions found in existing and newly manufactured vehicles. The range of truck axle dimensions was small enough that truck dynamic performance, gradeability, and road impacts were unaffected. Force effects on forest bridges and truck off-tracking were affected, however, and were re-assessed for this version of the report. Figure 3 summarises the ranges of axle dimensions for both 9-axle B-trains considered in the re-assessment. In 2019, FPInnovations conducted an analysis to redefine the methodology for assessing pavement impacts of steering axles equipped with widebase tires and then applied the results to refine estimates of pavement impacts of the tridem-drive 9-axle B-train (Bradley and Thiam, 2020). Subsequently, TRAN accepted the new method of calculating pavement impacts from widebase tires and increased the permitted steering load of the tridem-drive 9-axle to 7,300 kg (and the truck's GVW to 72,300 kg).



Allowable Dimensions	Tridem-drive	Tandem-drive
Tractor Wheelbase (WB-1)	6.6 - 6.8 m	5.7 - 6.2 m
Lead Trailer Wheelbase (WB-2)	9.48 – 9.78 m	8.62 - 8.92 m
Rear Trailer Wheelbase (WB-3)	6.79 - 7.39 m	7.24 - 7.84 m
Drive group spread (AS-1)	2.4 – 2.8 m	1.3 – 1.55 m
Trailer tridem group spread (AS-2)	2.7 – 3.1 m	2.7 – 3.1 m
Trailer tandem group spread (AS-3)	1.3 – 1.6 m	NA
Axle spacing : drives to lead trailer (AS-4)	6.0 – 6.5 m	6.2 – 6.8 m
Axle spacing : lead to rear trailer (AS-5)	6.0 – 6.6 m	6.0 – 6.5 m

Maximum trailer axle width should not exceed 2.60 m

Bunk width should be 2.9 m

* For future consideration, bridge analyses should be conducted with a steering axle load of 7300 kg and a GVW of 72300 kg for the tridem-drive 9-axle B-train

Figure 3. Approved ranges of B.C. 9-axle B-train axle dimensions.

3 ANALYSES AND RESULTS

3.1 General

This report provides an initial screening process for:

a) Simple span, and select multiple span, bridges based on the original bridge design vehicle configuration used; and

b) Road geometry based on original design criteria, and on seven reference log haul and lowbed vehicles.

Bridge analysis. The screening analysis of simple span bridges compared the resistance of common forestry bridge designs, in terms of design vehicle force effects, against the demands of 9-axle B-trains. When the 9-axle B-train demand was less than the bridge design resistance, for the range of span lengths considered, the bridge design was considered adequate to support 9-axle B-train traffic. When the 9-axle B-train demands exceeded the bridge design resistance at some span length, the bridge was considered inadequate to support 9-axle B-trains for that span length and longer. If this analysis indicates that a bridge is inadequate for 9-axle B-train traffic, the owner should consult a bridge engineer to conduct a detailed structural evaluation of the bridge for 9-axle B-train vehicles.

Road Geometry Analysis. The 9-axle vehicle configurations were assessed for their theoretical turning, clearance, and grade climbing performance, in consideration of road design criteria. Common log haul and lowbed configurations were analyzed, as well. The results were used to screen the 9-axle configurations against active log haul and lowbed configurations to determine whether the 9-axle B-trains fit within the swept path curve envelopes and gradeability limits of the reference vehicles. Where the 9-axle configurations are within the bounds of the reference vehicles, it can be concluded is expected that the 9-axle vehicles can operate where the reference vehicles have been operating.

If the 9-axle B-train is found to exceed the swept paths of the currently operated log hauling vehicles, consideration should be given to the magnitude of excess requirement and how this might be accommodated by the road network. For example, a small swept path increase on 10-m wide mainline resource road may not warrant further consideration. Local knowledge of road width, curve locations, and traffic composition will be required to judge this aspect of road fit.

If the 9-axle B-train gradeability is found to be substantially less than that of configurations currently active on the road network, this could indicate that the 9-axle B-trains should be restricted from certain haul routes or that they should be used only under dry summer (good traction) conditions.

3.2 Bridge Capacity

Standard design vehicle configurations have evolved over time for bridges on forest service roads in B.C. A general screening analysis compared the force effects of the 9-axle tandem- and tridem-drive B-train configurations against bridge resistance (i.e., bridge design vehicle force effects). Schematics of the bridge design vehicles and the 9-axle B-trains can be found in

Appendix A. Bridge force effects for the tridem-drive 9-axle B-train were evaluated using a maximum steering axle load of 7300 kg equivalent to loading approved for other B.C. tridem-drive configurations, instead of the currently permitted limit of 6900 kg. The bridges were evaluated for up to 80 m long spans; however, most B.C. forestry bridges have span lengths of between 5 and 36 m. The program QuickBridge V1.3 was used to calculate the force effects on the bridges.

If the maximum end support reaction, shear, and bending moment (and pier reaction in the case of multiple spans) from the 9-axle B-trains were less than the design resistances then the capacity of the bridge was deemed sufficient to support the 9-axle B-train–for the span length evaluated. If any of the force effects from the 9-axle truck exceeded the corresponding bridge design resistances, the span was considered to be under-capacity.

Table 1 summarizes the maximum length of simply supported, single span, bridge capable of supporting 9-axle B-trains for 6 forestry bridge designs commonly utilized in the B.C. Interior. Maximum spans differ by 1.0 to 2.5 m from those reported in Table 1 of Version 1 of this report. These differences are the result of using QuickBridge software (which calculates force effects at different spacings than did the previously utilized software), evaluating variants of the 9-axle B-trains with closer axle spacings, and because the dynamic load allowances for the BCL-625, CL-625, and the 9-axle B-trains were changed from 0.25 to 0.30 to be consistent with values used for the other design vehicle analyses.

The Bridge Engineering Section of the B.C. Ministry of Transportation and Infrastructure (TRAN) reports that concrete span bridges designed according to pre-2000 design codes, including pre-stressed concrete beam and concrete slab girder bridges, may be under-designed for shear when compared to results from the current modified compression field theory (G. Farnden, personal communication, September 25, 2015). This under-design could be expected to reduce the maximum safe spans of concrete span bridges designed according to pre-2000 design codes because, in many cases, the maximum span was governed by shear capacity.

There are many concrete slab girder bridges in service on resource roads in B.C. The maximum length of concrete slab girder bridges is about 18 m, however, this length is rare and 5 to 12 m lengths are more the norm. No more than two tandem and one tridem axle or two tridem axles of the 9-axle trucks will fit on clear spans of under 18.5 m at one time. For all bridge spans under 18.5 m, therefore, the force effects caused by the 9-axle trucks are no more than that caused by current log hauling configurations (e.g., 8-axle B-trains, tridem-drive/ tridem semi-trailer hayracks). As there have been no known safety concerns with operating current log hauling configurations on pre-2000 concrete slab girder bridges, operating 9-axle trucks at legal highway loads also should pose no safety concerns. **For spans over 18.5 m, however, this report's general analysis cannot be applied to bridges with concrete beams of pre-2000 design and separate shear analyses should be conducted to evaluate their capacity with respect to the 9-axle trucks.**

This analysis assumed that the 9-axle B-trains were loaded to maximum permitted axle weights (except for the steering axle load of the tridem-drive unit which was evaluated at 7300 kg). Their axle weights were increased by a design live load factor of 1.6 to account for variation. This live load factor is consistent with that used for permitted traffic and assumes that a higher degree of load control is imposed on these trucks than with normal highway traffic.

Table 1. Maximum span length of simply supported, single span, forestry bridges capable of supporting 9-axle B-trains[a]

Design Loading	Max. length of simple, single-span, bridges for 9-axle tridem-drive B-trains (m) [a b]
L-45 [c]	5.5 m [9.5 to 11 spans OK also]
L-60	23 m
CL-625	32.5 m
BCL-625	37.5 m
L-75	80 m
L-100	80 m

a. This table is offered as a general guide. Specific bridges may have higher load limits if evaluated individually. The calculated span limits assume that the bridge is in good condition with no deterioration that would reduce the capacity of the bridge.

b. Concrete beam and slab girder bridges >18.5 m in length require evaluation by a professional engineer.

c. The definition of the L-45 design loading has varied since it's introduction. The reader should refer to the design documentation for the specific bridge to determine which version of the L-45 design specification applies. If the L-45 definition for a specific bridge differs from the current definition, the above table values do not apply.

Although multiple-span bridges are less commonly used on B.C. resource roads, a limited evaluation was undertaken of some 2-equal span bridges for completeness and illustration purposes. Table 2 summarises the results for bridges with 2 simply supported spans, and Table 3 summarises the results for continuous two-span bridges. Table 2 results were provided for the project by the Bridge Engineering Section of TRAN. All multispan bridge configurations that were evaluated were assumed to have spans of equal length which is often not the case in the field. As in the case of single, simple span, bridges, most values in Table 2 were slightly less than those reported in Version 1 of this report. If a company has a multispan bridge that appears to be under capacity according to these tables or has spans of unequal length, the bridge's sufficiency to handle 9-axle B-trains should be assessed by a professional engineer.

Table 2. Maximum span length of simply supported, 2-equal span, forestry bridges capable of supporting 9-axle B-trains

Bridge design vehicle configuration	Maximum length of simple 2-span bridges able to support 9-axle tandem-drive B-trains	Maximum length of simple 2-span bridges able to support 9-axle tridem-drive B-trains
L-45	19.0 m (9.5 m + 9.5 m)	11 m (5.5 m + 5.5 m) [16 to 17.5 m spans also OK]
L-60	22.5 m (11.25 m + 11.25 m)	22.5 m (11.25 m + 11.25 m)
CL-625	35.0 m (17.5 m + 17.5 m)	31 m (15.5 m + 15.5 m)
BCL-625	42.0 m (21 m + 21 m)	37.5 m (18.75 m + 18.75 m)
L-75	116.0 m (58 m + 58 m)	83 m (41.5 m + 41.5 m)
L-100	160.0 m (80 m + 80 m)	160 m (80 m + 80 m)

Table 3 presents the results of an analysis of continuous 2-equal span bridge capacities, in increments of 5 m. The governing force effect for continuous span bridges often is negative moment at the midspan pier, and this tends to be greatest for 9-axle configurations with the widest axle spacings.

The analysis identified an anomaly in the pattern of acceptable bridge lengths for L-75 bridges. L-75 continuous 2-equal span forestry bridges, with 18 to 22 m long spans, appeared to develop excessive negative moment at the midspan pier in response to both the tridem- and tandem-drive 9-axle B-trains. It is recommended, therefore, that the capacity of 2-span continuous L-75 bridges of these lengths should be determined with a detailed structural analysis.

Table 3. Maximum span length of continuous, 2-span, bridges capable of supporting 9-axle B-trains

Bridge design vehicle configuration	Maximum length of continuous 2-span bridges able to support 9-axle tandem-drive B-trains	Maximum length of continuous 2-span bridges able to support 9-axle tridem-drive B-trains
L-45	10 m (5 m + 5 m)	10 m (5 m + 5 m)
L-60	20 m (10 m + 10 m)	20 m (10 m + 10 m)
CL-625	30 m (15 m + 15 m)	30 m (15 m + 15 m)
BCL-625	30 m (15 m + 15 m)	30 m (15 m + 15 m)
L-75	80 m (40 m + 40 m) EXCEPTION: continuous 2-span bridges with spans of 18 – 22 m each require a detailed analysis	60 m (30 m + 30 m) EXCEPTION: continuous 2-span bridges with spans of 18 – 22 m each require a detailed analysis
L-100	100 m (50 m + 50 m)	100 m (50 m + 50 m)

A note of caution. Logging truck design vehicle configurations and loads have increased over time. Some bridges that were designed for lower design vehicle configurations have been evaluated for upgrading to higher allowable loads (eg. L-45 upgraded to L-75) based on a bridge specific evaluation for a specific higher load configuration. **Any structures that have been upgraded in such a manner, for the purposes of 9-axle evaluation captured by the analysis in this document, must be evaluated based on its original design vehicle configuration**. It is recommended that any structure that is suspect for having been upgraded in load capacity be reviewed to confirm its original design vehicle configuration prior to application of the guidance in this document.

3.3 Resource Road and Bridge Approach Horizontal Alignment

Assessing the safe use of the 9-axle B-train configurations included determining whether they could negotiate existing forestry roads and bridges without the need to widen existing horizontal curves. Since detailed geometric information for resource roads in B.C. is not readily available, theoretical analyses of horizontal and vertical geometry requirements of the 9-axle B-trains were compared with geometric requirements of seven reference trucks and with FLNR, TRAN, and Transportation Association of Canada (TAC) geometric design standards (FLNR, 2018; TRAN, 2007; TAC, 1999). The comparison distinguishes between high-speed roads with rates of travel greater than 30 km/h, and low-speed roads with rates of travel below 30 km/h.

For this comparison, FSR 'mainline' roads were assumed to have a running surface width of between 5.0 and 8.0 m while lower standard roads were assumed to have running surface widths of less than 5.0 m. This corresponds with design standards found in FLNR (2018). For mainline roads, several curve paths were assessed to account for railway crossings, bridge approaches, wildlife sight-line breaks, by-passing oil and gas infrastructure, and road junctions. Lower standard roads were assumed to be in-block roads where curves typically are tighter but design speeds are low. It should be noted that, for a variety of reasons, older resource roads often are wider than the FLNR minimum specifications (e.g., mainline roads in some locations may be 10-15 m wide, and secondary roads may be wider than 5 m).

Results for the 27.5 m-long 9-axle configurations were compared with 7 reference configurations currently used under various terrain conditions by the B.C. forest industry. The logic of this approach was that if the 9-axle B-trains have comparable road width and grade climbing performance to current (reference) truck configurations then the road networks would be suitable for 9-axle B-train use without modification. Vehicle configurations currently used in flat-to-moderately-sloped terrain in B.C. include the 23 m-long 7-axle tridem-drive/tridem semi-trailer (hayrack) and three variations of 8-axle B-trains: the 25.24 m-long tandem-drive 8-axle (super) B-train, the 25.23 m-long tridem-drive 8-axle B-train, and the 27.5 m-long tridem-drive 8-axle B-train. The 8-axle tridem-drive tractor/ quad-axle full trailer (wagon) is a configuration currently used in steeper terrain in B.C. where curves can be tighter. A seventh reference vehicle, used throughout B.C. for transporting forestry equipment, is the 8-axle tridem-drive tractor/ tridem-axle lowbed with a single booster axle. Appendix B contains schematics of each of the configurations evaluated.

Table 4 and Table 5 summarize the maximum road width requirement (swept path) of the 7 reference truck configurations, relative to a 9-axle tridem-drive B-train, for a variety of curves associated with higher design speed roads (e.g., FSRs). If not using any of these reference vehicles, forest operations can calculate their own log hauling vehicles' swept path values to compare with the 9-axle B-train values. Alternately, the forest operation could compare the 9-axle B-train swept path requirements to actual road width measurements from their tightest low- and high-speed curves. Appendix C contains swept path values for the 9-axle B-trains and the reference configurations.

Maximum swept-path values are used to assess the horizontal requirement of trucks in curves and intersections. The road running surface must be as least as wide as the swept path in order to accommodate truck turns. Additional road width is needed to account for poor driver judgement and slippery conditions that lead to sub-optimal turning. The analyses in this version of the report differ from that used for previous versions of the report. Swept path estimates were completed using AutoTurn V1.3 software capable of automatically determining maximum swept path (previous versions of the software required the user to make manual measurements on a graphic of vehicle path to determine the maximum width). Additionally, minor changes to inputs were made to improve the accuracy of the vehicle dimensions.

High speed curves. The 9-axle B-train swept paths were between 2.33 and 2.15 m less than the FLNR-recommended minimum curve widths for high speed curves. If a forest operation has mainline roads that meet these FLNR-recommended design criteria, their curve widths will accommodate 9-axle B-train traffic.

If a forest operation's mainline road curves do not adhere to FLNR-recommended design criteria or it isn't known whether they do or not, then the forest operation can judge whether curve widening may be required for 9-axle B-trains by considering the swept path requirements of current truck configurations. The thesis is that if the high speed horizontal curves accommodate trucks with comparable turning requirements to the 9-axle B-trains then no curve widening would be needed. The swept path requirements of 9-axle tridem-drive B-trains for higher speed curves were within 21 cm of the 8-axle tridem-drive lowbed swept paths and within 15 cm of the tridem-drive 8-axle B-train reference truck swept paths. These differences in swept path requirements are considered to be minor under most mainline operating conditions. If a forest operation currently utilizes 8-axle tridem-drive B-trains and (or) 8-axle tridem-drive lowbeds with booster axles, therefore, their mainline road curve widths also should accommodate 9-axle B-trains.

If a forest operation does not currently utilize 8-axle tridem-drive B-trains and (or) 8-axle tridem-drive lowbeds with booster axles, then it should compare the maximum swept path requirements of their current truck configuration(s) to that of 9-axle B-trains. Results for a number of common reference trucks are provided, however, if none of these apply, then the forest operation should have their fleet configurations evaluated. If the 9-axle B-train swept path requirements exceed those of current configurations by more than a minor amount (e.g., 50 cm), then the forest operation must judge whether curve widening is needed to accommodate the 9-axle B-trains. Given the large size of some licensee's road networks, this task may by onerous. One approach would be to survey as-built curves along the proposed mainlines, and estimate the current safety buffer (difference between maximum truck swept path and actual curve width). Based on this review, the forest operation can quantify the change in curve width safety buffer with 9-axle B-trains, and then judge whether the remaining safety buffer is sufficient. As mentioned previously, local knowledge of road width, curve locations, and traffic patterns will be required to make these judgements. Particular attention should be paid to actual road width vs. FLNR design standards, and the volume of current or expected traffic along with their configurations.

Table 4. Comparison of swept path for high-speed curves for various forestry trucks relative to a 9-axle tridem-drive B-train

Configuration	Minimum road width in curve [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Swept path (m)				
				Curve path				
				15°	20°	30°	45°	90°
9-axle tridem-drive B-train (27.5 m-long)	6.0	50	100	3.66	3.77	3.83	3.85	3.85
	5.8	60	140	3.47	3.52	3.55	3.55	3.55
9-axle tandem-drive B-train (27.5 m-long)	6.0	50	100	-0.12	-0.13	-0.13	-0.13	-0.13
	5.8	60	140	-0.08	-0.08	-0.09	-0.09	-0.08
Reference vehicles								
6-axle tandem-drive/ tridem semi-trailer (hayrack)	6.0	50	100	-0.44	-0.47	-0.48	-0.48	-0.48
	5.8	60	140	-0.40	-0.41	-0.42	-0.41	-0.41
7-axle tridem-drive/ tridem semi-trailer (hayrack)	6.0	50	100	-0.33	-0.32	-0.27	-0.25	-0.25
	5.8	60	140	-0.27	-0.26	-0.25	-0.25	-0.24
8-axle tridem-drive tridem lowbed + single booster axle	6.0	50	100	-0.21	-0.16	-0.07	-0.03	-0.02
	5.8	60	140	-0.16	-0.13	-0.10	-0.09	-0.08
8-axle tridem-drive quad trailer (short logs)	6.0	50	100	-0.66	-0.74	-0.79	-0.81	-0.81
	5.8	60	140	-0.61	-0.65	-0.68	-0.68	-0.67
8-axle tandem-drive (super) B-train (25.24 m-long)	6.0	50	100	-0.41	-0.46	-0.46	-0.47	-0.48
	5.8	60	140	-0.38	-0.40	-0.42	-0.42	-0.42
8-axle tridem-drive B-train (25.23 m-long)	6.0	50	100	-0.12	-0.15	-0.15	-0.15	-0.14
	5.8	60	140	-0.09	-0.10	-0.11	-0.11	-0.11
8-axle tridem-drive B-train (27.5 m-long)	6.0	50	100	-0.05	-0.05	-0.03	-0.02	-0.02
	5.8	60	140	0.01	0.01	0.01	0.02	0.01

a. *Recommended minimum value from FLNR (2018).*

Moderate speed curves. Table 5 summarizes the swept path for trucks tracking through moderate speed curves. Recommended minimum road surface widths for these curves are from FLNR (2018).

The 9-axle B-train swept path requirements for 15° to 90° moderate-speed curves were between 3.88 and 5.91 m wide. These requirements are 2.82 and 1.09 m less than the FLNR-recommended minimum curve widths. If a forest road network has moderate speed curves that meet the FLNR design criteria, therefore, their gentle moderate-speed curves should accommodate 9-axle B-train traffic.

For moderate speed curves narrower than the FLNR-recommended specifications of 6.7 to 7 m, the swept path requirements of 9-axle tridem-drive B-trains must be considered in light of the actual curve widths. Alternately, one could compare the 9-axle B-train swept paths with the requirements of trucks operating on the road. For example, for gentle (15° to 30°) curves, the 9-axle tridem-drive B-train swept paths were within 26 cm of the 8-axle tridem-drive lowbed swept paths and within 31 cm of the tridem-drive 8-axle B-train swept paths. These differences are relatively small and likely are not relevant to normal resource road operating conditions (Matt Campbell, CANFOR, March 2019). In this case, the response might be to accept that loaded 9-axle B-trains may track up to 31 cm closer to or even onto the road shoulder at some point in the curve, to add must call signage at the curve, and(or) to do minor curve widening.

The swept path requirements of the 9-axle B-train and the tridem-drive lowbed were comparable for 45° to 90° moderate-speed curves; therefore, if 8-axle tridem-drive lowbeds with booster axles currently operate on the road, then it should also accommodate 9-axle B-trains. The swept path requirements of the 9-axle B-train through 35 m-radius, 45° to 90°, moderate-speed curves, however, exceed those of tridem-drive 8-axle B-trains by 31 to 42 cm. Based on this, the specific circumstances for the curve(s) in question needs to be considered. And, as before, the response might be to accept that loaded 9-axle B-trains may track closer to or even onto the road shoulder at some point in the curve, to add must call signage at the curve, and(or) to do minor curve widening.

If a forest operation does not currently utilize 8-axle tridem-drive B-trains and (or) 8-axle tridem-drive lowbeds with single booster axles then it should compare the maximum swept path requirements of their current truck configuration(s) to that of 9-axle B-trains. Results for a number of common reference trucks are provided in Table 5, however, if none of these apply, then the forest operation should have their fleet configurations evaluated. If the 9-axle B-train swept path requirements exceed those of current configurations by more than a minor amount (e.g., 20 or 25 cm), then the forest operation must decide whether curve widening is needed to accommodate 9-axle B-trains.

Table 5. Comparison of swept path for moderate-speed curves for various forestry trucks relative to a 9-axle tridem-drive B-train

Configuration	Minimum road width in curve [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Maximum swept path relative to 9-axle tridem drive B-train (m)				
				Curve path				
				15°	20°	30°	45°	90°
9-axle tridem-drive B-train (27.5 m-long)	7.0	30	35	4.10	4.46	5.07	5.52	5.91
	6.7	40	65	3.88	4.11	4.31	4.42	4.45
9-axle tandem-drive B-train (27.5 m-long)	7.0	30	35	-0.15	-0.17	-0.21	-0.25	-0.28
	6.7	40	65	-0.13	-0.15	-0.17	-0.18	-0.18
Reference Vehicles								
6-axle tandem-drive/ tridem semi-trailer (hayrack)	7.0	30	35	-0.50	-0.57	-0.69	-0.82	-0.94
	6.7	40	65	-0.47	-0.52	-0.58	-0.62	-0.62
7-axle tridem-drive/ tridem semi-trailer (hayrack)	7.0	30	35	-0.40	-0.42	-0.49	-0.55	-0.44
	6.7	40	65	-0.37	-0.40	-0.37	-0.32	-0.29
8-axle tridem-drive tridem lowbed + single booster axle	7.0	30	35	-0.26	-0.25	-0.22	-0.17	+0.15
	6.7	40	65	-0.24	-0.23	-0.13	-0.02	+0.07
8-axle tridem-drive quad trailer (short logs)	7.0	30	35	-0.77	-0.89	-1.16	-1.43	-1.75
	6.7	40	65	-0.72	-0.83	-0.97	-1.06	-1.08
	7.0	30	35	-0.28	-0.54	-0.68	-0.81	-0.93

Configuration	Minimum road width in curve [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Maximum swept path relative to 9-axle tridem drive B-train (m)				
				Curve path				
				15°	20°	30°	45°	90°
8-axle tandem-drive (super) B-train (25.24 m-long)	6.7	40	65	-0.45	-0.50	-0.56	-0.60	-0.61
8-axle tridem-drive B-train (25.23 m-long)	7.0	30	35	-0.19	-0.23	-0.31	-0.37	-0.42
	6.7	40	65	-0.16	-0.18	-0.20	-0.22	-0.22
8-axle tridem-drive B-train (27.5 m-long)	7.0	30	35	-0.17	-0.20	-0.27	-0.30	-0.30
	6.7	40	65	-0.13	-0.16	-0.15	-0.13	-0.12

b. Recommended minimum value from FLNR (2018).

Slow-speed, tight-radius, curves. Table 6 summarizes the minimum road width (swept path) of seven reference truck configurations, relative to a 9-axle tridem-drive B-train, required for a variety of slow- speed, tight-radius curves. Although these curves are not likely to be used on mainline roads (i.e., FSRs) they are included in the discussion for completeness.

The swept path of 9-axle tridem-drive B-trains in 180°, 15 m-radius, curves only slightly exceeded the FLNR-recommended minimum 9.0 m width, and was less than the recommended limit for smaller angle, 24 m-radius, curves. These results indicate that, if tight radius curves adhere to FLNR-recommended design specifications, then these will accommodate 9-axle B-train traffic.

For slow speed tight-radius curves not meeting FLNR-recommended minimum curve widths, the swept path requirements of 9-axle tridem-drive B-trains should be considered. In low speed, 15 m-radius, curves between 30° and 180° curve path, the 9-axle tridem-drive B-train's swept path was 0.37 to 1.01 m greater than that of the reference 25.23 m-long 8-axle tridem-drive B-train (and even more for other reference vehicles). In low-speed, 24 m-radius, curves between 30° and 180°, the 9-axle tridem-drive B-train's swept path was 0.35 to 0.62 m greater than that of the reference 25.23 m-long 8-axle tridem-drive B-train (and even more for other reference vehicles).

At the 20 km/h design speed of these tight curves the consequences of increased swept path requirements are believed to be more operational than safety related. Loaded vehicles should be able to stop easily and, if necessary, negotiate the curve by reversing to jack knife the unit prior to proceeding.

It should be reiterated that tight, low speed curves are not commonly found on mainline FSRs. If such a curve was present, it likely would have been widened and signed for industrial traffic (particularly lowbeds) to safely negotiate. In this case, local knowledge and evaluation of the circumstances is required.

Table 6. Comparison of swept path low-speed tight-radius curves for various truck configurations relative to a 9-axle tridem-drive B-train

Configuration	Minimum curve width [a] (m)	Design speed (km/h)	Curve radius (m)	Maximum swept path relative to 9-axle tridem-drive B-train (m)				
				Curve path				
				30°	60°	75°	90°	180°
9-axle tridem-drive B-train (27.5 m-long)	9.0	20	15	5.46	6.57	7.60	8.48	9.15
	7.6		24	5.43	6.29	6.74	7.03	7.23
9-axle tandem-drive B-train (27.5 m-long)	9.0	20	15	- 0.25	- 0.42	- 0.48	- 0.53	- 0.63
	7.6		24	- 0.23	- 0.34	- 0.35	- 0.36	- 0.40
Reference vehicles								
6-axle tandem-drive/ tridem semi-trailer (hayrack)	9.0	20	15	- 1.75	- 2.91	- 2.91	- 1.58	- 2.23
	7.6		24	- 1.73	- 2.06	- 1.69	- 1.21	- 1.33
7-axle tridem-drive/ tridem semi-trailer (hayrack)	9.0	20	15	- 0.56	- 0.79	- 0.88	- 0.98	- 1.23
	7.6		24	- 0.52	- 0.69	- 0.71	- 0.72	- 0.59
8-axle tridem-drive tridem lowbed + single booster axle	9.0	20	15	- 1.51	- 2.43	- 2.20	- 0.38	- 0.02
	7.6		24	- 1.49	- 1.57	- 0.97	- 0.15	+ 0.28
8-axle tridem-drive quad trailer (short logs)	9.0	20	15	- 2.02	- 3.39	- 3.59	- 2.86	- 4.39
	7.6		24	- 1.99	- 2.53	- 2.35	- 2.27	- 2.60
8-axle tandem-drive B-train (25.24 m-long)	9.0	20	15	- 0.74	- 0.90	- 1.21	- 1.54	- 2.14
	7.6		24	- 0.72	- 1.04	- 1.12	- 1.19	- 1.33
8-axle tridem-drive B-train (25.23 m-long)	9.0	20	15	- 0.37	- 0.64	- 0.74	- 0.82	- 1.01
	7.6		24	- 0.35	- 0.53	- 0.55	- 0.57	- 0.62
8-axle tridem-drive B-train (27.5 m-long)	9.0	20	15	- 0.33	- 0.55	- 0.61	- 0.66	- 0.63
	7.6		24	- 0.31	- 0.44	- 0.43	- 0.42	- 0.42

a. Recommended minimum value from FLNR (2018).

3.4 Resource Road and Bridge Vertical Alignment

The proper design of the vertical alignment of roads and bridge approach curves is critical to user safety and, in the case of bridge approaches, structure service life. Sudden grade changes may reduce driver visibility, cause vehicle clearance issues, and increase impact loading of bridges. The abilities of the proposed 9-axle B-train logging trucks to navigate vertical curves were assessed using conventional vertical curve formulae and comparing these results to current guidelines, and by comparing 9-axle B-train requirements to those of 7-axle hayracks and 8-axle super B-trains.

Table 7 compares the findings of crest vertical curve assessments for the two 9-axle B-train configurations with results for 7-axle hayracks and 8-axle super B-trains. The breakover angle K (K_{BA}) value is a parabolic function of the total horizontal curve length and change in grade. The higher the value of K_{BA}, the less abrupt the curve. K_{BA} also applies to sag curves. The largest K_{BA} values required by the 9-axle configurations were for their lead trailers (0.23 and 0.27 for the tandem-drive and tridem-drive units, respectively). These requirements are less than the minimum design K_{BA} values recommended by TRAN (which are 3.0 and 4.0 for crest and sag curves, respectively), and less than those calculated from the FLNR stopping sight distance values (FLNR, 2018). The 9-axle configurations, therefore, should be capable of negotiating any vertical curves that meet these design standards. Additionally, the maximum 9-axle K_{BA} values are comparable to the maximum K_{BA} value for the 8-axle super B-train, and less than the maximum K_{BA} value for the 7-axle hayrack. As both of these configurations currently operate on resource roads throughout B.C., the 9-axle B-train configurations also should be able to negotiate the vertical curves on these road networks.

Table 7. Comparison of vertical curve specifications

	Clearance (m)	Wheelbase (m)	Breakover angle (˚)	Grade break (%)	K value (K_{BA})
7-axle tridem-drive semi-trailer (hayrack)					
tridem-drive tractor	0.56	6.6	19.3	34.9	0.19
3-axle semi-trailer (hayrack)	0.79	11.5	15.6	28.0	0.41
8-axle tandem-drive B-train					
tandem-drive tractor	0.56	6.00	21.15	38.68	0.16
3-axle lead B-train semi-trailer	0.79	8.92	20.09	36.57	0.24
2-axle rear B-train semi-trailer	0.79	6.25	28.37	54.01	0.12
9-axle tandem-drive B-train					
tandem-drive tractor	0.56	6.00	21.2	38.8	0.16
3-axle lead B-train semi-trailer	0.84	8.92	21.3	39.0	0.23
3-axle rear B-train semi-trailer	0.98	7.54	29.1	55.8	0.14

	Clearance (m)	Wheelbase (m)	Breakover angle (˚)	Grade break (%)	K value (K_{BA})
9-axle tridem-drive B-train					
tridem-drive tractor	0.56	6.60	19.3	34.9	0.19
3-axle B-train lead semi-trailer	0.84	9.68	19.7	35.8	0.27
2-axle B-train rear semi-trailer	0.98	7.00	31.3	60.8	0.12

3.5 Gradeability

An analysis of 9-axle B-train gradeability was made to assess whether their introduction might have operational limitations and require changes to design grade limits. Estimates of traction-limited gradeability were made for long grades on which the truck travels at a constant (sustained) rate of speed and for short grades on which the trucks slow down as they climb (i.e., because they are utilizing momentum to assist with climbing). Power-limited gradeability varies with each truck's drive train specifications and must be calculated individually with an analysis of wheel forces and loads while on a grade; however, traction-limited gradeability is typically less and governs in the case of resource road evaluations. Several truck fleets in B.C. utilize tire pressure control systems (TPCS) to improve gradeability, traction, ride, soft road mobility, and to reduce road impacts.

Table 8 tabulates the estimated summer and winter gradeability for all of the subject truck configurations. Gradeability results are reported for the 9-axle B-trains, if equipped with TPCS, also. Sustained gradeability estimates are illustrated in Figure 4 for select configurations.

Table 8. Estimated traction-limited sustained gradeability

Truck configuration	Loading condition	Estimated traction-limited sustained gradeability	
		With tire chains on packed snow surfaces	On good gravel surfaces
6-axle tridem-drive/ tandem semi-trailer (hayrack)	Unloaded	12.0%	17.0%
	Loaded	14.0%	20.0%
7-axle tridem-drive/ tridem semi-trailer (hayrack)	Unloaded	11.0%	16.0%
	Loaded	12.0%	17.0%
8-axle tridem-drive tridem lowbed with single booster axle	Unloaded	11.0%	16.0%
	Loaded	10.0%	14.5%
8-axle tri-drive truck/ quad-axle full trailer	Unloaded (trailer on tractor)	20.0%	27.0%
	Loaded	10.5%	15%
8-axle tandem-drive B-train (25.24 m-long)	Unloaded	8.5%	12.5%
	Loaded	6.5%	10.5%

Truck configuration	Loading condition	Estimated traction-limited sustained gradeability	
		With tire chains on packed snow surfaces	On good gravel surfaces
8-axle tridem-drive B-train (25.23 m-long)	Unloaded	12.5%	18.0%
	Loaded	9.5%	14.0%
8-axle tridem-drive B-train (27.5 m-long)	Unloaded	12.5%	17.5%
	Loaded	9.5%	14.0%
9-axle tandem-drive B-train	Unloaded	8.0% (8.5%) *	12.0% (13.5%) *
	Loaded	5.5% (6.0%) *	9.0% (10.0%) *
9-axle tridem-drive B-train	Unloaded	10.0% (10.5%) *	14.5% (16.0%) *
	Loaded	8.5% (9.5%) *	13.0% (14.5%) *

* *value in brackets indicates estimated gradeability with TPCS on drive axles.*

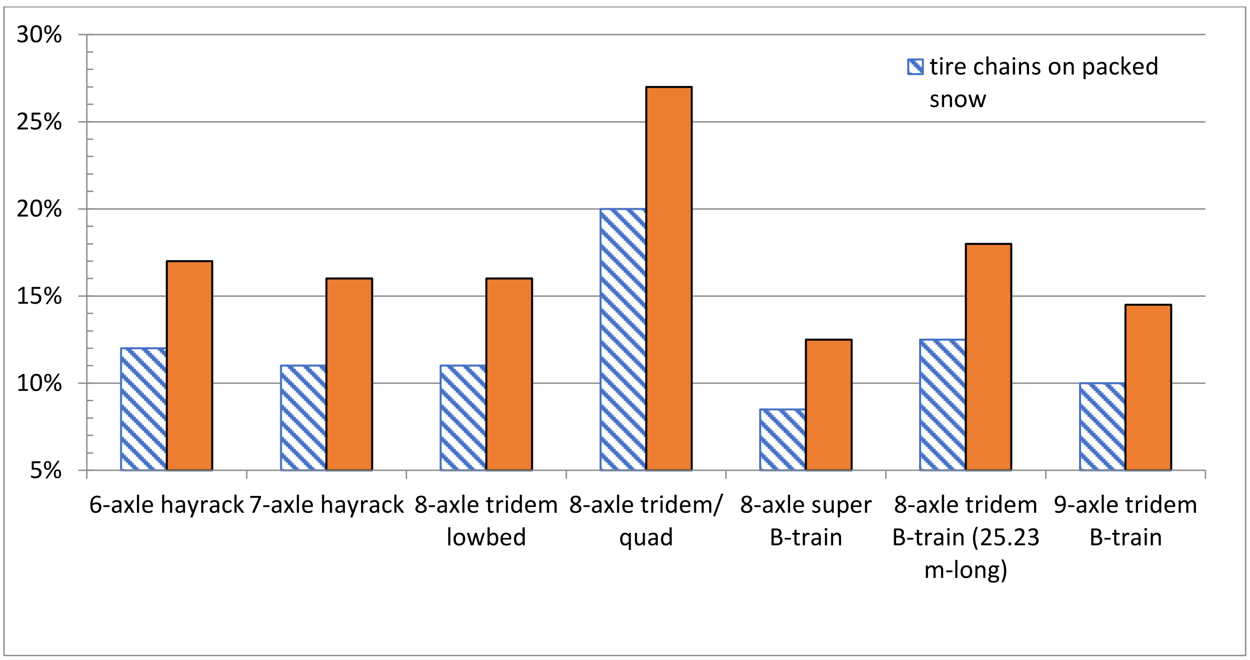


Figure 4. Estimated traction-limited sustained gradeability for unloaded trucks in winter and summer.

Trucks are capable of climbing steeper grades in the case of short pitches with some loss of speed (i.e., using momentum to assist with the climb). Momentum-assisted gradeability estimates are presented in Table 9 and values are rounded to the nearest 0.5%; the 9-axle B-train gradeabilities are estimated without and with TPCS. Momentum-assisted gradeability is higher for shorter pitches; momentum typically runs out, with the truck transitioning to sustained gradeability limits, on pitches of 300 m or longer.

Gradeability estimates are provided for both medium length (200 m) and short (50 m) pitches. The calculations assume that trucks start climbing the hill at 25 km/h and slow to no more than

5 km/h by the time they reach the top. Results are presented for both loaded and unloaded trucks. The unloaded 6- and 7-axle hayracks and the 8-axle lowbed are assumed to pull their trailers while the other configurations are assumed to carry their rear trailer when travelling unloaded.

Table 9. Estimated traction-limited momentum-assisted gradeability for medium and short pitches

Truck configuration	Loading condition	Estimated traction-limited, momentum-assisted, gradeability			
		With tire chains on packed snow surfaces		On good gravel surfaces	
		200 m-long	50 m-long	200 m-long	50 m-long
6-axle tridem-drive/ tridem semi-trailer	Unloaded	13.0%	16.0%	17.5%	21.5%
	Loaded	15.0%	19.0%	20.5%	24.0%
7-axle tridem-drive/tridem semi-trailer	Unloaded	12.0%	15.5%	17.0%	20.5%
	Loaded	13.0%	16.0%	18.0%	21.5%
8-axle tridem-drive tridem lowbed with single booster axle	Unloaded	12.0%	15.5%	17.0%	20.5%
	Loaded	11.0%	14.5%	15.5%	19.0%
8-axle tri-drive truck/ quad-axle full trailer	Unloaded (trailer on tractor)	20.5%	24.0%	27.5%	31.0%
	Loaded	11.5%	15.0%	16.0%	19.5%
8-axle tandem-drive B-train (25.24 m-long)	Unloaded	9.5%	12.5%	13.5%	16.5%
	Loaded	7.5%	10.5%	11.0%	14.5%
8-axle tridem-drive B-train (25.23 m-long)	Unloaded	13.5%	17.0%	18.5%	22.5%
	Loaded	11.0%	14.5%	15.5%	19.0%
8-axle tridem-drive B-train (27.5 m-long)	Unloaded	13.5%	17.0%	18.5%	22.0%
	Loaded	11.0%	14.5%	15.5%	19.0%
Tandem-drive 9-axle B-train	Unloaded	9.0% (10.0%) *	12.5% (13.5%) *	13.0% (14.5%) *	16.5% (18.0%) *
	Loaded	7.0% (7.5%) *	10.5% (11.0%) *	10.5% (11.0%) *	14.0% (15.0%) *
Tridem-drive 9-axle B-train	Unloaded	11.0% (11.5%) *	14.5% (15.0%) *	15.5% (17.0%) *	19.0% (20.5%) *
	Loaded	10.0% (10.5%) *	13.5% (14.0%) *	14.0% (15.5%) *	17.5% (19.0%) *

** value in brackets indicates estimated gradeability with TPCS on drive axles.*

The following trends were identified in this gradeability analysis:

- **Loaded vs unloaded.** All of the B-train configurations and the tridem-drive/ quad trailer have better gradeability when unloaded than when loaded. The 6- and 7-axle tridem hayracks are the reverse, with loaded gradeability being better than when unloaded.
- **Favourable grades.** Unloaded 8-axle tridem-drive quad trailers can climb steeper grades than all of the other configurations – under both winter and summer conditions. Unloaded 9-axle tridem-drive B-trains have unloaded gradeabilities that are comparable to the 6- and 7-axle hayracks, 27.5 m-long 8-axle tridem-drive B-trains, and 8-axle tridem lowbed with single booster axle, slightly better gradeability than 8-axle super B-trains, and slightly worse gradeability than 8-axle tridem-drive B-trains.

- **Adverse grades**. Loaded tridem-drive 9-axle B-trains will have better gradeability (by 1.5% to 2.0%) than 8-axle super B-trains. Loaded 6- and 7-axle hayracks and tridem-drive/ quad trailers can climb steeper grades than any of the loaded 8- and 9-axle B-train configurations – under both winter and summer conditions.
- **Momentum grades.** Trucks can negotiate steeper grades if their momentum can carry them to the top (i.e., the length is short enough for momentum-assisted gradeability to apply to the whole climb). For all of the trucks, momentum-assisted gradeability was 1% to 4.5% higher than sustained gradeability, depending on pitch length.
- **Traction enhancement.** Trucks utilizing traction enhancing technology (e.g., TPCS, a drive-tire sanding box) can negotiate even steeper grades. TPCS is predicted to offer only minor improvements to wintertime gradeability (e.g., increases of 0.4% to 0.7%); however, summertime estimated improvements are double this (i.e., increases of 1.0% to 1.5%).

In summary, it is anticipated that the introduction of 9-axle B-trains will not result in any grade climbing concerns if tandem-drive 8-axle B-trains can already negotiate the route, and the maximum sustained grades are less than about 13% on haul summer routes and less than about 9% on winter routes. Tire-to-ground friction (traction) can change during the day as weather and trafficking changes the road surface conditions. Gradeability under actual service conditions, therefore, will vary somewhat from the general estimates in the report tables. According to Matt Campbell, of CANFOR (March 2019 communication) integration of 9-axle tridem-drive B-trains into log hauls operating with 8-axle B-trains has presented no operational problems.

To further reduce the likelihood of 9-axle trucks getting stuck on hills, the steepness of non-uniform grades should be conservatively estimated, the report's gradeability predictions should be validated under field conditions, drivers should fully load drive axle groups, tire chains should be used on steep hills, drivers should use momentum whenever possible and avoid gear changes while climbing, and TPCS use should be encouraged. Further, attention should be paid to ensuring good traction is maintained on steeper grades and that opportunities for drivers to use momentum to climb hills be supported through the strategic location of pull-outs and sight line maintenance.

3.6 Vehicle Dynamics

The dynamic performance of heavy vehicles is an important consideration when assessing the safety of new configurations in terms of stability, handling, and steering when driving. The assessment typically features 12 standard measures that compare predicted high-speed handling, ease of rollover, off-tracking, and other key dynamic responses against accepted performance ranges.

In order to gain approval to use the 9-axle B-train log trucks on public highways, FPInnovations conducted a formal analysis of the dynamic performance of these configurations (Parker et al., 2014). The vehicle performance levels estimated in this report were confirmed by a second dynamic study (UMTRI 2016). From these evaluations, FPInnovations found that both 9-axle B-trains performed within accepted ranges. Further, they had comparable dynamic performance ratings to the 7-axle hayrack and 8-axle super B-train. On the basis of these findings, the 9-axle dynamic performance will be sufficient to negotiate B.C. resource roads safely.

Application of the vehicle dynamic performance assessment findings

In order to ensure vehicle stability is maintained, it is important to use the full length of trailers for loading. This means carrying four bundles when hauling 5-m cut-to-length logs. The B-train trailers should be equipped with wide (2.9 m) bunks as this was found to be necessary in the analysis to reduce overall load height and maintain vehicle stability.

Acceleration performance. As with all heavy or heavier vehicles there may be questions about the 9-axle vehicle's capacity to accelerate to road speeds quickly, climb grades without stalling or slowing too much, or brake adequately. Heavy vehicles licensed in B.C. must comply with a regulation stipulating maximum gross weight-to-power ratio of 150 kg per horsepower (CVSE, 2016). This regulation is designed to ensure that heavy vehicles accelerate to road speeds within safe time limits and negotiate adverse highway grades without stalling or undue slowing. When propelled by a 500 hp engine, the 9-axle B-train configurations will satisfy this regulation with gross weight-to-power ratios of 144 and 141 for the tridem- and tandem-drive units, respectively.

Braking performance. 9-axle B-trains have comparable braking performance to 8-axle configurations despite being a heavier truck. This is due to the fact that, compared to the 8-axle configurations, the 9-axle B-train's number of non-steering, braking axles is increased by 14% while its gross weight is increased only by 11%–13% (7–8.4 t). For the same reason, the 9-axle B-train's braking performance is better than all smaller current log hauling configurations (Figure 5).

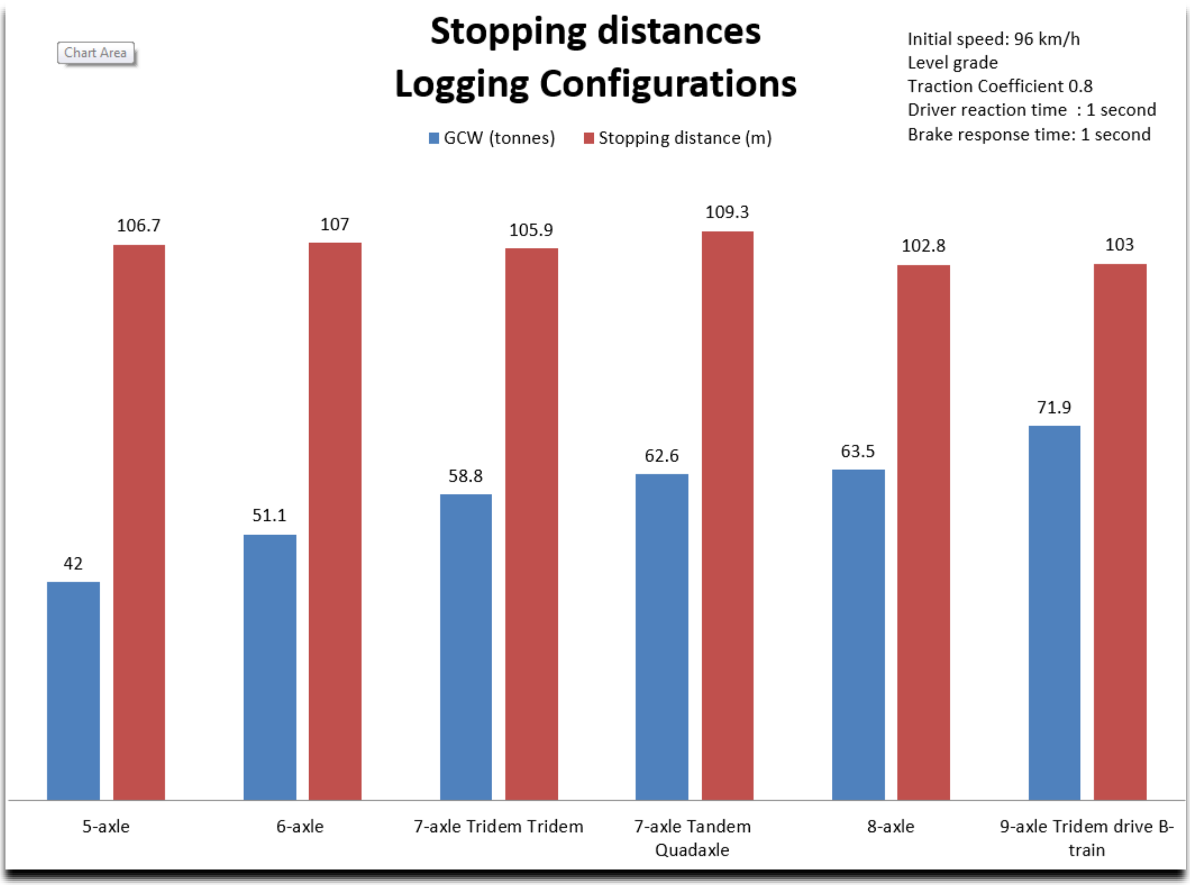


Figure 5. Comparison of theoretical stopping distance of the 9-axle B-train and smaller log hauling configurations (Parker et al. 2014).

3.7 Resource Road Impacts

An analysis of the potential unpaved road impacts relative to a baseline truck was conducted to assess whether the two 9-axle B-train configurations might accelerate road surface rutting and increase road maintenance requirements. Potential road impacts (expressed as equivalent single-axle loads or ESALs) caused by the 9-axle B-train configurations were compared against those caused by a variety of common B.C. forestry trucks. A methodology utilized by the USDA Forest Service's Surface Thickness Program (Copstead 1991) was used to calculate the gravel road impacts. The results of this analysis are presented in

Table 10.

The preceding analysis assumed that all configurations were loaded to maximum legal GVW and had typical tare weights. Adopting 9-axle tridem-drive B-trains in place of the various reference vehicles is estimated to change road impacts by from 3.2% more to 25% less, depending on the current log hauling configurations. The annual impacts of the 9-axle B-train configurations on resource roads are anticipated to be less than if currently hauling with the 8-axle super B-trains or hayrack configurations but marginally more if currently hauling with tridem-drive quad trailers or 8-axle tridem-drive B-trains.

Table 10. Comparison of resource road rutting impacts with introduction of 9-axle tridem-drive B-trains

Configuration	Roundtrip impact (ESALs)	GVW (tonnes)	Payload (tonnes)	Impact per tonne payload (ESALs per tonne)	Impact with change to 9-axle tridem-drive B-trains
6-axle tridem-drive/tandem semi-trailer (hayrack)	7.6	48.3	28.3	0.268	-24.8%
7-axle tridem-drive/tridem semi-trailer (hayrack)	8.14	55.3	34.0	0.237	-14.9%
8-axle tridem-drive/ quad trailer	8.9	63.5	45.6	0.195	+3.2%
8-axle tridem-drive/ tridem lowbed with single booster axle	10.1	63.5	37.9	0.266	n/a
8-axle tandem-drive B-train	9.3	63.5	43.0	0.217	-6.9%
8-axle tridem-drive B-train	8.9	63.5	45.6	0.196	+3.2%
9-axle tandem-drive B-train	9.9	70.5	48.8	0.203	-0.4%
9-axle tridem-drive B-train	10.0	71.9	50.0	0.200	0.0%

4 CONCLUSINS

Those planning to implement 9-axle configurations on B.C. resource roads are **advised to review the capacity of the infrastructure on their networks** in light of the findings of this analysis. Bridges with less capacity than L-75 bridges were found to have length restrictions (that is, 9-axle B-trains generated force effects in excess of the bridge design vehicle). The capacity of L-45, L-60, CL-625, and BCL-625 bridges that exceed the maximum span lengths identified in this report should be independently evaluated and certified by a professional bridge engineer for use with the 9-axle B-trains. Concrete beam bridges, designed according to pre-2000 design codes, may be under-designed for shear. This report's general analysis must not be applied to pre-2000 concrete beam bridges of over 18.5 m span and a consulting bridge engineer should be engaged to determine their shear capacity.

9-axle B-trains are well suited to flat or gently rolling terrain. Given their gradeability limitations and swept path requirements 9-axle B-trains are not appropriate for use on steep, tightly curving roads. Accordingly, 9-axle B-trains are suitable for replacing log hauling configurations commonly used in flat or rolling terrain, such as 8-axle super B-trains. Given their limitations, 9-axle B-trains do not appear to be suitable for replacing log hauling configurations commonly used in steep terrain, such 8-axle tridem-drive tractor/ quad wagon trailers. Those planning to implement 9-axle configurations on B.C. resource roads are **advised to review the geometry of their network roads** in light of the findings of this report.

Horizontal curve alignment. The swept path requirements of 9-axle B-trains were found to be met by FLNR (2018)-recommended curve criteria. Provided that curves are at least as wide as the FLNR design criteria, no additional curve widening will be needed to accommodate 9-axle B-trains.

Comparisons of swept path requirements of 9-axle B-trains versus the requirements of 7 common log haul vehicles (reference vehicles) also provided a basis for assessing whether curve widening might be needed. In comparison to an 8-axle tridem-drive lowbed with a single booster axle or a tridem-drive 8-axle B-train, the analysis predicts only minor differences from the turning performance of the 9-axle configurations for most FSR curves. Annecdotal reports from operations already implementing 9-axle B-trains indicate seamless integration of the trucks on routes also used by tridem-drive 8-axle B-trains and 8-axle tridem-drive lowbeds (with single booster axles). For FSR curves in which the 9-axle B-train swept path requirements exceed that of the current truck configurations by more than a small amount (e.g., 50 cm), the forest company should consider curve widening and posting must call signs or other measures to ensure safe passage of the 9-axle B-trains. The 9-axle B-trains have greater curve width requirements than all but the 8-axle tridem-drive lowbed with single booster axle on tight radius, slow speed curves; however, these curves are not normally found on FSRs and any difficulties negotiating these curves are not expected to cause safety issues.

Vertical curve alignment. Provided the operation currently uses 8-axle B-trains or 7-axle hayracks, no changes to vertical curves (crest or dip curves) were indicated by the analysis of K values and stopping sight distances.

Gradeability. It is anticipated that grade climbing concerns will not result from the introduction of 9-axle tridem-drive B-trains if tandem-drive 8-axle B-trains can already negotiate the roads without experiencing grade climbing issues, and the grades over 200 m long are less than 14.5% for summer routes and 10% for winter routes. To further reduce the likelihood of 9-axle trucks getting stuck on hills, the grades of non-uniform grades should be conservatively estimated, the report’s gradeability predictions should be validated under field conditions, drivers should fully load drive axle groups, tire chains should be used on steep hills in the winter, and TPCS use should be encouraged in the summer. Further, attention should be paid to ensuring good traction is maintained on steeper grades and that opportunities for drivers to use momentum to climb hills be supported through the strategic location of pull-outs and sight line maintenance.

The analysis of potential road impacts found that the 9-axle configurations are more road-friendly than the 7-axle hayrack or 8-axle B-train configurations. It is concluded, therefore, that road maintenance would not be increased if 9-axle B-trains were used for log hauling in place of conventional 8-axle B-trains.

The dynamic performance of the 9-axle configurations on resource roads is anticipated to be the same as on paved roads and the findings of (Parker et al. 2014) are considered representative of resource roads. Those implementing 9-axle B-trains are advised to **ensure that trailers are equipped with 2.9 m-wide bunks, and that the full length of trailers is used for loading.** This means carrying four bundles when hauling 5-m cut-to-length logs.

On the basis of the findings and qualifications cited in this report, appropriately applied by qualified personnel, the performance of the 9-axle B-trains is sufficient to negotiate many B.C. resource roads safely. Ultimately safe truck travel on resource roads is contingent upon many factors including the use of trained and experienced drivers, appropriate travel speed for given road and load conditions, appropriate loading practices and load arrangement, and the mechanical condition and maintenance of tractors and trailers. Successful implementation of the new 9-axle configurations requires consideration of the technical elements addressed in this report coupled with application of appropriate professional consideration and practice, and overall best practices for log hauling.

5 IMPLEMENTATION HIGHLIGHTS

5.1 Bridges

Design Loading	Max. length of simple, single-span, bridges for tridem-drive 9-axle B-trains (m) [a b]
L-45 [c]	5.5 m [9.5 to 11 spans OK also]
L-60	23 m
CL-625	32.5 m
BCL-625	37.5 m
L-75	80 m
L-100	80 m

a. This table is offered as a general guide. Specific bridges may have higher load limits if evaluated individually. The calculated span limits assume that the bridge is in good condition with no deterioration that would reduce the capacity of the bridge.

b. Concrete beam and slab girder bridges >18.5 m in length require evaluation by a professional engineer.

c. The definition of the L-45 design loading has varied since it's introduction. The reader should refer to the design documentation for the specific bridge to determine which version of the L-45 design specification applies. If the L-45 definition for a specific bridge differs from the current definition, the above table values do not apply.

5.2 Road Gradeability and Alignment

Justification for 9-axle B-train use on an FSR or Road Use Permit road can be based on the successful use of a reference vehicle(s) on that road. For example, if a given road network is currently being successfully negotiated by 8-axle tridem-drive B-trains, 9-axle B-trains can be expected to succeed as well in terms of horizontal/ vertical alignment and gradeability. In these circumstances, a simple comparison of bridge capacities and spans with the tables in this report may be all that is required to complete the road assessment process from a due diligence perspective.

If the road fit of 9-axle B-trains cannot be justified by comparison to the reference vehicles in this report, its geometric requirements may need to be compared to the design standards for gradeability and curve geometry used along the intended route(s). If the roads proposed for 9-axle implementation were constructed using FLNR (2018)-recommended curve criteria, then no concerns are expected with respect to horizontal and vertical alignment. If a forest operation's mainline road curves were not constructed to FLNR-recommended design criteria or it isn't known whether as-built horizontal curves are at least this wide, then a review of as-built road specifications and design standards may be indicated.

General guidance for a methodology for completing resource road assessments for 9-axle B-train use can be found in Bradley (2020).

6 REFERENCES

Bradley, A. 2020. *Resource road assessments for implementation of 9-axle log B-trains*. Research Report –December 2020.

Bradley, A. and P-T Thiam. 2020. *Use of a newly developed methodology for estimating widebase steering tire ESALs to predict pavement damage from new 9-axle log trucks*. Paper prepared for presentation at the 2020 TAC Conference & Exhibition. Vancouver, BC.

British Columbia Commercial Vehicle Safety and Enforcement. 2016. *Specialized vehicle size and weight guidelines and permits: Section 5.3.6.C equipment requirements*. Retrieved from http://www.cvse.ca/ctpm/chapter_5.pdf

British Columbia Ministry of Forests, Lands and Natural Resource Operations. 2018. *Engineering manual*. Retrieved from https://www.for.gov.bc.ca/hth/engineering/publications_guidebooks.htm

British Columbia Ministry of Transportation and Infrastructure. 2007. Alignment chapter: Section 300. In *Supplement to TAC Geometric Design Guide, 2007 edition.* Retrieved from http://www.th.gov.bc.ca/publications/eng_publications/geomet/TAC/TAC_2007_Supplement/Ch300-2007.pdf

Copstead, Ron. 1991. *Using the Region 6 Surfacing Thickness Program to predict some effects of tire pressures on roads*. USDA Forest Service San Dimas Technology and Development Center. San Dimas, CA. March 1991.9 pp.

Parker, S.; Bradley, A.; and J. Sinnett. 2014. *Proposed 9-axle B-train configurations for log-hauling in British Columbia.* Technical Report 30. FPInnovations. Vancouver, B.C.

Transportation Association of Canada. 1999. *Geometric design guide for Canadian roads: Section 2.1.* Ottawa, Ontario.

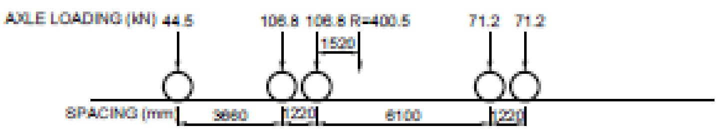
University of Michigan Transportation Research Institute [UMTRI]. 2016. *Vehicle Dynamics Computer Simulation Analysis for 9-axle Tridem-drive Configuration: Final Report.* Ann Arbor, Michigan.

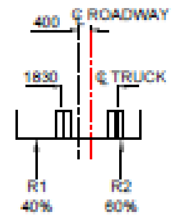
APPENDIX A: B.C. FOREST BRIDGE DESIGN VEHICLE DEFINITIONS

HISTORICAL STANDARD BCFS DESIGN VEHICLE LOADING DIAGRAMS
LOGGING TRUCK AXLE AND WHEEL LOADS ON FOREST ROAD BRIDGES

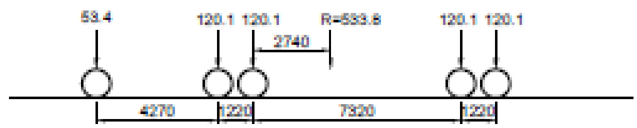
*For L-45 to L-100 configurations - 400 mm eccentricity applies only to 4268 mm wide running decks. For wider deck, increase eccentricity by 50% of the increase in deck width over 4268 mm

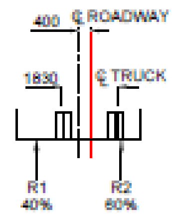
LOADING DIAGRAM L-45 ON HIGHWAY G.V.W. 40,640 kg



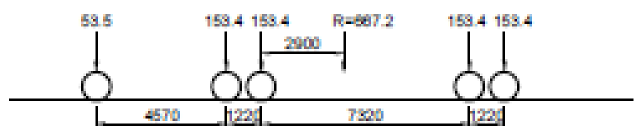


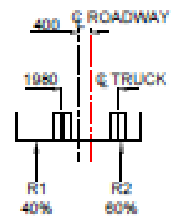
LOADING DIAGRAM L-60 ON HIGHWAY G.V.W. 54,430 kg



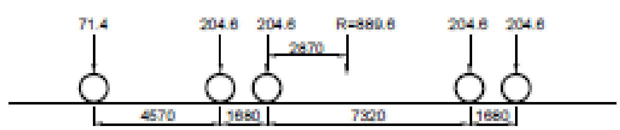


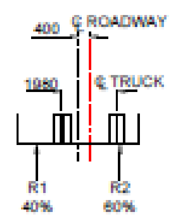
LOADING DIAGRAM L-75 OFF HIGHWAY G.V.W. 68,040 kg



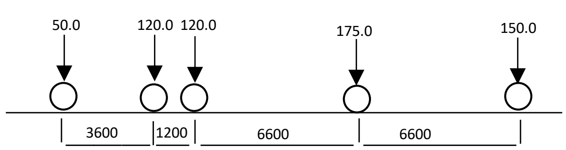


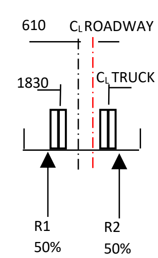
LOADING DIAGRAM L-100 OFF HIGHWAY G.V.W. 90,680 kg



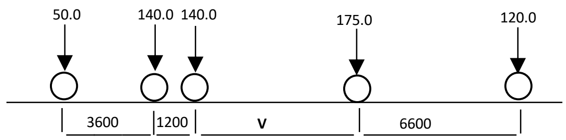


LOADING DIAGRAM CL- 625 G.V.W. 63,730 kg

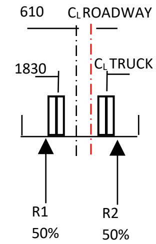




LOADING DIAGRAM BCL- 625 G.V.W. 63,730 kg



V = variable spacing – 6.6 m to 18 m inclusive. Spacing to be used is that which produces the maximum stresses.



APPENDIX B: SCHEMATICS OF CONFIGURATIONS EVALUATED FOR GRADEABILITY, AND HORIZONTAL AND VERTICAL ALIGNMENT

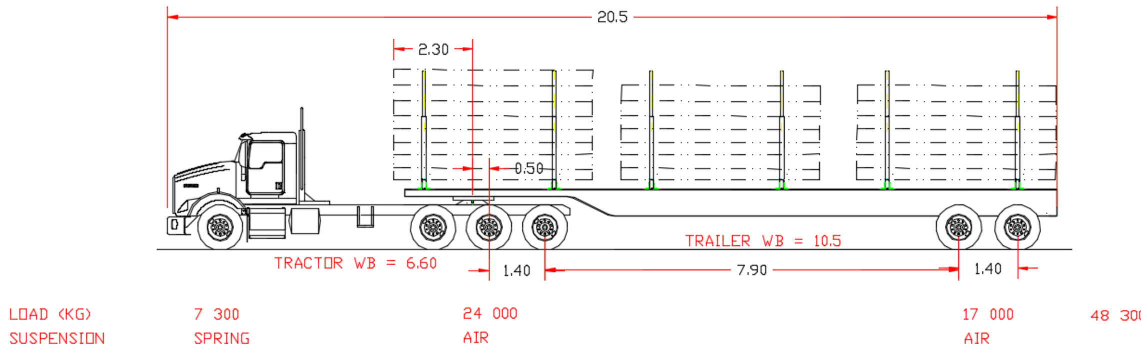


Figure A. 6-axle tridem-drive, tandem semi-trailer (hayrack) (20.5 m long)

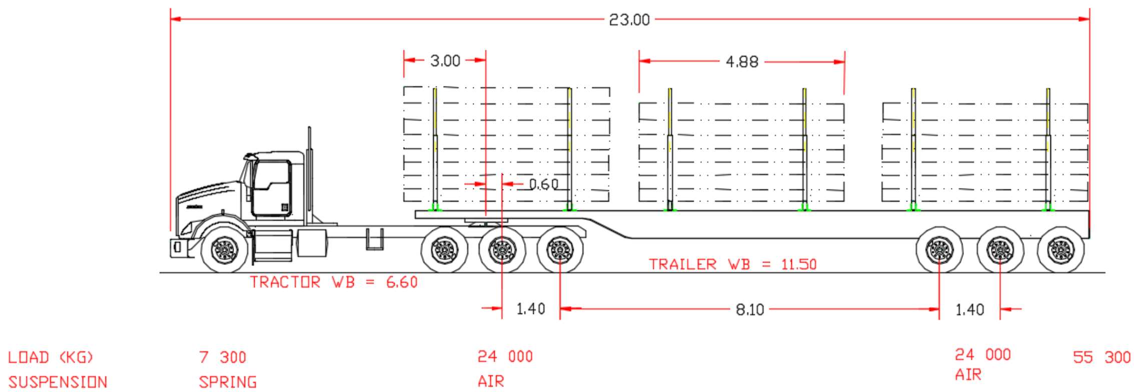


Figure B. 7-axle tridem-drive, tridem semi-trailer (hayrack) (23.0 m long)

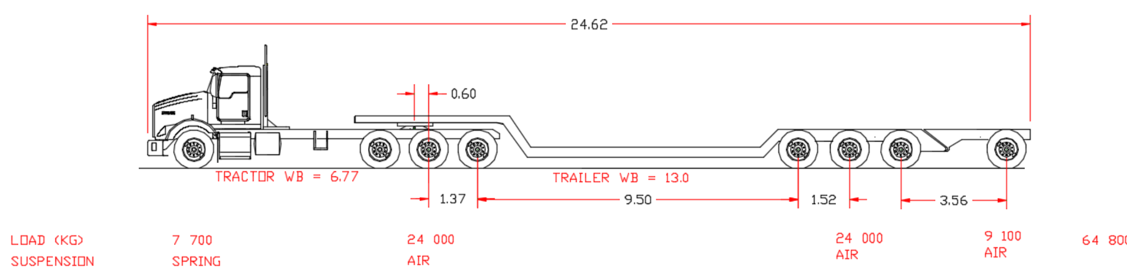


Figure C. 8-axle tridem-drive tractor/ tridem lowbed trailer with single booster axle (24.62 m long)

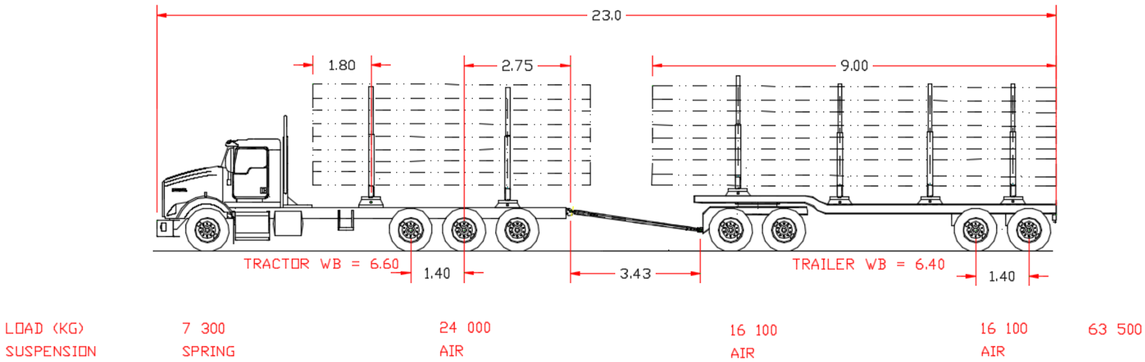


Figure D. 8-axle tridem-drive, quad-axle trailer (short log payload) (23.0 m long)

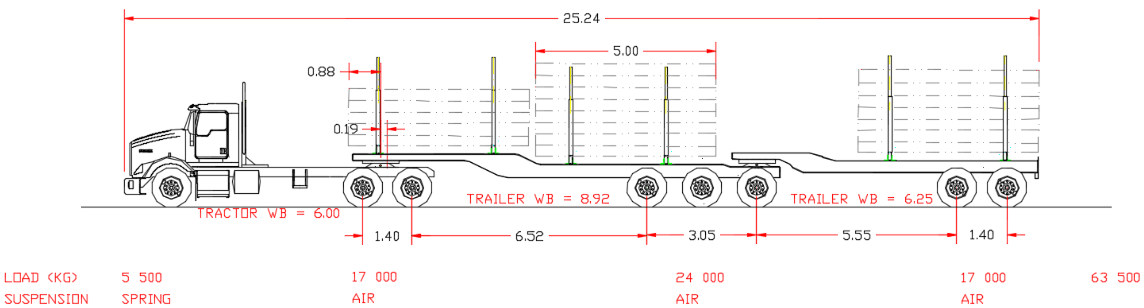


Figure E. 8-axle tandem-drive ('super') B-train (25.24 m long)

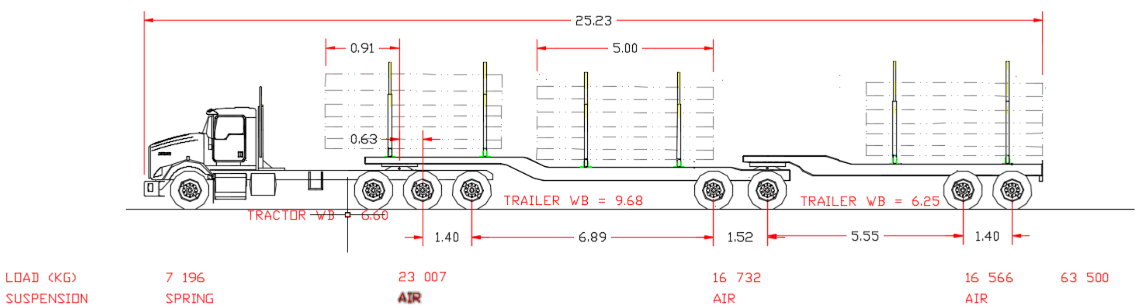


Figure F. 8-axle tridem-drive B-train (25.23 m long)

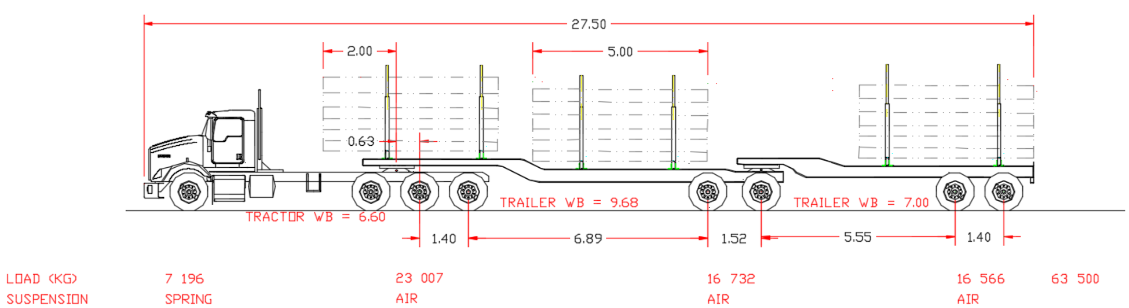


Figure G. 8-axle tridem-drive B-train (27.5 m long)

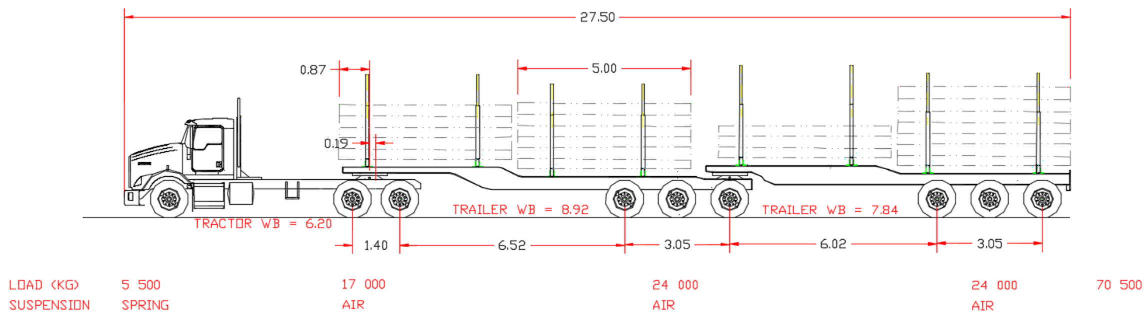


Figure H. 9-axle tandem-drive B-train (27.5 m long)

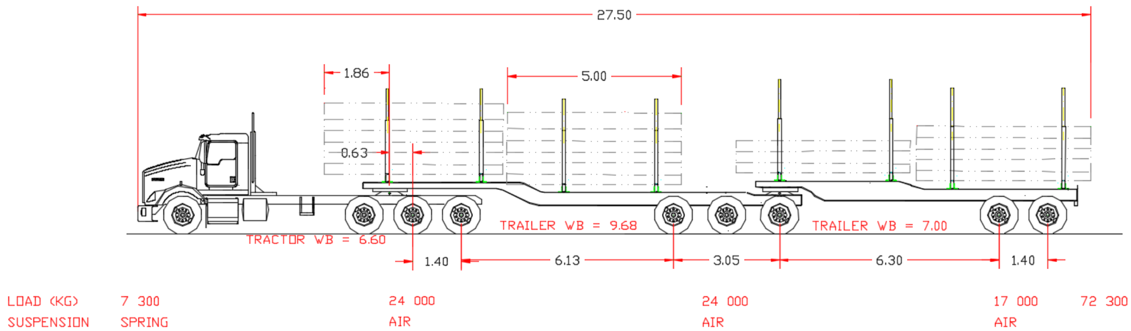


Figure I. 9-axle tridem-drive B-train (27.5 m long)

APPENDIX C: HORIZONTAL CURVE WIDTH REQUIREMENTS FOR 9-AXLE B-TRAINS AND SELECT REFERENCE VEHICLES

This appendix contains the swept path results upon which Tables 4, 5, and 6 in the report were assembled. That is, the high-speed curve swept path results in Table 4, the moderate-speed curve swept path results in Table 5, and the tight, low-speed curve swept path results in Table 6.

Comparison of swept path for high-speed curves

Configuration	Minimum road width in curve [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Swept path (m)				
				Curve path				
				15°	20°	30°	45°	90°
9-axle tridem-drive B-train (27.5 m-long)	6.0	50	100	3.66	3.77	3.83	3.85	3.85
	5.8	60	140	3.47	3.52	3.55	3.55	3.55
9-axle tandem-drive B-train (27.5 m-long)	6.0	50	100	3.54	3.64	3.70	3.72	3.72
	5.8	60	140	3.39	3.44	3.46	3.46	3.47
6-axle tandem-drive/ tridem semi-trailer (hayrack)	6.0	50	100	3.22	3.30	3.35	3.37	3.37
	5.8	60	140	3.07	3.11	3.13	3.14	3.14
7-axle tridem-drive/ tridem semi-trailer (hayrack)	6.0	50	100	3.33	3.45	3.56	3.60	3.60
	5.8	60	140	3.20	3.26	3.30	3.30	3.31
7-axle tridem-drive tridem lowbed with single booster axle	6.0	50	100	3.45	3.61	3.76	3.82	3.83
	5.8	60	140	3.31	3.39	3.45	3.46	3.47
8-axle tridem-drive quad trailer (short logs)	6.0	50	100	3.00	3.03	3.04	3.04	3.04
	5.8	60	140	2.86	2.87	2.87	2.87	2.88
8-axle tandem-drive (super) B-train (25.24 m-long)	6.0	50	100	3.25	3.31	3.37	3.38	3.37
	5.8	60	140	3.09	3.12	3.13	3.13	3.13
8-axle tridem-drive B-train (25.23 m-long)	6.0	50	100	3.54	3.62	3.68	3.70	3.71
	5.8	60	140	3.38	3.42	3.44	3.44	3.44
8-axle tridem-drive B-train (27.5 m-long)	6.0	50	100	3.61	3.72	3.80	3.83	3.83
	5.8	60	140	3.48	3.53	3.56	3.57	3.56

a. Recommended minimum value from FLNR (2018).

Comparison of swept path for moderate-speed curves

Configuration	Minimum road width in curve [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Swept path (m)				
				Curve path				
				15°	20°	30°	45°	90°
9-axle tridem-drive B-train (27.5 m-long)	7.0	30	35	4.10	4.46	5.07	5.52	5.91
	6.7	40	65	3.88	4.11	4.31	4.42	4.45
9-axle tandem-drive B-train (27.5 m-long)	7.0	30	35	3.95	4.29	4.86	5.27	5.63
	6.7	40	65	3.75	3.96	4.14	4.24	4.27
6-axle tandem-drive/ tridem semi-trailer (hayrack)	7.0	30	35	3.60	3.89	4.38	4.70	4.97
	6.7	40	65	3.41	3.59	3.73	3.80	3.83
7-axle tridem-drive/ tridem semi-trailer (hayrack)	7.0	30	35	3.70	4.04	4.58	4.97	5.47
	6.7	40	65	3.51	3.71	3.94	4.10	4.16
7-axle tridem-drive tridem lowbed with single booster axle	7.0	30	35	3.84	4.21	4.85	5.35	6.06
	6.7	40	65	3.64	3.88	4.18	4.40	4.52
8-axle tridem-drive quad trailer (short logs)	7.0	30	35	3.33	3.57	3.91	4.09	4.16
	6.7	40	65	3.16	3.28	3.34	3.36	3.37
8-axle tandem-drive (super) B-train (25.24 m-long)	7.0	30	35	3.82	3.92	4.39	4.71	4.98
	6.7	40	65	3.43	3.61	3.75	3.82	3.84
8-axle tridem-drive B-train (25.23 m-long)	7.0	30	35	3.91	4.23	4.76	5.15	5.49
	6.7	40	65	3.72	3.93	4.11	4.20	4.23
8-axle tridem-drive B-train (27.5 m-long)	7.0	30	35	3.93	4.26	4.80	5.22	5.61
	6.7	40	65	3.75	3.95	4.16	4.29	4.33

a. *Recommended minimum value from FLNR (2018).*

Comparison of swept path for low-speed tight-radius curves

Configuration	Minimum curve width [a] (m)	Design speed (km/h)	Minimum curve radius [a] (m)	Maximum swept path (m)					
				Curve path					
				30°	45°	60°	75°	90°	180°
9-axle tridem-drive B-train (27.5 m-long)	9.0	20	15	5.46	6.57	7.60	8.48	9.15	11.12
	7.6		24	5.43	6.29	6.74	7.03	7.23	7.59
9-axle tandem-drive B-train (27.5 m-long)	9.0	20	15	5.21	6.22	7.18	8.00	8.62	10.49
	7.6		24	5.20	5.97	6.40	6.68	6.87	7.19
6-axle tandem-drive/ tridem semi-trailer (hayrack)	9.0	20	15	3.71	4.05	4.69	5.57	7.57	8.89
	7.6		24	3.70	4.05	4.68	5.34	6.02	6.26
7-axle tridem-drive/ tridem semi-trailer (hayrack)	9.0	20	15	4.90	5.89	6.81	7.60	8.17	9.89
	7.6		24	4.91	5.65	6.05	6.32	6.51	7.00
7-axle tridem-drive tridem lowbed with single booster axle	9.0	20	15	3.95	4.38	5.17	6.28	8.77	11.10
	7.6		24	3.94	4.38	5.17	6.06	7.08	7.87
8-axle tridem-drive quad trailer (short logs)	9.0	20	15	3.44	3.71	4.21	4.89	6.29	6.73
	7.6		24	3.44	3.71	4.21	4.68	4.96	4.99
8-axle tandem-drive B-train (25.24 m-long)	9.0	20	15	4.72	5.61	6.70	7.27	7.61	8.98
	7.6		24	4.71	5.35	5.70	5.91	6.04	6.26
8-axle tridem-drive B-train (25.23 m-long)	9.0	20	15	5.09	6.05	6.96	7.74	8.33	10.11
	7.6		24	5.08	5.81	6.21	6.48	6.66	6.97
8-axle tridem-drive B-train (27.5 m-long)	9.0	20	15	5.13	6.11	7.05	7.87	8.49	10.49
	7.6		24	5.12	5.88	6.30	6.60	6.81	7.17

a. *Recommended minimum value from FLNR (2018).*

info@fpinnovations.ca
www.fpinnovations.ca

OUR OFFICES

Pointe-Claire
570 Saint-Jean Blvd.
Pointe-Claire, QC
Canada H9R 3J9
(514) 630-4100

Vancouver
2665 East Mall
Vancouver, BC
Canada V6T 1Z4
(604) 224-3221

Québec
1055 rue du P.E.P.S.
Québec, QC
Canada G1V 4C7
(418) 659-2647