INVESTIGATION OF A 9-AXLE CONFIGURATION FOR LOG-HAULING IN BRITISH COLUMBIA

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Abstract
This paper gives an overview of preliminary evaluations undertaken for potential 9-axle configurations for hauling logs on steep forest roads. Two versions of a Tridem truck/ quint-axle full trailer were investigated with either a tandem-tridem or tridem-tandem axle groups on the trailer. In order to meet acceptable highway performance for these configurations, a roll-coupled hitch will be required particularly to ensure acceptable stability and dynamic performance. These configurations were also evaluated for their off-highway performance and had similar manoeuverability to existing quad-axle trailers when the drawbar was shortened to its recommended off-highway operating position. And hence requires an adjustable drawbar to ensure good highway and off-highway performance. The quint-axle trailer can be loaded on a longer wheelbase truck for hauling the trailer back to the bush when empty allowing the truck to climb favorable grades of 25% or greater. However the overall length and overhang are higher than with existing configurations, which will require additional regulatory allowances.

Keywords: High Productivity Vehicles, Modelling, Performance Based Standards.

1. Introduction

9-axle B-trains for log hauling have been approved for use on several routes in British Columbia (BC), a result of several years of research and testing by the BC forest industry (Parker, Bradley, Sinnett 2014). Approved 9-axle configurations have vehicle specifications that have been shown to meet vehicle performance standards while reducing infrastructure impacts per tonne of payload hauled by at least 5% (Bradley, 2017). The introduction of 9-axle B-trains enables the BC Industry to improve transport efficiency and improve their global competiveness. However, the 9-axle B-train's suitability is limited to highways and forest roads with good horizontal and vertical alignment (with road grades less than 10%). Much of the BC forest road network is unsuitable for running B-trains due to the increased off-tracking and reduced uphill grade ability of these configurations.

FPInnovations has initiated research to investigate alternative 9-axle configurations that can operate on the narrow, winding, and steep roads typically found throughout BC and thereby extend the productivity benefits of 9-axles to these areas. One of the most productive configurations currently in use on steep forest roads in BC is the 8-axle tridem truck/ quad-axle full trailer (also known as a wagon). Therefore a 5-axle (quint-axle) full-trailer coupled to a tridem truck was selected as a potential configuration to investigate for its operational suitability. This configuration was previously approved for hauling ore in a northern BC application in 2009 (Figure 1).One of the main benefits of this configuration was its ability to be stacked on the truck during the empty phase of the haul (Figure 2), a key requirement for hauling on steep forest roads. It is important to note that any new configuration must meet the vehicle performance standards prescribed by Commercial Vehicle Safety and Enforcement (CVSE)[1], as well as demonstrate a reduction in infrastructure impact of at least 5%. FPInnovations is therefore exploring options that will meet these requirements.

Objective: To investigate 9-axle configuration options suitable for operating on steep forest roads while maintaining safe highway performance.

Figure 1 – Tridem truck/ quint-axle full trailer hauling ore

[1] Branch of the BC Ministry of Transportation and Infrastructure (BCMOTI)

Figure 2. Quint-axle trailer(ore) stacked on truck when empty

2. Methodology

Two potential 9-axle arrangements were investigated:

- Tridem truck/ tandem-tridem quint-axle full trailer (Figure 3)
- Tridem truck/ tridem-tandem quint-axle full trailer (Figure 4)

Each configuration's performance was evaluated using either a typical non-roll coupled hitch or a roll-coupled hitch. A roll-coupled hitch was developed to improve dynamic performance of pony and full trailers (Parker, Sinnett 2010). Performance was compared relative to existing tridem truck/ quad-axle trailers which are currently widely used for accessing steep forest roads (Figure 5)

The load positions were estimated for each option with 5 m logs assuming a block load density of 500 kg/m^3 and a bunk width of 2.9 m. The wider bunks were proposed to reduce load heights and improve stability. The quad-axle trailer was evaluated using standard 2.6 m bunks.

For each configuration option highway and off-highway axle spacings were investigated; while off-highway, the inter-axle spacing can be reduced between the drive axles and dolly to improve manoeuverability for narrow forest roads. The proposed configuration dimensions and axle loads are summarized in Table 1. The inter-axle spacing from the drives to the tandem dolly is approximately 0.5 m greater than the minimum 5.5 m TAC requirement to improve dynamic performance. The truck wheelbase is also increased to 7.11 m to facilitate loading of the longer wheelbase trailer on the truck when empty. The inter-axle spacing between the drives and dolly can be potentially shortened to 4.5 m when off-highway through an adjustable drawbar which would improve off-highway manoeuverability.

In addition, the ease of loading the empty trailer on the truck was also assessed. The ability to load the complete trailer on the truck as currently accomplished with existing quad-axle trailers is critical for empty manoeuverability and grade-ability when climbing grades of 25% or greater

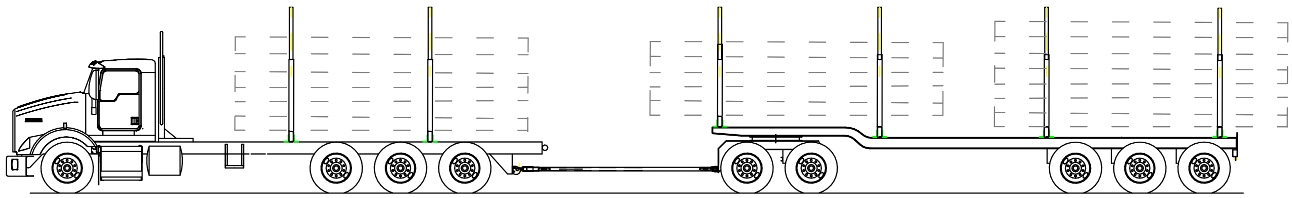

Figure 3 – Tridem Truck/ tandem-tridem quint-axle full-trailer

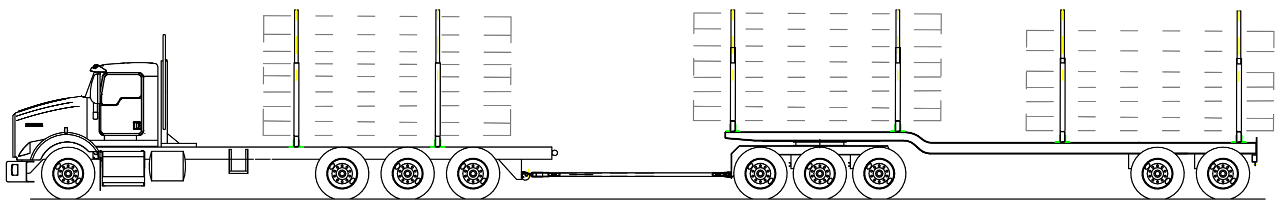

Figure 4 – Tridem Truck/ tridem-tandem quint-axle full-trailer

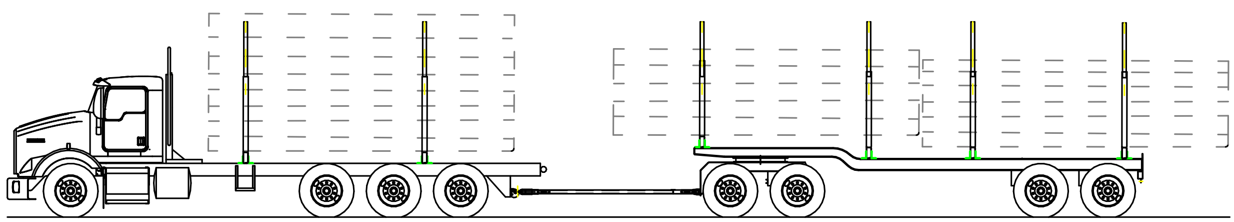

Figure 5 – Tridem Truck/ tandem-tandem quad-axle full-trailer

Table 1 – Summary of proposed configuration specifications

Parameter	Tandem-Tridem Trailer		Tridem-Tandem Trailer		Tandem-Tandem Trailer
	Highway mode	Bush mode	Highway mode	Bush mode	Highway& Bush mode
Dimensions (m)					
Truck wheelbase	7.11				6.60
Trailer wheelbase	7.76				6.50
Hitch offset	2.60				2.60
Axle spacing last drive axle to first dolly axle	6.00	4.50	6.00	4.50	5.50
Overall length	27.50	26.00	27.50	26.00	25.00
Loads (kg)					
Steering axle	7 300				6 500
Drive group	24 000				23 000
Dolly group	17 000		24 000		17 000
Trailer group	24 000		17 000		17 000

The performance of the two proposed configurations was evaluated through computer modelling using Mathworks Simulink/Simmechanics™ models for both highway and off-highway performance.

2.1 Highway performance

The following "on-highway" performance measures were evaluated against the CVSE specific performance criteria:

<u>Handling performance:</u> Three measures are typically used to evaluate handling performance at steady-state conditions. These measures were developed by the National Research Council of Canada (NRC) and have only been adopted by the province of British Columbia within Canada.
The first measure (Point #1) is the lateral acceleration where the transition from understeer to over-steer (i.e. the point where the understeer coefficient is zero) takes place. The remaining two handling measures are the understeer coefficient at 0.30 g (Point #2) and 0.15 g (Point #3). Understeer coefficient is expressed in degrees per g which represents the slope of the handling diagram. Positive and negative values indicate understeer and over-steer levels respectively. This performance measure is determined during a ramp steer manoeuvre (ramp steer rate of 2 deg/sec at steering wheel) at a forward velocity of 100 km/h. For the purposes of this paper only point #1 will be presented, where the performance requirement is to be greater than 0.2 g.

Static Rollover Threshold (SRT): This is the level of steady lateral acceleration beyond which the configuration rolls over. The measure is expressed as the lateral acceleration (in g's) at which all wheels on one side, except the steer axle, lift off the ground. Configuration performance is considered satisfactory if the static rollover threshold is greater than or equal to 0.40 g. (TAC[2] and CVSE benchmark). However, internationally a SRT of 0.35 g is considered satisfactory. Most existing BC log hauling configurations are typically between 0.35 to 0.40 gs.

Load Transfer Ratio (LTR): The load transfer ratio is defined as the ratio of the absolute value of the difference between the sum of right wheel loads and the sum of the left wheel loads, to the sum of all the wheel loads. The front steering axle is excluded from the calculations because of its relatively high roll compliance. Configuration performance is considered satisfactory if the LTR is less than or equal to 0.60 (TAC performance standard). This performance measure is evaluated during a rapid lane change manoeuvre conducted at 88 km/h, yielding lateral acceleration amplitude of 0.15 g and a period of 2.5 seconds at the tractor's steering axle.

Rearward Amplification (RA): Rearward amplification is defined as the ratio of the peak lateral acceleration at the mass centre of the rearmost trailer to that developed at the mass centre of the tractor. Configuration performance is considered satisfactory if the RA is less than or equal to 1.6, which is the current CVSE target, but the TAC performance standard is to be less than 2.0. This performance measure is evaluated in the same manoeuvre as LTR.

Friction Demand (FD): The friction demand performance measure describes the non tractive tire friction levels required at the drive axles of a tractor. Excessive friction demand is a contributing factor to jackknife and also results in excessive tire wear. Friction demand is the absolute value of the ratio of the resultant shear force acting at the drive tires divided by the cosine of the tractor/trailer articulation angle to the vertical load on the drive tires. Configuration performance is considered satisfactory if FD is less than or equal to 0.1 (TAC performance standard). This performance measure is evaluated in a 90-degree turn at a vehicle speed of 8.25 km/h. During the manoeuvre, the centre of the front steer axle tracks an arc with a 12.8-m radius (approximately a 14-m outside-wheel-path radius).

Lateral Friction Utilization (LFU): Lateral friction utilization is a measure proposed by NRC to characterize the highest level of the lateral friction utilization at the steering axle. LFU is defined as the ratio of the sum of lateral forces to the vertical load, and the peak tire/road coefficient of adhesion. The tires of a steering axle that achieves a lateral friction utilization level of 1 are said to be saturated. Configuration performance is considered satisfactory if LFU is less than or equal to 0.80 (NRC recommended performance standard). Initially this performance measure was evaluated on a high friction surface. FERIC[3] modified this measure by evaluating LFU on low friction surfaces, which are more critical for steering performance, by using low friction tire characteristics ($\mu = 0.2$). This performance measure is evaluated using the same manoeuvre as FD, but on a low friction surface.

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[2] TAC – Transportation Association of Canada (formerly known as RTAC)

[3] Predecessor of FPInnovations – In 2007 FERIC was amalgamated with two other Canadian forest industry research institutes (PAPRICAN and FORINTEK)

Low Speed Off-tracking (LSOT): Low speed off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if LSOT is less than or equal to 6.0 m (TAC performance standard). This performance measure is evaluated using the same manoeuvre as FD and LFU.

High Speed Steady State Off-tracking (HSOT): High speed off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if HSOT is less than or equal to 0.46 m (TAC performance standard). This value represents a minimal clearance of 0.15 m between the trailer tires and the outside of a 3.66-m wide conventional traffic lane when the steering axle is in the centre of the lane. This performance measure is evaluated when the vehicle is operated in a 393-m curve radius, at a speed of 100 km/h, thereby attaining a steady lateral acceleration level of 0.2 g.

Transient off-tracking (TOT): Transient off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if TOT is less than or equal to 0.8 m (TAC performance standard). This performance measure is evaluated in the same manoeuvre as LTR and RA.

2.2 Off-highway performance

In addition to the nine standard highway performance measures, the following six performance measures were also evaluated for each operating mode to evaluate off-highway performance:

Grade-ability (GA): The maximum grade (%) that the configuration can climb. This is evaluated at a coefficient of friction (μ) of 0.4 which represents the typical average for forest roads. The proposed configuration performance is for GA to be greater than or equal to 12%.

Load Transfer Ratio (LTR_{OH}): This is the same performance measure as calculated in the highway performance measures, but at a different speed and manoeuvre at a lower road friction. This performance measure is evaluated during a rapid lane change manoeuvre conducted at 70 km/h, yielding lateral acceleration amplitude of 0.20 g and a period of 3 seconds at the tractor's steering axle. The measure is evaluated at a moderate road surface friction (μ= 0.5). The proposed configuration performance is for LTR_{OH} to be less than or equal to 0.80. This is LTR level is higher than tolerated on the highway due to the reduced risk to the public on off-highway roads.

Lateral Friction Utilization (LFU_{OH}): This is the same performance measure as calculated in the highway performance measures for assessing steering performance, but at a different speed, curve and surface friction. This performance measure is evaluated in a 180-degree turn at a vehicle speed of 10 km/h. During the manoeuvre, the centre of the front steer axle tracks an arc with a 13.8-m radius (approximately a 15-m outside-wheel-path radius). The measure is evaluated at a low road surface friction (μ= 0.3). The proposed configuration performance is for LFU_{OH} to be less than or equal to 0.80 (current LFU performance standard).

Friction Demand (FD_{OH}): This is the same performance measure as calculated in the highway performance measures, but at a different speed, curve and surface friction. This performance measure is evaluated using the same manoeuvre as used for LFU_{OH}., but at a moderate road surface friction level (μ= 0.5). The proposed configuration performance is for FD_{OH} to be less than or equal to 0.15 slightly higher than the current TAC FD performance level for on-highway performance.

Low Speed Off-tracking ($LSOT_{OH}$): This is the same performance measure as calculated in the highway performance measures at the same speed, curve and surface friction as used to evaluate LFU_{OH}. The proposed configuration performance is for $LSOT_{OH}$ to be less than or equal to 5 m. This requirement is a higher standard than required on highways due to the narrow roads and high prevalence of tight switchbacks typically found on forest road networks.

Transient off-tracking (TOT_{OH}): This is the same performance measure as calculated in the highway performance measures at the same speed, curve and surface friction as used to evaluate LTR_{OH} and RA_{OH}. The proposed configuration performance is for TOT_{OH} to be less than or equal to 0.8 m, which is the same as the TAC performance standard.

3. Results and Discussion

3.1 Highway performance

Both quint-axle trailer options fail to meet the critical highway performance measures of Static Rollover Threshold (SRT), Load Transfer Ratio (LTR), and Rearward Amplification (RA) when using a non-roll-coupled hitch (Table 2). However in this non-roll-coupled condition the dynamic performance is improved relative to existing quad-axle trailers, with SRT marginally degraded and steering performance as characterized by Lateral Friction Utilization improved. The failure to meet three of the critical CVSE performance benchmarks means that a non-roll coupled version of the quint-axle trailer cannot be recommended for on-highway use in British Columbia despite its improved performance relative to existing and widely used quad-axle trailers. However a roll-coupled version of either quint-axle trailer is recommended for implementation, meeting the SRT and LTR performance benchmarks in both cases. The RA benchmark was just achieved for the tridem-tandem trailer, but was only slightly over the required performance level at 1.62 for the tandem-tridem trailer. The RA performance is essentially the same for both trailer versions and in the author's opinion the noted deviation in RA performance can be safely tolerated due to its minor deviation (0.02), but mostly due to improved level of LTR achieved with roll-coupled hitch and improved dynamic performance relative to existing quad-axle trailers. The only disadvantage of the quint-axle trailer is the increased level of low-speed off-tracking (LSOT) by approximately 1 m relative to quad-axle trailers. Despite this the quint-axle meets the LSOT performance target and has improved performance relative to 9-axle B-trains where LSOT is typically greater than 5.5 m (Parker, Bradley, Sinnett 2014). As well the tridem-tandem trailer experienced increased levels of Friction Demand which is not a safety concern, but could potentially lead to more tire wear on the dolly's tridem group.

Table 2 – Simulation Results – Highway performance

Performance Measure	Performance Standard	Tandem-Tridem Trailer		Tridem-Tandem Trailer		Tandem-Tandem Trailer
		Non-roll-coupled	Roll-coupled	Non-roll-coupled	Roll-coupled	Non-roll-coupled
Handling Performance (P1) Oversteer transition	> 0.20 g	0.334	0.344	0.331	0.343	0.336
Static Rollover Threshold	>0.40 g	**0.385**	0.407	**0.384**	0.404	**0.395**
Load Transfer Ratio	< 0.60	**0.679**	0.389	**0.654**	0.403	**0.744**
Rearward Amplification	<1.6	**1.661**	**1.620**	**1.620**	1.580	**1.920**
Lateral Friction Utilization	<0.80	0.757	0.757	0.771	0.767	**0.847**
Friction Demand	<0.10	0.073	0.073	0.095	0.095	0.071
Low-speed off-tracking	<6.00 m	4.530	4.530	4.705	4.705	3.672
High-speed off-tracking	<0.46 m	0.423	0.423	0.418	0.418	0.385
Transient off-tracking	<0.80 m	0.417	0.392	0.400	0.373	0.519

Red BOLD text indicates performance measure not met

The use of a roll-coupled hitch will enable this configuration to meet the conservative CVSE performance requirements and increase the likelihood of obtaining approval for this configuration. There are other technologies that may achieve the same result such as forced steering axles controlled electronically. However, these technologies have not progressed to the point that they can be implemented at this time in an off-highway environment. A roll-coupled hitch is currently available that has been tested in off-highway applications (forestry, oil and gas) throughout Canada (Parker, Sinnett 2010).

3.2 Off-highway performance

The off-highway performance of the quint-axle trailer was assessed for a non-roll-coupled condition since this allows improved manoeuverability on the typical narrow and winding forest roads. The roll-coupled hitch may be unlocked remotely from the driver's cab when hauling on forest roads. Despite the non-roll-coupled condition, the off-highway dynamic performance requirements (Load Transfer Ratio, Transient off-tracking) are easily achieved, even when the drawbar is retracted for improved in bush manoeuverability (Table 3). The only off-highway performance measure which was not achieved was LSOT for both quint-axle trailer versions when in the extended drawbar position. The tridem-tandem trailer version just exceeded the 5 m LSOT, when the drawbar was in the retracted bush position. The tandem-tridem trailer just achieved the required off-highway LSOT performance with the drawbar retracted, illustrating the need for an adjustable drawbar for this configuration. The increased proportion of load carried by the quint-axle trailer relative to the quad-axle resulted in a reduced level of grade ability by approximately 2%.

Table 3 – Simulation Results – Off-highway performance

Performance Measure	Performance Standard	Tandem-Tridem Trailer		Tridem-Tandem Trailer		Tandem-Tandem Trailer
		Extended drawbar	Retracted drawbar	Extended drawbar	Retracted drawbar	Standard drawbar
Gradeability	> 12%	12.93	12.93	12.58	12.48	14.66
Load Transfer Ratio	< 0.80	0.710	0.745	0.689	0.738	0.739
Lateral Friction Utilization	<0.80	0.753	0.702	0.692	0.698	0.775
Friction Demand	< 0.15	0.142	0.137	0.114	0.148	0.144
Low-speed off-tracking	<5.00 m	**5.739**	4.986	**6.058**	**5.142**	4.246
Transient off-tracking	<0.80 m	0.333	0.376	0.303	0.371	0.481

Red bold text indicates performance measure not met
All conditions non-roll-coupled

3.3 Empty trailer loading considerations

The empty tandem-tridem quint-axle trailer can be potentially stacked on a tridem truck as illustrated in Figure 6. The overall length and rear overhang exceeds what is currently permitted for quad-axle trailers, but is similar to what is permitted when the truck is equipped with a self-loader. Currently, CVSE allows an overall length of 14.5 m and rear overhang of 6.5 m when the truck has a self-loader. However there may be potential securement and wear issues on the rear tail frame, which need to be examined more closely. Preliminary discussions with manufacturers indicate that this loading arrangement can be accommodated. Other potential solutions include a retractable trailer frame to reduce the overhang when stacked on the truck, which would increase trailer tare weight as well as maintenance requirements. The placement of an empty tridem-tandem quint-axle trailer may be more easily achieved despite the tandem axles being rearward of the tail frame (Figure 7). The weight distribution for this trailer is biased more forward due to the tridem dolly. However, a loading support would be necessary on the trailer frame to support the trailer on the truck tail frame.

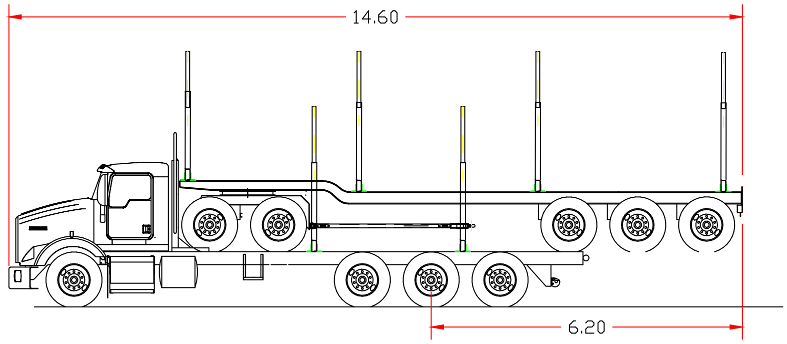

Figure 6. Empty loading – tandem-tridem quint-axle trailer

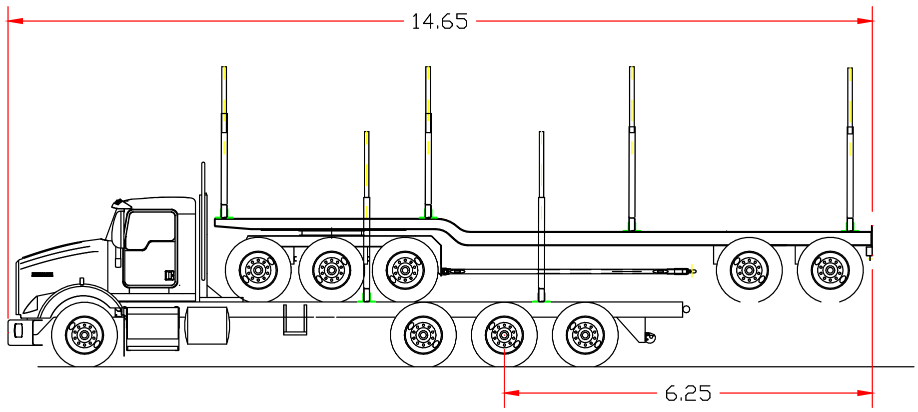

Figure 7. Empty loading – tridem-tandem quint-axle trailer

Overall the two quint-axle trailer designs with a roll-coupled hitch meet the required highway performance required to obtain approval for these configurations from CVSE. As well the off-highway performance required for operation on typical steep and narrow forest road networks can also be achieved. Further discussion with industry stakeholders and trailer manufacturers should be undertaken to ensure all practical considerations are addressed before proceeding with an application to CVSE for configuration approval.

4. Conclusions

- A tridem truck/ quint-axle full trailer is a viable option for accessing steep narrow roads typical of BC off-highway road networks and maintaining safe highway performance.

- Both tandem-tridem and tridem-tandem quint-axles were investigated with similar dynamic performance achieved for both versions. However the tridem-tandem quint-axle exhibited slightly greater levels of off-tracking and friction demand indicating potentially higher levels of tire scuffing and wear.

- The tridem truck/quint-axle full trailer can only meet the critical highway performance measures of SRT and LTR for all loading conditions with a roll-coupled hitch. The roll-coupled hitch however does not allow the RA performance measure to be achieved when loaded with 5 m logs, just exceeding the CVSE performance benchmark of 1.6. This deviation in performance can be safely tolerated given the conservatism of this benchmark and the significantly reduced LTR level achieved when roll-coupled.

- The off-highway manoeuverability of the tridem truck/quint-axle trailer is reduced relative to the quad-axle due to its increased length, but does approach acceptable levels of off-tracking when the drawbar is shortened to its recommended off-highway position (1.5 m shorter from highway position). Therefore the drawbar will need to be adjustable to accommodate these different operational modes.

- The uphill climbing grade-ability of the tridem truck/quint-axle trailer is approximately 2% less than its quad-axle counterpart. This will still allow this configuration to access relatively steep roads of up to 13%.

- The quint-axle trailer can be loaded on a longer wheelbase truck (7.11 m) for hauling the trailer back to the bush when empty allowing the truck to climb favourable grades of 25% or greater. However the overall length and overhang are higher than with tridem truck/quad-axles. Therefore increased regulatory dimensional allowances will be required.

- The loading of empty quint-axle trailers onto the truck requires further review with manufacturers to ensure the trailer can be retained securely.

- Further discussion with industry stakeholders and trailer manufacturers should be undertaken to ensure all practical considerations are addressed before proceeding with an application to CVSE for configuration approval.

5. References

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