

## DEVELOPMENT OF A ROLL-COUPLED HITCH FOR TRUCK/TRAILERS

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### Abstract

Truck/trailer configurations, consisting of a truck connected to a trailer via a pintle hitch, are widely used throughout Canada and the world and have proven very versatile. However, the pintle connection does not provide any roll-coupling between the truck and trailer making these configurations less dynamically stable than tractor/semi-trailer configurations. Previous research by FPInnovations – Feric Division has shown that the performance of these configurations could be improved through the addition of roll-coupling. Based on these findings, Feric and Wolf Trailers Inc. fabricated two prototype hitches and initiated testing in 2009. This paper summarizes the results of torsional strength tests completed for both prototype hitches, as well stability tests conducted for a truck/pony trailer equipped with the Wolf trailer hitch.

**Keywords:** Roll-coupling, truck configurations, stability testing, torsional stiffness

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<sup>1</sup> The Feric Division of FPInnovations was formerly the Forest Engineering Research Institute of Canada (FERIC)

## 1. Introduction

### 1.1 Background

Truck/trailer configurations, consisting of a truck connected to a trailer via a pintle hitch, are widely used throughout Canada and the world for hauling a variety of commodities (Figure 1). These configurations have proven very versatile and manoeuvrable under a wide range of operating conditions. However, the pintle connection does not provide any roll-coupling between the truck and trailer making these configurations less dynamically stable than tractor/semi-trailer configurations. Two types of truck/trailer configurations that are widely used in Canada are truck/pony trailers and truck/full trailers.



**Figure 1. Truck/trailer configurations**

In Canada, the truck/full trailer and truck/pony trailer were incorporated into the federal-provincial-territorial memorandum of understanding (MOU) on interprovincial weights and dimensions in September 1991. The regulatory limits applied to these configurations in the MOU were based on testing and analysis conducted by the Ontario Ministry of Transportation (Billing, Lam, 1992). As a result of this work, trailer weight allowances were capped at 17 000 kg, 24 000 kg and 31 000 kg for 2-axle, 3-axle, and 4-axle full trailers respectively and 21 000 kg for 3-axle pony trailers in the MOU.<sup>2</sup> This resulted in reductions of up to 3 000 kg in the payload capacity of the 3- and 4-axle full-trailers and 3-axle pony trailers relative their allowable axle capacity.

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<sup>2</sup> The MOU has not been universally applied by all provinces and territories.

## 1.2 Preliminary Work

In previous research (Parker, 2004) Feric determined<sup>3</sup> that adding roll-coupling could significantly improve the dynamic performance of truck/full trailers – meeting or exceeding performance standards – most importantly, Load Transfer Ratio (LTR) – at full payloads.

Feric, in conjunction with Arctic Manufacturing Ltd. of Prince George, BC, designed a prototype hitch to add roll-coupling to the truck/full trailer (Figure 2).



**Figure 2. Feric prototype full-trailer drawbar**

Wolf Trailers Inc. of Vernon, BC developed a hitch to address the need for roll-coupling specifically for pony trailers (Figure 3), and approached Feric to evaluate the concept. Using computer simulation, Feric concluded that the addition of roll-coupling would result in improved dynamic performance and stability for the truck/pony trailer at maximum axle weights (Parker, 2008).



**Figure 3. Wolf Trailers roll-coupled pony-trailer hitch**

With improved dynamic performance (and the corresponding improvement in overall safety), it was hoped that jurisdictions would increase the weight allowances for these configurations;

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<sup>3</sup> Computer simulations were conducted using the University of Michigan Transportation Institute (UMTRI) yaw/roll model.

increasing overall productivity, and decreasing fuel consumption and greenhouse gas emissions (per unit of delivered payload).

Based upon these overriding objectives, Feric developed a test plan to evaluate the effectiveness of the Feric hitch. Following the creation of this test plan, Wolf Trailers agreed to follow a similar testing methodology for their hitch. Where possible, the testing of the two hitches would be conducted cooperatively in order to save both time and cost, standardize test procedures and improve testing repeatability.

The test plan included the following phases:

1. Evaluation of hitch torsional stiffness
2. Evaluation of vehicle performance
3. Evaluation of hitch performance in-service

To date, only phase 1 (hitch torsional stiffness evaluation) has been completed for both hitches (Sinnott, Parker 2009). Phase 2 (vehicle performance testing) (Parker, Sinnott 2009) as well as phase 3 (in-service testing) has been partially completed for the Wolf Trailer (pony trailer) hitch, but these phases have yet to be completed for the Feric prototype (full-trailer) hitch. This paper will focus on the torsional testing conducted for both hitches, as well as stability tests conducted for the Wolf Trailer hitch.

## 2. Methodology

### 2.1 Torsional Stiffness Evaluation

The proposed torsional strength requirements for the Feric hitch were based on Transport Canada's C-dolly performance requirements (Transport Canada, 1993), increased proportionally to recognize the higher gross vehicle weight (GVW) associated with quad-axle full-trailers as compared with the C-dolly (34 000 kg versus 26 100 kg).

The resulting torsional strength requirements<sup>4</sup> proposed were:

- The ability of sustaining a torque of at least 60 kN·m
- A torsional stiffness of at least 4 kN·m/deg, with respect to the longitudinal direction
- Residual deformation in the hitch (after removal of the torque) of less than 0.5 degrees.

While pony trailers do not have the same higher GVW as full-trailers, the Wolf Trailer hitch was designed and tested to the same requirements as the Feric hitch.<sup>5</sup>

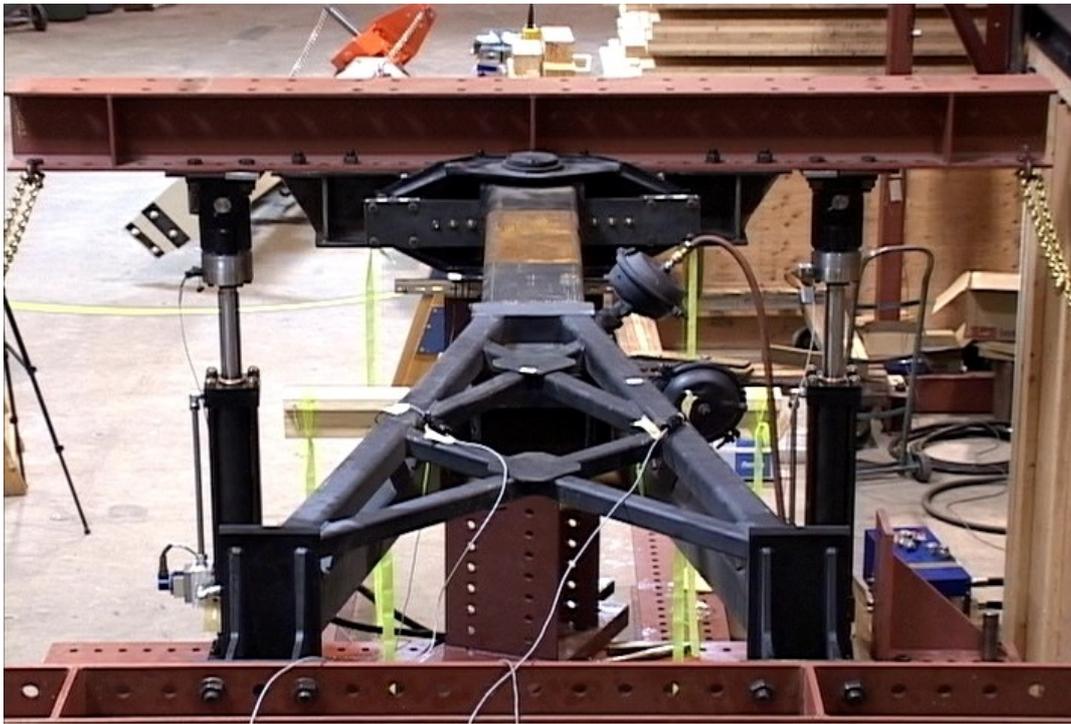
The torsional stiffness tests were conducted at the FPInnovations – Forintek facility in Vancouver, BC. The test apparatus (Figure 4) consisted of an H-shaped frame, anchored to the floor, which one end of the hitch was attached to and fixed in place. The other end of the hitch was attached (through a jig assembly) to two vertically mounted hydraulic cylinders that were attached via a mounting frame to the floor.

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<sup>4</sup> In addition to the torsional strength requirements, the hitches were specified to have a static load rating of 400 kN in longitudinal direction, 130 kN in vertical direction and 40 kN in lateral direction.

<sup>5</sup> While the Wolf Trailer hitch was specifically designed for pony trailers, it could be in the future adapted to be used on full-trailers. Thus, testing it to the higher requirements was deemed appropriate.

The two cylinders were controlled independently using a computer control system, which recorded both cylinder displacement and cylinder force continuously throughout the test. Controlling the cylinders via displacement ensured that, as one cylinder extended and the other cylinder retracted, the centre of twist<sup>6</sup> would remain fixed in space through the entire loading cycle, thus allowing the hitch to experience pure torsion along its longitudinal axis for the entire test. The control system also recorded data from ten displacement sensors attached to the hitch, which were used to calculate drawbar twist.



**Figure 4. Torsional stiffness test apparatus with Feric hitch**

### ***Test Procedure***

The test procedure developed (using the computer control system software) consisted of the following steps:

1. Move cylinders to their zero positions; defined as the height at which the hitch is level – longitudinally and laterally. Cylinder loads are equalized; this is the zero torque starting position for the test.
2. Gradually apply a torque to the hitch about its longitudinal axis until 60 kN·m is reached and until either of the following limits is reached.
  - a. A maximum cylinder load of 35.6 kN.
  - b. A maximum twist angle of 15 degrees.<sup>7</sup>
3. Gradually remove the torque to the hitch about its longitudinal axis and continue to apply a torque in the opposing direction until 60 kN·m is reached in the opposite

<sup>6</sup> The cylinder's centre of twist equates to a point equidistant between the top pinned connections of the two cylinders. This point is aligned with the longitudinal axis of the hitch to ensure a purely torsional loading.

<sup>7</sup> Once the twist reaches 15 degrees, if the torque has not already reached 60 kN·m, then the torsional stiffness requirement of 4 kN·m/deg will not be reached and the hitch will have failed.

direction. This is accomplished by reversing the direction of cylinder movement according to the same conditions and constraints as previously described.

4. Gradually remove the torque from the hitch. In order to ensure enough data are collected to identify the zero point, the cylinders are twisted back through to zero to 17.8 kN in each cylinder in opposing directions, or to a cylinder offset of 12.5 cm.

Hitch torque (T) in kN·m is calculated with the following formula:

$$T = F \times D \times \cos\phi \quad (1)$$

Where F = force in each cylinder (kN)

D = lateral distance between cylinders<sup>8</sup> (m)

Ø = angle of twist (at cylinders)

## 2.2 Vehicle Performance Evaluation

### *Steady State Stability*

The performance measure used to measure steady state stability is the static rollover threshold (SRT), which is the lateral acceleration (measured in g) where the roll unit just achieves complete axle lift-off.<sup>9</sup> For a non-roll-coupled truck/pony trailer, the trailer and truck are separate roll units, whereas the truck and trailer make up one roll unit for the roll-coupled configuration. This test was conducted on the tilt table (similar to SAE recommended practice J2180), whereby both the truck and trailer were free to roll. Safety chains were used to prevent complete rollover.

### *Differential Roll Stability*

It is also desirable to quantify the potential improvements that could be achieved from roll-coupling under dynamic conditions. Previous research has demonstrated significant improvements in dynamic stability with roll-coupling during a lane change manoeuvre where a “phase shift” in lateral acceleration occurs between the truck and trailer centres of gravity (CG). In simulations, the performance measure most frequently used to evaluate the dynamic stability is the load transfer ratio (LTR), which is defined as:

$$LTR = \frac{(L_l - L_r)}{(L_l + L_r)} \quad (2)$$

Where  $L_l$  = sum of roll unit axle loads on left side

$L_r$  = sum of roll unit axle loads on right side

This performance measure is difficult to measure experimentally in a dynamic manoeuvre due to the cost and complexity of installing load sensors at each wheel end to allow continuous wheel load measurement. Therefore, a static test was devised on the tilt table to demonstrate the lateral acceleration phase shift phenomenon and estimate the relative improvements that could be achieved from roll-coupling for this configuration. This was accomplished by restraining the truck from rolling relative to the tilt table while allowing the trailer to roll, in effect resulting in different lateral accelerations at the truck and trailer. This test will

<sup>8</sup> Lateral distance between cylinders was fixed at 1.83 m

<sup>9</sup> Due to its low compliance, steering axle of truck is not included when determining SRT

henceforth be referred to as the “differential roll stability” test. Both tests were conducted at Arrow Transport’s side dump facility in Ashcroft, BC.

### ***Test Procedure***

For each test, the test configuration was secured to prevent complete rollover in order to maintain safety and prevent damage to the configuration and facilities. In the steady state stability (SRT measurement) test, the truck was free to roll with the trailer. In the differential roll test, the truck was restrained with ratchet binders to prevent any roll relative to the tilt table.

The tilt table was raised up to the point where full wheel lift-off had occurred on the high side of the tilt table for all axles of the trailer. The rotation angles were measured at the tilt table, trailer and truck frames, and drawbar.

In addition, individual wheel loads on the high side<sup>10</sup> of the tilt table were also recorded to measure the load transfer progression of the configuration throughout the test. The static LTR was computed for the truck and trailer using the following formula:

$$LTR = \frac{(1 - L_t)}{L_0} \quad (3)$$

Where  $L_t$  = sum of roll unit axle loads on left side (high side of tilt table) at time t  
 $L_0$  = sum of roll unit axle loads on left side on level ground

The lateral acceleration (LA) throughout each tilt (measured in g) was computed using the following formula:

$$LA = \tan \theta \quad (4)$$

Where  $\theta$  = tilt angle (in degrees)

$$SRT = LA \text{ when the roll unit } LTR = 1 \text{ (i.e. full axle lift-off)} \quad (5)$$

The following two measures were used to evaluate the effect of roll-coupling in the differential roll test:

- LTR at a trailer lateral acceleration of 0.3 g (i.e. when tilt table is at 16.7 degrees)
- Lateral acceleration at trailer axle lift-off

The tandem drive truck/tridem pony trailer was loaded to target loads of 9 100 kg and 17 000 kg on the steering and drive axles, respectively. The tridem pony trailer was loaded to two separate target load conditions: 21 000 and 24 000 kg to evaluate the effect of an increased trailer load above the MOU allowance to full axle weight potential.

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<sup>10</sup> Only the high side wheel loads were measured, due to safety concerns related to raising the right side wheels above the curb rail on the tilt table. The data analysis was adjusted to neutralize the effect of this.

### 3. Results and Discussion

#### 3.1 Torsional Stiffness Evaluation

A total of five and three tests were conducted for the Feric and Wolf trailer hitches respectively. For all tests, the hitches were twisted (in both directions) to a torque that exceeded the required 60 kN·m.

There was significant hysteresis exhibited during the tests as illustrated in Figure 5. The exact mechanism of this energy loss is unknown, however friction losses between parts in the hitch assembly is one probable factor. The hysteresis meant that the hitch followed a different path while loading and unloading. Thus, when the control system indicated that the cylinders had returned to equal loading conditions (zero torque), the hitch would always be at a different angle from where it started. This was not indicative of any residual deformation in the hitch, but it did make any direct measurements of residual deformation difficult.

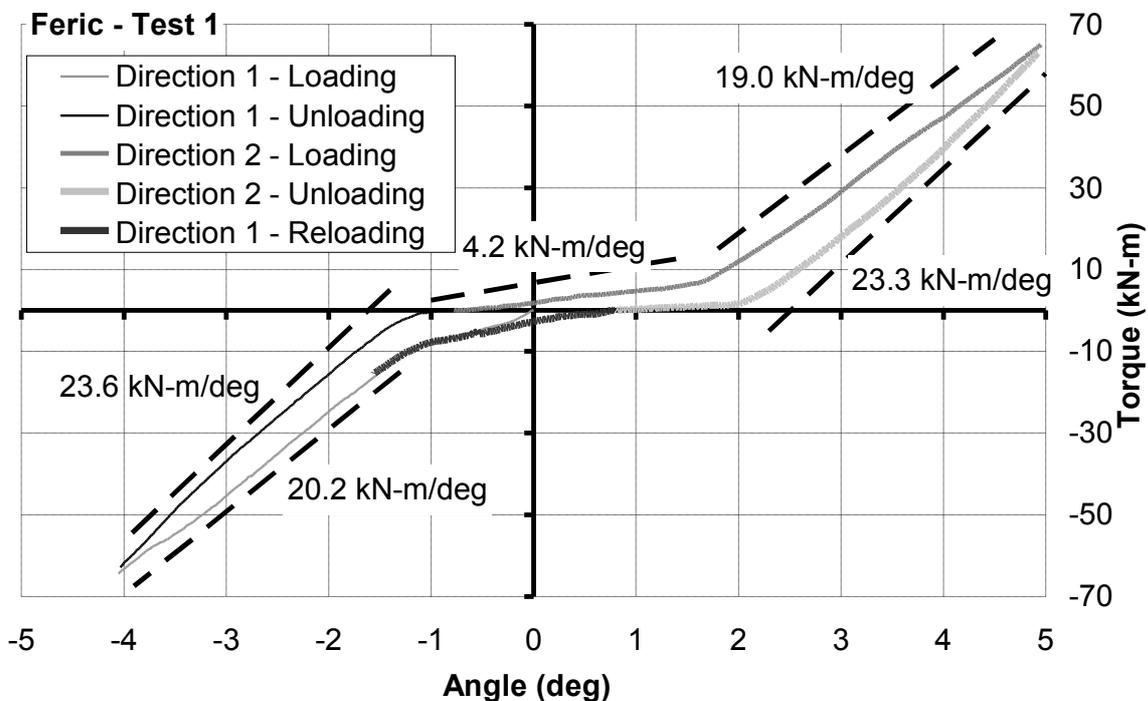


Figure 5. Sample torsional test

The testing demonstrated that there were two distinct stiffness levels for both hitches as illustrated in Figure 5. However, even at low levels of torque, significant stiffness was encountered, and there was no range in which true slack<sup>11</sup> occurred. The stiffness encountered in this low range (between 3 and 4 kN·m/deg) was a great deal less than the rest of the loading/unloading curve. However, as 4 kN·m/deg is considered an adequate overall hitch stiffness, this stiffness is clearly significant and cannot be considered true slack (although it being much lower does indicate that slack is being taken up in this phase).

<sup>11</sup> Slack, as defined as angular motion (twist) with little or no torque.

The average stiffness results are summarized in Table 1. The overall stiffness of the hitch was determined by using the overall change in torque and overall change in angle. This methodology, using the whole test in both directions to determine an overall stiffness was similar to that used by the NRC (Preston-Thomas, 1994) to determine tractor and trailer frame torsional stiffness.

**Table 1 - Torsional Testing Summary**

	Feric Hitch		Wolf Trailer Hitch	
	Direction1	Direction 2	Direction1	Direction 2
Maximum torque (kN·m)	-64.4	64.8	-63.5	64.2
Maximum angle (deg)	-4.0	5.0	-4.3	5.1
Stiffness (kN·m/deg)				
Loading	20.6	19.7	19.8	19.1
Unloading	23.5	22.7	20.2	20.8
Stiffness (kN·m/deg)				
Low range	3.9		2.9	
Overall	14.4		13.6	

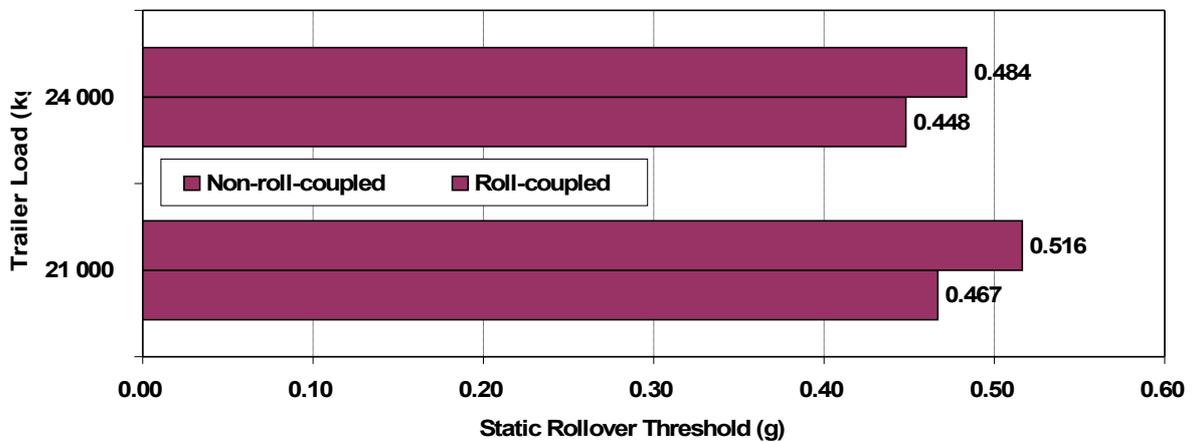
Both the Feric hitch and the Wolf Trailer hitch exhibited the ability to sustain a torque of at least 60 kN·m. The maximum applied torque resulted in roughly 5 degrees of twist, much less than the 15 degrees allowable. Both hitches exhibited a torsional stiffness nearly 3.5 times the required 4 kN·m/deg, with average stiffness levels of 14.4 and 13.6 kN·m for the Feric and Wolf Trailer hitches respectively. These results suggest that both hitches may be over-designed, and that design refinements could reduce these factors somewhat – saving weight. However, this is not recommended to any great extent as truck/trailer hitches can operate in extreme environments, where a great deal of vibration and atypical loading conditions can occur.

The energy loss (hysteresis) during the tests made direct measurement of potential residual deformation problematic. The hysteresis ensured that the zero load point while unloading would always be quite different from that when loading. It is possible, however, to use the test results to indirectly analyze whether any deformation occurred. The consistency of results between the tests indicates that the drawbars were never stressed beyond their elastic limits suggesting that no deformation had occurred.

### 3.2 Vehicle Performance Evaluation

#### *Steady State Stability*

The presence of roll-coupling improved the steady state stability of the truck/pony trailer with an improvement in SRT of 10.5% and 8% for the 21 000 kg and 24 000 kg trailer loads, respectively (Figure 6). This improvement was largely due to the truck being included as part of the critical roll unit for the roll-coupled cases. In the non-roll-coupled cases, the trailer was the critical roll unit as it rolled prior to the truck. These results showed that a roll-coupled truck/pony trailer at an increased trailer load of 24 000 kg had an improved SRT (0.484 g) relative to the non-roll-coupled configuration carrying the MOU trailer weight of 21 000 kg (0.467 g).



**Figure 6. Comparison of steady state stability.**

#### *Differential Roll Stability*

The use of roll-coupling was demonstrated to improve the differential roll stability of the truck/pony trailer. This is illustrated by the increased lateral acceleration of trailer axle lift-off (Figure 7) and decreased LTR (Figure 8). The lateral acceleration at which trailer axle lift-off occurred increased with roll-coupling by 5.6% and 11.2% for the 21 000 kg and 24 000 kg loads respectively. Improved performance was achieved at an increased trailer load of 24 000 kg with roll-coupling compared with the existing allowable trailer weight of 21 000 kg without roll-coupling. The overall improvement in LTR at 0.3 g lateral acceleration resulting from roll-coupling was approximately 30%, and was largely due to the combined effect of the truck and trailer in the LTR calculation. Similar levels of LTR were achieved for the roll-coupled unit at both trailer loads.

The differential roll tests demonstrated that the roll-coupled drawbar functioned as intended, and allowed the truck and trailer to act together as one unit and improve configuration stability when the truck and trailer lateral accelerations are “out of phase” with each other. It is anticipated that under dynamic conditions, the difference in lateral accelerations between the truck and trailer would be higher than was achieved under the static test conditions, resulting in a further improvement in performance.

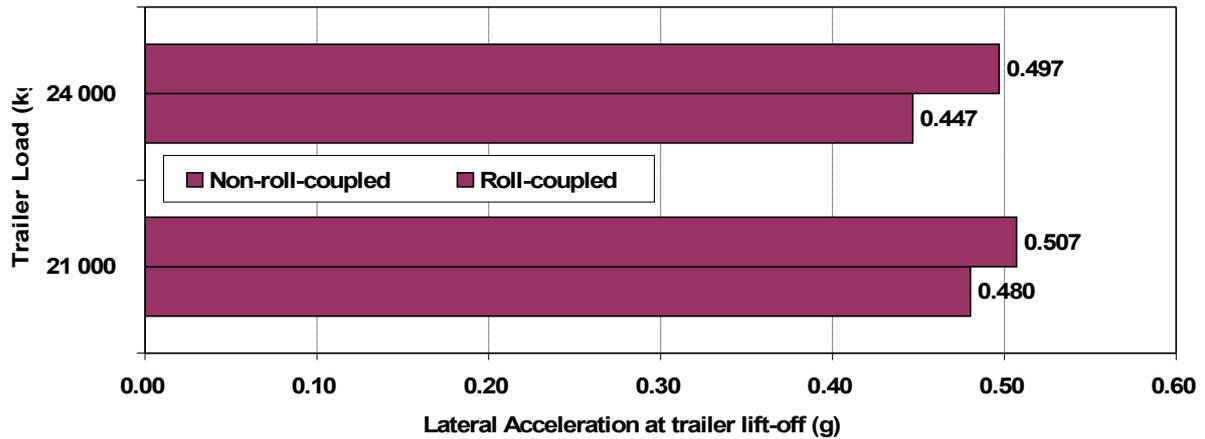


Figure 7. Differential roll performance – lateral acceleration at trailer lift-off.

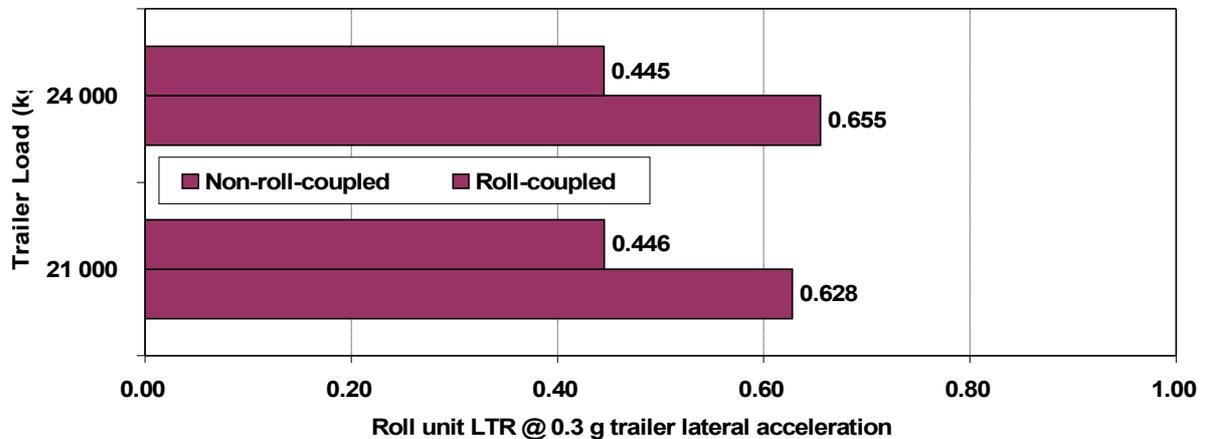


Figure 8. Differential roll performance – roll unit load transfer ratio at 0.3 g trailer lateral acceleration.

#### 4. Conclusions

- Both the prototype hitches achieved the prescribed torsional strength and stiffness requirements of 60 kN·m and 4 kN·m/degree respectively. The measured torsional stiffness exceeded the minimum stiffness requirement by a significant factor, with average stiffness levels of 14.4 and 13.6 kN·m for the Feric and Wolf Trailer hitches respectively. The maximum applied torque resulted in approximately 5 degrees of twist, much less than the prescribed 15 degrees.
- The hysteresis observed in the torsional tests made direct measurement of potential residual deformation problematic. However, the consistency of test results indicates that both hitches were not stressed beyond their elastic range, and that minimal deformation occurred.
- Tilt table testing showed that roll-coupling improved the steady state stability of the truck/pony trailer with an improvement in SRT of 10.5% and 8% for the 21 000 kg and

24 000 kg trailer loads, respectively. It was also demonstrated that the steady state stability of the roll-coupled truck/pony trailer with an increased trailer load of 24 000 kg had improved stability relative to the status quo, non-roll-coupled unit with 21 000 kg load.

- The differential roll tests demonstrated that the roll-coupled drawbar functioned as intended, and allowed the truck and trailer to act together as one unit and improve configuration stability when the truck and trailer lateral accelerations are “out of phase” with each other. There is estimated to be an overall improvement in LTR of approximately 30% which is largely due to the combined effect of the truck and trailer in the LTR calculation.

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