Evaluation of the Dynamic Performance of Truck-Recreational Trailer Combinations

Prepared for

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ABSTRACT

This work used computer simulation to assess the dynamic performance of a straight truck carrying a small travel trailer while towing either a fifth wheel recreational trailer or a travel trailer.

EXECUTIVE SUMMARY

A motor carrier is using a straight truck to carry a travel trailer, while towing a second recreational trailer in Saskatchewan. The truck is fitted with a combination fifth wheel and ball hitch. This allows it to tow either a fifth wheel recreational trailer, or a travel trailer, which uses a ball hitch. The hitch can be positioned so the hitch offset of the truck ranges from 3.07 to 4.90 m (121 to 193 in). This range is well beyond the maximum hitch offset of 1.80 m (71 in) allowed a straight truck in Saskatchewan.

The hitch offset of a truck-trailer combination was limited in the national Memorandum of Understanding on Vehicle Weights and Dimensions in order to control the high-speed dynamic performance of the combination, particularly in an evasive manoeuvre.

Saskatchewan Highways and Transportation wishes to ensure the configuration can tow the range of recreational trailers available safely. This report assessed the dynamic performance of the specific truck in combination with a range of size and weight of fifth wheel and travel trailer, over the full range of the adjustable hitch, for travel at 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h).

The high-speed dynamic performance measures all increase with an increase in trailer size, hitch offset and vehicle speed.

Some combinations exceed the high-speed offtracking performance standard, but is not expected that this will result in potential for conflict with other traffic.

The load transfer ratio performance of travel trailers is poor. The transient offtracking performance standard is exceeded for the longest trailers at the greatest hitch offsets and highest speeds. Satisfactory levels of load transfer ratio and transient offtracking performance can be ensured by some appropriate combination of restriction on vehicle speed and hitch offset, or a requirement that a suitable weight distributing hitch be used to tow a travel trailer.

This combination can reach the maximum overall length with a large trailer, but low-speed offtracking of these combinations is much less than that of the largest tractor-semitrailer because the trailers have a relatively short wheelbase. However, a large hitch offset results in significant front outswing for fifth wheel trailers, and significant rear outswing for both fifth wheel and travel trailers. Some of the large trailers may exceed the 4.0 m (157 in) rear overhang limit that applies to a pony trailer, which exacerbates rear outswing.

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1. INTRODUCTION

A motor carrier is using a straight truck to carry one recreational trailer, while towing a second recreational trailer in Saskatchewan, as shown in Figure 1. The truck is fitted with a combination fifth wheel and ball hitch, as shown in Figure 2. This hitch can accommodate a fifth wheel recreational trailer, or a travel trailer, which uses a ball hitch. The hitch can be extended so that its rearmost point is up to 1.83 m (72 in) behind the rear of the truck, which allows clearance between the rear of a long trailer on the deck and a towed fifth wheel trailer.

With the hitch in its rearmost position, the truck is 12.45 m (490 in) long, which is just within the allowable overall length of 12.50 m (492 in) [1]. When the hitch is extended beyond about 0.91 m (36 in), the truck exceeds the allowable effective overhang of 4.0 m (157 in) ([1] Section 8 (1) (a)). With the hitch in any position, it exceeds the allowable hitch offset of 1.80 m (71 in) ([1] Section 8 (1) (b)). Any recreational trailer that can be towed within an overall length of 23 m (75 ft 6 in) is within the allowable box length of 20 m (65 ft 7 in) for a truck-trailer combination [1]. The truck can tow a travel trailer up to about 12.34 m (40 ft 6 in) in length within the overall length of 23 m (75 ft 6 in) with the ball hitch in the most forward position, or a lesser length trailer according to any rearward offset of the hitch. The truck can also tow a fifth wheel trailer of the same length, neglecting that part of the trailer ahead of its kingpin. The effective overhang of some of the longest trailers may exceed the allowable effective overhang of 4.0 m (157 in) ([1] Section 8 (1) (a)).

The hitch offset is known to be a significant parameter in the dynamic performance of a truck-trailer combination [2]. Hitch offset was limited in the national Memorandum of Understanding on Vehicle Weights and Dimensions in order to control the high-speed dynamic performance of the combination, particularly in an evasive manoeuvre [3]. Saskatchewan Highways and Transportation wishes to ensure the configuration can tow the range of recreational trailers available safely.

This report presents an assessment the dynamic performance of the specific truck in combination with a range of size and weight of fifth wheel and travel trailer, over the full range of the adjustable hitch, for travel at 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h).

Figure 1: Vehicle Configuration

Figure 2: Detail of Truck Hitch

2. ASSESSMENT OF DYNAMIC PERFORMANCE

2.1 Performance Measures

This work used the same approach to assess vehicle dynamic performance as the CCMTA/RTAC Vehicle Weights and Dimensions Study [4], [5], [6]. This approach has served as the basis for all new vehicle weight and dimension regulations since 1985, and for evaluation of many special permit applications by most provinces.

A performance measure is some response of a system to a standardized input. The input is standardized so that responses of different systems can be compared to each other. The performance standard is the criterion or boundary between satisfactory and unsatisfactory performance. Evaluating vehicle performance consists of three steps:

1. Subject the vehicle to a standardized input;
2. Evaluate the performance measure; then
3. Compare the performance measure to the performance standard.

The evaluation process requires standardized inputs, performance measures and performance standards to be defined in a consistent and coherent manner.

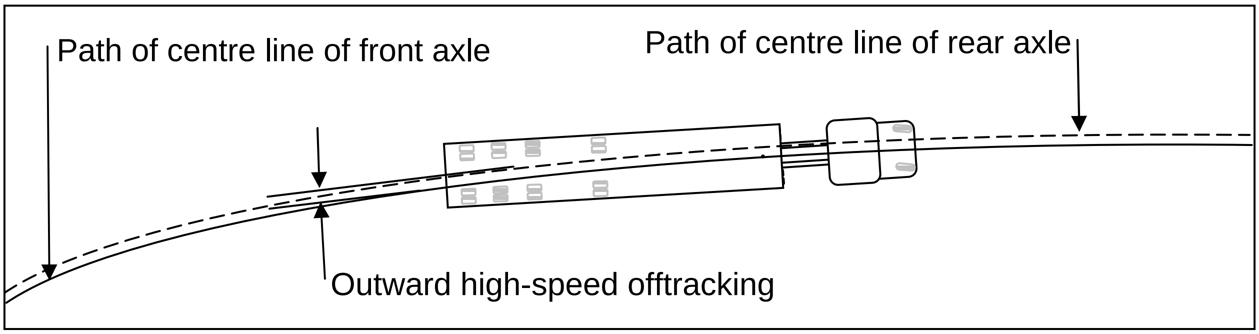
Dynamic performance was assessed using the so-called “RTAC” performance measures, developed during the CCMTA/RTAC Vehicle Weights and Dimensions Study [4], [6]. These are also consistent with performance measures proposed for vehicles that might operate North America-wide under possible future provisions of the North American Free Trade Agreement [7]. The CCMTA/RTAC Vehicle Weights and Dimensions Study principally examined the dynamic performance of trailers, so the RTAC performance measures were primarily aimed at characterizing the performance of the trailer within the whole vehicle. The RTAC performance measures have been supplemented with others that address particular aspects of the vehicles that were the subject of this work. The performance measures were all determined by computer simulation using five manoeuvres that produce all the required responses to compute the performance measures, as outlined in the following sections.

Braking efficiency was one of the original RTAC performance measures, which assessed how effectively the braking system of a combination vehicle could use the available tire-road friction to stop a vehicle [4]. An antilock brake system (ABS) has been required on tractors since 1997, and trailers since 1998. An ABS automatically ensures the braking efficiency performance standard should be met over a much wider range of road and load conditions than the original RTAC performance measure. This performance measure is therefore no longer relevant, and was not evaluated.

2.1.1 High-speed Turn

A high-speed turn, made at a speed of 90, 100 or 110 km/h (55.9, 62.1 or 68.3 mi/h), on a high-friction surface, was used to evaluate the static rollover threshold and high-speed offtracking performance measures. This manoeuvre is shown in Figure 3. The turn starts with a short tangent segment, and is followed by a spiral entry to a curve whose radius corresponds to a lateral acceleration of 0.20 g at the specified speed. This curve is held until 15 s into the run, to allow steady state high-speed offtracking to be achieved. Steering wheel angle is then increased at 2 deg/s, until the vehicle rolls over, or becomes unstable in yaw.

Figure 3: High-speed Turn



The **Static Roll Threshold** performance measure is the lateral acceleration, in g, at which a vehicle just rolls over in a steady turn. This measure is known to correlate well with the incidence of single truck rollover crashes [8].

The CCMTA/RTAC Vehicle Weights and Dimensions Study set a target static roll threshold of 0.40 g [4]. This value was not used when vehicles were configured for the national M.o.U. [3], because it was recognized that certain commodities inherently have a high centre of gravity at the axle and gross weights allowed in Canada. So, vehicles that meet the M.o.U. may have a static roll threshold less than 0.40 g. However, provinces that use an assessment of dynamic performance as part of the review of a special permit application often do impose the 0.40 g static roll threshold.

New Zealand has narrow winding roads, and its regulations resulted in short, high vehicles. The outcome was a much higher rollover rate than common in North America. New Zealand therefore established a minimum static roll threshold of 0.35 g, for both new and existing vehicles [9]. Carriers could either reduce the payload on an existing vehicle that did not meet this roll threshold, modify the vehicle to improve its roll threshold, or replace it. Overall length was also increased for some configurations, which allowed new vehicles to be built that could carry the same payload weight as before, with a lower centre of gravity.

Australia is considering a minimum static roll threshold of 0.35 g for its proposed new regulation that would allow vehicles carrying general freight to be configured simply to performance standards [10].

Studies in the U.S. considered static roll thresholds of 0.35 and 0.38 g, and concluded that any roll threshold higher than 0.35 g would restrict commerce, and would require a considerable number of exemptions. This is a similar conclusion to that reached when vehicles were configured for the national M.o.U., as noted above. The static roll threshold is not considered in U.S. Federal regulations, nor is it known to be a factor in any state law, regulation or permit.

Tank trucks are now being treated more cautiously. While the Australian performance-based standards set a minimum static roll threshold of 0.35 g for vehicles carrying general freight, the minimum is 0.40 g for tank trucks [10]. The minimum static roll threshold for tank trucks in European countries is now 0.40 g based on a tilt test, or 0.42 g based on a specified calculation procedure [11]. New Zealand sets a minimum static roll threshold of 0.45 g for tank trucks, but its allowable axle weights and gross weight are modest by Canadian standards, so tank trucks have a low centre of gravity and meet this without difficulty.

This work will consider 0.35 g as the minimum static roll threshold that should be considered for vehicles that will carry general freight under a special permit, and 0.40 g as the minimum static roll threshold that should be considered for tank trucks under a special permit. These values were adopted simply for presentation of this work, and should not preclude setting a higher limit when warranted for any configuration.

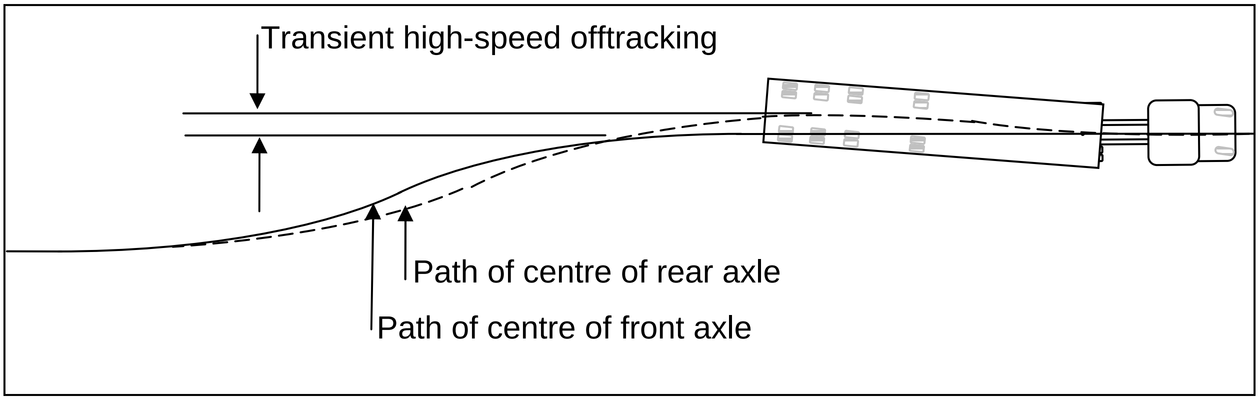
The **High-Speed Offtracking** performance measure is the lateral offset between the path of the steer axle of a tractor and the path of the last axle of the vehicle in a steady turn of 0.20 g lateral acceleration, as shown in Figure 3. Since the driver guides the tractor along a desired path, there is a clear safety hazard if the rearmost axle follows a more outboard path that might intersect a curb or other roadside obstacle, or intrude into an adjacent lane of traffic. This performance measure is a particularly significant for a long semitrailer equipped with self-steering axles, and double trailer combinations.

High-speed offtracking should not exceed 0.46 m (18 in) outboard of the path of the tractor. This allows the rearmost wheel of a vehicle with a 2.59 m (102 in) wide trailer whose tractor is centred in a 3.66 m (12 ft) wide lane within 0.08 m (3 in) of the edge of its lane.

2.1.2 High-speed Lane Change

A high-speed lane change, made at a speed of 90, 100 or 110 km/h (55.9, 62.1 or 68.3 mi/h), on a high-friction surface, was used to evaluate the load transfer ratio and transient high-speed offtracking performance measures. This manoeuvre is shown in Figure 4. The path was a side-step which corresponds to a single sinusoidal cycle of lateral acceleration of 0.15 g with a period of 3.0 s at the tractor front axle, and represents a manoeuvre made to avoid an obstacle in the path of the vehicle [6]. This

Figure 4: High-speed Lane Change



manoeuvre is sufficiently gentle that it does not cause the rearmost trailer of a multi-trailer combination to roll over. The period corresponds to that at which the greatest response occurred for most trucks in the simulations for the CCMTA/RTAC Vehicle Weights and Dimensions Study [6], but is not necessarily the period at which greatest response would actually occur for any particular vehicle. The two performance measures do not depend strongly on steer period for tractor-semitrailers, whereas they usually do for double and triple trailer combinations, and truck-trailer combinations.

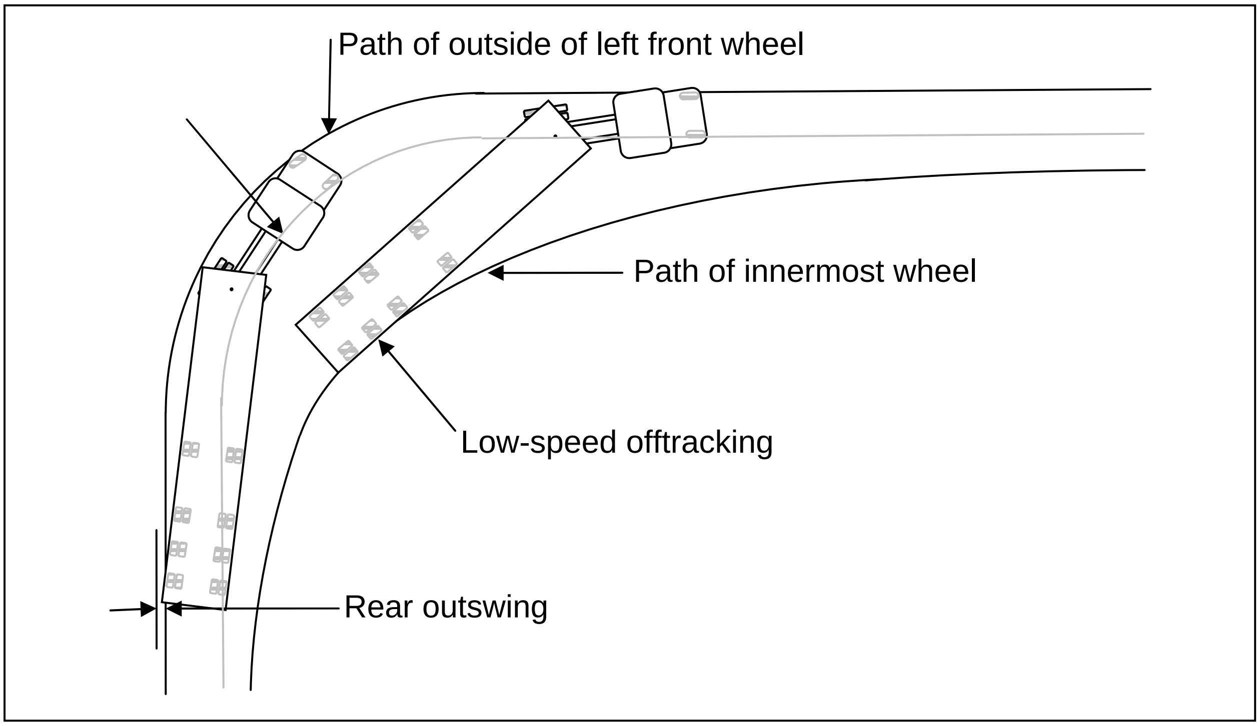
The **Load Transfer Ratio** performance measure is the fractional change in load between left- and right-hand side tires in an obstacle avoidance manoeuvre. It indicates how close all of the tires on one side of the rearmost roll-coupled unit came to lifting off, a precursor to rollover. The load transfer ratio should not exceed 0.60, which is equivalent to an 80%-20% left-right division of wheel loads. This is a particularly significant performance measure for any vehicle with a high payload centre of gravity, double and triple trailer combinations, and truck-trailer combinations [2].

The **Transient High-Speed Offtracking** performance measure is the peak overshoot in the lateral position of the rearmost trailer axle from the path of the tractor front axle in an obstacle avoidance manoeuvre, as shown in Figure 4. It is an indication of potential for side-swipe of a vehicle in an adjacent lane, or for impact-induced rollover due to a curb strike. This measure quantifies the "tail-wagging" response to a rapid steer input. The transient high-speed offtracking should not exceed 0.80 m (31.5 in). This is a particularly significant performance measure for double and triple trailer combinations, and truck-trailer combinations [2].

2.1.3 Low-speed Right-hand Turn on a High-friction Surface

A 90 degree right-hand turn at a typical intersection, made at a speed of 8.8 km/h (5.5 mi/h) on a high-friction surface, was used to evaluate the low-speed offtracking and rear outswing performance measures. This manoeuvre is shown in Figure 5. The CCMTA/RTAC Vehicle Weights and Dimensions Study used a turn radius of 10.97 m (36 ft) at the outside of the left front wheel of the power unit [6].

Figure 5: Low-speed Right-hand Turn



However, not all long-wheelbase power units can turn so tightly, and a vehicle can only be evaluated in a turn that it can make. Some previous studies have used a turn radius of 14.00 m (46 ft) at the outside of the left front wheel of the power unit, because it was the radius used to establish the geometry of the curb line for design of open throat intersections. This radius has also been recommended for assessment of vehicle configurations to be agreed under provisions of the North American Free Trade Agreement (NAFTA) [7]. The 14.00 m (46 ft) turn radius was therefore used to evaluate the low-speed performance measures.

The **Low-Speed Offtracking** performance measure is the extent of inboard offtracking of the rearmost trailer from the front axle of the power unit in a 90 degree right-hand turn at a typical intersection, as shown in Figure 5. This property is of concern to the "fit" of the vehicle on the road system, and has implications for safety as well as abuse of roadside appurtenances. The NAFTA proposal sets the low-speed offtracking at 5.60 m (18.4 ft) in a turn of 14.00 m (46 ft) radius [7], based on the turning performance of the configuration with the greatest offtracking allowed by the M.o.U., which is a tractor with 6.20 m (244 in) wheelbase and its fifth wheel over its turn centre towing a semitrailer with 12.50 m (41 ft) wheelbase. This is a particularly significant performance measure for long semitrailers, and long double and triple trailer combination vehicles.

The **Rear Outswing** performance measure is the extent of intrusion of the left-hand side rear corner of a vehicle unit into the lane to the left of that occupied by the vehicle as it makes a right-hand turn, as shown in Figure 5. The left rear corner becomes a potential obstacle to another vehicle traveling in that lane, and offers the possibility of a serious collision if that vehicle is traveling at a higher speed than the turning truck. Rear outswing should be less than 0.20 m (8 in). This is a particularly significant performance measure for tractor-semitrailers and truck-trailer combinations, where the power unit or trailer has a long effective rear overhang.

The **Front Outswing** performance measure is the extent of intrusion of the front left-hand side corner of a vehicle unit into the lane to the left of that occupied by the vehicle as it makes a right-hand turn, in a similar manner to that for rear outswing shown in Figure 5. The left front corner becomes a potential obstacle to another vehicle traveling in that lane, and offers the possibility of a serious collision if that vehicle is traveling at a higher speed than the turning truck. Front outswing should be less than 0.20 m (8 in). This is a particularly significant performance measure for tractor-semitrailers and truck-trailer combinations, where the trailer has a long front overhang.

2.2 Computer Simulations

The dynamic performance of vehicles has always been evaluated by computer simulation. While it is possible to determine some performance measures in a full-scale test, there is no practical way to measure friction demand or load transfer ratio in a test.

The simulation study was conducted using a version of the Yaw/roll model [12]. The Yaw/roll model is a dynamic simulation of moderate complexity that represents the combined lateral, yaw and roll response of heavy articulated vehicles as a result of either closed or open loop steering input with relatively simple input data. The model can represent vehicle combinations with up to six vehicle units and eleven axles, with up to eight axles on any vehicle unit. Up to five axles, other than the front steering axle, may be self-steering or forced steering. The model is structured so that any of these limits can easily be changed if necessary. Fifth wheel, turntable, pintle hook, C-dolly and other couplings allow representation of A-, B- and C-train combinations, and others. The non-linear characteristics of these coupling devices are represented directly by the model. The non-linear characteristics of tires, suspensions and self-steering axles are represented by lookup tables of input data. The model does not represent longitudinal tire forces needed for drive and brake torque, so is restricted to travel at constant longitudinal velocity on a smooth, level road surface with uniform frictional characteristics. The model operates either in closed loop mode by defining a specific steer input, either at the steering wheel or the front steering axle, or in open loop mode, by defining a path that the vehicle should follow and using a driver model to steer the steering wheel to cause the vehicle to follow that path. The steer input is defined in the closed loop mode, and the vehicle does not follow any specific path on the ground, it goes where it wants to, depending on its own dynamic characteristics. Two different vehicles subjected to the same closed loop input may follow quite different paths on the ground. The path to be followed is defined in the open loop mode, and choice of parameters in a driver model determines how closely the specified path is actually followed. These parameters are normally chosen to represent an alert driver so that the vehicle follows the desired path closely.

The Yaw/roll simulation program has been used extensively in previous simulation studies [5], [13], and has been shown to provide reasonable agreement with test results for a large number of vehicle configurations [2], [12], [15]. The absolute accuracy of a vehicle simulation depends critically both on how well the model represents the vehicle system, and how accurately the component data are known. The relative accuracy, for purposes of comparison of similar vehicles, is less dependent upon the accuracy of component data. The simulation can be expected to provide a proper ranking of vehicles in a comparison as long as the data are reasonably representative.

The performance measures were obtained from the three manoeuvres described in Section 2.1, which were designed to provide the necessary responses. This procedure is completely consistent with that used in the CCMTA/RTAC Vehicle Weights and Dimensions Study [5], and other studies conducted for a variety of purposes [2], [13]. High-speed manoeuvres were run at speeds of 90, 100 and 110 km/h (55.6, 62.1 and 68.3 mi/h) for all configurations.

3. TRUCK-RECREATIONAL TRAILER COMBINATION

3.1 Vehicle Configuration

This work addresses a straight truck and recreational trailer, as shown in Figure 1. The truck may tow either a fifth wheel trailer, or a travel trailer, which is towed by a ball hitch.

3.1.1 Truck

This work used a generic straight truck, with a front axle setback of 1.02 m (40 in), a single drive axle, and a 6.53 m (257 in) wheelbase. The front of the load bed was 4.01 m (158 in) aft of the front of the truck, and the load bed was 6.60 m (260 in) in length. The truck was fitted with a combination fifth wheel and ball hitch, which could be adjusted fore-and-aft over a range of 1.83 m (72 in). In the most forward position, the ball hitch was approximately flush with the rear of the truck, for a hitch offset of 3.07 m (121 in). The fifth wheel was about 0.30 m (12 in) forward of the ball hitch. The motor carrier indicated that the hitch had a rating of 2,268 kg (5,000 lb) when extended in its most rearward position.

The truck had a tare weight of 6,727 kg (14,830 lb). The front axle was assumed to weigh 454 kg (1,000 lb), with a rating of at least 3,628 kg (8,000 lb), and a tare load of 3,402 kg (7,500 lb). The drive axle was assumed to weigh 907 kg (2,000 lb), with a rating of 7,938 kg (17,500 lb). Moments of inertia of the truck were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6].

3.1.2 Truck Payload

The truck payload was an arbitrary 6.10 m (20 ft) long travel trailer with a weight of 2,268 kg (5,000 lb). The carrier indicated this was a typical payload. This was loaded so that 227 kg (500 lb) was added to the front axle weight of the truck. A typical heavy 6.10 m (20 ft) long travel trailer might weigh 1,587 to 1,905 kg (3,500 to 4,200 lb), so the assumption is conservative. The truck was well within its gross axle weight ratings and gross vehicle weight rating when carrying this payload.

3.1.3 Recreational Trailers

This work used generic fifth wheel and travel recreational trailers as the towed vehicles. Properties of these two types of trailer were derived from data in the on-line catalogues of two manufacturers whose products are shipped by the motor carrier. The products of these two companies appear typical of the range of recreational trailers that can be towed by this truck within the overall dimensional limits. Figure 6 shows the dry gross weight and dry hitch weight of 109 different models of fifth wheel trailer against trailer overall length. Three trailer lengths were used for each type of trailer, the shortest, the longest, and one about halfway between. The weight of each trailer was estimated using the trend shown in Figure 6, and the result was increased by 226 kg (500 lb) so that the weight was towards the upper end of the range for that length, and then

Figure 6: Weight and Hitch Load for Fifth Wheel Trailers

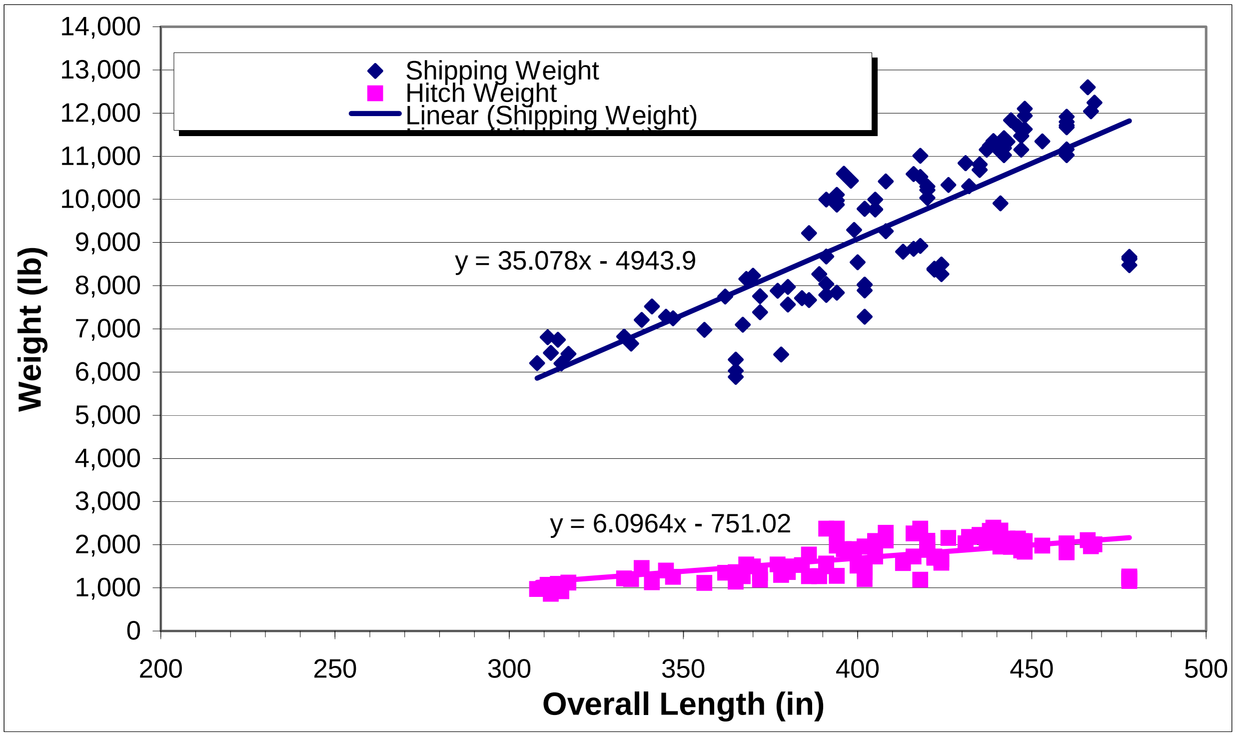
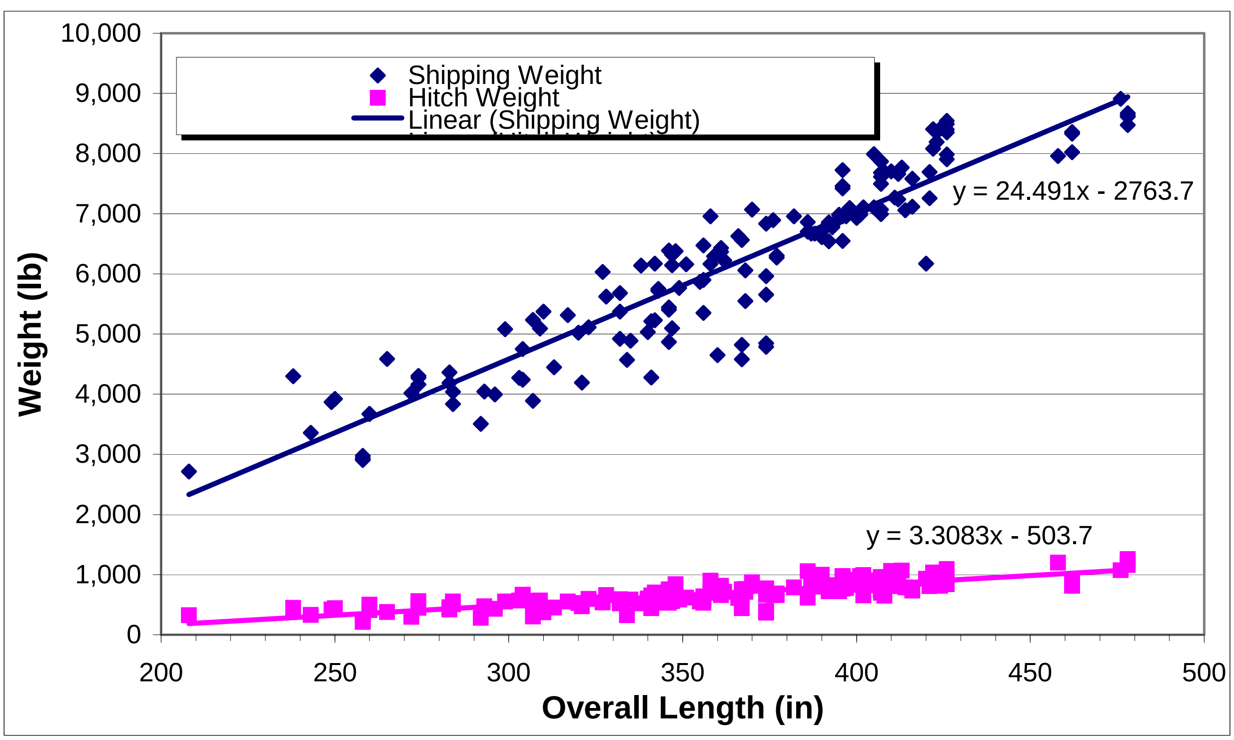


Figure 7: Weight and Hitch Load for Travel Trailers



rounded to the nearest 113 kg (250 lb). The hitch load was obtained using the average hitch load of 18.5% of the dry gross weight for this class of trailer. The results are summarized in Table 1. The centre of gravity height of a fifth wheel trailer was assumed as the average of 40% of the distance between the bottom exterior of a trailer and the top exterior of a trailer, over all trailers. The average value of 2.11 m (83 in) was used for all trailers. This was probably rather a conservative (high) value, as the overall exterior height is the maximum value, and most fifth wheel trailers have a roofline that slopes down towards the rear. The same process was followed for travel trailers. Figure 7 shows weight data for 148 different models of travel trailer, and Table 2 shows the results. The average hitch load was 11.3% of the dry gross weight for this class of trailer, and the average centre of gravity height was 1.88 m (74 in).

Table 1: Fifth Wheel Trailer Dimensions and Weights

Size	Length	Weight	Hitch Load
Small	7.87 m (310 in)	2,948 kg (6,500 lb)	544 kg (1,200 lb)
Medium	9.91 m (390 in)	4,195 kg (9,250 lb)	775 kg (1,710 lb)
Large	11.94 m (470 in)	5,443 kg (12,000 lb)	1,007 kg (2,220 lb)

Table 2: Travel Trailer Dimensions and Weights

Size	Length	Weight	Hitch Load
Small	6.10 m (240 in)	5,000 kg (3,500 lb)	181 kg (400 lb)
Medium	9.14 m (360 in)	2,948 kg (6,500 lb)	333 kg (735 lb)
Large	12.19 m (480 in)	5,000 kg (9,500 lb)	485 kg (1,070 lb)

The weight of each trailer was well within the provincial allowable axle weight, and also well within the gross weight rating of the vehicle, because the trailer as shipped has no personal effects, and no fluids. Moments of inertia for these trailers were generated in the same way as for a semitrailer during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6].

The suspension and tires selected for each trailer were appropriate for the gross weight rating of each size of trailer.

The motor carrier apparently recognizes that a travel trailer with a weight-carrying ball hitch is less stable than a fifth wheel trailer, and proposed use of a heavy duty weight-distributing hitch to provide some roll stiffness to a travel trailer. This was modeled by treating the weight-distributing ball hitch as a fifth wheel with a low roll stiffness of 113 N-m/deg (1000 in-lb/deg). The damping that arises from friction in the linkages of the weight-distributing hitch could not be modeled.

3.2 Computer Simulation

3.2.1 Scope

There were:

- 3 hitch types (fifth wheel, weight carrying ball, and weight-distributing ball);
- 3 trailer lengths for each hitch type (short, medium and long); and
- 4 hitch offsets (1.8, 3.07, 3.98 and 4.90 m (71, 121, 157 and 193 in)).

There were therefore a total of 3 x 3 x 4 = 36 total conditions for this vehicle configuration. The travel trailers were the same for the weight-carrying and weight-distributing hitches.

Hitch offset is known to be a critical parameter in the dynamic performance of truck-trailer combinations [2]. While the hitch offset of 1.80 m (71 in) is not physically feasible for this particular combination, inclusion of this artificial hitch offset does identify the level of dynamic performance associated with the largest hitch offset allowed by regulation [1].

3.2.2 Evaluation of Performance Measures

This work evaluated the following customary performance measures:

- Static roll threshold;
- High-speed offtracking;
- Load transfer ratio;
- Transient offtracking;
- Low-speed offtracking;
- Front outswing; and
- Rear outswing.

The high-speed performance measures were evaluated for a vehicle traveling at 90, 100, or 110 km/h (55.9, 62.1 and 68.3 mi/h), and there were two simulation runs for each of these speeds. The low-speed performance measures were evaluated for a vehicle traveling at 8.8 km/h (5 mi/h), and there was one simulation run at this speed. There were therefore seven simulation runs for each of 36 vehicle conditions, so there were (36 x 7) = 252 total simulation runs.

3.2.3 Results

The high-speed offtracking, load transfer ratio and transient offtracking performance measures semitrailers are presented in Table 3.

The low-speed offtracking and front and rear outswing performance measures are presented in Table 4.

Table 3: High-speed Performance Measures

Type	Size	HO	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
			90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
F	S	0	0.350	0.367	0.383	0.402	0.434	0.471	0.433	0.509	0.578
F	S	1	0.392	0.410	0.422	0.414	0.448	0.487	0.502	0.587	0.671
F	S	2	0.435	0.452	**0.458**	0.424	0.460	0.501	0.571	0.666	0.760
F	S	3	**0.478**	**0.493**	**0.499**	0.434	0.473	0.515	0.646	0.759	**0.856**
F	M	0	0.365	0.392	0.406	0.408	0.448	0.491	0.477	0.565	0.645
F	M	1	0.412	0.435	0.448	0.426	0.466	0.506	0.556	0.652	0.750
F	M	2	0.453	**0.464**	**0.514**	0.439	0.487	0.526	0.634	0.748	**0.850**
F	M	3	0.506	**0.516**	**0.550**	0.454	0.501	0.545	0.724	**0.854**	**0.970**
F	L	0	0.389	0.414	0.438	0.407	0.450	0.487	0.512	0.611	0.705
F	L	1	0.433	0.458	**0.478**	0.421	0.465	0.502	0.599	0.710	**0.818**
F	L	2	**0.475**	**0.502**	**0.513**	0.438	0.488	0.524	0.685	**0.817**	**0.933**
F	L	3	**0.522**	**0.534**	**0.533**	0.459	0.502	0.542	0.791	**0.932**	**1.070**
T	S	0	0.340	0.361	0.377	0.424	0.473	0.516	0.369	0.428	0.484
T	S	1	0.390	0.407	0.422	0.478	0.531	0.572	0.426	0.497	0.563
T	S	2	0.426	0.446	0.456	0.520	0.571	**0.616**	0.469	0.552	0.624
T	S	3	**0.470**	**0.485**	**0.497**	0.561	**0.610**	**0.661**	0.522	0.613	0.692
T	M	0	0.358	0.380	0.395	0.552	**0.620**	**0.671**	0.444	0.528	0.601
T	M	1	0.414	0.431	0.442	**0.621**	**0.686**	**0.737**	0.525	0.624	0.713
T	M	2	0.455	**0.471**	**0.495**	**0.671**	**0.734**	**0.794**	0.595	0.701	**0.806**
T	M	3	**0.498**	**0.514**	**0.541**	**0.722**	**0.792**	**0.850**	0.671	0.789	**0.906**
T	L	0	0.383	0.404	0.424	0.565	**0.634**	**0.688**	0.485	0.579	0.668
T	L	1	0.429	0.459	**0.487**	**0.641**	**0.704**	**0.765**	0.581	0.690	0.796
T	L	2	**0.469**	**0.517**	**0.475**	**0.692**	**0.761**	**0.828**	0.662	0.790	**0.901**
T	L	3	**0.487**	**0.566**	0.000	**0.748**	**0.826**	**0.899**	0.758	**0.900**	**1.033**
D	S	0	0.339	0.361	0.378	0.366	0.388	0.412	0.376	0.432	0.489
D	S	1	0.389	0.408	0.423	0.370	0.393	0.417	0.426	0.496	0.562
D	S	2	0.426	0.445	0.456	0.373	0.397	0.425	0.468	0.552	0.623
D	S	3	**0.470**	**0.486**	**0.497**	0.377	0.402	0.431	0.519	0.612	0.690
D	M	0	0.358	0.380	0.398	0.373	0.401	0.439	0.443	0.527	0.600
D	M	1	0.411	0.433	0.440	0.381	0.417	0.457	0.524	0.622	0.711
D	M	2	0.455	**0.471**	**0.485**	0.389	0.427	0.468	0.593	0.700	**0.805**
D	M	3	**0.497**	**0.520**	**0.509**	0.401	0.444	0.480	0.670	0.787	**0.904**
D	L	0	0.377	0.405	0.427	0.369	0.412	0.445	0.484	0.578	0.667

D	L	1	0.429	**0.473**	**0.487**	0.390	0.426	0.463	0.579	0.689	0.795
D	L	2	**0.469**	**0.483**	**0.543**	0.404	0.449	0.487	0.661	0.788	**0.899**
D	L	3	**0.512**	**0.511**	**0.606**	0.420	0.462	0.503	0.756	**0.898**	**1.030**

Table 4: Low-speed Performance Measures

Size	Hitch Offset	Fifth Wheel Trailers			Travel Trailers	
		Low-speed offtracking (<5.60 m)	Rear outswing (<0.20 m)	Front outswing (<0.20 m)	Low-speed offtracking (<5.60 m)	Rear outswing (<0.20 m)
S	0	2.279	0.128	0.047	2.539	0.069
S	1	2.158	0.212	0.148	2.494	0.170
S	2	2.027	**0.341**	**0.300**	2.422	**0.307**
S	3	1.883	**0.526**	**0.517**	2.407	**0.502**
M	0	2.723	0.200	0.047	2.628	0.142
M	1	2.600	**0.284**	0.148	2.478	**0.246**
M	2	2.466	**0.409**	**0.301**	2.341	**0.381**
M	3	2.316	**0.588**	**0.518**	2.192	**0.572**
L	0	3.230	**0.297**	0.047	3.252	**0.333**
L	1	3.109	**0.380**	0.148	3.104	**0.442**
L	2	2.975	**0.503**	**0.301**	2.967	**0.575**
L	3	2.822	**0.675**	**0.518**	2.812	**0.761**

In these tables:

- **Type** is the type of trailer and hitch, where **F** is for a fifth wheel trailer, **T** for a travel trailer with a ball hitch, and **D** for a travel trailer with a weight distributing hitch;
- **Size** is the trailer size, where **S** is for small, **M** for medium, **L** for large, as given in Table 1 for fifth wheel trailers and Table 2 for travel trailers;
- **HO** is hitch offset, where **0** is for 1.80 m (71 in), **1** for 3.07 m (121 in), **2** for 3.98 m (157 in) and **3** for 4.90 m (193 in); and
- Any performance measure that exceeds its performance standard is highlighted in bold.

3.3 Discussion

3.3.1 Static Roll Threshold

It proved difficult to obtain an estimate the static roll threshold of these combinations, as there was a tendency for the truck to become unstable in yaw at a lateral acceleration below the static roll threshold. The truck becomes oversteer, when it will spin out in a steady high-speed turn. This is fairly common for straight trucks.

From the limited results obtained, where the static roll threshold was below the threshold of yaw instability, the static roll threshold of the entire vehicle (for a fifth wheel trailer), or the trailer, for a travel trailer, was not significantly affected by the hitch offset. The static roll threshold of these combinations was also not affected by forward speed.

It appears that the static roll threshold for the combination towing a fifth wheel trailer is at least 0.42 g, essentially regardless of trailer size. It appears that the static roll threshold for the combination towing a travel trailer ranges between 0.42 g for a large trailer, to 0.48 g for a small trailer. These results show that recreational trailers meet the static rollover performance standard.

All the results for static rollover are based on the relatively conservative assumption that the centre of gravity of a recreational trailer sprung mass is 40% of the distance from the exterior bottom to the exterior top of the trailer. This is particularly conservative for fifth wheel trailers, which tend to have a roof line that drops towards the rear. All the values reported above would diminish if the trailer sprung mass centre of gravity height would be less than 40%.

3.3.2 High-speed Performance Measures

High-speed offtracking, load transfer ratio and transient offtracking are collectively considered the high-speed performance measures, and were presented in Table 3. All three high-speed performance measures increased with trailer size, hitch offset and vehicle speed.

The results in Table 3 show that recreational trailers may exceed the high-speed offtracking performance standard by up to about 0.10 m (4 in) for the largest trailer, the greatest hitch offset and speeds of 100 or 110 km/h (62.1 or 68.9 mi/h), or 0.15 m (6 in) when a weight-distributing hitch is used. The high-speed offtracking performance standard of 0.46 m (18 in) allows a 2.59 m (102 in) wide trailer driving in a 3.66 m (12 ft) wide lane within 0.08 m (3 in) of the edge of the lane. These recreational trailers are invariably 2.44 m (96 in) wide, so an additional 0.10 m (4 in) of high-speed offtracking would only bring the trailer 0.03 m (1 in) outside the high-speed offtracking allowed a 2.59 m (102 in) wide trailer. If this vehicle only travels at speeds of 100 km/h (62.1 mi/h) or more on freeways with a design speed that is greater than 110 km/h (68.9 mi/h), then the curves on the highway will be of such a large radius that the unbalanced lateral acceleration will not approach the 0.20 g level that is used for evaluation of the high-speed offtracking performance standard, and high-speed offtracking will be greatly reduced. A curve on a freeway usually only provides a relatively small change in heading, so the curve is relatively short, and the vehicle is not in the curve long enough to develop the full amount of high-speed offtracking.

Fifth wheel trailers, and travel trailers with a weight-distributing hitch, meet the load transfer ratio performance standard for all sizes of trailer, hitch offsets and speeds. Medium and large travel trailers with a weight-carrying hitch do not meet the performance standard, particularly at speeds of 100 and 110 km/h (62.1 and 68.9 mi/h). An evasive manoeuvre made at 100 km/h (62.1 mi/h) or more would carry with it a significant risk that the trailer might roll over.

Fifth wheel and travel trailers of all sizes fail the transient offtracking performance standard for the greatest hitch offset and speeds of 100 and 110 km/h (62.1 and 68.9 mi/h). This elevates the risk that an evasive manoeuvre will result in sideswiping a vehicle in an adjacent lane, or running trailer wheels off the paved surface where there is no paved shoulder. The simple model for the weight-distributing hitch did not include the friction damping that is built into this type of hitch, and is intended to control trailer sway. Personal experience by the author in tests of a freight trailer towed by either a weight-carrying or a weight-distributing hitch showed very clearly that a weight-distributing hitch substantially tamed the tendency to trailer sway in response to an evasive manoeuvre. The results presented for this hitch in Table 3 are therefore conservative, i.e. worse than would be expected in real life. The author is inclined to expect that any travel trailer within the range considered here would meet the transient offtracking performance standard when towed with a properly installed and properly adjusted weight-distributing hitch.

All the results for these dynamic performance standards are based on the relatively conservative assumption that the centre of gravity of a recreational trailer sprung mass is 40% of the distance from the exterior bottom to the exterior top of the trailer. This is particularly conservative for fifth wheel trailers, which tend to have a roof line that drops towards the rear. All the values reported in Table 3 would diminish if the trailer sprung mass centre of gravity height would be less than 40%.

The results in Table 3 show that satisfactory levels of load transfer ratio and transient offtracking performance can be ensured by some appropriate combination of restriction on vehicle speed and hitch offset, or a requirement that a suitable weight distributing hitch be used to tow a travel trailer.

3.3.3 Low-speed Performance Measures

Low-speed offtracking and front and rear outswing are collectively considered low-speed performance measures, and were presented in Table 4. The low-speed performance measures of travel trailers are not affected by whether a weight carrying or weight distributing hitch is used.

Low-speed offtracking is not close to critical for any of these combinations. Low-speed offtracking increases as the wheelbase of the trailer increases, and decreases as the hitch offset increases.

When the vehicle starts to make the turn, the front axle departs along the circular arc while the rear axle is still on the tangent approach. This causes the hitch to swing outside the approach, which initially causes the front left corner of a fifth wheel trailer to swing outside the envelope of the truck, then causes the trailer to track slightly to the left. As the truck progresses further into the turn, and the trailer starts to rotate to the right, the left rear corner of the trailer swings out. Front outswing is not an issue for a travel trailer due to the A-frame drawbar. The values shown in Table 4 for front outswing assume that the front of the trailer is square, so are a slight over-estimate for a trailer with rounded front corners.

Table 4 shows that:

- Front and rear outswing both increase with trailer length;
- Front and rear outswing both increase with hitch offset;
- Rear outswing is greater for a travel trailer than for a fifth wheel trailer, because of the more forward location of the turn centre on the travel trailer; and
- For any particular fifth wheel trailer, rear outswing exceeds front outswing.

While front and rear outswing both exceed the performance standard of 0.20 m (8 in) for a range of vehicle configurations, and particularly with the adjustable hitch anywhere rearward of its most forward position, this may not be a significant issue for this particular combination. The combination is a “large vehicle”, particularly when towing a trailer approaching 12.19 m (40 ft) in length, when it is comparable in size to a 6.20 m (244 in) wheelbase tractor towing a 16.2 m (53 ft) semitrailer.

The truck has a fairly long wheelbase, so may have to keep somewhat to the left to make a right-hand turn at an intersection, but the trailer will track relatively closely to the truck because of its relatively short wheelbase, so the low-speed offtracking of this combination is relatively modest compared to that of the largest tractor-semitrailer. If the driver keeps the truck at least 0.30 m (12 in) to the right of the lane stripe as the vehicle enters a right-hand turn, then the vehicle should be able to make the turn, and front and rear outswing will be correspondingly reduced.

The driver cannot see the rear outswing during a turn, because it is hidden by the front of the trailer. The driver will therefore generally be unaware that rear outswing is taking place. However, the driver can see the front outswing in the rear-view mirror, so should be aware of it. It is reasonable to expect that a driver would be aware of the outswing tendencies of these trailers, simply from the need to manoeuvre in tight quarters when in pick-up and delivery yards.

Front and rear outswing are generally of a similar magnitude, though rear outswing may be larger by up to 0.15 m (6 in). If the driver makes a turn in a situation where there may be a potential conflict with other traffic, and is aware of front outswing and makes the turn in such a way that front outswing is controlled, then rear outswing will also be controlled.

4. CONCLUSIONS

This work has assessed the dynamic performance of a straight truck that carries a travel trailer on its deck and also tows another recreational trailer, by either a fifth wheel or a ball hitch.

The high-speed dynamic performance measures all increase with an increase in trailer size, hitch offset and vehicle speed.

Some combinations exceed the high-speed offtracking performance standard, but is not expected that this will result in potential for conflict with other traffic.

The load transfer ratio performance of travel trailers is poor. The transient offtracking performance standard is exceeded for the longest trailers at the greatest hitch offsets and highest speeds. Satisfactory levels of load transfer ratio and transient offtracking performance can be ensured by some appropriate combination of restriction on vehicle speed and hitch offset, or a requirement that a suitable weight distributing hitch be used to tow a travel trailer.

This combination can reach the maximum overall length with a large trailer, but low-speed offtracking of these combinations is much less than that of the largest tractor-semitrailer because the trailers have a relatively short wheelbase. However, a large hitch offset results in significant front outswing for fifth wheel trailers, and significant rear outswing for both fifth wheel and travel trailers. Some of the large trailers may exceed the 4.0 m (157 in) rear overhang limit that applies to a pony trailer, which exacerbates rear outswing.

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