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STEERING EVALUATIONS OF A TRIDEM DRIVE TRACTOR IN COMBINATION WITH POLE TRAILERS

Séamus P.S. Parker, Eric J. Amlin, David V. Hart

ABSTRACT

Over the last decade, the log transportation sector of the forest industry in western Canada has improved productivity by adding more axles to the trailing system of traditional 5-axle configurations, to the detriment of vehicle mobility. However, if payload capacity is increased by adding a drive axle to a tandem drive group, the resulting tridem drive system will provide both productivity and traction benefits. Unfortunately, adding the third driven axle to the drive group of the tractor changes the handling performance of the vehicle, specifically the steering response during low speed, tight turns. To determine the tridem tractor's steering response, a testing program was undertaken to validate computer simulation models; these models were then used to determine the appropriate vehicle parameters to ensure acceptable handling on both high and low friction surfaces. Recommendations for vehicle parameters are presented in terms of the respective weights and dimensions regulations for the provinces of British Columbia and Alberta.

INTRODUCTION

Trucks that are equipped with tridem drive axles[1] have increased off-highway mobility over the standard tandem drive units and therefore offer operational benefits to the forest industry. On behalf of the industry and in collaboration with various government agencies, the Western Division of the Forest Engineering Research Institute of Canada (FERIC) began to explore the potential of this technology in 1989. Initially, a feasibility study was undertaken in which the tractive and dynamic behaviors of conventional log truck configurations were compared to those with tridem drive axles, through computer simulation (Marshall and Amlin 1990). These simulations determined that :

Tridem tractors have more tractive ability than tandem tractors.

- Configurations with a single degree of articulation freedom[2] exhibit superior dynamic stability compared to vehicles with multiple degrees of articulation freedom.

- Tridem tractor configurations generally exhibit acceptable levels of high speed dynamic performance but have increased levels of understeer during low speed turns (the driver must input a greater steering angle than for an equivalent tandem tractor configuration to follow a desired path, thereby increasing the likelihood of plough-out on a slippery road).

Based on these findings, a follow-up project was initiated in 1992 (Amlin, Klawer, and Hart. 1995). In conjunction with a cooperating fleet, a tridem drive tractor was purchased and evaluated during regular log hauling service for a 1.5 year period. During this time, operating costs and productivity were monitored and a series of controlled tests was conducted to evaluate traction and steering performance. The results of this study were:

- Operating and maintenance costs for the test truck were acceptable with no noticeable deviations from this fleet's experience with conventional tandem drive trucks.

- Payloads increased as a result of the additional axle capacity and trip cycle times became shorter, especially when traction-challenging conditions prevailed.

- The tridem drive tractor had more tractive ability as measured through drawbar pull force than a tandem drive tractor due to higher load allowance of the tridem group; the improvement ranged from 28 to 55% depending on axle loads and the number of differentials locked.

- Compared to a tandem drive tractor, the tridem drive unit had increased understeer, but these levels remained within the ability of the tractor to negotiate a tight turn on pavement. In addition, drivers of the tridem drive unit reported satisfactory steering response on low friction surfaces, such as ice- and snow-covered roads, and equivalent or improved high speed performance characteristics relative to tandem drive units.

Although the steering tests and drivers' experiences indicated that the steering performance of the tridem drive tractor used in the study was acceptable, the need to address regulatory concerns beyond this one-truck experiment remained. Specifically, the implications of varying tractor wheelbase, steering axle loading, tridem drive group loading and other parameters with respect to the truck's ability to negotiate a low speed 90 degree tight turn on both low and high friction surfaces needed to be understood. Tight turning performance was perceived to be the greatest operational challenge by users, researchers, and regulators.

Steering performance is characterized by the steer tires ability to develop sufficient lateral force to overcome the resistive moment of the drive group tires and thereby turn the vehicle. Ploughout occurs if steer tires saturate before sufficient lateral force is generated to turn the vehicle. Saturation refers to the point where the tires' lateral force reaches the maximum possible based on the available friction, as defined by the normal tire force (F_z) multiplied by the peak tire adhesion coefficient (μ_p), such that full tire slip initiates and the ability to maintain heading and traction is lost. To describe steer tire ploughout, the National Research Council of Canada (NRC) developed a performance measure called 'Lateral Friction Utilization' (LFU) (El-Gindy 1992).[3] LFU defines the proportion of the available lateral friction used by the steer tires to guide a truck through a low-speed, tight-radius turn.

The most practical approach to quantifying a given truck's dynamic performance is to use validated computer modeling. The standard method for validating simulation models is verification through simplified full-scale field testing. For example, this methodology was employed in the Transportation Association of Canada (TAC) Heavy Vehicle Weights and Dimensions Study (Ervin and Guy 1986) where the University of Michigan Transportation Research Institute (UMTRI) vehicle dynamic models were used, followed by full-scale testing to validate model predictions. There are a number of recognized truck performance models, but they have not been validated for steering performance, tridem tractors, or low friction surfaces. A dynamic yaw-roll model developed by NRC in cooperation with the University of Victoria (UVic) (Tong, Tabarrok and El-Gindy 1995) most closely approximates the performance of the tractor/pole trailer logging configuration. Although this model works well when comparing relative performance of different compensating reach type configurations, estimates of absolute values are considered questionable at best particularly on low friction surfaces. Therefore, additional field test measurements were necessary in order to use it with confidence for low friction surfaces.

OBJECTIVES

The primary objective of this study was to develop recommendations for the on-highway regulation of tridem-drive tractor / pole trailer configurations. The following specific objectives were established to achieve this primary goal:

- On a low friction surface, obtain low speed test data for at least two different wheelbase tridem tractors to determine the steer tires' LFU and compare the data to computer simulation predictions for low friction surfaces for validation.

- Using the validated computer simulation, conduct sensitivity analyses on the tridem tractor / pole trailer configurations for the key parameters (i.e. tractor wheelbase, steering axle loading, drive group loading, trailer group loading, drive group spread, trailer group spread, interaxle spacing, hitch offset) to determine the ranges for critical dimension and weight that will ensure safe operation of these configurations.

SCOPE

This study is limited to the evaluation of tridem drive tractors in terms of low speed turning performance on low friction surfaces ($\mu_p \leq 0.2$). Although other dynamic performance measures should be considered in the overall evaluation of a particular configuration, they are of a high speed nature and have been previously addressed (Tong et al 1995; Parker and Amlin 1997).

The most popular log hauling configurations in western Canada use the sliding compensator reach mechanism and of them, the tractor/pole trailer (only one degree of articulation freedom) has been found to be the most stable dynamically. Therefore, the study only addresses the tridem tractor in combination with tandem and tridem pole trailers (**Figure 1.**) and, because of their regional use, only in terms of the existing weights and dimension regulations for the provinces of Alberta and British Columbia. The authors do not advise the application of these results in the consideration of tridem tractors used for other vehicle configurations or with other loading distributions outside the range presented in this report.

METHODOLOGY

Field testing and correlation with yaw/roll model

Test vehicle description

Two tridem-drive tractor units with different wheelbases were tested as straight trucks: a 5.6-m wheelbase Peterbilt and a 6.6-m wheelbase Kenworth (**Figure 2.**). Both trucks had a 2.74-m drive group spread. Different wheelbase trucks were used to evaluate the effect of wheelbase on lateral force, and to increase confidence in the model. Testing was conducted with straight trucks only since the validity of the simulation's trailer compensator model had been demonstrated through previous NRC testing. Being able to use straight trucks, dramatically simplified the test procedure and analysis of results. Once the simulation is validated for straight truck ploughout on a low-friction surface, the model could be used for all combinations, because the effects of trailer dynamics are well understood and are a function of geometric relationships.

Prior to testing, each of the trucks was outfitted with tires that had been characterized during previous testing conducted by FERIC and NRC (Preston-Thomas 1994).

The trucks were also fitted with calibrated rotary potentiometers, mounted on the kingpins (**Figure 3**.), to measure the angles of the steer wheels, $Ø_{left}$ and $Ø_{right}$. A Campbell Scientific CR10 data logger powered the potentiometers and recorded their outputs, sampling at 12 Hz.

Test procedure

- The test trucks were loaded to legal axle weights[4] .The majority of the loading was accomplished with water in the tank compartments and large solid steel weights on the tractor chassis for the Peterbilt and Kenworth respectively. Fine tuning of the axle weights was accomplished with small steel weights ranging from 20 kg to 500 kg.

- The test trucks were driven around a 14-m radius (at outside steer tire), 90 degree right hand turn at 3 km/h on an ice surface[5] (**Figure 4.**), ensuring that the steer tires did not saturate and ploughout did not occur. Ploughout was deemed to have occurred when the front wheels could no longer follow within a 0.25-m tolerance path outside of the 14 m arc. The steer wheel angles were recorded during the turn using the datalogger.

- After gathering data for at least three successful runs, the coefficient of adhesion, μ_p, was determined using a procedure outlined later.

- The steering axle load was incrementally reduced, while maintaining the drive group load essentially constant; approximately ±100 kg., and the test truck was driven around the test turn until saturation occurred. If the path fell within 14.15-m and 14.25-m for at least three runs, then saturation was deemed to have occurred and the recorded steer wheel angle data for these runs became the saturation steering angles.

- The coefficient of adhesion was measured again to ensure that the ice surface characteristics had remained consistent throughout the testing period.

Coefficient of adhesion determination

The single-most effective method to give the closest determination of the coefficient of adhesion (μ_p) is to use the same steer tire type, at actual test loading and speed. Therefore, the loaded tridem tractor itself was used as the measuring device. A single steer wheel brake was isolated, so that it could be operated by a hand-operated air regulator, independently of the treadle valve, to develop a resistive wheel force. The test truck was towed behind a farm tractor, and the towing force was measured using a 44.4 kN load cell. Load cell data were obtained prior to brake application to determine the truck's rolling resistance. Once sufficient rolling resistance data had been gathered, the brake was slowly applied until wheel lock-up occurred. The brake was released and reapplied a number of times within each run to obtain an average friction force profile. The force prior to brake application, the rolling resistance, is subtracted from the peak force to give the maximum friction force. Because the wheel load is known, μ_p can be quickly determined for each test condition (μ_p = (max force - rolling resistance)/(wheel load)).

Estimating lateral friction utilization from the test data

The following formula was used to calculate the LFU at the steer tires for each group of legal axle loads, and wheelbases (Parker, Amlin, Hart 1997):

$$LFU = [(F_{zsat} \bullet \cos \varnothing_{sat}) / (F_{zleg} \bullet \cos \varnothing_{leg})] \bullet 80\%$$

where	F_{zleg}	=	legal steering axle load
	F_{zsat}	=	steering axle load at saturation
	$\varnothing_{leg}$	=	peak steer wheel angle at legal steering axle load
	$\varnothing_{sat}$	=	peak steer wheel angle at saturation steering axle load

Note that 80% is considered the maximum practical level of LFU that can be achieved.

Correlation of field test data with yaw/roll model

The NRC/UVic yaw/roll model was run for each of the field test conditions and the peak LFU at the steer tires was determined. The model was run using the open loop steering inputs collected during testing, and measured tractor characteristics (e.g., wheelbase, drive group spreads, axle loads, axle widths etc.). The characteristics of the tires used in the model for each test were estimated by combining the high friction tire characteristics determined in a previous study and the tire adhesion coefficients estimated from the field tests.

The model estimates of LFU for the test conditions were statistically compared with the field test estimates by: determining 95% confidence limits[6] for the variation of model estimates from the field test estimates, and determining the linear correlation coefficient[7] for the relationship between the model and field test estimates.

Simulations of logging configurations

Sensitivity analysis

Following the satisfactory correlation of the field test data with the yaw/roll model, simulations were performed of a representative logging configuration to determine the sensitivities of various tractor and trailer parameters on steering performance (i.e., LFU at the steer tires). The configuration modeled for this analysis was a tridem tractor/tridem pole trailer configuration with the following specifications: tractor wheelbase 6.6-m; steering axle load 6 100 kg; drive group load 24 000 kg; trailer group load 24 000 kg; drive group axle spread 2.74-m; trailer group axle spread 2.74-m; hitch offset 2.5-m; and interaxle spacing 6.0-m (see **Figure 5**. for illustration of these parameters). The analysis was conducted by keeping all but one of the parameters constant and varying one of the parameters by +10%, +20%, -10%, and -20% to determine the relative sensitivity of steer tire LFU to each of the following individual parameters:

1. tractor wheelbase
2. steering axle load
3. drive group load
4. trailer group load
5. drive group spread
6. trailer group spread
7. hitch offset
8. interaxle spacing

The simulations were done in the closed loop mode (prescribed trajectory) for a low speed (8.25 km/h) tight turn maneuver (90 degree 14-m outside radius) on a 0.2 coefficient of friction surface to evaluate steering performance. This maneuver is based on TAC's low speed tight turn maneuver, which was modified by using a bigger curve radius, and by using low friction tire characteristics. The TAC curve radius of 11-m (at outside steer tires) was increased to 14-m to meet NRC recommendations so that the physical limits of long wheelbase tractors could be assessed (El Gindy 1995). Low friction tire characteristics were used since steering performance is most critical on low friction surfaces. A 0.2 coefficient of friction surface is the minimum tire/road adhesion level that was cited in the TAC study (Ervin et al 1986), and a study conducted in the United States (Fancher et al 1989).

The results of this analysis were used to guide the selection of configurations to simulate in the subsequent determination of tridem tractor specifications for good steering performance.

Determination of tridem tractor specifications

Tridem tractor specifications necessary for good steering performance were determined using the NRC LFU performance measure. This performance measure requires that the LFU at the steer tires be less than 80% of the peak coefficient of adhesion (El Gindy 1995).

Various permutations of tractor wheelbase, steering axle load, drive group load, trailer group load and drive group spread for tridem tractor/pole trailer configurations were simulated in the same manner as previously described in the sensitivity analysis, and the LFU of the steer tires was calculated. In these simulations the trailer was loaded and the interaxle spacing was adjusted to simulate the worst case for steering performance. The minimum steering axle load necessary (i.e., steering axle load at 80% LFU) for the configuration to successfully complete the maneuver was extrapolated for each tractor wheelbase/configuration loading condition from the simulation data.

RESULTS AND DISCUSSION

Field testing and correlation with yaw/roll Model

The primary objective of the field tests was to obtain steering performance data which could be used to validate the yaw/roll model on low friction surfaces. These data cannot be applied directly to predict the steering performance of typical logging configurations since the testing was conducted with straight trucks. However, providing that there is acceptable correlation of these data with the yaw/roll model estimates, trailer parameters may be input to the model thereby allowing the steering performance of logging configurations to be predicted. Not all of the target load conditions were tested since the saturation loading in many cases occurred between 5 500 and 6 100 kg.

The field test results (Table 1) illustrate the importance of truck wheelbase and load distribution to the steering performance of a straight truck, which will have a similar influence on the steering performance of a logging configuration. The experimental test results show that steer tires LFU for a straight truck in a low speed tight turn maneuver on a low friction surface is highly sensitive to steering axle load, drive group load, and wheelbase.

Table 1 - Field test and yaw/roll model estimates of lateral friction utilization at the steer tires

Test #[a]	Wheel base (m)	Nominal drive group load (kg)	Nominal steering axle load (kg)	Nominal adhesion coefficient	Field test LFU estimates (%)	Model LFU estimates (%)	Field test variation from model (%)
1*	5.6	24 000	6 100	0.16	78.7	81.2	- 3.1
2	5.6	21 000	6 100	0.16	75.6	77.6	- 2.7
3*	5.6	21 000	5 500	0.16	77.9	75.8	+ 2.7
4*	6.6	27 000	6 100	0.15	79.9	77.1	+ 3.7
5	6.6	24 000	6 100	0.13	63.6	71.1	- 10.6
6*	6.6	24 000	5 500	0.13	78.3	77.8	+ 0.7
7	6.6	21 000	6 100	0.19	60.4	62.1	- 2.8
8	6.6	21 000	5 500	0.20	61.7	65.0	- 5.0
9*	6.6	21 000	4 700	0.14	79.9	77.1	+ 3.7

a - Saturation loading (i.e. Tractor just makes maneuver) marked by asterisk (*)

The NRC/UVic yaw/roll model showed good correlation with the experimental results (Table 1). Eight of the tests had a variation of 5% or less from the model prediction. Test #5 deviated from the model to a greater extent than the majority of the tests, most likely due to surface variations. The 95% confidence limits for the nine valid tests for the variation of the experimental results from the model estimate are -3.0% to +0.1% (i.e., model over estimates slightly), indicating a high level of agreement between the experimental results and the model predictions. The linear correlation coefficient between the two sets of data is 0.927, indicating a strong linear relationship between the experimental test results and the yaw/roll model estimates. These statistical results give a high level of confidence in the NRC/UVic Yaw/Roll Model for simulating low speed maneuvers on low friction surfaces.

Simulations of Logging Configurations

Sensitivity Analysis

The sensitivity analysis illustrates that LFU at the steer tires is most influenced by tractor parameters (i.e., steering axle loading, drive group loading, drive group spread, and wheelbase) (**Figure 6.**), with the trailer parameters having a very minor effect on LFU. The two parameters influencing the resistive moment generated by drive group (drive group loading and drive group spread) show a strong direct linear relationship, since LFU increases as the parameters are increased. The remaining tractor parameters (steering axle load and wheelbase) have an inverse non-linear relationship, with LFU decreasing at a reduced rate as the parameters are increased. LFU is minimized at high steering axle loads, while the lateral force necessary at the steer tires that is to counteract the resistive moment generated by the drive axle tires, is reduced as tractor wheelbase increases. Individually, the trailer parameters have a very minor influence on the steer tires' LFU. However, the trailer parameters and hitch offset combined have a more significant influence on the steer tires' LFU. Steering performance is improved, when the trailer is heavily loaded, the hitch offset is increased, the trailer group spread is increased, and the interaxle spacing is decreased. However, since the steering performance is influenced more by the tractor parameters, the optimum steering performance occurs when drive group spread is minimized, and tractor wheelbase and the proportion of the tractor load carried by the steering axle are maximized. These results further validate the testing approach of using only a straight truck, since the tractor parameters have a significantly greater influence than the trailer parameters on steering performance.

Determination of tridem tractor specifications

The critical parameters governing steering performance were identified in the sensitivity analysis as tractor steering axle load, tractor drive group load, tractor wheelbase, and drive group spread. Based on the results of the sensitivity analysis, the trailer was loaded and positioned to simulate the worst case situation for steering performance, by loading the trailer to a minimum level, minimizing the trailer group spread, and maximizing the interaxle spacing between the drive and trailer axle groups. The envelope of acceptable steering performance characterized by these parameters has been summarized for Alberta and British Columbia axle group loadings at short (2.74-m) and medium spreads (3.02-m) in **Figure 7.** and Figure 8. respectively. The lines on the graphs represent 80% LFU for the respective loading condition (e.g., 21 000 kg drive group load). Steering axle load / wheelbase combinations which are above the lines have an LFU less than 80% and are therefore acceptable combinations. The tandem pole trailer configuration consistently required a higher steering axle load than the equivalent tridem pole trailer configuration. Therefore the figures incorporate the simulation results for tandem pole trailers since they are the worst case configuration. In Alberta, there is a load advantage at longer axle spreads, so a medium spread tractor was investigated in addition to the short spread tractor, whereas in BC only the short spread tractor was investigated.

At a drive group load of 21 000 kg (legal Alberta summer loads), a short wheelbase (5.6-m) short spread tractor (Figure 7.) requires a minimum steering axle loading of 6 100 kg for acceptable steering performance, whereas a long wheelbase (6.6-m) short spread tractor requires a steering axle load of 5 100 kg. The tractor's steering axle load requirement increases to 8 200 kg and 6 690 kg for short and long tractor wheelbases respectively when the drive axle is loaded to 27 000 kg (Alberta winter). BC drive group load allowances and therefore steering axle load requirements fall between Alberta legal and winter loads. At a drive group loading of 25 500 kg

(BC winter tolerance), a steering axle load of 8 125 kg and 6 175 kg is required for good steering performance for 5.6-m and 6.6-m wheelbase short spread tractors respectively. In order to achieve a steering axle load of greater than 6 600 kg, a self-loader mounted on tractor is usually required. A 6.6-m wheelbase short spread tridem tractor/ tandem pole trailer configuration has successfully operated in northern Alberta on winter green routes (Amlin et al 1995). For the first two winters of operation, the steering axle loading was only 6 100 kg, which is 9% less than the minimum estimated from the simulation (6 690 kg). In this period no steering problems were encountered, suggesting that the simulation steering axle estimates are conservative and provide an adequate safety margin. The difference between the operational experience of the tridem tractor and the simulations is most likely due to the extreme simulation conditions —coefficient of adhesion = 0.2; turn radius (outside tire path) = 14 m; speed = 8.25 km/h— which are rarely encountered even under the most extreme winter hauling conditions.

In Alberta, the regulations allow the drive group load to be increased to 23 000 kg for a medium spread tractor for legal summer loads. The increased load allowance on the drives increases the payload capability of the configuration by 2 000 kg and improves traction for legal summer loads. These benefits are major incentives for the use of medium spread tractors. Based on the simulation results, the longer drive group spread significantly increases the steering axle load and wheelbase requirements to achieve acceptable steering performance (**Figure 8**). A short wheelbase (5.6-m) medium spread tractor can be operated only at a drive group load of 25 000 kg or less provided that the steering axle load is 9 100 kg, which is the maximum allowable steering axle load (when tractor equipped with self-loader). A 6.6-m wheelbase medium spread tractor is capable of operating with a drive group load of 27 000 kg, when the steering axle is loaded to 7 880 kg and greater.

CONCLUSIONS

1. Field testing of straight trucks demonstrated that the tridem truck's steering performance deteriorated at increased drive group load, decreased steering axle load, and decreased tractor wheelbase.

2. The NRC/UVic yaw roll model was validated as a tool for predicting low speed steering performance on a low friction surface. The model showed a strong correlation with the testing results, with a 95% confidence limit of the variation of the field test estimates from the model of - 3.0% to + 0.1%, and a high linear correlation coefficient of 0.927.

3. The sensitivity analysis showed that the following parameters have a major influence on lateral friction utilization at the steer tiresfor tridem tractor / pole trailer configurations:
    - Steering axle load (maximize for best performance)
    - Tractor wheelbase (maximize for best performance)
    - Drive group load (minimize for best performance)
    - Drive group spread (minimize for best performance)

4. The sensitivity analysis showed that the following parameters have a minor influence on lateral friction utilization at the steer tiresfor tridem tractor / pole trailer configurations:
    - Hitch offset (maximize for best performance)
    - Trailer group load (maximize for best performance)
    - Interaxle spacing (minimize for best performance)
    - Trailer group spread (maximize for best performance)

5. The predictions of steering axle loads necessary for good steering performance are slightly conservative and provide an adequate safety margin, based on the operational experience of a tridem tractor/tandem pole trailer configuration in northern Alberta.

RECOMMENDATIONS

The following recommended tridem tractor specifications are only for use with tandem and tridem pole trailer configurations

1. The minimum steering axle load is determined by tractor wheelbase, drive group spread, and drive group loading condition (Table 2, and Table 3). The steering axle components and tires must have a load capacity exceeding the maximum steering axle load.

2. The bunk should be located to ensure the required steering axle load is achieved for the maximum drive group load allowance[8]

Table 2 - Minimum Steering Axle Loads for Tridem Tractors
Maximum Drive group spread: 2.74-m

Tractor Wheelbase (m)	Minimum Steering Axle Loads (kg)			
	21 000 kg drive group load	24 000 kg drive group load	25 500 kg drive group load	27 000 kg drive group load
5.6 up to but not including 5.8	6 150	7 450	8 100	8 200
5.8 up to but not including 6.0	5 950	7 100	7 750	7 900
6.0 up to but not including 6.2	5 750	6 750	7 400	7 600
6.2 up to but not including 6.4	5 500	6 400	7 000	7 300
6.4 up to but not including 6.6	5 300	6 100	6 600	7 000
6.6 and greater	5 100	5 800	6 150	6 700

Table 3 - Minimum Steering Axle Loads for Tridem Tractors
Maximum Drive group spread: 3.02-m

Tractor Wheelbase (m)	Minimum Steering Axle Loads (kg)		
	23 000 kg drive group load	25 000 kg drive group load	27 000 kg drive group load
5.6 up to but not including 5.8	8 150	9 100	NR
5.8 up to but not including 6.0	7 800	8 700	NR
6.0 up to but not including 6.2	7 400	8 250	9 100
6.2 up to but not including 6.4	7 000	7 850	8 700
6.4 up to but not including 6.6	6 650	7 400	8 300
6.6 up to but not including 6.8	6 350	7 000	7 900
6.8 up to but not including 7.0	6 150	6 750	7 550
7.0 and greater	5 950	6 550	7 250

NR - not recommended- in excess of maximum steering axle load allowance.

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FOOTNOTES

1 A tridem is defined as a group of three axles that are equally spaced and equally share the load. All axles within the group are attached to a common framework, and are all equipped with identical tire and wheel assemblies.

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2 Strictly speaking, there are two degrees of articulation freedom on a pole trailer configuration (reach articulation angle and load articulation angle) and one constraint load length which remains constant. This geometric constraint effectively negates the bunk pivot as an articulation point and reduces the two degrees of articulation freedom to one effective degree of freedom.

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3 LFU = (net sum of lateral forces at steer tires) divided by (sum of vertical forces at steer tires multiplied by μ_p).

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4 Drive group loads: 21 000 kg (Alberta legal), 24 000 kg (BC legal), 27 000 kg (Alberta winter (green route)).
Steering axle loads: 6 100 kg and 5 500 kg (where possible).

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5 Testing was suspended when the ice temperature rose above -2°C and during periods of snowfall due to the wide variations in the coefficient of adhesion which occurs under these conditions.

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6 95% confidence limits **-** if the tests were conducted 100 times the results would fall within the predicted limits in 95 of the tests.

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7 Linear correlation coefficent **-** index of the linear relationship between two variables; the closer to 1, the stronger or closer the linear relationship.

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8 The tables tabulate worst case conditions. If the bunk is located for these worst case conditions steering performance will be improved as drive group load is reduced below the maximum allowance because steering axle loads are reduced at a lower rate than drive group loads.

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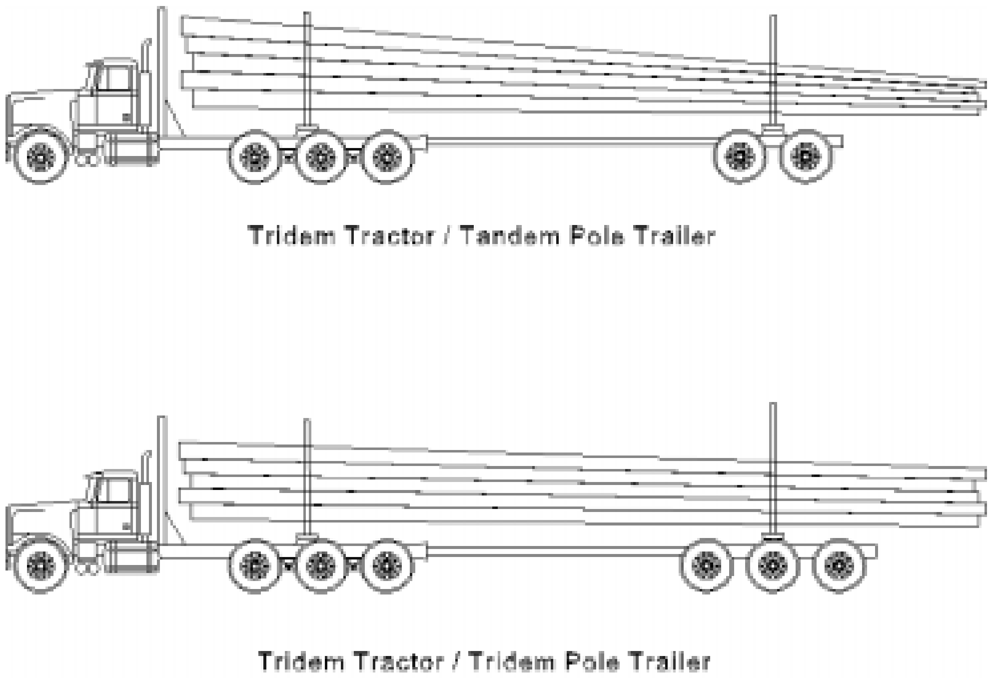

Figure 1: Tridem tractor / pole trailer configurations.

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Figure 2 - Test trucks.

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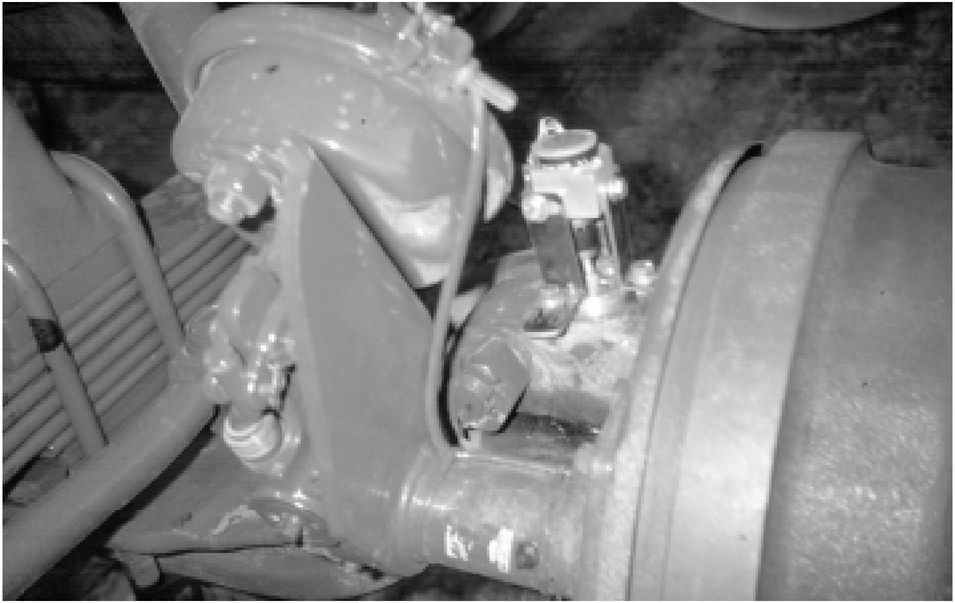

Figure 3 - Rotary potentiometers on kingpins to measure steer wheel angles.

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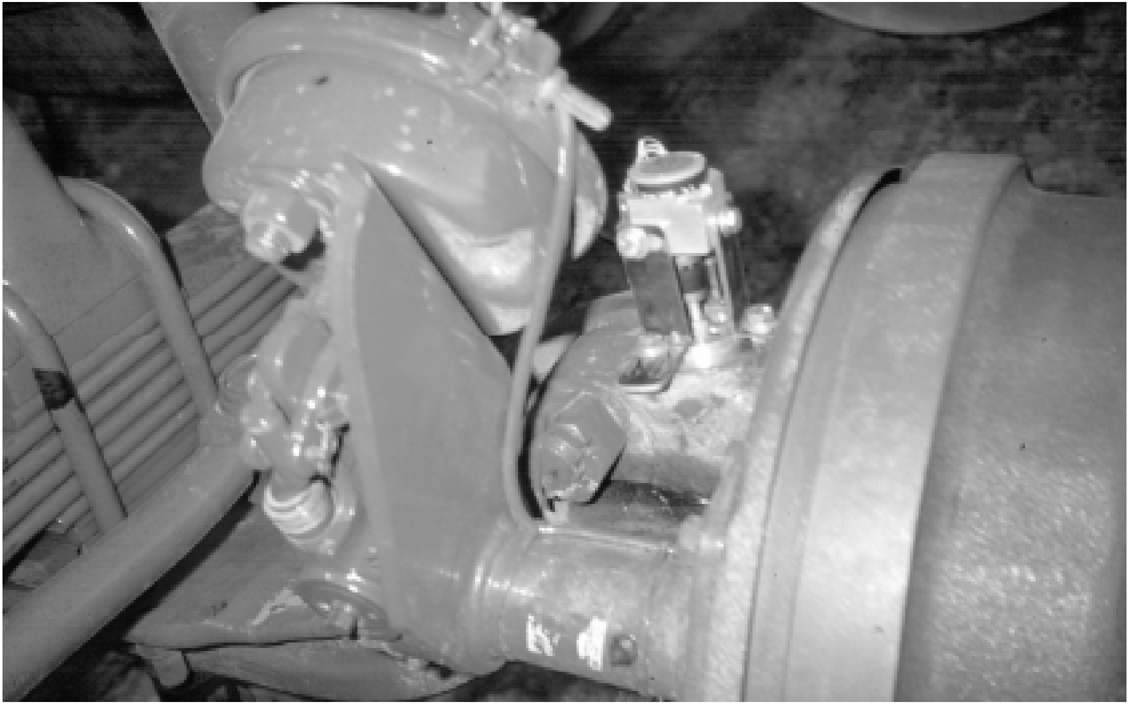

Figure 4 - Tridem tractor making test turn.

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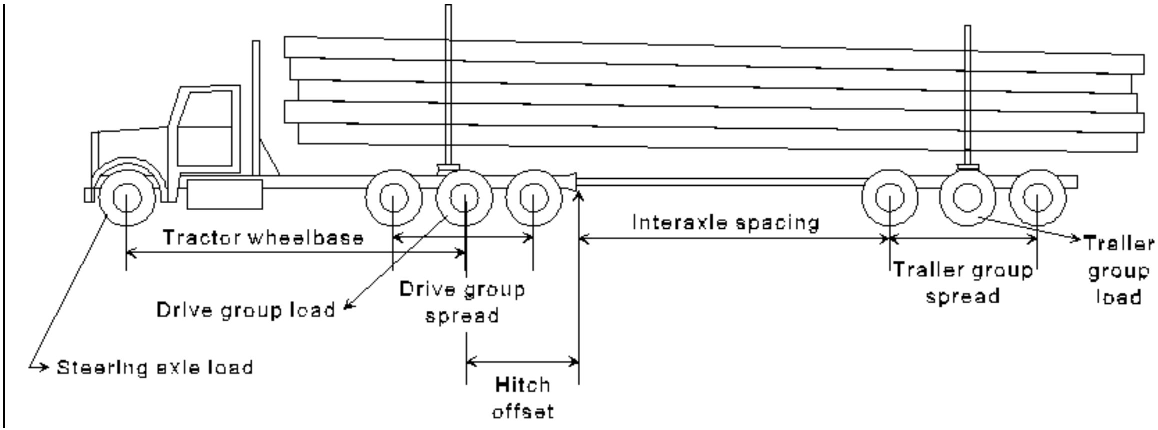

Figure 5 - Tractor and trailer parameters.

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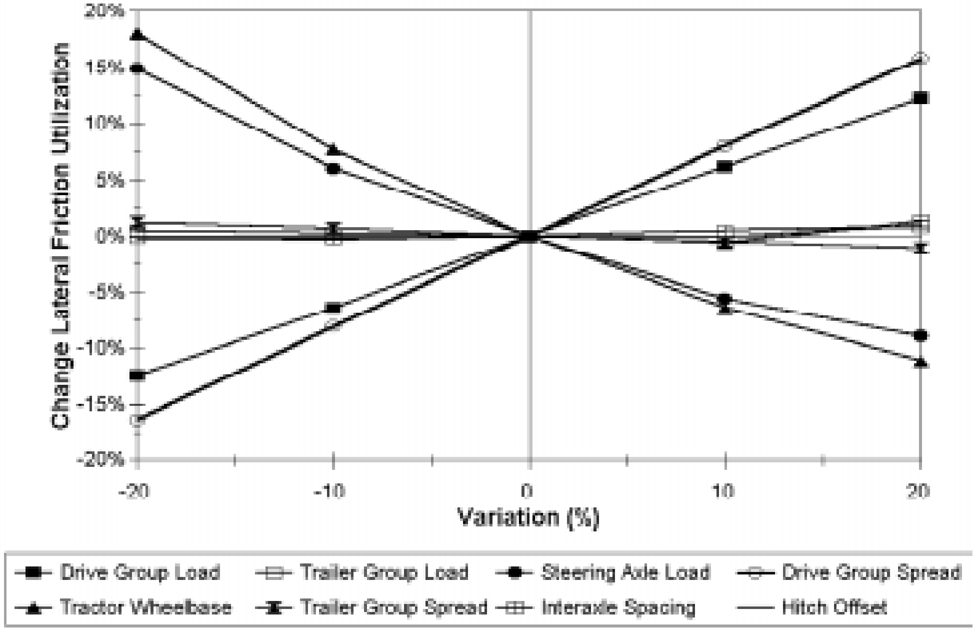

Figure 6 - Sensitivity of lateral friction utilization of steer tires to changes in various configuration parameters.

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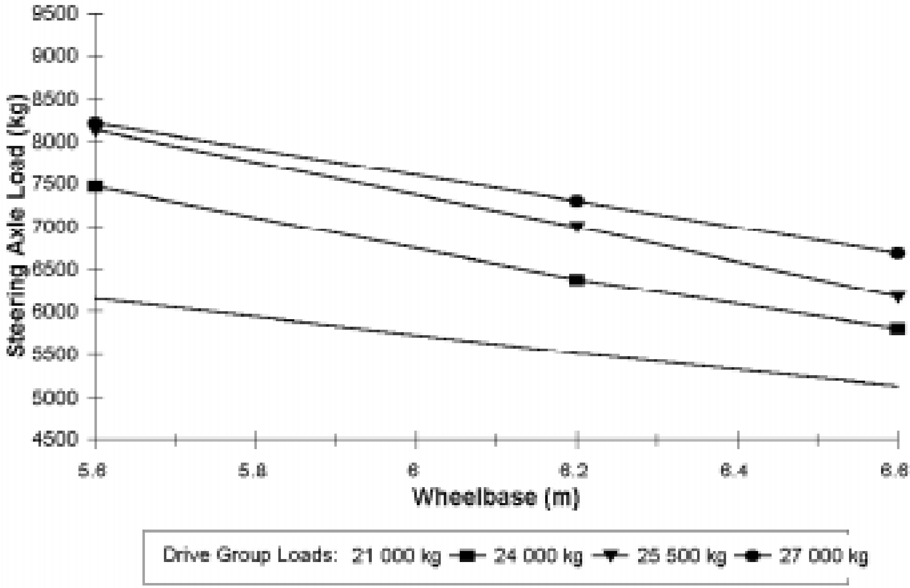

Note: Acceptable steering axle / load wheelbase combinations for each loading condition fall above the respective line. Lines define 80% LFU; LFU decreases (improved steering performance) above lines.

Figure 7 - Envelope of acceptable steering performance for tridem tractor / pole trailer configurations (2.74-m drive group spread).

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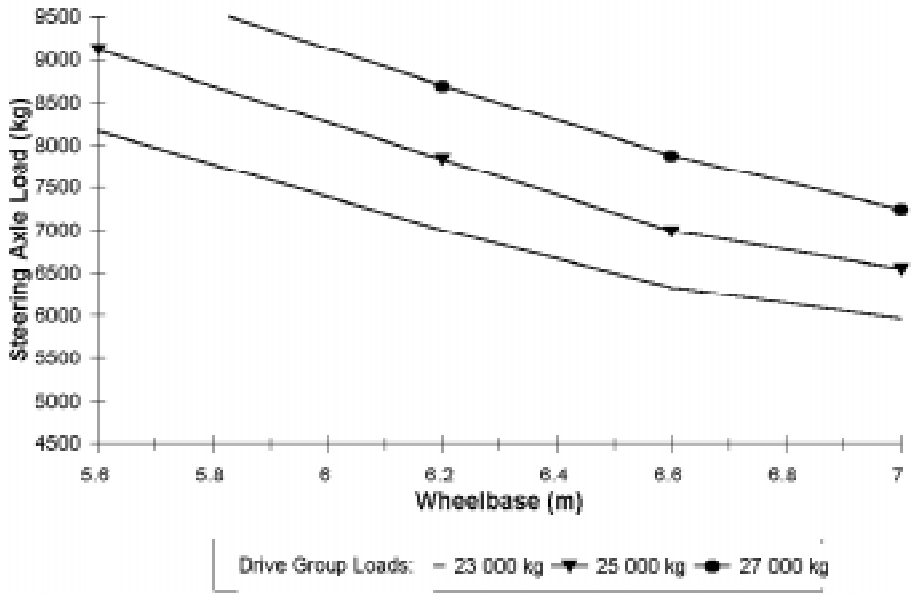

Note: Acceptable steering axle /load wheelbase combinations for each loading condition fall above the respective line. Lines define 80% LFU; LFU decreases (improved steering performance) above lines.

Figure 8 - Envelope of acceptable steering performance for tridem tractor / pole trailer configurations (3.02-m drive group spread).

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