

A Dynamic Performance Assessment of Two Log Hauling Combinations Utilizing Current Performance Measures from Two Different Regulatory Regimes

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The Canadian log hauling sector continues to investigate strategies to improve log hauling efficiency. This paper investigates the dynamic performance characteristics of two recently approved high payload configurations: the 9-axle King B-train in the province of Saskatchewan; and the 8-axle J-train in the province of Alberta. The Forest Engineering Research Institute of Canada (FERIC) is currently evaluating these configurations in terms of their operational efficiency, and safety performance. The increased load capacity and length of these configurations have safety implications which require further investigation. Standard North American performance measures, as well as selected Australian/New Zealand Performance Based Standards were used in this analysis, thereby allowing these configurations' performance to be assessed on an international perspective. Both configurations demonstrated good stability and dynamic performance characteristics, but have increased space requirements in tight turn manoeuvres. The J-train's greatest deficiency is its significant frontal out-swing of the semi-trailer in a tight turn manoeuvre, while the King B-train's greatest deficiency is its high level of off-tracking during high-speed steady state manoeuvres. The different performance measures applied in these two regulatory regimes were compared in the context of the configurations discussed in the paper. The application of performance based standards developed in the Australia /New Zealand regulatory regime would enhance the evaluation of configurations in North America.

1. INTRODUCTION

The Canadian forest industry is highly dependent on heavy trucks to transport logs from harvesting sites to mills. As the commercial timber resource has become more distant from the mills, log transportation costs have increased to the point that they represent half the total cost of supplying logs to the mills. In an effort to contain these increasing transportation costs and remain globally competitive, the forest industry has developed new log hauling configurations with increased payload capacity. Two examples of configurations with increased payload capacity are the King B-train (Figure 1) in the province of Saskatchewan, and the J-train (Figure 2) in the province of Alberta.



Figure 1. King B-train



Figure 2. Tridem drive J-train

King B-trains have been utilized in Saskatchewan over the last several years for hauling legal weights. In 2003, Weyerhaeuser Canada's Prince Albert division conducted a trial of a prototype King B-train hauling tree length logs at an increased gross combination weight (GCW) allowance of 92 500 kg under partnership agreement with Saskatchewan Highways and Transportation. Under this program the net benefits obtained from the increased payloads are shared between the province and Weyerhaeuser. In order to carry this increased payload capacity and maintain stability the axle and bunk widths needed to be increased to 3.05 m. The results of the initial trial were favourable which prompted Weyerhaeuser to investigate strategies for implementing the use of this configuration throughout their operations in Saskatchewan. As the capital cost of implementing King B-trains throughout the fleet was enormous, the concept of a transitional King B-train was introduced. A transitional King B-train utilizes existing tridem semi-trailers as either the lead or rear trailer for the remainder of its economic life, in combination with one new King B-train trailer. A second King B-train trailer would be purchased following the retirement of the original trailer. However most of the existing semi-trailers available for this conversion are equipped with 2.59 m axles and therefore the stability and dynamic performance of this configuration would not be the same as that observed for the prototype King B-train in Prince Albert.

The tridem drive J-train evolved from the need to maximize payloads during legal haul periods. The 7-axle tridem drive tractor/ tridem semi-trailer is a popular log hauling unit during winter hauling periods due to its enhanced traction capability and high GCW during the winter (3 months) of 63 000 kg. However during legal hauling periods, the GCW of this configuration is limited to 54 300 kg, a significant reduction in payload capacity. In order to maintain a favourable payload capacity with these units throughout the year, the Alberta forest industry investigated practical alternatives of adding an extra axle to this unit which could be easily removed for winter hauling. The resulting configuration involves a single axle jeep inserted between the tractor and semi-trailer, and achieves a legal GCW of 63 400 kg. This configuration is very similar to the 8-axle tandem drive J-train (with tandem jeep) which was approved for use in 2002. These J-train units allow for the transport of variable log lengths, but the insertion of the jeep and its fifth wheel location results in an increase in load height. The increased load height and its inherent stability reduction are mitigated by the use of wider 2.9 m axles on the semi-trailer which are required for winter weights.

The Forest Engineering Research Institute of Canada (FERIC) is currently evaluating these configurations in terms of their operational efficiency, and safety performance. The increased load capacity and length of these configurations have safety implications which will be investigated in this paper through the application of performance based standards.

2. METHODOLOGY

A series of simulations were conducted using the University of Michigan Transportation Research Institute (UMTRI) yaw/roll model for the two configurations (See Figure 3 for configuration weights and dimensions used in this analysis) and the following eight Transportation Association of Canada (TAC) performance measures were evaluated (Ervin, Guy 1986):

1. Static Rollover Threshold (SRT)

2. Understeer coefficient (USC) at 0.25 g lateral acceleration
3. Load transfer ratio (LTR)
4. Rearward amplification (RA)
5. Friction demand (FD)
6. Low-speed off-tracking (LSOT)
7. High-speed off-tracking (HSOT)
8. Transient off-tracking (TOT)

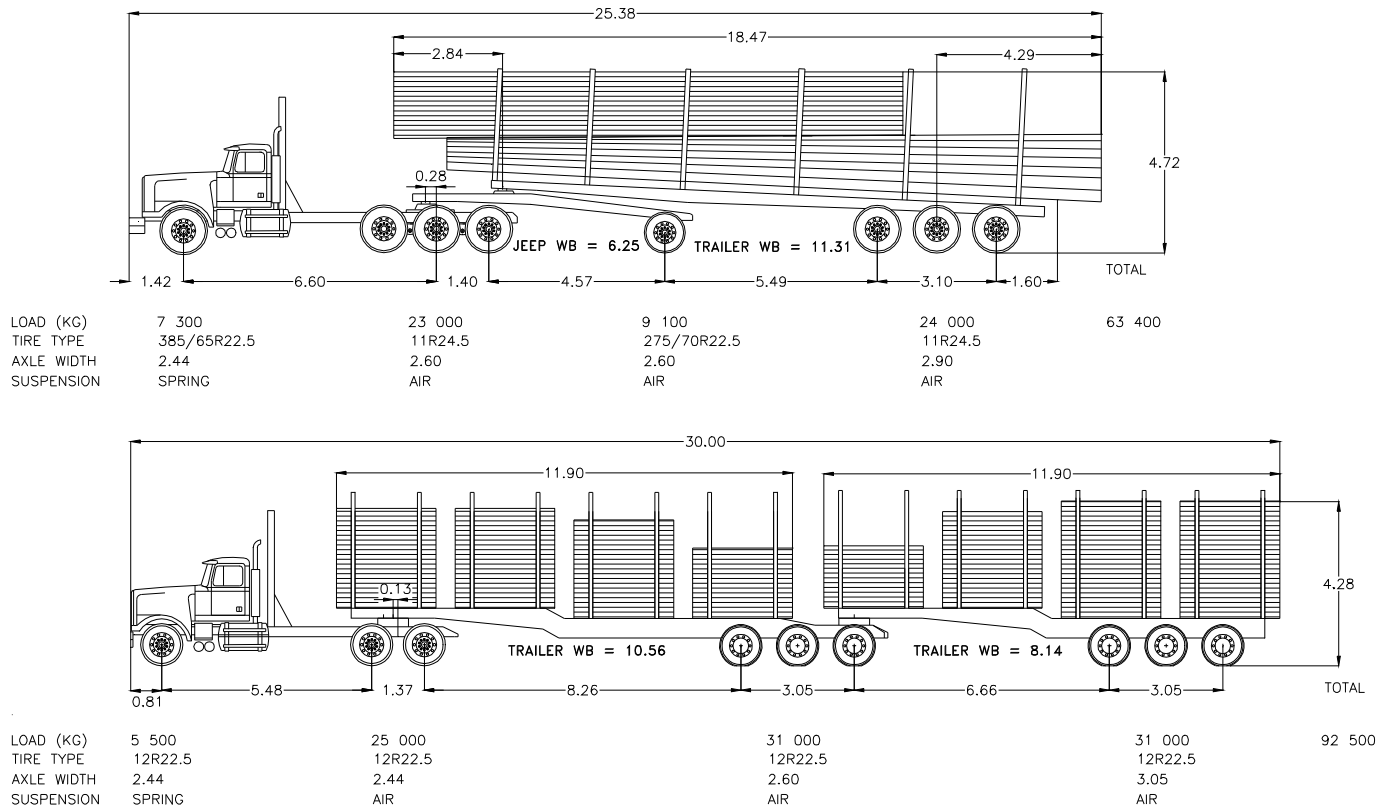


Figure 3. Configuration weights and dimensions

In addition to the aforementioned eight TAC performance standards the following performance standards characterizing the low-speed turning performance were evaluated:

9. Lateral friction utilization (LFU)
10. Front Swing-out (FSO)
11. Rear Swing-out (RSO)

LFU is a performance standard first proposed by the National Research Council of Canada (NRC) to evaluate the steering performance of truck configurations (El-Gindy 1992). This

performance standard was modified by FERIC to evaluate steering performance on low friction surfaces (Parker, Amlin, Hart 1998).

FSO, and RSO have been endorsed by the Land Transportation Standards Subcommittee established under the North American Free Trade Agreement (NAFTA) of 1994, with the goal of harmonizing vehicle weights and dimension limits within the NAFTA partnership within an international access network (Pearson, 2002).

In recent years significant efforts have been undertaken in Australia and New Zealand in the development of a Performance Based Standards (PBS) approach to heavy vehicle regulation. Therefore selected performance standards endorsed by the Australia and New Zealand regulatory regimes have also been included in this analysis to provide a contrast with the North American performance standards. These standards are as follows (National Transport Commission, 2005):

12. Low-speed Swept Path (SPW_{max})
13. Frontal Swing of prime mover (FS_{max})
14. Semi-trailers- Maximum of Difference (MoD)
15. Semi-trailers – Difference of Maxima (DoM)
16. Tail Swing (TS)
17. Steer-tyre Friction Demand (SFD)¹
18. Rearward Amplification - modified (RA_{mod})
19. High-Speed Transient Off-tracking (HSTOT)
20. Yaw Damping Coefficient (YDC)

Note that performance standards 12 through 17 are low-speed performance standards similar to 5, 6 and 9 through 11. However an important distinction to make is that the North American standards involve a larger radius turn (14 m to outside steer tire) relative to the Australia/New Zealand standards (12.5 m radius turn). In addition, different methods of calculating rearward amplification (RA measures #4 and #18) are employed. The original method (measure #4) evaluates the RA of the rearmost sprung mass, while the modified method (measure #18) evaluates RA for rearmost roll-coupled unit, which can include several sprung masses. Furthermore in the modified performance measure RA is evaluated at three separate steering frequencies to determine the worst case response, while the original method calculates RA at only one steering frequency (0.4 Hz).

3. RESULTS AND DISCUSSION

The simulation results for the J-train and King B-train are summarized in Table 1. The J-train failed to meet three performance measure criteria under the North American (NA) regime: low speed off-tracking (LSOT), high –speed off-tracking (steady state) (HSOT), and front swing-out (FSO). This configuration also failed to meet the following three selected Australia/New Zealand (ANZ) performance measures: maximum frontal swing (of prime mover) (FS_{max}), frontal swing maximum of difference (MoD), and frontal swing difference of maxima (DoM). Conversely the King B-train met all of the selected ANZ measures, and failed to meet only two of the NA measures: LSOT and HSOT.

¹ Same as LFU

Table 1. Comparison of performance measures for candidate configurations

	Performance Measure	Performance Criteria	Configuration	
			J-train	King B-train
1	SRT	> 0.35 g	0.35	0.38
2	USC ^a	> -57.3(WB)g/V ²	1.17	1.50
		> -4.49 deg/g		
		> -4.81 deg/g		
3	LTR	< 0.60	0.46	0.32
4	RA	< 2.00	0.98	1.19
5	FD	< 0.10	0.03	0.07
6	LSOT	< 5.60 m	5.77	6.32
7	HSOT	< 0.46 m	0.51	0.72
8	TOT	< 0.80 m	0.37	0.43
9	LFU ^b	< 0.80	0.75	0.73
10	FSO	< 0.45 m	0.99	0.37
11	RSO	< 0.20 m	0.16	0.04
12	SPW _{max}	< 10.1 m	9.35	9.59
13	FS _{max}	< 0.70 m	0.75	0.43
14	MoD	< 0.40 m	0.75	0.32
15	DoM	< 0.20 m	0.21	0.01
16	TS	< 0.35 m	0.18	0.04
17	SFD ^d	< 0.80	0.46	0.35
18a	RA _{mod} @ 0.33 Hz	< 5.7SRT	1.11	0.95
		< 2.0		
		< 2.17		
18b	RA _{mod} @ 0.4 Hz	< 5.7SRT	0.96	0.81
		< 2.0		
		< 2.17		
18c	RA _{mod} @ 0.5 Hz	< 5.7SRT	0.80	0.66
		< 2.0		
		< 2.17		
19	HSTOT ^e	< 1.0 m	0.48	0.55
20	YDC	> 0.15	0.42	0.27

a WB = tractor wheelbase; g = gravitational constant (9.81 m/s²)

V = vehicle speed (100 km/h)

b Coefficient of friction =0.2

c Performance criteria for measures 12 to 20 assumed to be Level 3

d Coefficient of friction =0.8

e Maximum HSTOT occurred at 0.33 Hz

f Performance measures not met highlighted in **Bold type**

The J-train exhibits good overall performance meeting the stability (SRT) and dynamic performance measures, despite its high load height due to the use of 2.9 m axles on the semi-trailer. This configuration's high and low-speed off-tracking deficiencies are minor and can be safely tolerated due to the remote areas in which this configuration operates. Its main deficiency is its high level of frontal swing-out (FSO), exceeding the performance criteria by 0.54 m, a condition which needs to be addressed. The level of FSO could be reduced to acceptable levels if the amount of front log overhang were reduced to 2.0 m, or alternatively its area of operation could be restricted to reduce the occurrence of 90 degree intersection turns.

The King B-train's overall performance is generally improved relative to the J-train. In particular FSO is reduced to acceptable levels and the configuration's stability is increased, despite a significant increase in payload capacity. However more significant deficiencies exist for this configuration relative to the J-train for low-speed off-tracking (LSOT) and high-speed off-tracking (HSOT). The deficiency for LSOT (0.72 m above threshold) can be safely tolerated since it also operates in remote areas, but its HSOT deficiency (0.26 m above threshold) requires further review and rationalization due to the consequences of this level of lane excursion at high speeds.

The HSOT performance measure was first introduced as part of the TAC vehicle weights and dimensions study conducted in the 1980s (Ervin, Guy 1986). The performance standard of less than 0.46m off-tracking is based on maintaining a clearance of 0.15 m (6 inches) between the edge of the tires of the last axle and the edge of a standard highway lane (3.66 m) for a 2.44 m axle (8') when the prime mover is traveling in the centre of the lane. The evaluation of this measure is conducted while the vehicle is making a steady state turn at a lateral acceleration of 0.2 g (100 km/h around a 393.3 m radius curve), a relatively high steady state acceleration which is rarely experienced under normal driving conditions. The use of wider axles results in a reduction of the prescribed clearance between the edge of the lane and the rearmost tires at the same target level of 0.46 m. The clearance is reduced to 0.075 m for 2.59 m (8'6") axles and in the case of 3.05 m (10') axles the edge of the tires cross over into the other lane by 0.155 m. A small level of lane excursion can be safely tolerated (up to 15 cm). However at a HSOT of 0.72 m the King B-train's lane excursion is significant (> 0.4 m). If the speed is reduced to 80 km/h for the same radius curve (0.128 g) HSOT is reduced to 0.50 m, a tolerable lane excursion level. Under most driving conditions, the phenomenon described here is unlikely to occur. However, drivers of these configurations need to be made aware of its potential and countermeasures prescribed to reduce the risk of its occurrence. One solution is to reduce travel speeds on curves by at least 10 km/h below posted limits. Another means of achieving safe lane excursion levels is for the tractor to offset its travel path to the inside of the curve.

The relative differences between the NA and ANZ performance measures evaluated in this paper are summarized in Table 2. Static rollover threshold (SRT) is the only performance measure that is consistent between regimes. Transient off-tracking (TOT), rearward amplification (RA), lateral friction utilization (LFU), rear swing-out (RSO), low-speed off-tracking (LSOT), and Frontal swing-out (FSO) have equivalent measures in the ANZ regime with differing evaluation methods. The main difference between the low-speed directional performance measures between the two regimes is the larger turn radius used in North America (14 m compared to 12.5 m in ANZ). Under the NA regime, the high-speed directional performances measures are evaluated at only one steering frequency, while under the ANZ regime these equivalent measures are evaluated at three steering frequencies. Currently there are four NA performance measures (LTR, FD, HSOT, and understeer coefficient (USC)) which do not have an equivalent ANZ performance measure, although work is currently underway to develop an equivalent measure for USC. Of the nine ANZ performance measures evaluated in this paper only yaw damping coefficient (YDC) does not have an equivalent NA measure. However, there are several other ANZ measures (not included in this paper) which do not have an equivalent NA measure.

Table 2. Comparison of Performance Measures

	Performance Measure Regime		Differences	
	North America (NA)	Australia New Zealand (ANZ)	NA	ANZ
Consistent Measures	SRT	SRT	none	
Similar Measures	TOT	HSTOT	1 steering frequency	ANZ - 3 steering frequencies (worst case reported)
	RA	RA _{mod}	1 steering frequency	3 steering frequencies (worst case reported)
			RA calculated for rearmost sprung mass	RA calculated for rearmost roll coupled unit (can include several sprung masses)
	LFU	SFD	14 m curve radius	12.5 m curve radius
			Coefficient of friction 0.2	Coefficient of friction 0.8
	RSO	TS	14 m curve radius	12.5 m curve radius
	LSOT	SPW _{max}	14 m curve radius	12.5 m curve radius
			differential track between centre of leading axle and centre of rearmost axle	differential track between outermost and innermost parts of vehicle
	FSO	FS _{max}	14 m curve radius	12.5 m curve radius
		MoD	Outermost track of trailer units (worst case) relative to drive tires on curve exit	FS - outermost track of primemover relative to steer tire path
				MoD - maximum difference between primemover and semi- trailer tracks
		DoM		DoM - difference between maximum excursion points for primemover and trailer tracks
Different Measures	LTR			
	FD			
	HSOT			
	USC			Handling performance measure currently under development
		YDC		

The different methods of rearward amplification (RA) calculation result in opposing relative dynamic performance between the two candidate configurations. The conventional (NA) method results in a higher level of RA for the King B-train relative to the J-train, whereas the modified (ANZ) method results in a higher level of RA for the J-train (Table 1). At a steering frequency of 0.4 Hz, the J-train RA levels are very similar for both methods, while the RA level is reduced significantly for the King B-train using the ANZ method. This is due to the greater influence of the King B-train's lead trailer (higher mass and forward position), which reduces the lateral acceleration acting at the centre of the roll-coupled unit relative to the rear trailer. Regardless of which method is used, both configurations exhibit good dynamic performance due to the roll-coupling between trailer units, which is confirmed by the relatively low values of load transfer ratio (LTR). The evaluation of dynamic performance at a range of steering frequencies is a noteworthy development which should be implemented in North America. The application of LTR was discontinued in the ANZ regime due to difficulties in experimentally measuring this

performance measure as well as variable results between different simulation programs (Prem, de Pont, Edgar 2002). It was concluded that only one measure RA or LTR was required to characterize high-speed directional stability which led to the development of the modified RA measure. Despite these problems, LTR is a valuable measure to assess dynamic performance provided that care has been exercised when applying the computer simulation software. Therefore LTR should continue to be applied in the NA regime, but at a range of steering frequencies.

The two different methods of determining steering performance (lateral friction utilization (LFU), steer friction demand (SFD)) result in very different performance levels for the two candidate configurations. The LFU performance criterion is achieved by a small margin whereas the SFD performance criterion is easily met. This difference is primarily due to the significantly different surface friction levels between the two methods. The LFU performance measure should prevail in the NA regime, particularly in Canada where operation on low friction surfaces is frequent.

The low-speed tracking performance measures differ slightly between the two evaluation regimes. Low-speed off-tracking (LSOT) evaluates the differential axle movement between the centre of the steering axle and the centre of the trailing axle, whereas maximum low-speed swept path (SPW_{max}) evaluates the maximum swept path of the entire vehicle. SPW_{max} can be more readily measured experimentally and gives a more direct measurement of turning envelope requirements accounting for the path of the front bumper rather than the steering tire. Therefore SPW_{max} is a more appropriate measure to use for evaluating low-speed turning envelope requirements.

The North American method of evaluating frontal swing-out (FSO) is simpler compared to the ANZ method which incorporates three measures (frontal swing of prime-mover (FS_{max}), maximum difference between semi-trailer and prime mover paths (MoD), and difference of maximum excursion points for semi-trailer and prime-mover paths (DoM)). These four different measures are presented for comparison in Figure 4 for the King B-train. FSO measures the maximum out-swing of the lead trailer relative to the drive axle tires, thereby measuring the potential lane incursion of the lead trailer assuming that the drive tires are on the lane edge at the curve exit. The ANZ method accounts for the frontal sweep of the tractor bumper (FS_{max}) relative to the steer tire path, and the movement of the lead trailer relative to the front bumper which is characterized by two measures (MoD and DoM). MoD is the maximum difference between the paths taken by the semi-trailer and the front bumper taken at the same point on the exit tangent. DoM is the difference of maximum swing-out distances between the paths taken by the semi-trailer and front bumper, with the maximum swing-out points usually occurring at different locations along the exit tangent. The NA method of calculating frontal out-swing provides the most direct means of assessing the safety implications of a tight turn manoeuvre since the semi-trailer movement cannot always be closely monitored by the driver. The frontal out-swing of the front bumper is of secondary importance, since it can be more easily monitored by the driver.

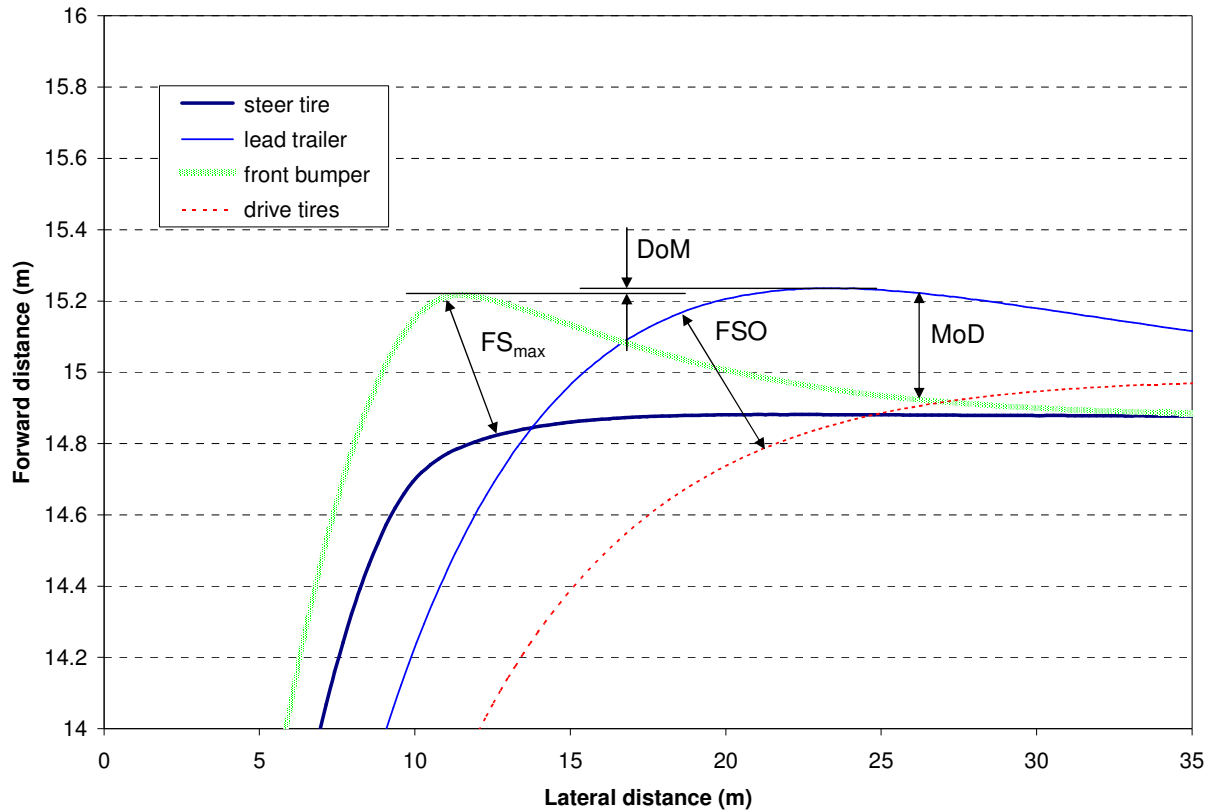


Figure 4. Comparison of front swing-out performance measures for King B-train

The NA performance measures not currently applied in the ANZ regime (LTR, HSOT, FD, and USC) should continue to be used, as they each have their merits and assist in characterizing a configuration's overall performance. However, as discussed earlier the HSOT performance measure should be refined or an alternative measure developed to evaluate rear trailer movement under typical operating conditions. One potential measure to replace HSOT is the ANZ measure: tracking ability on a straight path, which measures total swept width when a configuration travels along a straight path under the influence of cross slope, road surface unevenness, and driver steering input. Another example of ANZ measures having merit for implementation in the NA regime is yaw damping coefficient (YDC). This measure evaluates the configuration's ability to dampen sway oscillations, which is an important consideration for overall configuration performance.

4. CONCLUSIONS

1. Both the J-train and King B-train are examples of innovative configurations with increased load capacity which demonstrate good stability and dynamic performance characteristics.
2. Both candidate configurations have increased space requirements in tight turn manoeuvres, exceeding the maximum low-speed off-tracking criterion (> 5.6 m). However this deficiency can be safely tolerated since these configurations generally operate in remote areas.
3. The J-train's greatest deficiency is its significant frontal out-swing of the semi-trailer during tight turn manoeuvres. This issue could be resolved if the front log overhang were reduced to 2.0 m.
4. The King B-train's greatest deficiency is its high level of off-tracking during high-speed steady state manoeuvres. This phenomenon is unlikely to occur under normal operating conditions. However drivers of these configurations need to be made aware of its potential and countermeasures prescribed to reduce the risk of its occurrence. One solution is to reduce travel speeds on curves by at least 10 km/h below posted limits. Another means of achieving safe lane excursion levels is for the tractor to offset its travel path to the inside of the curve.
5. The application of performance based standards developed in the Australia /New Zealand (ANZ) regulatory regime would enhance the evaluation of configurations in North America (NA). In particular the following improvements are recommended for consideration in the NA regulatory regimes:
 - Evaluate the dynamic performance measures (LTR, TOT, and RA) at a range of steering frequencies (0.33 to 0.5 Hz).
 - For evaluating low-speed turning envelope requirements, utilize the ANZ performance measure SPW_{max} in place of LSOT.
 - Investigate modifications or alternatives to the HSOT performance measure to evaluate rear trailer movement under typical operating conditions. One potential measure is the ANZ measure: tracking ability on a straight path.
 - Apply the ANZ measure YDC for evaluating a configuration's ability to dampen sway oscillations.

5. REFERENCES

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