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Standardizing the Design of Approach Alignment to Bridges on Forestry Roads in British Columbia: Review and Analysis

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By: Alexander Forrester RPF, EIT

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COVER PHOTO

Main: Tight approach curve to bridge CK-2140 on the West Harrison Lake FSR, Chilliwack Forest District, British Columbia

REVIEWERS

Brian Chow, P.Eng., Chief Engineer, Engineering Branch, British Columbia Ministry of Forests, Lands and Natural Resource Operations

CONTACT

Alexander Forrester, E.I.T., R.P.F.
Researcher, Resource Roads Group
(604) 222-5655
alex.forrester@fpinnovations.ca

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1. EXECUTIVE SUMMARY

FPInnovations was approached in January, 2015, by the Engineering Branch of the British Columbia Ministry of Forests, Lands and Natural Resource Operations (FLNRO) to assess the state-of-practice of bridge approach alignment design on forest roads, and to make recommendations for the standardization of this process. The lack of uniform standards for the design of forest bridge approach is a concern because it creates potential safety risks to public and industrial users of resource roads. Further to the safety implications, inadequate alignment leads to increased risk of damage to bridge structures, costly repairs and ongoing maintenance. Additionally, forest road user groups, such as oil & gas, B.C. Hydro and mining, often use specialized transport trucks to haul large equipment that may have different road alignment requirements than conventional forestry vehicles.

A state-of-practice survey was targeted at forest bridge design engineers, however, FLNRO engineers, B.C. Ministry of Transportation and Infrastructure (MOTI) engineers and transport truck drivers were also included. The purpose of this survey was to document current practices for designing bridge approach alignment on forest roads; the current direction being given by government agencies to forest bridge design engineers, and the type(s) of design vehicles used for design. Through this survey it was found that forest road design processes vary throughout the province and, currently, no standard method or direction is given by government for the design of crossing alignment.

Horizontal and vertical curve requirements for seven design vehicle configurations were assessed and based on these, recommendations were made for standardizing bridge approach alignment design. The design vehicle configurations were identified by bridge design engineers, FLNRO and MOTI staff. Horizontal off-tracking and minimum horizontal tangent requirements were calculated for each design vehicle using a standard geometric equation and computer software. Next, a geometric equation which incorporates vehicle clearance and wheel base was used to determine vertical curve limitations of each vehicle.

Results of the curve assessments were compared with current road design guidelines and codes to evaluate the applicability of the design vehicles to a forestry setting. It was found that guidance for the design of bridge approach alignment on forest roads is not clearly established in these documents, and in some instances conflicts.

Several recommendations were made for the standardization of bridge approach alignment of forest roads. Due to the diverse nature of forest road networks in B.C., making a single recommendation for bridge approach alignment was not practical. As a result, recommendations were based on mainline and secondary roads. Recommendations include a design vehicle, horizontal tangent requirements, and minimum K values for vertical approach curves. When deviating from these standards, it was recommended that design engineers include justification as part of the design package.

2. INTRODUCTION

British Columbia's forestry roads are host to a range of large, heavy, industrial vehicles such as off-highway logging trucks, fuel tankers, low-beds, rock trucks, graders and heavy construction equipment. Ensuring these vehicles can safely navigate on and off of bridge structures is important to a safe and productive forest industry. Approach alignment is a critical component in the design of bridges on forestry roads, and is often a limiting factor in bridge location. Approach alignment affects the overall planning, layout, design, and construction, and has significant effects on user safety, vehicle navigability, and bridge maintenance costs. FPInnovations was requested by the Engineering Branch of the British Columbia Ministry of Forests, Lands and Natural Resource Operations to assess current practices for the design of bridge approach alignment on resource roads, and make recommendations for standardizing this process. The assessment, conducted in early 2015, focused on bridge approaches and their effects on safety, design vehicle selection, and horizontal and vertical tangents. Recommendations for the future standardization of this process include the selection of design vehicles for various road types, horizontal and vertical approach alignment, and professional responsibility.

3. BACKGROUND

Due to their industrial purpose, bridges on forestry roads are often two-way, single lane, crossings with approach alignment designed to a less conservative standard than highway standards (Transportation Association of Canada 1999, British Columbia Ministry of Transportation 2007a). Section 1.5.1 of the Can/CSA-S6-06 (Canadian Standards Association 2006) states; "Preference shall be given to straight horizontal alignments for bridges. The bridge deck longitudinal profile shall be continuous with the approach road profile." However, in British Columbia's rugged and varied terrain it is not always practical to plan for long horizontal and vertical tangents; geology, site conditions, and economics often result in roads being narrow and (or) having sharp curves adjacent to bridge structures. In these situations, it is important that a team of qualified professionals use all relevant planning tools to design a crossing. Planning tools should account for user safety, design vehicle geometry, and crossing lifespan.

While current design manuals provide some guidance on these subjects, in many parts of the province, alignment is based solely on experience or site conditions. The resulting use of rules of thumb or best-fit approaches has led to a lack of design consistency (that is, a mix of approaches and methods are being used across the province). FLNRO's *Engineering Manual* (Engineering Branch 2013) recommends minimal horizontal and vertical tangents of 15 m, while FLNRO (Engineering Branch 1999) recommends 10 m. The United States Forest Service (2014b) recommends minimum horizontal approach tangents of 100 ft. (30.5 m) and 50 ft. (15.2 m), depending on road use. Page 2.1.2.37 in the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) is more applicable to highway bridges because it specifies approach alignment in context of super elevation, which is not common when designing forestry roads, and does not provide specific tangent distances. The alignment chapter (Section 300) in the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation 2007a) also recommends that bridges be located outside of curves, with an appropriate tangent but, again, does not specify a tangent distance and, in any case, is referring to highway bridges. This lack of standardization for designing bridge approaches on forestry roads results in the potential for unsafe user conditions and increased repair and maintenance costs to bridges across provincial resource road networks.

Bridge approach design is an iterative process that incorporates detailed field assessments with office-based analysis and computer-aided design (CAD) to determine the most suitable bridge alignment. For bridges on forestry roads, the design is typically carried out by a consulting engineer. The design process begins with field technicians performing site reconnaissance, layout, and surveys, followed by the design which is certified by an Engineer of Record. The entire process is managed by a Coordinating Registered Professional who, depending on scope of practice, is responsible for issuing a crossing assurance statement, and ensuring all elements of the crossing design and construction are safe and comply with current legislation. This process is described in detail in the *APEGBC/ABCFP Guidelines for Professional Services in the Forest Sector—Crossings* (2014). In addition to user safety, the Coordinating Registered Professional must also consider values, such as water quality, soil, habitat, and fish protection, throughout the entire process.

4. OBJECTIVES

The objectives of this project are to provide an overview of the practices currently used in British Columbia for designing the approach alignment to bridges on forestry roads, and to analyze these practices in order to provide recommendations on four key areas of alignment design: planning tools, design vehicles, approach alignment, and professional responsibility.

5. METHODOLOGY

In January 2015, FPInnovations conducted a detailed telephone survey of nine B.C. professional engineers located throughout British Columbia, who have responsibility for designing bridges on forestry roads. The survey participants are noted in Appendix A.

The survey questions were:

1. What design manual(s) do you use for bridge approach design?
2. What design aid(s) do you use for bridge approach design?
3. What is the typical design vehicle used for determining approach alignment, and why?
4. What are the typical horizontal and vertical tangents used for approach alignment?
5. What is the typical design speed on the bridge and (or) for the bridge approaches?

Through the survey and the discussions that ensued, FPInnovations identified the most common design vehicles, and used these to analyze the practices for designing bridge approach alignment on forestry roads and make recommendations for standardizing these practices. The discussions also provided insight into alternative approaches to bridge and alignment design which, in turn, informed the analysis and recommendations.

Additionally, British Columbia Ministry of Transportation and Infrastructure and FLNRO staff with knowledge of bridge approach alignment design were contacted to discuss their perspective, and gain further insight into operational implications of the design process.

Design Vehicles

FPInnovations selected seven design vehicles to analyze bridge approach alignment. The vehicles were selected based on the frequency of response in the industry survey (see Table 1 in the Results section), and the likelihood of a vehicle providing a worst-case scenario for off-tracking and hang-up.

Long-Load Logging Truck

The chapter on intersections and access (Section 700) in the *BC Supplement to 1999 TAC Geometric Design Guide* (British Columbia Ministry of Transportation 2007c), specifies the long-load logging truck (LLT) as a combination of two design vehicles that "effectively addresses the path requirements for all currently permitted Long-load Logging Trucks in BC."

The LLT combines two vehicles, an LG3 and an LG5 (Figure 1), so that it is possible to simulate at one time the greatest possible sweep (LG3) and the greatest possible off-tracking (LG5) of logging trucks. The LLT is typically used for intersection design; however, it was included in FPInnovations' analysis as a design vehicle for bridge approach assessment because it addresses the path requirements for all currently permitted LLTs in British Columbia (British Columbia Ministry of Transportation 2007c).

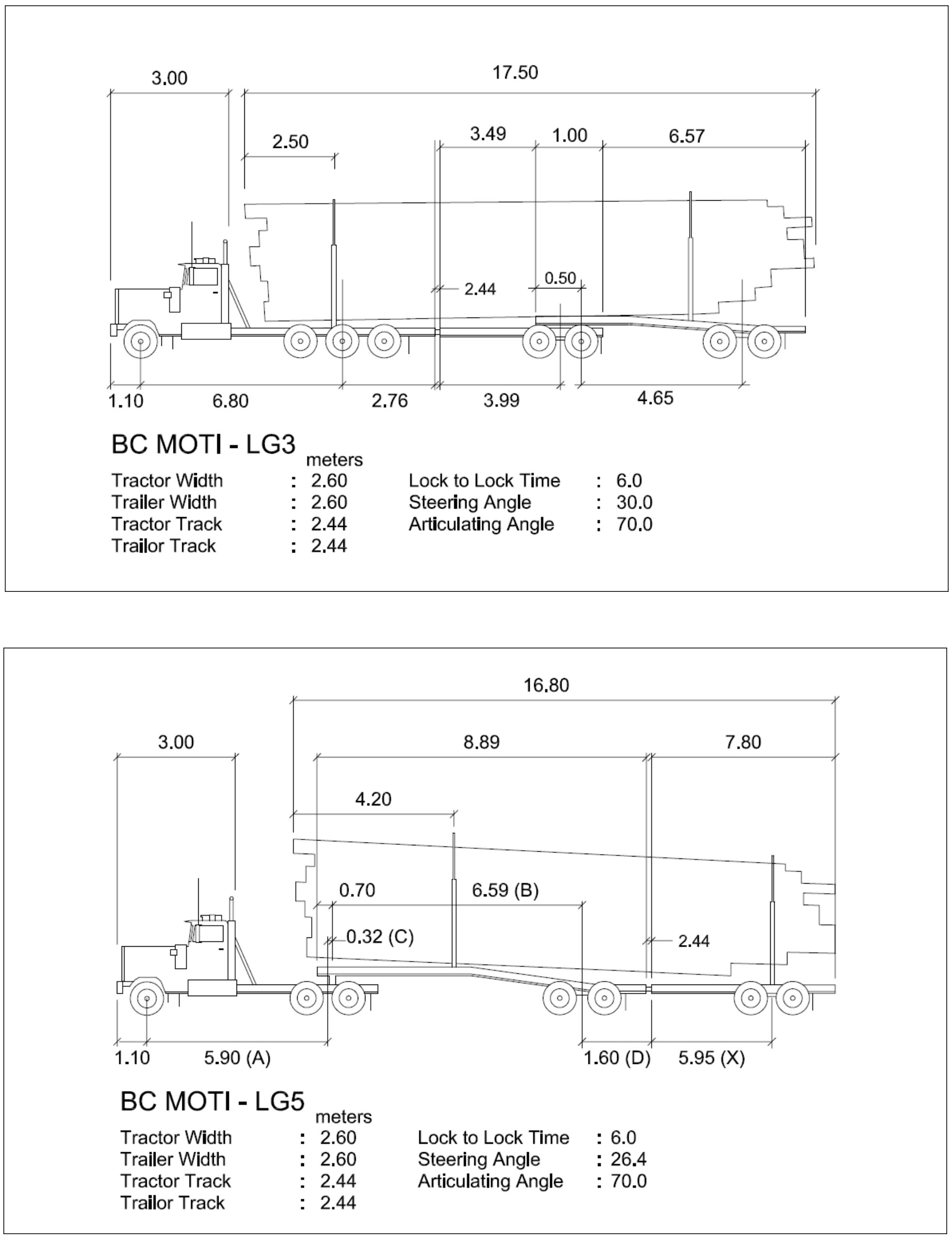
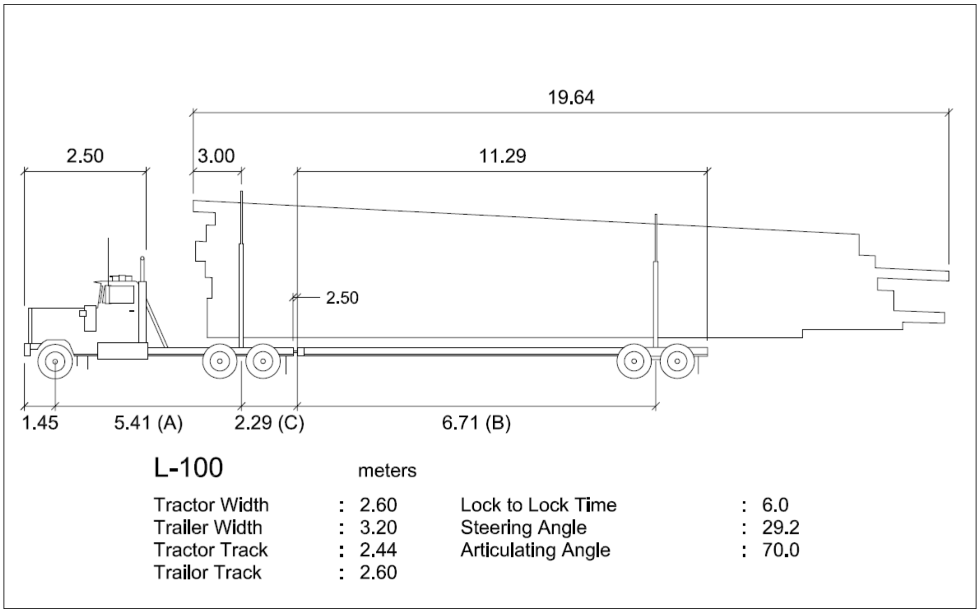


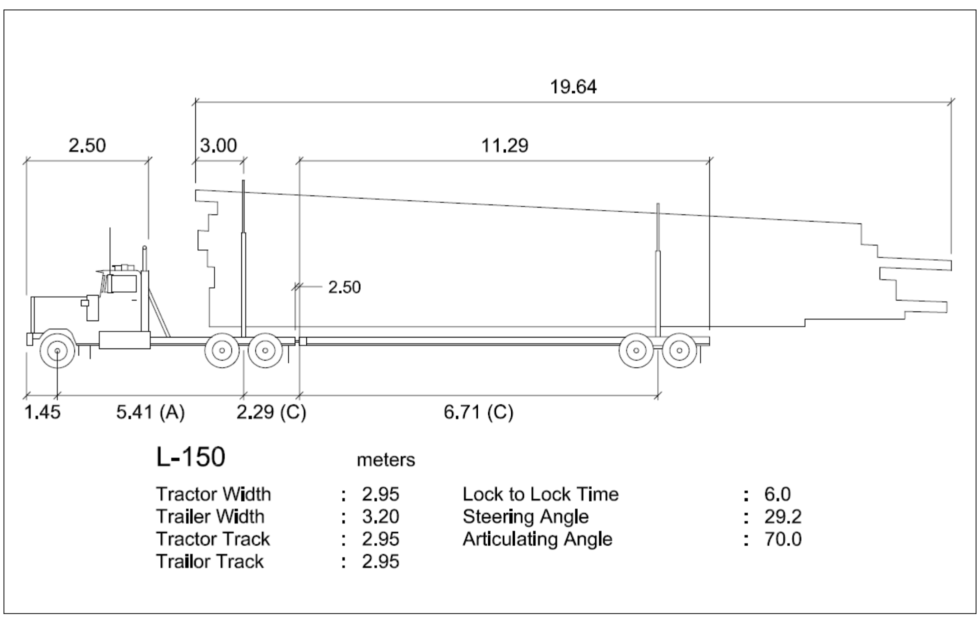
Figure 1. Schematics of the two log-hauling vehicles that comprise the long-load logging truck (LLT) design vehicle: the LG3 and the LG5.

Five-Axle Off-Highway Logging Truck

The *Engineering Manual* (Engineering Branch 2013) depicts several 5-axle off-highway logging trucks for bridge loading design purposes: the L-100, L-150, and L-165. FPInnovations used all three L series vehicles in the analysis of off-tracking and horizontal tangent requirements.

The five-axle off-highway logging vehicle was assumed to be a tandem tractor / pole trailer configuration with an overall length of 23 m (including load). A 3-m front overhang of the load was included, while the rear overhang was variable (Figure 2). Note, the *Standard Drawings for the Bridge Design & Construction Manual* (Henley 2013) does not provide full dimensions for these vehicles. Therefore, tractor dimensions were based on a Pacific P-16 off-highway tractor, with wheelbase and axle-width dimensions based on the standard drawings.





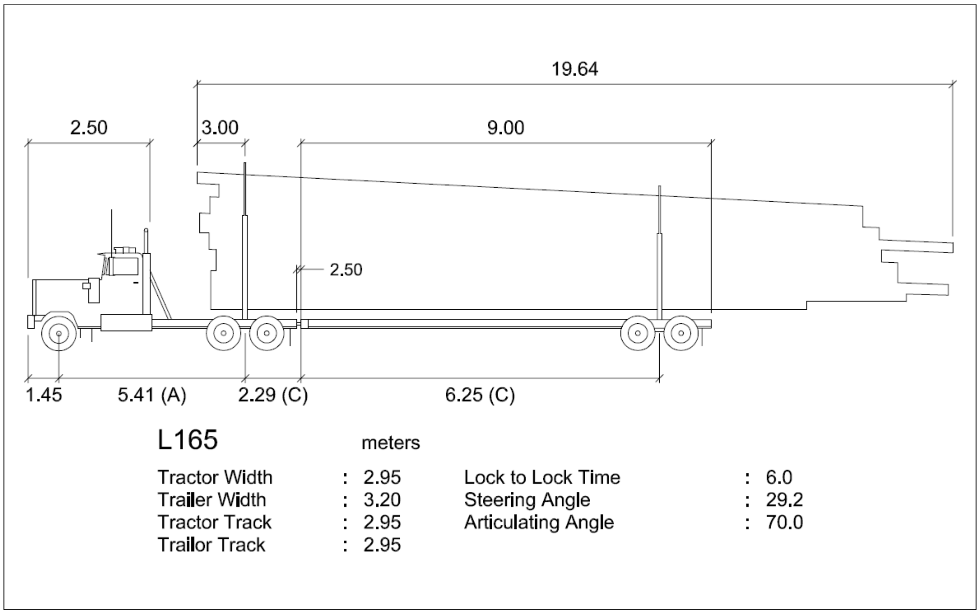


Figure 2. Schematics of the L-100, L-150, and L-165 design vehicles.

WB-19 Tractor Semitrailer

In the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) the WB-19 tractor semitrailer is specified as a design envelope vehicle used for designing roads, intersections, and site access characteristics (Figure 3). It has a tractor wheelbase of 6.2 m, a trailer wheelbase of 12 m, an overall length of 20.7 m, and a minimum turning radius of 10.7 m (outside front wheel) through a 90° curve path. Additionally, the WB-19 can represent flat-deck trailer combinations, which are used to transport forestry materials, supplies, and equipment during harvesting operations.

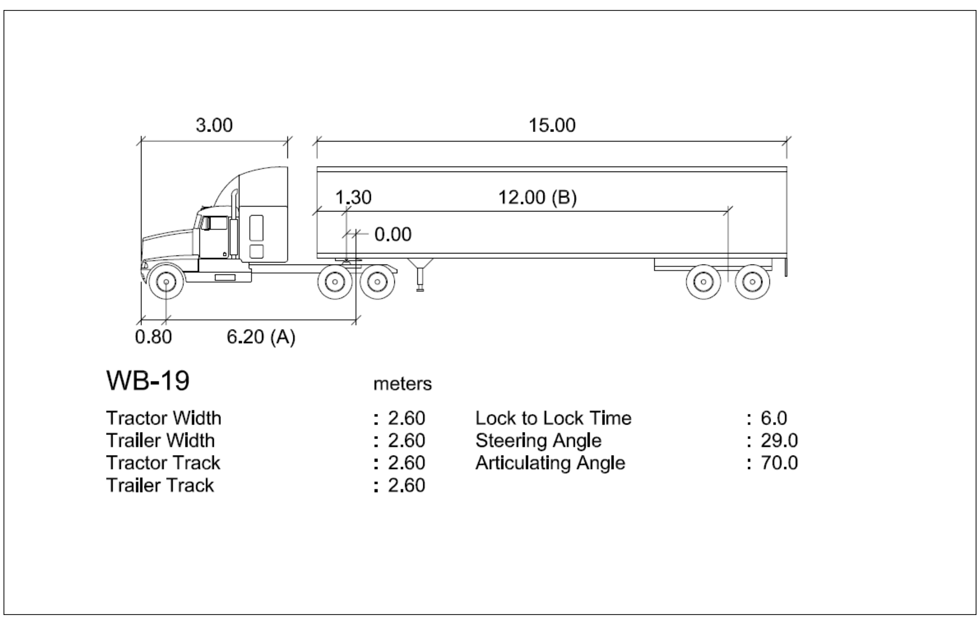


Figure 3. Schematic of the WB-19 tractor / semi-trailer design vehicle.

WB-20 Tractor Semitrailer

The WB-20 tractor semi-trailer design envelope vehicle (Transportation Association of Canada 1999) (Figure 4) is similar to the WB-19 (Figure 3), except that the WB-20 has a trailer wheelbase 2.0 m longer than the WB-19 for a total trailer wheelbase of 12.4 m.

The WB-20 has an overall length of 22.7 m, with a minimum turning radius of 10.7 m (outside front wheel). The longer wheelbase and overall length of this vehicle make it a good candidate for analyzing off-tracking and the minimum required horizontal approach tangent for bridges on forest roads. Like the WB-19, this vehicle can represent flat-deck trailer configurations that service harvesting operations.

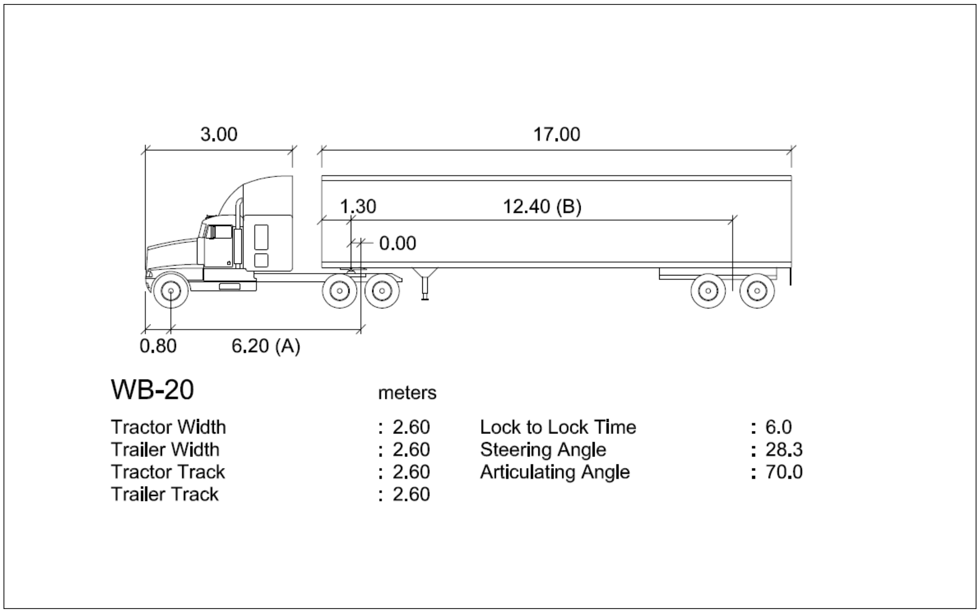
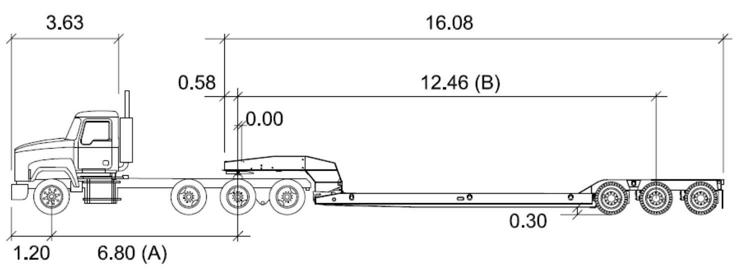


Figure 4. Schematic of the WB-20 tractor / semi-trailer design vehicle.

Tridem Tractor / Tridem Trailer Low-Bed

The tridem tractor / tridem trailer low-bed (Figure 5) was selected as a design vehicle for analysis in order to represent a worst-case scenario for low-beds. It is not mentioned in the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada's 1999) nor in FLNRO's *Engineering Manual* (Engineering Branch 2013), but this type of vehicle is commonly used to transport heavy equipment such as excavators, cranes, or bulldozers.

The tridem tractor / tridem trailer provides a worst-case scenario for off-tracking. The trailer is a drop-deck style with minimal clearance (i.e., from 76 to 305 mm), which provides a worst-case scenario for the trailer chassis to drag or hang-up when navigating abrupt grade changes.[1]



Tridem drive / Tridem Trailer Low-bed

	(m)		(m)
Tractor Width	: 2.60	Lock to Lock Time	: 6.0
Trailer Width	: 3.20	Steering Angle	: 31.8
Tractor Track	: 2.44	Articulating Angle	: 70.0
Trailer Track	: 3.05		

Figure 5. Schematic of the tridem tractor / tridem low-bed trailer design vehicle.

[1] Dimensions for the tridem tractor / tridem low-bed trailer design vehicle are based, in part, on information provided by DWB Consulting Services Ltd. (based in Prince George, British Columbia) and by Timber Services Ltd. (based in Quesnel, British Columbia), and on dimensions specified by the *Commercial Transport Procedures Manual* (British Columbia Ministry of Transportation and Infrastructure 2014b).

Curve/Tangent Alignment

For each of the design vehicles identified through the survey, FPInnovations evaluated how the vehicle navigated two different bridge deck widths based on various approach curve radii (Table 2). The purpose of the analysis was to determine minimum required horizontal approach tangents for each vehicle. Vertical alignment was assessed based on vehicle characteristics and standardized parabolic curve processes for the design of bridge approach alignment. Additionally, an evaluation of the minimum required bridge width was performed based on the 10 m and 15 m horizontal tangents (Table 3) specified in the Engineering Manual (Engineering Branch 2013) and FLNRO (Engineering Branch 1999).

Horizontal

FPInnovations assessed off-tracking of the design vehicles, both geometrically and through AutoTURN simulations (Appendix B). The purpose of this was to determine if current road-widening tables in the *Engineering Manual* (Engineering Branch 2013) are adequate, and to gauge which design vehicle would provide a worst-case scenario for tracking on and off of a bridge. FPInnovations used the following equation to calculate the geometric off-tracking for each of the design vehicles (Figure 6): and to reveal which vehicle exhibited the most significant off-tracking:

$$Offtracking\ (OT) = R - \sqrt{R^2 - L^2}\ \times\ (1 - e^{\left(-0.015\,\Delta_{deg}\frac{R}{L}+0.216\right)})$$

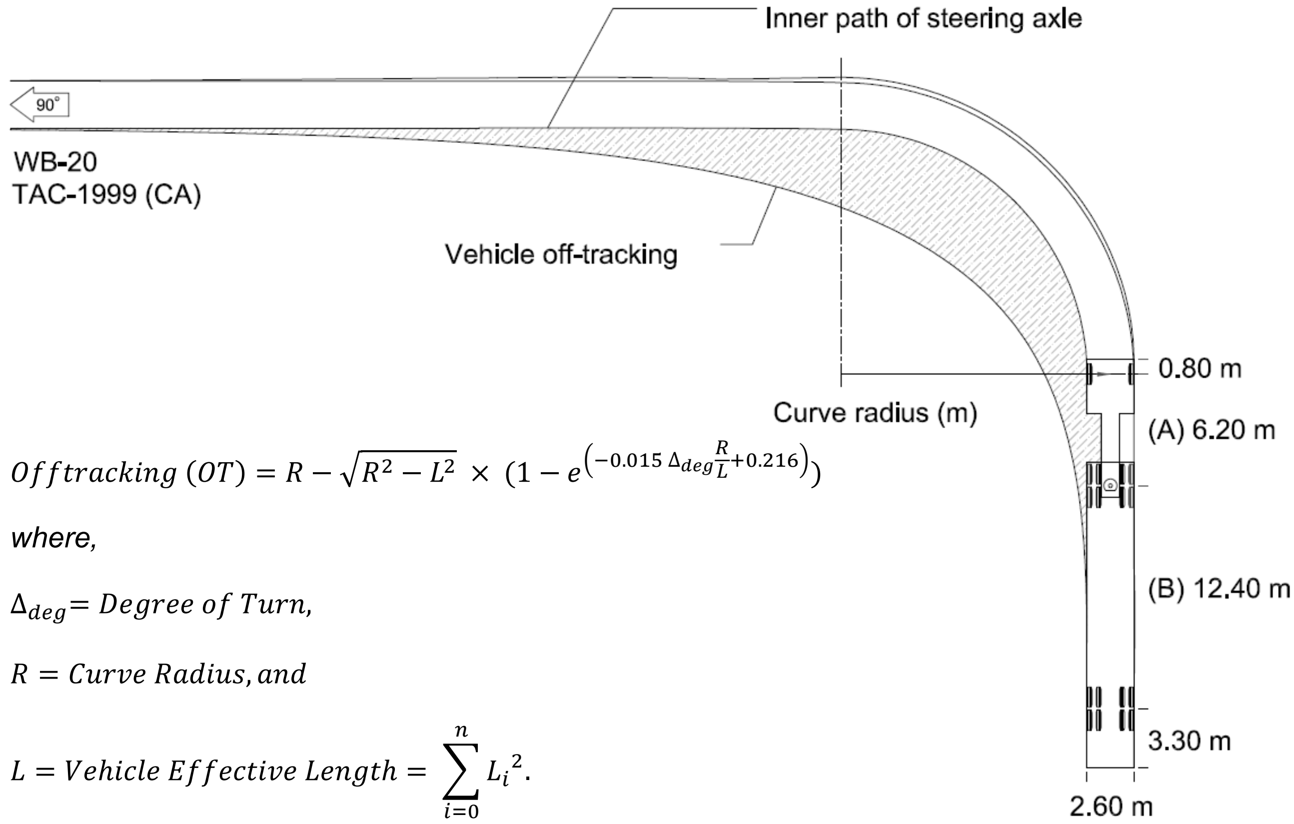
where,

$\Delta_{deg} = Degree\ of\ Turn$,

$R = Curve\ Radius$, and

$L = Vehicle\ Effective\ Length = \sum_{i=0}^{n} {L_i}^2$.

The hypothesis was that the vehicle with the worst off-tracking would require the longest horizontal tangent to safely manoeuvre on and off a bridge. The off-tracking equation takes into consideration curve radius, degree of turn, tractor wheelbase, and wheelbases of all trailers including hitch offsets. Also, using AutoTURN Pro 3D 9 for AutoCAD, FPInnovations simulated and measured the off-tracking of each design vehicle. The results were compared to the geometric calculation results.



$$Offtracking\ (OT) = R - \sqrt{R^2 - L^2} \times \left(1 - e^{\left(-0.015\,\Delta_{deg}\frac{R}{L} + 0.216\right)}\right)$$

where,

$\Delta_{deg} = Degree\ of\ Turn,$

$R = Curve\ Radius, and$

$$L = Vehicle\ Effective\ Length = \sum_{i=0}^{n} {L_i}^2.$$

Figure 6. Geometric off-tracking equation and off-tracking diagram for the WB-20 tractor semitrailer design vehicle.

Using AutoTURN, minimum horizontal tangents were calculated for each design vehicle by simulating various turning paths (Figure 7). Twenty-four horizontal curve paths were simulated for each design vehicle; which included turns of 45°, 90°, 135° and 180° for 15-m, 35-m, and 100-m curve radii. The curve radii reflect design specifications presented in Table 3-2 “Summary of Alignment Controls for Forest Roads” in FLNRO’s *Engineering Manual* (Engineering Branch 2013). Bridge deck widths used in the simulation were 4268 mm and 4876 mm, as per the widths outlined in the *Standard Drawings for the Bridge Design & Construction Manual* (Henley 2013). An additional 400-mm offset from the guard-rails was included because this is a requirement outlined in FLNRO standard drawings STD-EC-000-01 and 02 (Henley 2013). The offset distance is measured from the guardrail to the centerline of the out-side-of-curve steering tire and the inside-of-curve rear trailer tire. The guardrail is assumed to be 150 mm outside of the bridge deck, measured from the edge of bridge deck, which is common because most guardrails are attached outside of the bridge deck by steel or wooden brackets (STD-EC-010-01 to 05 in Henley 2013).

The minimum required horizontal tangents were determined through 2D simulations using AutoTURN. Tangents were determined by measuring the distance from the end of the curve to where the design vehicle started to clear the guardrail (Figure 7). For modelling purposes, the bridge deck was simulated by lines offset from the road centreline, corresponding to the two bridge deck widths (4268 mm and

4876 mm). The design vehicle was given a 250-mm clearance on either side to allow for the 150-mm guardrail offset outside the bridge deck. Results were recorded in an Excel table for further analysis. Over-steering was not considered part of the simulations, and vehicles were assumed to drive the road centreline and start turning at the beginning of curve.

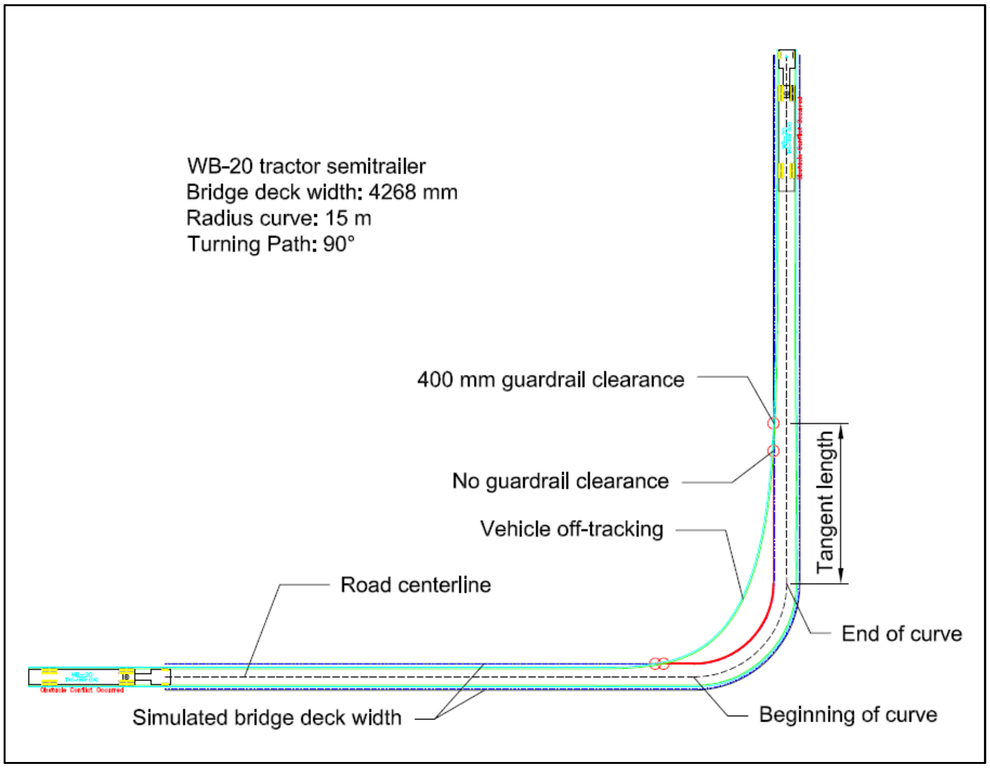


Figure 7. Example of a turning path simulation for a WB-20 tractor semitrailer design vehicle, created with AutoTURN Pro 3D 9 for AutoCAD.

Minimum Bridge Width

To provide another perspective on forest bridge approach design, analysis using 10 m and 15 m horizontal approach tangents was done to evaluate the minimum required bridge width for each design vehicle identified in the survey. AutoTURN was used to simulate each design vehicle navigating a 15 m, 35 m and 100 m radii curve for 45°, 90°, 135° and 180° curve paths. 10 m and 15 m horizontal tangents were marked on the simulation following the end of the curve. A 400 mm envelope was applied to each vehicle. The required bridge width was measured at the end of the tangent and included the 400 mm buffer (Figure 8).

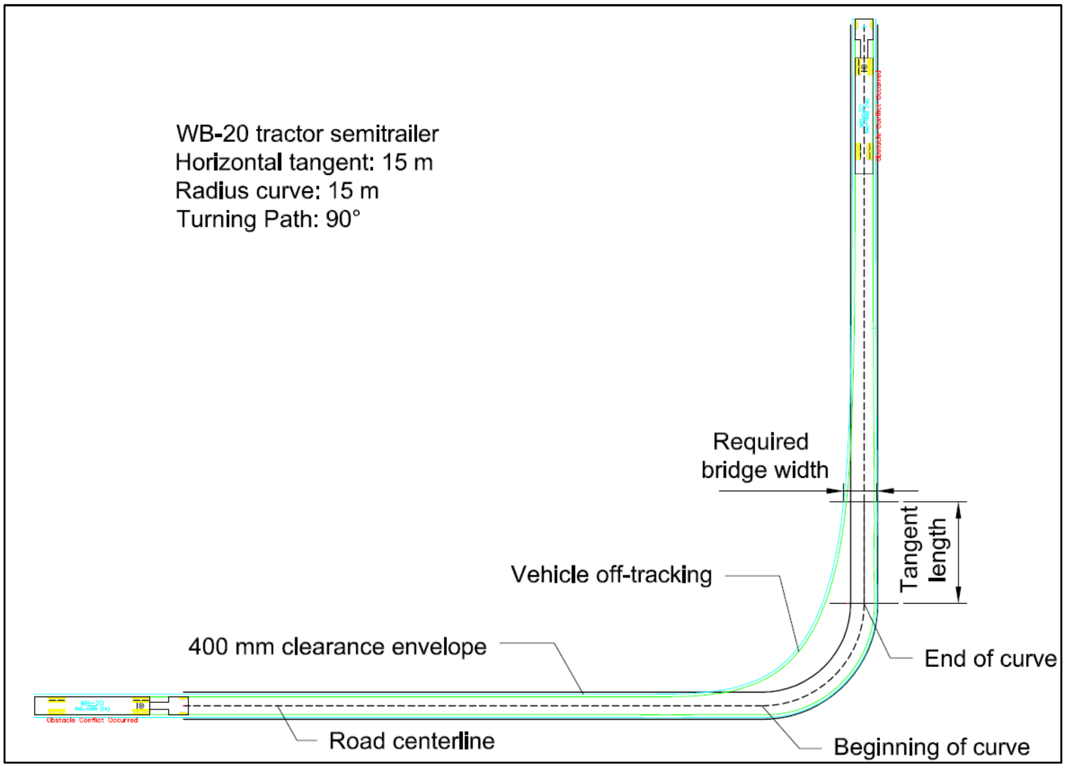


Figure 8. Example of bridge width measurement for a WB-20 tractor semitrailer design vehicle, created with AutoTURN Pro 3D 9 for AutoCAD.

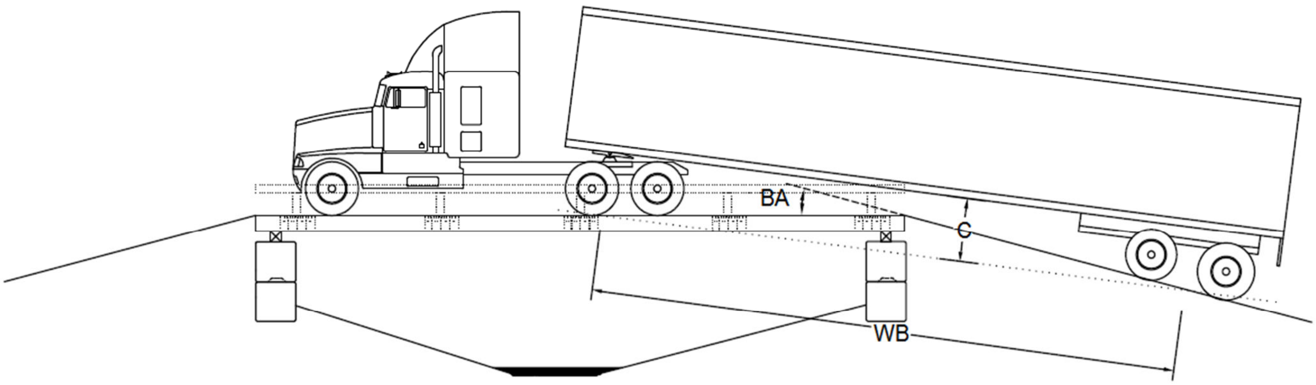
Vertical

For determining vertical alignment, the break-over angle[2] of the tractor and trailer (Figure 9) was determined and compared to recommended design K values (British Columbia Ministry of Transportation 2007b).

Using the break-over angle, a minimum K value for each design vehicle ($K_{vehicle}$) was determined. The K value is a parabolic function of the total horizontal curve length, and change in grade. The higher the value of K is, the less abrupt the curve. $K_{vehicle}$ is determined by modifying the K value equation Eq. 2.1.23 in the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) to assume the horizontal length of the curve is equal to the wheelbase of the design vehicle.

[2] The break-over angle is the maximum angular difference (degrees), or grade break (%), that a vehicle can safely navigate without hanging up (i.e., without its chassis contacting the bridge or road surface).

When $K_{vehicle} > K_{design}$ there is a high likelihood of vehicle hang-up, resulting in unsafe conditions, and lost productivity (Figure 10)



$$Breakover\ angle = 2 \times \tan^{-1}\left(\frac{2\ \times\ ground\ clearance}{wheel\ base}\right)$$

$$K_{Vehicle} = \frac{wheel\ base}{100\ \times\ \tan(breakover\ angle)}$$

Figure 9. Schematic of an example of sufficient vertical alignment for the design vehicle's break-over angle: tractor semitrailer.

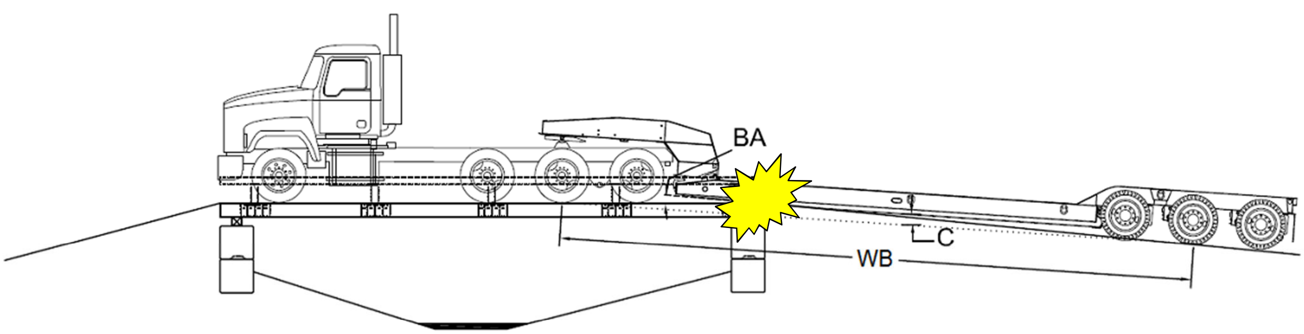


Figure 10. Schematic of an example of insufficient vertical alignment for the design vehicle's break-over angle: tridem tractor / tridem trailer low-bed.

6. RESULTS AND DISCUSSION

Observations from Discussions with FLNRO's Engineering Groups

FPInnovations' discussions with FLNRO Engineering Branch staff around the province provided insight to the process of bridge alignment design relative to implementation of the design in the field. The discussions are summarized in Appendix C.

The discussions revealed that often the consulting design engineer, does not actually see the completed bridge in daily operation, meanwhile FLNRO engineering staff are responsible for ensuring crossings are maintained in a safe condition. The disconnect between design and operations can lead to a variety of serious issues related to safety, repairs, and maintenance, and even to the need to re-design or replace the bridge.

The Southern Engineering Group, based In Kamloops, often specifies a WB-19 design vehicle, with 500-mm of clearance on either side. This design vehicle was specified following measurement of several low-beds that frequent forest roads in the southern region (Appendix C). Based on this, the group determined that the WB-19 represents the majority of vehicle dimensions travelling the roads in their region. Additionally, it was discussed that the 500-mm clearance allows other stakeholders—such as BC Hydro and the oil and gas industry, who do use the roads but not frequently—to bring in larger configuration loads. Vertical alignment is also an issue, with break-over angles often being insufficient for the crossing. An example of this is a bridge that had a crest curve grade break at the bridge of 10.5%, which resulted in low-beds becoming hung up on the crest. In general, the Group felt that having minimum standards would mitigate the issues they are seeing, and act as an opportunity to educate design engineers to think critically about approach alignment.

The Southern Engineering Group also noted that more bridges include pedestrian handrails. These handrails are higher than traditional timber guardrails. Historically, wide vehicles could drive onto the bridge with the load overhanging the low guardrails, but the higher guardrails have made this impractical and have resulted in damage to several bridges.

The Northern Engineering Group, based in Prince George, typically relies on professional judgement in regards to horizontal and vertical alignment. Recommendations from staff to designers include using the 15-m horizontal and vertical tangents specified in the *Engineering Manual* (Engineering Branch 2013), but do not specify a vehicle for off-tracking purposes. When designers deviate from the *Manual*'s tangents, they are expected to provide documentation and justification for their decisions. Typically, tracking is more of a concern on mainline roads frequented by low-beds and similar vehicles. Currently there is a push from industry to allow longer off-highway haul trucks, carrying larger loads, on the roads because there is a shortage of drivers in the region. The larger loads help maintain sufficient timber volume delivery to mills despite the driver shortage; however, there is concern from the Group that longer trucks may have issues with existing bridge approach alignments. Bridge approach alignment on secondary roads is not a significant concern in the region because off-highway trucks can often navigate tight alignment, and the short lifespan of these crossings allows for a higher level of risk acceptance.

The Coastal Engineering Group, based in Nanaimo, provides bridge approach alignment criteria to consulting design engineers. However, it is recognized that steep terrain often requires the design of bridges and approaches to be innovative. When constructing mainlines or providing permanent access to communities or high-value recreation, a WB-19 design vehicle is specified with a 300 to 500-mm clearance depending on the site. Similar to the Southern Engineering Group, the WB-19 was decided upon following measurement of several “fat” off-highway configuration logging trucks that are commonly used on northern Vancouver Island (Appendix C). The 500-mm clearance ensures these “fat” trucks can safely navigate on and off of bridges. For secondary access, depending on highway or off-highway configurations, the BCL-625 or an L series design truck is specified. FLNRO engineering staff specify the use of 10-m horizontal and vertical tangents as described in the *Forest Service Bridge Design and Construction Manual* (Engineering Branch 1999); however, site conditions may require a deviation from this practice. Often a minimum 7-m horizontal tangent is designed in combination with flared end panels to provide additional horizontal clearance. Vertical curve K values for bridge approaches are specified at 12 for crests and 13 for sags; these values have a long history of use in this region, and to date have proven adequate.

Survey Outcomes

The survey participants provided a range of responses, and all responses were considered. The survey questions often led to in-depth discussions with the respondents. Often the respondent considered approach design to be a site-specific process; this led to survey participants giving multi-part responses based on road use (e.g., in-block vs. mainline roads). The responses are summarized in Appendix A.

Design Manuals

All nine respondents use the FLNRO’s *Engineering Manual* (Engineering Branch 2013) and *Forest Service Bridge Design and Construction Manual* (Engineering Branch 1999). Two designers also use the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) as a supplement. All three of these manuals discuss approach tangents, although they provide limited details.

Through follow-up conversations with respondents, FPInnovations discovered that most designers use the design manuals only as guidelines and they typically design bridge approaches based on site conditions. In regions with steep topography, approach alignment is designed on the basis of best fit to the terrain and conditions; modifications to the bridge deck width (enlargement or flaring) and/or an acceptance of significant maintenance and repair costs are common.

Design Aids

Most design engineers surveyed use a version of AutoTURN, with one respondent using the British Columbia Ministry of Transportation and Infrastructure’s PathTracker software.

Both of these programs calculate off-tracking of a vehicle based on dimensions and curve specifications that are input by the user. Both programs are useful in ensuring the approach alignment is safe for the bridge/road user, and that collisions between the design vehicle and bridge will not occur. However, some respondents believe software programs are too conservative in their solutions, and that during construction the alignment can be shortened to better fit the site and to reduce costs. These are important observations, as first-hand construction experience can often provide practical solutions that office-based analysis does not.

Typical Design Vehicles

Several design vehicles, both on-highway and off-highway, were reported (Table 1). Respondents often employ a range of design vehicles, depending on the situation. For the purpose of analysis and discussion here, FPInnovations placed the vehicles into three categories: 5-axle off-highway logging trucks (L-

100 and L-165), tractor/semitrailer combinations (WB-15, WB-18, WB-19, and WB-20), and low-beds (respondent-defined dimensions).

Respondents said they commonly select a design vehicle that approximates low-bed off-tracking, because this is considered the most limiting design condition for bridge approaches (Appendix A). There were variations on this theme, with some designers using the WB series vehicles, while others choose a low-bed based on known dimensions (e.g., a tridem tractor/ tridem trailer low-bed). The L series off-highway logging trucks are more commonly used for bridge load design; however, the dimensions can be used to design bridge approaches for in-block roads, i.e., where a higher level of risk (in terms of damage to the structure or signs) is acceptable and heavy equipment is expected to "walk" the road as opposed to being delivered on a low-bed. Based on survey results, the WB-19 was the most common vehicle used for the purposes of bridge approach design (Table 1).

Table 1. Types of design vehicles that survey respondents said they use to design bridges and alignments on forestry roads

Type of design vehicle	Respondents using this vehicle (no.)
5-axle off-highway design truck (L series vehicles)	
L-165	2
L-100	1
Tractor / semitrailer combinations (WB series vehicles)	
WB-15	1
WB-18	1
WB-19	4
WB-20	1
Tractor / low-bed trailer	
Tridem tractor / tridem trailer	1
Configuration not specified	2

Typical Horizontal and Vertical Tangents

Respondents said that horizontal tangents range from 30 m long to "whatever fits". Vertical tangents range from 5 to 10 m long but are consistently less than the horizontal tangents. Two respondents did not give specific values, because they believe that each bridge approach has different challenges and, therefore, they specify a tangent length based on site conditions and economics.

Typical Design Speeds of the Bridge and/or Bridge Approach

Respondents said that design speed depends on road class: traffic is assumed to travel at 20 km/h on spur roads, 30 km/h on access roads, and 50 km/h on mainlines. Typically, designers base horizontal and vertical curve alignment on Table 3-2 "Summary of alignment controls for forestry roads" in the *Engineering Manual* (Engineering Branch 2013), which establishes alignment controls and minimum curve radii for various road speeds and widths. In general, speed was found to be a function of the road and not the bridge approach unless site-specific conditions required a reduced speed.

Analysis

Horizontal Alignment

Vehicle off-tracking

In all scenarios, the tridem tractor / tridem trailer low-bed showed the most significant off-tracking. In the case of a 15-m radius curve, the geometric method of solving off-tracking gave a minimum subgrade width of 10.18 m, which is greater than the 9-m minimum specified in the *Engineering Manual* (Engineering Branch 2013) (Appendix B).

Not all forestry roads are the same, and a one-size-fits-all approach to curve widening is not practical. Typically, mainline forestry roads are constructed to accommodate significant traffic loads, and they have straighter alignment and higher travel speeds than secondary roads. Addressing off-tracking on mainline roads is critical to user safety because corners or bridge approaches are travelled at speeds ≥50 km/h. The recommended minimum curve radius is 100 m for roads with a 50 km/h design speed (Engineering Branch 2013). With this size of curve, vehicle off-tracking is minimized; however, higher travel speeds do increase user risk. It should be noted that mainline roads may have significant levels of public traffic; in these cases, designers need to consider more conservative curve designs to ensure user safety. Secondary roads, i.e., either in-block or end-of-system roads, serve the specific purposes of accessing harvest units for a defined period of time, and possibly for providing subsequent periodic access. Often, they are steep and narrow with tight curves and poor visibility. Excessive curve widening in these conditions may not be practical and efficient (i.e., the steep slopes would result in significant sidecast or expensive end hauling). In these situations, it is more practical to determine what type of vehicles will be accessing the blocks and then use this information to create an efficient road design.

Horizontal tangents

Table 2 summarizes the results of an analysis of four curves and seven design vehicles (Figures 1 to 5). As expected, the tridem tractor / tridem trailer low-bed produced the greatest required horizontal tangent for all turning scenarios.

These results indicate that current recommendations regarding horizontal tangents may not be adequate for construction support vehicles and other industrial road user demands (e.g., oil and gas, mining, large-scale licensees, etc.). While some of the turning scenarios may be rare for bridge approaches (i.e., 15 m radius, 180° curve onto a bridge), these situations do arise in terrain with deeply incised gullies (Figures 11, 12, and 13), and when accessing steep slopes where switchbacks are required for elevation gain. Therefore, it is important to note that curves may sometimes need a longer transition than is currently specified in the *Engineering Manual* (Engineering Branch 2013).

Figure 11. Example of a 180° curve path with a bridge located inside the curve, resulting in restricted approach alignment. Bridge CK-2134 located at KM 23.5 on the West Harrison FSR.

Figure 12. Example of recent damage to the guardrail on Bridge CK-2134, likely resulting from the restricted approach alignment.

Figure 13. Example of approach curve directly onto the bridge deck at Bridge CK-2140, located at KM 44.5 on the West Harrison FSR. Note the damaged guardrail on the inside of the curve and the knocked-down sign on the outside, which likely occurred as a result of restricted approach alignment.

Table 2. Minimum horizontal tangent lengths for a range of common bridge approach curves and design vehicles

Design vehicle	Bridge deck width (mm)	Minimum horizontal tangent length (m) [b]											
		45° approach curve			90° approach curve			135° approach curve			180° approach curve		
		15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve
Long-load Logging Truck (LLT)													
LLT	4269	11.27	5.71	1.96	13.54	6.18	n/a	14.06	6.11	n/a	14.42	6.17	n/a
	4877	7.67	2.04	n/a	10.12	2.72	n/a	10.67	2.49	n/a	10.81	2.51	n/a
5-axle off-highway logging truck (L series)													
L-100	4269	12.15	7.02	4.43	13.72	7.35	n/a	14.17	7.30	n/a	14.47	7.35	n/a
	4877	6.83	1.60	n/a	8.48	1.91	n/a	8.95	1.87	n/a	8.99	1.93	n/a
L-150	4269	12.16	7.04	4.42	13.73	7.35	n/a	14.51	7.30	n/a	14.64	7.36	n/a
	4877	6.82	1.60	n/a	8.46	1.93	n/a	8.96	1.90	n/a	9.00	1.91	n/a
L-165	4269	11.29	6.27	3.87	12.67	6.53	n/a	13.19	6.48	n/a	13.29	6.55	n/a
	4877	6.17	1.05	n/a	7.64	1.36	n/a	8.05	1.30	n/a	8.06	1.33	n/a
Tractor/semitrailer combinations (WB series vehicles)													
WB-19	4269	19.09	12.85	6.90	23.72	14.32	1.19	25.75	14.38	2.06	26.68	14.50	1.22
	4877	13.99	7.73	1.74	18.66	9.23	n/a	20.70	9.37	n/a	21.63	9.44	n/a
WB-20	4269	20.68	14.55	7.65	25.79	15.97	1.92	27.99	15.59	2.77	28.83	15.67	1.95
	4877	15.42	9.10	2.34	20.59	10.72	n/a	22.78	10.33	n/a	23.60	10.42	n/a
Tractor / low-bed trailer													
Tridem / tridem low-bed	4269	29.92	23.60	17.46	34.90	25.26	11.72	37.12	25.43	12.58	38.22	25.50	11.75
	4877	20.74	14.41	8.19	25.77	16.11	2.43	28.03	16.23	3.27	29.11	16.31	2.43

[a] Values assume that a 400-mm buffer from guardrail is maintained.

[b] Curve radius and speed limits as per FLNRO's *Engineering Manual* (Table 3-2 in Engineering Branch 2013).

Minimum Bridge Widths

Table 3 summarizes the results of evaluating minimum required bridge widths for each design vehicle. It was found that smaller curve radii and larger curve paths required wider bridge widths. This was common for all AutoTURN simulations.

FLNRO standard bridge deck widths are specified to be 4269 mm and 4877 mm wide, with guardrails typically mounted to the outside of the bridge deck. 168 AutoTURN simulations were performed using the various vehicle configurations, curve radii, curve paths and standard approach tangents. Of the results 89 indicated that a bridge width of 4269 was too narrow, and for 42, a bridge width of 4877 mm was too narrow. As would be expected, the severity increases with smaller curve radius and degree of approach road curve. This illustrates the importance of applying higher level engineering and the value of identifying standard vehicle configurations for bridge approach road design. It is suggested that FLNRO undertake a review of its standards for bridge deck widths in concert with bridge approach road tangent lengths.

Table 3. Minimum bridge widths for a range of common bride approach curves and design vehicles

Design vehicle	Tangent Length (m)	Minimum Bridge Width (m) [a]											
		45° approach curve			90° approach curve			135° approach curve			180° approach curve		
		15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve	15-m radius curve	35-m radius curve	100-m radius curve
Long-load Logging Truck (LLT)													
LLT	10	4.42	3.98	3.75	4.80	4.02	3.62	4.97	4.02	3.63	5.02	4.02	3.62
	15	4.05	3.76	3.63	4.27	3.78	3.53	4.37	3.77	3.54	4.40	3.78	3.53
5-axle off-highway logging truck (L series)													
L-100	10	4.67	4.36	4.24	4.87	4.38	4.13	4.92	4.38	4.14	4.95	4.38	4.13
	15	4.39	4.20	4.14	4.48	4.21	4.07	4.52	4.21	4.08	4.52	4.21	4.07
L-150	10	4.68	4.36	4.24	4.86	4.37	4.13	4.93	4.37	4.14	4.94	4.37	4.35
	15	4.38	4.20	4.14	4.49	4.21	4.07	4.52	4.21	4.08	4.53	4.21	4.07
L-165	10	4.61	4.32	4.22	4.76	4.33	4.12	4.82	4.33	4.13	4.82	4.34	4.12
	15	4.33	4.71	4.12	4.42	4.18	4.06	4.44	4.18	4.07	4.45	4.18	4.06
Tractor/semitrailer combinations (WB series vehicles)													
WB-19	10	4.71	4.22	3.90	5.36	4.34	3.73	5.74	4.36	3.75	5.93	4.36	3.73
	15	4.33	3.98	3.75	4.78	4.06	3.63	5.04	4.06	3.64	5.16	4.07	3.63
WB-20	10	4.80	4.28	3.93	5.51	4.42	3.75	5.93	4.44	3.77	6.19	4.44	3.76
	15	4.40	4.03	3.78	4.88	4.12	3.65	5.18	4.12	3.67	5.34	4.12	3.65
Tractor / low-bed trailer													
Tridem / tridem low-bed	10	5.22	4.77	4.46	5.91	4.90	4.32	6.34	4.91	4.34	6.58	4.92	4.32
	15	4.88	4.56	4.34	5.33	4.64	4.22	5.59	4.65	4.24	5.83	4.65	4.22

[a] Values include a 400-mm buffer from the guardrails.

Vertical Alignment

The proper design of the vertical alignment of bridge approaches is critical to user safety and bridge lifespan. Sudden grade changes may reduce driver visibility, cause vehicle clearance issues, and increase live loading on the structure.

FLNRO typically recommends that bridge structures have a relatively flat longitudinal grade that is vertically aligned with the approach tangents. Both the FLNRO's *Engineering Manual* (Engineering Branch 2013) and the *Forest Service Handbook* (United States Forest Service 2014a,b) recommend bridge decks be no steeper than 4% and aligned with approach tangents, while the chapter on alignment (Section 300) in the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation 2007a) recommends bridge decks be no steeper than 2% and aligned with approach tangents (Table 3). These grades promote drainage across the structure and reduce the potential for ponding; smooth transitions increase user safety, decrease live loading, and mitigate clearance issues.

When discussing vertical alignment, tangency is not the only consideration. Sight stopping distance, approach curve K values, and grade break are also important; and, approach curve K values and grade break may provide alternatives to long vertical approach tangents. For example, in situations where terrain restricts the vertical tangent length, if the designer ensures the vertical approach curves do not exceed the $K_{vehicle}$ or vehicle break-over angle for the worst-case scenario vehicle, then this performs the same function as using an adequate vertical approach tangent. It should be noted that the designs of the horizontal and vertical approach alignments are not exclusive of each other, and the design process must consider both to ensure an optimal design.

Sight Stopping Distance

Sight stopping distance is an issue for both crest and sag curves. However, in the context of approaches to bridges on forestry roads, the issue is largely mitigated by the roads' radio call procedures, slower travel speeds, and vegetation clearing along the road right-of-way. But on forestry roads frequently travelled by the public, the design of vertical curves should follow the standards in the low-volume roads chapter (Section 500) of the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation 2007b) (Table 4) and the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) (Table 5), because of the added risk created by fast-moving public vehicles whose drivers are likely unfamiliar with industrial road use and the constraints of driving on gravel surfaces.

Table 4. Minimum curve K values for vertical curves on low-volume roads (British Columbia Ministry of Transportation and Infrastructure (2007b)[a,b]

Design speed (km/h)	Minimum sight stopping distance (m)	Minimum curve K value	
		Sag [a]	Crest [b]
30	30	4	3
40	45	7	5
50	65	12	11
60	85	17	18
70	110	24	30
80	140	32	50
90	170	40	90

[a] Sag vertical curves design for sight stopping distance using headlight control criteria of 0.6 m above road surface with 1° upward angle.
[b] Crest vertical curves design for sight stopping distance using 1.05-m driver eye height and 150-mm fixed object height.

Table 5. Minimum sight stopping distance for one-lane, two-way bridges (British Columbia Ministry of Transportation and Infrastructure 1999)[a, b, c]

Operating speed (km/h)	Minimum stopping sight distance (m)	
	On two-way roads	On one-lane, two-way bridges [c]
30	30	30 + L + F1 + F2
40	45	45 + L + F1 + F2
50	65	65 + L + F1 + F2

[a] Bridges are not designed in sag curves.
[b] L = span distance. F1 & F2 = flare distance at bridge ends.
[c] Crest curve K (one-lane, two-way bridges) $K = \frac{SD^2}{398.745}$

Live Loads

Excessive live loading caused by poor vertical approach alignment may, over time, cause a structure to fatigue or fail, and will likely increase overall maintenance costs due to frequent repairs. Live loads are imposed by vehicles, pedestrians, equipment, or any components that are subject to movement. When designing bridges on national highways a CL-W truck is used to account for live loading. Other factors taken into consideration are vehicle count, multi-lane loading, and dynamic load allowance (Canadian Standards Association 2006). For bridges on forestry roads, live loading is based on the BCL-625, L-100, L-150, or L-165 design vehicles. It is assumed that vehicles cross one at a time, down the centre of the bridge (Engineering Branch 2013).

A smooth transition from the roadway to the bridge deck ensures live loads are consistent with design, and that no unnecessary "punching out" or "slamming" onto the bridge occurs. These conditions typically occur on sag curves where poor alignment causes an abrupt transition from the road to the bridge. Sag curves transition the road grade from a downward trajectory to a more upward one; the change in trajectory causes an acceleration perpendicular to the centre of the curve. As a result, the vehicle travelling the sag curve exerts an increased downward force onto the roadway or bridge deck. This can be felt by the driver and is referred to as g-force. The effects of this increased load can potentially cause abutment failure and/or structure failure; and/or vehicle and bridge deck damage can occur, caused by the vehicle bottoming out. Due to these excessive loads, bridges should not be designed in sag curves, but only tangent to the curve (British Columbia Ministry of Transportation 2007a).

Vehicle Clearance

In FPInnovations' discussions with design engineers, FLNRO engineering staff and operators of heavy haul trucks several respondents revealed that hang-up is a significant concern in both the design and operation of bridges on forestry roads. This hazard, which is associated with vertical alignment of bridge approaches, occurs when the underside of the vehicle chassis contacts the road or bridge structure. This may result in minor scarification or significant damage to the road or bridge deck, and lost productivity due to a stuck vehicle. An abrupt change in grade at a crest curve approach, which exceeds the design vehicle's break-over angle, cause this problem on forestry road bridges. Traditionally, this problem was mitigated by designing the approach alignment tangent to the bridge; however, in situations where this is not possible, bridge approaches should be designed such that vertical approach alignment does not exceed the break-over angle, or that $K_{design} > K_{vehicle}$, for the worst-case vehicle likely to navigate the road.

A similar problem exists with level rail crossings on public roads and highways, and is identified in the specifications (Transportation Association of Canada 1999, British Columbia Ministry of Transportation and Infrastructure 2014a). The specifications for railway crossings (Section 1100) in the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation and Infrastructure 2014a) recommend a maximum grade differential at rail crossings of 0% for road speeds ≥60 km/h, 1% for road speeds of 40 to 59 km/h, and 2% for road speeds <40 km/h. A similar design process would work for the approaches to bridges on forestry roads; however, due to the industrial nature of forestry roads the grade differential will likely be larger. To adopt a speed-limit-based standard for grade differential at bridge crossings, further analysis would be required.

As discussed, it is important to determine the worst-case vehicle that will navigate a road. For clearance issues this can be accomplished by determining a design vehicle's break-over angle and then calculating a $K_{vehicle}$. From the survey it was found that a drop-deck low-bed with a minimum clearance of 76 mm would require a K value of 5.09 to avoid hang-up (Table 6). Minimum crest curve K values specified by the British Columbia Ministry of Transportation (2007b) are less than this, and will potentially lead to hang-up issues. While some damage to a gravel road surface due to dragging may be acceptable, such damage is not acceptable at bridges. Therefore, the K value for crest curves at bridge approaches should be increased to accommodate low-clearance vehicles.

Table 6. Minimum $K_{vehicle}$ values for design vehicles.

Design vehicle	Vertical clearance [a] (m)	Wheelbase L [b] (m)	Break-over angle [c] (°)	Max. grade break for vehicle [c] (%)	Minimum K-vehicle value [d] ($K_{vehicle}$)
Tractor	0.54	6.20	19.83	36.07	0.17
Trailer					
WB-19	0.79	12.00	15.04	26.87	0.45
WB-20	0.79	12.40	14.52	25.90	0.48
LLT	1.00	7.55	29.67	56.98	0.13
5-axle off-highway logging truck trailer	1.00	10.85	20.89	38.16	0.28
Tridem tractor / tridem trailer low-bed					
Option 1 (lowest clearance)	0.08	12.46	1.40	2.45	5.09
Option 2	0.10	12.46	1.87	3.26	3.82
Option 3	0.18	12.46	3.27	5.72	2.18
Option 4	0.30	12.46	5.60	9.81	1.27

[a] Clearance = vertical distance between vehicle chassis and road or bridge deck (m).

[b] L = wheelbase (m) = horizontal distance between the turning centre at front and rear of vehicle (tractor or trailer unit).

[c] See Figure 3.

[d] K_{design} should be greater than $K_{vehicle}$, in order to avoid hang-up. See Figure 4.

Alternatives to Typical Bridge Approach Alignment

In cases where the location and approaches to a bridge on a forestry road are limited by topography and geology, alternatives to typical design practice must be considered.

One option, when material and economics allow, is to widen the bridge deck or flare the ends of the bridge deck. This alternative permits the use of shorter horizontal tangents because the vehicle can complete the curve tracking on the bridge. A widening of the bridge deck by 608 mm can reduce horizontal tangents by as much as 9 m (Table 2). This is also illustrated in Table 3 which shows a 5 m tangent length reduction requires an average increase in deck width of 0.49 m for a 15 m curve radii and 90° curve path. Widening works well with log stringer bridges where materials are readily available and crossing spans are short; examples can be found in the *Log Bridge Construction Handbook* (Nagy et al. 1980). Flaring works well for concrete deck bridges and can be incorporated as part of the initial design, or once a problem has been identified (e.g., Figure 14).

A second option for reducing tangent lengths is to skew the bridge alignment. Bridges are typically designed at right angles to stream direction in order to reduce overall bridge length. However, aligning the bridge like this may not be the best option if it will result in high construction costs due to large fill slopes, retaining walls, or rip rap embankments. In these situations, a skewed bridge may provide a better alternative. For example, a 6-m reduction in tangent length is achieved when turning paths are reduced from 90° to 45° for a tridem tractor / tridem trailer low-bed on a 15-m-radius curve (Table 2). Analysis and professional judgement would be required to determine if the extra length of a skewed bridge would incur high construction costs relative to a typical bridge alignment.

Another option that should be considered for alternatives to a typical approach design is a reduction in vehicle horizontal clearance requirements, along with accepting a higher risk of damage to components of the bridge such as delineator signs and guardrails. By reducing the clearance requirements the risk of off-tracking, driver error or maintenance equipment, such as graders, causing damage to guardrails and delineator signs increases. To reduce the frequency of sign damage, the design can include a provision for delineators that move or bend when contacted by a vehicle. One method used for this purpose is to connect the delineator to the guardrail with a flexible piece of 25-mm-diameter cable. The cable allows the delineator to be knocked over by a vehicle, and then it springs back into place. Similarly, spring-loaded delineators are available that function in the same way (Figure 15). Accepting a reduced horizontal clearance envelope and a higher risk of damage to delineator signs and guardrails does not allow the design professional to reduce user safety. Bridges with tight alignment should always have adequate signage indicating the upcoming conditions and requiring drivers to slow down.

Figure 14. The end panel on Bridge CK-2133, located at KM 18.5 on the West Harrison FSR, is flared due to tight horizontal alignment. The guardrails were replaced in February, 2015.

Figure 15. A spring-mounted delineator on a bridge in northeast Alberta.

7. CONCLUSIONS

A one-size-fits-all approach to bridge approach alignment design on forestry roads is not practical, especially as there are significant differences between mainline and secondary roads. Defaulting to the most conservative design vehicle or recommended tangent for bridge approach alignment is not efficient for in-block roads or roads at the end of a network where traffic is minimal and/or slow moving. Often terrain dictates bridge and road location, and constructing long, horizontal tangents is cost prohibitive. In these situations, experience and professional judgement must be used to develop a solution. Solutions may include reduced design speeds, designing specifically for vehicles that will travel the road, increasing risk/damage tolerance, or using an alternative to typical bridge alignment. As part of the design process, designers should take into consideration expectations associated with the bridge's current and future use, loading, local geography, vehicle type, hydrology, constructability, and the economics of developing a safe crossing. Where applicable, accepted practice, standards, and regulations should be followed; in their absence professional judgement must be used. When deviating from accepted practice, standards, or regulations, it is the design professional's responsibility to provide documented justification as part of the necessary due-diligence.

Following in-depth interviews with bridge designers, and with British Columbia Ministry of Transportation and Infrastructure and FLNRO staff, and after calculating minimum required horizontal and vertical approach tangents for various design vehicles, it is apparent that a standardized process for designing approach alignments to bridges on forestry roads is needed. A standardized process must take into consideration the industrial nature of forestry roads while ensuring the safety of all road users. Bridges built to standards outlined in the *Geometric Design Guide for Canadian Roads* (Transportation Association of Canada 1999) or the *BC Supplement to TAC Geometric Design* Guide (British Columbia Ministry of Transportation 2007a,b,c) will result in approach alignment that may be impractical or too costly for forestry road conditions. At the same time, there are many different classes of forestry roads (mainlines, in-block roads, spur roads, etc.) and a one-size-fits-all approach to alignment design is not efficient.

Design Distinctions for the Interior and Coastal Areas of British Columbia

FPInnovations was requested to review whether distinctions exist between coastal and interior alignment design vehicles. Larger timber in the coastal region, such as northern Vancouver Island, requires larger trucks and equipment to maintain effective operations. For example, northern Vancouver Island has a population of "fat" off-highway logging trucks which can transport up to 65 m^3 (Webb 2000) of timber versus typical highway truck configurations which typically do not exceed loads of 40 m^3 (Jokai 2006). Additionally, the larger coastal timber requires larger yarders than found in the interior, and subsequently larger off-highway low-beds and other specialized transport equipment to move them between settings.

Based on the survey results and in-depth conversations with FLNRO Engineering Branch staff, FPInnovations found, that designers in the interior and coast are using a common design vehicle for approach road alignment design. Of the nine survey respondents, four currently use the WB-19 for bridge approach alignment design (Appendix A). The four survey respondents using the WB- 19 design vehicle are known to design bridges throughout the province. Additionally, conversations with FLNRO Engineering Branch staff revealed that on the coast and southern interior the WB-19 is specified for design of bridge approach alignment (Appendix C). This includes designs in the northern Vancouver Island area, where the WB-19, with a 500-mm clearance envelope, was decided upon after FLNRO staff measured various off-highway configuration vehicles and found the WB-19 with clearance envelope to be sufficient for design purposes. Similarly, the south interior specifies using a WB-19 with 500 mm clearance envelope. To further support the suitability of the WB-19 as an accurate design vehicle, it would be beneficial to review real-world vehicle configurations, and objectively compare these with the WB-19.

8. RECOMMENDATIONS

Bridge Alignment Design

This section presents FPInnovations' recommended minimum standards for bridge approach alignment design on mainline and secondary forestry roads. These standards, which are intended as a default, specify design vehicles, speed, and recommended horizontal and vertical alignments. Additional factors that should be taken into consideration for designing approach alignment include user safety, construction safety, local geography, hydrology, life cycle costs, vehicle loading, current and expected use, and alternatives to standard bridge approach alignment. Economics and practicality may require some compromises or trade-offs; but never at the expense of user safety.

Vertical Alignment

FPInnovations' recommendations for vertical bridge approach alignment include continued use of the vertical alignment controls specified in the *Engineering Manual* (Engineering Branch 2013) and the low-volume roads chapter (Section 500) in the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation 2007b), in addition to vehicle K values specified in Table 6 of this report. The *Engineering Manual* specifies a 15-m vertical approach tangent, which allows for smooth transition onto the bridge with a maximum longitudinal bridge grade of 4%; this standard should be used as the default vertical alignment control. If these tangents are not possible, the break-over angle method, or the $K_{vehicle}$ method of analysis, should be used to determine if vertical approach alignment is appropriate. For bridges designed on a crest curve, see the criteria for minimum K values of the approach crest curve in Tables 6, 7, and 8. A bridge should not be designed within a sag curve; however, it may be designed tangent to a sag curve as recommended in the alignment chapter (Section 300) in the *BC Supplement to TAC Geometric Design Guide* (British Columbia Ministry of Transportation and Infrastructure 2007a).

Mainline Roads

FPInnovations recommends that bridge designers use a WB-19 design vehicle with a 500-mm clearance envelope (Figure 16, Table 7) for designing bridge approach alignment on mainline forestry roads.

The WB-19 has been selected because it represents the host of large vehicles that navigate British Columbia's diverse forestry road network, such as large off-highway configuration logging trucks, tridem drive / tridem trailer low-beds, specialty off-highway configuration low-beds, and other flat-deck style trailers. The 500-mm clearance envelope is larger than originally analyzed by FPInnovations, however it allows for the majority of large off-highway logging trucks, such as those common to northern Vancouver Island, and low-beds to safely navigate bridge crossings on mainline forestry roads. Additionally, the design vehicle clearance, for the purpose of determining $K_{vehicle}$, has been set at 76 mm.

The WB-19 has the added benefit of familiarity and acceptance throughout the province. Currently, many road and bridge designers are using the WB-19 vehicle to approximate low-beds, with some designers incorporating a clearance envelope in their designs to accommodate “unknown” vehicles that may travel the road. Additionally, this type of design vehicle will assist other resource industries, such as oil and gas, or mining, where roads are built with the intention of eventually being turned over to FLNRO.

The assumptions for using this design vehicle are that roads will have speeds >30 km/h, and will have curve radii that reflect this speed as outlined in the *Engineering Manual* (Engineering Branch 2013). When deviating from applicable design standards, additional scrutiny and professional judgement will be required to ensure the safety of the bridge users, and justification for the deviations must be documented and provided as part of the design.

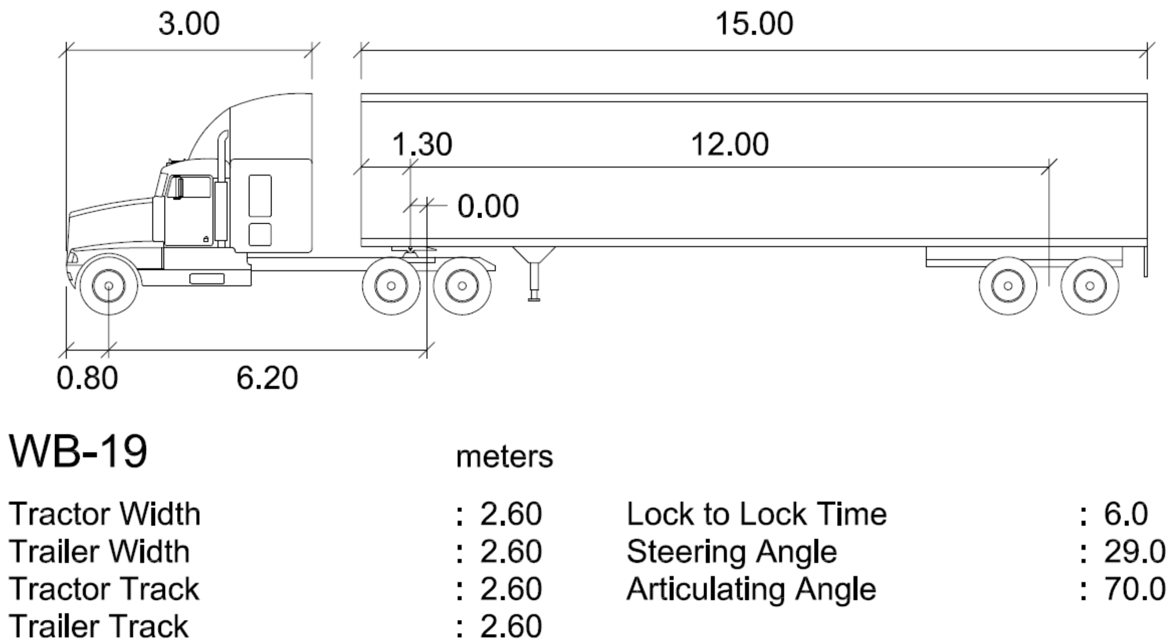


Figure 16. Schematic of the recommended design vehicle for designing bridge approaches on mainline forestry roads: the WB-19 with a 500-mm clearance envelope

Table 7. Recommended minimum horizontal tangent lengths for bridges on mainline forestry roads in British Columbia: WB-19 design vehicle with a 500-mm clearance envelope [a,b,c,d]

Bridge deck width	Recommended minimum horizontal tangent length (m)					
	0 to 45° approach curve		45 to 90° approach curve		>90° approach curve	
	Min. 35-m radius	Min. 100-m radius	Min. 35-m radius	Min. 100-m radius	Min. 35-m radius	Min. 100-m radius
4268 mm	16	10	17	5	18	5
4879 mm	10	5	11	5	12	5

[a] Avoid bridges in sag curves.
[b] Design vertical bridge approach tangent lengths ≥15 m, unless otherwise specified by the Engineer of Record / Coordinating Registered Professional.
[c] Design approach grades at 4% maximum, aligned with bridge longitudinal grade to allow smooth transition.
[d] Design bridge approach crest curve K values >7.64 or grade break <2.5% at the bridge when a vertical tangency of 15 m is not practical.

Secondary Roads

Highway configurations

FPInnovations recommends that bridge designers use a highway-configured logging truck (Figure 17, Table 8) as the design vehicle for bridge approach design on secondary roads where travel speeds are between 20 and 30 km/h.

FPInnovations recommends this vehicle because it requires less conservative approach alignment than the WB-19, and because it is more efficient for designing bridge approaches on road networks located beyond the reach of low-beds. An example is secondary roads that branch off of a mainline to access several cut blocks but do not go beyond. Less conservative alignment requirements also allow bridge approach designs to conform to the natural topography of the site, which can reduce the overall cost of the bridge. This design vehicle can represent logging trucks or flat-deck trailers, which are often used to deliver material or equipment. Because this vehicle is an envelope vehicle, designers still have a responsibility to confirm that all vehicles likely to travel the road can safely navigate that road’s bridges.

The highway configuration design truck is based on dimensions outlined in FPInnovations’ *B.C. Log Hauling Configurations: Maximum Weights and Dimensions Guide* (Jokai 2006). The vehicle was assumed to be a tandem tractor / pole trailer configuration with an overall length of 23 m. A 3-m front and a 5-m rear overhang were incorporated into the design vehicle to account for load sweep. These dimensions also meet standards presented in the *Commercial Transport Procedures Manual* (British Columbia Ministry of Transportation and Infrastructure 2014b). Note that the minimum crest K value for this vehicle is 3, which allows for tighter vertical alignment at the bridge approach.

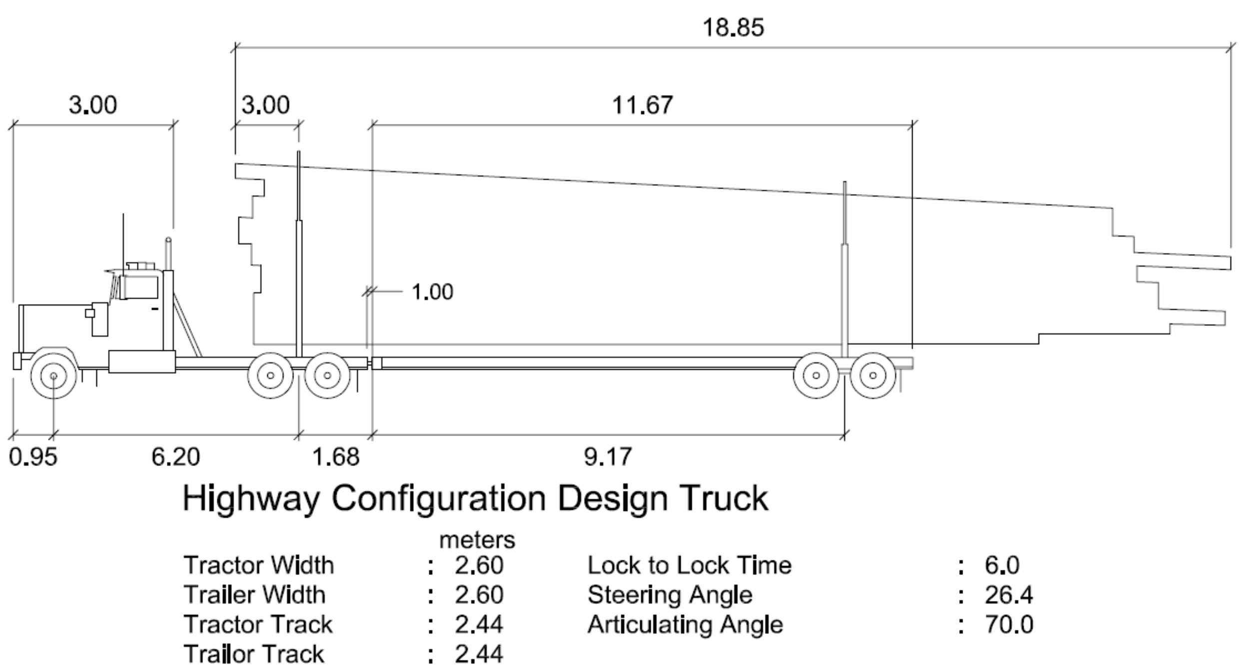


Figure 17. Schematic of the recommended design vehicle for designing bridge approaches on secondary forestry roads: the highway configuration log truck.

Table 8. Recommended horizontal minimum tangent lengths for bridges on secondary forestry roads in British Columbia: highway configuration design truck [a,b,c,d]

Bridge deck width	Recommended minimum horizontal tangent length (m)											
	0 to 45° approach curve				45 to 90° approach curve				>90° approach curve			
	Min. 15-m radius		Min. 35-m radius		Min. 15-m radius		Min. 35-m radius		Min. 15-m radius		Min. 35-m radius	
	400-mm guardrail clearance (m)	Min. guardrail clearance (m)	400-mm guardrail clearance (m)	Min. guardrail clearance (m)	400-mm guardrail clearance (m)	Min. guardrail clearance (m)	400-mm guardrail clearance (m)	Min. guardrail clearance (m)	400-mm guardrail clearance (m)	Min. guardrail clearance (m)	400-mm guardrail clearance (m)	Min. guardrail clearance (m)
4268 mm	17	13	11	7	20	16	12	7	21	17	12	7
4879 mm	11	9	5	5	14	12	6	5	16	13	6	5

[a] Avoid bridges in sag curves.

[b] Design vertical bridge approach tangent lengths ≥10 m unless otherwise specified by the Engineer of Record / Coordinating Registered Professional.

[c] Design approach grades at 4% maximum, aligned with bridge longitudinal grade to allow smooth transition.

[d] Design bridge approach crest curve K values >3 or grade break <5% at the bridge when vertical tangency of 10 m is not practical.

Planning Tools

It is recommended that the FLNRO's *Engineering Manual* (Engineering Branch 2013) be updated to specify a broader range of bridge approach tangents based on various turning paths and design vehicles. This information could be presented as a default minimum standard that would protect the public interest and user safety, but allow bridge designers the flexibility to choose the tangent and vehicle combinations that best reflect the site conditions. This would place responsibility onto the Engineer of Record and Coordinating Registered Professional for justifying their decisions.

Additionally, an updated *Engineering Manual* would result in field staff having better direction when laying out and surveying bridge sites; the need to make adjustments to field layout following the CAD process would then be minimal. Better synchronizing of the field and office phases of planning would reduce the need for costly rework, and allow for a more standardized design process across the province.

Professional Responsibility

Ultimately the Coordinating Registered Professional or Engineer of Record is responsible for the bridge approach design, and for ensuring user safety, structure location, and vehicle navigability, and for ensuring that expected costs are acceptable. The recommendations provided in this report are intended as minimum default standards. As discussed, there are many factors that affect bridge approach alignment and it is up to the design professional to use judgement when determining whether or not to follow the standards. Often, compromises or trade-offs are required to construct a forestry road efficiently and avoid excessive costs. However, compromises must not affect user safety. When deviating from accepted practices, standards, or regulations, the professional must, as part of the overall design package, justify and document the reasons for the deviations, and the user or client must be made aware of the deviations.

Future Works

Results in this report have been drawn largely from the commentary of designers. In order to provide objective and quantifiable data in support of a design vehicle and minimum horizontal and vertical approach tangents for forest bridge approach design, further work is needed. It is recommended that future works include the following:

1. Conduct a survey and measure equipment transport vehicles (low-beds) and logging trucks used by the forest industry across the province. This will provide an objective assessment of design vehicle suitability, and assist in ascertaining if any regional differences should be addressed.
2. Compare the L-150 and L-165 design logging truck configurations with actual logging truck measurements to determine how representative these are as models for the purposes of horizontal and vertical curve design.
3. Assess the accuracy of use of horizontal and vertical alignment design tool modelling, such as AutoTURN, through evaluating theoretical results against real-world vehicle configurations by:
    a. comparing AutoTURN simulations with real world off-tracking results
    b. obtaining/generating as-built survey records of bridges with restricted approach alignment, and use AutoTURN to model design vehicles navigating these bridges
    c. recording the tracking of large vehicles navigating restricted approach alignment using a UAV and comparing with AutoTURN simulations
    d. assessing parameters that designers need to be aware of which effect vehicle tracking, and may influence the clearance envelope. For example, some assessment of the sensitivity of driver's in-

fluence on off-tracking; how much do road approach barriers of other visual aids influence driver behavior that could be used to have vehicles track as designed?

e. involving AutoTURN software developers in discussing simulation accuracy.

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10. APPENDIX A – SURVEY: SUMMARY OF PARTICIPANTS AND RESPONSES

	Bridge design company								
	Allnorth Consultants Ltd.	Calibre Bridge & Design Ltd.	Chartwell Consultants Ltd.	DWB Consulting Services Ltd.	McElhanney	Onsite Engineering Ltd.	Stonecroft Project Engineering Ltd.	TDB Consultants Inc.	SNT Engineering Ltd.
Location	Prince George	Campbell River	North Vancouver	Prince George	Prince George & Terrace	Campbell River & Salmon Arm	Campbell River	Prince George	Nelson
Bridge designer	Don Williams, P.Eng.	Greg Honeysett, P.Eng.	Lindsey McGill, P.Eng., RPF	Dave Holland, P.Eng.	Chris Grant, P.Eng. & Chris Houston, P.Eng.	Michael Foster, P.Eng.	Brad Beaton, A.Sc.T.	Christina Hutchinson, P.Eng.	Les Thiessen, P.Eng.
Design manuals	*Engineering Manual* (Engineering Branch 2013) & *Geom. Design Guide for Cdn. Roads* (TAC 1999) (incl. supplements)	*Engineering Manual* (Engineering Branch 2013)	*Engineering Manual* (Engineering Branch 2013)	*Engineering Manual* (Engineering Branch 2013)	*Engineering Manual* (Engineering Branch 1999, 2013)	*Engineering Manual* (Engineering Branch 2013) & *Geom. Design Guide for Cdn. Roads* (TAC 1999) (incl. supplements)	*Engineering Manual* (Engineering Branch 2013)	*Engineering Manual* (Engineering Branch 1999, 2013)	*Engineering Manual* (Engineering Branch 2013)
Design aids	AutoCAD (AutoTURN)	AutoCAD (AutoTURN)	AutoCAD (AutoTURN)	AutoCAD (AutoTURN)	AutoCAD (AutoTURN)	Path Tracker	AutoCAD (AutoTURN)	n/a	Path Tracker
Typical design vehicles	Tractor / low-bed trailer	L-165 & WB-19	WB-19	Tridem tractor / tridem low-bed trailer	WB-15 or WB-20	WB-19 (highway vehicles); L-165 & TS-7 (off highway application)	WB-19	L-100	WB-18

	Bridge design company								
	Allnorth Consultants Ltd.	Calibre Bridge & Design Ltd.	Chartwell Consultants Ltd.	DWB Consulting Services Ltd.	McElhanney	Onsite Engineering Ltd.	Stonecroft Project Engineering Ltd.	TDB Consultants Inc.	SNT Engineering Ltd.
Reason for selection of design vehicle	Provides a worst-case scenario for off-tracking.	WB-19 used to simulate low-beds on mainline roads. L-165 used for designing in-block roads or roads with alignment constraints.	WB-19 used to simulate low-beds on mainline roads. Once off mainline, design vehicle depends on what contractor is using.	The tridem tractor / tandem low-bed provides the worst-case for off-tracking.	WB-19 & WB-15 used for tracking purpose unless otherwise specified by client. These vehicles typically encompass most low-beds for tracking purposes. They include a 500-mm buffer to account for infrequent travel by larger vehicles.	WB-19 used for highway or mainline road applications. The L-165 or a TS-7 vehicle used for off-highway and in-block roads.	Does not believe in “one-size-fits-all approach”. WB-19 used for mainlines because it simulates most highway low-bed configurations. Depending on the contractor, they have many other low-beds they design for, for in-block and off-highway applications.	L-100 vehicle is specified in contract documents.	Used to simulate low-beds on forestry roads at front end of the road network where low-bed traffic is anticipated.
Typical horizontal and vertical tangents on/off the bridge	n/a	10-m vertical & horizontal (when practical)	n/a	10-m vertical (typical) & 30-m horizontal (ideal)	10-m vertical & 30-m horizontal (where practical)	5-m vertical & horizontal (ideal)	6-m vertical & horizontal (where practical)	5-m vertical & 10-m horizontal	More concerned with ability of vehicle to track on to the bridge
Typical design speed for bridge approach	50 km/h	20 to 50 km/h (site dependent)	n/a	20 km/h (minimum)	20 km/h (minimum)	30 km/h	30 km/h on mainlines & 10 km/h on spur roads	40 to 50 km/h on mainlines and 20 km/h on spur roads	n/a

	Bridge design company								
	Allnorth Consultants Ltd.	Calibre Bridge & Design Ltd.	Chartwell Consultants Ltd.	DWB Consulting Services Ltd.	McElhanney	Onsite Engineering Ltd.	Stonecroft Project Engineering Ltd.	TDB Consultants Inc.	SNT Engineering Ltd.
Additional notes	Mainline approach speeds can be >50 km/h.	Has found AutoCAD to be conservative when determining curve radii and approach tangents. Can be changed to fit in field conditions.	Reduce design speeds as appropriate, based on approach curve and terrain. Has found that skewed crossings sometimes provide a more cost-effective solution. Has found that industry clients are willing to accept more risk and do not account for 400-mm guardrail clearance.	Rule of thumb for horizontal approach curve is one truck length. Have found that contractors sometimes grade in a super-elevated curve. Typically the vertical curve is more limiting than the horizontal in respect to the topography.		On the Coast, clearance for bridge rails etc. not provided; Southern Interior provides this information.	May choose to widen deck on log stringer bridges to allow for off-tracking. FLNRO specs higher than with private clients who are willing to accept more risk.		For roads further back in the system where low-beds are not anticipated, will design based on a logging truck. Often have short wide spans to accommodate turning on the bridge deck. Also commonly use flared bridge panels on ends.

11. APPENDIX B – OFF-TRACKING RESULTS

Curve path and design vehicle	Steering track width (m)	Trailer track width (m)	A (m)	C (m)	B (m)	D (m)	X (m)	Effective length – L (m)	Off-tracking (m)	Maximum swept path / road width (m)	AutoTURN required road width (m)
15 m-radius curve through 90°											
5-axle off-highway long-load logging truck (LLT) (L series vehicles)	2.44	2.44	5.90	0.32	6.59	1.60	5.95	10.77	3.70	6.14	6.19
L-100	2.44	2.60	5.41	-2.29	6.71	0.00	0.00	8.31	2.24	4.84	5.86
L-150	2.95	2.95	5.41	-2.29	6.71	0.00	0.00	8.31	2.24	5.19	5.96
L-165	2.95	2.95	5.41	-2.29	6.25	0.00	0.00	7.94	2.05	5.00	5.83
Tractor/semitrailer combinations (WB series vehicles)											
WB-19	2.60	2.60	6.20	0.00	12.00	0.00	0.00	13.51	6.13	8.73	7.48
WB-20	2.60	2.60	6.20	0.00	12.40	0.00	0.00	13.86	6.60	9.20	7.70
Low-bed											
Tridem tractor / tridem trailer	2.44	3.05	6.80	0.00	12.46	0.00	0.00	14.20	7.13	10.18	8.08
35 m-radius curve through 90°											
5-axle off-highway long-load logging truck (LLT) (L series vehicles)	2.44	2.44	5.90	0.32	6.59	1.60	5.95	10.77	1.67	4.11	4.30
L-100	2.44	2.60	5.41	-2.29	6.71	0.00	0.00	8.31	1.00	3.60	4.51
L-150	2.95	2.95	5.41	-2.29	6.71	0.00	0.00	8.31	1.00	3.95	4.51
L-165	2.95	2.95	5.41	-2.29	6.25	0.00	0.00	7.94	0.91	3.86	4.43
Tractor/semitrailer combinations (WB series vehicles)											
WB-19	2.60	2.60	6.20	0.00	12.00	0.00	0.00	13.51	2.61	5.21	5.21
WB-20	2.60	2.60	6.20	0.00	12.40	0.00	0.00	13.86	2.75	5.35	5.36
Low-bed											
Tridem tractor /	2.44	3.05	6.80	0.00	12.46	0.00	0.00	14.20	2.88	5.93	5.66

Curve path and design vehicle	Steering track width (m)	Trailer track width (m)	A (m)	C (m)	B (m)	D (m)	X (m)	Effective length – L (m)	Off-tracking (m)	Maximum swept path / road width (m)	AutoTURN required road width (m)
100 m-radius curve through 90°											
5-axle off-highway long-load logging truck (LLT) (L series vehicles)	2.44	2.44	5.90	0.32	6.59	1.60	5.95	10.77	0.58	3.02	3.17
L-100	2.44	2.60	5.41	-2.29	6.71	0.00	0.00	8.31	0.35	2.95	3.68
L-150	2.95	2.95	5.41	-2.29	6.71	0.00	0.00	8.31	0.35	3.30	3.68
L-165	2.95	2.95	5.41	-2.29	6.25	0.00	0.00	7.94	0.32	3.27	3.66
Tractor/semitrailer combinations (WB series vehicles)											
WB-19	2.60	2.60	6.20	0.00	12.00	0.00	0.00	13.51	0.92	3.52	3.55
WB-20	2.60	2.60	6.20	0.00	12.40	0.00	0.00	13.86	0.97	3.57	3.55
Low-bed											
Tridem tractor / tridem trailer	2.44	3.05	6.80	0.00	12.46	0.00	0.00	14.20	1.01	4.06	3.78

12. APPENDIX C – DISCUSSIONS WITH FLNRO ENGINEERING STAFF: SUMMARY

Topic/question	Coastal Engineering Group (Chilliwack)	Coastal Engineering Group (Vancouver Island)	Northern Engineering Group (Prince George)	Southern Engineering Group (Kamloops)
Is a design vehicle specified? What is the design vehicle, and why?	• WB-19 with 300-mm to 500-mm clearance depending on site conditions is specified for mainline roads, and for access to communities or high-value recreation. • BCL-625 specified for blocks accessed by highway configuration trucks. • L series truck specified for off-highway conditions, but depends on the site.	• WB-19 with 500-mm clearance specified based on experience and field measurements of various off-highway configuration low-beds in the north Vancouver Island area.	• No vehicle specified for alignment purpose. • Specify the L-100 for loading.	• WB-19 with 500-mm clearance is specified for mainline roads. • Staff has measured several low-beds that frequent mainline roads, and found the WB-19 is an adequate envelope vehicle for the roads. • A 500-mm clearance provides an added buffer in the event larger vehicles, or other stakeholders, use the roads and are not familiar with crossing alignments. • Secondary road bridge approach alignment varies, and relies on professional judgement.
Are alignment criteria specified? What are the criteria and why?	• Best practice is *FS Bridge Design & Const. Manual* (Engineering Branch 1999), 10-m horizontal tangent and 10-m vertical tangent. • Often this not possible on steep roads with tight curves. • Often allow designers	• The 15 m specified in the *Engineering Manual* (Engineering Branch 2013) is ideal; however, alignment is site dependent. • Main concern is confirming the WB-19 can safely navigate the bridge.	• Recommend using 15-m horizontal and 15-m vertical tangents specified in the *Engineering Manual* (Engineering Branch 2013). • Typically rely on professional judgement, and do	• Minimum horizontal and vertical tangents as per *FS Bridge Design & Const. Manual* (Engineering Branch 1999). • Recommended horizontal alignment based on WB-19 with 500-mm clearance

Topic/question	Coastal Engineering Group (Chilliwack)	Coastal Engineering Group (Vancouver Island)	Northern Engineering Group (Prince George)	Southern Engineering Group (Kamloops)
	to reduce tangents, and flare or widen bridges to accommodate off-tracking. • Vertical curve K values are 12 for crest and 13 for sag curves on bridge approaches.		not strictly hold designers to the tangents in the *Engineering Manual* (Engineering Branch 2013).	either side. • Recommend providing a LVC on bridge approaches as long as vehicle length, or 20-m minimum for vertical approach alignment.
Observations	• Terrain dictates bridge approach alignment; often not possible to achieve horizontal tangents of 10 m. • Designing bridges with flared end panels, or widened decks is a common method of mitigating tight approach alignment.	• K-value and "hang-up" are serious concerns. • Tail sweep is also a significant concern for off-highway trucks.	• Multiple stakeholders use the roads, and they often have large vehicles that bridge approaches were not designed to accommodate. • New vehicles are becoming longer, and wider, which pushes the design envelope of legacy bridges.	• There is a disconnect between crossing design and how the bridge performs in the field. • Would like to see designers on site during construction, and when bridge is operational, to get a better understanding of how the design affects the users. • Standardization would help mitigate some of the disconnect, and provide an educational opportunity for designers to start thinking about approach alignment early in the design process.

Head Office

Pointe-Claire

570, Saint-Jean Blvd

Pointe-Claire, QC

Canada H9R 3J9

T 514 630-4100

Vancouver

2665 East Mall

Vancouver, BC.

Canada V6T 1Z4

T 604 224-3221

Québec

319, rue Franquet

Québec, QC

Canada G1P 4R4

T 418 659-2647

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