EVALUATION OF A TRIDEM DRIVE TRACTOR FOR LOG TRANSPORTATION

1995

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EXECUTIVE SUMMARY

In Western Canada, log-transportation costs are often the highest phase cost of supplying wood to the mills. The industry has attempted to reduce costs by adding axles to trailers to increase the legal payloads. However, with increased payloads, traction has become a limiting factor for Class 8 tractors, especially in the off-highway portion of the log hauling cycle. In response, the Forest Engineering Research Institute of Canada (FERIC) initiated a feasibility study in 1989 to investigate the potential of a tridem tractor addressing the industry's needs for improved tractive performance. A computer simulation indicated that a tridem tractor has more tractive ability than the conventional tandem drive tractors, and that log truck combinations with a single articulation point are more dynamically stable than those with two or more articulation points. The principal drawback predicted by the simulations was a reduced level of steering responsiveness for the tridem tractor configurations. The report recommended that a tridem tractor be evaluated while in revenue service to verify the simulation results, and that operational costs and productivities be determined (Amlin 1992).

In 1992, this recommendation was followed up through a cooperative project involving FERIC, Vanderwell (1971) Contractors Ltd., Canadian Kenworth Company, the Canadian Forest Service, Alberta Economic Development and Tourism, and Alberta Transportation and Utilities. A Kenworth T800 model tridem drive tractor began operating in the Slave Lake region of Alberta in December 1992 as part of the Vanderwell log-hauling fleet. During the project's field evaluation period, which ended in May 1994, the truck's productivity and maintenance history were documented, and tests were conducted to measure its tractive ability and steering response. Over the trial period the truck accumulated 185 079 km and was operated by six different drivers. They were all favourably impressed with the tractive performance and reported no problems with steering responsiveness. Productivity and maintenance costs for the 1.5-year monitoring term were acceptable in context of Vanderwell's operation. In the steering trials, the tridem tractor demonstrated the ability to follow the required 14-m radius steering path on both wet and dry surfaces, despite significant increases in measured aligning force compared to that of a baseline tandem tractor. In terms of traction measurements, the tridem tractor had more drawbar pull than a tandem tractor; the improvement ranged from 28% to 55%, depending on axle loads and the number of differentials locked. The study finds that, at least, tridem tractors would be suitable for log transportation with combinations similar to those evaluated during this trial.

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INTRODUCTION

In Western Canada, log-transportation costs are often the highest phase cost of supplying wood to the mills. The log-hauling contractors have attempted to reduce costs by adding axles to trailers to increase the legal payloads. However, with increased trailer payloads, traction has become a limitation for Class 8 tractors, especially in the off-highway portion of the log-hauling cycle.

In response, the Forest Engineering Research Institute of Canada (FERIC), the National Research Council (NRC), and the Transportation Development Centre of Transport Canada (TDC) proposed a feasibility study to develop a tractor with three driven axles for log transportation (subsequently referred to as a tridem[1] tractor). In 1989 a project was initiated to model tractive and dynamic behaviours of various log-truck combinations through computer simulations. This project also surveyed the available tridem components and systems that could be adapted to log-hauling vehicles. The computer analysis compared two hypothetical tridem tractors with a baseline tandem tractor in a variety of popular western Canadian log-hauling configurations. These simulations determined that:

- Tridem tractors have more tractive ability than tandem tractors with equivalent axle loading (Preston-Thomas and Wong 1989).
- Vehicles with a single tractor/trailer articulation point[2] have superior dynamic stability compared to vehicles with multiple articulation points (El-Gindy and Woodrooffe 1990).
- Tridem tractor configurations had reduced levels of steering responsiveness that were characterized by increased levels of understeer and vehicle response times during specific manoeuvres.

The reduced responsiveness resulted primarily from the greater overall spread between the front and rear axles in the drive-axle group, and from a lower proportion of the total tractor axle load being carried by the steer axle. At the conclusion of the project, FERIC recommended that a tridem tractor be evaluated while operating in revenue service to verify the simulation results, determine operational costs and productivities (Amlin 1992), and better assess the potential impact of the reduced steering responsiveness.

In 1992 this recommendation was followed-up through a cooperative project involving FERIC, Vanderwell Contractors (1971) Ltd., Canadian Kenworth Company, the Canadian Forest Service, the Forest Industry Development Branch of Alberta Economic Development and Tourism, and Alberta Transportation and Utilities (AT&U). In Alberta, the use of tridem tractors was a departure from the status quo and as such required evaluation before licensing for public roads. In this case the primary concern was the potential reduction of steering response in tight turns due to increased friction demand at the interface on the steering tires and road. Friction demand for a single vehicle unit is defined as the friction coefficient that is required to generate the necessary side force at the front axle to maintain the vehicle on a prescribed path through a turning manoeuvre. The friction demand arises from the lateral or aligning force that originates as the trailing tires are redirected when the

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[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 all are equipped with identical tire and wheel assemblies.

[2] For the purpose of this study, an articulation point is defined as the attachment link between vehicle chassis. Examples include pintle hook couplings (in combination with compensating reaches), fifth wheel couplings of tractor jeeps, and turntables that attach steering axles of a triaxle or quadaxle to trailer frames. Therefore, a bunk's pivot (i.e. cup-and-saucer assembly) is not considered an articulation point.

truck begins a turn. Aligning force is a function of, among other things, the number of fixed drive axles, the loading on the drive axle group, the locking of drive axle differentials, the distance between axles within the drive group, and the distance between the steering axle and the drive axles (i.e. wheelbase) (Ervin and Guy 1986). With respect to minimizing the aligning force generated by the tridem group the wheelbase was set at a minimum of 6.6 m, and the axle spacing within the group was held to a maximum of 1.4 m. Through this study FERIC set out to monitor the operational performance of the tridem tractor log truck in revenue service, and to compare the steering responsiveness and tractive abilities with those of a tandem drive log truck. AT&U granted a permit to facilitate this evaluation and in December 1992 a new Kenworth Model T800, in combination with a pole trailer, began log hauling in the Slave Lake Region of Alberta. Overall, the duration of the study was 2.5 years.

OBJECTIVES

The objectives of this project were to:

- Monitor the operational performance and maintenance requirements of a new tridem tractor designed with the stability enhancing features (see Description of Test Vehicle) recommended by the initial study (Amlin 1992).
- Compare the steering response of two- and three-drive axle log haul tractors in combination with a tandem axle pole trailer under three different load conditions. A secondary objective was to compare the steering response while applying the various drive axle differential lock combinations.
- Compare the tractive ability of a tridem drive axle tractor with a conventional tandem drive unit.

SCOPE

A single tridem tractor was used for this project. The operational performance and maintenance requirements were monitored for a 1.5-year period while the vehicle was used on a daily basis as part of the Vanderwell Contractors (1971) Ltd. log-hauling operation. During the winter hauling period (December through March) the unit operated 24 h/day for 7 days/week, and during the other seasons it operated a single shift/day for 5 days/week. In accordance with the preliminary findings of the computer simulations in the feasibility study, the tractor was operated exclusively in a single-articulated combination, i.e. with a pole trailer (Figure 1).

To achieve the second and third objectives, a series of controlled steering response and traction tests were devised. In these comparison tests the tridem tractor was appropriately instrumented and tested with either all three drive axles on the ground, or with the rearmost axle lifted and the tractor bunk moved forward to simulate a tandem drive tractor configuration.

DESCRIPTION OF TEST VEHICLE

Under the authority of a special permit from AT&U, the tridem test vehicle entered regular service in December of 1992 as part of the Vanderwell Contractors (1971) Ltd. log-hauling fleet. During the evaluation period, which ended in May of 1994, the test vehicle was operated by six different drivers to provide a diversity of opinion and experience. The test tractor, a T800 Kenworth, had a Rockwell

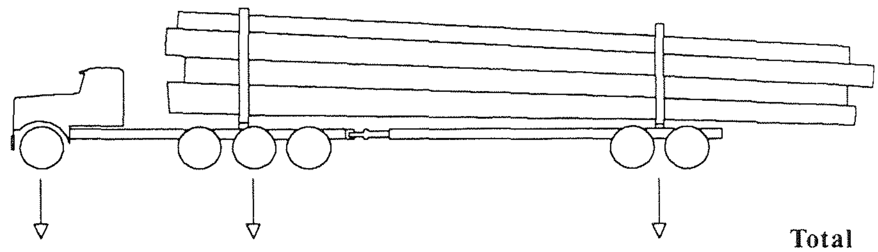
Figure 1. Tridem drive tractor and pole trailer.

tridem drive axle group mounted on a load-equalizing Neway air suspension incorporating two valves for side-to-side height control. The distance between axles within the drive group was 1.4 m (maximum desired) and the tractor wheel base was 6.6 m (minimum desired); both parameters are important in minimizing the effects of the tridem group's aligning force on steering response. As is common with logging trucks, this vehicle is equipped with an option that provides the driver with a means of locking the differentials to improve traction when off-highway conditions warrant. By means of five switches, the driver can lock any or all of the three axle differentials and the two inter-axle differentials.

As a demonstration of new truck technology for industry, the tractor was also equipped with an antilock brake system (ABS) and wide-track drive axles (overall width 2.59 m, compared to conventional 2.44 m); both features enhance truck stability. Additional specifications are provided in Appendix I. The tractor purchase price was approximately $118 000 (1992).

The tridem tractor, complete with log bunk rigging and in combination with a tandem axle pole trailer (Figure 2), has a tare weight of 17 300 kg (13 400 kg without trailer) when clean and without driver. With legal maximum winter weight capacities (Figure 2), payload potential for this truck is 40 800 kg. Under summer weight regulations, maximum payload potential is 26 800 kg. See Table 4 for actual weights from the in-service monitoring. The tridem drive axle group allowed this truck to carry larger loads and have better traction than single-articulated combinations with tandem drive axle groups.

During the steering and traction evaluations, the tridem test tractor was modified to form the tandem tractor by raising the rearmost axle and sliding the bunk forward on the frame. As a result of this approach, the tandem tractor version had a stinger (tailframe) length of 3.1 m (Appendix I). This dimension must be considered during steering measurement trials because it directly influences the responsiveness of tractor/pole trailer combinations (i.e. an increase in stinger length corresponds



				Total
Winter permit (kg)	6 100	27 000	25 000	58 100
Summer regulations (kg)	6 100	21 000	17 000	44 100

Figure 2. Maximum legal weights for tridem tractor / pole trailer configuration in Alberta.

to an increase in the steering force required to turn these trucks). For purposes of this project, the 3.1 m was considered acceptably close to the 3.0 m typical of the tandem tractors in the Vanderwell tractor/ pole trailer fleet. Using the same tractor allowed for a one-time installation of the instrumentation/data acquisition system, and minimized the number of variables that would change with the use of two different vehicles. Both combinations were tested with the same tandem axle pole trailer. The wheel-base of the tridem tractor was 6.6 m (260 inches), while the tandem tractor wheelbase was 6.0 m (235 in) which was considered to be acceptably close to a typical tandem tractor in log-haul service.

METHODOLOGY

Project Organization

A cooperating fleet operator was selected according to the following criteria: a) agreeable to purchasing or providing a test vehicle with stability-enhancing components such as wide-track drive axles and ABS, b) willing to assist with data collection and make the tractor available for the detailed evaluation of tractive ability and steering response, and c) able to manage an effective maintenance record-keeping system. Through consultations with AT&U, the relevant weight and dimension guidelines were established for the test vehicle.

In-Service Evaluation

A data collection procedure was implemented to tally the truck's production, record the driver's comments and observations, and track the vehicle maintenance activities. FERIC staff periodically conducted field visits to collect operational data and interview drivers.

Steering Response Comparison

FERIC developed an evaluation procedure to compare the ability of the tridem drive test vehicle to negotiate a tight turn with that of a tandem drive vehicle with similar axle loading and trailer. The steering response was measured by driving each configuration along a 14-m radius curve [3] at a con-

[3] An arc of 14-m radius describes the path for the outer steering tire to follow. It is based on accepted geometric road design standards (initially developed by Ontario's Ministry of Transportation) and has been subsequently adopted as a standard to test the slow-speed turning ability of trucks in Canada.

stant speed, and measuring the side force generated at the front axle suspension throughout the turn. The steering test area was a paved yard located at the AT&U weigh scale and inspection station in Slave Lake, Alberta. The friction coefficient for the test site pavement was measured using a μ-meter skid trailer from the AT&U Materials Engineering Branch. An average skid number [4] of 52 was determined for the test site (wet pavement). Figure 3 illustrates the prescribed path used for the testing. A pointer was attached to the front bumper of the test tractor and extended outward on the driver's side to guide the driver through the turn (Figure 4). To scribe the initial path for the pointer to follow, the test tractor was driven slowly through the turn with the outside steer tire following the assigned 14-m radius while a chalk line was drawn corresponding to the pointer's path. A short chain was suspended from the end of the pointer down to the chalk line to compensate for the offset of the driver's eye.

Instrumentation on the test tractor consisted of two rotary potentiometers located on the front axle kingpins to track the left and right steering wheel angles, a linear string potentiometer to track the bunk angle, and instrumented front suspension components to track the side force throughout the test turns. The instrumented front suspension components were the four shackles between the truck frame and the rears of the steering axle leaf springs. The shackles were reduced in cross section, and fitted with strain gauges to measure the shear force in the plane perpendicular to the tractor's frame rails. In the design of the shackle load cells, it was assumed that the shackles carried half of the side force applied to the front of the tractor, and that the other half was carried by the anchor pins at the front of the leaf springs. The pins and shackles are equi-distant from the axle, and the leaf springs were assumed to function as simply supported beams. The measured shear force is an indication of the force required to turn the configuration through the curve.

To maintain the tractor at constant speed throughout the turn, the driver held the engine at the governed revolutions per minute in a set gear. The tractor's relatively slow test speed of 9.4 km/h was set to minimize both the effects of centripetal acceleration and weight transfer to the outside wheels. The data acquisition system in the tractor included a Keithley K500 and a 386 PC-computer equipped with Viewdac software. A Weir-Jones ST41B signal conditioner was used in combination with a 10-Hz four-pole Butterworth low-pass filter to amplify and filter the output signals from the four shackle transducers. The data-acquisition system scanned for transducer readings at a rate of 50 Hz. Details of the instrumentation and data acquisition setup are outlined in Appendix II.

Before running the steering tests the strain gauge transducers required calibration. The instrumented shackles were installed on the truck and calibrated by applying known side loads to the steer axle of the tractor and measuring the output of the transducers. A relationship between transducer output (mV) and side force was developed. Specific details regarding the calibration are outlined in Appendix II.

Four different loading conditions were compared: Empty (with trailer loaded on tractor) (Figure 5), Alberta licensed summer weights, Alberta winter permit weights, and BC licensed weights (Table 1). The BC weights vary from the Alberta summer weights in that the target steering axle loading is slightly increased and the drive axle group loading is 24 000 kg as opposed to Alberta's 21 000 kg. Experimentally, the steer axle weights of these two loading conditions differed by only 20 kg. The

[4] Friction test procedures involved towing the u-meter skid trailer, which contains two rotating test wheels angled (15°) to the direction of motion, over a wetted pavement surface at 64.4 km/h (40 miles/h) while the two test wheels are under a constant static load. The angled wheels generate a lateral force that is recorded to arrive at the appropriate skid number.

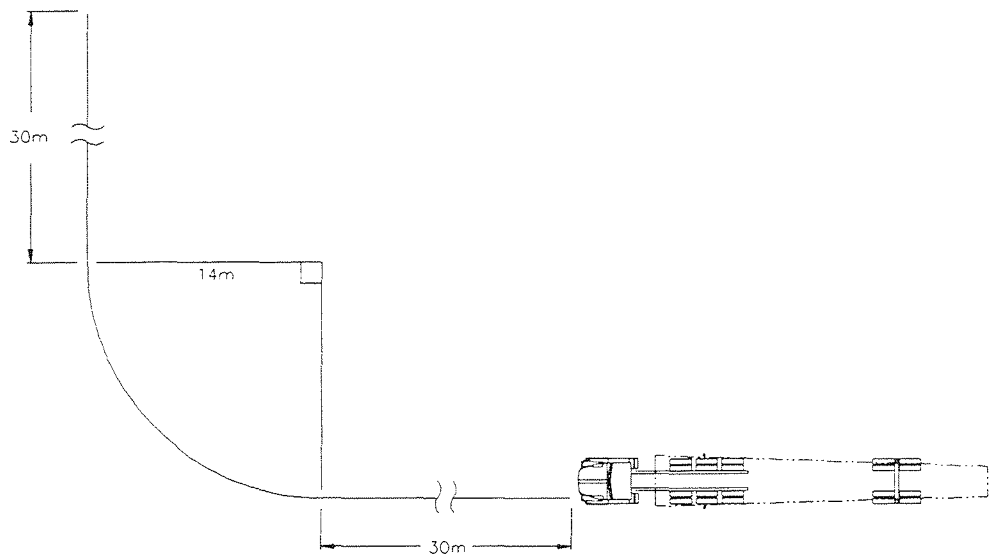


Figure 3. Steering response test path.

Figure 4. Path-following guide for driver's reference.

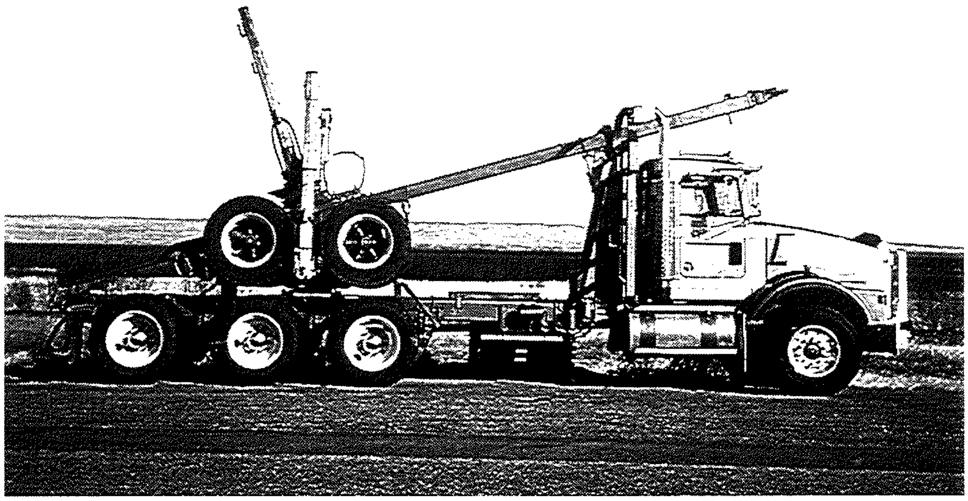


Figure 5. Tridem tractor and empty pole trailer.

Table 1. Weights for Steering Tests, by Axle Group.

Loading conditions	Steering axle		Drive axle group		Trailer axle group	
	Licensed (kg)	Actual test (kg)	Licensed (kg)	Actual test (kg)	Licensed (kg)	Actual test (kg)
Tandem[a]						
Empty		5 310		11 570		
Alberta summer weights	6 100	4 940	17 000	18 490	17 000	16 930
Alberta winter permit weights	6 100	5 130	25 000	25 440	25 000	25 500
Tridem[b]						
Empty		5 980		11 020		
Alberta summer weights	6 100	6 000	21 000	21 330	17 000	16 620
Alberta winter permit weights	6 100	5 940	27 000	27 070	25 000	24 640
BC weights	6 100	5 980	24 000	23 820	17 000	16 470

[a] (Tandem = tandem tractor / tandem pole trailer) [b] (Tridem = tridem tractor / tandem pole trailer)

two conditions provided an opportunity to observe the effects of increased drive axle loading. For each configuration the log bunk was relocated on the tractor's frame to achieve legal weights on the steering and drive axle groups.

Because logging trucks must operate in challenging tractive conditions on forest roads they are usually equipped with lockable drive axle differentials. When locked, differential action ceases and the left wheels mechanically lock to the right wheels, and the forward drive axle locks to the rear drive axle. While locked differentials do improve traction, they also increase the understeer tendency of a tractor. Typically, these devices are used only at slow speeds and are not normally used when travelling on public roads. With this in mind, the test program was primarily concerned with measuring the steering response in the no-differentials-locked condition; however, measurements were also taken with all of the possible combinations of locked and unlocked differentials. To facilitate testing, the test tractor was provided with five separate switches for locking each of the three drive axles and the two inter-axle differentials (see Description of Test Vehicle). Table 2 lists the combinations of locked/unlocked differentials tested.

For each condition a minimum of three runs were recorded. Typically the test tractor was run three times for a right-hand turn and once for a left-hand turn to ensure that there were no directionally dependent influences. The sample size of three acceptable runs was selected because good repeatability was encountered in the data-collection process and time considerations were a factor. Test runs for the no-lock condition were conducted on both dry and wet pavements, and all runs with one or more locked differentials were performed on wet pavement because testing on dry pavement with locked differentials would impose significant drive line stress and tire wear. The test tractor was equipped with the type of tires typically used in the Alberta log transport industry (Appendix I). Tire pressures for each load/test condition were set at the manufacturer's recommended pressures.

Traction Evaluation

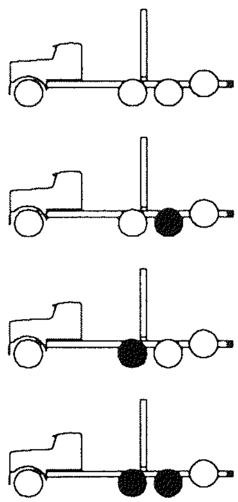
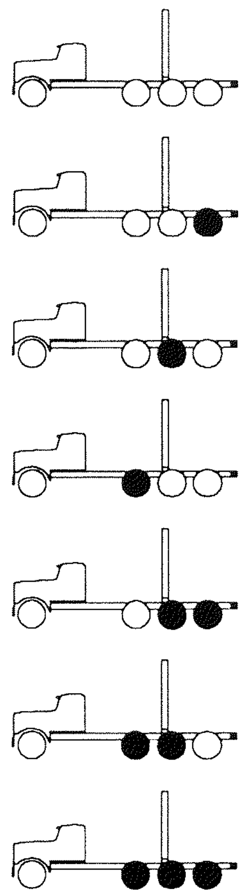
The relative tractive abilities of the tridem and tandem tractors were compared using a tractor-pull sled in combination with a load cell (Figure 6). The sled is designed to increase its drawbar force demand progressively by transferring weight forward on its frame as it travels. Figure 7 illustrates the load cell and the sled towing linkage. The tow lines were attached to the tractor at the height of the drive axle centreline (55 cm above ground) to minimize the influence of a drawbar moment on traction.

A Campbell Scientific CR10 data logger recorded the output from the BLH Model U362 load cell at a scanning rate of 10 Hz. The test tractor was ballasted to achieve the desired drive axle loadings as shown in Table 3.

Tire inflation was adjusted according to the manufacturer's recommended pressures, and tire footprint measurements were taken for each loading condition. Tread depth measurements were recorded at the beginning and end of the test program. As described in the methodology for the steering response test, the drive axles are equipped with driver-controlled locking differentials to improve tractive ability in adverse off-highway conditions. Test measurements were taken both with all drive-axle differentials locked and with all unlocked. The gravel-surfaced test area at an AT&U highway maintenance yard was prepared initially by drag-blading with a utility tractor.

The test run pattern began in one corner, and proceeded in a straight line along the length of the yard to its end. The truck and sled would then reverse to the start-end of the yard, move to an adjacent

Table 2. Differential Lock Combinations for Steering Tests

Tandem version of test truck with third axle lifted	Tridem test truck
	
○ Unlocked differential	● Locked differential

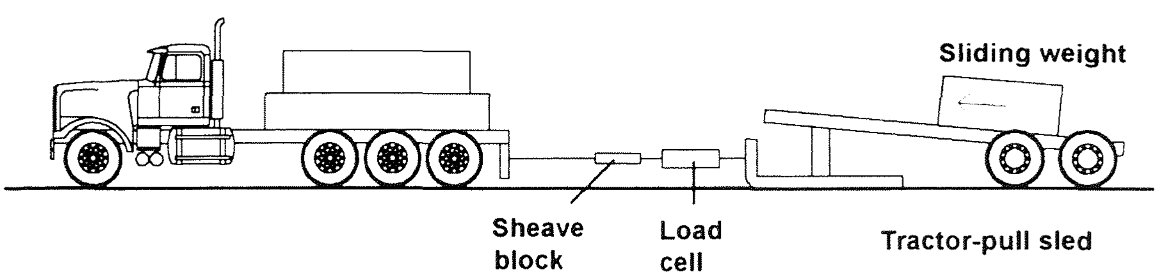


Figure 6. Test truck pulling tractor-pull sled.

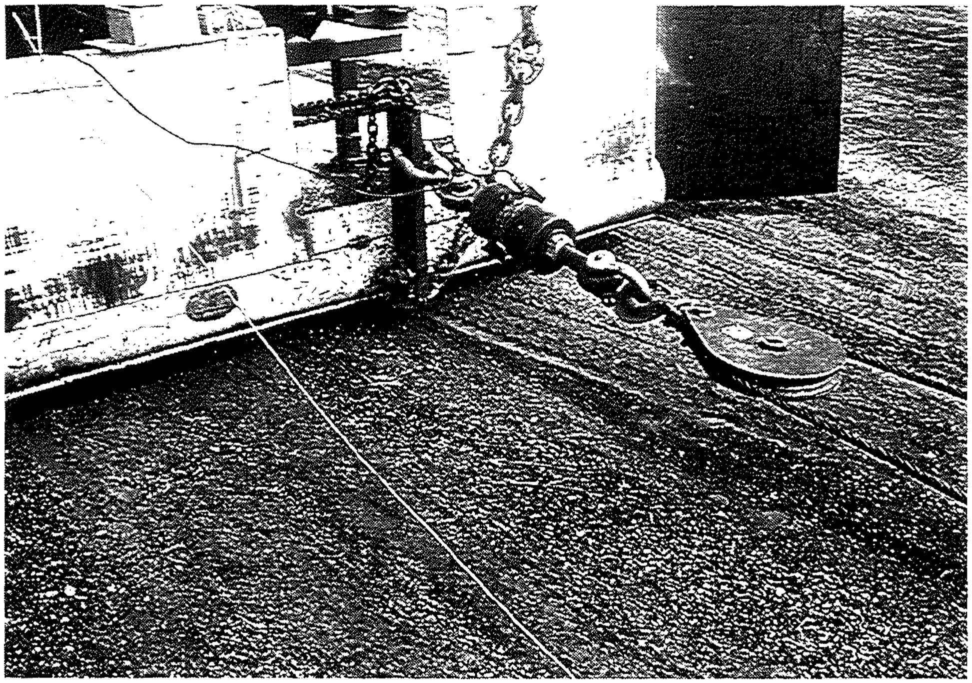


Figure 7. Sheave block and load cell assembly.

Table 3. Drive Axle Weights for Traction Evaluation.

	Weight on group (kg)	Weight per axle (kg)
Tandem	9 430	4 715
	13 980	6 990
	17 000	8 500
Tridem	14 210	4 737
	21 010	7 003

lane, and repeat the process. Once the surface had been completely used for testing it was again drag-bladed and made ready for another series of runs. Low gear was used exclusively throughout the testing and the engine was set at the peak governed speed of 2100 rpm, yielding travel speeds of less than 10 km/h prior to the engine stalling.

RESULTS AND DISCUSSION

Operational Experience

The Vanderwell fleet comprises 18 log-hauling trucks, including 5-axle tractor / pole trailer combinations, 7-axle tractor / tandem jeep / pole trailer combinations, and the test vehicle—a 6-axle tridem tractor / tandem pole trailer combination. The first two combinations are the most common log-hauling vehicles operating in Alberta today. Weigh scale data for 5968 loads from the hauling season of November 1993 to June 1994 are summarized in Table 4 for the three combination types. As expected, the 6-axle tridem combination carried average seasonal payloads that were between those of the 5-axle and 7-axle units. The replacement of the tandem pole trailer with a tridem pole trailer would improve the productivity of the tridem tractor and still satisfy the single articulation requirement. At a projected tare weight of 18 400 kg, and with summer regulations, such a combination would potentially carry payloads equivalent to the average for the 7-axle combination with the tandem jeep. As well, the tridem/tridem combination would encourage a more balanced load distribution (i.e. mixing of butts and tops within the load) between front and rear bunks; in turn, this lowers the load's centre of gravity location and improves the roll stability of the combination.

Most of the tridem tractor drivers voluntarily praised the braking ability of this vehicle relative to any others they had operated. Because most braking occurs under non-emergency conditions it is not likely that the ABS influenced their favourable impression (the other trucks were not ABS equipped). A more likely explanation relates to the simpler chassis configuration of the tridem drive vehicle. Traditionally, axles have been added to the basic 5-axle tandem tractor/tandem pole trailer by means of introducing another chassis component to the configuration, such as a tractor jeep or a triaxle trailer dolly. Tridem axle groups are a means of adding axles without adding chassis components, which simplifies the brake system and improves brake balance and timing relative to vehicles configured with three or more chassis elements. Furthermore, a balanced application of brake forces through all wheels to the road surface is more likely to occur when there is even load distribution between axles such as occurs on tridem axle groups. Compared to the braking behaviour of 5-axle configurations, the tridem tractor combination may feel more responsive in that less application pressure is required to generate the needed brake torque for the customary sense of deceleration; for the 10% more gross vehicle weight, the tridem has approximately 20% more braking capability.

The vehicle monitoring period ended May 31, 1994. At that time the tridem tractor had accumulated 185 079 km in log-haul service. A review of the repair history to that point indicated that $1200 had been spent on repairs that were directly related to tridem components (Table 5). Most notable were

Table 4. Load Data from Vanderwell Truck Fleet

	Combination type					
	5 axle		7 axle		6 axle tridem	
Season	Weight (kg)	Loads in database (no.)	Weight (kg)	Loads in database (no.)	Weight (kg)	Loads in database (no.)
Summer weight regulations		255		109		14
Average gross weight	41 777		53 655		44 856	
Average tare weight	16 436		20 746		17 864	
Average payload	25 341		32 909		26 991	
Winter weight regulations		4146		1240		204
Average gross weight	52 930		61 771		56 971	
Average tare weight	15 737		19 420		17 711	
Average payload weight	37 193		42 351		39 260	

Table 5. Repair Details: Tridem Drive and Suspension System.

Date	Odometer	Description	Total cost
January 6, 1993	5000 km	Replace right side air spring, and left side attachment bracket, on rearmost drive axle. Labour: $250. Parts: $400.	$650
November 25, 1993	74 763 km	Replace right side attachment bracket on front drive axle, and reinforce right side attachment bracket on centre axle. Labour: $300. Parts: $250.	$550

repairs to the suspension attachment at the axle; a reinforcement of the bracket has relieved the problem. Other repairs to the on-board weigh scales, fuel injectors, radiator, and alternator, as well as routine preventive maintenance, were not considered relevant to the study. The drive tires were replaced after 75 000 km of use which is considered normal service for this fleet.

The drivers of the tridem combination reported no handling problems in terms of operating with a longer-than-usual wheel base, nor were any problems with steering responsiveness reported. Once accustomed to the tractive performance of the tridem drive system, drivers found that tire chains were unnecessary in poor road conditions. When especially poor sections of forest roads presented the possibility of traction loss, the differential locks were momentarily engaged by the driver by means of the dash switches; depending on the severity of the situation the driver would lock either one, two, or all three differentials. Because of the increase in understeer when the locks are engaged, the drivers used this option conservatively. Rockwell International, the manufacturer of the drive axles, publishes a Driver Instruction Kit (Rockwell 1991) to guide in the use of these mechanisms. From the general perspective of a logging operations manager or planner, the benefits of improved tractive ability include: less need to have a towing support machine on site; fewer interruptions of traffic flow because trucks do not spin-out on slippery grades and block the road while waiting for assistance; reduced driveline failures; and, forest road grade construction becomes less critical. In addition, if the chaining activity is eliminated, truck cycle times are reduced. Although cycle time reductions can be expected to reduce operating costs, this is only a direct benefit when it allows an extra trip per day. Specific hauls and rate structures will benefit differently as a result of cycle time reductions; an analysis of this is beyond the scope of this study.

In Alberta the log-hauling regulations permit log loads to be 4.8-m high and 3.2-m wide at the front bunk. When the tridem combination was loaded to this extent the drivers were favourably impressed with the roll stability when negotiating corners compared with previous experiences on tandem units, although the tridem group was generally loaded with 2000 kg more. This was likely a result of three influences: 1) the wide-track drive axles (approximately 16-cm wider than conventional) theoretically raise the rollover threshold by 5-6% as reported in the feasibility study (Amlin 1991); 2) the even distribution of load across three axles, which provided 50% more roll resistance than the usual two drive axles; and 3) the load per drive axle is less (i.e. a total of 9000 kg in the tridem group and 12 500 kg in the tandem group under the Alberta winter weight permit conditions). By means of computer simulation the following rollover thresholds have been estimated for Alberta winter weight permit conditions: tandem tractor / tandem jeep and pole trailer, 0.304 g; tandem tractor / pole trailer, 0.333 g; and tridem tractor / pole trailer, 0.348 g. These estimates support the drivers' comments.

Steering Response Comparisons
A series of test runs to measure steering response was conducted in September 1993 at the AT&U weigh scale and truck inspection station near Slave Lake. Lateral force measurements form 168 runs were recorded and analysed for the various combinations described in Tables 1 and 2. Following the test, the conversion of the instrumentation output to force values resulted in forces that were significantly higher than expected and beyond the values of aligning force that could be developed at the steering tire road interface. However, this discrepancy was consistent throughout the test and the instrumentation output is used in a comparative analysis. The steering test results are presented on relative scales in Figures 9-12. Each figure has a baseline representing 100%, i.e. the lateral force measurement recorded at the rear shackles of the baseline tractor's steer axle suspension.

The no-differentials-locked condition is the first order of interest because heavy trucks normally operate on the public highways in this condition. Figure 8 illustrates the test results for this condition on dry pavement. All tractors, in this condition, followed the test path without exceeding the available friction force at the steering tire/road interface.

The no-differentials-locked tests were repeated on a wet surface (i.e. a lower friction surface) and the relative results are illustrated in Figure 9. Again all tractors in this condition followed the test path successfully.

In the above dry and wet surface tests there was a direct relationship between drive group loading and the aligning force generated. An exception was the tridem tractor during the dry tests where an increase in drive axle loading (from Alberta summer weights at 21 330 kg/drive group to BC weights at 23 820 kg/drive group) resulted in a small increase in aligning force (Figure 8). The cause of this exception is unclear.

Figure 10 is a summary of all the test runs for the Alberta summer weight loadings. The baseline tractor for this figure is the same as in Figure 9. Results include wet and dry runs with various differential lock combinations. Contrary to expectations, the aligning forces for the tandem and tridem did not consistently increase as the locking of differentials moved forward. This suggests that other factors are influencing the results; one possibility is that the tractor's effective turn centre (pivot point) relocates as a result of a locked differential. Investigation of this is beyond the scope of the study, however. The tridem with two differentials locked simultaneously (the middle and rear) remained on track with aligning forces 149% greater than Figure 10's baseline; whereas, the tandem tractor, at 123% above baseline with both differentials locked, was unable to complete the turn. The tandem slipped from the turn at a lower aligning force as its steer axle loading was lower than that of the tridem. The tandem's steer axle load was targeted to be the same as that of the tridem at 6100 kg (Table 1), but was loaded only to ~5000 kg. This underloading affected the results for the tandem tractor when it was unable to negotiate the test turn. Steer axle load is directly related to the maximum aligning force (friction force) that can be developed at the steering tire/road interface. The other double and triple differential lock combinations for the tridem were unable to remain on the path, i.e. when the aligning force reached 158-169% above baseline.

Figure 11 summarize all of the runs for the Alberta winter weight loadings. The highlighted locked differential combinations were unable to negotiate the turn. When the middle differential alone is locked, the tridem does not complete the path-following manoeuvre, but when either the front or rear is locked it remains on track; although this is not the case in the Alberta summer weights results (Figure 10), a similar trend is evident.

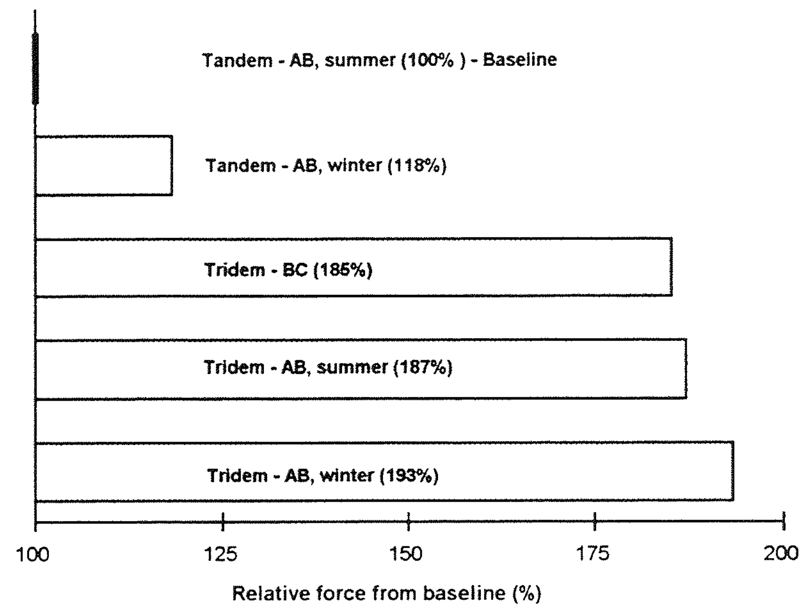


Figure 8. Peak aligning force comparison for dry surface, no differentials locked.

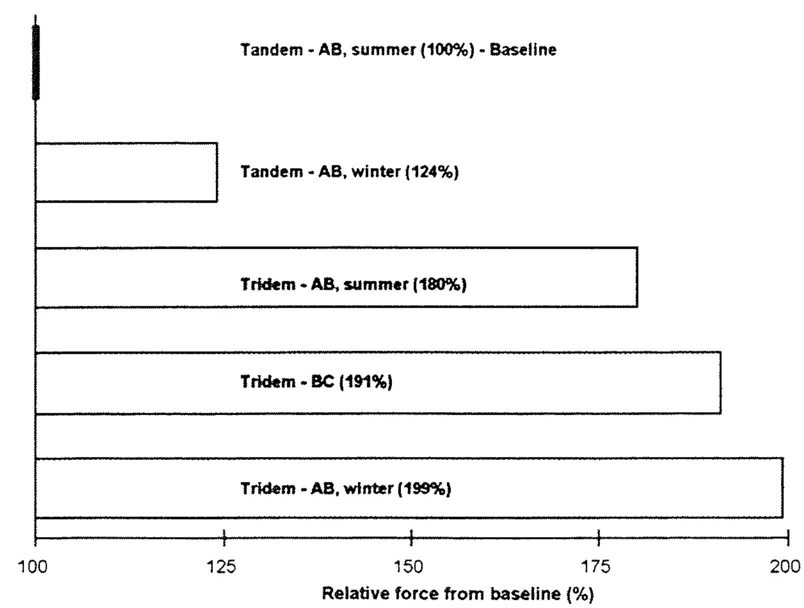


Figure 9. Peak aligning force comparison for wet surface, no differentials locked.

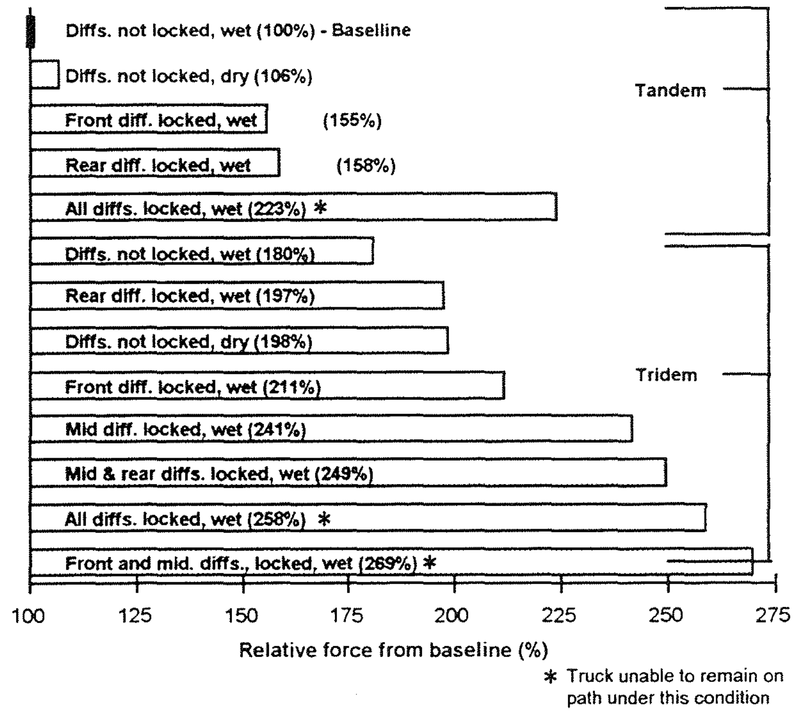


Figure 10. Peak aligning force comparison for Alberta summer weight regulations.

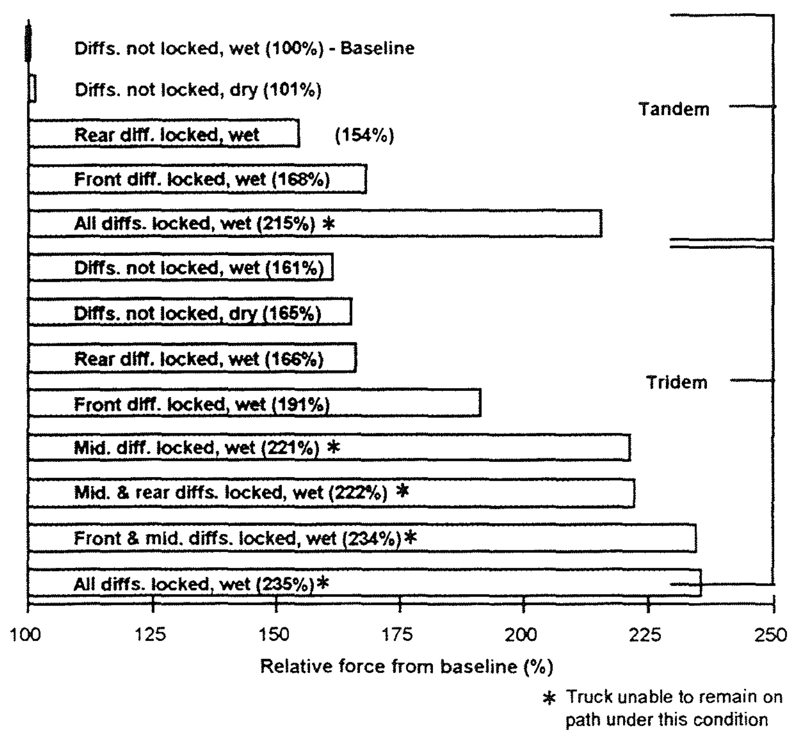


Figure 11. Peak aligning force comparison for Alberta winter weight regulations.

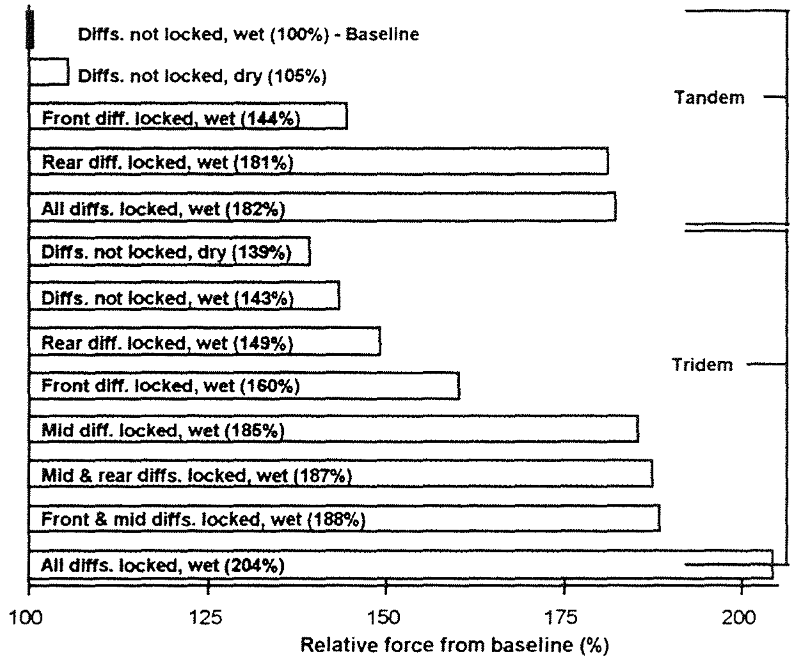


Figure 12. Peak aligning force comparison for empty trucks.

Figure 12 summarizes results for the empty, unloaded conditions. For these runs the trailer is loaded onto the tractor. All tractor/differential combinations completed the path following manoeuvre in this empty condition. Similar to what occurred with the loaded test runs, locking the empty tridem's middle differential resulted in larger aligning forces than locking the front or the rear.

This study provides a first-order measurement of the lateral forces at the spring shackle location and does not necessarily reflect the values at the steering tire/road interface. Because the results require further validation, FERIC does not recommend their direct application to characterize the friction demand at the steering tires.

Traction Evaluations

A series of trials was conducted to determine the peak drawbar forces generated by a tandem drive axle and a tridem drive axle tractor with differentials both locked and unlocked and under a variety of loads. The trials took place at a site provided by AT&U near Leduc, Alberta in April 1994. Table 6 illustrates the average peak drawbar forces recorded during 109 test runs for the various combinations. These results, although specific to the gravelled surface on which the tests were conducted, illustrate the relative performance of the two tractor types, and they can be adjusted for other surface types or used in gradeability calculations. In all cases during these trials, spin-out occurred as a result of the gravelled running surface failing under high shear forces; in other words, the tires were digging into the surface and spinning out gravel rather than exceeding the available friction at the tire/surface interface. This type of spin-out or traction loss is typical of log-hauling operations on unfrozen gravel roads.

Figure 13 compares the tandem and tridem tractors' drawbar performances with their respective maximum drive axle loadings allowed under the Alberta summer weight regulations. The tandem

Table 6. Average Peak Drawbar Forces

	Weight/axle (kg)	Weight/group (kg)	Average peak forces Differentials locked (kN)	Differentials unlocked (kN)
Tandem	4 715	9 430	58.7	59.8
	6 990	13 980	88.4	85.4
	8 500	17 000	106.4	107.9
Tridem	4 737	14 210	91.6	74.2
	7 003	21 010	136.6	105.3

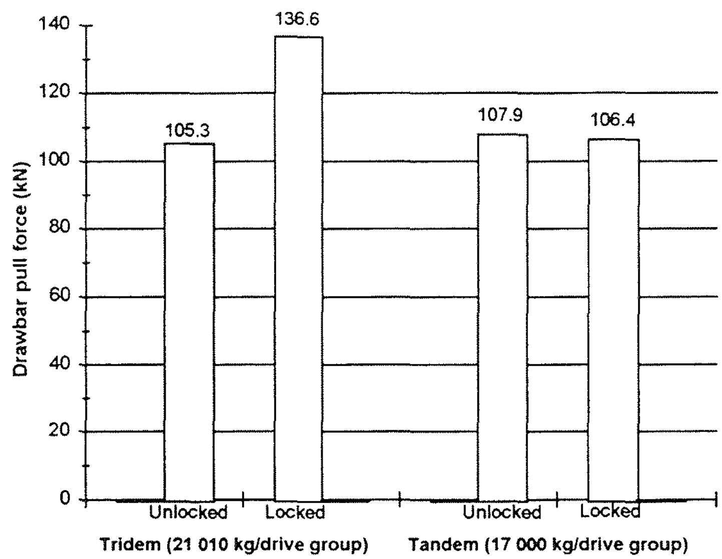


Figure 13. Comparison of drawbar force for the unlocked and locked differentials, legal loads on drive groups.

has nearly the same performance with the differentials locked or unlocked. The flatness and uniformity of the test surface is the likely reason because at spin-out all four wheels, in both cases, were simultaneously rotating and the longitudinal forces applied to the surface would be approximately equal; surface consistencies as such are seldom encountered in off-highway log-hauling operations especially where poor traction conditions exist. The tandem results were matched by the unlocked tridem although its individual axle loads within the group were 1497 kg less.

With differentials unlocked, torque distribution between tandem drive axles is typically a 50%/50% split. However, on a tridem, the torque is distributed 50%/25%/25% from front to rear within the group. With this uneven torque distribution, initial spin-out would be expected to occur on the front axle of the tridem group, and this was confirmed during the tests. However, as drawbar force is proportional to axle loading, and because the tridem's front drive axle is usually under a lighter load than either axle of a tandem group, one would expect tridem axle spin out to occur at drawbar pull forces below those of tandem groups; this was not the case as results were nearly identical, and further study is required to clarify this. With all differentials locked, the tridem generated 28% more drawbar pull than the tandem.

When drawbar test results with equal axle loads are compared, the tridem's performance increases significantly relative to the tandem as illustrated by the averaged results depicted in Figures 14 and 15. For this particular surface, the tandem yields about the same results whether or not the differential locks are used; this is not the case for the tridem which improves its performance when differentials are locked by 30% and 23% respectively for 7003 kg and 4737 kg axle loads. The tridem demonstrates 55% to 56% more drawbar pull than the tandem when the locked condition is examined. The drawbar pull results can be expressed in terms of tractive coefficient (μ), which is defined as drawbar pull divided by the drive axle group weight. The tractive coefficient can be used to predict gradeability in truck performance models. Using the tractive coefficient obtained from the trials, gradeabilities have been estimated for a tridem and a tandem drive tractor with identical gross vehicle weight combinations (Table 7).

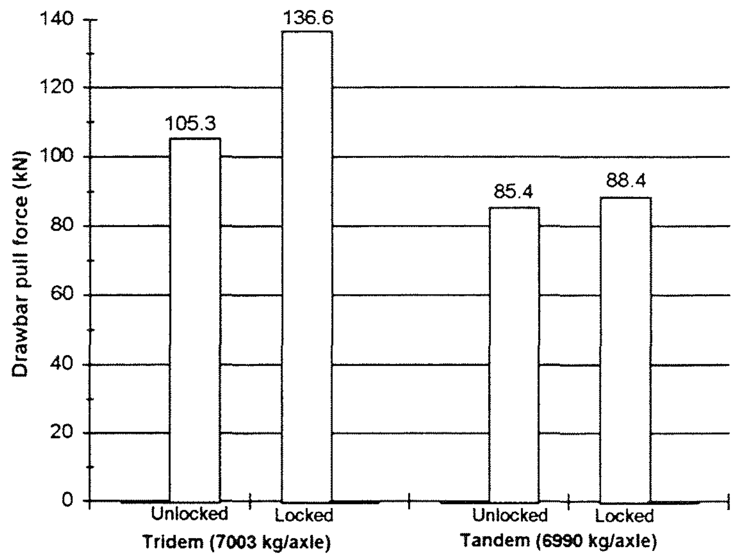


Figure 14. Comparison of drawbar force for unlocked and locked differentials, similar axle loads.

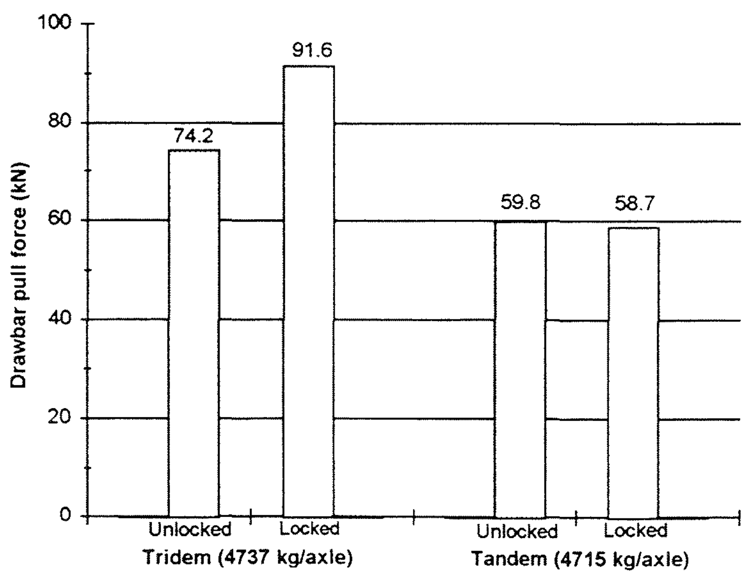


Figure 15. Comparison of drawbar force for unlocked and locked differentials, similar axle loads.

Table 7. Gradeability Comparisons for a Firm, Packed, Gravel Surface (μ=0.65)

	Alberta winter weights		Alberta summer weights	
	GVW (kg)	Gradeability (%)	GVW (kg)	Gradeability (%)
Tridem tractor/ tandem pole trailer	58 100	30	44 100	31
Tandem tractor/ tridem pole trailer	58 100	28	44 100	25

CONCLUSIONS

In response to the recommendations of the feasibility study conducted in 1989, FERIC initiated an operational evaluation of a tridem tractor in Alberta. A Kenworth model T800 tractor with a tridem drive axle group began regular log-hauling service in December 1992 as part of the Vanderwell Contractors (1971) Ltd. fleet in the Slave Lake region of Alberta. FERIC monitored the truck's productivity and maintenance requirements and conducted tests to compare steering responsiveness and tractive ability with those of a conventional tandem drive tractor.

The tridem tractor was operated by six different drivers and accumulated 185 079 km over the trial period which ended in May 1994. All drivers reported tractive improvements that overcame their requirement for tire chains during challenging winter road conditions. They also reported that there were no steering response concerns with respect to influence of the three fixed driving axles. Furthermore, the roll stability of the tridem tractor was felt to be better than that of tandem axle tractors, and the drivers perceived better braking performance.

Over the monitoring period of 1.5 years, $1200 was spent on tridem related maintenance including the driveline and suspension. In addition, the 12 drive axle tires were replaced after 75 000 km of use and again at 155 000 km which closely compares to this fleet's experience with tandem drive axle tractors. Because these expenditures are considered minimal for this type of operation, maintenance costs are not a concern for this particular truck at this time. However, for the long term, component life and the maintenance implications of tridem drives are unknown.

The payload averages for the tridem tractor / tandem pole trailer (6-axle) combination fell between those of the 5-axle and 7-axle averages, as was expected. This level of productivity, although acceptable in terms of this operation, could be improved by replacing the tandem axle pole trailer with a tridem version; this would also better utilize the tractive potential of the tridem tractor. As well, a 7-axle tridem tractor / tridem pole trailer configuration, by virtue of its single articulation point, is more desirable in terms of dynamic stability than the 7-axle tandem jeep / tandem pole trailer configuration with two articulation points.

Compared to the tandem drive tractor, the three fixed axles in a tridem grouping increase the aligning forces when differentials are unlocked, but these levels remain within the ability of the tractor to negotiate a tight turn on pavement.

The aligning force generated by the drive axle group of either tractor type increases when the load carried by the group is increased. The aligning force decreases as the surface coefficient of friction decreases, i.e. from dry to wet pavement.

Logging trucks are equipped with locking differentials as a driver-selected aid to improve traction under severe conditions. When differentials are locked, an aligning force is generated that increases the understeer characteristic; in general, both the tridem and tandem drive axle tractors exhibited aligning force increases directly proportional with the number of locked differentials. It is important to note that the practice of locking differentials is usually limited to use on forest roads because of the challenging grades and poor surface conditions. Because the public road system does not present these types of traction demands, especially for slow-speed tight turns (i.e. intersections are zero grade), differential locks are not employed, and therefore steering is not adversely affected.

The tandem tractor could not complete the path-following manoeuvre with both differentials locked except when in the empty mode. However, the tandem tractor's steer axle was underloaded during the steering tests. The target steer axle load was 6100 kg while the actual test loads were ~5000 kg. The tandem tractor slipped prematurely because steer axle load is directly related to the amount of aligning force that can be generated at the steering tire/road interface. With either one of the differentials locked, the tandem successfully negotiated the turns under all of the loaded conditions.

With either the front or rear differential locked, the tridem tractor was able to complete the turns under all loaded conditions. With the centre differential locked and under winter weight loading, the tridem tractor was unable to follow the prescribed path; as well, this was the case when any two or all three differentials were locked simultaneously. When in the empty mode, the tridem tractor successfully negotiated the path-following manoeuvre with all of the differentials locked or unlocked.

A series of trials was undertaken to compare the traction of a tridem and a tandem tractor under a variety of axle loads and conditions of differential locked and unlocked. The tridem tractor had more drawbar pull than the tandem version; the improvement ranged from 28% to 55% depending on axle loads and the number of differentials locked.

RECOMMENDATIONS

This study found that tridem drive tractors would be suitable for log-hauling applications in Alberta for combinations similar to those evaluated during this trial; specifically, tractor/trailer combinations utilizing a single articulation point, a tractor wheel base with a minimum dimension of 6.6 m, a drive axle group inter-axle spacing of 1.4 m maximum, a drive axle width of 2.6 m (wide-track type), and a stinger length that is no longer than 2.6 m.

This study provides initial insights with respect to the aligning force values that are present at the connecting point of the truck frame and front suspension. Further testing should be undertaken to isolate the measurements from suspension influences and to extend these values to the tire/road interface to determine such things as friction utilization. This additional testing would also be designed to provide measurements that directly relate to the appropriate Transportation Association of Canada (TAC) criteria of friction demand and slip angle of the steering tires; although TAC previously evaluated a tridem drive vehicle by means of computer simulations (Lam and Billing 1989), this research involved a straight truck configuration with a shorter wheelbase. Also, the relationship of steering sensitivity to wheelbase dimension remains to be quantified through experimental measurement and this should be undertaken to provide a means for deciding the minimum acceptable dimension.

The truck owners and drivers need to ensure that bunks are located to provide proper payload distribution between the steering and drive axle group as this directly influences the steering responsiveness. It is also important that the bunks be relocated in response to the seasonal changes in Alberta's weight regulations.

This study identified that locking only the middle axle of a tridem group caused the highest steering aligning force when compared to locking either of the other axles. Because the truck manufacturer provides for selective locking of any of the differentials, drivers who choose to lock a single differential should avoid the option of locking only the middle.

Although it is generally the practice, it should be emphasized that the locking of axle differentials imposes additional demands on steerability and this option should be avoided except where required for climbing hills.

Tridem groups offer some inherent benefits in terms of load distribution and they are a means of adding axles to the basic 5-axle log-hauling configuration without increasing the number of articulation points. Compared to tractor/jeeps, triaxle trailers, or dog-loggers, the even-load distribution across the three axles of a tridem group provides a more balanced brake system and improved dynamic stability. The magnitude of these improvements should be quantified through further evaluation.

Drive axle manufacturers are encouraged to supply tridem assemblies with even torque distribution.

Further research should be undertaken to investigate why the aligning force does not increase as the locking of differentials moves forward.

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APPENDIX I

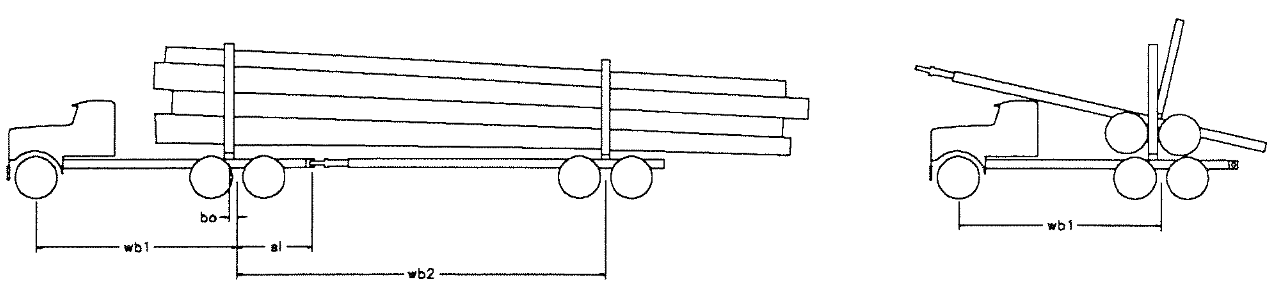
Selected Specifications of the Test Tractor

Table I-A. Selected Components of the Test Tractor

Tractor type[a]	Kenworth T800 tridem drive axle
Engine	Cummins N14-460E, governed @ 2100RPM
Transmission	Fuller RTLO 18 speed
Rear axles	Rockwell RZ-53-166 (wide track)
Rear axle ratio	4.30:1
Rear axle suspension	Neway Tridem ARD-ST-369 69K
Rear axle spacing	1.4 m
Steer tires	Michelin XZY 12R24.5
Drive tires	Michelin XM + S4 11R24.5
Antilock brake system	Rockwell / Wabco - 4 channel

[a] During testing, the tridem tractor, with the third axle lifted, was used to simulate a tandem tractor.

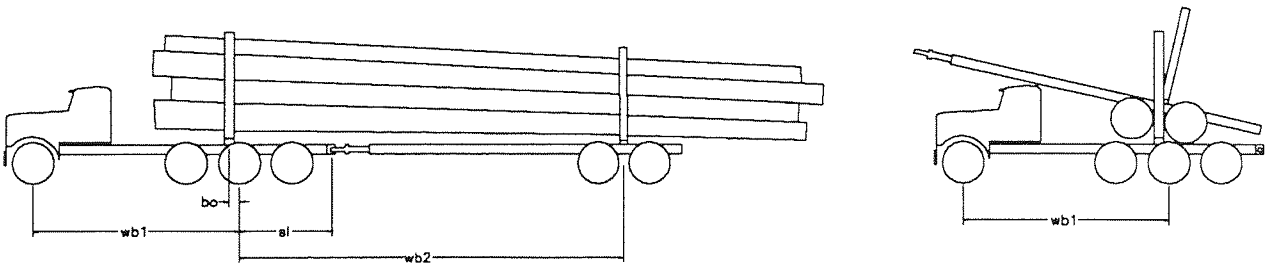
Table I-B. Dimensions of the Tandem Tractor / Tandem Pole Trailer



Loading condition	wb1[a] (m)	bo[b] (m)	sl[c] (m)	wb2[d] (m)	bo + wb2[e] (m)
Empty	6.0	-	-	-	-
Alberta summer	6.0	0.15	3.1	11.5	11.65
Alberta winter	6.0	0.15	3.1	11.5	11.65

[a] wb1 = tractor wheelbase. [b] bo = bunk offset. [c] sl = stringer length. [d] wb2 = trailer wheelbase.
[e] bo + wb2 = bunk-to-bunk spacing.

Table I-C. Dimensions of the Tridem Tractor / Tandem Pole Trailer



Loading condition	wb1[a] (m)	bo[b] (m)	sl[c] (m)	wb2[d] (m)	bo + wb2[e] (m)
Empty	6.6	-	-	-	-
Alberta summer	6.6	0.14	2.4	11.2	11.34
Alberta winter	6.6	0.14	2.4	11.2	11.34
BC	6.6	0.14	2.4	11.2	11.34

[a-e] See Table I-B.

APPENDIX II

Instrumentation System

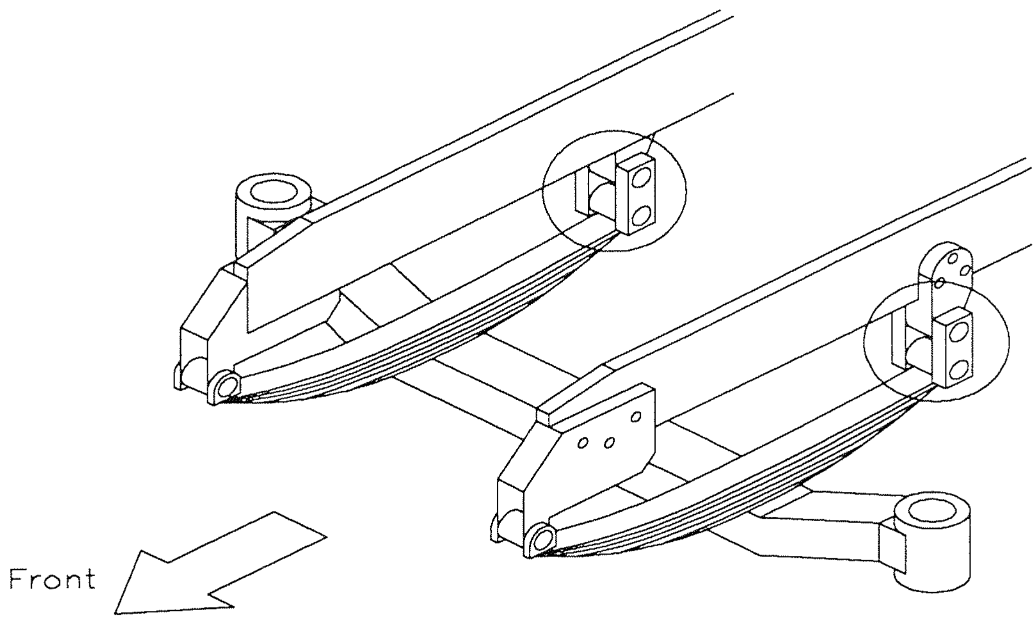


Figure II-A. Location of shackles in front suspension (circles indicate shackle pairs).

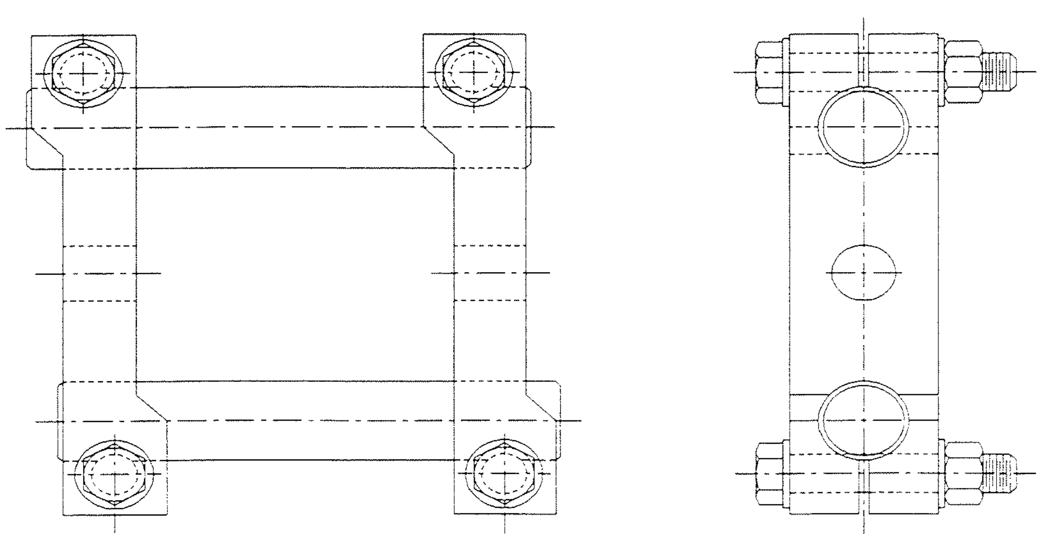


Figure II-B. Detail of 1 of 2 Shackle Pairs (shackles shown are as modified for use as transducers).

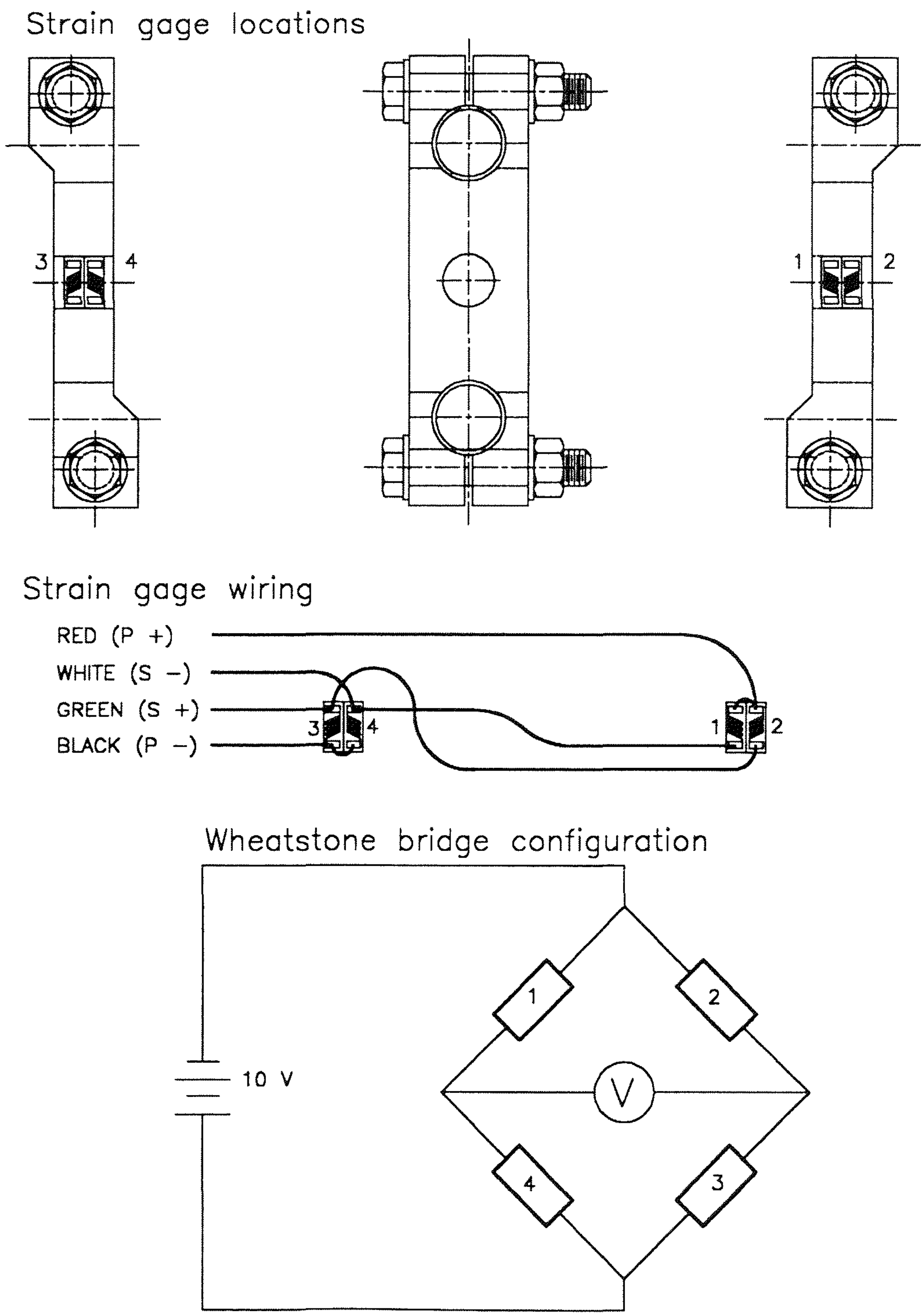


Figure II-C. Detail of shackle transducer design.

Potentiometers and Their Locations
Rotary potentiometers are located on the left and right kingpins of the steer wheels.
Excitation: 5 volts (provided by the AIM1A board in K500)
Transducer output: 0-5 volts

String Potentiometer is located on the tractor-mounted log bunk turntable with the string attached to the rotating bunk.
Excitation: 5 volts (provided by the AIM1A board in K500)
Transducer output: 0-5 volts

Data Acquisition System
Cables: Shielded, twisted pair 4 conductor
Signal Conditioner: Weir-Jones ST41B configured with four channels with a gain of 1000, and a 10-Hz four-pole Butterworth low pass filter
Data Acquisition Module: Kiethley K500 with AIM1A and AIM8 board
Computer: 386 processor with Kiethley Asyst Viewdac software

Calibration Method of the Shackle Transducers
The in-field calibration of the instrumented shackles calibrated the truck front end with respect to known lateral loads. The calibration was carried out in two steps: 1) response of shackles 1+2 to the known lateral loads, and 2) response of shackles 3+4 to the known lateral loads.

The procedure consisted of raising the front end of the tractor, removing the wheels, and, while supporting a hub vertically on one side, disconnecting the axle from the leaf springs on that side. With the use of a fabricated pulling bracket a cable was attached to the opposite hub on the opposite side and pulled upon with known lateral loads. The forces applied were in the direction perpendicular to the tractor frame and parallel with the ground. The pulling bracket was then removed and placed onto the hub which was suspended. Again, a cable was attached and pulled upon with known lateral loads. The shackle transducer readings were recorded. This provided responses from the gauges for forces in both the left and right directions. Because of the calibration method, the responses of 1+2 and 3+4 required averaging to achieve a reading of the external lateral force.