Advantage

Restricted to FERIC Members and Partners Vol. 5 No. 16 April 2004

Contents

Evaluating an 8-axle pole-style double trailer configuration for regulatory approval in Alberta

Abstract

Lower delivered wood costs can be achieved by reducing the tare weight of logging trucks and thereby maximizing the payload. The Forest Engineering Research Institute of Canada (FERIC) evaluated a low tare weight, double pole trailer design operating in Alberta under a special permit. FERIC conducted several individual studies to assess the dynamic performance and facilitate regulatory approval of the new design. This report summarizes these studies and presents the results of the dynamic performance evaluation.

Keywords

Logging trucks, Vehicle dynamics, Truck configurations, Carbon emissions, Performance, Computer simulations.

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Introduction

In 2001, Mallock Trucking Ltd., an Alberta-Pacific Forest Industries Inc. (Al-Pac) log hauling contractor, modified a conventional super B-train trailer to reduce the tare weight, or empty weight, of the configuration by 3000 kg. This was accomplished by replacing the ladder-style trailer frames with single rectangular steel tubing reach-style frames (Figure 1). In addition, the suspension of the lead trailer was changed to use two levelling valves and a split air circuit to control the air suspension of the tridem group, while the suspension of the pup trailer was changed to use a walking beam suspension. As these modifications were a significant departure from conventional designs, Alberta Transportation was reluctant to permit this configuration on public roads until evaluations of dynamic performance were completed.

Figure 1. Pole-style trailer frames.

FERIC, in cooperation with Al-Pac, Mallock Trucking Ltd., and Alberta Transportation, undertook a series of four studies to quantify the dynamic performance of this vehicle beginning in the fall of 2001. This report summarizes the results of the performance evaluation studies that led to Al-Pac's fleet-wide implementation of pole-style configurations in the spring of 2003. The first study consisted of a series of field trials to determine the torsional stiffness and braking performance of the prototype trailer design. Subsequently, tilt table testing and evasive lane change maneuvers were conducted to evaluate the dynamic performance, and the results were used to validate computer modelling of the configuration. A second computer study predicted the dynamic performance of the configuration to compare the effects of increasing the two log bundle lengths from 9.14 m (30 feet) to 11.27 m (37 feet). Additional field trials assessed the rearward amplification differences when transporting the shorter and longer log lengths, and compared the results to those predicted from the computer simulations. Costing and greenhouse gas emissions analyses were also performed.

Objectives

The objectives of this project were to assess the operational performance of the prototype pole-style trailers and to evaluate their suitability to operate on public roads in Alberta. The specific tasks performed to achieve these were to:

- Evaluate the dynamic performance of the prototype pole-style trailers compared to conventional ladder-frame designs. This required determining the torsional stiffness of the trailers in both loaded and unloaded configurations, and investigating the effect of the lead trailer hinge mechanism on braking performance and load distribution.
- Conduct full-scale testing for stability and dynamic performance.
- Use computer simulations to assess the effect of lengthening the log bundles from 9.14 m to 11.27 m on the dynamic performance of the configuration.
- Field-test the rearward amplification and validate the computer simulations for the pole-style configuration carrying longer log bundles.

Figure 2. Loaded pole-style configuration.

Equipment description

The federal-provincial-territorial memorandum of understanding on inter-provincial weights and dimensions defines a B-train as a combination of vehicles composed of a tractor and a semi-trailer, followed by another semi-trailer attached to the first semi-trailer by means of a fifth wheel mounted on the rear of the first semi-trailer (Anonymous 1999). As neither the frame construction nor the suspension design are discussed in this memorandum of understanding, the pole-style trailers meet the accepted definition of a B-train by using fifth wheel couplings between the tractor and lead trailer, and lead trailer and pup trailer.

The pole-style configuration (Figure 2) began trial operation with one set of trailers in the spring of 2001. Recently, a new trailer design that does not include a hinge mechanism on the lead trailer has been developed. The configuration using a hinged lead trailer is referred to as a double pole trailer while the configuration without a hinge is referred to as a B-train.

With regulatory approval granted in the summer of 2002, Al-Pac's log haul fleet has now expanded to include approximately 39 pole-style configurations with rigid or hinged poles on the lead trailer. The tare weight of the pole-style configuration is approximately 16 500 kg, compared to 19 500 kg for a conventional super B-train.

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ISSN 1493-3381

The increased payload, reduced carbon emissions, and lower delivered wood costs are the primary motivation for this work.

The pole-style semi-trailer design can only be used where the trailer frame does not support any of the payload, i.e., the logs are long enough to span from the front bunk to the rear bunk without any supporting structure in between. At Al-Pac, the log bundles are approximately 9.14 m and span from the front bunk to the rear bunk on both the lead and pup trailers. As a result, the log bundles are supported similarly to the load on a pole trailer and account for most of the rigidity of the trailer.

The pole-style semi-trailers use a single rectangular tube frame that connects the front bunk/king pin assembly to the rear bunk frame and axle assembly. The prototype lead trailer includes a hinge (Figure 3) and length compensation mechanism that allows movement in the pitch plane, which enables the trailer's suspension to follow undulations in the road surface. This mechanism prevents the pole frame from being loaded in vertical bending when travelling on uneven road surfaces, and is necessary because the lead trailer is constrained by both its load and the pup trailer. The length compensation only occurs as the trailer follows the undulations in the road surface and not while the vehicle is cornering.

The suspension of the tridem axle group of the hinged lead trailer is controlled by two levelling valves and a split air circuit, while the rigid-style lead trailer is controlled using a single air circuit and levelling valve. The pup trailer does not require a hinge or length compensation mechanism as it is only constrained by its load. As well, the pup trailer is equipped with a walking beam suspension, which typically connects to the trailer frame via a single pivot point, isolating the frame from the uneven road surface. Fifth wheel couplings are used between the lead trailer and the tractor, and between the pup trailer and the lead trailer. A length extension is incorporated into the pole frame that provides operational flexibility and allows the configuration to haul logs of varying lengths.

Figure 3. Lead trailer hinge mechanism.

Alberta Transportation raised concerns regarding the dynamic performance due to the hinged lead trailer frame, and the dual levelling valves with the split air circuit. Consequently, the dynamic assessment focused on the torsional stiffness, the performance of the hinge mechanism, and the load distribution of the lead trailer tridem group because the pole-style semi-trailer frames and lead trailer suspension are significant departures from conventional B-train semi-trailer designs. The new design would not receive regulatory approval until a full engineering evaluation was conducted to verify its dynamic performance. B-trains are among the most dynamically stable configurations in both on- and off-highway haul fleets due to their roll coupling (provided by fifth wheel connections) between the tractor and semi-trailers, and the torsional stiffness of the semi-trailers. The torsional stiffness of a configuration will resist the tendency of the configuration to roll over and sway.

There was also a concern raised that during braking, the hinge-equipped lead trailer suspension might pitch forward. This could cause a considerable amount of additional loading on the lead axle of the tridem group and result in reduced braking performance. As delivered wood length requirements change to suit woodrooms, the effect of wood length on the dynamic performance of the pole-style configuration needed to be quantified. Computer simulations can be used to model the dynamic performance of the configuration. However, validation of the models with field tests and experimental results is prudent.

The prototype pole-style trailers with the hinged lead trailer uses two levelling valves and a split air circuit to control the air suspension of the tridem group on the lead trailer. The first levelling valve controls the lead and centre axles, while the second valve controls the last axle. Consequently, concerns were raised regarding achieving legal axle weight distribution when the lead trailer is loaded and the pup trailer is empty. These concerns were addressed by an additional study conducted by Al-Pac and submitted to Alberta Transportation (Mallock and Ellison 2002).

Alberta Transportation approved the pole-style configuration for operation on public roads in May 2002, and allowed the same weights as for super B-trains according to the weights and dimension regulations (Province of Alberta 2000). This new configuration is allowed a maximum height of 4.15 m and a maximum width of 2.6 m. The overall length is limited to 25.0 m but is extended to 30.5 m with a valid log haul route map and over-dimensional permit. The wheelbase of the trailers must be between 6.25 and 12.5 m. In the configuration permits, the configuration with a hinged lead trailer is not referred to as a B-train, but as a tractor and two pole frame trailers. The rigid pole-style trailer with a single air circuit is considered to be a super B-train.

Figure 4. Testing the torsional stiffness of a log trailer.

Study methods

Torsional stiffness

A primary concern was that the single tube frame would exhibit reduced torsional stiffness which would adversely affect the dynamic performance and stability of this configuration. A full-scale field test was developed to evaluate the torsional stiffness of both the conventional and new pole-style trailers based on previous work by National Research Council Canada (NRC) (Preston-Thomas 1994). Lead and pup trailers from three conventional super B-train trailers of different ages and manufacturers and the pole-style trailers were tested independently in both loaded and empty conditions.

During testing, the tractor was driven onto raised ramps. Then, the rear of the trailer was lifted to a level position using two wheel loaders (one on each side) and twisted through six degrees clockwise and six degrees counterclockwise relative to the longitudinal axis (Figure 4). Instrumentation included load cells in the lifting lines and weigh scales under each tractor axle to determine the reaction forces. Inclinometers were placed on the axles, bunks, tractor's fifth wheel, and front bumper to record the input and reaction angles.

Braking tests

Braking tests were conducted with the prototype trailers to determine the influence of the lead trailer's hinge mechanism on brake balance. The concern was that excessive pitching during braking would generate load transfer to the lead axle of the tridem group and result in an imbalance in braking performance. The configuration was instrumented and loaded to Alberta highway legal weights (Province of Alberta 2000). Then, several aggressive stops were made from speeds between 80 and 100 km/h. The amount of pitching was measured using linear potentiometers, front and rear brake temperatures for the tridem group were recorded using infrared temperature guns, and stopping distance and decelerations were measured using accelerometers. Tests were performed with the hinge free to allow pitching and locked to prevent pitching.

Dynamic performance field tests

In October 2001, full-scale testing of the static rollover threshold and the rearward amplification of the pole-style trailers and conventional super B-train were conducted as part of a larger series of dynamic tests involving NRC, the Royal Canadian Mounted Police, and Innovative Vehicle Testing Ltd. (Parker 2003).

The static rollover threshold is the lateral acceleration at which a configuration becomes unstable and rolls over, and is generally believed to occur when all axles, except for the steering axle on one side of the roll unit,[1] have lifted off the ground. The static rollover threshold of the pole-style and conventional super B-trains were evaluated using Arrow Transport Ltd.'s side dumping facility in Ashcroft, B.C. as a tilt table. Each loaded configuration was parked on the tilt table. Then, the table was slowly raised on one side causing the configuration to pivot about its tires on the lower side. Restraints were used to prevent complete rollover and for safety considerations. To accurately determine the moment of first wheel lift-off, inclinometers were used to measure tilt angles and wheel loads were monitored.

A series of lane change maneuvers was conducted on an airport runway in Cache Creek, B.C. to compare the dynamic performance of the pole-style trailers and conventional super B-trains and to characterize the rearward amplification ratio. These tests are similar to the SAE J2179 (SAE 1993) and ISO 14791 (ISO 2000) test standards but due to limitations at the airfield, the maximum speed reached was 70 km/h. The tests were modified to achieve peak lateral accelerations comparable to the standard tests but at the lower speed. The configurations were instrumented with accelerometers and a speed sensor to record the necessary data.

Computer simulation

The University of Michigan Transportation Research Institute (UMTRI) yaw/roll model was used to predict the nine performance measures (Appendix I) for the pole-style trailers and conventional super B-train log trucks (Figure 5) (MacAdam et al. 1980). The simulations were conducted according to the weight and dimension regulations of Alberta's Motor Transport Act (Province of Alberta 2000), with axle loads of 5 500 kg, 17 500 kg, 24 500 kg, and 17 500 kg on the steering axle, drive group, lead trailer group, and pup trailer groups, respectively. The pole-style trailers and conventional super B-trains were compared using the measured torsional stiffness and compared to a super B-train using the model default values (Parker and Amlin 1998). The results are presented for a range of block load densities[2] (340 kg/m^3 to 555 kg/m^3) that is representative of the Alberta resource.

Computer simulation of longer log bundles

The UMTRI yaw/roll model was used to predict the effect of lengthening the trailers to accommodate 11.27-m log lengths and modelled two different combinations of trailer suspensions:

- air suspended lead trailer, air suspended pup trailer
- air suspended lead trailer, walking beam suspended pup trailer

These two suspension combinations with longer logs were then compared to a conventional super B-train and the pole-style trailers with 9.14-m long logs. Dimensions of the pole-style configuration hauling 11.27-m long logs are presented in Figure 6.

[1] On roll-coupled units such as the B-train, the entire configuration is considered as one roll unit.

[2] Block load density is calculated from payload weight and block volume (including air voids, which typically make up 40% of the volume). For example, a load with a weight conversion of 925 kg/m^3 with 40% voids would result in a 555 kg/m^3 block load density (925×(1-0.40)). The lower block load density would represent drier wood which typically results in higher load heights.

Figure 5. Dimensions for dynamics simulations.

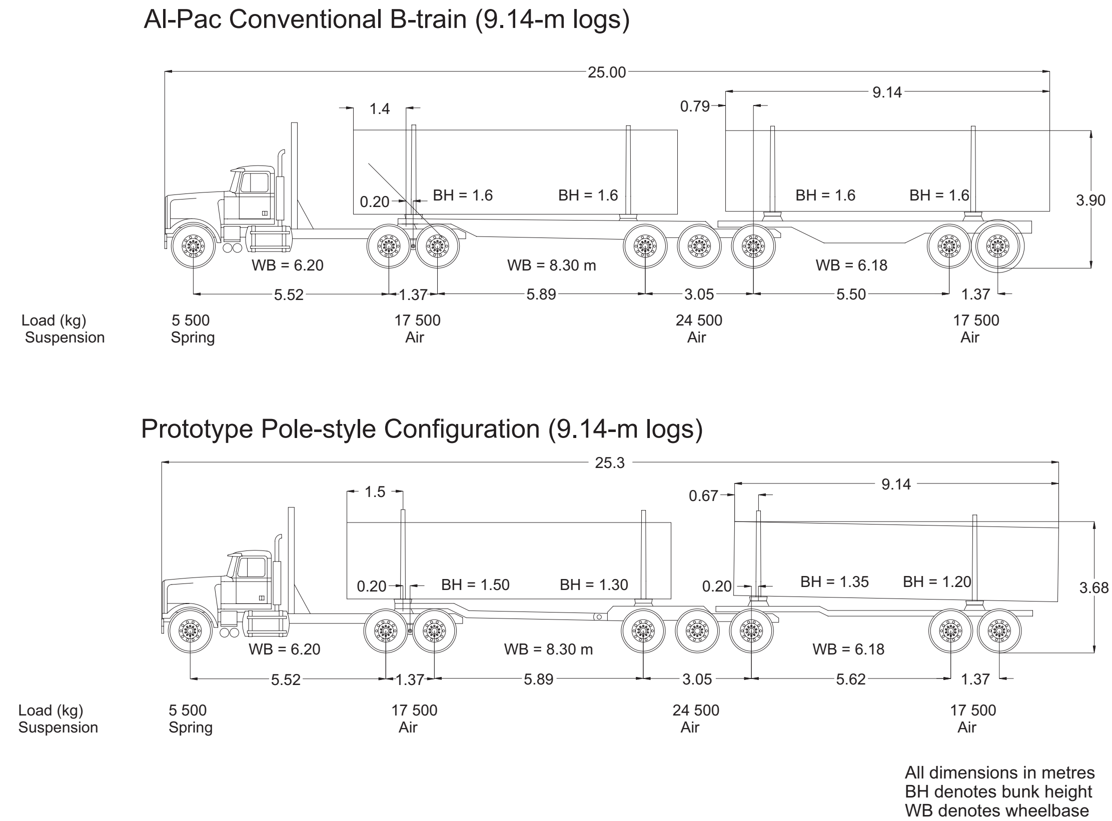
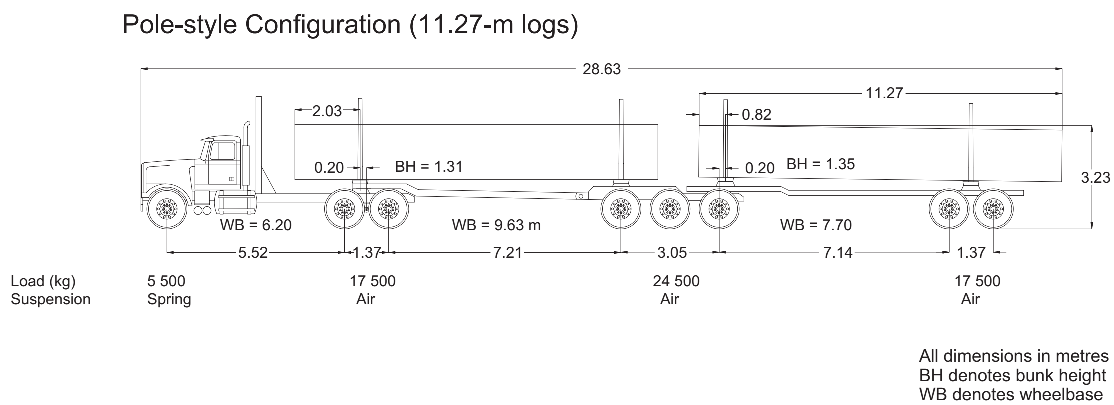


Figure 6. Dimensions of pole-style configuration hauling 11.27-m long logs.



Field validation of rearward amplification

In the summer of 2003, full-scale field tests were undertaken to validate the computer simulation results for the longer wood. To validate the computer results with respect to rearward amplification, evasive lane change maneuvers were conducted with the vehicle instrumented to measure the relevant accelerations.

The tests differed from the SAE J2179 and ISO 14791 test standards as lane change maneuvers did not follow a marked course, but were of a "free form" variety. The vehicles followed a complete lane change from one lane to the other and back to the original lane over a time period of 7.5 to 8.5 s at a speed of 80–90 km/h. This yielded a peak lateral acceleration of approximately 0.20 g (where g is the acceleration of gravity) at the steering axle. Runs not meeting the frequency (7.5 to 8.5 s) and lateral acceleration magnitude (greater than or equal to 0.15 g) requirements were discarded from the analysis.

The development of a solid frame design that eliminates the need for the hinge mechanism as well as the two levelling valves on the lead trailer tridem group retains the essential attributes of a B-train and was also included in the field testing of the rearward amplification.

Several fully loaded test runs were conducted with two versions of the pole-style trailers:

- hinged lead trailer with 9.14-m and 11.27-m logs
- solid lead trailer reach with 9.14-m and 11.27-m logs

The relative difference in rearward amplification resulting from the change in log length was computed for the two trailer designs. Comparisons were made between these test results and the previous simulation predictions.

Cost analysis

An estimate of the haul cost savings due to the reduced tare weight of the pole style configuration was made using the Foothills Model Forest Log Transportation Cost Model (Blair 1999). These savings were estimated by comparing the ownership and operating costs of the pole style configuration with a maximum payload of 47 000 kg to a conventional B-train with a maximum payload of 44 000 kg operating on a typical Alberta log haul.

Greenhouse gas emissions

Reduced tare weights can contribute to reduced greenhouse gas (GHG) emissions by reducing the amount of fuel consumed during the empty portion of the log haul cycle, and by delivering more wood to the mill per volume of fuel consumed. A computer model was used to estimate the improved fuel economy. The model calculated the amount of energy required to overcome rolling resistance and aerodynamic drag, and accounted for the auxiliary loads and drivetrain losses for both a conventional super B-train and pole-style configuration. The carbon emissions per cubic metre of delivered wood were calculated using consumed fuel conversion factors (Anonymous 2003).

Results and discussion

Torsional stiffness

The torsional stiffness tests for the pole-style and conventional trailers from different manufacturers were conducted in September 2001 at the Al-Pac mill site near Boyle, Alta. The torsional stiffness comparison for both the loaded and empty configurations of the lead trailers is presented in Figure 7.

Torsional stiffness values were reported for the midpoint of the trailer frame to match the reference locations used in the UMTRI model. The loaded pole-style trailer exhibited a torsional stiffness of 76.7 kNm/deg while the conventional trailers (trailers A, B, and C) exhibited a torsional stiffness range of 47.2 to 83.7 kNm/deg. The torsional stiffness of 47.2 kNm/deg (Trailer B) was likely a result of disturbing the “as arrived” load to balance

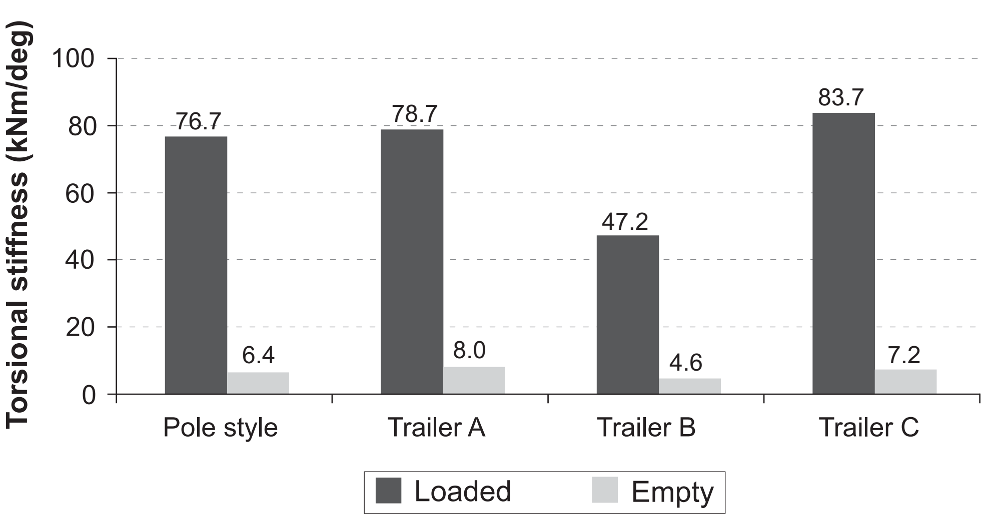


Figure 7. Torsional stiffness comparison of lead trailers.

the side-to-side weight imbalance. The torsional stiffness of the empty pole-style trailer was 6.4 kNm/deg, whereas the torsional stiffness of the conventional trailers ranged between 4.6 and 8.0 kNm/deg. Clearly, the load played an important role in determining the torsional stiffness of the configuration. In general, the torsional stiffness of the lead pole-style trailer compared favourably with conventional B-train trailers in both the loaded and empty configurations.

Figure 8 compares the loaded and empty torsional stiffness of the pup trailers. Due to time constraints with the log haul schedule, the empty pup for conventional trailer A was not available for testing. The torsional stiffness of the loaded conventional pup trailers ranged between 24.0 and 34.4 kNm/deg, while the torsional stiffness of the pole-style pup was 74.4 kNm/deg. The reason for this considerable difference is twofold:

- The bunks of the pole-style pup trailer are located at the kingpin and axle group centre, while the bunks on the conventional trailers are located rearward of the kingpin and the axle group centre.
- The wheelbase of the conventional trailer is longer than the wheelbase of the pole-style pup trailer.

Both of these properties would result in a lower measured torsional stiffness for the conventional trailers compared to the pole-style trailer. The tests of the empty trailers showed that the pole-style pup trailer exhibited a torsional stiffness of 3.2 kNm/deg compared to between 3.9 and 4.1 kNm/deg for the conventional pup trailers. Again, the log bundles contributed considerably to the torsional stiffness of the loaded configuration.

The effect of various load securement techniques was evaluated by measuring the torsional stiffness of the loaded trailer using load wrappers that automatically tensioned, load wrappers that manually tensioned, and no wrappers. The wrappers used on the pole-style trailers are fixed to the log bunks, which better ties the load to the trailer frame compared to conventional wrappers that wrap around the log bundle but are not secured to the trailer frame. The tests were performed using the lead trailer where the torsional stiffness was 77.8 kNm/deg, 76.5 kNm/deg, and 70.0 kNm/deg for the automatic tensioners, manually tensioned, and loose wrapper cases, respectively. In the loose wrapper test, the wrappers had tightly bound the logs to the bunks prior to the tension being released. If the wrappers had not been properly tensioned initially, it is likely that the torsional stiffness would have been considerably less. These results showed that the wrappers affected the torsional stiffness and reinforced the importance of maintaining properly tensioned wrappers.

Figure 8. Torsional stiffness comparison of pup trailers.

Braking tests

The braking tests to determine the effect of the hinge mechanism on chassis pitch and load distribution on the tridem group were also tested near the Al-Pac mill site. The braking tests with the hinge locked and unlocked indicated that the stopping distances were similar when the initial speeds and decelerations were similar. The stopping distance for an initial speed of 80 km/h with an average deceleration of 0.16 g was 172 m with the hinge unlocked and 174 m with the hinge locked. For an initial speed of 90 km/h with an average deceleration of 0.15 g, the stopping distance was 227 m for the unlocked hinge and 236 m for the locked hinge. No significant difference was found in terms of stopping distance as a result of the hinge mechanism.

The analysis of variance to compare the brake temperatures for the first and third axles in the tridem group demonstrated no significant difference in the brake temperatures between the unlocked hinge and locked hinge operations. No significant amount of pitching of the tridem group was detected using the string potentiometers. Based on the stopping distance, temperature, and pitch testing results, the hinge mechanism did not appear to affect the braking performance of the configuration when the loads were properly distributed over the tridem axle group.

Dynamic performance field tests

The tilt table testing found that, in terms of estimated static rollover threshold, the pole-style configuration exhibited superior rollover stability relative to the conventional design (Figure 9). The estimated static rollover threshold of the pole-style configuration was 0.381 g and exceeded the NRC performance standard of 0.35 g. The conventional super B-train exhibited a static rollover threshold of 0.341, which was just below the performance standard. The improved performance of the pole-style configuration was predominantly due to the lower bunk heights (0.3 to 0.4 m lower) and correspondingly lower centre of gravity of its two loads.

From the results of the evasive maneuver tests, the pole-style configuration exhibited an average rearward amplification of 1.57, an increase of 14% compared to the conventional super B-train (rearward amplification of 1.38). This measured increase in rearward amplification in the pole-style configuration can be attributed to its shorter pup trailer wheelbase and is not due to its frame design. Regardless, the increased rearward amplification exhibited by the pole-style configuration still meets the NRC performance standard of being less than 2.20.

Computer simulation

The UMTRI yaw/roll model uses a default torsional stiffness of 113 kNm/deg measured at the midpoint of the trailer. A comparison was made using the default torsional stiffness and the measured values for both the conventional designs (79 and 84 kNm/deg) and the pole-style design (77 kNm/deg)

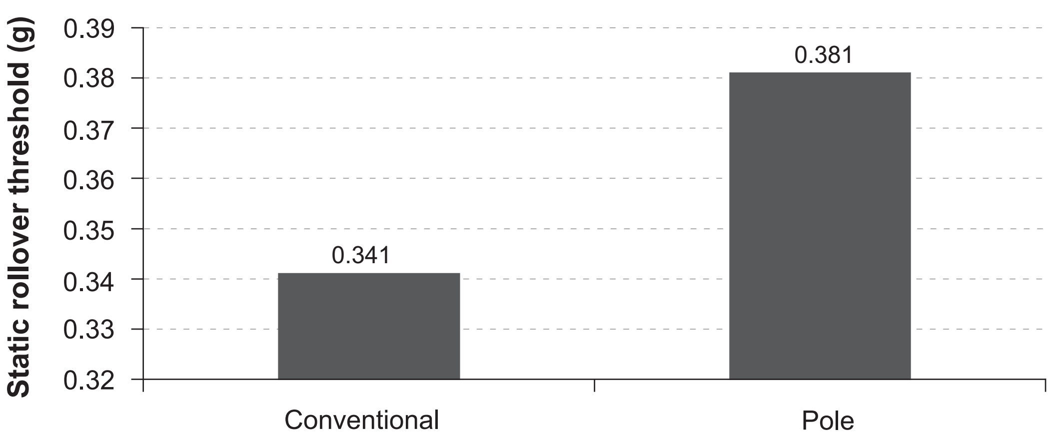


Figure 9. Lateral acceleration of estimated rollover threshold for tested configurations.

(Table 1). The range in values shown for performance measures were obtained by using two block load densities (340 and 555 kg/m^3).

All of the configurations exhibited similar trends with respect to the performance measures. The static rollover threshold and rearward amplification were most affected by torsional stiffness, while the remaining measures were negligibly affected. As B-trains do not experience a large increase in gross vehicle weight as a result of Alberta winter green route[3] weight allowances, the vehicle dynamics are not expected to vary significantly.

The pole-style configuration has lower bunk heights compared to the conventional designs, which improve the static rollover threshold. The short wheelbase of the pole-style pup trailer accounted for the reduced performance of the rearward amplification, load transfer ratio, and transient off-tracking measures. The performance of these measures was reduced compared to the standard, but they were still well within the acceptable range and could have been improved if the trailer wheelbases were increased to haul longer wood.

Computer simulation of longer log bundles

The UMTRI yaw/roll model was used to predict the performance of hauling 11.27-m long logs. The results of the longer wood were compared to performance predictions for the conventional super B-train and the prototype pole-style configuration hauling the shorter 9.14-m long logs. The configurations were loaded to 65 000 kg gross combination vehicle weight (GCVW) using a block load density of 465 kg/m^3 representing typical green route weights. A summary of the results is presented in Table 2, which includes the various suspensions evaluated for the pole-style configuration. The first pole-style configuration was simulated with air suspensions on both trailers and with the vehicle hauling 9.14-m long logs. The second pole-style configuration was simulated with air suspensions and 11.27-m long logs. The third pole-style configuration was simulated with an air suspension lead trailer and a walking beam pup trailer, and 11.27-m long logs.

The dynamic performance of the pole-style configuration exhibited similar trends compared to the conventional super B-train. None of the configurations met the performance criteria for high-speed off-tracking but all met the performance standard for the static rollover threshold and load transfer ratio. Improvements were evident for the pole-style configuration in the static rollover threshold

[3] Alberta winter green route weights are the maximum allowable weights that a configuration may carry on public roads in Alberta.

Table 1. Dynamic performance measures based on measured torsional stiffness (Alberta legal weights, GCVW 63 500 kg)

Performance measure	Pass criteria	Conventional super B-train	Conventional super B-train	Conventional super B-train	Pole-style configuration
Torsional stiffness (kNm/deg)		113	84	79	77
Understeer coefficient	>-4.81	-2.74 to -2.01	-2.72 to -1.84	-2.65 to -1.90	-2.63 to -1.87
Static rollover threshold (g)	>0.35	0.33 [a] to 0.40	0.36 to 0.40	0.40 to 0.41	0.40 to 0.41
Load transfer ratio	<0.60	0.36 to 0.48	0.36 to 0.48	0.36 to 0.48	0.36 to 0.48
Rearward amplification	<2.20	1.63 to 1.68	1.64 to 1.69	1.64 to 1.70	1.46 to 1.70
Friction demand	<0.10	0.10	0.10	0.10	0.10
Lateral friction utilization	<0.80	0.66	0.66	0.66	0.66
Low-speed off-tracking (m)	<6.00	5.80	5.80	5.80	5.80
High-speed off-tracking (m)	<0.46	0.65 [a] to 0.70 [a]	0.65 [a] to 0.70 [a]	0.65 [a] to 0.70 [a]	0.65 [a] to 0.70 [a]
Transient off-tracking (m)	<0.80	0.54 to 0.62	0.54 to 0.63	0.54 to 0.63	0.54 to 0.63

[a] Indicates the performance standard was not met.

Performance measure	Pass criteria	Conventional super B-train	Pole-style 1	Pole-style 2	Pole-style 3
Understeer coefficient	>-4.81	0.99	1.35	1.99	2.76
Static rollover threshold (g)	>0.35	0.35	0.39	0.43	0.44
Load transfer ratio	<0.60	0.52	0.46	0.34	0.34
Rearward amplification	<2.20	1.78	1.79	1.60	1.58
Friction demand	<0.10	0.12 [a]	0.11 [a]	0.10	0.10
Lateral friction utilization	<0.80	0.58	0.58	0.59	0.59
Low-speed off-tracking (m)	<6.00	4.71	4.70	5.78	5.79
High-speed off-tracking (m)	<0.46	0.67 [a]	0.64 [a]	0.66 [a]	0.58 [a]
Transient off-tracking (m)	<0.80	0.61	0.58	0.5	0.46
Lead trailer suspension		air	air	air	air
Pup trailer suspension		air	air	air	walking beam
Lead trailer wheelbase (m)		8.30	8.30	9.63	9.63
Pup trailer wheelbase (m)		6.18	6.18	7.70	7.70
Log length (m)		9.14	9.14	11.27	11.27
Load height (m)		3.90	3.68	3.23	3.23

Table 2. Computer simulations of longer log lengths

[a] Indicates the performance standard was not met.

and load transfer ratio, and were due to the reduced load height. The longer wheelbase of the pup trailer for the configurations hauling longer logs also resulted in an improvement of the rearward amplification.

Field validation of rearward amplification

Variations in the steering axle input accelerations were attributed to different drivers and the lack of a marked course. Despite the variability in both driver and course, the test data showed an improvement in rearward amplification for both the hinged and solid-frame trailers when the log length was increased from 9.14 m to 11.27 m.

To make direct comparisons between the four test conditions, the rearward amplifications were normalized based on the linear fit shown in Figure 10 at input accelerations of 0.21 g and 0.15 g. An acceleration of 0.21 g represented the average

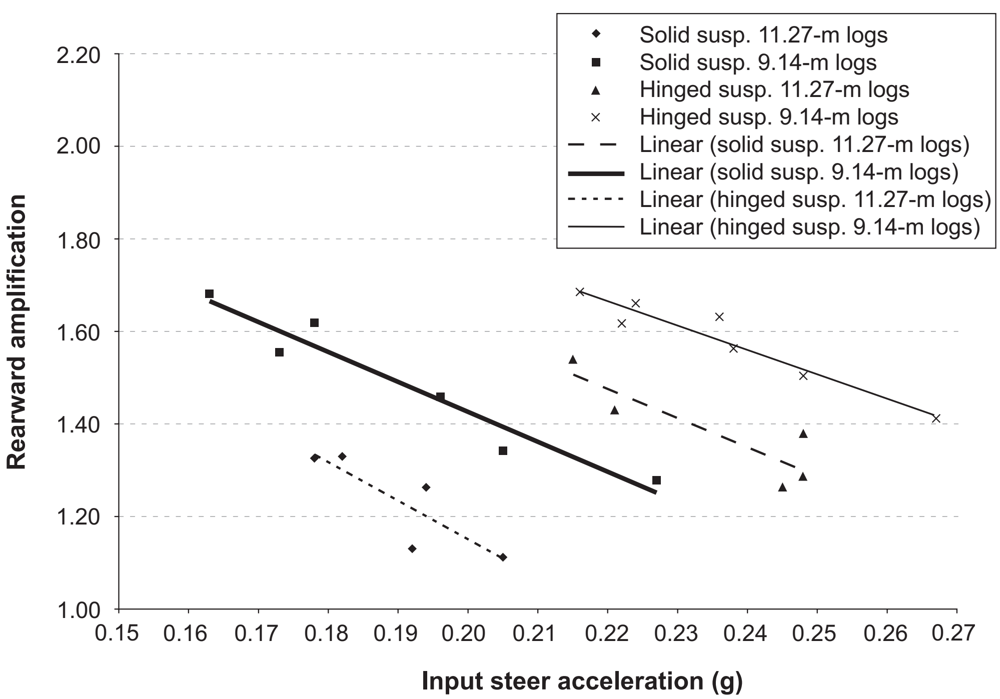


Figure 10. The influence of input acceleration on rearward amplification.

input acceleration for the four tests, while 0.15 g represented the standard input lateral acceleration conducted in the previous computer simulations. The results of the field tests and computer simulations are presented in Figure 11.

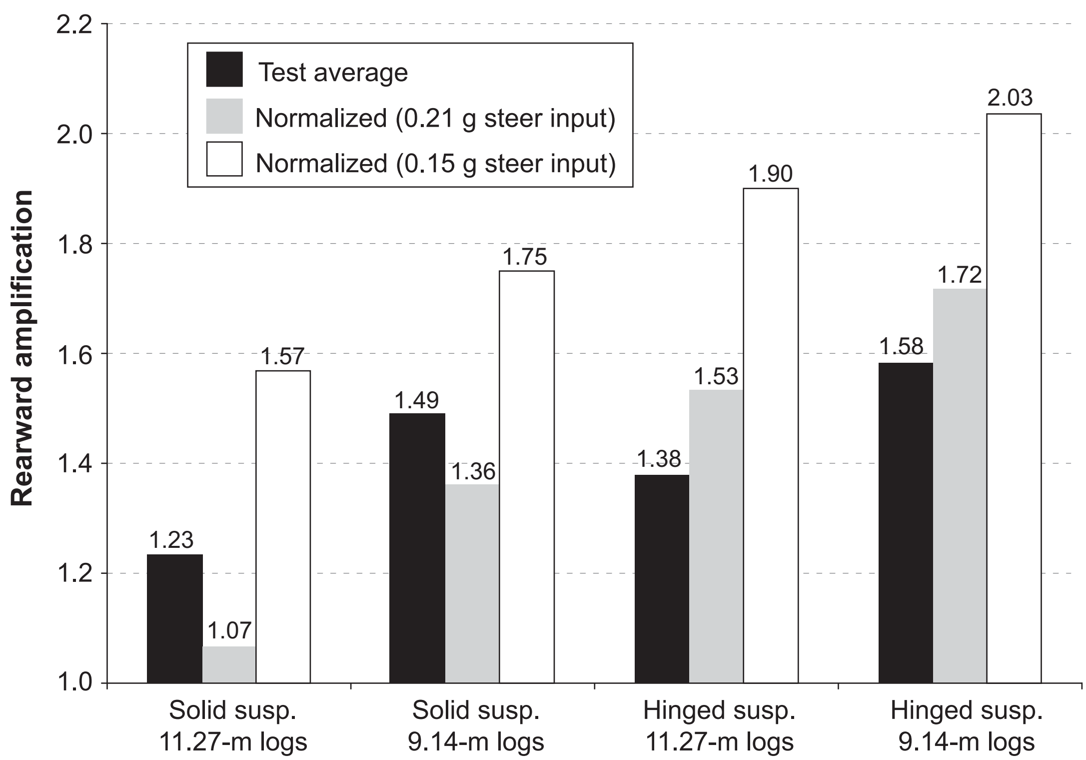
The normalized rearward amplifications at 0.21 g (Figure 11) illustrated an improvement in dynamic performance when the log length was increased from 9.14 m to 11.27 m. Improvements of 21.3% and 11.0% were realized for the solid and hinged suspension designs, respectively, when the log length was increased from 9.14 m to 11.27 m. This improvement resulted from the increased wheelbase of both the lead and pup trailers when longer logs were placed on the trailers. Stability was also improved as the longer logs reduced the load height.

The normalized test data also illustrated the improved performance of the solid frame design relative to the hinged design. The improvement in dynamic performance of the solid design resulted from the elimination of the hinge mechanism, and this feature helped dampen the rear trailer motions. Despite the hinge design's higher rearward amplification value, it continued to meet the performance standard even with the shorter 9.14-m log lengths. The projected rearward amplifications from the test data at 0.15 g for the solid suspension design were very similar to the rearward amplifications predicted in the preliminary simulations conducted for this configuration. The simulations predicted that rearward amplification would be reduced from 1.79 to 1.60 (an improvement of 10.6%) when the log length was increased from 9.14 m to 11.27 m. The normalized test results showed a decrease from 1.75 to 1.57. This close correlation between the simulation and test results at 0.15 g steer input demonstrated the accuracy of the computer model and further validated its use with this configuration.

Cost analysis

Previous work has shown that increasing payloads can reduce delivered wood costs (Blair 1999). The potential payload increase is 3000 kg for the pole-style configuration compared to conventional B-trains. Based on operating 3000 hours per year with an 8-hour cycle time, it is estimated that the increased

Figure 11. Comparison of rearward amplifications for test conditions.



payload offered by the pole-style trailers could reduce haul costs by about $1.07/m^3. This analysis assumed that the trucks delivered their maximum potential payload.

Greenhouse gas emissions

A simple model was used to predict the effect of the reduced tare weight of the pole-style configuration on GHG emissions (Appendix II). The model compares a conventional super B-train (19 500 kg tare weight) and a pole-style configuration (16 500 kg tare weight) with maximum GVWs of 63 500 kg. The analysis is based on a general representation of the Al-Pac haul cycle: 50% highway travel with a total cycle time of about 8 hours. The average travel speeds were 90 km/h highway loaded; 100 km/h highway empty; 60 km/h off-highway loaded and 70 km/h off-highway empty. The reduced tare weight of the pole-style trailers results in an estimated fuel savings of over 1.5% due to the empty portion of the haul cycle. With the fuel savings and increased payload taken into consideration, the overall carbon emissions can be reduced by about 8% per cubic metre of delivered wood. Based on a truck delivering nearly 18 000 m^3 annually, a fleet of 65 trucks would experience a carbon emission reduction of over 1700 tonnes annually.

Conclusions

The goal of these studies was to assess the operational and dynamic performance of pole-style trailers and their suitability to operate on public roads in Alberta. The pole-style configuration exhibited performance similar to that of conventional super B-trains, based on both computer simulations and field testing. Consequently, pole-style configurations should be allowed to operate on public roads in Alberta and incorporated into log haul fleets where appropriate.

The torsional stiffness test results demonstrated that the torsional stiffness of a loaded trailer is considerably higher than an unloaded trailer. The pole-style trailers exhibited similar torsional stiffness compared to conventional ladder-frame trailers. Increased wrapper tension improved the torsional stiffness as the more secure load prevented the logs from sliding against each other, thereby increasing the torsional stiffness.

No significant effect on the braking performance was measured as a result of the hinge mechanism on the lead trailer of the prototype pole-style trailer. The stopping distances were similar with the hinged locked or unlocked, and no significant differences were found between the measured brake temperatures in the lead trailer tridem group. In addition, the difference in chassis pitch, and consequently load transfer, was found to be negligible with the hinge locked or unlocked.

In the Ashcroft tilt table tests, the pole-style configuration exhibited superior rollover stability performance due to its lower bunk heights relative to the conventional super B-train. The estimated static rollover threshold for the pole-style configuration was 0.381 g which exceeds the performance standard (0.35 g).

In the Cache Creek evasive lane change maneuver tests, the pole-style configuration exhibited reduced performance relative to the conventional super B-train, with an average rearward amplification of 1.57 compared to 1.38. This reduced performance was a result of the shorter wheelbase of the pole-style pup trailer. However, the 95% confidence interval for the rearward amplification for the pole-style configuration was between 1.37 and 1.86, and met the performance standard of 2.2.

Computer simulations were performed using the dimensions and torsional stiffness of the pole-style trailers. Acceptable results were achieved for all performance measures except for the high-speed off-tracking. However, conventional super B-trains also failed to meet the performance criteria for high-speed off-tracking. The pole-style configuration exhibited superior static rollover threshold compared to the accepted standard due to the lower bunk heights that can be achieved using the pole-style trailers. The pole-style trailers also exhibited higher load transfer ratios and rearward amplification as a result of the shorter wheelbase of the pup trailer, but the results were still acceptable. Where practical, increased pup wheelbases should be encouraged and can be achieved when hauling longer logs.

Dynamic performance was improved when log lengths increased from 9.14 m to 11.27 m—by 21.3% and 11.0% for the solid and hinged suspension designs, respectively, at a normalized input lateral acceleration of 0.21 g experienced during the field trials.

The solid pole trailer design exhibited improved dynamic performance relative to the hinged pole design. The projected dynamic performance of the solid suspension design at 0.15 g, based on field testing, was very similar to the dynamic performance predicted in the computer simulations. This result further validated the use of the computer model to evaluate the dynamic performance of this configuration.

The cost analysis showed that haul costs could be reduced by about $1.07/m^3 as a result of the additional 3000 kg payload potential offered by the pole-style configuration compared to conventional B-trains.

It was estimated that the reduced tare weight and the increased payload of the pole-style configuration would result in an 8% reduction annually in carbon emissions. For a fleet of 65 trucks, this reduction would amount to over 1700 tonnes of carbon dioxide emissions.

With respect to the hinged version of this configuration, it is difficult to achieve proper load distribution on the lead trailer axle group when the pup trailer is empty as a result of the dual levelling valves on the tridem suspension. Furthermore, the permits issued by Alberta Transportation stipulate that both the lead and pup trailers must be loaded.

Implementation

As Alberta Transportation has allowed the pole-style configuration to operate on public roads in Alberta, this configuration should be incorporated into log haul fleets where appropriate. The log lengths should allow the log bundles to span the inter-bunk distance without any need for supporting structure in between. Typical log lengths should be between 9.14 m and 11.27 m and allow for adequate load extension beyond the bunk stakes.

The tare weight of this configuration is considerably lower than conventional super B-trains, resulting in a payload increase, reduced carbon emissions, and reduced wood transportation costs. In some operations, it may be cost-effective to alter the log length so that the pole-style trailers can be used to achieve an overall reduction in delivered wood costs.

As the dynamic performance of the pole-style configuration is improved when hauling the longer log length (11.27 m), it is recommended that log length be increased whenever possible to take advantage of the improved dynamic performance. In addition, the static rollover threshold is improved due to the lower load heights, and the rearward amplification improves as a result of the longer wheelbase of the pup trailer.

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Acknowledgements

The authors would like to thank the following for their assistance with this project: Eric Amlin, Rob Jokai, Garth Fraser, and Jim Ewart of FERIC for their assistance with the field trials, their expertise, and guidance; John Ellison, Michael Mallock, and the crew from Al-Pac for their cooperation; and Jon Preston-Thomas of NRC for his insight and assistance with developing the methodology.

APPENDIX I

Definition of performance measures [a]

Friction demand (FD): Friction demand is a measure of the resistance of multiple axles to travel around a tight-radius turn, such as at an intersection. It results in a "demand" for tire side force at the tractor drive axles. When the pavement friction level is low, a vehicle whose friction demand exceeds the friction available will produce a jackknife-type response of the tractor. Friction demand describes the minimum tire-pavement friction necessary for a vehicle to negotiate an intersection turn without suffering such loss of control.

High-speed off-tracking (HSOT): High-speed off-tracking is the lateral offset, in metres, between the path of the steer axle of the tractor and the path of the last axle of the vehicle in a steady turn of 0.2 g lateral acceleration. Since the driver guides the tractor along a desired path, there is a potential safety hazard if the trailer tires follow a more outboard path that might intersect a curb or other roadside obstacle, or intrude into an adjacent lane of traffic.

Lateral friction utilization (LFU): Lateral friction utilization is the lateral friction at the front axle necessary for the vehicle to be able to make a right-hand turn at an intersection.

Load transfer ratio (LTR): The load transfer ratio is the fractional change in load between left-hand and right-hand side tires of a vehicle in an obstacle avoidance maneuver. It indicates how close the vehicle came to lifting off all the tires on one side, a precursor to rollover.

Low-speed off-tracking (LSOT): Low-speed off-tracking is the extent to which the path of the rearmost axle of a vehicle tracks inside the path of the tractor front axle in a typical 90-degree right-hand turn at an intersection. This property is relevant to the "fit" of the vehicle on the road system, and has implications for safety as well as abuse of roadside appurtenances.

Rearward amplification (RA): Rearward amplification is the ratio of rearmost trailer peak lateral acceleration to tractor peak lateral acceleration in an obstacle avoidance maneuver. It is another way to quantify the "tail-wagging" response of a trailer to a rapid steer input.

Static rollover threshold (SRT): The static rollover threshold is the lateral acceleration, in g, at which the vehicle just rolls over in a steady turn. This is the point at which all axles with the exception of the steering axle have lifted off. This measure is known to correlate well with the incidence of single truck rollover accidents in highway service.

Transient high-speed off-tracking (TOT): Transient high-speed off-tracking is the peak overshoot, in metres, in the lateral position of the rearmost trailer axle from the path of the tractor front axle in an obstacle avoidance maneuver. It is an indication of potential to sideswipe a vehicle in an adjacent lane, or for rollover due to the impact of a curb strike. This measure quantifies the "tail-wagging" response of a trailer to a rapid steer input in a manner related directly to highway safety.

Understeer coefficient (USC): The understeer coefficient is a measure of vehicle lateral directional stability and handling. It is calculated at a lateral acceleration of 0.25 g in a steady turn.

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[a] From Billing and Preston-Thomas (2000).

APPENDIX II

Greenhouse gas emissions

$$\text{Rolling resistance}^{a} = \left(\left(0.0041 + 0.000041V\right)C_h\right)V$$

where C_h is road factor
C_h = 1.0 for pavement
C_h = 1.7 for gravel roads
V = velocity (mph)

$$\text{Aerodynamic drag}^{b} = \frac{1}{2}\rho V^2 C_D A$$

where ρ = density of air
C_D[c] = drag coefficient
V = velocity (m/s)
A = frontal area (m^2)

[a] Gillespie 1992.
[b] Gillespie 1992.
[c] Garner 1980.

Table A1. Energy requirements

	Conventional				Pole-style			
	Loaded cycle		Unloaded cycle		Loaded cycle		Unloaded cycle	
	Hwy	Off Hwy	Hwy	Off Hwy	Hwy	Off Hwy	Hwy	Off Hwy
Speed (km/h)	90	60	100	70	90	60	100	70
Distance (km)	155	155	155	155	155	155	155	155
Time (h)	1.72	2.58	1.55	2.21	1.72	2.58	1.55	2.21
Rolling resistance (hp)	132.56	132.49	47.01	49.59	132.56	132.49	39.78	41.96
Aerodynamic drag (hp)	136.95	40.58	153.73	52.73	136.95	40.58	153.73	52.73
Auxiliary loads [a] (hp)	20	20	20	20	20	20	20	20
Drive train losses [b] (hp)	15	15	15	15	15	15	15	15
Total energy (hp)	304.52	208.07	235.75	137.32	304.52	208.07	228.51	129.69
Energy consumption (hp•h)	524.44	537.52	365.41	304.06	524.44	537.52	354.2	287.17

[a] Bradley 2000.
[b] Bradley 2000.

Energy savings: Conventional = 524.44 + 537.52 + 365.41 + 304.06 = 1731.43

Pole-style = 524.44 + 537.52 + 354.20 + 287.17 = 1703.33

$$\text{Savings} = \frac{1731.43 - 1703.33}{1731.43} \bullet 100\% = 1.62\%$$

Truck	Conventional	Pole-style
Tare (kg)	19 500	16 500
GVW (kg)	63 500	63 500
Delivered payload (kg)	41 000	44 000
Cycle time[a] (h)	8.0	8.0
Fuel consumption (l/h)	40.0	39.4
Availability (h/yr)	3 000	3 000
Loads per year	333	333
Annual fuel consumption (l)	120 000	118 052
CO_2 conversion (kg/l)	2.64	2.64
CO_2 production (kg)	316 800	311 658
Delivered wood[b] (m^3)	16 078	17 255
CO_2 production per m^3 wood (kg/m^3)	19.70	18.06

Table A2. Greenhouse gas emissions

[a] Includes driving, loading, and unloading time.
[b] Wood density = 850 kg/m^3.

$$\text{Percent improvement} = \frac{19.70 - 18.06}{19.70} \bullet 100\% = 8.32\%$$

Fleet size = 65 trucks

Fleet CO_2 reduction = 65 trucks (16078 m^3/truck)(19.70 – 18.06 kg CO_2/m^3 wood)
= 1715 tonnes