Two 9-Axle B-Train Log-Hauling Configurations Authorized for Designated Provincial Highways in British Columbia: Evaluating Their Use on Resource Road Infrastructure

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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 and Natural Resource Operations, 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 36 m spans), vehicle fit to the resource road, 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 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 for spans of 36 m or less). The capacity of L-45, L-60, CL-625, and BCL-625 bridges that exceed the maximum 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, instead, a consulting bridge engineer should be engaged to determine their shear capacity.

Also, **the as-built geometry of network roads should be reviewed in light of the findings of this report**. In comparison to a 7-axle hayrack or an 8-axle B-train, the analysis predicts only minor differences from the turning performance of the 9-axle configurations for most curves. Provided that curve widening is done according to FLNRO standards, no additional curve widening will be needed to accommodate 9-axle B-trains for most curves. An exception to this is the case of tight-radius curves on slow-speed roads that have more than a 90° curve path. On these curves, some widening is anticipated to accommodate the 9-axle units. No changes to vertical curves (crest or dip curves) were indicated by the analysis of K values and stopping sight distances.

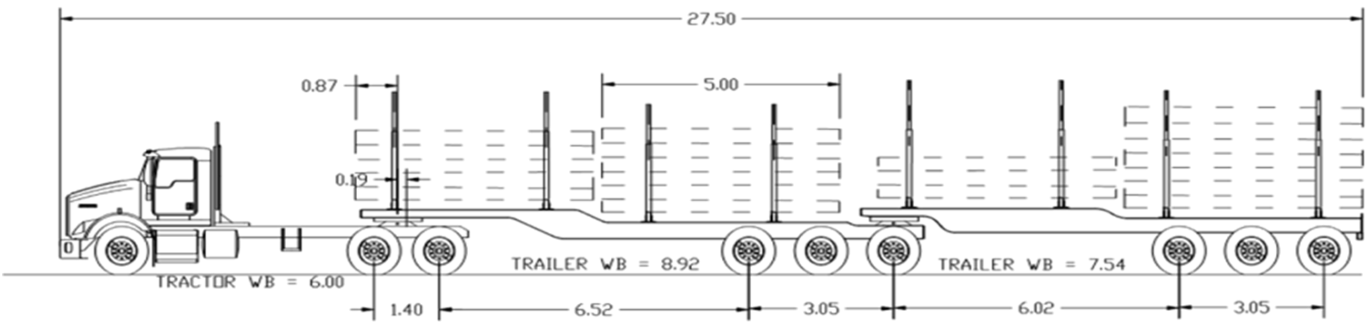
Like that of the 8-axle super B-train, the estimated gradeabilities of the 9-axle configurations are less than that of the 7-axle hayrack and other log hauling configurations with smaller trailers. The tridem drive 9-axles' estimated gradeability is limited to sustained adverse grades of about 9% in the winter and 13% in the summer (favourable grade limits are about 1% more). The tandem drive 9-axles' estimated gradeability is limited to sustained grades of about 5.5% in the winter and 9% in the summer (favourable grade limits are 2% to 3% more). These grade limitations can be increased by 1% to 4% for short pitches, depending on pitch length. 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 observed under field conditions, drivers should fully load drive axle groups, tire chains should be used on steep hills, and tire pressure control system (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.

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.

In order to gain approval to use the trucks on public highways FPInnovations studied the dynamic performance of these configurations and their potential impacts to road pavements (Parker et al., 2014). The dynamic performance of the 9-axle configurations on resource roads is anticipated to be the same as on paved roads and the 2014 findings 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.

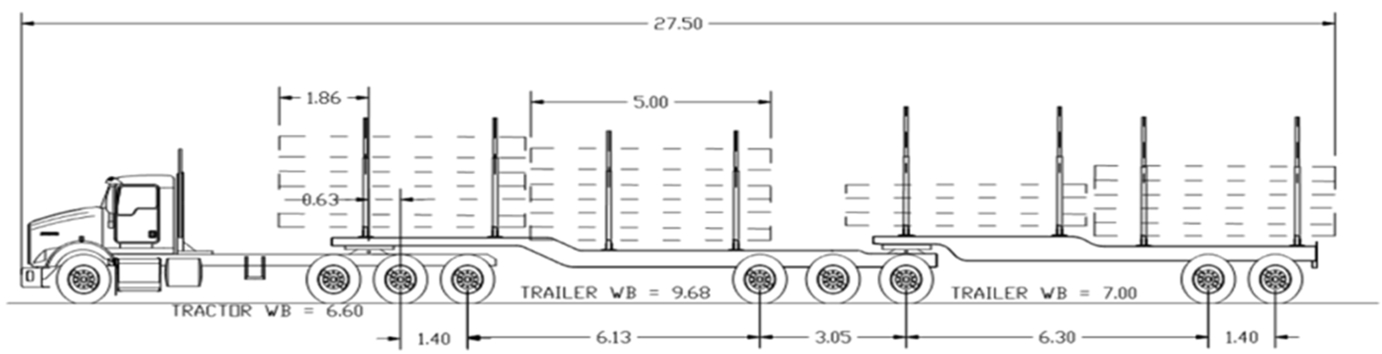
INTRODUCTION

The B.C. forest industry can realize substantial benefits by implementing new 9-axle log-hauling configurations (Figure 1 and Figure 2). In 2014, FPInnovations evaluated the dynamic performance of these 9-axle B-trains and their effects on road pavements (Parker, Bradley, & Sinnett, 2014). More recently, at the request of the B.C. Ministry of Forests, Lands and Natural Resource Operations (FLNRO), FPInnovations analyzed the impacts of the two new configurations on forestry 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.



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



Axle group	Steering	Drives	Lead trailer	Rear trailer	Total
Axle load (kg)	6 900	24 000	24 000	17 000	71 900
Axle width (m)	2.50	2.50	2.60	2.60	
Bunk width (m)		2.90	2.90	2.90	

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

ANALYSES AND RESULTS

Bridge capacity

Standard design vehicle configurations for bridges on forest service roads in B.C. have evolved over time. A general analysis was undertaken to compare the force effects of the proposed tandem-drive and tridem-drive 9-axle B-train configurations against those of the forestry bridge designs commonly used in the interior of B.C. The bridges were evaluated over the range of common span lengths of resource road bridges (3 to 36 m).

Where the maximum shear and bending moment, and pier reaction in the case of multiple spans, from the 9-axle B-train were less than that from the bridge design truck, then the design capacity of the bridge, at the length evaluated, was deemed sufficient to support the 9-axle B-train. If the shear or bending moment of the subject truck configuration exceeded that of the bridge design vehicle, the span was considered to be under-capacity. Under some circumstances, professional bridge designers may consider bridge capacity sufficient if the excess force effect is small; however, no attempt to make this sort of judgement was made in this general analysis.

Table 1 summarizes the maximum simple single span capable of supporting the 9-axle configurations for BC forest bridge designs.

Table 1. Evaluation of simple single-span bridge capacity for 9-axle B-trains

Bridge design vehicle configuration	Max. length of simple single-span bridges able to support tandem-drive 9-axle B-trains (m)	Max. length of simple single-span bridges able to support tridem-drive 9-axle B-trains (m)
L-45	13.8	12.5
L-60	25.0	25.0
CL-625	30.0	33.0
BCL-625	35.0	35.0
L-75	>36.0	>36.0
L-100	>36.0	>36.0

The B.C. Ministry of Transportation and Infrastructure (MOTI), Bridge Engineering Section, reports that concrete span bridges, including pre-stressed concrete beam and concrete slab girder bridges, designed according to pre-2000 design codes 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 these bridges because, in many cases, the maximum span was governed by shear capacity. There are many concrete slab girder bridges in service on forest roads in BC. The maximum length of concrete slab girder bridges is 18 m, however, this length is rare and 5 to 8 m lengths are the norm. No more than two tandem and one tridem axle group or two tridem axle groups 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.

Although multiple-span bridges are less commonly used on B.C. resource roads, an evaluation was undertaken of simple 2-span bridges (Table 2) and continuous 2-span bridges (Table 3). This work was provided for the project by the MOTI Bridge Engineering Section. Continuous 3- and 4-span bridges also were evaluated and the results are included in Appendix A. All multispan bridge configurations that were evaluated were assumed to have spans of equal length. 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. CL-625 spans were not evaluated by the time of publication; however, it is anticipated that CL-625 bridge configurations will be evaluated by MOTI in the near future.

Table 2. Evaluation of simple 2-span bridge capacity for 9-axle B-trains

Bridge design vehicle configuration	**Maximum length of simple 2-span bridges able to support tandem-drive 9-axle B-trains**	**Max. length of simple 2-span bridges able to support tridem-drive 9-axle B-trains**
L-45	17.5 m (8.75 m, 8.75 m)	17.5 m (8.75 m, 8.75 m)
CL-625	*to be evaluated*	*to be evaluated*
L-60	25.0 m (12.5 m, 12.5 m)	25.0 m (12.5 m, 12.5 m)
BCL-625	40.0 m (20 m, 20 m)	37.5 m (18.75 m, 18.75 m)
L-75	150.0 m (75 m, 75 m)	100 m (50 m, 50 m)
L-100	160.0 m (80 m, 80 m)	160 m (80 m, 80 m)

Table 3. Evaluation of continuous 2-span bridge capacity for 9-axle B-trains

Bridge design vehicle configuration	Maximum length of continuous 2-span bridges able to support tandem-drive 9-axle B-trains	Maximum length of continuous 2-span bridges able to support tridem-drive 9-axle B-trains
L-45	10 m (5 m, 5 m)	10 m (5 m, 5 m)
CL-625	*To be evaluated*	*To be evaluated*
L-60	20 m (10 m, 10 m)	20 m (10 m, 10 m)
BCL-625	30 m (15 m, 15 m)	30 m (15 m, 15 m)
L-75	80 m (40 m, 40 m)	60 m (30 m, 30 m)
L-100	>100 m (50 m, 50 m)	>100 m (50 m, 50 m)

Application of bridge capacity tables

The information in the preceding tables can be used to review the infrastructure of the bridges along the routes proposed to be traversed by the 9-axle B-trains. The following will need to be determined for each bridge on the route(s):

- the original design vehicle configuration
- the bridge span and configuration (single or continuous span)
- whether any of the concrete beam bridges longer than 18.5 m were designed using a pre-2000 bridge design code (if designed with a pre-2000 code, the shear values in the report tables do not apply and the shear capacity will need to be determined separately using current bridge design methods)
- any structural deficiencies that may limit capacity (i.e., structural defects causing the bridge to be down-rated)

Each bridge needs to be reviewed and the preceding tables can be used to determine which have sufficient capacity based on the underlying general analysis and the resulting limitations. Bridges falling outside of the identified limits or not falling within the scope of the general analysis will need to be individually assessed for adequacy by a professional engineer.

The preceding analysis assumed that the 9-axle B-trains were loaded to maximum permitted axle weights. The GVWs were increased by a design live load factor of 1.6 to account for load 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.

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 for road widening in curves and at intersections. Since detailed geometric information for resource roads in B.C. is not readily available, theoretical analyses of horizontal and vertical geometry limitations of the 9-axle B-trains were carried out in comparison with current, large, log-haul vehicle configurations and with FLNRO, MOTI, and Transportation Association of Canada (TAC) design standards (FLNRO, 2013; MOTI, 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 the comparison, it was assumed that high-speed roads have a running surface width of between 5.0 and 8.0 m, and low-speed roads have running surface widths of less than 5.0 m. This corresponds with design standards found in FLNRO (2013). For high-speed 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. Low-speed roads were assumed to be in-block roads where the analyzed curve paths reflect curved road segments, junctions, bridge approaches, and switchbacks.

Results for the 27.5-m-long 9-axle configurations were compared with those for a 23-m-long tridem-drive/tridem semi-trailer (hayrack) and a 25.24-m-long 8-axle super B-train which are commonly used in the B.C. interior for log hauling. Maximum swept-path road width is used to assess the horizontal requirement of trucks in curves and intersections. The road must be as least as wide as the swept path in order to accommodate truck turns. Additional road width is needed to accommodate sub-optimal turns.

Table 4 summarizes the swept path (predicted maximum road width requirement) for the trucks tracking through a variety of curves associated with higher-speed roads. Table 5 summarizes the swept path for trucks tracking through tight-radius curves often associated with low-speed, in-block roads. Recommended minimum road surface widths for these curves are from FLNRO (2013).

The results indicated that there were only minor differences for most curves in the turning performance of the 9-axle versus the 7-axle and the 8-axle configurations. Provided that the existing roads were constructed following FLNRO recommendations for curve widening, and currently accommodate both 7-axle tridem-drive hayracks and 8-axle super B-trains, no road widening would be required on most roads with the introduction of 9-axle B-trains. That is, the 9-axle's swept path is very similar to that of the 7- and 8-axle units, and does not exceed the recommended curve width in most cases.

For low-speed, tight-radius curves of 90° or more, however, the 9-axle trucks' swept path was as much as 1.9 m wider than that of the 8-axle B-trains, and it also exceeded the 9.0 m minimum recommended curve width. These results indicate that the tight radius curves may require extra widening to accommodate 9-axle B-trains. To determine the extent of tight-radius curve widening required the reader should compare the swept path requirement for their current truck configuration(s) to their current curve widths and then apply the difference to the 9-axle swept path requirement. That is, the swept path is the minimum road width needed to complete a turn and switchbacks and other tight-radius curves are normally constructed wider than this to accommodate poor traction conditions, sub-optimal driving, etc.

Table 4. Comparison of swept path for high-speed curves

Configuration	Minimum recommended curve width (m)	Design speed (km/h)	Minimum recommended curve radius (m)	Swept path (m)				
				Curve path				
				15°	20°	30°	45°	90°
30 and 40 km/h design speed roads								
7-axle tridem-drive/ tridem semi-trailer	7.0	30	35	3.81	3.99	4.27	4.50	5.43
	6.7	40	65	3.51	3.60	3.68	3.73	4.16
8-axle super B-train	7.0	30	35	3.58	3.74	3.95	4.11	4.94
	6.7	40	65	3.27	3.34	3.39	3.41	3.82
Tandem-drive 9-axle B-train	7.0	30	35	4.03	4.21	4.45	4.64	5.58
	6.7	40	65	3.62	3.70	3.77	3.80	4.25
Tridem-drive 9-axle B-train	7.0	30	35	4.15	4.35	4.62	4.83	5.85
	6.7	40	65	3.73	3.82	3.90	3.93	4.43
50 and 60 km/h design speed roads								
7-axle tridem-drive/ tridem semi-trailer	6.0	50	100	3.26	3.30	3.32	3.33	3.60
	5.8	60	140	3.09	3.10	3.11	3.11	3.30
8-axle super B-train	6.0	50	100	3.06	3.09	3.10	3.10	3.36
	5.8	60	140	2.93	2.93	2.94	2.93	3.12
Tandem-drive 9-axle B-train	6.0	50	100	3.37	3.40	3.41	3.41	3.71
	5.8	60	140	3.24	3.25	3.25	3.25	3.45
Tridem drive 9-axle B-train	6.0	50	100	3.47	3.50	3.52	3.52	3.84
	5.8	60	140	3.32	3.33	3.33	3.33	3.55

Table 5. Comparison of swept path for low-speed tight-radius curves

Configuration	Recommended curve width (m)	Design speed (km/h)	Minimum recommended curve radius (m)	Maximum swept path (m)			
				Curve path			
				30°	45°	90°	180°
7-axle tridem drive/ tridem semi-trailer (hayrack)	9.0	20	15	5.19	5.87	8.02	8.76
	7.6		24	4.71	5.12	6.54	6.62
8-axle super B-train	9.0	20	15	4.73	5.33	7.29	8.07
	7.6		24	4.32	4.65	5.92	6.04
Tandem-drive 9-axle B-train	9.0	20	15	5.41	6.09	8.31	**9.32**
	7.6		24	4.91	5.29	6.72	6.89
Tridem drive 9-axle B-train	9.0	20	15	5.58	6.32	8.69	**9.89**
	7.6		24	5.08	5.50	7.05	7.26

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.Erreur ! Source du renvoi introuvable.Table 6 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 that K_{BA} is, 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 MOTI (which are 3.0 and 4.0 for crest and sag curves, respectively), and less than those calculated from the FLNRO stopping sight distance values (FLNRO, 2013). 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 roads.

Table 6. 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 super 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
Tandem-drive 9-axle 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
Tridem-drive 9-axle 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

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. Gradeability estimates were made for long (sustained) grades on which the truck travels at a constant rate of speed (i.e., they do not utilize momentum to assist the climb). Some trucks in B.C. are equipped with tire pressure control systems (TPCS) to improve traction, ride, soft ground mobility and road impacts. Sustained gradeability estimates are presented in Table 7 and values are rounded to the nearest 0.5%; the 9-axle B-train gradeabilities are estimated for winter and summer conditions, without and with TPCS. Tire-to-ground friction (traction) changes from truck to truck, and 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.

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 8 and values are rounded to the nearest 0.5%; the 9-axle B-train gradeabilities are estimated without and with TPCS. Momentum-assisted gradeabilty is higher for shorter pitches; momentum generally runs out, with the truck transitioning to sustained gradeability levels, on pitches of 300 m or longer.

Table 8 provides gradeability estimates for both medium length (200-m-long) and short (50-m-long) pitches. The calculations assume that trucks start climbing the hill at 25 km/h and slow to no more than 10 km/h by the time they reach the top. Results are presented for both loaded and unloaded trucks; the unloaded 7-axle hayrack is assumed to pull its trailer but the unloaded B-trains are assumed to carry their rear trailers on their front trailers.

Table 7. Estimated traction-limited sustained gradeability, without and with TPCS

Truck configuration	Loading condition	Estimated traction-limited sustained gradeability (with TPCS)	
		With tire chains on packed snow surfaces	On good gravel surfaces
7-axle tridem-drive/tridem semi-trailer (hayrack)	Unloaded	11.0%	16.0%
	Loaded	12.0%	17.5%
8-axle super B-train	Unloaded	8.5%	12.5%
	Loaded	6.5%	10.5%
Tandem-drive 9-axle B-train	Unloaded	8.0% (8.5%) *	12.0% (13.5%) *
	Loaded	5.5% (6.0%) *	9.0% (10.0%) *
Tridem-drive 9-axle B-train	Unloaded	10.0% (10.5%) *	14.5% (16.0%) *
	Loaded	9.0% (9.5%) *	13.0% (14.5%) *

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

Table 8. Estimated traction-limited momentum-assisted gradeability for medium and short pitches, without and with TPCS

Truck configuration	Loading condition	Estimated traction-limited momentum-assisted gradeability (with TPCS)			
		With tire chains on packed snow surfaces		On good gravel surfaces	
		200 m-long	50 m-long	200 m-long	50 m-long
7-axle tridem-drive/tridem semi-trailer	Unloaded	12.0%	15.5%	17.0%	20.0%
	Loaded	13.0%	16.0%	18.0%	21.0%
8-axle super B-train	Unloaded	9.5%	12.5%	13.5%	16.5%
	Loaded	7.5%	10.5%	11.0%	14.5%
Tandem-drive 9-axle B-train	Unloaded	9.0% (9.5%) *	12.0% (13.0%) *	13.0% (14.0%) *	16.0% (17.5%) *
	Loaded	7.0% (7.0%) *	10.0% (10.5%) *	10.0% (11.0%) *	13.0% (14.0%) *
Tridem-drive 9-axle B-train	Unloaded	11.0% (11.5%) *	14.0% (14.5%) *	15.0% (16.5%) *	18.5% (20.0%) *
	Loaded	10.0% (10.5%) *	13.0% (13.5%) *	14.0% (15.0%) *	17.0% (18.5%) *

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

The following trends were identified in this gradeability analysis:

- Tridem-drive 9-axle B-trains will have better gradeability (by 1.5% to 2.0%) than 8-axle super B-trains, but tandem-drive 9-axle B-trains will have worse gradeability (by 0.5% to 1.0%) than 8-axle super B-trains. 7-axle hayracks can climb steeper grades than all of the B-train configurations – under both winter and summer conditions.
- All of the B-train configurations have worse gradeabilities when loaded than when unloaded. The 7-axle tridem hayrack is the reverse, with unloaded gradeabilities being worse than loaded.
- 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% higher than sustained gradeability, depending on pitch length.
- Trucks utilizing traction enhancing technology (e.g., a TPCS, a drive tire sanding box) can negotiate even steeper grades. TPCS offers only minor improvements to wintertime gradeabilities (e.g., increases of 0.4% to 0.7%); however, summertime gradeability improvements are double this (i.e., increases of 1.0% to 1.5%).

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. The 9-axle configurations have improved braking performance compared to the baseline 8-axle super B-train. This is due to the fact that, compared to the 8-axle B-train, the gross weight has increased by 11–13% (7–8.4 t) while the number of braked, non-steering axles has increased by 14%. The gradeability analysis indicates that 7-axle hayracks can climb steeper sustained grades than all of the B-train configurations under both winter and summer conditions. The tridem-drive 9-axle B-train is predicted to have slightly better gradeability than 8-axle B-trains while the tandem-drive 9-axle B-trains are predicted to have slightly poorer gradeability than 8-axle B-trains.

Application of horizontal and vertical alignment and gradeability tables

The information in the preceding tables can be used to review the geometry of the resource roads along the routes proposed to be traversed by the 9-axle B-trains. Several assessments will need to be made for each road on the route(s):

- The as-built curve widths should be assessed to ensure that they meet the minimum specifications recommended by FLNRO (2013), especially for curves of 90° or greater. Where the actual curve widths are close to or less than the maximum swept values listed in the table, curve widening is strongly recommended.
- If 7-axle hayracks or 8-axle super B-trains are currently negotiating the roads and bridges in an area, it is anticipated that no vertical alignment changes will be required to accommodate the introduction of 9-axle B-trains. Similarly, if as-built minimum K values meet or are less than those specified by MOTI or calculated from FLNRO stopping sight distance values, it is anticipated that no vertical alignment changes will be required to accommodate the introduction of 9-axle B-trains.
- Haul routes and the season of their use should be selected in consideration of the preceding gradeability estimates. To avoid trucking delays and truck assists, the maximum adverse grades along the haul route(s) should be comparable to the estimated loaded 9-axle gradeabilities shown in the tables – recognizing that these are just estimates and actual gradeabilities may vary given different weather and road surface conditions during the day, tire tread, sanding, etc. Similarly, favourable grades along the haul route(s) should be comparable to the estimated unloaded 9-axle gradeabilities shown in the tables. For example, a route for wintertime hauling by tridem-drive 9-axle B-trains with tire chains but without TPCS, is likely to have fewer traction-related issues if sustained adverse grades are no more than 9.0% and favourable grades are no more than 10.0%. If the haul route has short pitches of under 300 m in length, these gradeability limits likely can be increased by 1% to 4%, depending on length.
- The gradeability analysis assumed full legal axle group loads, loss of no more than 15 km/h on momentum-assisted grades, and uniform grades. To further reduce the likelihood of 9-axle B-trains getting stuck on hills, the following practices are recommended:

- When assessing routes for use by 9-axle B-trains, conservatively estimate the steepness of hills with non-uniform grades.
- Select an appropriate gear for grade and traction conditions.
- Fully load the drive axles.
- When on snow or ice covered hills, all drive tires should be equipped with tire chains.
- Ensure diligent snow ploughing/ice blading/sanding of steeper hills.
- Maintain line of sight at steep grades by brushing and snow ploughing, and ensure pullout procedures are followed. Given these measures, the 9-axle B-trains can gather momentum prior to grades which will assist them in climbing hills.
- Consider the cost-benefits of TPCS in the context of local operating conditions.

Road impacts

An analysis of the potential road impacts relative to a baseline truck was conducted to assess whether the two 9-axle B-trains 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 7-axle hayrack or an 8-axle super B-train. The results of this analysis are presented in Table 9.

Table 9. Potential resource road rutting impacts

Configuration	Roundtrip impact (ESALs)	GVW (tonnes)	Payload (tonnes)	Impact per tonne payload (ESALs per tonne)
7-axle tridem-drive/tridem semi-trailer (hayrack)	10.0	54.9	32.9	0.305
8-axle super B-train	9.3	63.5	43.0	0.217
Tandem-drive 9-axle B-train	9.9	70.5	48.8	0.203
Tridem-drive 9-axle B-train	10.0	71.9	50.0	0.200

The 9-axle B-trains' ESALs per tonne payload are 6.5% to 7.8% less than for the 8-axle super B-Train and 33% to 34% less than for the 7-axle tridem hayrack. The annual impacts of the 9-axle B-train configurations on resource roads, therefore, are anticipated to be less than if hauling were conducted with the 8-axle super B-trains and much less than if hauling with 7-axle tridem hayracks.

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.

CONCLUSIONS

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 for spans of 36 m or less). The capacity of L-45, L-60, CL-625, and BCL-625 bridges that exceed the maximum 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.

Also, those planning to implement 9-axle configurations on B.C. resource roads are **advised to review the as-built geometry of their network roads** in light of the findings of this report. In comparison to a 7-axle hayrack or an 8-axle B-train, the analysis predicts only minor differences from the turning performance of the 9-axle configurations for most curves. Provided that curve widening is done according to FLNRO standards, no additional curve widening will be needed to accommodate 9-axle B-trains for most curves. An exception to this is the case of switchbacks or other 15 m-radius curves on slow-speed roads that have more than a 90° curve path. On these curves, the tridem-drive 9-axle B-trains had up to 1.9 m more swept path than an 8-axle B-train. On routes identified to have these types of curves some widening to accommodate 9-axle B-trains is anticipated. To determine the extent of tight-radius curve widening required the reader should compare the swept path requirement for their current truck configuration(s) to their as-built curve widths and then apply the difference to the 9-axle swept path requirement. The swept path is the minimum road width needed to complete a turn and under normal practice switchbacks and other tight-radius curves are constructed wider than this to accommodate poor traction conditions, sub-optimal driving, etc. No changes to vertical curves (crest or dip curves) were indicated by the analysis of K values and stopping sight distances.

Like that of the 8-axle super B-train, the estimated gradeabilities of the 9-axle configurations are less than that of the 7-axle hayrack and other log hauling configurations with smaller trailers. The tridem drive 9-axles' estimated gradeability is limited to sustained adverse grades of about 9% in the winter and 13% in the summer (favourable grade limits are about 1% more). The tandem drive 9-axles' estimated gradeability is limited to sustained grades of about 5.5% in the winter and 9% in the summer (favourable grade limits are 2% to 3% more). These grade limitations can be increased by 1% to 4% for short pitches, depending on pitch length. 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, 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.

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 will be sufficient to negotiate 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 overall best practices for log hauling.

IMPLEMENTATION HIGHLIGHTS

Bridges

Design Loading	Max. length of simple single-span bridges for 9-axle B-trains (m) [a]
L-45	12.5
L-60	25.0
CL-625	30.0
BCL-625	35.0
L-75 [b]	36.0
L-100 [b]	36.0

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

[b] Simple single-span bridges >36 m in length were not analysed in this study and require evaluation by a professional engineer.

Road alignment and gradeability

If the roads proposed for 9-axle implementation have been successfully navigated by 8-axle super B-trains then no concerns are expected with respect to horizontal alignment (for curves <90 degrees), vertical alignment or gradeability [c].

[c] Only minor reductions in gradeability were estimated for the tandem-drive 9-axle (the tridem-drive configuration's gradeability was superior to the 8-axle super B-train). The reductions for the tandem-drive are not considered to be operationally significant and will in practice be overcome by driver adjustments to shift patterns, momentum assist, chains, road maintenance practices, TPCS technology, and other mitigating factors commonly applied in log hauling.

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APPENDIX A. CAPACITY TABLES FOR CONTINUOUS 3- AND 4-SPAN BRIDGES

These bridge capacity tables were provided for the project by the MOTI Bridge Engineering Section. They apply to continuous span bridges featuring shorter, equal length, approach spans and longer middle span(s).

Evaluation of continuous 3-span bridge capacity for 9-axle B-trains

Bridge design vehicle configuration	Maximum length of continuous 3-span bridges able to support tandem-drive 9-axle B-trains	Maximum length of continuous 3-span bridges able to support tridem-drive 9-axle B-trains
L-45	12.5 m (3.75 m, 5 m, 3.75 m)	12.5 m (3.75 m, 5 m, 3.75 m)
CL-625	*To be evaluated*	*To be evaluated*
L-60	37.5 m (11.25 m, 15 m, 11.25 m)	37.5 m (11.25 m, 15 m, 11.25 m)
BCL-625	50 m (15 m, 20 m, 15 m)	37.5 m (11.25 m, 15 m, 11.25 m)
L-75	>125 m (37.5 m, 50 m, 37.5 m)	>112 m (33.5 m, 45 m, 33.5 m)
L-100	>125 m (37.5 m, 50 m, 37.5 m)	>125 m (37.5 m, 50 m, 37.5 m)

Evaluation of continuous 4-span bridge capacity for 9-axle B-trains

Bridge design vehicle configuration	Maximum length of continuous 4-span bridges able to support tandem-drive 9-axle B-trains	Maximum length of continuous 4-span bridges able to support tridem-drive 9-axle B-trains
L-45	12.5 m (3.75 m, 5 m, 5 m, 3.75 m)	12.5 m (3.75 m, 5 m, 5 m, 3.75 m)
CL-625	*To be evaluated*	*To be evaluated*
L-60	37.5 m (7.5 m, 10 m, 7.5 m)	37.5 m (7.5 m, 10 m, 7.5 m)
BCL-625	70 m (15 m, 20 m, 20 m, 15 m)	52.5 m (11.25 m, 15 m, 15 m, 11.25 m)
L-75	70 m (15 m, 20 m, 20 m, 15 m)	52.5 m (11.25 m, 15 m, 15 m, 11.25 m)
L-100	>175 m (37.5 m, 50 m, 50 m, 37.5 m)	>175 m (37.5 m, 50 m, 50 m, 37.5 m)

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