DRAFT REPORT

The Influence of Tri-Drive Power Units on the Stability Performance of Various Vehicle Combinations

Prepared for Saskatchewan Highways and Transportation

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1. BACKGROUND

This report documents a stability and control analysis of various vehicle configurations utilizing tri-axle drive systems. The generic vehicle classes examined include tractor trailer, B-train double, straight truck, straight truck and pony trailer and straight truck and full trailer. The use of tridem drive axles can cause high aligning moments which causes understeer particularly at slow speeds. Understeer causes the vehicle to plough ahead trough curves thereby reducing manoeuvrability. This problem can be offset by increasing steer axle loads and increasing the wheelbase of the tractor or truck. Saskatchewan has developed policy governing these vehicles and this analysis will assess the performance of vehicles governed by the various policy options.

2. VEHICLE DESCRIPTION

The vehicles examined can be categorized as four separate vehicle classes; tractor semi trailer, B-train doubles and straight truck and straight truck combination.

The width of all trailers and axles are approximately 2.6m, and the width of the straight truck and tractor drive axles is 2.4m. Line drawings of the vehicles including axle weights and a brief description of important variables found in Figures 1 - 10.

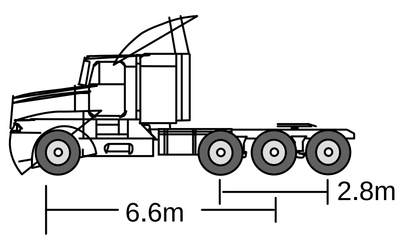


Figure 1. Tractor layout used for all cases.

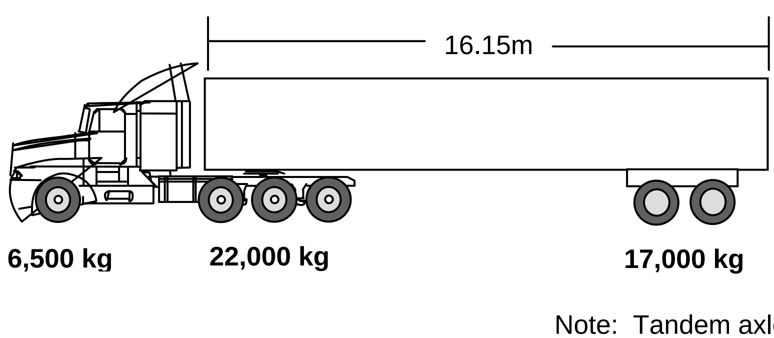
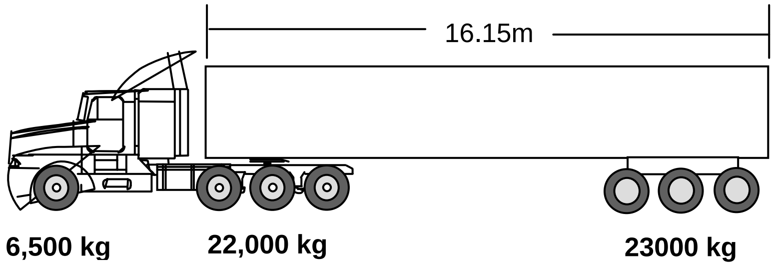
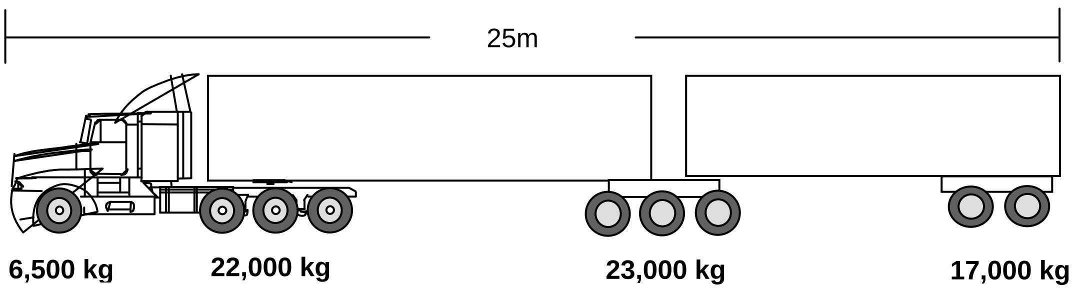


Figure 2. Tractor semi-trailer 4S2 GVW 45,500kg.



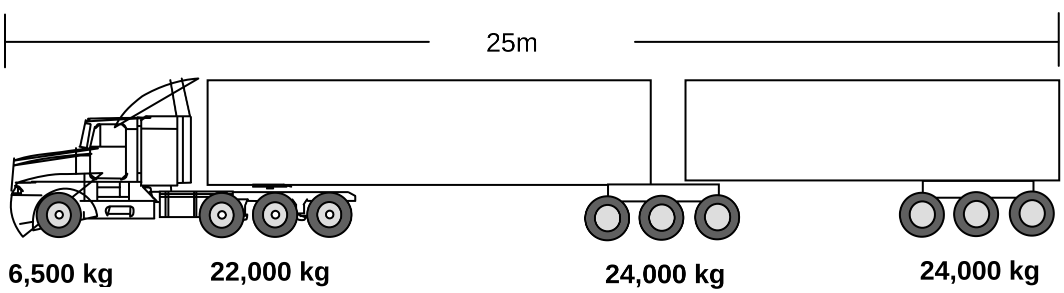
Note: Trailer tridem axle spread is 3.00 m

Figure 3. Tractor semi-trailer 4S3 GVW 51,500kg.



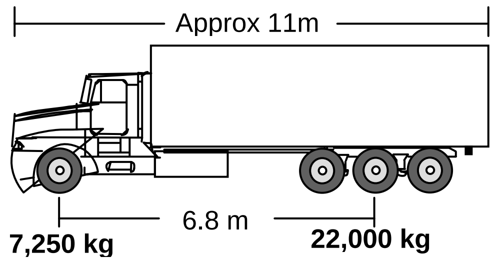
Note: Trailer tridem axle spread is 3.00 m, tandem axle spread is 1.37m. The sum of the trailer wheelbases should not exceed 17m. The wheelbase of the last trailer is 7m.

Figure 4. Nine Axle B-Train Double GVW 68,500kg



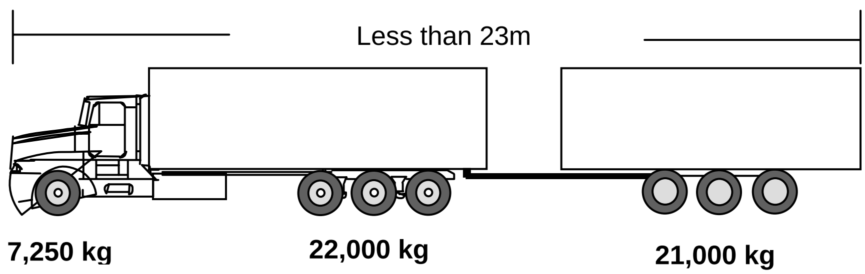
Note: Trailer tridem axle spread is 3.70 m, tandem axle spread is 1.37m. The sum of the trailer wheelbases should not exceed 17m. The wheelbase of the last trailer is 7m. The tridem trailer axle spreads are 3.0m

Figure 5. Ten Axle B-Train Double GVW 76,500kg



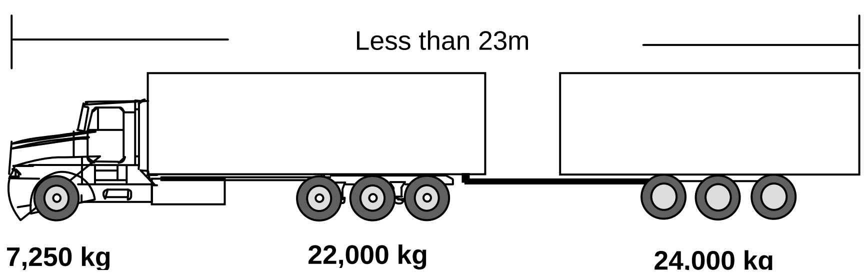
Note: Truck tridem drive spread is 2.8m. Front bumper to steer axle 1.35m.

Figure 6. Four Axle Straight Truck GVW 29,250kg



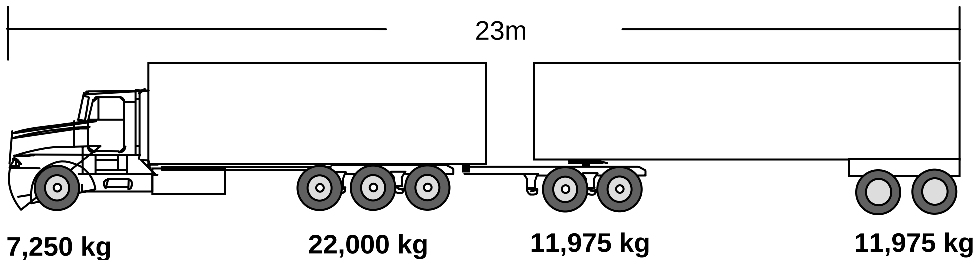
Note – Truck max CVW is constrained to 29,250 kg. and the GCW is 50,000kg and 53,250 kg.
Truck tridem drive spread is 2.8m. Hitch offset from center of tridem to trailer hitch 2.6m.

Figure 7. Four Axle Straight Truck with Pony Trailer GVW 50,000kg



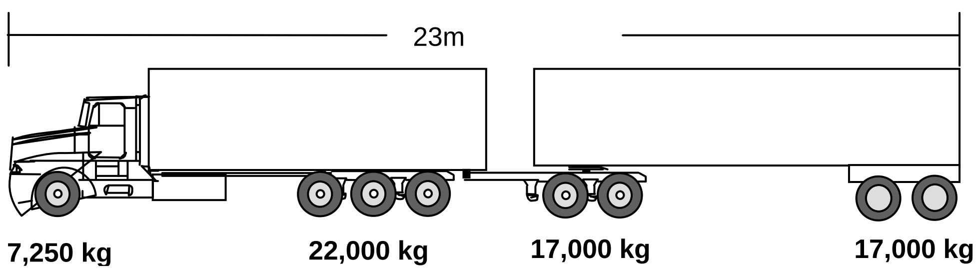
Note – Truck max CVW is constrained to 29,250 kg. and the GCW is 50,000kg and 53,250 kg.
Truck tridem drive spread is 2.8m. Hitch offset from center of tridem to trailer hitch 2.6m.

Figure 8. Four Axle Straight Truck with Pony Trailer GVW 53,000kg



Note – Truck max CVW is constrained to 29,250 kg. and the CCW is 53,300 kg
Truck tridem drive spread is 2.8m. All tandem axle spreads are 1.37m. Trailer wheelbase should be 6.5m. Interaxle spacing between the last axle of the tridem and the first axle of the trailer dolly 5.5m. Hitch offset from center of tridem to trailer hitch 2.6m.

Figure 9. Four Axle Straight Truck with Full Trailer GVW 53,250kg



Note – Truck max CVW is constrained to 29,250 kg. and the CCW is 63,250 kg
Truck tridem drive spread is 2.8m. All tandem axle spreads are 1.37m. Trailer wheelbase should be 6.5m. Interaxle spacing between the last axle of the tridem and the first axle of the trailer dolly 5.5m. Hitch offset from center of tridem to trailer hitch 2.6m.

Figure 10. Four Axle Straight Truck with Full Trailer GVW 63,250kg

Each payload for the van trailers was comprised of two homogeneous cuboids of equal size, one on top of the other. The bottom cuboid was assumed to constitute 70 % of the payload mass and the top potion accounted for 30%. This approach is intended to produce loading conditions representative of typical van trailers.

3. ANALYSIS DETAILS & PERFORMANCE MEASURES

The dynamic characteristics of the vehicle were evaluated by computer simulation techniques. Using the procedures developed as part of the TAC Heavy Vehicle Weights and Dimensions study and other performance measures, the following vehicle performance attributes were examined using the University of Michigan Transportation Research Institute (UMTRI) Yaw/Roll program:

- roll stability
- load transfer ratio
- rearward amplification
- low-speed offtracking
- high-speed steady-state offtracking
- high-speed dynamic offtracking
- high-speed friction utilization
- low-speed friction utilization

3.1 Steady-State Rollover Threshold

Heavy trucks can withstand limited lateral acceleration in a curve before rolling over. This rollover limit is expressed in terms of the lateral acceleration, and is given as a proportion of gravitational acceleration (g). The trailers of the B-train are coupled in roll via the trailer fifth wheel; and therefore benefit from the symbiotic righting moment that each unit can provide. Fully roll-coupled vehicles tend to perform better in roll. A-trains and truck trailer combinations have simple pintel hook type connections and therefore can not benefit from roll coupling.

Total rollover occurs when all the wheels on one side of the combination vehicle (on the inside of the turn) lift off the road surface as shown in Figure 11. Rollover occurs when the lateral acceleration equals or exceeds the vehicle's rollover limit (which may be assisted by roadway cross-fall or camber). Lateral acceleration on a curve is highly sensitive to speed, and the speed required to produce rollover reduces as the curve radius reduces.

The center of gravity (COG) height influences roll stability, the effective track width provided by the axles and tires and the suspension roll characteristics. The COG height is affected by the chassis height, load space length and average freight density and tie-down security. The significance of roll stability depends on the commodity, body type and operation involved.

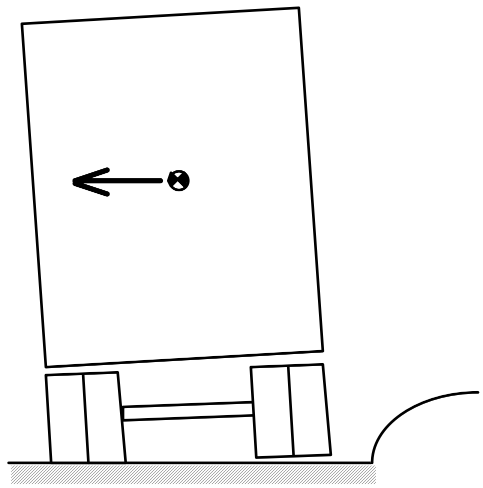


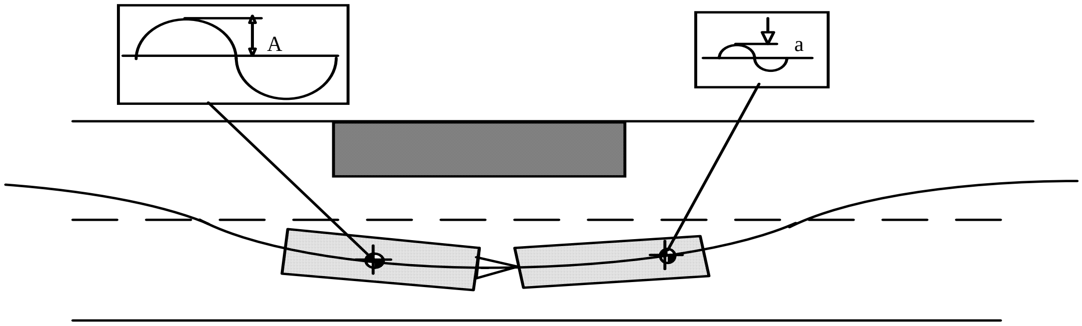
Figure 11. Onset of vehicle rollover

3.2 Rearward Amplification

When articulated vehicles undergo rapid steering, the steering effect at the trailer is magnified. This results in increased side force, or lateral acceleration, acting on the rear trailer. This in turn increases the likelihood of the trailer rolling over under some circumstances.

Rearward amplification is defined as the ratio of the lateral acceleration at COG of the rearmost unit to that at the hauling unit in a dynamic maneuver of a particular frequency. As shown in Figure 12, steering from side to side produces more lateral movement at the rear unit than at the hauling unit. Rearward amplification (RA) expresses the tendency of the vehicle combination to develop higher lateral accelerations in the rear unit when undergoing avoidance maneuvers. It is therefore an important consideration, additional to roll stability of the rear unit, in evaluating total dynamic stability. It also expresses the amount of additional road space used by the vehicle combination in an avoidance maneuver.

The number of articulation points and the overall length generally influences rearward amplification. Other important factors are the cornering stiffness of the trailer tires and their relationship with the axle weights of the trailer.



RA= A/a

Figure 12. Rearward amplification.

3.3 Load Transfer Ratio

Load transfer ratio is defined as the proportion of load on one side of a vehicle unit transferred to the other side of the vehicle in a transient manoeuvre. Where vehicle units are roll-coupled - as in the stabilized A-train unit - the load transfer ratio is computed for all axles on the vehicle. When the vehicle units are not roll-coupled, as with truck-full trailer configurations, they are evaluated as separate units. When the load transfer ratio reaches a value of 1, rollover occurs. The LTR is the ultimate measure of rollover stability.

3.4 High -Speed Steady-State Offtracking

High-speed offtracking is defined as the extent to which the rearmost tires of the vehicle track outboard of the tires of the hauling unit in a steady-turn at highway speed. High-speed offtracking relates closely to road width requirements for the travel of combination vehicles. It is an important part of the total swept width of the combination vehicle (that is, the extent to which the lateral excursions of the rear of the vehicle exceed those of the hauling unit in normal operation).

3.5 High-Speed Dynamic Offtracking

High-speed dynamic offtracking is a measure of the lateral excursion of the rear of the vehicle with reference to the path taken by the front of the vehicle during a dynamic manoeuvre. This expresses the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

3.6 Low-Speed Offtracking

Low-speed offtracking represents a measure of the swept path of the vehicle and the lateral road space requirement when turning at intersections or when turning into loading areas. The offtracking of the vehicle depends on axle position, trailer tongue length and hitch location.

3.7 Friction Utilization

Friction utilization is the non-tractive friction levels between the tires and the road surface at the steer axle of the truck. It is a measure of the shear force between the tires and the road that results from the vehicle negotiating a curve in the road. As the aligning moment of an axle group increases, this measure becomes more significant. Friction utilization at the steer axle and drive axles was evaluated at high and low speed. This measure is particularly important in the analysis of tri-dive power units. The tridrive axles impose a high aligning moment which the steer axle must overcome to steer the vehicle. Extended power unit wheelbase and increased steer axle loads are treatments that reduce the friction utilization.

4. ASSESSMENT OF DYNAMIC PERFORMANCE

4.1 Tractor Semi-Trailers

Table 1 contains the results of the assessment of dynamic performance of the two tractor semi-trailers. The term 4S2 refers to a 4-axle tractor and a 2-axle **S**emi-trailer; 4S3 represents a 4-axle tractor and a 3-axle **S**emi-trailer.

Table 1. Results of the assessment of dynamic performance
Tractor –semi trailers

Performance Measure	**TAC Target Value**	**4S2 45,500 kg**	**4S3 51,500 kg**
Static roll threshold (ideal)	0.40g (ideal)	0.36g	0.36g
Load transfer ratio	0.60 (max)	0.45	0.41
Rearward amplification	2.00 (max)	1.2	1.1
High speed dynamic offtracking	0.80 m (max)	0.12m	0.11m
High speed offtracking	0.46 m (max)	0.25m	0.25m
Low speed offtracking	6.00 m (max)	6.2m	6.2m
High speed friction utilization			
Tractor axle 1		20%	20%
Low speed friction utilization			
Tractor axle 1		48%	50%

The tractor semi trailer performs well in the 4S2 and 4S3 configuration. The addition of the third trailer axle slightly improves the dynamic performance despite the additional 6,000kg vehicle mass. The vehicle is in compliance with all of the TAC performance measures except for low speed offtracking which suffers as a result of the extended tractor wheelbase. Failing to meet the low speed offtracking requirement is not considered to be a significant issue provided the road geometry of the selected travel routes can accommodate the vehicles.

The low speed friction utilization at the steer axles is relatively high at 53%. In general, the fiction utilization will allow good slow speed manoeuvrability of the vehicle however under certain conditions of variable road friction such as icy patches, there may be some slow speed manoeuvrability problems. This would most likely occur when the steer axle is on ice and the drive axles are on bare pavement particularly while braking. Under these conditions, the power unit slow speed steering response would likely be sluggish therefore the vehicle would require a larger radius to turn.

4.2 B-Trains

The results of the 9-axle and 10-axle B-trains are found in Table 2. Both of these vehicles are in compliance with the TAC performance measures and both vehicles perform similarly. The 10-axle B-train with the additional 8,000kg mass has slightly higher load transfer ratio (7%), rearward amplification, high speed dynamic offtracking and high speed offtracking. The 10-axle B-train has slightly better low speed offtracking compared with the 9-axle unit. However these differences in performance are not considered to be significant.

Table 2. Results of the assessment of dynamic performance 9-Axle and 10 Axle B-Trains

Performance Measure	TAC Target Value	4S3S2 68,500 kg	4S3S3 76,500 kg
Static roll threshold (ideal)	0.40g (ideal)	0.36g	0.36g
Load transfer ratio	0.60 (max)	0.45	0.48
Rearward amplification	2.00 (max)	1.5	1.6
High speed dynamic offtracking	0.80 m (max)	0.29m	0.35m
High speed offtracking	0.46 m (max)	0.37m	0.40m
Low speed offtracking	6.00 m (max)	5.2m	4.8m
High speed friction utilization			
Tractor axle 1		25%	28%
Low speed friction utilization			
Tractor axle 1		53%	53%

The low speed steer-axle friction utilization for both B-trains are slightly higher than the tractor semi-trailer case. The same cautionary comments should apply.

4.3 Straight Trucks and Pony Trailer

The results of the straight truck and straight truck with trailers are found in Table 3. The straight truck without trailer complies with all of the TAC performance measures. The axle low speed friction utilization of the steer axle is significantly lower than the tractor semi-trailer and therefore the low speed manoeuvrability of the straight truck can be expected to be superior to the tractor semi trailers.

When a pony trailer is added, the dynamic performance becomes unacceptable as the load transfer ratio fails to meet TAC standards of minimum performance. Of all performance measures, load transfer ration sis the most critical. Vehicles that cannot comply with this measure should not be permitted to operate.

The poor dynamic performance of the truck –pony trailer could be attributed to the greater hitch offset required because of the tri-drive axle group, and the length of the drawbar. It may possible to engineer this vehicle combination to comply with the TAC performance criteria however it would likely have very specific vehicle dimensions that may or may not be compatible with other important factors such as the bridge formula.

Table 3. Results of the assessment of dynamic performance
Straight Truck and Straight Truck Pony Trailer

Performance Measure	TAC Target Value	Straight Truck 29,250 kg	Straight Truck & Pony Trailer 50,000 kg	Straight Truck & Pony Trailer 53,000 kg
Static roll threshold (ideal)	0.40g (min)	0.41g	0.41g	0.41g
Load transfer ratio	0.60 (max)	0.38	0.75	0.80
Rearward amplification	2.00 (max)	1.0	1.7	1.7
High speed dynamic offtracking	0.80 m (max)	0.10m	0.31m	0.36m
High speed offtracking	0.46 m (max)	0.15m	0.32m	0.34m
Low speed offtracking	6.00 m (max)	2.0m	3.4m	3.4m
High speed friction utilization				
Tractor axle 1		21%	33%	43%
Low speed friction utilization				
Tractor axle 1		43%	35%	35%

4.4 Straight Trucks and Full Trailer

The results of the straight truck full trailers are found in Table 4. The performance of this vehicle is similar to the straight truck and pony trailer. While the low speed friction utilization of the steer axle is good, the load transfer ratio fails to comply with the TAC standards. Therefore this vehicle combination in its current layout is not suitable for use.

Table 4. Results of the assessment of dynamic performance
Straight Truck and trailer

Performance Measure	TAC Target Value	4S3S2 53,250 kg	4S3S3 63,250 kg
Static roll threshold (ideal)	0.40g (min)	0.41g	0.37g
Load transfer ratio	0.60 (max)	0.72	0.83
Rearward amplification	2.00 (max)	1.7	1.8
High speed dynamic offtracking	0.80 m (max)	0.35m	0.49m
High speed offtracking	0.46 m (max)	0.37m	0.42m
Low speed offtracking	6.00 m (max)	3.9m	3.9m
High speed friction utilization			
Tractor axle 1		33%	34%
Low speed friction utilization			
Tractor axle 1		38%	38%

5. CONCLUSIONS

The analysis found that the tractor semi-trailer and B-train units equipped with a tri-drive tractor performed within acceptable bounds. However the low speed offtracking of the tractor semi-trailer was outside of the standard limits which will require care in vehicle route selection particularly in more urban or on geometrically challenged roads and at intersections. The low speed offtracking of the B-trains was significantly better than the tractor semi-trailers and were in compliance with the performance measures.

The low speed friction utilization at the steer axles of the tractor semi-trailers and the B-trains were relatively high. Of the two, the B-train friction utilization was slightly higher than that of the tractor semi trailers. The higher friction utilization of the tractor semi-trailers and the B-trains indicates that in general, the vehicle should have acceptable slow speed manoeuvrability however under certain conditions such as variable road friction, there may be some slow speed manoeuvrability problems. Under these conditions it is anticipated that power unit slow speed steering response would likely be sluggish particularly under braking therefore the vehicle would require a larger radius to turn.

The tri-drive straight truck without trailers performed well and had comparatively better low speed friction utilization at the steer axel when compared with the tractor powered units.

The tri-drive trucks with either the pony trailer or the full trailer performed poorly and were found to have unacceptable vehicle performance characteristics.