A Study Of The Aligning Forces Generated From A Tridem Drive Axle Group

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ABSTRACT

The log transportation sector of the forest industry in Western Canada is challenged with tractive limitations in the off-highway segment of the cycle. A 1989 feasibility study indicated that a tridem drive axle tractor offers improved traction on the mountainous grades and snowy conditions that are typical of Western Canadian logging roads. Subsequently, a tridem drive axle tractor was built for evaluation purposes; it continues to operate in combination with a pole trailer hauling logs in north central Alberta. Significant traction gains are realized with the tridem over the conventional tandem drive units; however, there are concerns with respect to the influence that the three fixed drive axles have on steering response. The paper discusses the methodology for measuring aligning force values for both the tandem and tridem tractor versions and presents the results of field tests conducted in 1992-1994. Test results include comparisons for wet and dry pavements, and the influences of drive axle differential locks.

INTRODUCTION

In Western Canada, log-transportation costs are often the highest of all the phases of supplying wood to the mills. Log-hauling contractors have attempted to reduce costs by adding axles to trailers to increase the legal payloads. However, with trailers carrying larger 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 to study the feasibility of developing a tractor with three driven axles for log transportation (subsequently referred to here as a tridem* tractor). In 1989, in cooperation with NRC and TDC, FERIC initiated a project to model tractive and dynamic behaviours of various log truck combinations through computer simulations. This project also surveyed the commercially available tridem components and systems that could be adapted to log-hauling vehicles. The computer analysis compared two hypothetical tridem tractors to a baseline tandem tractor in a variety of western Canadian log-hauling configurations. These simulations determined that:

- Tridem tractors have more tractive ability than tandem tractors with equivalent axle loading.**
- Vehicles with single tractor/trailer articulation points*** have superior dynamic stability than vehicles with multiple articulation points (El-Gindy and Woodrooffe 1990).
- The tridem tractor configurations had reduced levels of steering responsiveness that were characterized, during specific manoeuvres, by increased levels of understeer and vehicle response times. The reduced responsiveness resulted primarily from the greater overall spread (i.e. than the tandem) between the front and rear axles in the drive axle group, and from a lower proportion of the total load on the tractor axle being carried by the steer axle.

At the conclusion of the project, FERIC recommended that a tridem tractor be evaluated in revenue service to verify the simulation results, determine operational costs and productivities (Amlin 1992), and better assess the influence of reduced steering response on vehicle performance. In 1992 this recommendation was followed up through a cooperative project involving FERIC, Vanderwell Contractors Limited, Canadian Kenworth Company, the Canadian Forest Service, the Forest Industry Development Division of Alberta Environmental Protection, and Alberta Transportation and Utilities (AT&U).

* 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.

** Simulations were conducted by the Vehicle Systems Development Corporation (Preston-Thomas and Wong 1989).

*** For the purpose of this study an articulation point is the attachment link between vehicle chasis. Examples include pintle hook couplings (in combination with compensating reaches), fifth wheel couplings of tractor jeeps, and turntables that attach the steering axles of a tri-axle or quad-axle to trailer frames. A bunk's pivot (i.e. cup and saucer assembly) is therefore not considered an articulation point.

In Alberta, tridem tractors are a departure from the status quo and as such required evaluation before being licensed for use on public roads. The primary concern is related to potential reduction of steering response in tight turns due to excessive friction demand at the steering tire / road interface. Friction demand for a single vehicle unit is defined as the friction coefficient 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 truck begins a turn. Among other things, aligning force is a function of 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). FERIC set out to monitor the operational performance of the tridem drive 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 work in the Slave Lake Region of Alberta. To minimize 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.

The objective of this paper is to present the methodology and results of the steering trials that were part of this evaluation; the methodology was designed to measure the aligning forces for two- and three-drive axle log tractors in combination with a tandem axle pole trailer (Figure 1) under three different load conditions and to compare the steering response while applying the various drive axle differential lock combinations.

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 Limited 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 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. This vehicle is equipped with an option that is common on logging trucks; the differentials can be locked 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/or the two inter-axle differentials.

To demonstrate other developments in truck technology, the tractor was also equipped with an antilock brake system (ABS) and wide-track drive axles (overall width 2.59 m, compared to the usual 2.44 m); both features enhance truck stability.

The tridem tractor, complete with log bunk rigging and in combination with a tandem axle pole trailer, has a tare weight of 17 300 kg (13 400 kg without trailer), i.e. when clean and without driver. With winter weight regulations (Figure 2), the maximum payload potential for this truck is 40 800 kg. Under the summer weight regulations the maximum payload potential is 26 800 kg.

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, the tandem tractor version had a hitch offset (stringer steering tailframe) of 3.1 m. This

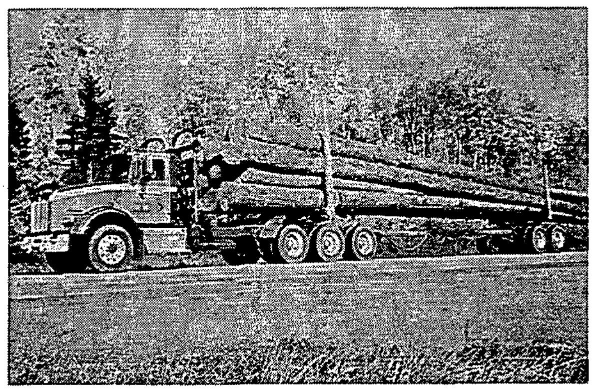
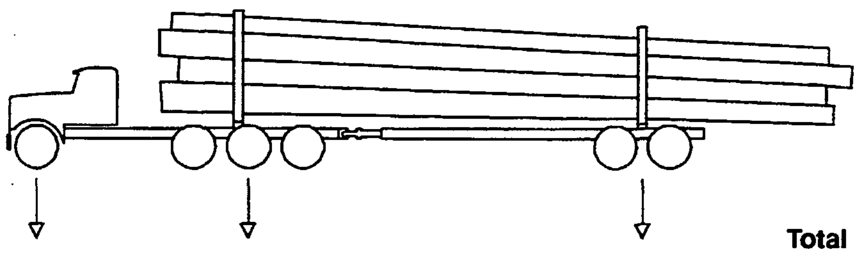


Figure 1. Tridem drive tractor and pole trailer.



				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 configurations in Alberta.

dimension must be considered during steering measurement trials because it directly influences the responsiveness of tractor / pole trailer combinations (i.e. an increase in hitch offset corresponds 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 the single 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 wheelbase of the tridem tractor was 6.6 m (260 in), 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

FERIC developed an evaluation procedure for comparing the ability of the tridem drive test vehicle to negotiate a tight turn with that of a tandem drive vehicle with a similar axle loading and trailer. Steering response was measured by driving each configuration along a 14-m radius curve* at a constant speed, and measuring the side force generated at the front axle suspension throughout the turn. 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** 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. 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 chalkline was drawn corresponding to the pointer's path. A short chain was suspended from the end of the pointer down to the chalkline 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 (Figure 4). The shackles were reduced in cross section, and fitted with strain gages 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 equidistant 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

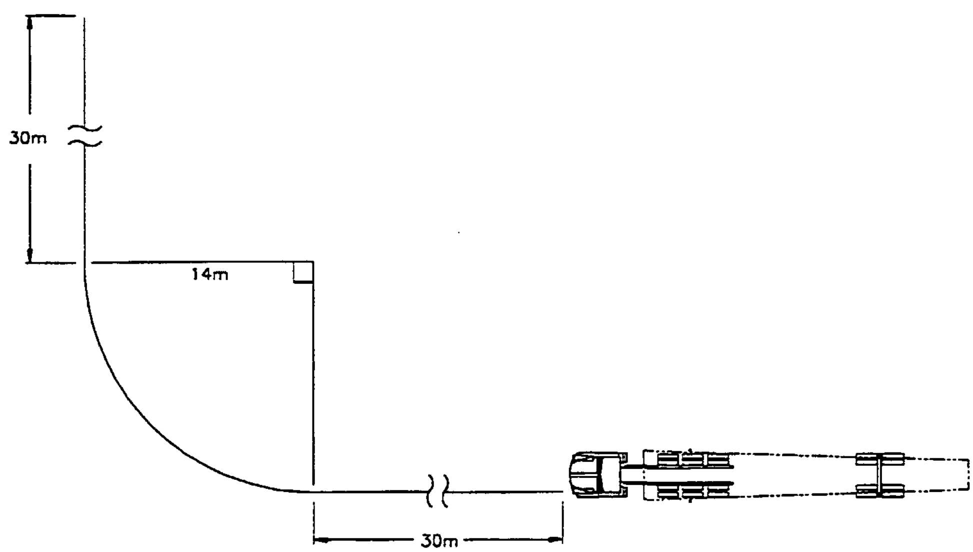


Figure 3. Steering response test path.

* 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.

** Friction test procedures involved towing the μ-meter skid trailer, which contains two rotating test wheels angled (15°) to the direction of motion, over a wetted pavement surface at 64.4kph (40mph) while the two test wheels are under a constant static load. The angled wheels generate a lateral force which is recorded to arrive at the appropriate Skid Number.

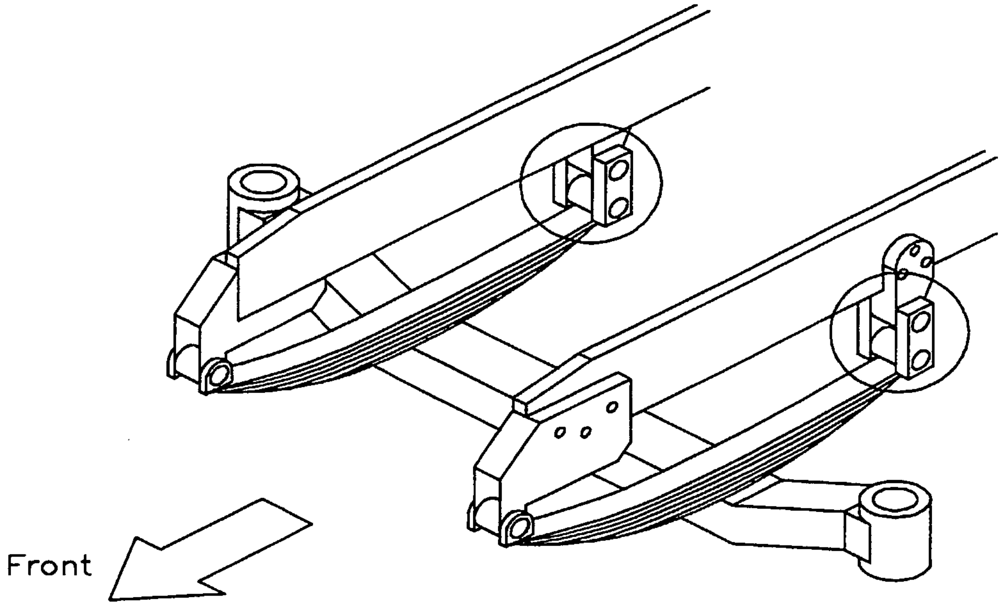


Figure 4. Location of instrumented shackles in front suspension.

turn, the driver held the engine at the governed rpm 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 Kiethley 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.

Before running the steering tests the strain gage 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.

Four different loading conditions were compared: Empty (with the trailer loaded on the tractor) (Figure 5), Alberta licensed summer weights, Alberta winter permit weights, and British Columbia (BC) licensed weights (Table 1). The tridem - 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 only by 20 kg. The 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 forest roads present challenging tractive conditions, logging trucks 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 not normally 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 variety of differential(s) locked/unlocked combinations tested.

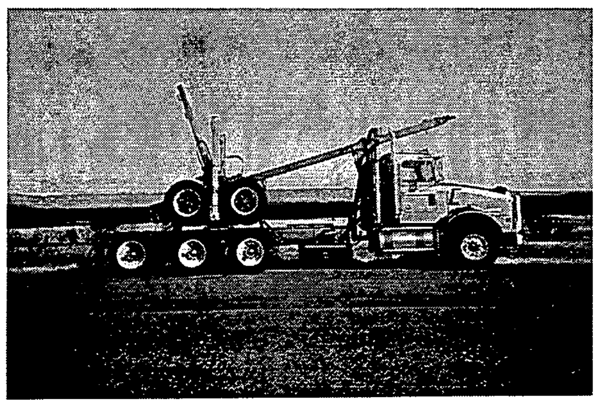


Figure 5. Tridem tractor and empty pole trailer.

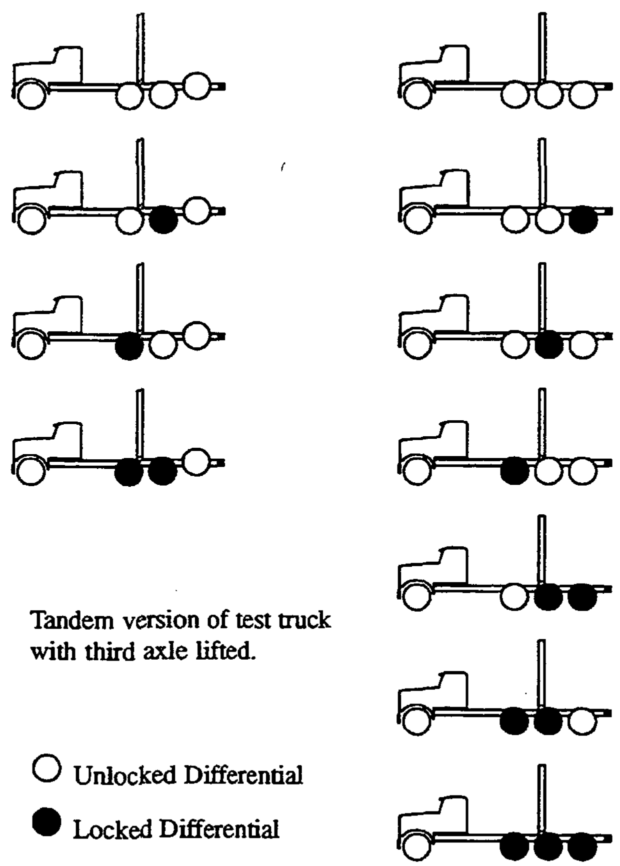
For each condition a minimum of three runs were recorded. Typically the test tractor was run three times for a right turn and once for a left turn to ensure that there were no directionally dependent influences. The sample size of three acceptable runs was selected because good repeatability was encountered in the data collection process and time consid-

Table 1. Weights by axle group for steering tests.

	Axle group					
	Steering axle		Drive axle group		Trailer axle group	
Loading conditions	Licensed weight (kg)	Test weight (kg)	Licensed weight (kg)	Test weight (kg)	Licensed weight (kg)	Test weight (kg)
TANDEM[a]						
Empty		5 310		11 570		n/a
Alberta summer weights	5 500	4 940	17 000	18 490	17 000	16 930
Alberta winter permit weights	5 500	5 130	25 000	25 440	25 000	25 500
TRIDEM[b]						
Empty		5 980		11 020		n/a
Alberta summer weights	5 500	6 000	21 000	21 330	17 000	16 620
Alberta winter permit weights	5 500	5 940	27 000	27 070	25 000	24 640
British Columbia 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

Table 2. Differential Lock Combinations for Steering Tests



erations 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 tires typically used in the Alberta log transport industry: steering, Michelin XZY 12R24.5; and drive, Michelin XM+S4 11R24.5. Tire pressures for each load/test condition were set at the manufacturer's recommended pressures.

RESULTS AND DISCUSSION

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 from 168 runs were recorded and analyzed according to the various combinations described in Tables 1 and 2. The results are presented on a relative scale with the baseline tandem tractor representing the status quo at a value of 100%. In other words, the value of 100% is the peak lateral force measurement made with the rear shackles of the tandem tractor's steering axle suspension, and all other readings for the same conditions are relative to this baseline. Under current Alberta weight regulations, gross axle group weights can increase from summer to winter (Figure 2); both conditions were addressed in the testing.

The no-differentials-locked condition is the first order of interest because heavy trucks normally operate on the public highways in this condition. Figure 6 illustrates the test results for this condition as measured on dry pavement. The baseline reference here is the tandem tractor with a loading of 18 490 kg on the drive axle group; when the same axle group was loaded to 25 440 kg (Alberta winter weight target of 25 000 kg) the aligning force increased by 18%.

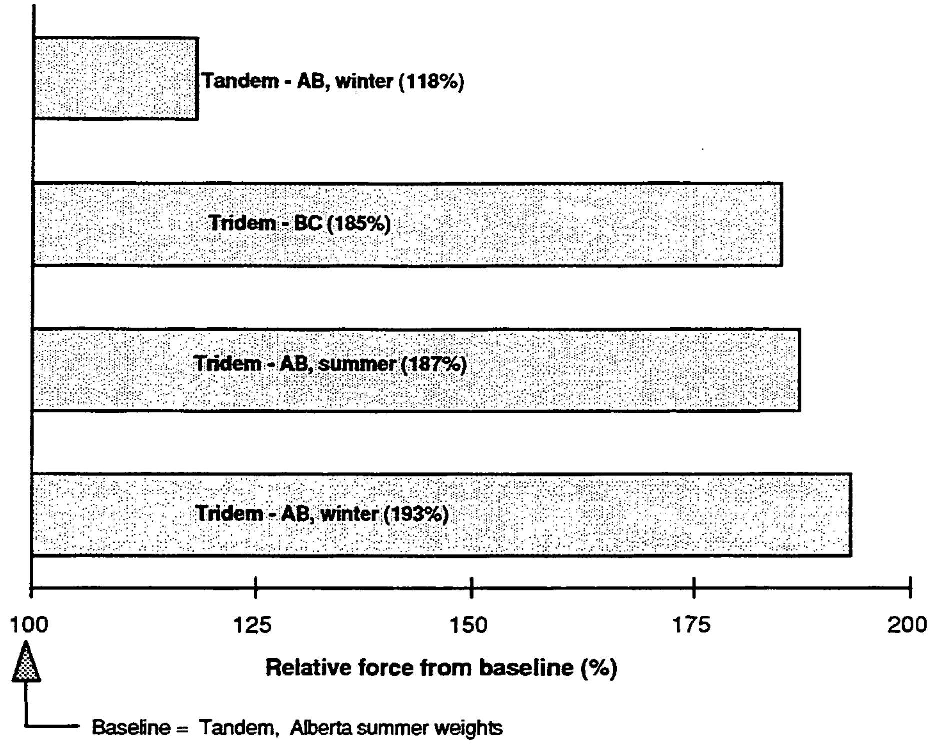


Figure 6. Peak force comparison: dry surface, no differentials locked.

Using the same tandem tractor baseline, the aligning force for the tridem tractor increased by 87% when loaded to 21 330 kg (Alberta summer weight); 85% when loaded to 23 820 kg (a BC reference target load of 24 000 kg); and 93% when loaded to 27 070 kg (Alberta winter weight). In all test cases the truck followed the desired path without exceeding the available friction force at the steering tire/road interface. A difference of 6% in increased aligning force occurred between Alberta summer weights and winter weights for the tridem combination, i.e. compared to the tandem.

The steering response tests were repeated on a wet surface and the relative results are illustrated in Figure 7. The results indicate that the aligning force for the tandem increases by 24% when loaded to a drive group winter weight of 25 440 kg, and the tridem forces are 80%, 91%, and 99% greater for the respective drive group loads of 21 330 kg, 23 820 kg, and 27 070 kg. All tractor versions successfully negotiated the curve during this phase of the wet surface trials.

In both the wet and dry pavement trials there was a direct relationship between loading and aligning force; however, the tridem tractor on a dry surface had an inconsistent increment that could have resulted from minor variations in test conditions, such as surface temperature differences; further study is required to establish the true cause.

Figure 8 is a summary of all the runs for the Alberta summer weight loadings with the baseline reference being the tandem tractor on wet pavement. Included are the results from wet and dry surface runs as well as the runs with locked differential(s). Under wet conditions, the aligning force of the tandem tractor increased 55% when only the front differential was locked, and 58% when only the rear differential was locked. And, under wet conditions, the tridem tractor generated increased forces of 17%, 31%, and 61% for rear, front, and middle locked differentials respectively. It is interesting to note that with both the tandem and tridem, the forces do not necessarily increase as the locking of differentials moves forward. This suggests that other factors are influencing the dynamics of the test; one possibility is the relocation of tractor turn centre (pivot point) due to a locked differential; however, the investigation of this was beyond the scope of this study. It is also important to note that the tridem with two differentials (the middle and rear) locked simultaneously remained on track with aligning forces 149% greater than the baseline tandem tractor, whereas the tandem, at 123% above baseline with both differentials locked, was unable to complete the turn. The other double and triple locked combinations for the tridem were unable to remain on path; when the aligning force reached the range of 158 - 169% above baseline, the friction demand at the steering tires was beyond what the tire/road interface could supply.

Figure 9 summarizes the runs for the Alberta winter weight loadings on both dry and wet surfaces using the tandem tractor on the wet surface as the baseline reference. Included are results from the runs in which tractors with locked differentials in some cases were unsuccessful in following the prescribed path. When the tandem tractor's rear and front differentials are separately locked, the aligning force increases by 54% and 68% respectively; when both are locked simultaneously, the aligning force rose to

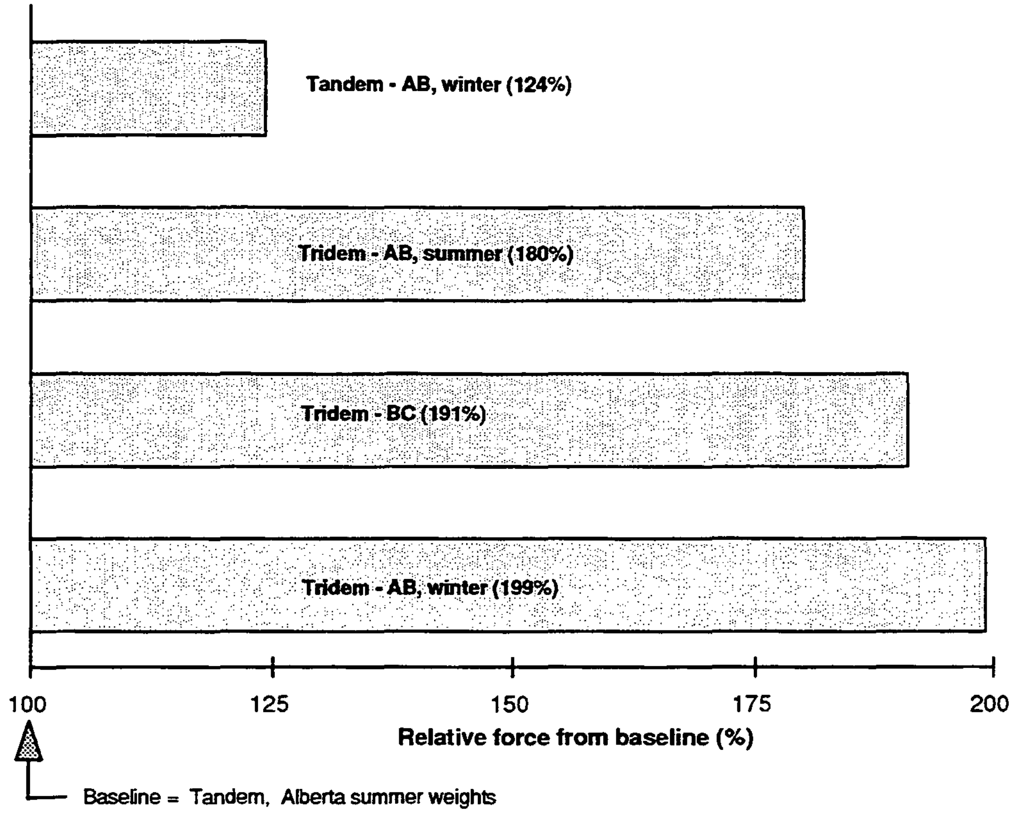


Figure 7. Peak force comparison: wet surface, no differentials locked.

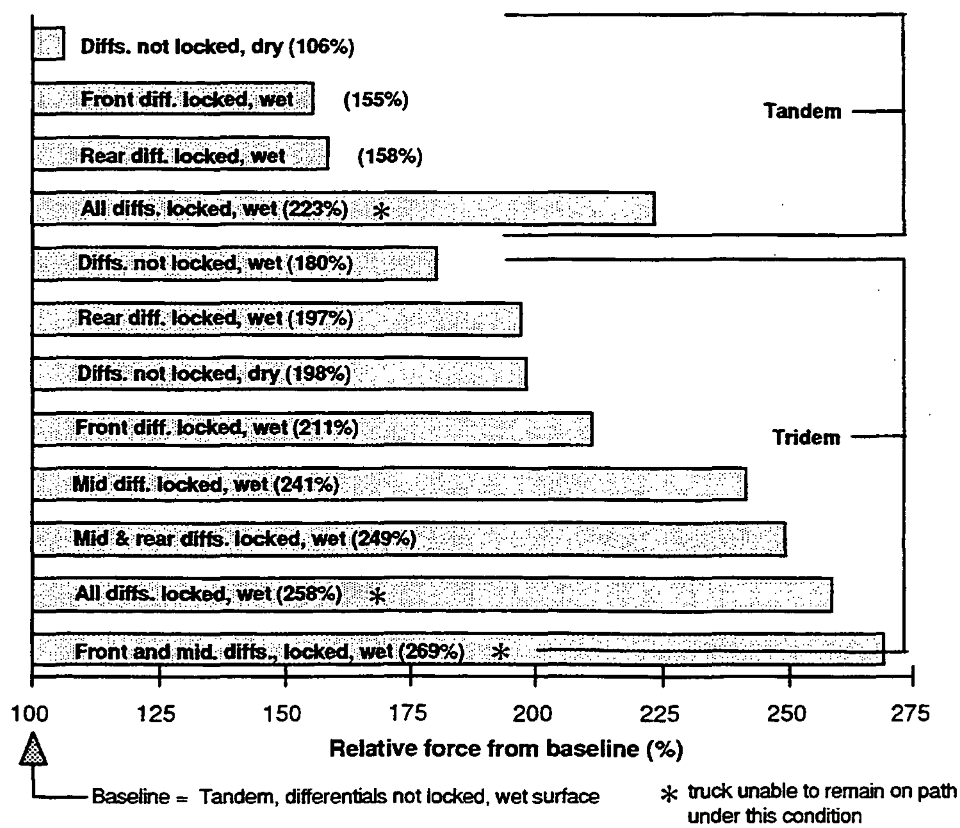


Figure 8. Peak force comparison: Alberta summer weight regulations.

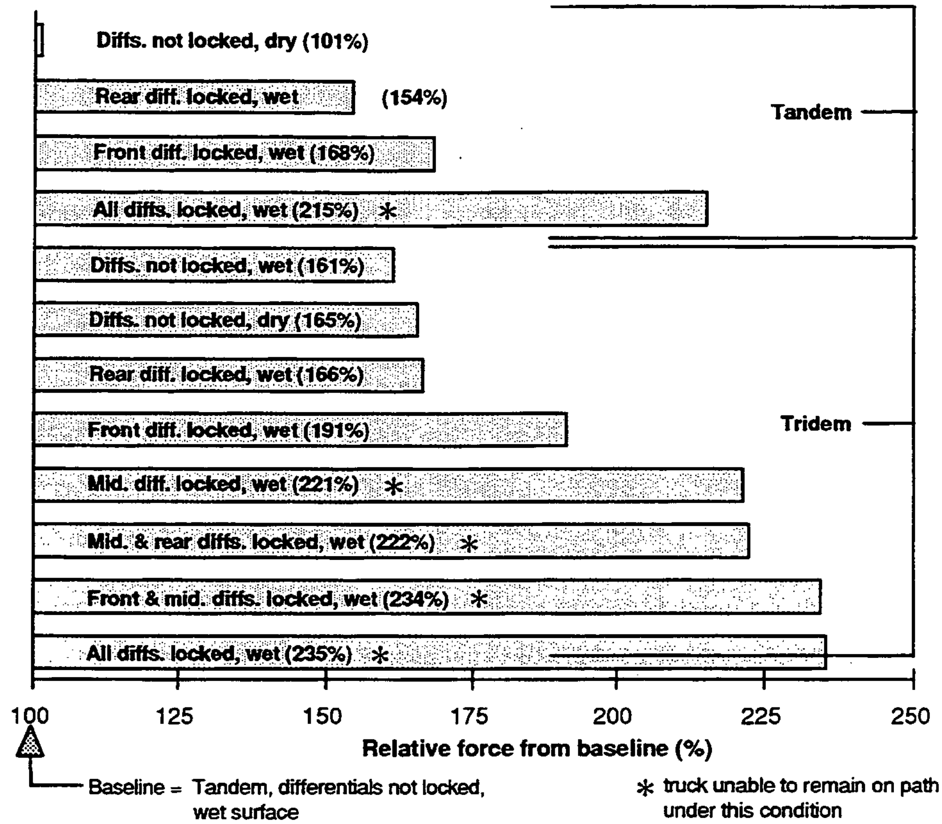


Figure 9. Peak force comparison: Alberta winter weight regulations.

115% above the baseline and it was unable to negotiate the turn. In comparison with the baseline, the tridem tractor on the wet surface with no differentials locked exhibits 61% more aligning force; when the rear and front differentials are locked separately there are increases of 66% and 91% respectively. All other combinations of locked differentials shown in Figure 9 signify the tridem's inability to negotiate the turn for that condition with force values in the range of 121-135% above the baseline. It is interesting to note that 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 with summer weights (Figure 8), a similar trend is evident.

A review of Figures 8 and 9 indicates that the aligning force is reduced as the surface coefficient of friction is reduced (i.e. as the surface changes from dry to wet).

Figure 10 ranks the empty tractors (carrying the trailer), and once again the baseline is the tandem tractor on the wet surface with no differentials locked. During this series of tests both tractor versions under all combinations of differentials locked/unlocked completed the path-following manoeuvre. The tridem tractor with all differentials locked generated the largest alignment force increases, exceeding the baseline by 104%. As shown in the loaded test measurements, these tests also illustrate that the locking of the middle differential of the tridem group generates a higher force than locking either the front or the rear.

CONCLUSIONS

A study of the feasibility of using tridem tractors in log-hauling in Western Canada was conducted by FERIC, NRC, and TDC in 1989 and recommended that a tridem tractor be placed in revenue service and evaluated. In response, 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 Limited fleet in the Slave Lake region of Alberta. FERIC conducted tests to compare steering responsiveness to that 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 that there were no steering response concerns related to the tridem drive axle group.

Although the trials demonstrate that the tridem drive tractor has relatively more aligning force than the tandem tractor, the tridem tractor was able to negotiate the 14-m radius curve on wet 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 payment.

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

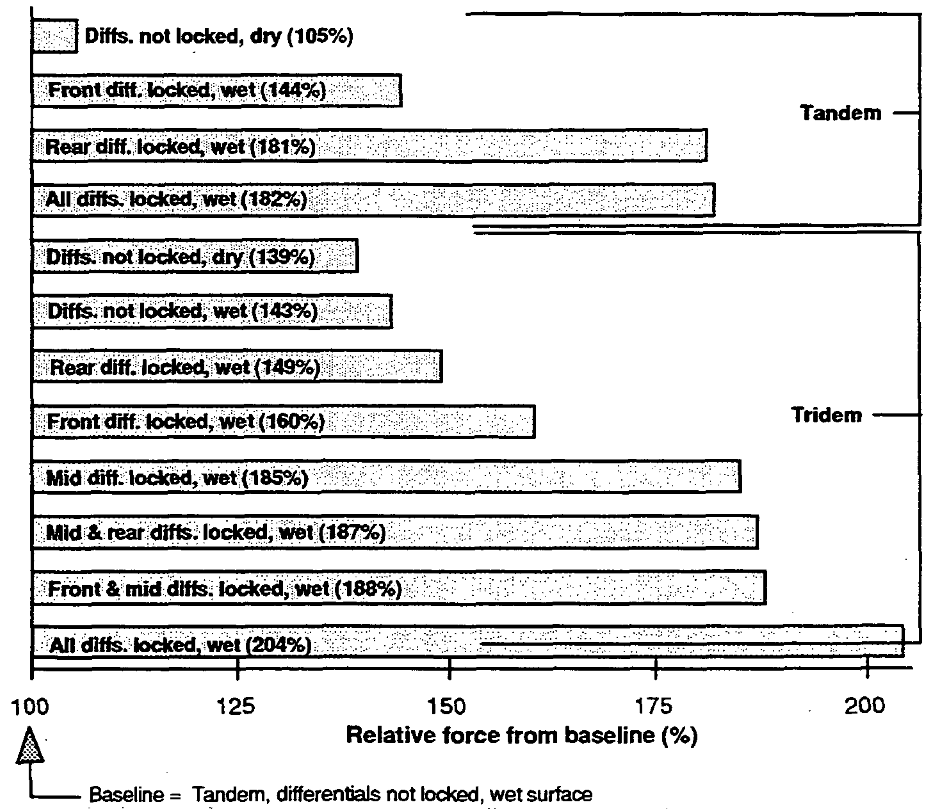


Figure 10. Peak force comparison: empty trucks.

generated that increases the understeer characteristic; in general, both the tridem and tandem drive axle tractors exhibited increases in aligning force directly proportional with the number of locked differentials. However, because the practice of locking differentials is usually limited to use on forest roads with challenging grades and poor surface conditions. The resulting undesirable understeer characteristic is not experienced when operating on the public road system.

The tandem tractor could not complete the path-following manoeuvre with both differentials locked except when in the empty mode; once the aligning force rose to the range of 115-123% of baseline, loss of control occurred.

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. Depending on the load, once the aligning force rose to the range of 121-169% above baseline, loss of control occurred. When in the empty mode the tridem tractor successfully negotiated the path-following manoeuvre with all of the differentials locked or unlocked.

RECOMMENDATIONS

Based on the conclusions, this study finds 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 hitch offset 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 truck frame/front suspension connection. 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 previous TAC research evaluated a tridem drive vehicle (Lam and Billing 1989) by means of computer simulations, it was 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 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 others. Since the truck manufacturer provides for selective locking of any of the differentials, drivers who choose to lock a single differential should avoid the middle option.

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 hill-climbing.

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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