Evaluation of the Dynamic Performance of Candidate Special Permit Truck Configurations

Prepared for

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27 August 2006

ABSTRACT

This work used computer simulation to assess the dynamic performance of a number of vehicle configurations that are not currently covered by Nova Scotia's regulations, but are becoming common in other regions of Canada. Nova Scotia Department of Transportation and Public Works may consider allowing operation of these configurations by special permit. The work generates the dynamic performance of the candidate configurations for typical axle arrangements, an envelope of payload weight and payload height, and various vehicle speeds.

EXECUTIVE SUMMARY

The national Memorandum of Understanding on Vehicle Weights and Dimensions (“the M.o.U.”) was signed in 1988, and initially defined the most common configurations used in inter-provincial commerce. It was amended in 1991 to add straight trucks and truck-trailer combinations. The Atlantic provinces subsequently agreed to harmonize their regulations, and each province has now amended its regulations so that configurations, allowable weights, and dimensions, are all identical within the four provinces. The dimensions are compatible with those in the national M.o.U., though some weights are higher than in the national M.o.U.

A number of new vehicle configurations have been developed and adopted in various provinces and regions of Canada since the M.o.U. was signed. Ontario has introduced the self-steer tri-axle semitrailer, and Ontario and Québec have an agreement on uniform provisions for self-steer quad semitrailers. New Brunswick has allowed quad-axle and self-steer quad semitrailer log trucks and chip vans to operate by special permit. Tridem drive tractors and straight trucks were developed in B.C. and Alberta to improve traction of log trucks on mountain roads, and once adopted into regulation, became more widely used for other heavy haul applications. Tridem drive tractor-semitrailers were recently adopted into regulation in Ontario, and operate by special permit in other provinces. Long combination vehicles (LCV’s), typically composed of two long trailers or three short trailers with an overall length between 30 and 40 m (98 and 132 ft), have operated by special permit in the three prairie provinces and Québec. New Brunswick has recently allowed an LCV combination composed of twin 16.2 m (53 ft) trailers to operate by special permit.

Nova Scotia Department of Transportation and Public Works may consider allowing some of these configurations to operate by special permit. As a pre-requisite to this, it was necessary to assess the dynamic performance of the various candidate configurations by computer simulation, using the now-customary objective standards for the dynamic performance of heavy vehicles developed during the CCMTA/RTAC Vehicle Weights and Dimensions Study, that serve as the basis for the vehicle configuration and weight and dimension limits defined in the M.o.U. This work has assessed the dynamic performance of:

1. Long combination vehicles (LCV’s) for general freight;
2. LCV’s for international containers;
3. Self-steer quad semitrailers for general freight;
4. Self-steer quad semitrailers for bulk liquids;
5. Tridem drive tractor-semitrailers;
6. Tridem drive straight trucks; and
7. Tridem drive truck-trailer combinations.

It also includes a brief assessment of the effect of wind on rollover of tractor-semitrailers and LCV’s.

LCV's for General Freight

These LCV's were A-train double trailer combinations made up in what were judged the most likely arrangements of 14.65 and 16.20 m (48 and 53 ft) tandem and tridem van semitrailers. This resulted in the following five configurations:

1. Twin 16.20 m (53 ft) tandem semitrailers;
2. 16.20 m (53 ft) tridem semitrailer and 16.20 m (53 ft) tandem semitrailer;
3. Twin 14.65 m (48 ft) tandem semitrailers;
4. 16.20 m (53 ft) tandem semitrailer and 14.65 m (48 ft) tandem semitrailer; and
5. 16.20 m (53 ft) tridem semitrailer and 14.65 m (48 ft) tandem semitrailer.

Each LCV combination was loaded close to its allowable gross weight of 62,500 kg (137,787 lb), with several payload weights and payload heights.

Any of the LCV configurations with a typical tandem semitrailer payload weight up to about 20,411 kg (45,000 lb), and up to 2.44 m (96 in) in height, would be expected to have a static roll threshold close to or higher than 0.40 g. Higher payload weight on the lead semitrailer, with a height over 1.83 m (72 in), results in a static roll threshold for the tractor-semitrailer between 0.35 and 0.40 g. A static roll threshold over 0.40 g can be achieved either by limiting payload weight on the each semitrailer to about 20,411 kg (45,000 lb), or by limiting payload height to 1.83 m (72 in) if the payload weight exceeds 20,411 kg (45,000 lb).

The load transfer ratio and transient offtracking of each configuration approaches or exceeds the respective performance standards for the heaviest vehicles with the highest payloads when operated at 100 km/h. The results suggest there may be a trade-off between limiting speed and limiting payload height and/or weight. A speed limit of 90 km/h (55.9 mi/h) would be appropriate to ensure moderate load transfer ratio and transient offtracking, when combined with the payload limits described above.

The high-speed offtracking of some LCV configurations may exceed the performance standard for some payload conditions using the standard method of evaluation. However, in practice, if LCV's are restricted to operation only on freeways at 90 km/h (55.9 mi/h), curves will have a much larger radius than that used in the standard method of evaluation, so the lateral acceleration should always be much less than 0.20 g, and the performance standard should never be approached. It may be appropriate to limit speed to control high-speed offtracking on any access route that has curves with a radius between about 250 and 400 m (820 and 1,312 ft).

It is known that traffic moving below the legal speed limit on freeways is a concern to some road safety authorities. However, there are a number of trucking companies that voluntarily operate at around 90 km/h (55.9 mi/h) to conserve fuel. It is also evident that certain classes of vehicle, like mobile cranes, certain heavy haul vehicles, and convoys of military vehicles, consistently operate on freeways at a speed less than 100 km/h (62.1 mi/h).

These LCV's exceed both low-speed offtracking and rear outswing performance standards by a wide margin. However, this should not be an issue since these vehicles will presumably operate under a route-specific permit that only allows them to go where they can make the turns.

When there is a difference in weight between the two trailers, the high-speed dynamic performance is better when the heavier of the two is the lead trailer. There is no apparent reason from the point of view of dynamic performance why the rear trailer, or both trailers, should not be empty.

If existing trailers are modified to add a pintle hook and air supplies for the pup trailer, the work should be done to objective standards, preferably by the original manufacturer of the trailer, or another company properly qualified to do the work. The airbrake timing of the modified trailer, and of an entire combination, should be checked.

LCV's for International Containers

These LCV's were A-train double trailer combinations made from 12.19 m (40 ft) container chassis in the following configurations:

1. Twin tandem container chassis;
2. Twin tridem container chassis;
3. Tridem and tandem container chassis; and
4. Tandem and tridem container chassis.

Each LCV combination was loaded close to its allowable gross weight of 62,500 kg (137,787 lb), with high-cube 12.19 m (40 ft) containers with several payload weights and payload heights.

The roll threshold for tractor-semitrailers, and these vehicles, carrying high-cube containers loaded to their loaded rating with a high payload, is poor. All configurations exceed the load transfer ratio and transient offtracking performance standards, even with a moderate payload height, and at 90 km/h (55.6 mi/h). Most configurations exceed the high-speed offtracking performance standard, but this will also not be an issue for permit operation at 90 km/h (55.9 mi/h) on freeways, as discussed above for LCV's.

Self-steer Quad Semitrailer for General Freight

Self-steer quad semitrailers were configured according to the rules of Ontario and Québec at lengths of 14.65 and 16.20 m (48 and 53 ft), with a quad-axle group weight of 32,000 kg (70,547 lb), and an allowable gross weight of 55,500 kg (122,355 lb).

Self-steer quad semitrailers exceed the high-speed offtracking performance standard for the highest payload heights and speeds, but only by about 0.10 m (4 in) at 110 km/h (68.3 mi/h). This level of deviation has been accepted by Ontario and Québec in their specifications for self-steer quad semitrailers. These vehicles should not exceed the performance standard if their only operation at speeds over 90 km/h (55.9 mi/h) is on freeways. There is little difference in high-speed offtracking performance between 14.65 and 16.20 m (48 and 53 ft) semitrailers. In contrast, the load transfer ratio and transient offtracking of 14.65 m (48 ft) semitrailers is consistently higher than for 16.20 m (53 ft) semitrailers, due to their shorter wheelbase, but all configurations meet these performance standards. All configurations also meet all low-speed performance standards.

The length of a self-steer quad semitrailer depends largely on the body style of the semitrailer. A van needs to be 16.20 m (53 ft) long so that it is available for backhauls that would normally travel in a 16.20 m (53 ft) tandem or tridem semitrailer, at a payload weight appropriate to those semitrailers. Other body styles, like flatbeds, tankers and log trucks, that carry dense or bulk commodities, or heavy loads, lose payload due to additional tare weight if they are longer than the minimum length necessary for inter-axle spacings. In practice, most of these are 14.65 m (48 ft) long.

Self-steer Quad Semitrailer Tanker

Self-steer quad semitrailer tankers were configured according to the rules of Ontario and Québec at lengths of 14.65 and 16.20 m (48 and 53 ft), with a quad-axle group weight of 32,000 kg (70,547 lb), and an allowable gross weight of 55,500 kg (122,355 lb).

Tank trucks have a significantly higher rate of rollover than the truck fleet as a whole. European countries now have a minimum static roll threshold of 0.40 g for tank trucks, and Australia is considering the same value. This would be an appropriate standard for consideration. Any requirement should probably be phrased as "for the critical (maximum) payload, either demonstrate a static roll threshold above 0.40 g by test, or the combined centre of gravity of the sprung mass and payload shall be as low as possible, but not more than 2.30 m above the ground". It would also be appropriate to require that both tractor and semitrailer should each be equipped with an electronic roll stability system. Other aspects of dynamic performance of self-steer quad tankers are essentially the same as for general freight vehicles.

Tridem Drive Tractor-semitrailers

A tridem drive tractor configured according to the rules of Ontario, Alberta and British Columbia was used to haul a single axle, tandem, tridem or self-steer quad semitrailer, or a tandem-tandem B-train. The tridem drive axle group weight was 21,000 kg (46,296 lb).

A tridem drive tractor with a single axle, tandem, tridem or self-steer quad semitrailer meets all the performance standards when loaded to its allowable gross weight with a high payload, except for high-speed offtracking for a self-steer quad. However, this should not be an issue if their only operation at speeds over 90 km/h (55.9 mi/h) is on freeways. The wheelbase of any semitrailer must be limited to 12.00 m (616 in) to meet the low-speed offtracking performance standard. When a tridem drive tractor pulls a tandem-tandem B-train log hauler, the high-speed offtracking and transient offtracking fail the performance standard at 110 km/h (68.3 mi/h). High-speed offtracking is not a significant issue for operation on freeways, but transient offtracking is. The relatively low allowable load on the tridem drive axle group ensures that the lateral friction utilization performance standard is met.

Tridem Drive Straight Trucks

A tridem drive straight truck was configured according to the rules of Alberta and British Columbia, with a tridem drive axle group weight of 21,000 kg (46,296 lb).

A tridem drive straight truck needs wide-track axles to achieve a satisfactory static roll threshold and load transfer ratio, though it still exceeds these performance standards for the heaviest and highest payloads. The relatively low allowable load on the tridem drive axle group ensures that the lateral friction utilization performance standard is met.

Tridem Drive Truck-trailer Combinations

The tridem drive straight truck pulled a tandem or tridem pony trailer configured according to the M.o.U.

These vehicles fail the load transfer ratio performance standard for essentially any commodities they might haul, though performance is best for dense loads like asphalt and aggregates. A tridem pony trailer should have as long a box as possible to minimize the payload height. The hitch offset should be the minimum possible.

Effect of Wind on Van Semitrailers

A strong or gusting wind may blow over a vehicle with a large exposed face, like a 16.20 m (53 ft) van semitrailer, or an LCV composed of two such semitrailers, and may also cause the semitrailers to offtrack. It is appropriate to use the load transfer ratio performance measure to assess rollover, and the high-speed offtracking performance measure to assess wind-induced offtracking.

Load transfer ratio and offtracking both increase with wind speed, and for a given wind speed, both diminish with vehicle speed. The critical case is for a pure side wind, at 90 deg to the direction of travel of the vehicle.

An empty tractor- 16.20 m (53 ft) van tandem semitrailer reaches both the load transfer ratio and offtracking performance standards when a steady non-gusting wind reaches about 75 km/h (46.6 mi/h), or the steady component of a strongly gusting wind reaches about 50 km/h (31 mi/h). These values are lower for stationary or slow-moving vehicles. It requires a payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) to achieve a significant increase in the resistance to wind-induced rollover and offtracking.

An empty LCV with 16.20 m (53 ft) van tandem semitrailers reaches the load transfer ratio performance standard when a steady non-gusting wind reaches about 75 km/h (46.6 mi/h), or the steady component of a strongly gusting wind reaches about 50 km/h (31 mi/h). These are the same values as for a tractor-semitrailer, though the second trailer always blew over before the tractor and lead semitrailer. An empty LCV reaches the offtracking performance standard when a steady non-gusting wind reaches about 55 km/h (34.2 mi/h), or the steady component of a strongly gusting wind reaches about 40 km/h (24.8 mi/h). A payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) in each semitrailer provides a significant increase in the resistance to wind-induced rollover, but there is little improvement in wind-induced offtracking until there is a payload of 11,340 kg (25,000 lb) in each semitrailer. This allows travel while the steady component of a strongly gusting wind does not exceed about 55 km/h (34.2 mi/h).

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1. INTRODUCTION

The national Memorandum of Understanding on Vehicle Weights and Dimensions ("the M.o.U.") was signed in 1988, and defined the most common configurations used in inter-provincial commerce [1]. It was amended in 1991, to add straight trucks and truck-trailer combinations, and has since been amended twice to refine details. The four western provinces immediately adopted the M.o.U. as the basis for their regulations. However, Ontario maintained its prior semitrailer length of 14.65 m (48 ft) and overall length of 23 m (75 ft 6 in) until 1994, when it adopted the respective M.o.U. standards of 16.2 m (53 ft) and 25 m (82 ft). Québec and the Atlantic provinces were then able to align their regulations with the M.o.U. The Atlantic provinces subsequently agreed to harmonize their regulations [2], and each province has now amended its regulations so that configurations, allowable weights and dimensions are identical within the four provinces. The dimensions are compatible with the dimensions in the national M.o.U., though some weights are higher than the national M.o.U. [3].

A number of new vehicle configurations have been developed and adopted in various provinces and regions of Canada since the M.o.U. was signed. Ontario has introduced the self-steer tri-axle semitrailer, and Ontario and Québec have an agreement on uniform provisions for self-steer quad semitrailers. New Brunswick has allowed a number of quad-axle and self-steer quad semitrailer log trucks and chip vans to operate by special permit. Tridem drive tractors and straight trucks were developed in B.C. and Alberta to improve traction of log trucks on mountain roads, and once adopted into regulation, they became more widely used for other heavy haul applications. Tridem drive tractor-semitrailers were recently adopted into regulation in Ontario [4], and operate by special permit in other provinces. Long combination vehicles (LCV's), typically composed of two long trailers or three short trailers with an overall length between 30 and 40 m (98 and 132 ft), have operated by special permit in the three prairie provinces and Québec. New Brunswick has recently allowed an LCV combination composed of twin 16.2 m (53 ft) trailers to operate by special permit. Ontario has recently adopted new five- and six-axle semitrailer configurations into regulation [4].

Nova Scotia Department of Transportation and Public Works may consider allowing some of these configurations to operate by special permit. As a pre-requisite to this, it is necessary to assess the dynamic performance of the various candidate configurations, using the now-customary objective standards for the dynamic performance of heavy vehicles developed during the CCMTA/RTAC Vehicle Weights and Dimensions Study [5], that serve as the basis for the vehicle configuration and weight and dimension limits defined in the M.o.U. [1].

This report presents the findings of the computer simulations, and assessments for LCV's for general freight and international containers, self-steer quad semitrailers for general freight and bulk liquids, tridem drive tractor-semitrailers, tridem drive straight trucks, and tridem drive truck-trailer combinations. It also includes a brief assessment of the effect of wind on rollover of tractor-semitrailers and LCV's.

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 [5], [6], [7]. 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.

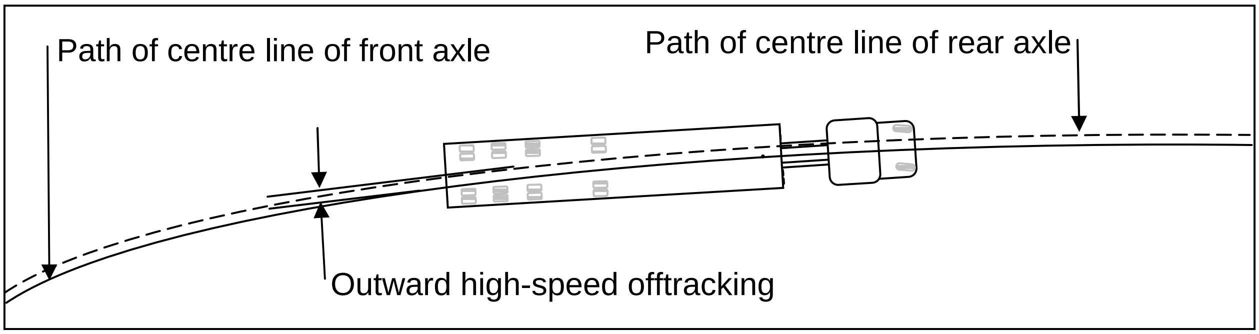
Dynamic performance was assessed using the so-called “RTAC” performance measures, developed during the CCMTA/RTAC Vehicle Weights and Dimensions Study [5], [7]. These are also consistent with performance measures proposed for vehicles that might operate North America-wide under possible future provisions of the North American Free Trade Agreement [1]. 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 [5]. 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, 95, 100 or 110 km/h (55.9, 59.0, 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 1. 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 1: 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 [9].

The CCMTA/RTAC Vehicle Weights and Dimensions Study set a target static roll threshold of 0.40 g [5]. This value was not used when vehicles were configured for the national M.o.U. [2], 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 [10]. 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 [11].

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 [11]. 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 [12]. 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.

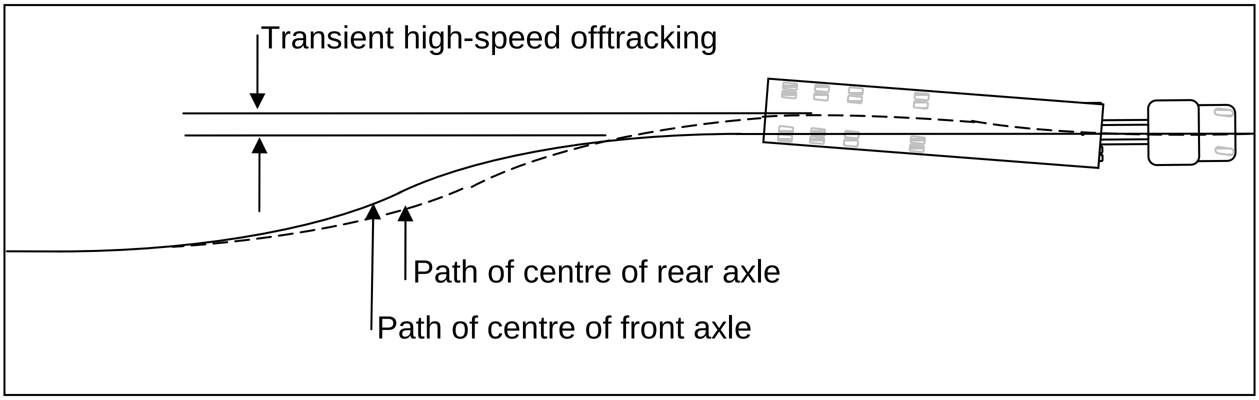
The **High-Speed Offtracking** performance measure is the lateral offset between the path of the steer axle of a tractor and the path of the last axle of the vehicle in a steady turn of 0.20 g lateral acceleration, as shown in Figure 1. Since the driver guides the tractor along a desired path, there 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, 95, 100 or 110 km/h (55.9, 59.0, 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 2. 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 [7]. This

Figure 2: 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 [7], 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.

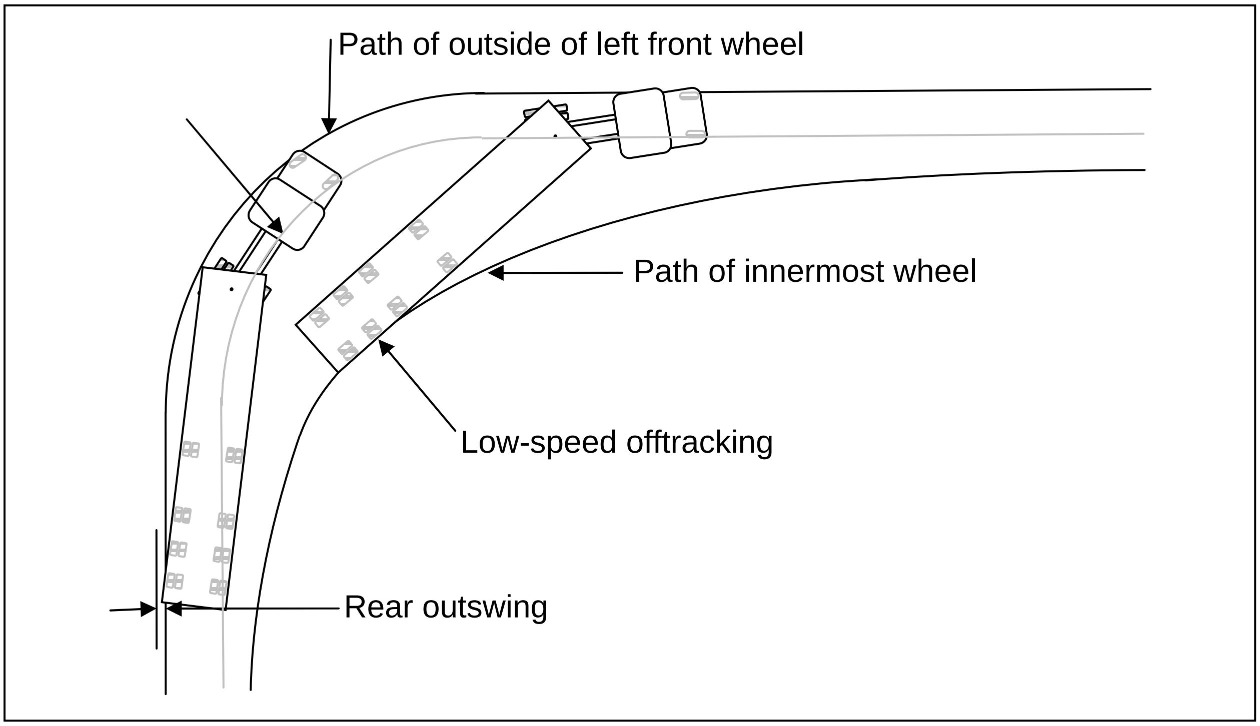
The **Load Transfer Ratio** performance measure is the fractional change in load between left- and right-hand side tires in an obstacle avoidance manoeuvre. It indicates how close all of the tires on one side of the rearmost roll-coupled unit came to lifting off, a precursor to rollover. The load transfer 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.

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 2. 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.

2.1.3 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, rear outswing and friction demand performance measures. This manoeuvre is shown in Figure 3. 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 [7].

Figure 3: 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) [1]. 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 3. 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 [1], 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 any left-hand side corner of the vehicle into the lane to the left of that occupied by the vehicle as it makes a right-hand turn, as shown in Figure 3. The left rear corner becomes a potential obstacle to another vehicle traveling in that lane, and offers the possibility of a serious collision if the vehicle in it 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, where the tractor or semitrailer has a long effective rear overhang.

The **Friction Demand** performance measure is a measure of the resistance to turning of a vehicle with multiple widely-spaced axles in a turn as at an intersection. It results in a "demand" for tire side force at the tractor's drive axles. The performance measure was developed from the hypothesis that a tractor-semitrailer whose friction demand exceeds that which is available could produce a jackknife-type response of the tractor [7]. The friction demand measure describes the minimum tire-pavement friction necessary for the vehicle to negotiate an intersection turn without suffering such loss of control. The friction demand should be less than 0.10. This is a particularly significant performance measure for vehicles with a semitrailer with multiple widely-spaced axles.

Early tests were unable to produce a jackknife with a tri-axle semitrailer [7]. A recent series of full-scale tests with five-axle semitrailers with two self-steering axles did produce a jackknife, and also showed that a tractor could plough out of the turn [13]. A tractor ploughs out of a turn when the front axle has insufficient side-force capability, and the vehicle departs from the turn heading straight along a tangent to the turn. The tendency to plough out is addressed by the load transfer ratio performance measure, discussed below. Both jackknife and plough-out occurred in these tests, but at a speed well above that at which any driver would make such a turn. It was shown that a reduction in the self-steering axle centring force, which is a resistance to self-steering, an increase in turn radius, or a reduction in speed, all reduced friction demand. It was suggested that carriers would control the centring force setting to minimize tire wear, and drivers would control turn radius and speed, to keep friction demand at a level that allowed turns to be made for a satisfactory level of effort. It was therefore concluded that friction demand was an operational consideration, and the safety warrants for the performance measure no longer pertain [13]. This work will evaluate and present the friction demand performance measure, but it should not be a factor in assessment of the candidate vehicles.

2.1.4 Low-speed Right-hand Turn on a Low-friction Surface

A 90 degree right-hand turn, made at a speed of 8.8 km/h (5.5 mi/h) on a low-friction surface, was used to evaluate the lateral friction utilization performance measure. This manoeuvre is shown in Figure 3. It was also made using a turn radius of 14.00 m (46 ft) at the outside of the left front wheel of the power unit.

The **Lateral Friction Utilization** performance measure is the proportion of the available tire-pavement friction required by the front steer axle to make a low-speed turn at an intersection. Such a turn results in a "demand" for tire side force at the front axle of the power unit, and this must be within the friction available from the tire-pavement interface for the vehicle to be able to turn. If the lateral friction utilization reaches 1.0, the limit of control has been reached and the driver is unable to turn the vehicle more tightly. The power unit therefore departs out-of-control, along a tangent to the turn. This outcome is known as a plough-out. Lateral friction utilization should not exceed 0.80, which is 80% of the tire-pavement friction available [14]. This performance measure is particularly significant for vehicles with a tridem drive power unit.

2.1.5 Low-speed Tight Right-hand Turn

A 90 degree right-hand turn, made at a speed of 8.8 km/h (5.5 mi/h) on a high-friction surface, was used to evaluate the maximum self-steer angle of a self-steering axle. This manoeuvre is also shown in Figure 3. It was made for a turn radius of 12.00 m (39.4 ft) at the outside of the left front wheel of the power unit, which is close to the minimum turning radius of tractors that are likely to be used with self-steer quad semitrailers.

The **Maximum Self-steer Angle** performance measure, for a vehicle with a self-steering axle, is the maximum self-steer angle that is required during a low-speed turn at an intersection. The maximum self-steer angle should not exceed the maximum wheel cut provided by the self-steering axle, because if it does, the self-steer will bottom, and the high loads produced by tire-pavement friction will cause serious tire wear, and may also damage the frame, suspension or wheel components. The amount of steer required from a self-steering axle increases as the self-steering axle moves further away from the turn centre of a semitrailer, as the turn radius decreases, and as the turn angle increases [15]. A vehicle with a self-steering axle needs sufficient self-steer for normal operations on highways and roads. When a vehicle operates off-highway, such as in a yard, it is possible for the tractor to get to an articulation angle of 90 deg, when it simply pulls the semitrailer sideways, and the self-steering axle will quickly bottom. However, a self-steering axle is normally raised for operations off-highway. This performance measure is only significant for a vehicle fitted with a self-steering axle.

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 [16]. 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 [7], [15], and has been shown to provide reasonable agreement with test results for a large number of vehicle configurations [17], [13]. 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 five 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 [7], and other studies conducted for a variety of purposes [15], [18]. High-speed manoeuvres were run at speeds of 90, 95 and 100 km/h (55.6, 59.0 and 62.1 mi/h) for LCV’s, and 90, 100 and 110 km/h (55.6, 62.1 and 68.3 mi/h) for other configurations.

This work assumes the payload centre of gravity is on the centre-line of the vehicle. The static roll threshold deteriorates significantly as the payload centre of gravity moves laterally away from the centre-line of the vehicle, perhaps of the order of 0.10 g for each 0.30 m (12 in) of movement.

2.3 Presentation of Results

The following sections present the details of each configuration, and the simulation results, generally in the same format.

The axle arrangement, key dimensions, and the allowable axle weights of the vehicle are shown in a diagram, not drawn to scale, and a table presents the payload weights considered.

The static roll thresholds are presented in a table, for the various payload weights and centre of gravity heights considered. Static roll threshold is not significantly affected by speed, as a vehicle rolls over in the evaluation manoeuvre when it reaches that turn radius which corresponds to the rollover lateral acceleration for the particular speed. The high-speed offtracking, load transfer ratio and transient offtracking performance measures are presented in a table, for the various payload weights, centre of gravity heights and speeds considered. The low-speed performance measures are not affected by payload weight, centre of gravity height or speed, and are generally summarized in the text. Any performance measure presented in a table that fails the applicable performance standard is highlighted in bold.

The results are followed by discussion of the implications of the results, and conclusions and recommendations relevant to the particular configuration.

3. LCV'S FOR GENERAL FREIGHT

3.1 Vehicle Configurations

These long combination vehicles were A-train double trailer combinations made up in what were judged the most likely arrangements of 14.65 and 16.20 m (48 and 53 ft) tandem and tridem van semitrailers. This resulted in the following five configurations:

1. Twin 16.20 m (53 ft) tandem semitrailers;
2. 16.20 m (53 ft) tridem semitrailer and 16.20 m (53 ft) tandem semitrailer;
3. Twin 14.65 m (48 ft) tandem semitrailers;
4. 16.20 m (53 ft) tandem semitrailer and 14.65 m (48 ft) tandem semitrailer; and
5. 16.20 m (53 ft) tridem semitrailer and 14.65 m (48 ft) tandem semitrailer..

3.1.1 Tractor

This work used a generic tandem drive tractor with a front axle setback of 0.91 m (36 in), a 4.83 m (190 in) wheelbase, a tandem drive axle with a spread of 1.37 m (54 in), and a fifth wheel placed 0.25 m (10 in) forward of the centre of the drive tandem. The tractor had a tare weight of 8,164 kg (18,000 lb). The front axle was assumed to weigh 544 kg (1,200 lb), with a rating of at least 5,500 kg (12,125 lb), and a tare load of 4,762 kg (10,500 lb). Each drive axle was assumed to weigh 1,134 kg (2,500 lb). Moments of inertia were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

3.1.2 Semitrailers

This work used generic 14.65 and 16.2 m (48 and 53 ft) van semitrailers. The kingpin setback was 0.91 m (36 in). A semitrailer was fitted either with a tandem axle with a 1.22 m (48 in) spread, or a tridem axle with a 3.66 m (144 in) spread, as it was assumed that any tridem semitrailer would also be used as a single semitrailer. Three wheelbases were used for each semitrailer, as shown in Table 1. The long wheelbase was the maximum possible, with the centre of the rearmost axle no closer than 0.71 m (28 in) to the rear of the semitrailer, and not more than 12.50 m (492 in). The short wheelbase was that arising from 35% effective rear overhang. The middle wheelbase was midway between the long and short wheelbases. The front edge of the pintle hook

Table 1: Wheelbases of LCV Semitrailers

Semitrailer	Bogie	Wheelbase		
		Long	Middle	Short
16.20 m (53 ft)	Tandem	12.50 m (492 in)	11.89 m (468 in)	11.29 m (444 in)
16.20 m (53 ft)	Tridem	12.50 m (492 in)	11.89 m (468 in)	11.29 m (444 in)
14.65 m (48 ft)	Tandem	12.40 m (488 in)	11.29 m (444 in)	10.16 m (400 in)

on a towing semitrailer was assumed in the plane of the rear of the semitrailer. The tare weight of a tandem semitrailer was 6,350 kg (14,000 lb), and the tare weight of a tridem semitrailer was 7,484 kg (16,500 lb), regardless of length, because 16.20 m (53 ft) semitrailers are of more recent and generally lighter construction than 14.65 m (48 ft) semitrailers. Each fixed axle was assumed to weigh 680 kg (1,500 lb). Moments of inertia for these semitrailers were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

3.1.3 Converter Dolly

This work used a generic tandem axle converter dolly, whose wheelbase was measured from the front of the inside of its tow-eye to the turn centre of its tandem axle. A 2.29 m (90 in) wheelbase results in a gap of 1.37 m (54 in) between the two trailers, assuming the pintle hook is in the rear plane of the towing trailer. This dolly wheelbase is about the minimum feasible to allow a vehicle to make normal turns without interference between the two semitrailers. The fifth wheel was placed directly over the turn centre of the tandem axle. The dolly frame and drawbar was assumed to weigh 680 kg (1,500 lb). Each fixed axle was assumed to weigh 680 kg (1,500 lb). Moments of inertia for the converter dolly were as used during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

3.1.4 Load Distribution

Vehicle configurations were created using the generic tractor, semitrailers, and converter dolly described above. The allowable front axle weight was 5,443 kg (12,000 lb). The allowable weight on a tandem axle group was 18,000 kg (39,682 lb). The allowable weight on a 3.66 m (144 in) spread tridem axle group was 26,000 kg (57,319 lb). The sum of allowable axle loads for an LCV with two tandem axle semitrailers is 77,443 kg (170,730 lb), and it is 85,443 kg (188,367 lb) for an LCV with a tandem axle semitrailer and a tridem axle semitrailer. The allowable gross weight was limited to 62,500 kg (137,787 lb) for each LCV combination, regardless of the sum of allowable axle loads. The sum of allowable axle loads exceeds the allowable gross weight by a wide margin, so there are a large number of ways that these LCV's can be loaded, and most do not challenge any allowable axle group load.

Vehicles were loaded with a solid block of payload of uniform density and of a specified height, over a width of 2.44 m (96 in), and over the maximum possible length of deck. The density of the payload varied, depending on the payload weight and volume selected. This is a different loading strategy than used for the simulations conducted for the CCMTA/RTAC Vehicle Weights and Dimensions Study [7] and other studies, where a constant payload density of 545 kg/cu m (34 lb/cu ft) was used to generate a high centre of gravity. This density represents a payload like dressed lumber, products packed 1.52-1.83 m (60-72 in) high on a pallet and weighing 1,000-1,500 kg (2,204-3,306 lb), and many other commodities of moderate density.

The maximum payload weight for any LCV combination was the difference between the allowable gross weight and the tare weight of the vehicle, rounded down to the nearest thousand pounds, because the simulation program takes input in Imperial inch and pound dimensions. This payload was then split between the two semitrailers. Payload was distributed on a semitrailer depending on whether the sum of its allowable axle weights of the tractor-semitrailer or full trailer equalled the allowable gross weight, or exceeded it. When the sum of allowable axle weights was equal to the allowable gross weight, the payload centre of gravity was fixed, and the block of payload was generally shorter than the length of the semitrailer, and was positioned against the front bulkhead of the semitrailer to ensure proper distribution of weight to the axles. When the sum of allowable axle weights exceeded the allowable gross weight, the payload centre of gravity can vary, and the block of payload was fixed in length at 0.30 m (12 in) less than the length of the semitrailer.

The typical maximum payload for a tandem semitrailer is about 20,411 kg (45,000 lb), based on a maximum gross weight of 36,287 kg (80,000 lb) for operation into the U.S., and taking off about 1,360 kg (3,000 lb) of payload to allow for variations in tractor weight, load distribution and bogie placement without overloading either tandem axle. The average payload for a tandem semitrailer is about 15,875 kg (35,000 lb). The typical maximum payload for a wide spread tridem semitrailer is about 29,483 kg (65,000 lb). The average payload is considerably less, because many tridem semitrailers make backhauls or other trips with loads that could go in a tandem semitrailer. Table 2 shows the approximate maximum payload for each semitrailer in an LCV, whether tandem or tridem, and the approximate maximum payload as limited by the allowable gross weight of 62,500 kg (137,787 lb). The payload diminishes with a tridem semitrailer in the combination, due to the additional tare weight of the semitrailer.

Table 2: Payload Capacity of LCV Semitrailers

Lead Semitrailer	Pup Semitrailer	Maximum Payload Weight (lb)		
		Lead	Pup	Combined
Tandem	Tandem	59,000	43,500	87,000
Tridem	Tandem	66,000	42,000	84,000

Four load cases were considered for each combination. The first load case used the maximum payload capacity on the lead semitrailer, as given in Table 2, with the balance of the payload weight on the rear semitrailer. The second load case used half the maximum payload on each semitrailer. The third load case used the maximum payload capacity on the lead semitrailer, with the rear semitrailer empty. Both semitrailers were empty for the fourth load case.

3.2 Twin 53' Tandem Semitrailers

3.2.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 4. Table 3 shows the load cases considered for this combination. Each load case was also considered with a payload height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in), and for 50% or 75% of its nominal weight.

Figure 4: Twin 53' Tandem Semitrailers

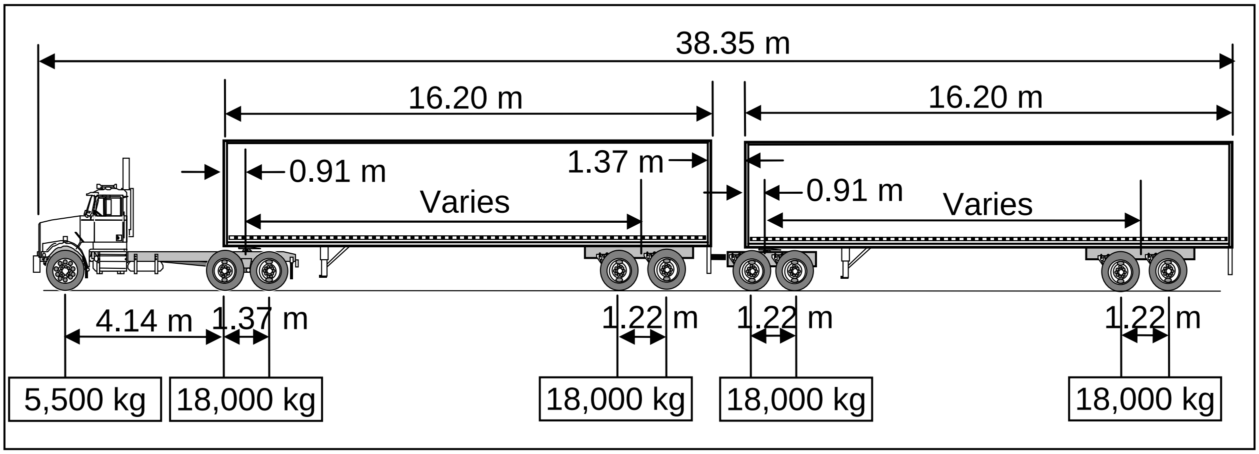


Table 3: Payload Weights for Twin 53' Tandem Semitrailer LCV

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	59,000	28,000	87,000
2	43,500	43,500	87,000
3	59,000	Empty	59,000
4	Empty	Empty	0

3.2.2 Results

Table 4 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer wheelbase and vehicle speed had no significant effect on static roll threshold. The tractor and lead semitrailer roll over first in all cases.

Table 4: Roll Thresholds for Twin 53' Tandem Semitrailer LCV

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g) Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	59,000	28,000	87,000	0.368	0.496	0.587
1	75%	44,250	21,000	65,250	0.403	0.525	0.605
1	50%	29,500	14,000	43,500	0.444	0.551	0.623
2	100%	43,500	43,500	87,000	0.406	0.524	0.604
2	75%	32,625	32,625	65,250	0.433	0.545	0.620
2	50%	21,750	21,750	43,500	0.471	0.569	0.637
3	100%	59,000	0	59,000	0.368	0.496	0.587
3	75%	44,250	0	44,250	0.406	0.525	0.605
3	50%	29,500	0	29,500	0.443	0.551	0.623
4	0%	0	0	0	0.716		

Table 5 through Table 7 show the high-speed offtracking, load transfer ratio and transient offtracking for long, medium and short wheelbase trailers respectively, as given in Table 1, for all load levels of Load Cases 1, 2, 3 and 4, as given in Table 3. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face.

The results in Table 5 through Table 7 show that high-speed offtracking, load transfer ratio and transient offtracking all increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. This configuration exceeds the high-speed offtracking performance standard for most conditions presented in the tables, while it meets load transfer ratio and transient offtracking performance standards for most conditions. The issue of high-speed offtracking is discussed in Section 3.7.4 below. The other two performance measures would be mitigated by travel at 90 km/h (55.9 mi/h).

The low-speed turning performance was not greatly affected by payload weight or centre of gravity height. The low-speed offtracking was about 7.85 m (309 in), and there was also significant rear outswing, from 0.39 to 0.66 m (15 to 26 in). While these exceed the performance standards, they are not an issue because any permit will only allow such vehicles to go where they can make turns, and make them in a safe manner. Friction demand was about 0.02, and is not relevant for this class of vehicle.

Table 5: High-speed Performance Measures for Long Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.552**	**0.608**	**0.654**	0.591	**0.645**	**0.695**	0.614	0.734	**0.853**
1/100%	M	**0.484**	**0.539**	**0.583**	0.411	0.452	0.493	0.475	0.581	0.684
1/100%	L	0.458	**0.513**	**0.558**	0.344	0.378	0.413	0.431	0.531	0.628
1/ 75%	H	0.455	**0.509**	**0.554**	0.494	0.543	0.592	0.476	0.582	0.688
1/ 75%	M	0.411	**0.465**	**0.510**	0.364	0.400	0.436	0.396	0.491	0.584
1/ 75%	L	0.395	0.450	**0.495**	0.312	0.343	0.373	0.371	0.461	0.551
1/ 50%	H	0.376	0.430	**0.475**	0.409	0.440	0.478	0.361	0.451	0.542
1/ 50%	M	0.355	0.409	0.454	0.317	0.347	0.379	0.323	0.407	0.494
1/ 50%	L	0.345	0.400	0.445	0.281	0.309	0.337	0.309	0.390	0.476
2/100%	H	**0.511**	**0.565**	**0.612**	**0.631**	**0.686**	**0.733**	0.585	0.710	**0.839**
2/100%	M	0.457	**0.511**	**0.556**	0.430	0.472	0.512	0.454	0.558	0.660
2/100%	L	0.439	**0.493**	**0.538**	0.354	0.389	0.424	0.418	0.515	0.611
2/ 75%	H	0.433	**0.487**	**0.532**	0.540	0.591	**0.638**	0.446	0.549	0.650
2/ 75%	M	0.406	**0.460**	**0.505**	0.388	0.426	0.465	0.385	0.476	0.568
2/ 75%	L	0.396	0.450	**0.495**	0.326	0.358	0.391	0.365	0.451	0.541
2/ 50%	H	0.377	0.432	**0.477**	0.443	0.487	0.531	0.349	0.438	0.530
2/ 50%	M	0.354	0.408	0.453	0.336	0.369	0.403	0.311	0.393	0.480
2/ 50%	L	0.344	0.399	0.444	0.290	0.320	0.350	0.297	0.376	0.461
3/100%	H	**0.475**	**0.529**	**0.577**	0.547	0.568	0.585	0.502	0.603	0.709
3/ 75%	H	0.395	0.450	**0.495**	0.481	0.501	0.520	0.400	0.495	0.584
3/ 50%	H	0.335	0.390	0.435	0.409	0.428	0.445	0.316	0.399	0.482
4/ 0%	H	0.246	0.301	0.346	0.213	0.228	0.248	0.207	0.272	0.341

Table 6: High-speed Performance Measures for Load Case 1, Medium Wheelbase

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.593**	**0.641**	**0.683**	**0.641**	**0.696**	**0.750**	0.697	**0.821**	**0.949**
1/100%	M	**0.523**	**0.572**	**0.616**	0.448	0.493	0.536	0.545	0.655	0.762
1/100%	L	**0.498**	**0.547**	**0.589**	0.371	0.409	0.447	0.498	0.599	0.704
1/ 75%	H	**0.499**	**0.548**	**0.592**	0.538	0.590	**0.640**	0.553	0.668	0.779
1/ 75%	M	0.454	**0.503**	**0.545**	0.395	0.435	0.476	0.466	0.564	0.665
1/ 75%	L	0.439	**0.487**	**0.529**	0.339	0.374	0.409	0.438	0.529	0.628
1/ 50%	H	0.415	**0.464**	**0.506**	0.432	0.474	0.517	0.424	0.515	0.612
1/ 50%	M	0.394	0.443	**0.485**	0.344	0.377	0.411	0.384	0.470	0.560
1/ 50%	L	0.386	0.435	**0.477**	0.305	0.334	0.364	0.369	0.454	0.540
2/100%	H	**0.558**	**0.608**	**0.651**	**0.677**	**0.731**	**0.787**	0.685	**0.817**	**0.948**
2/100%	M	**0.500**	**0.548**	**0.590**	0.465	0.508	0.548	0.532	0.646	0.754
2/100%	L	**0.480**	**0.529**	**0.571**	0.381	0.420	0.458	0.490	0.592	0.697
2/ 75%	H	**0.470**	**0.518**	**0.561**	0.584	**0.635**	**0.686**	0.515	0.626	0.732
2/ 75%	M	0.444	**0.493**	**0.535**	0.419	0.462	0.505	0.449	0.541	0.641
2/ 75%	L	0.435	**0.484**	**0.526**	0.353	0.389	0.426	0.427	0.515	0.611
2/ 50%	H	0.415	**0.463**	**0.505**	0.479	0.527	0.575	0.413	0.503	0.601
2/ 50%	M	0.394	0.443	**0.484**	0.365	0.401	0.437	0.372	0.458	0.547
2/ 50%	L	0.385	0.433	**0.475**	0.316	0.346	0.378	0.358	0.441	0.526
3/100%	H	**0.515**	**0.565**	**0.608**	0.562	0.582	**0.600**	0.571	0.680	0.788
3/ 75%	H	0.441	**0.490**	**0.532**	0.488	0.510	0.530	0.469	0.569	0.664
3/ 50%	H	0.375	0.424	**0.466**	0.416	0.436	0.455	0.375	0.457	0.545
4/ 0%	H	0.286	0.334	0.376	0.227	0.247	0.268	0.255	0.326	0.395

Table 7: High-speed Performance Measures for Short Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.631**	**0.672**	**0.710**	**0.692**	**0.753**	**0.810**	0.790	**0.920**	**1.054**
1/100%	M	**0.564**	**0.606**	**0.644**	0.490	0.537	0.581	0.623	0.736	**0.849**
1/100%	L	**0.538**	**0.579**	**0.619**	0.408	0.448	0.485	0.570	0.675	0.785
1/ 75%	H	**0.544**	**0.587**	**0.625**	0.589	**0.645**	**0.698**	0.648	0.770	**0.886**
1/ 75%	M	**0.502**	**0.543**	**0.582**	0.440	0.483	0.525	0.551	0.654	0.765
1/ 75%	L	**0.484**	**0.525**	**0.564**	0.375	0.413	0.451	0.517	0.616	0.721
1/ 50%	H	0.455	**0.496**	**0.536**	0.470	0.516	0.561	0.497	0.594	0.696
1/ 50%	M	0.436	**0.477**	**0.516**	0.376	0.414	0.453	0.452	0.546	0.639
1/ 50%	L	0.428	**0.469**	**0.507**	0.334	0.368	0.402	0.436	0.527	0.617
2/100%	H	**0.608**	**0.650**	**0.688**	**0.735**	**0.795**	**0.853**	**0.803**	**0.941**	**1.081**
2/100%	M	**0.548**	**0.590**	**0.628**	0.510	0.555	0.599	0.634	0.756	**0.872**
2/100%	L	**0.525**	**0.565**	**0.604**	0.420	0.459	0.496	0.581	0.691	**0.805**
2/ 75%	H	**0.507**	**0.550**	**0.588**	**0.633**	**0.690**	**0.742**	0.602	0.719	**0.830**
2/ 75%	M	**0.485**	**0.525**	**0.564**	0.462	0.506	0.550	0.524	0.623	0.730
2/ 75%	L	**0.475**	**0.516**	**0.554**	0.387	0.429	0.468	0.498	0.595	0.694
2/ 50%	H	0.454	**0.494**	**0.533**	0.525	0.576	**0.625**	0.486	0.583	0.684
2/ 50%	M	0.434	**0.475**	**0.514**	0.401	0.442	0.483	0.441	0.534	0.626
2/ 50%	L	0.426	**0.468**	**0.506**	0.348	0.383	0.418	0.426	0.516	0.604
3/100%	H	**0.557**	**0.598**	**0.637**	0.577	0.597	**0.615**	0.648	0.764	**0.873**
3/ 75%	H	**0.488**	**0.531**	**0.569**	0.500	0.521	0.541	0.554	0.658	0.763
3/ 50%	H	0.416	0.458	**0.496**	0.427	0.448	0.468	0.440	0.529	0.618
4/ 0%	H	0.325	0.366	0.405	0.248	0.271	0.294	0.309	0.385	0.460

3.3 Tridem 53’ and Tandem 53’ Semitrailers

3.3.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 5. Table 8 shows the load cases considered for this combination. Each load case was also considered with a payload height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in), and for 50% or 75% of its nominal weight.

Figure 5: Tridem 53’ and Tandem 53’ Semitrailers

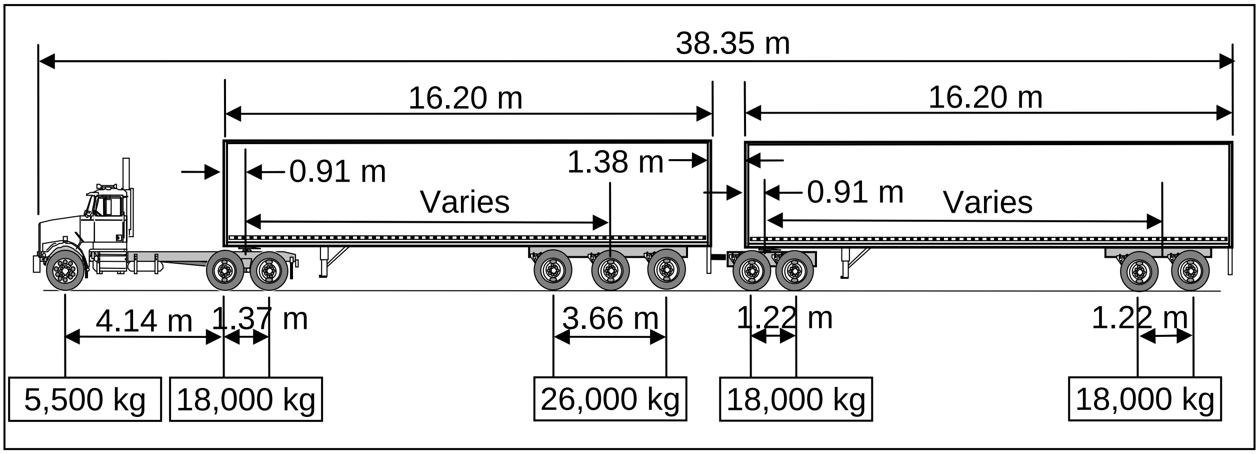


Table 8: Payload Weights for Tridem 53’ and Tandem 53’ Semitrailer LCV

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	66,000	18,000	84,000
2	42,000	42,000	84,000
3	66,000	Empty	66,000
4	Empty	Empty	0

3.3.2 Results

Table 9 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer wheelbase and vehicle speed had no significant effect on static roll threshold. The tractor and lead semitrailer roll over first in all cases.

Table 9: Roll Thresholds for Tridem 53' and Tandem 53' Semitrailer LCV

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g) Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	66,000	18,000	84,000	0.378	0.507	0.605
1	75%	49,500	13,500	63,000	0.405	0.523	0.612
1	50%	33,000	9,000	42,000	0.448	0.554	0.631
2	100%	42,000	42,000	84,000	0.420	0.533	0.616
2	75%	31,500	31,500	63,000	0.452	0.557	0.635
2	50%	21,000	21,000	42,000	0.496	0.595	0.664
3	100%	66,000	0	66,000	0.377	0.507	0.605
3	75%	49,500	0	49,500	0.405	0.523	0.612
4	0	0	0	0	0.750		

Table 10 through Table 12 show the high-speed offtracking, load transfer ratio and transient offtracking for long, medium and short wheelbase trailers respectively, as given in Table 1, for all load levels of Load Cases 1, 2, 3 and 4, as given in Table 8. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face.

The results in Table 10 through Table 12 show that high-speed offtracking, load transfer ratio and transient offtracking all increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. This configuration exceeds the high-speed offtracking performance standard for most conditions presented in the tables, while it meets load transfer ratio and transient offtracking performance standards for most conditions. The issue of high-speed offtracking is discussed in Section 3.7.4 below. The other two performance measures would be mitigated by travel at 90 km/h (55.9 mi/h).

The low-speed offtracking was about 7.85 m (309 in), and there was also significant rear outswing, from 0.39 to 0.66 m (15 to 26 in). While these exceed the performance standards, they are not an issue because any permit will only allow such vehicles to go where they can make turns, and make them in a safe manner. Friction demand was in the range 0.10 to 0.18, which is typical for a tridem semitrailer.

Table 10: High-speed Performance Measures for Long Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.460**	**0.515**	**0.562**	0.515	0.535	0.559	0.498	0.600	0.709
1/100%	M	0.411	**0.466**	**0.511**	0.364	0.384	0.419	0.411	0.506	0.597
1/100%	L	0.393	0.448	**0.494**	0.305	0.334	0.364	0.384	0.476	0.563
1/ 75%	H	0.394	0.449	**0.495**	0.464	0.484	0.505	0.410	0.505	0.597
1/ 75%	M	0.368	0.423	**0.468**	0.336	0.354	0.385	0.356	0.447	0.534
1/ 75%	L	0.357	0.412	0.458	0.286	0.313	0.340	0.338	0.426	0.511
1/ 50%	H	0.344	0.398	0.444	0.395	0.413	0.431	0.327	0.415	0.501
1/ 50%	M	0.325	0.379	0.425	0.304	0.319	0.345	0.297	0.378	0.462
1/ 50%	L	0.316	0.371	0.416	0.264	0.287	0.313	0.285	0.364	0.446
2/100%	H	0.455	**0.510**	**0.555**	0.588	**0.641**	**0.689**	0.502	0.616	0.735
2/100%	M	0.418	**0.472**	**0.517**	0.410	0.450	0.490	0.409	0.506	0.601
2/100%	L	0.404	0.459	**0.504**	0.338	0.373	0.407	0.382	0.473	0.564
2/ 75%	H	0.402	0.457	**0.502**	0.510	0.561	**0.610**	0.402	0.500	0.594
2/ 75%	M	0.377	0.431	**0.476**	0.371	0.408	0.445	0.351	0.438	0.527
2/ 75%	L	0.366	0.420	**0.465**	0.312	0.344	0.375	0.333	0.416	0.502
2/ 50%	H	0.350	0.404	0.449	0.422	0.464	0.505	0.319	0.404	0.492
2/ 50%	M	0.329	0.383	0.428	0.323	0.355	0.389	0.287	0.366	0.449
2/ 50%	L	0.320	0.374	0.419	0.281	0.310	0.338	0.276	0.352	0.433
3/100%	H	0.409	**0.464**	**0.509**	0.515	0.535	0.555	0.435	0.527	0.624
3/ 75%	H	0.357	0.412	0.457	0.465	0.485	0.505	0.368	0.455	0.538
3/ 50%	H	0.321	0.376	0.421	0.395	0.413	0.431	0.304	0.387	0.468
4/ 0%	H	0.243	0.298	0.342	0.205	0.225	0.244	0.207	0.272	0.341

Table 11: High-speed Performance Measures for Medium Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.504**	**0.554**	**0.597**	0.523	0.561	**0.609**	0.578	0.687	**0.801**
1/100%	M	0.452	**0.501**	**0.543**	0.382	0.420	0.459	0.479	0.579	0.676
1/100%	L	0.434	**0.483**	**0.526**	0.330	0.363	0.397	0.450	0.545	0.639
1/ 75%	H	0.433	**0.481**	**0.524**	0.476	0.498	0.529	0.475	0.576	0.671
1/ 75%	M	0.408	0.457	**0.499**	0.349	0.384	0.419	0.422	0.513	0.607
1/ 75%	L	0.397	0.447	**0.489**	0.310	0.339	0.371	0.403	0.490	0.582
1/ 50%	H	0.383	0.431	**0.473**	0.403	0.423	0.448	0.388	0.474	0.567
1/ 50%	M	0.364	0.412	0.455	0.312	0.340	0.370	0.355	0.438	0.524
1/ 50%	L	0.355	0.404	0.446	0.282	0.310	0.337	0.343	0.423	0.507
2/100%	H	**0.493**	**0.543**	**0.586**	**0.631**	**0.685**	**0.733**	0.587	0.707	**0.829**
2/100%	M	0.456	**0.505**	**0.547**	0.441	0.482	0.523	0.479	0.582	0.686
2/100%	L	0.442	**0.490**	**0.533**	0.365	0.402	0.439	0.449	0.543	0.642
2/ 75%	H	0.439	**0.488**	**0.530**	0.555	**0.605**	**0.653**	0.467	0.569	0.672
2/ 75%	M	0.414	**0.463**	**0.505**	0.401	0.442	0.483	0.412	0.499	0.595
2/ 75%	L	0.404	0.452	**0.494**	0.338	0.373	0.408	0.392	0.476	0.568
2/ 50%	H	0.388	0.436	**0.478**	0.458	0.504	0.549	0.381	0.467	0.560
2/ 50%	M	0.369	0.417	0.459	0.352	0.385	0.420	0.347	0.429	0.513
2/ 50%	L	0.360	0.408	0.450	0.306	0.335	0.366	0.334	0.414	0.495
3/100%	H	0.454	**0.503**	**0.548**	0.523	0.546	0.569	0.507	0.606	0.706
3/ 75%	H	0.395	0.444	**0.487**	0.475	0.497	0.519	0.427	0.519	0.607
3/ 50%	H	0.360	0.408	0.451	0.403	0.423	0.442	0.361	0.443	0.529
4/ 0%	H	0.283	0.331	0.373	0.224	0.245	0.265	0.257	0.326	0.394

Table 12: High-speed Performance Measures for Short Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.549**	**0.590**	**0.628**	0.568	**0.621**	**0.673**	0.675	0.793	**0.913**
1/100%	M	**0.495**	**0.536**	**0.576**	0.425	0.469	0.511	0.566	0.673	0.778
1/100%	L	**0.478**	**0.519**	**0.559**	0.367	0.404	0.442	0.532	0.631	0.735
1/ 75%	H	**0.471**	**0.512**	**0.552**	0.491	0.533	0.579	0.555	0.661	0.765
1/ 75%	M	0.448	**0.489**	**0.529**	0.382	0.421	0.459	0.498	0.591	0.693
1/ 75%	L	0.438	**0.480**	**0.518**	0.339	0.374	0.409	0.477	0.568	0.666
1/ 50%	H	0.422	**0.463**	**0.502**	0.415	0.448	0.489	0.457	0.549	0.645
1/ 50%	M	0.404	0.445	**0.483**	0.340	0.373	0.408	0.421	0.510	0.598
1/ 50%	L	0.396	0.437	**0.475**	0.309	0.339	0.371	0.408	0.495	0.580
2/100%	H	**0.535**	**0.578**	**0.616**	**0.679**	**0.736**	**0.795**	0.688	**0.812**	**0.939**
2/100%	M	**0.496**	**0.537**	**0.577**	0.482	0.526	0.567	0.568	0.678	0.788
2/100%	L	**0.481**	**0.522**	**0.562**	0.400	0.437	0.474	0.530	0.631	0.739
2/ 75%	H	**0.477**	**0.518**	**0.557**	**0.603**	**0.657**	**0.709**	0.547	0.656	0.764
2/ 75%	M	0.453	**0.494**	**0.533**	0.440	0.485	0.529	0.482	0.577	0.677
2/ 75%	L	0.442	**0.483**	**0.521**	0.370	0.410	0.449	0.460	0.552	0.646
2/ 50%	H	0.427	**0.468**	**0.507**	0.500	0.550	**0.600**	0.450	0.544	0.640
2/ 50%	M	0.409	0.450	**0.488**	0.386	0.425	0.463	0.413	0.501	0.589
2/ 50%	L	0.401	0.441	**0.479**	0.336	0.369	0.403	0.399	0.485	0.568
3/100%	H	**0.499**	**0.542**	**0.581**	0.540	0.564	0.585	0.593	0.702	**0.807**
3/ 75%	H	0.435	**0.476**	**0.515**	0.490	0.514	0.535	0.501	0.595	0.693
3/ 50%	H	0.399	0.440	**0.479**	0.414	0.435	0.455	0.426	0.512	0.600
4/ 0%	H	0.322	0.364	0.401	0.246	0.269	0.291	0.312	0.386	0.458

3.4 Twin 48' Tandem Semitrailers

3.4.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 6. Table 13 shows the load cases considered for this combination. Each load case was also considered with a payload height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in), and for 50% or 75% of its nominal weight.

Figure 6: Twin 48' Tandem Semitrailers

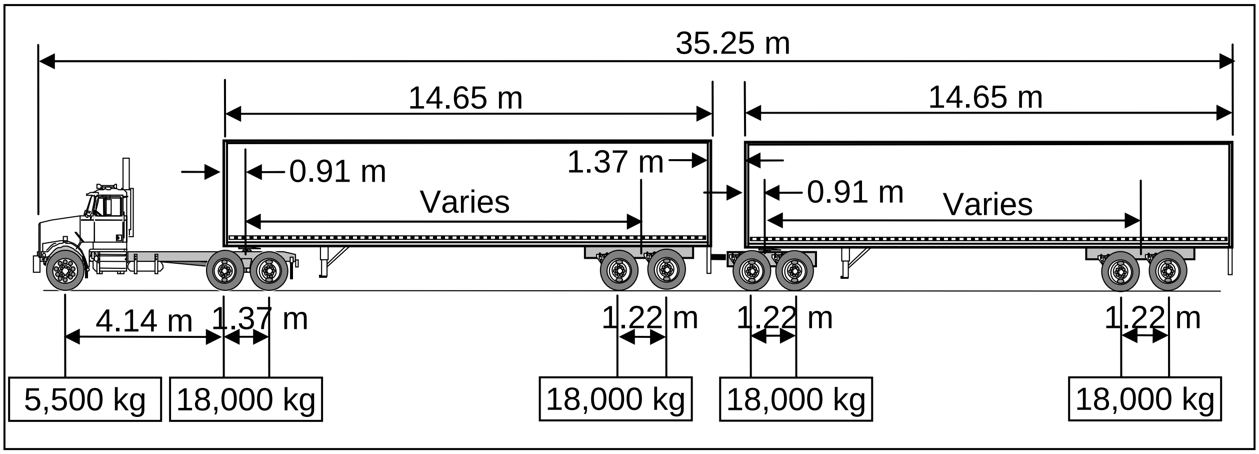


Table 13: Payload Weights for Twin 48' Tandem Semitrailer LCV

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	57,000	30,000	87,000
2	43,500	43,500	87,000
3	57,000	Empty	57,000
4	Empty	Empty	0

3.4.2 Results

Table 14 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer wheelbase and vehicle speed had no significant effect on static roll threshold. The tractor and lead semitrailer roll over first in all cases.

Table 14: Roll Thresholds for Twin 48' Tandem Semitrailer LCV

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	57,000	30,000	87,000	0.371	0.496	0.584
1	75%	42,750	22,500	65,250	0.404	0.521	0.601
1	50%	28,500	15,000	43,500	0.444	0.552	0.622
2	100%	43,500	43,500	87,000	0.402	0.522	0.601
2	75%	32,625	32,625	65,250	0.429	0.540	0.616
2	50%	21,750	21,750	43,500	0.470	0.567	0.633
3	100%	57,000	0	57,000	0.371	0.496	0.584
3	75%	42,750	0	42,750	0.405	0.521	0.601
4	0	0	0	0	0.717		

Table 15 through Table 17 show the high-speed offtracking, load transfer ratio and transient offtracking for long, medium and short wheelbase trailers respectively, as given in Table 1, for all load levels of Load Cases 1, 2, 3 and 4, as given in Table 13. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face.

The results in Table 15 through Table 17 show that high-speed offtracking, load transfer ratio and transient offtracking all increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. This configuration exceeds the high-speed offtracking performance standard for most conditions presented in the tables, while it meets load transfer ratio and transient offtracking performance standards for most conditions. The issue of high-speed offtracking is discussed in Section 3.7.4 below. The other two performance measures would be mitigated by travel at 90 km/h (55.9 mi/h).

The low-speed offtracking was from 7.00 to 7.85 m (275 to 309 in), and there was also significant rear outswing, from 0.27 to 0.50 m (11 to 20 in). While these exceed the performance standards, they are not an issue because any permit will only allow such vehicles to go where they can make turns, and make them in a safe manner. Friction demand was about 0.02, which is typical for a tandem semitrailer.

Table 15: High-speed Performance Measures for Long Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.489**	**0.544**	**0.590**	0.569	**0.619**	**0.669**	0.558	0.673	0.784
1/100%	M	0.427	**0.480**	**0.525**	0.397	0.433	0.471	0.436	0.530	0.629
1/100%	L	0.403	0.456	**0.501**	0.329	0.360	0.392	0.396	0.486	0.577
1/ 75%	H	0.395	0.448	**0.493**	0.488	0.525	0.572	0.435	0.529	0.630
1/ 75%	M	0.360	0.413	0.458	0.354	0.386	0.419	0.362	0.450	0.535
1/ 75%	L	0.348	0.401	0.447	0.304	0.332	0.360	0.339	0.424	0.505
1/ 50%	H	0.336	0.389	0.434	0.415	0.434	0.471	0.333	0.421	0.504
1/ 50%	M	0.314	0.367	0.412	0.317	0.341	0.370	0.293	0.376	0.455
1/ 50%	L	0.304	0.357	0.403	0.276	0.301	0.326	0.279	0.359	0.436
2/100%	H	0.449	**0.501**	**0.549**	**0.613**	**0.665**	**0.712**	0.531	0.649	0.766
2/100%	M	0.405	0.457	**0.502**	0.420	0.457	0.495	0.417	0.509	0.604
2/100%	L	0.392	0.445	**0.490**	0.342	0.376	0.410	0.387	0.475	0.561
2/ 75%	H	0.392	0.445	**0.490**	0.529	0.577	**0.624**	0.422	0.518	0.615
2/ 75%	M	0.364	0.416	**0.461**	0.377	0.414	0.450	0.355	0.443	0.526
2/ 75%	L	0.352	0.405	0.450	0.317	0.347	0.377	0.333	0.418	0.498
2/ 50%	H	0.337	0.390	0.435	0.429	0.470	0.512	0.321	0.409	0.491
2/ 50%	M	0.314	0.367	0.412	0.327	0.357	0.388	0.281	0.363	0.443
2/ 50%	L	0.304	0.356	0.401	0.283	0.308	0.336	0.267	0.346	0.424
3/100%	H	0.411	**0.463**	**0.509**	0.543	0.564	0.582	0.450	0.547	0.637
3/ 75%	H	0.334	0.386	0.432	0.488	0.507	0.527	0.359	0.443	0.530
3/ 50%	H	0.294	0.347	0.393	0.415	0.433	0.449	0.290	0.369	0.444
4/ 0%	H	0.213	0.266	0.311	0.217	0.226	0.236	0.186	0.247	0.309

Table 16: High-speed Performance Measures for Medium Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.555**	**0.602**	**0.639**	**0.653**	**0.707**	**0.759**	0.703	**0.825**	**0.943**
1/100%	M	**0.493**	**0.539**	**0.578**	0.456	0.499	0.541	0.553	0.660	0.764
1/100%	L	**0.470**	**0.516**	**0.555**	0.381	0.417	0.454	0.506	0.606	0.701
1/ 75%	H	**0.463**	**0.509**	**0.549**	0.549	**0.600**	**0.649**	0.556	0.662	0.769
1/ 75%	M	0.427	**0.473**	**0.510**	0.404	0.443	0.482	0.470	0.565	0.657
1/ 75%	L	0.414	**0.461**	**0.498**	0.345	0.377	0.411	0.444	0.533	0.623
1/ 50%	H	0.398	0.444	**0.481**	0.447	0.488	0.530	0.435	0.525	0.615
1/ 50%	M	0.378	0.424	**0.462**	0.353	0.386	0.420	0.393	0.475	0.563
1/ 50%	L	0.369	0.415	0.453	0.312	0.342	0.371	0.378	0.457	0.543
2/100%	H	**0.519**	**0.567**	**0.604**	**0.693**	**0.743**	**0.795**	0.690	**0.817**	**0.941**
2/100%	M	**0.471**	**0.517**	**0.555**	0.477	0.519	0.557	0.535	0.643	0.749
2/100%	L	0.455	**0.501**	**0.538**	0.391	0.427	0.462	0.495	0.593	0.689
2/ 75%	H	0.450	**0.496**	**0.534**	0.596	**0.649**	**0.699**	0.529	0.636	0.741
2/ 75%	M	0.425	**0.471**	**0.508**	0.428	0.468	0.508	0.460	0.552	0.645
2/ 75%	L	0.416	**0.462**	**0.499**	0.359	0.395	0.430	0.437	0.523	0.614
2/ 50%	H	0.399	0.445	**0.482**	0.488	0.533	0.579	0.425	0.513	0.606
2/ 50%	M	0.377	0.423	**0.460**	0.372	0.407	0.443	0.382	0.463	0.550
2/ 50%	L	0.368	0.414	0.451	0.322	0.353	0.384	0.366	0.445	0.529
3/100%	H	**0.478**	**0.526**	**0.564**	0.569	0.590	**0.608**	0.573	0.670	0.775
3/ 75%	H	0.405	0.451	**0.489**	0.501	0.522	0.542	0.466	0.559	0.647
3/ 50%	H	0.358	0.404	0.441	0.427	0.446	0.464	0.382	0.463	0.544
4/ 0%	H	0.278	0.324	0.361	0.229	0.250	0.271	0.266	0.332	0.400

Table 17: High-speed Performance Measures for Short Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.617**	**0.651**	**0.680**	**0.760**	**0.818**	**0.872**	**0.882**	**1.012**	**1.138**
1/100%	M	**0.558**	**0.592**	**0.624**	0.539	0.584	**0.627**	0.699	**0.810**	**0.919**
1/100%	L	**0.534**	**0.569**	**0.601**	0.448	0.488	0.528	0.643	0.744	**0.852**
1/ 75%	H	**0.538**	**0.572**	**0.604**	**0.654**	**0.710**	**0.766**	0.723	**0.844**	**0.957**
1/ 75%	M	**0.498**	**0.533**	**0.565**	0.485	0.530	0.573	0.623	0.725	**0.832**
1/ 75%	L	**0.484**	**0.519**	**0.551**	0.416	0.455	0.492	0.586	0.684	0.787
1/ 50%	H	**0.461**	**0.497**	**0.529**	0.527	0.575	**0.620**	0.568	0.664	0.764
1/ 50%	M	0.443	**0.477**	**0.511**	0.418	0.456	0.494	0.519	0.613	0.705
1/ 50%	L	0.436	**0.470**	**0.503**	0.368	0.403	0.438	0.500	0.592	0.681
2/100%	H	**0.600**	**0.634**	**0.664**	**0.804**	**0.866**	**0.923**	**0.905**	**1.049**	**1.194**
2/100%	M	**0.545**	**0.579**	**0.611**	0.557	**0.603**	**0.651**	0.719	**0.841**	**0.957**
2/100%	L	**0.524**	**0.558**	**0.590**	0.460	0.500	0.539	0.661	0.771	**0.881**
2/ 75%	H	**0.511**	**0.545**	**0.577**	**0.691**	**0.745**	**0.798**	0.687	**0.805**	**0.917**
2/ 75%	M	**0.488**	**0.523**	**0.555**	0.510	0.554	0.594	0.598	0.697	**0.802**
2/ 75%	L	**0.479**	**0.513**	**0.546**	0.429	0.469	0.506	0.569	0.665	0.764
2/ 50%	H	**0.460**	**0.494**	**0.527**	0.578	**0.631**	**0.681**	0.559	0.655	0.755
2/ 50%	M	0.442	**0.476**	**0.509**	0.441	0.481	0.522	0.508	0.602	0.694
2/ 50%	L	0.435	**0.468**	**0.501**	0.381	0.418	0.455	0.490	0.582	0.669
3/100%	H	**0.545**	**0.579**	**0.612**	0.599	**0.619**	**0.637**	0.712	**0.826**	**0.932**
3/ 75%	H	**0.482**	**0.517**	**0.550**	0.523	0.544	0.564	0.616	0.717	**0.818**
3/ 50%	H	0.423	0.457	**0.491**	0.447	0.469	0.490	0.500	0.588	0.676
4/ 0%	H	0.342	0.376	0.408	0.269	0.293	0.321	0.367	0.440	0.515

3.5 Tandem 53’ and Tandem 48’ Semitrailers

3.5.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 7. Table 18 shows the load cases considered for this combination. Each load case was also considered with a payload height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in), and for 50% or 75% of its nominal weight.

Figure 7: Tandem 53’ and Tandem 48’ Semitrailers

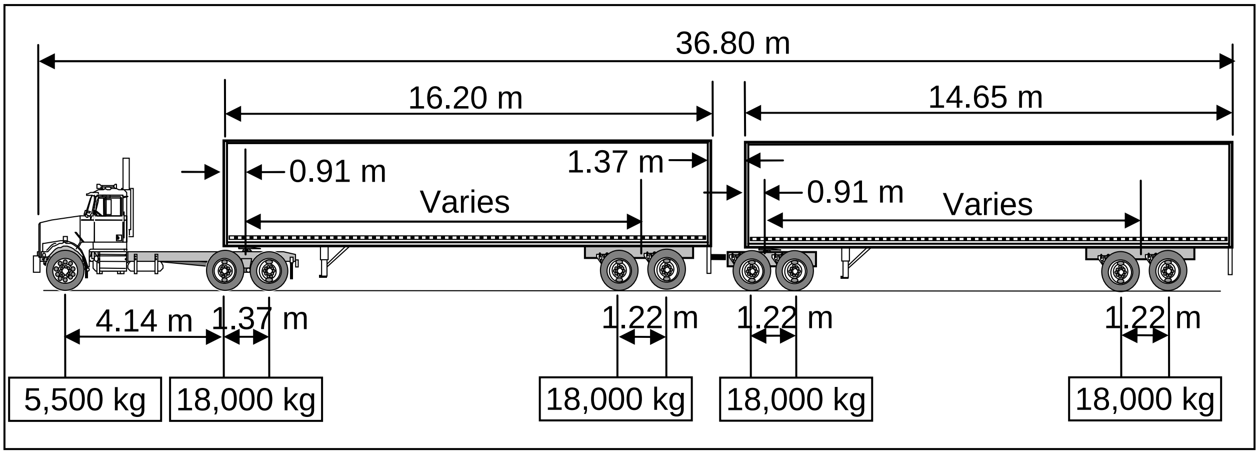


Table 18: Payload Weights for Tandem 53’ and Tandem 48’ Semitrailer LCV

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	59,000	28,000	87,000
2	43,500	43,500	87,000
3	59,000	Empty	59,000
4	Empty	Empty	0

3.5.2 Results

Table 19 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer wheelbase and vehicle speed had no significant effect on static roll threshold. The tractor and lead semitrailer roll over first in all cases.

Table 19: Roll Thresholds for Tandem 53' and Tandem 48' Semitrailer LCV

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	59,000	28,000	87,000	0.369	0.496	0.586
1	75%	44,250	21,000	65,250	0.404	0.523	0.605
1	50%	29,500	14,000	43,500	0.444	0.551	0.623
2	100%	43,500	43,500	87,000	0.406	0.525	0.603
2	75%	32,625	32,625	65,250	0.433	0.544	0.618
2	50%	21,750	21,750	43,500	0.471	0.567	0.636
3	100%	59,000	0	59,000	0.368	0.496	0.586
3	75%	32,625	0	32,625	0.405	0.523	0.605
3	50%	21,750	0	21,750	0.445	0.551	0.623
4	0%	0	0	0	0.715		

Table 20 through Table 22 show the high-speed offtracking, load transfer ratio and transient offtracking for long, medium and short wheelbase trailers respectively, as given in Table 1, for all load levels of Load Cases 1, 2, 3 and 4, as given in Table 18. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face.

The results in Table 20 through Table 22 show that high-speed offtracking, load transfer ratio and transient offtracking all increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. This configuration exceeds the high-speed offtracking performance standard for most conditions presented in the tables, while it meets load transfer ratio and transient offtracking performance standards for most conditions. The issue of high-speed offtracking is discussed in Section 3.7.4 below. The other two performance measures would be mitigated by travel at 90 km/h (55.9 mi/h).

The low-speed offtracking was about 7.85 m (275 to 309 in), and there was also significant rear outswing, from 0.22 to 0.47 m (8 to 19 in). While these exceed the performance standards, they are not an issue because any permit will only allow such vehicles to go where they can make turns, and make them in a safe manner. Friction demand was about 0.02, which is typical for a tandem semitrailer.

Table 20: High-speed Performance Measures for Long Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.550**	**0.607**	**0.653**	0.599	**0.653**	**0.705**	0.619	0.739	**0.866**
1/100%	M	**0.482**	**0.536**	**0.581**	0.419	0.459	0.499	0.475	0.583	0.688
1/100%	L	0.455	**0.510**	**0.554**	0.351	0.385	0.419	0.431	0.529	0.632
1/ 75%	H	0.453	**0.507**	**0.552**	0.501	0.550	0.599	0.475	0.586	0.691
1/ 75%	M	0.409	**0.463**	**0.508**	0.370	0.405	0.442	0.396	0.490	0.587
1/ 75%	L	0.393	0.447	**0.493**	0.316	0.346	0.378	0.369	0.459	0.552
1/ 50%	H	0.373	0.428	**0.473**	0.409	0.446	0.484	0.360	0.450	0.543
1/ 50%	M	0.352	0.407	0.452	0.323	0.354	0.386	0.321	0.405	0.493
1/ 50%	L	0.343	0.398	0.443	0.287	0.315	0.343	0.307	0.389	0.475
2/100%	H	**0.505**	**0.558**	**0.605**	0.652	**0.705**	**0.753**	0.583	0.715	**0.849**
2/100%	M	0.454	**0.508**	**0.553**	0.445	0.487	0.526	0.451	0.554	0.661
2/100%	L	0.437	**0.491**	**0.536**	0.363	0.398	0.433	0.418	0.511	0.610
2/ 75%	H	0.431	**0.486**	**0.530**	0.551	**0.604**	**0.653**	0.450	0.553	0.657
2/ 75%	M	0.404	0.458	**0.503**	0.396	0.433	0.470	0.384	0.473	0.571
2/ 75%	L	0.393	0.447	**0.492**	0.331	0.364	0.397	0.362	0.449	0.541
2/ 50%	H	0.376	0.431	**0.475**	0.449	0.493	0.536	0.349	0.439	0.533
2/ 50%	M	0.352	0.407	0.452	0.342	0.376	0.409	0.309	0.393	0.479
2/ 50%	L	0.342	0.396	0.441	0.297	0.326	0.354	0.294	0.376	0.459
3/100%	H	**0.475**	**0.529**	**0.577**	0.547	0.567	0.585	0.502	0.605	0.711
3/ 75%	H	0.395	0.450	**0.495**	0.481	0.501	0.520	0.400	0.495	0.585
3/ 50%	H	0.335	0.390	0.435	0.409	0.428	0.446	0.316	0.399	0.483
4/ 0%	H	0.247	0.302	0.346	0.212	0.230	0.251	0.206	0.273	0.342

Table 21: High-speed Performance Measures for Medium Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.590**	**0.639**	**0.681**	**0.651**	**0.707**	**0.760**	0.703	**0.830**	**0.960**
1/100%	M	**0.521**	**0.569**	**0.613**	0.452	0.496	0.537	0.547	0.656	0.770
1/100%	L	**0.494**	**0.543**	**0.585**	0.379	0.416	0.452	0.497	0.598	0.707
1/ 75%	H	**0.498**	**0.547**	**0.591**	0.546	0.599	**0.650**	0.557	0.672	0.783
1/ 75%	M	0.452	**0.500**	**0.542**	0.402	0.442	0.482	0.466	0.563	0.669
1/ 75%	L	0.435	**0.484**	**0.526**	0.344	0.378	0.413	0.436	0.530	0.628
1/ 50%	H	0.413	**0.462**	**0.504**	0.440	0.482	0.524	0.424	0.516	0.614
1/ 50%	M	0.393	0.441	**0.483**	0.348	0.381	0.416	0.382	0.471	0.560
1/ 50%	L	0.384	0.433	**0.475**	0.308	0.339	0.369	0.366	0.454	0.539
2/100%	H	**0.550**	**0.600**	**0.641**	**0.698**	**0.750**	**0.803**	0.685	**0.822**	**0.962**
2/100%	M	**0.495**	**0.543**	**0.585**	0.479	0.523	0.565	0.529	0.638	0.754
2/100%	L	**0.478**	**0.527**	**0.568**	0.394	0.433	0.470	0.486	0.586	0.695
2/ 75%	H	**0.468**	**0.517**	**0.560**	0.594	**0.647**	**0.699**	0.520	0.626	0.739
2/ 75%	M	0.442	**0.490**	**0.532**	0.428	0.469	0.510	0.448	0.544	0.644
2/ 75%	L	0.432	**0.481**	**0.523**	0.359	0.394	0.429	0.425	0.516	0.611
2/ 50%	H	0.414	**0.462**	**0.504**	0.487	0.534	0.582	0.413	0.507	0.604
2/ 50%	M	0.392	0.440	**0.482**	0.369	0.405	0.442	0.370	0.459	0.546
2/ 50%	L	0.382	0.430	**0.472**	0.320	0.351	0.383	0.354	0.441	0.524
3/100%	H	**0.515**	**0.565**	**0.608**	0.562	0.582	**0.600**	0.571	0.682	0.789
3/ 75%	H	0.441	**0.490**	**0.532**	0.488	0.510	0.530	0.470	0.569	0.666
3/ 50%	H	0.375	0.424	**0.466**	0.416	0.436	0.456	0.375	0.458	0.545
4/ 0%	H	0.286	0.334	0.377	0.228	0.248	0.270	0.255	0.326	0.397

Table 22: High-speed Performance Measures for Short Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.629**	**0.670**	**0.708**	**0.705**	**0.765**	**0.823**	0.794	**0.929**	**1.065**
1/100%	M	**0.560**	**0.603**	**0.641**	0.495	0.540	0.583	0.624	0.737	**0.858**
1/100%	L	**0.535**	**0.575**	**0.615**	0.411	0.450	0.489	0.568	0.678	0.788
1/ 75%	H	**0.543**	**0.586**	**0.624**	0.598	**0.653**	**0.707**	0.653	0.776	**0.892**
1/ 75%	M	**0.499**	**0.539**	**0.579**	0.442	0.486	0.529	0.551	0.658	0.770
1/ 75%	L	**0.480**	**0.522**	**0.561**	0.380	0.419	0.456	0.515	0.618	0.723
1/ 50%	H	0.454	**0.494**	**0.534**	0.479	0.525	0.570	0.496	0.597	0.698
1/ 50%	M	0.434	**0.476**	**0.514**	0.381	0.419	0.456	0.450	0.547	0.638
1/ 50%	L	0.426	**0.468**	**0.506**	0.338	0.370	0.404	0.433	0.527	0.617
2/100%	H	**0.595**	**0.637**	**0.675**	**0.750**	**0.811**	**0.872**	**0.805**	**0.947**	**1.096**
2/100%	M	**0.540**	**0.582**	**0.620**	0.524	0.567	**0.610**	0.627	0.746	**0.872**
2/100%	L	**0.520**	**0.561**	**0.600**	0.430	0.471	0.510	0.573	0.684	0.799
2/ 75%	H	**0.506**	**0.548**	**0.586**	**0.648**	**0.701**	**0.753**	0.604	0.719	**0.839**
2/ 75%	M	**0.482**	**0.522**	**0.561**	0.468	0.514	0.557	0.523	0.627	0.731
2/ 75%	L	**0.472**	**0.513**	**0.551**	0.394	0.434	0.471	0.495	0.596	0.694
2/ 50%	H	0.452	**0.493**	**0.532**	0.533	0.586	**0.636**	0.485	0.588	0.689
2/ 50%	M	0.432	**0.473**	**0.511**	0.405	0.446	0.486	0.439	0.535	0.627
2/ 50%	L	0.423	**0.465**	**0.503**	0.351	0.385	0.420	0.422	0.515	0.606
3/100%	H	**0.557**	**0.599**	**0.637**	0.577	0.597	**0.615**	0.649	0.765	**0.874**
3/ 75%	H	**0.488**	**0.529**	**0.569**	0.500	0.521	0.541	0.555	0.658	0.764
3/ 50%	H	0.416	0.458	**0.496**	0.426	0.448	0.468	0.440	0.530	0.618
4/ 0%	H	0.326	0.367	0.405	0.250	0.272	0.294	0.310	0.385	0.461

3.6 Tridem 53' and Tandem 48' Semitrailers

3.6.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 8. Table 23 shows the load cases considered for this combination. Each load case was also considered with a payload height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in), and for 50% or 75% of its nominal weight.

Figure 8: Tridem 53' and Tandem 48' Semitrailers

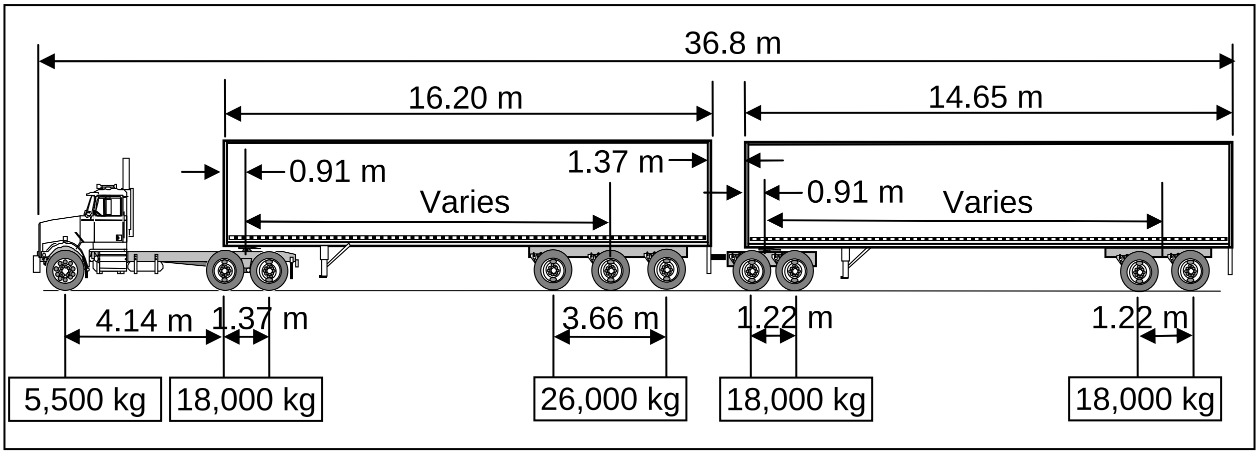


Table 23: Payload Weights for Tridem 53' and Tandem 48' Semitrailer LCV

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	66,000	18,000	84,000
2	42,000	42,000	84,000
3	66,000	Empty	66,000
4	Empty	Empty	0

3.6.2 Results

Table 24 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer wheelbase and vehicle speed had no significant effect on static roll threshold. The tractor and lead semitrailer roll over first in all cases.

Table 24: Roll Thresholds for Tridem 53' and Tandem 48' Semitrailer LCV

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g) Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	66,000	18,000	84,000	0.379	0.506	0.608
1	75%	49,500	13,500	63,000	0.405	0.522	0.610
1	50%	33,000	9,000	42,000	0.449	0.554	0.631
2	100%	42,000	42,000	84,000	0.422	0.533	0.617
2	75%	31,500	31,500	63,000	0.452	0.556	0.633
2	50%	21,000	21,000	42,000	0.497	0.595	0.661
3	100%	66,000	0	66,000	0.378	0.506	0.608
3	75%	49,500	0	49,500	0.405	0.522	0.610
4	0	0	0	0	0.748		

Table 25 through Table 27 show the high-speed offtracking, load transfer ratio and transient offtracking for long, medium and short wheelbase trailers respectively, as given in Table 1, for all load levels of Load Cases 1, 2, 3 and 4, as given in Table 23. CG is the payload height; H corresponds to a payload height of 2.44 m (96 in), M to a payload height of 1.83 m (72 in) and L to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face.

The results in Table 25 through Table 27 show that high-speed offtracking, load transfer ratio and transient offtracking all increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. This configuration exceeds the high-speed offtracking performance standard for most conditions presented in the tables, while it meets load transfer ratio and transient offtracking performance standards for most conditions. The issue of high-speed offtracking is discussed in Section 3.7.4 below. The other two performance measures would be mitigated by travel at 90 km/h (55.9 mi/h).

The low-speed offtracking was about 7.85 m (275 to 309 in), and there was also significant rear outswing, from 0.20 to 0.45 m (8 to 18 in). While these exceed the performance standards, they are not an issue because any permit will only allow such vehicles to go where they can make turns, and make them in a safe manner. Friction demand was in a range 0.10 to 0.18, which is typical for a tridem semitrailer.

Table 25: High-speed Performance Measures for Long Wheelbase Semitrailers

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.458**	**0.512**	**0.560**	0.515	0.535	0.568	0.499	0.604	0.713
1/100%	M	0.408	**0.464**	**0.509**	0.364	0.391	0.425	0.409	0.506	0.598
1/100%	L	0.391	0.446	**0.491**	0.310	0.339	0.368	0.382	0.475	0.564
1/ 75%	H	0.392	0.447	**0.492**	0.465	0.485	0.505	0.407	0.506	0.598
1/ 75%	M	0.365	0.420	**0.466**	0.336	0.358	0.389	0.355	0.445	0.535
1/ 75%	L	0.354	0.409	0.455	0.290	0.317	0.345	0.337	0.423	0.511
1/ 50%	H	0.341	0.395	0.441	0.395	0.413	0.431	0.326	0.412	0.501
1/ 50%	M	0.322	0.376	0.422	0.304	0.322	0.350	0.294	0.375	0.460
1/ 50%	L	0.313	0.368	0.413	0.266	0.293	0.318	0.282	0.360	0.444
2/100%	H	0.449	**0.503**	**0.550**	**0.605**	**0.656**	**0.705**	0.498	0.618	0.735
2/100%	M	0.415	**0.469**	**0.515**	0.422	0.463	0.502	0.408	0.502	0.602
2/100%	L	0.402	0.456	**0.501**	0.346	0.380	0.413	0.382	0.470	0.564
2/ 75%	H	0.401	0.455	**0.500**	0.523	0.572	**0.622**	0.405	0.502	0.602
2/ 75%	M	0.374	0.428	**0.473**	0.377	0.413	0.451	0.349	0.435	0.528
2/ 75%	L	0.362	0.417	**0.461**	0.318	0.350	0.382	0.330	0.413	0.501
2/ 50%	H	0.348	0.403	0.447	0.428	0.468	0.511	0.319	0.404	0.493
2/ 50%	M	0.327	0.382	0.426	0.328	0.362	0.394	0.285	0.365	0.448
2/ 50%	L	0.317	0.372	0.416	0.287	0.314	0.342	0.272	0.351	0.431
3/100%	H	0.409	**0.464**	**0.509**	0.515	0.535	0.555	0.436	0.528	0.625
3/ 75%	H	0.357	0.412	0.457	0.464	0.484	0.505	0.367	0.455	0.538
3/ 50%	H	0.321	0.376	0.422	0.395	0.413	0.431	0.304	0.387	0.469
4/ 0%	H	0.244	0.298	0.343	0.207	0.226	0.247	0.207	0.272	0.341

Table 26: High-speed Performance Measures for Medium Wheelbase Semitrailers

Load Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.502**	**0.553**	**0.595**	0.523	0.569	**0.616**	0.579	0.692	**0.807**
1/100%	M	0.450	**0.499**	**0.541**	0.387	0.425	0.464	0.479	0.579	0.680
1/100%	L	0.432	**0.481**	**0.523**	0.336	0.369	0.402	0.450	0.543	0.641
1/ 75%	H	0.430	**0.479**	**0.521**	0.476	0.498	0.533	0.476	0.576	0.676
1/ 75%	M	0.405	0.454	**0.497**	0.355	0.388	0.423	0.422	0.511	0.607
1/ 75%	L	0.395	0.444	**0.486**	0.314	0.343	0.374	0.402	0.489	0.582
1/ 50%	H	0.380	0.429	**0.471**	0.403	0.423	0.452	0.386	0.474	0.566
1/ 50%	M	0.361	0.410	0.452	0.314	0.346	0.376	0.352	0.436	0.522
1/ 50%	L	0.352	0.401	0.443	0.286	0.314	0.342	0.339	0.422	0.505
2/100%	H	**0.486**	**0.535**	**0.579**	**0.650**	**0.702**	**0.750**	0.582	0.709	**0.832**
2/100%	M	0.452	**0.500**	**0.543**	0.455	0.498	0.539	0.476	0.575	0.685
2/100%	L	0.440	**0.489**	**0.531**	0.375	0.413	0.449	0.447	0.539	0.639
2/ 75%	H	0.437	**0.486**	**0.529**	0.560	**0.615**	**0.667**	0.471	0.570	0.678
2/ 75%	M	0.411	**0.460**	**0.502**	0.408	0.448	0.487	0.410	0.501	0.596
2/ 75%	L	0.400	0.448	**0.490**	0.344	0.377	0.411	0.389	0.477	0.567
2/ 50%	H	0.387	0.435	**0.477**	0.464	0.509	0.554	0.380	0.469	0.561
2/ 50%	M	0.366	0.415	0.457	0.354	0.390	0.426	0.344	0.429	0.512
2/ 50%	L	0.357	0.405	0.447	0.309	0.340	0.370	0.330	0.413	0.492
3/100%	H	0.454	**0.504**	**0.548**	0.523	0.546	0.569	0.507	0.607	0.707
3/ 75%	H	0.395	0.444	**0.487**	0.476	0.497	0.519	0.428	0.519	0.608
3/ 50%	H	0.360	0.408	0.451	0.403	0.423	0.442	0.361	0.442	0.529
4/ 0%	H	0.283	0.331	0.373	0.226	0.246	0.267	0.256	0.326	0.394

Table 27: High-speed Performance Measures for Short Wheelbase Semitrailers

Load Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.547**	**0.589**	**0.627**	0.576	**0.628**	**0.679**	0.677	**0.800**	**0.920**
1/100%	M	**0.493**	**0.534**	**0.574**	0.430	0.473	0.514	0.567	0.673	0.784
1/100%	L	**0.475**	**0.517**	**0.556**	0.369	0.407	0.443	0.531	0.630	0.738
1/ 75%	H	**0.469**	**0.510**	**0.550**	0.491	0.539	0.585	0.557	0.661	0.770
1/ 75%	M	0.446	**0.487**	**0.526**	0.388	0.426	0.465	0.497	0.593	0.694
1/ 75%	L	0.436	**0.478**	**0.517**	0.344	0.378	0.413	0.475	0.569	0.665
1/ 50%	H	0.420	**0.461**	**0.499**	0.414	0.454	0.493	0.455	0.549	0.644
1/ 50%	M	0.401	0.442	**0.480**	0.343	0.375	0.410	0.418	0.508	0.596
1/ 50%	L	0.393	0.434	**0.472**	0.312	0.341	0.372	0.404	0.493	0.577
2/100%	H	**0.524**	**0.567**	**0.605**	**0.702**	**0.753**	**0.806**	0.684	**0.817**	**0.946**
2/100%	M	**0.490**	**0.531**	**0.570**	0.494	0.538	0.580	0.561	0.669	0.785
2/100%	L	**0.478**	**0.519**	**0.558**	0.411	0.451	0.488	0.524	0.627	0.733
2/ 75%	H	**0.475**	**0.516**	**0.555**	**0.614**	**0.668**	**0.719**	0.548	0.655	0.770
2/ 75%	M	0.449	**0.490**	**0.529**	0.446	0.491	0.534	0.480	0.579	0.678
2/ 75%	L	0.439	**0.480**	**0.518**	0.377	0.414	0.451	0.456	0.552	0.645
2/ 50%	H	0.426	**0.467**	**0.505**	0.508	0.558	**0.608**	0.449	0.547	0.643
2/ 50%	M	0.406	0.447	**0.485**	0.390	0.427	0.465	0.409	0.501	0.589
2/ 50%	L	0.397	0.438	**0.476**	0.339	0.371	0.405	0.394	0.483	0.570
3/100%	H	**0.499**	**0.542**	**0.581**	0.540	0.564	0.585	0.593	0.703	0.807
3/ 75%	H	0.435	**0.476**	**0.515**	0.490	0.514	0.535	0.501	0.594	0.693
3/ 50%	H	0.399	0.440	**0.479**	0.414	0.435	0.455	0.425	0.512	0.600
4/ 0%	H	0.323	0.364	0.402	0.248	0.270	0.292	0.310	0.385	0.459

3.7 Discussion

3.7.1 Assumption

All these LCV configurations exceed the low-speed offtracking and rear outswing performance standards by a wide margin, so it is assumed they would operate principally on freeways, by special permit. The permit would specify an access route between a terminal or vehicle assembly location and a freeway interchange, and the access route would be selected so that the vehicles can make any turns required, and can make them safely.

3.7.2 Static Roll Threshold

Any of these LCV configurations with a typical tandem semitrailer payload up to about 20,411 kg (45,000 lb) in weight, and 2.44 m (96 in) in height, have a static roll threshold close to or higher than 0.40 g. Loads at maximum lead semitrailer payload, up to about 26,762 kg (59,000 lb) on a tandem semitrailer, and 29,937 kg (66,000 lb) on a tridem semitrailer, and 2.44 m (96 in) in height, have a static roll threshold for the tractor-semitrailer between 0.35 and 0.40 g for a payload height greater than 1.83 m (72 in).

If a permit is issued simply for an allowable gross weight, the static roll threshold for each of these LCV configurations will essentially reflect the status quo for tandem and tridem semitrailers. While a tandem van semitrailer could be loaded with payload up to about 26,762 kg (59,000 lb) in weight, the typical maximum weight is around 20,411 kg (45,000 lb), and the average weight is only around 15,875 kg (35,000 lb). Thus, without any payload restrictions, it is expected there will be a low probability of a static roll threshold significantly below 0.40 g for an LCV composed of tandem semitrailers. This may not be the case with a tridem semitrailer, where loads commonly approach the typical 29,937 kg (66,000 lb) weight capacity of the trailer, so a static roll threshold between 0.35 and 0.40 g would be expected for an LCV with a tridem lead semitrailer.

It is possible to restrict the payload weight and height through permit conditions to ensure the static roll threshold of these LCV configurations is not significantly below 0.40 g. The simplest restriction would limit the payload weight in any semitrailer to no more than (say) 20,411 kg (45,000 lb). This would restrict any tridem semitrailer to carry no more than a tandem payload weight, and would effectively rule out a tridem as the lead semitrailer. If the tridem configurations considered above would be intended to carry their full payload capacity by weight, then the allowable payload weight could not be restricted on any semitrailer. However, the desired static roll threshold would be achieved by restricting the payload height to no more than (say) 1.83 m (72 in) when the total payload weight on the semitrailer was more than (say) 20,411 kg (45,000 lb). These restrictions are postulated simply as examples at this point, when the details of any possible LCV operation are unknown. It would be possible to tailor permit conditions to a specific LCV operation to achieve a static roll threshold of 0.40 g once details of the vehicles and payloads would be known.

3.7.3 Load Transfer Ratio and Transient Offtracking

The results presented above for each of the candidate LCV configurations show that load transfer ratio and transient offtracking each increase with an increase in payload weight, payload height, and vehicle speed, and with a reduction in semitrailer wheelbase. These performance measures are an issue for operation on freeways. If a driver makes a sufficiently aggressive evasive manoeuvre, then rearward amplification occurs, the pup trailer may move outside the path of the tractor, and may also roll over. These performance measures approach or exceed their respective performance standards for the heaviest and highest payloads in short wheelbase semitrailers when operated at speeds over 90 km/h (55.9 mi/h).

These combinations essentially meet these performance standards if speed is limited to 90 km/h (55.9 mi/h), and payload weight and/or height are limited in the same manner as suggested above to ensure a static roll threshold of at least 0.40 g, by restricting the payload height to no more than (say) 1.83 m (72 in) when the total payload weight on a semitrailer was more than (say) 20,411 kg (45,000 lb).

It is known that traffic moving below the legal speed limit on a freeway is a concern to some road safety authorities. However, a number of carriers voluntarily operate at around 90 km/h (55.9 mi/h) to conserve fuel. Certain other classes of vehicle, like mobile cranes, certain heavy haul vehicles, and convoys of military vehicles, also consistently operate on a freeway at a speed less than 100 km/h (62.1 mi/h).

Semitrailers that would be used to form these LCV's are usually equipped with a sliding bogie, which is adjusted as necessary to ensure that allowable drive and semitrailer axle group loads are not exceeded. The range of adjustment is limited by a maximum wheelbase of 12.50 m (492 in), and a maximum effective rear overhang of 35% of the semitrailer wheelbase, as shown in Table 1. The LCV permit conditions in Alberta allow a speed up to 100 km/h (62.1 mi/h), but limit the hitch offset to 2.8 m (110 in) [19]. This effectively restricts a 16.2 m (53 ft) lead semitrailer to its maximum wheelbase of 12.50 m (492 in), the long wheelbase considered here, and restricts a 14.65 m (48 ft) semitrailer to a wheelbase not less than about 10.92 m (430 in), which includes both long and medium wheelbases considered here. A limit on semitrailer wheelbase, whether directly imposed, or indirectly imposed through the hitch offset, would tend to restrict payload weight for a uniformly distributed load, especially for a tridem lead semitrailer. It appears preferable to use means other than a limitation on wheelbase to moderate these performance measures.

3.7.4 High-speed Offtracking

The results presented above show that high-speed offtracking of these LCV combinations exceeds the performance standard of 0.46 m (18 in) for many load cases and load levels. They come closer to meeting the performance standard in the evaluation manoeuvre if speed is limited to 90 km/h (55.9 mi/h), and payload weight and/or height are limited in the same manner as suggested above to ensure a static roll threshold of at least 0.40 g, by restricting the payload height to no more than (say) 1.83 m (72 in) when the total payload weight on a semitrailer was more than (say) 20,411 kg (45,000 lb). However, further thought suggests this performance measure is not critical if these LCV combinations are restricted to operation only on freeways and specified access routes to the freeways.

High-speed offtracking is strongly affected by curve radius. The performance measure is normally evaluated at a speed of 100 km/h (62.1 mi/h) in a curve with a radius of 393.3 m (1,290 ft), which corresponds to a lateral acceleration of 0.20 g, as described in Section 2.1.1 above. The curves for speeds of 90 and 95 km/h (55.9 and 59.0 mi/h) were set up with a radius of 318.5 m (1,045 ft) or 354.9 m (1,164 ft) respectively, so that the steady lateral acceleration in these curves was also 0.20 g. The effect of curve radius on high-speed offtracking was evaluated using other curves with a similar approach but different radii. The lowest curve radius of 30.5 m (100 ft) represents the tightest inner loop normally built at a freeway interchange. The other radii were selected arbitrarily. In each case the speed was selected so that the steady lateral acceleration in the curve was 0.20 g, except that for curves with a radius greater than 318.5 m (1,045 ft), the speed was held constant at 90 km/h (55.9 mi/h), which progressively reduced the lateral acceleration as the radius increased.

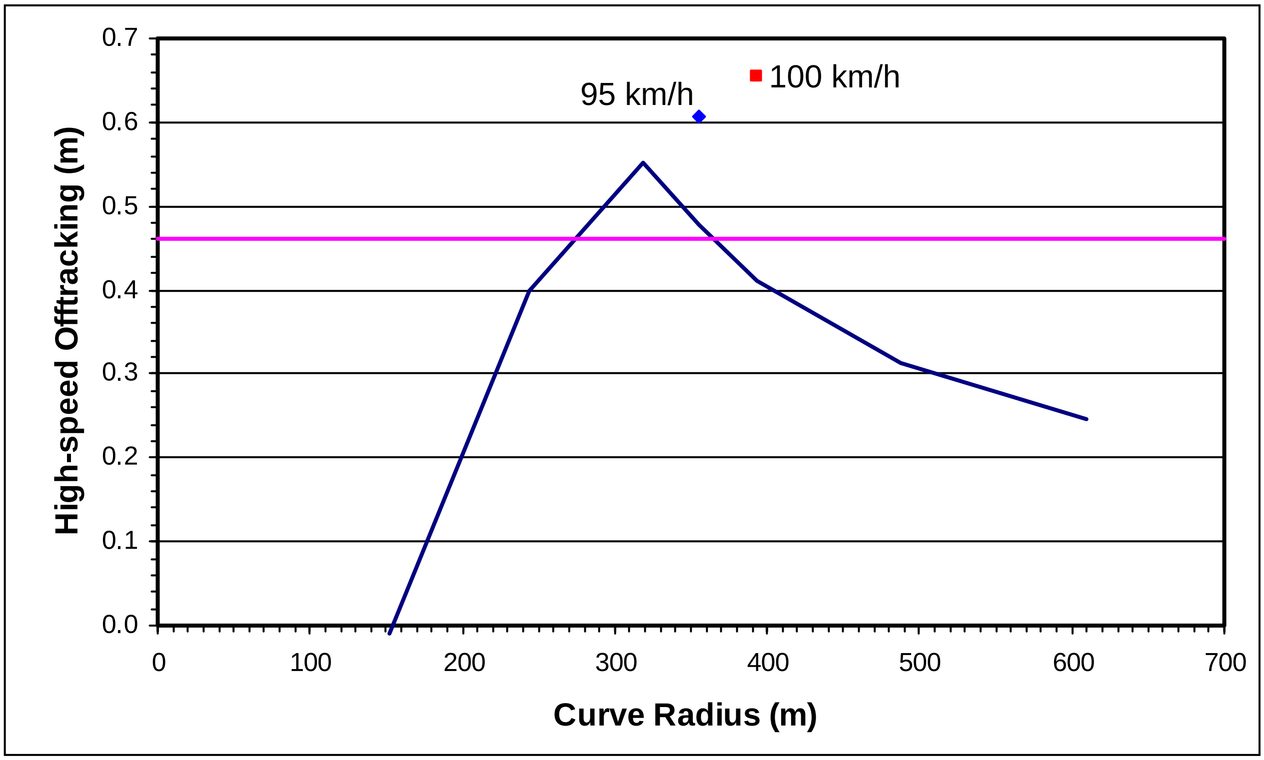
Table 28 shows the effect of curve radius on high-speed offtracking for the twin 53’ tandem semitrailers discussed in Section 3.2 with a long wheelbase, for Load Case 1 with 100% payload and a high payload height. The baseline case is the top row in Table 5, and the third row of data in Table 28. The negative value on the tightest curve indicates that offtracking would be inward. The results in Table 28 are also shown in Figure 9. The other two points shown in Figure 9 are for high-speed offtracking of this configuration at 95 and 100 km/h (59.0 and 62.1 mi/h) and a lateral acceleration of 0.20 g, from Table 5.

Figure 9 shows that high-speed offtracking with a 90 km/h (55.9 mi/h) speed limit increases up to a radius of 318.4 m (1,044 ft), then diminishes for larger curve radii. High-speed offtracking initially increases, because there is less inward offtracking to counter the outward offtracking due to lateral acceleration as the radius increases. High-speed offtracking diminishes for curve radii greater than 318.4 m (1,044 ft), because the speed is held at 90 km/h (55.9 mi/h), so the lateral acceleration is less than 0.20 g, which reduces the lateral force on the vehicle that is tending to cause high-speed offtracking. Freeways typically have a design speed of 112 to 120 km/h (70 to 75 mi/h), so main-line curves have a radius greater than 487.7 m (1,600 ft), when superelevation is considered. Figure 9 shows that high-speed offtracking should be well within the performance standard for operation at 90 km/h (55.9 mi/h) on freeways, where main-line curve radii should exceed 487.7 m (1,600 ft). It should also be well within the standard for operation on urban roads and freeway ramps, which typically have a speed limit up to 60 km/h (37.3 mi/h) and a radius less than 200 m (656 ft). The high-speed offtracking performance measure is therefore not relevant to a combination like these LCV’s if they will be restricted to operation entirely on freeways at a maximum speed well below the design speed of the highway, and on specified access routes

Table 28: Effect of Curve Radius on High-speed Offtracking at 90 km/h

Curve Radius	Speed	Lateral Acc'n (g)	HSOT (<0.46 m)
152.4 m (500 ft)	62.3 km/h (38.9 mi/h)	0.200	-0.010
243.8 m (800 ft)	78.8 km/h (48.9 mi/h)	0.200	0.400
318.4 m (1,045 ft)	90.0 km/h (55.9 mi/h)	0.200	0.552
393.3 m (1,290 ft)	90.0 km/h (55.9 mi/h)	0.162	0.410
487.7 m (1,600 ft)	90.0 km/h (55.9 mi/h)	0.131	0.313
609.6 m (2,000 ft)	90.0 km/h (55.9 mi/h)	0.105	0.245

Figure 9: Effect of Curve Radius on High-speed Offtracking at 90 km/h



between terminal or vehicle assembly locations and specified freeway intersections on roads where the speed limit does not exceed 60 km/h (37.3 mi/h). High-speed offtracking may be an issue on access routes where the speed limit is between 60 and 90 km/h (37.3 and 55.9 mi/h) and there are curves with a radius between about 250 and 400 m (820 and 1,312 ft). The performance measure is evaluated at a lateral acceleration of 0.20 g, which is above the range of about 0.07 to 0.17 g that generally results when a vehicle is driven through a curve at the legal speed limit, or an advisory speed limit posted with a yellow sign. The actual lateral acceleration of a vehicle traveling at the legal or posted advisory speed on a majority of curves would be less than 0.17 g, so a lateral acceleration of 0.20 g would represent travel at a speed that is clearly higher than the posted advisory speed. It is expected that access routes will be evaluated by trial runs with typical LCV combinations. Careful attention should be paid to any curves with a radius between about 250 and 400 m (820 and 1,312 ft). If high-speed offtracking appears to be an issue on any such curve, it may be addressed by reducing the speed of the vehicle by 10 km/h (6.2 mi/h) below the prevailing speed limit for that part of the route, or the whole route, if it is quite short.

Even though many of these configurations exceed the high-speed offtracking performance standard using the standard method of evaluation, they should be within the performance standard if they only operate on freeways at speeds up to 90 km/h (55.9 mi/h), and on approved access routes.

3.7.5 Other Issues

There are other issues that arise with a new LCV operation that need to be considered, but are beyond the direct scope of this work.

The early LCV's will probably be made up from existing semitrailers. The semitrailers used in the lead position will therefore need to be modified by addition of a pintle hook, safety cable attachments, air lines and an electrical connection to tow the dolly and pup semitrailer. Ontario Regulation 618 [19], and the New York Thruway permit conditions [21], each provide a suitable specification for design of the structure to which a pintle hook would be attached, and for safety chains. It would be appropriate for the department to require that any work to add pintle hook structure should be done in accordance with a specification like these, that the design should be done by someone with a suitable qualification, and that the modification should be done by a company qualified to modify vehicles in this manner, if not the original manufacturer. This company should be registered with Transport Canada as qualified to do this work, and should affix an Altered Vehicle compliance label to the vehicle after the work has been done. This is similar to a requirement impose by Ontario Ministry of Transportation for modification of semitrailers to meet their new regulation [4].

This work also involves adding to the airbrake system, which may affect compliance with the airbrake timing requirements of CMVSS 121 for the lead semitrailer, so the airbrake timing of modified semitrailers should be checked. The plumbing of a dolly may significantly slow the signal, resulting in slow application, and very slow release, of pup trailer brakes. The New York Thruway permit conditions address plumbing the airbrake system of the combination vehicle [21]. It would also be a very good idea to require checking the airbrake timing of typical combinations.

4. LCV'S FOR INTERNATIONAL CONTAINERS

4.1 Vehicle Configurations

These vehicles were A-train double trailer combinations from 12.19 m (40 ft) container chassis in the following configurations:

1. Twin tandem container chassis;
2. Twin tridem container chassis;
3. Tridem and tandem container chassis; and
4. Tandem and tridem container chassis.

4.1.1 Tractor and Converter Dolly

All vehicle configurations were created using the same generic tractor as described in Section 3.1.1, and the same generic converter dolly as described in Section 3.1.3.

4.1.2 Container Chassis

This work used generic tandem and tridem gooseneck container chassis designed to carry high-cube 12.19 m (40 ft) international containers, which have a height of 2.89 m (114 in).

The tandem container chassis had a kingpin setback of 0.76 m (30 in), was fitted with a tandem axle with a 1.22 m (48 in) spread, and had a wheelbase of 9.96 m (392 in). This chassis had a tare weight of 2,948 kg (6,500 lb).

The tridem container chassis had a trombone chassis with a 3.66 m (144 in) spread sliding tridem bogie. It had a kingpin setback of 0.91 m (36 in), and the bogie was set for a wheelbase of 8.74 m (344 in). This chassis had a tare weight of 4,309 kg (9,500 lb). This chassis was used because it is a lot more common than a chassis with a fixed narrow spread tridem, which has adequate capacity to carry a container loaded to a rating of at least 34,019 kg (75,000 lb).

The front edge of the pintle hook on a towing container chassis was assumed in the plane of the rear of the chassis. Each fixed axle was assumed to weigh 680 kg (1,500 lb). Moments of inertia for these semitrailers were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

4.1.3 Load Distribution

The allowable front axle weight was 5,500 kg (12,125 lb), the allowable weight on a tandem axle group was 18,000 kg (39,682 lb), and the allowable weight on a 3.66 m (144 in) spread tridem axle group was 26,000 kg (57,319 lb). The allowable gross weight for any combination was limited to 62,500 kg (137,787 lb).

A 12.19 m (40 ft) high-cube international container was assumed to weigh 3,855 kg (8,500 lb), with a load rating of 30,480 kg (67,200 lb), so the available payload was 26,655 kg (58,700 lb). There are containers of a similar size with a higher load rating. The door opening of a high-cube container is about 2.72 m (107 in) high, so the maximum payload height was assumed to be 2.59 m (102 in). An LCV that is set up to haul 12.19 m (40 ft) containers may also haul 6.10 m (20 ft) containers. A 6.10 m (20 ft) international container was assumed to weigh 2,177 kg (4,800 lb), with a load rating of 24,000 kg (52,910 lb), so the available payload was 21,822 kg (48,110 lb). There are containers of a similar size with a load rating of 30,480 kg (67,200 lb). The door opening of a 6.10 m (20 ft) container is about 2.28 m (90 in) high, so the maximum payload height was assumed to be 2.13 m (84 in). The 12.19 m (40 ft) high-cube container appears to be the critical case.

There are limited data available on the actual weights of containers [21]. These data indicate that 6.10 and 12.19 m (20 and 40 ft) containers being exported from Canada are predominantly loaded close to their weight ratings. This reflects both the resource nature of Canada's exports, and the ability of the highway and rail systems to move containers at these weights. Imported 6.10 m (20 ft) containers also tend to be loaded close to their weight rating. Imported 12.19 m (40 ft) containers tend to be more lightly loaded, which reflects the manufactured goods nature of many imports, and that the highways of many exporting countries cannot handle such a large and heavy container.

Each container was assumed loaded with a uniform distribution of freight over the entire length of the container. Table 29 shows the approximate maximum payload for each semitrailer in an LCV, whether tandem or tridem, and the approximate maximum payload as limited by the allowable gross weight of 62,500 kg (137,787 lb). The typical maximum payload for a tandem 12.19 m (40 ft) container chassis is about 27,896 kg (61,500 lb), which is slightly less than the rated load of 30,480 kg (67,200 lb) of a 12.19 m (40 ft) container. This container is intended for freight of modest density, so it is expected that this combination will be able to accommodate a majority of such containers. A tridem container chassis has a payload capacity of at least 34,109 kg (75,000 lb), so can easily take the most heavily loaded standard container, and also other 12.19 m (40 ft) containers with a higher rated load.

Table 29: Payload Capacity of LCV Container Chassis

Lead Semitrailer	Pup Semitrailer	Maximum Payload Weight (lb)		
		Lead	Pup	Combined
Tandem	Tandem	61,500	40,500	102,000
Tridem	Tandem	75,000	23,000	98,000
Tandem	Tridem	61,500	36,500	98,000
Tridem	Tridem	75,000	24,000	95,000

Four load cases were considered for a combination with a tandem axle lead semitrailer. The first load case used the maximum payload capacity on the lead semitrailer, as given in Table 29, with the balance of the payload weight on the rear semitrailer. The second load case used half the maximum combined payload on each semitrailer. The third load case used the maximum payload capacity on the lead semitrailer, with the rear semitrailer empty. Both semitrailers were empty for the fourth load case. A fifth load case was considered for a combination with a tridem axle lead semitrailer, with a 12.19 m (40 ft) container loaded to its typical rating of 30,480 kg (67,200 lb) on the lead semitrailer, and the balance of the payload weight on the rear semitrailer.

4.2 Twin 40' Tandem Container Chassis

4.2.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 10. Table 30 shows the load cases considered. "Empty" means the trailer is carrying a container that is empty, which amounts to a payload of 3,855 kg (8,500 lb).

Figure 10: Twin Tandem 40' Container Chassis

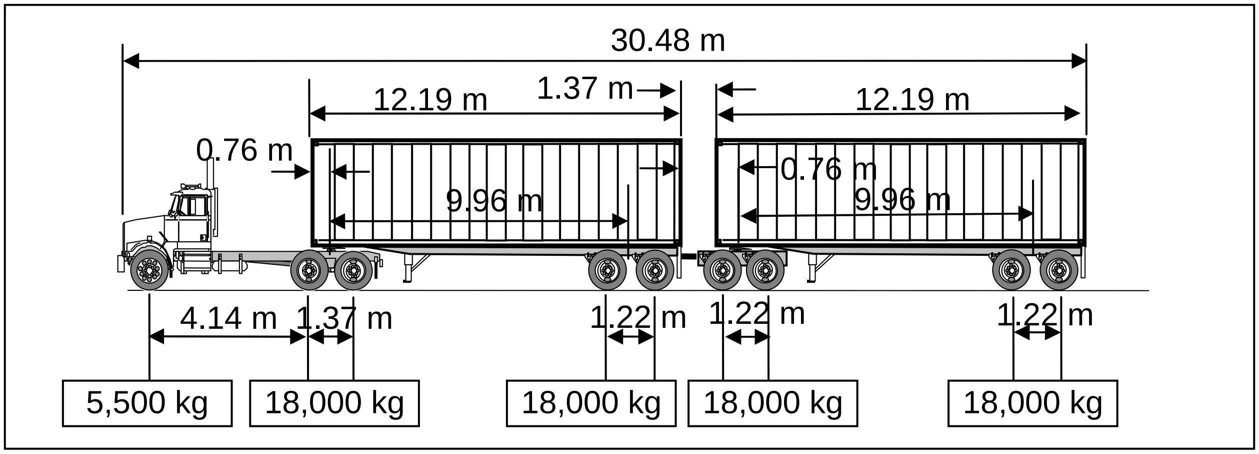


Table 30: Payload Weights for Twin 40' Tandem Container Chassis

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	61,500	40,500	102,000
2	51,000	51,000	102,000
3	61,500	Empty	70,000
4	Empty	Empty	17,000

4.2.2 Results

Table 31 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Values that do not meet the performance standard of 0.35 g are highlighted in bold face. The tractor-semitrailer rolls over first in all cases. The static roll threshold for these vehicles, and current tractor-semitrailers with a tandem semitrailer carrying a high-cube container loaded to close to the payload capacity of the trailer and close to full, are between 0.30 and 0.35 g.

Table 31: Roll Thresholds for Twin Tandem 40' Container Chassis

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	61,500	40,500	102,000	**0.337**	0.385	0.448
1	75%	48,250	32,500	80,750	0.364	0.409	0.473
1	50%	35,000	24,500	59,500	0.403	0.448	0.493
2	100%	51,000	51,000	102,000	0.355	0.403	0.465
2	75%	40,375	40,375	80,750	0.384	0.428	0.485
2	50%	29,750	29,750	59,500	0.423	0.465	0.505
3	100%	61,500	8,500	70,000	**0.338**	0.387	0.445
3	75%	48,250	8,500	56,750	0.361	0.409	0.469
3	50%	35,000	8,500	43,500	0.403	0.447	0.496
4	0%	8,500	8,500	17,000	0.580		

Table 32 shows the high-speed offtracking, load transfer ratio and transient offtracking for all conditions of Load Cases 1, 2, and 3 and 4, respectively. Load level is the percentage of the nominal load as given in Table 30. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in) within the container, **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with payload weight, payload height, and vehicle speed.

The low-speed offtracking was about 6.91 m (272 in), with no significant rear outswing. While the offtracking exceeds the performance standard, it is not an issue because any permit will only allow such vehicles to go where they can make turns. Friction demand was about 0.02, which is typical for a tandem semitrailer.

Table 32: High-speed Performance Measures for Twin Tandem 40' Container Chassis

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.644**	**0.678**	**0.706**	**0.842**	**0.872**	**0.897**	**0.969**	**1.087**	**1.192**
1/100%	M	**0.596**	**0.630**	**0.663**	**0.720**	**0.777**	**0.834**	**0.846**	**0.969**	**1.086**
1/100%	L	**0.556**	**0.589**	**0.623**	**0.606**	**0.658**	**0.710**	0.745	**0.853**	**0.968**
1/ 75%	H	**0.536**	**0.570**	**0.604**	**0.730**	**0.793**	**0.856**	0.762	**0.872**	**0.976**
1/ 75%	M	**0.505**	**0.541**	**0.574**	**0.634**	**0.684**	**0.733**	0.683	0.790	**0.894**
1/ 75%	L	**0.479**	**0.515**	**0.548**	0.544	0.592	**0.634**	0.623	0.724	**0.817**
1/ 50%	H	0.457	**0.492**	**0.525**	**0.601**	**0.652**	**0.700**	0.589	0.685	0.776
1/ 50%	M	0.440	**0.476**	**0.509**	0.541	0.588	**0.632**	0.550	0.639	0.733
1/ 50%	L	0.425	0.458	**0.493**	0.482	0.524	0.565	0.515	0.600	0.692
2/100%	H	**0.611**	**0.644**	**0.673**	**0.848**	**0.870**	**0.926**	**0.968**	**1.081**	**1.198**
2/100%	M	**0.567**	**0.601**	**0.634**	**0.745**	**0.801**	**0.848**	**0.841**	**0.967**	**1.089**
2/100%	L	**0.531**	**0.567**	**0.600**	**0.618**	**0.668**	**0.717**	0.731	**0.846**	**0.962**
2/ 75%	H	**0.525**	**0.559**	**0.592**	**0.771**	**0.829**	**0.866**	0.749	**0.859**	**0.967**
2/ 75%	M	**0.499**	**0.535**	**0.568**	**0.662**	**0.717**	**0.770**	0.670	0.781	**0.885**
2/ 75%	L	**0.478**	**0.513**	**0.546**	0.563	**0.609**	**0.654**	0.614	0.713	**0.808**
2/ 50%	H	0.456	**0.491**	**0.524**	**0.635**	**0.688**	**0.739**	0.579	0.674	0.767
2/ 50%	M	0.439	**0.474**	**0.507**	0.562	**0.612**	**0.657**	0.538	0.626	0.721
2/ 50%	L	0.423	0.457	**0.491**	0.493	0.536	0.579	0.503	0.589	0.679
3/100%	H	**0.545**	**0.579**	**0.613**	**0.661**	**0.693**	**0.711**	**0.746**	**0.849**	**0.944**
3/100%	M	**0.508**	**0.543**	**0.576**	0.557	0.577	0.598	0.674	0.767	**0.867**
3/100%	L	**0.479**	**0.513**	**0.547**	0.467	0.487	0.507	0.606	0.704	0.796
3/ 75%	H	0.459	**0.493**	**0.527**	0.596	**0.620**	**0.642**	0.609	0.704	0.795
3/ 75%	M	0.438	**0.473**	**0.507**	0.512	0.534	0.556	0.562	0.653	0.736
3/ 75%	L	0.420	0.454	**0.489**	0.443	0.460	0.478	0.528	0.611	0.696
3/ 50%	H	0.404	0.439	**0.472**	0.507	0.527	0.546	0.498	0.575	0.659
3/ 50%	M	0.393	0.427	**0.462**	0.452	0.471	0.488	0.474	0.552	0.634
3/ 50%	L	0.383	0.418	0.452	0.400	0.418	0.451	0.454	0.532	0.611
4/ 0%	H	0.308	0.342	0.376	0.346	0.376	0.407	0.329	0.397	0.463

4.3 Twin 40' Tridem Container Chassis

4.3.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 11. Table 33 shows the load cases considered. "Empty" means the trailer is carrying a container that is empty, which amounts to a payload of 3,855 kg (8,500 lb).

Figure 11: Twin Tridem 40' Container Chassis

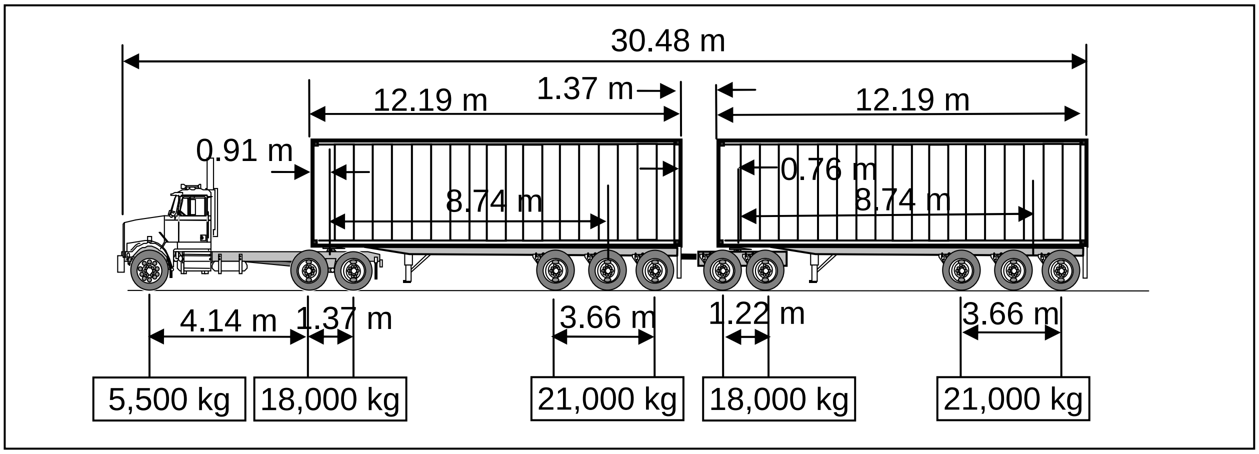


Table 33: Payload Weights for Twin 40' Tridem Container Chassis

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	75,000	21,000	96,000
2	67,200	28,800	96,000
3	48,000	48,000	96,000
4	67,200	Empty	75,700
5	Empty	Empty	17,000

4.3.2 Results

Table 34 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Values that do not meet the performance standard of 0.35 g are highlighted in bold face. The tractor-semitrailer rolls over first in all cases. The static roll threshold for these vehicles, and current tractor-semitrailers with a tridem semitrailer carrying a high-cube container loaded to close to its rating and close to full, are between 0.30 and 0.35 g.

Table 35 show the high-speed offtracking, load transfer ratio and transient offtracking for all conditions of Load Cases 1, 2, 3, and 4 and 5, respectively. Load level is the percentage of the nominal load as given in Table 33. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in) within the container, **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with payload weight, payload height, and vehicle speed.

The low-speed offtracking was about 5.83 m (230 in), with no significant rear outswing. While the offtracking exceeds the performance standard, it is not an issue because any permit will only allow such vehicles to go where they can make turns. Friction demand was about 0.15 to 0.18, which is typical for a tridem semitrailer.

Table 34: Roll Thresholds for Twin Tridem 40' Container Chassis

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	75,000	21,000	96,000	**0.343**	0.391	0.449
1	75%	58,375	17,875	76,250	0.367	0.414	0.474
1	50%	41,750	14,750	56,500	0.405	0.450	0.503
2	100%	67,200	28,800	96,000	0.354	0.400	0.461
2	75%	52,525	23,725	76,250	0.377	0.424	0.486
2	50%	37,850	18,650	56,500	0.418	0.464	0.510
3	100%	48,000	48,000	96,000	0.388	0.435	0.493
3	75%	38,125	38,125	76,250	0.416	0.463	0.508
3	50%	28,250	28,250	56,500	0.463	0.502	0.539
4	100%	67,200	8,500	75,700	0.355	0.399	0.458
4	75%	52,525	8,500	61,025	0.377	0.423	0.485
4	50%	37,850	8,500	46,350	0.418	0.463	0.510
5	0%	8,500	8,500	17,000	0.609		

Table 35: High-speed Performance Measures for Twin Tridem 40' Container Chassis

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.621**	**0.643**	**0.668**	**0.701**	**0.755**	**0.798**	**1.014**	**1.128**	**1.239**
1/100%	M	**0.586**	**0.608**	**0.633**	**0.634**	**0.686**	**0.737**	**0.928**	**1.042**	**1.150**
1/100%	L	**0.555**	**0.581**	**0.604**	0.569	**0.618**	**0.665**	**0.846**	**0.959**	**1.070**
1/ 75%	H	**0.537**	**0.563**	**0.586**	**0.635**	**0.676**	**0.727**	**0.847**	**0.953**	**1.061**
1/ 75%	M	**0.518**	**0.544**	**0.567**	0.571	**0.620**	**0.670**	0.786	**0.896**	**0.997**
1/ 75%	L	**0.501**	**0.527**	**0.553**	0.526	0.569	**0.614**	0.742	**0.842**	**0.941**
1/ 50%	H	**0.485**	**0.511**	**0.536**	0.545	0.590	**0.633**	0.705	**0.800**	**0.898**
1/ 50%	M	**0.473**	**0.498**	**0.524**	0.510	0.553	0.594	0.672	0.764	**0.862**
1/ 50%	L	**0.462**	**0.487**	**0.513**	0.477	0.516	0.559	0.640	0.734	**0.827**
2/100%	H	**0.602**	**0.625**	**0.650**	**0.769**	**0.833**	**0.889**	**0.994**	**1.115**	**1.228**
2/100%	M	**0.572**	**0.595**	**0.620**	**0.681**	**0.738**	**0.793**	**0.910**	**1.022**	**1.139**
2/100%	L	**0.545**	**0.571**	**0.595**	0.594	**0.646**	**0.697**	**0.831**	**0.947**	**1.056**
2/ 75%	H	**0.540**	**0.566**	**0.589**	0.680	**0.737**	**0.791**	**0.841**	**0.953**	**1.061**
2/ 75%	M	**0.521**	**0.547**	**0.571**	0.610	**0.662**	**0.715**	0.789	**0.896**	**0.996**
2/ 75%	L	**0.504**	**0.530**	**0.556**	0.550	0.596	**0.643**	0.743	**0.844**	**0.945**
2/ 50%	H	**0.485**	**0.510**	**0.535**	0.584	**0.632**	**0.680**	0.700	0.796	**0.897**
2/ 50%	M	**0.472**	**0.498**	**0.523**	0.538	0.581	**0.627**	0.665	0.760	**0.858**
2/ 50%	L	**0.461**	**0.486**	**0.511**	0.495	0.537	0.580	0.633	0.728	**0.822**
3/100%	H	**0.586**	**0.610**	**0.635**	**0.867**	**0.894**	**0.915**	**0.971**	**1.082**	**1.186**
3/100%	M	**0.561**	**0.587**	**0.611**	**0.763**	**0.826**	**0.879**	**0.886**	**1.008**	**1.129**
3/100%	L	**0.539**	**0.564**	**0.588**	**0.646**	**0.703**	**0.761**	**0.818**	**0.930**	**1.035**
3/ 75%	H	**0.536**	**0.562**	**0.586**	**0.773**	**0.839**	**0.888**	**0.824**	**0.939**	**1.043**
3/ 75%	M	**0.518**	**0.543**	**0.567**	**0.676**	**0.733**	**0.792**	0.770	**0.876**	**0.980**
3/ 75%	L	**0.501**	**0.526**	**0.551**	0.586	**0.634**	**0.685**	0.719	**0.817**	**0.924**
3/ 50%	H	**0.484**	**0.510**	**0.533**	**0.653**	**0.707**	**0.763**	0.686	0.784	**0.886**
3/ 50%	M	**0.472**	**0.497**	**0.522**	0.586	**0.636**	**0.685**	0.650	0.747	**0.845**
3/ 50%	L	**0.460**	**0.486**	**0.511**	0.525	0.569	**0.614**	0.617	0.714	**0.806**
4/100%	H	**0.553**	**0.579**	**0.604**	**0.668**	**0.697**	**0.716**	**0.872**	**0.977**	**1.074**
4/100%	M	**0.531**	**0.557**	**0.580**	0.572	0.597	**0.621**	**0.803**	**0.909**	**1.012**
4/100%	L	**0.511**	**0.536**	**0.560**	0.485	0.506	0.551	0.752	**0.853**	**0.947**
4/ 75%	H	**0.506**	**0.530**	**0.555**	**0.602**	**0.630**	**0.658**	0.752	**0.854**	**0.947**
4/ 75%	M	**0.492**	**0.518**	**0.543**	0.523	0.546	0.571	0.716	**0.812**	**0.905**
4/ 75%	L	**0.479**	**0.506**	**0.531**	0.452	0.485	0.512	0.686	0.775	**0.871**

4/ 50%	H	**0.466**	**0.492**	**0.515**	0.515	0.538	0.560	0.649	0.737	**0.831**
4/ 50%	M	0.457	**0.482**	**0.506**	0.459	0.481	0.502	0.624	0.713	**0.804**
4/ 50%	L	0.448	**0.473**	**0.499**	0.423	0.460	0.500	0.601	0.692	0.778
5/ 0%	H	0.383	0.409	0.434	0.384	0.420	0.450	0.467	0.540	0.617

4.4 Tridem and Tandem 40’ Container Chassis

4.4.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 12. Table 36 shows the load cases considered. ”Empty” means the trailer is carrying a container that is empty, which amounts to a payload of 3,855 kg (8,500 lb).

Figure 12: Tridem and Tandem 40’ Container Chassis

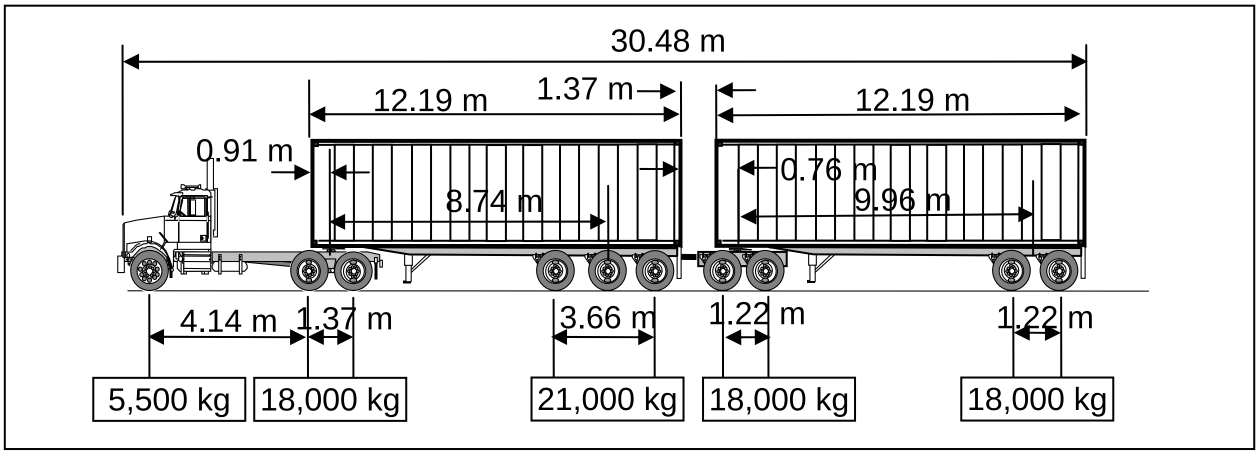


Table 36: Payload Weights for Tridem and Tandem 40’ Tridem Container Chassis

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	75,000	24,000	99,000
2	67,200	31,800	99,000
3	49,500	49,500	99,000
4	67,200	Empty	75,700
5	Empty	Empty	17,000

4.4.2 Results

Table 37 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Values that do not meet the performance standard of 0.35 g are highlighted in bold face. The tractor-semitrailer rolls over first in all cases. The static roll threshold for these vehicles, and current tractor-semitrailers with a tridem semitrailer carrying a high-cube container loaded to close to its rating and close to full, are between 0.30 and 0.35 g.

Table 38 show the high-speed offtracking, load transfer ratio and transient offtracking for all conditions of Load Cases 1, 2, 3, and 4 and 5, respectively. Load level is the percentage of the nominal load as given in Table 36. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in) within the container, **M** to a payload height of 1.83 m (72 in) and **L** to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with payload weight, payload height, and vehicle speed.

The low-speed offtracking was about 6.33 m (249 in), with no significant rear outswing. While the offtracking exceeds the performance standard, it is not an issue because any permit will only allow such vehicles to go where they can make turns. Friction demand was about 0.15 to 0.18, which is typical for a tridem semitrailer.

Table 37: Roll Thresholds for Tridem and Tandem 40' Container Chassis

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	75,000	24,000	99,000	**0.342**	0.390	0.447
1	75%	58,375	20,125	78,500	0.367	0.413	0.474
1	50%	41,750	16,250	58,000	0.404	0.451	0.503
2	100%	67,200	31,800	99,000	0.353	0.403	0.460
2	75%	52,525	25,975	78,500	0.377	0.424	0.486
2	50%	37,850	20,150	58,000	0.419	0.463	0.511
3	100%	49,500	49,500	99,000	0.382	0.430	0.491
3	75%	39,250	39,250	78,500	0.411	0.457	0.506
3	50%	29,000	29,000	58,000	0.458	0.498	0.538
4	100%	67,200	8,500	75,700	0.354	0.400	0.459
4	75%	52,525	8,500	61,025	0.377	0.425	0.484
4	50%	37,850	8,500	46,350	0.418	0.463	0.510
5	0%	8,500	8,500	17,000	0.610		

Table 38: High-speed Performance Measures for Tridem and Tandem 40' Container Chassis

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.607**	**0.633**	**0.662**	**0.762**	**0.814**	**0.870**	**0.968**	**1.083**	**1.197**
1/100%	M	**0.570**	**0.597**	**0.625**	**0.674**	**0.729**	**0.780**	**0.875**	**0.992**	**1.102**
1/100%	L	**0.537**	**0.567**	**0.594**	0.593	**0.642**	**0.689**	0.792	**0.903**	**1.016**
1/ 75%	H	**0.520**	**0.550**	**0.577**	**0.674**	**0.729**	**0.782**	0.798	**0.903**	**1.013**
1/ 75%	M	**0.500**	**0.530**	**0.559**	**0.603**	**0.655**	**0.707**	0.732	**0.842**	**0.946**
1/ 75%	L	**0.482**	**0.512**	**0.541**	0.546	0.591	**0.635**	0.685	0.786	**0.883**
1/ 50%	H	**0.462**	**0.492**	**0.521**	0.576	**0.625**	**0.671**	0.650	0.747	**0.842**
1/ 50%	M	0.449	**0.479**	**0.507**	0.533	0.576	**0.620**	0.616	0.707	**0.805**
1/ 50%	L	0.435	**0.466**	**0.495**	0.494	0.536	0.576	0.584	0.674	0.769
2/100%	H	**0.591**	**0.618**	**0.646**	**0.831**	**0.885**	**0.916**	**0.951**	**1.072**	**1.183**
2/100%	M	**0.557**	**0.587**	**0.614**	**0.719**	**0.779**	**0.844**	**0.861**	**0.977**	**1.090**
2/100%	L	**0.529**	**0.559**	**0.586**	**0.621**	**0.671**	**0.722**	0.778	**0.892**	**1.003**
2/ 75%	H	**0.525**	**0.555**	**0.582**	**0.724**	**0.783**	**0.848**	0.795	**0.904**	**1.016**
2/ 75%	M	**0.504**	**0.534**	**0.563**	**0.643**	**0.695**	**0.745**	0.735	**0.845**	**0.947**
2/ 75%	L	**0.485**	**0.515**	**0.544**	0.571	**0.617**	**0.663**	0.687	0.789	**0.888**
2/ 50%	H	**0.466**	**0.495**	**0.525**	**0.616**	**0.667**	**0.717**	0.650	0.747	**0.845**
2/ 50%	M	0.452	**0.482**	**0.511**	0.560	**0.606**	**0.652**	0.613	0.705	**0.805**
2/ 50%	L	0.438	**0.469**	**0.497**	0.510	0.555	0.596	0.580	0.672	0.766
3/100%	H	**0.588**	**0.616**	**0.644**	**0.866**	**0.907**	**0.969**	**0.989**	**1.104**	**1.228**
3/100%	M	**0.557**	**0.587**	**0.614**	**0.789**	**0.840**	**0.890**	**0.894**	**1.018**	**1.140**
3/100%	L	**0.531**	**0.561**	**0.590**	**0.663**	**0.717**	**0.767**	0.790	**0.914**	**1.031**
3/ 75%	H	**0.527**	**0.556**	**0.583**	**0.822**	**0.864**	**0.895**	0.803	**0.916**	**1.020**
3/ 75%	M	**0.506**	**0.535**	**0.564**	**0.707**	**0.766**	**0.823**	0.729	**0.842**	**0.949**
3/ 75%	L	**0.486**	**0.516**	**0.545**	**0.605**	**0.655**	**0.708**	0.673	0.774	**0.878**
3/ 50%	H	**0.469**	**0.498**	**0.527**	**0.684**	**0.740**	**0.804**	0.644	0.742	**0.843**
3/ 50%	M	0.455	**0.484**	**0.513**	**0.608**	**0.659**	**0.705**	0.604	0.698	0.797
3/ 50%	L	0.440	**0.470**	**0.499**	0.538	0.584	**0.628**	0.568	0.662	0.755
4/100%	H	**0.518**	**0.545**	**0.574**	**0.668**	**0.697**	**0.716**	0.787	**0.889**	**0.987**
4/100%	M	**0.493**	**0.523**	**0.550**	0.572	0.597	**0.620**	0.718	**0.822**	**0.923**
4/100%	L	**0.473**	**0.503**	**0.532**	0.485	0.514	0.547	0.668	0.766	**0.858**
4/ 75%	H	**0.468**	**0.498**	**0.528**	**0.602**	**0.630**	**0.657**	0.669	0.768	**0.860**
4/ 75%	M	0.454	**0.485**	**0.514**	0.523	0.546	0.571	0.635	0.727	**0.818**
4/ 75%	L	0.441	**0.472**	**0.500**	0.453	0.493	0.528	0.605	0.692	0.785

4/ 50%	H	0.428	0.458	**0.487**	0.515	0.538	0.559	0.572	0.657	0.747
4/ 50%	M	0.418	0.449	**0.478**	0.460	0.481	0.511	0.549	0.634	0.721
4/ 50%	L	0.409	0.440	**0.468**	0.430	0.462	0.504	0.529	0.613	0.697
5/ 0%	H	0.344	0.375	0.404	0.388	0.422	0.453	0.402	0.474	0.546

4.5 Tandem and Tridem 40' Container Chassis

4.5.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 13. Table 39 shows the load cases considered. "Empty" means the trailer is carrying a container that is empty, which amounts to a payload of 3,855 kg (8,500 lb).

Figure 13: Tandem and Tridem 40' Container Chassis

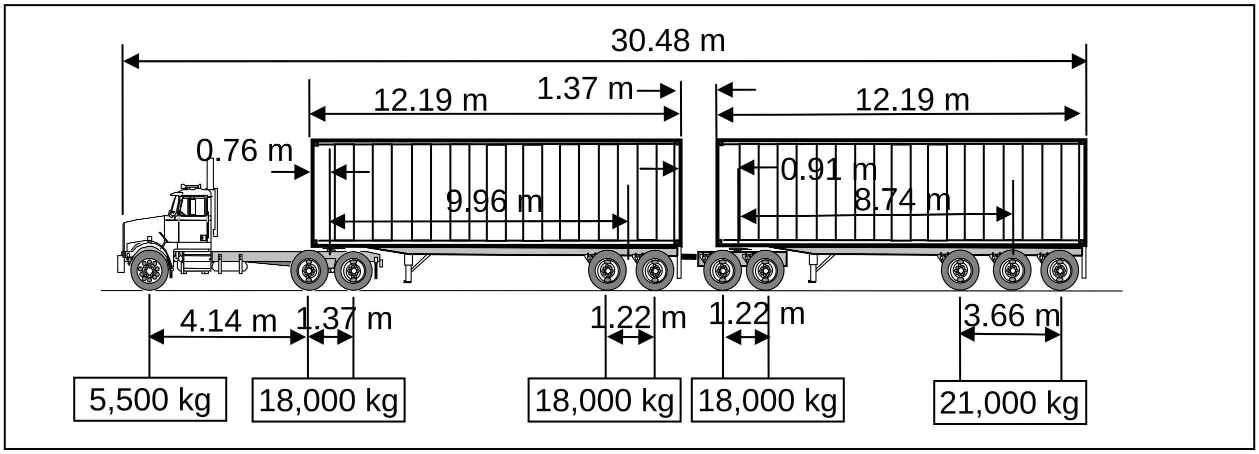


Table 39: Payload Weights for Tandem and Tridem 40' Tridem Container Chassis

Load Case	Lead Semitrailer	Pup Semitrailer	Gross Payload (lb)
1	61,500	37,500	99,000
2	49,500	49,500	99,000
3	61,500	Empty	70,000
4	Empty	Empty	17,000

4.5.2 Results

Table 40 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Values that do not meet the performance standard of 0.35 g are highlighted in bold face. The tractor-semitrailer rolls over first in all cases. The static roll threshold for these vehicles, and current tractor-semitrailers with a tandem semitrailer carrying a high-cube container loaded to close to its rating and close to full, are between 0.30 and 0.35 g.

Table 41 show the high-speed offtracking, load transfer ratio and transient offtracking for all conditions of Load Cases 1, 2, 3, and 4 and 5, respectively. Load level is the percentage of the nominal load as given in Table 39. CG is the payload height; H corresponds to a payload height of 2.44 m (96 in) within the container, M to a payload height of 1.83 m (72 in) and L to a payload height of 1.22 m (48 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with payload weight, payload height, and vehicle speed.

The low-speed offtracking was about 6.45 m (254 in), with no significant rear outswing. While the offtracking exceeds the performance standard, it is not an issue because any permit will only allow such vehicles to go where they can make turns. Friction demand was about 0.02, which is typical for a tandem semitrailer.

Table 40: Roll Thresholds for Tandem and Tridem 40' Container Chassis

Load Case	Payload Level	Lead Payload (lb)	Pup Payload (lb)	Total Payload (lb)	Roll Threshold (>0.35 g)		
					Payload Height (m)		
					2.44 m	1.83 m	1.22 m
1	100%	61,500	37,500	99,000	**0.339**	0.385	0.448
1	75%	48,250	30,250	78,500	0.364	0.411	0.474
1	50%	35,000	23,000	58,000	0.403	0.448	0.496
2	100%	49,500	49,500	99,000	0.359	0.407	0.468
2	75%	48,250	30,250	78,500	0.387	0.433	0.489
2	50%	35,000	23,000	58,000	0.428	0.469	0.508
3	100%	61,500	8,500	70,000	**0.339**	0.387	0.445
3	75%	39,250	39,250	78,500	0.362	0.410	0.470
3	50%	29,000	29,000	58,000	0.403	0.449	0.495
4	100%	8,500	8,500	17,000	0.581		

Table 41: High-speed Performance Measures for Tandem and Tridem 40' Tridem Container Chassis

Load Case/ Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h	90 km/h	95 km/h	100 km/h
1/100%	H	**0.652**	**0.682**	**0.707**	**0.784**	**0.845**	**0.884**	**0.986**	**1.101**	**1.210**
1/100%	M	**0.607**	**0.636**	**0.666**	**0.681**	**0.733**	**0.790**	**0.883**	**0.998**	**1.106**
1/100%	L	**0.568**	**0.598**	**0.628**	0.582	**0.630**	**0.680**	0.788	**0.898**	**1.009**
1/ 75%	H	**0.549**	**0.579**	**0.608**	**0.686**	**0.740**	**0.797**	**0.800**	**0.905**	**1.014**
1/ 75%	M	**0.522**	**0.552**	**0.582**	**0.601**	**0.651**	**0.700**	0.725	**0.834**	**0.935**
1/ 75%	L	**0.497**	**0.528**	**0.558**	0.526	0.570	**0.614**	0.671	0.770	**0.866**
1/ 50%	H	**0.474**	**0.505**	**0.535**	0.570	**0.617**	**0.664**	0.632	0.725	**0.819**
1/ 50%	M	**0.460**	**0.490**	**0.520**	0.518	0.561	**0.603**	0.594	0.683	0.778
1/ 50%	L	0.445	**0.475**	**0.506**	0.470	0.510	0.550	0.560	0.649	0.739
2/100%	H	**0.599**	**0.629**	**0.656**	**0.833**	**0.873**	**0.890**	**0.927**	**1.045**	**1.152**
2/100%	M	**0.566**	**0.595**	**0.625**	**0.714**	**0.774**	**0.831**	**0.826**	**0.939**	**1.057**
2/100%	L	**0.537**	**0.567**	**0.596**	**0.601**	**0.652**	**0.706**	0.746	**0.856**	**0.960**
2/ 75%	H	**0.532**	**0.562**	**0.592**	**0.721**	**0.784**	**0.843**	0.760	**0.871**	**0.977**
2/ 75%	M	**0.511**	**0.541**	**0.571**	**0.632**	**0.683**	**0.734**	0.704	**0.808**	**0.904**
2/ 75%	L	**0.490**	**0.521**	**0.551**	0.545	0.591	**0.635**	0.652	0.748	**0.848**
2/ 50%	H	**0.470**	**0.501**	**0.531**	**0.603**	**0.654**	**0.705**	0.613	0.706	**0.804**
2/ 50%	M	0.456	**0.487**	**0.517**	0.540	0.587	**0.632**	0.576	0.667	0.760
2/ 50%	L	0.442	**0.473**	**0.503**	0.480	0.522	0.563	0.543	0.632	0.721
3/100%	H	**0.583**	**0.613**	**0.643**	**0.661**	**0.693**	**0.711**	**0.822**	**0.926**	**1.021**
3/100%	M	**0.547**	**0.577**	**0.607**	0.557	0.578	0.598	0.748	**0.844**	**0.945**
3/100%	L	**0.517**	**0.547**	**0.578**	0.468	0.487	0.506	0.680	0.780	**0.874**
3/ 75%	H	**0.497**	**0.528**	**0.557**	0.596	**0.620**	**0.642**	0.681	0.780	**0.872**
3/ 75%	M	**0.477**	**0.507**	**0.536**	0.512	0.534	0.556	0.634	0.726	**0.812**
3/ 75%	L	0.459	**0.490**	**0.519**	0.442	0.460	0.476	0.597	0.681	0.772
3/ 50%	H	0.442	**0.473**	**0.503**	0.507	0.527	0.546	0.563	0.645	0.732
3/ 50%	M	0.431	**0.463**	**0.493**	0.451	0.470	0.488	0.538	0.621	0.703
3/ 50%	L	0.422	0.452	**0.482**	0.399	0.416	0.447	0.516	0.598	0.680
4/ 0%	H	0.347	0.376	0.406	0.347	0.375	0.404	0.385	0.453	0.523

4.6 Discussion

In general, the same points made in Section 3.7 above for van LCV's for general freight also apply to these container LCV's.

The static roll threshold for tractor-semitrailers carrying a high-cube container loaded to its rating with a high payload is poor. The tractor and lead semitrailer in these combinations is the same vehicle, and it has the same poor static roll threshold. Most configurations exceed the high-speed offtracking performance standard, by up to 0.25 m (10 in), depending on the load case, payload height and speed. This should not be an issue for permit operation on freeways and access routes, as discussed in Section 3.7.4. All configurations exceed the load transfer ratio and transient offtracking performance standards, even with a moderate payload height, and at 90 km/h (55.9 mi/h), the lowest speed considered.

LCV's that carry general freight will generally operate with both trailers loaded. However, it is not uncommon for an empty container to be moved between a yard or receiver and a shipper, or a receiver and a yard or shipper. There is no apparent problem with any of the dynamic performance measures when the rearmost semitrailer carries an empty container, or no container, or both semitrailers carry an empty container, or no container.

5. SELF-STEER QUAD SEMITRAILER FOR GENERAL FREIGHT

5.1 Principles for Configuration of "Infrastructure-friendly" Vehicles

Québec developed the self-steer quad semitrailer, where the self-steering axle carries the same load as each fixed axle of the tridem axle group. Ontario has generalized this concept to a defined class of "safe, productive and infrastructure-friendly" (SPIF) vehicles [4]. SPIF vehicles are configured to the following principles:

1. The load carried by all axles on a semitrailer must be shared equally among those axles when the semitrailer is operated in Ontario;
2. The axles of a self-steer quad semitrailer must have a device that allows the load on those axles to be determined;
3. Self-steering axles may be used in Ontario, provided they have sufficient steer capability for their location on the semitrailer;
4. A semitrailer must have more fixed axles than self-steering axles;
5. A self-steering axle may be fitted with single or dual tires;
6. A self-steering axle may be liftable, but any lift or axle load dump control must not be accessible to a driver in the cab;
7. A self-steering axle may lift automatically only when the driver reverses the vehicle, and any automatic lift device must sense reverse motion of its wheels, and not the gear selected or the backup light;
8. Rigid "invisible" liftable axles may be fitted for use in another jurisdiction, as long as they are always raised in Ontario; and
9. Load equalization may be disabled for operation in other jurisdictions.

5.2 Vehicle Configurations

5.2.1 Tractor

This work used a generic tandem drive tractor with a 6.20 m (244 in) wheelbase, a tandem drive axle with a spread of 1.37 m (54 in), and a fifth wheel placed 0.25 m (10 in) forward of the centre of the drive tandem. The tractor had a tare weight of 8,164 kg (18,000 lb). The front axle was assumed to weigh 544 kg (1,200 lb), with a rating of at least 5,500 kg (12,125 lb), and a tare load of 4,536 kg (10,500 lb). Each drive axle was assumed to weigh 1,134 kg (2,500 lb). Moments of inertia were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

5.2.2 Semitrailers

This work used generic 14.65 and 16.2 m (48 and 53 ft) van semitrailers. Figure 14 shows the dimensions for a typical self-steer quad semitrailer van with a 14.65 m (48 ft) length, and Figure 15 shows the same vehicle in a 16.20 m (53 ft) length. The symbol **S** indicates the liftable self-steering axle on an air suspension placed 2.54 m (100 in) ahead of a fixed tridem axle group with a 3.66 m (144 in) spread, also on an air suspension, so that the load was equalized between the four axles on the semitrailer. These vehicles are assumed to be compatible with Ontario and Québec rules. A variety of other quad-axle arrangements have previously been examined [15]. A closer spread tridem reduces the allowable gross weight if the vehicle will operate into Ontario or Québec, or reduces the value if it will subsequently be sold there. A greater offset of the self-steering axle simply increases the self-steer angle in turns, which increases the likelihood of bottoming the steer in a tight turn, and also increases the resistance to turning. There is therefore no apparent benefit to any other self-steer quad axle arrangement. The kingpin setback was 0.61 m (24 in) for each semitrailer, and the quad-axle group was set so that a vehicle loaded to its allowable gross weight with a uniformly distributed load was within all allowable axle group loads, which resulted in a wheelbase of 12.40 m (488 in) for a 16.20 m (53 ft) semitrailer, and 11.18 m (440 in) for a 14.65 m (48 ft) semitrailer.

Figure 14: 48' Self-steer Quad Van

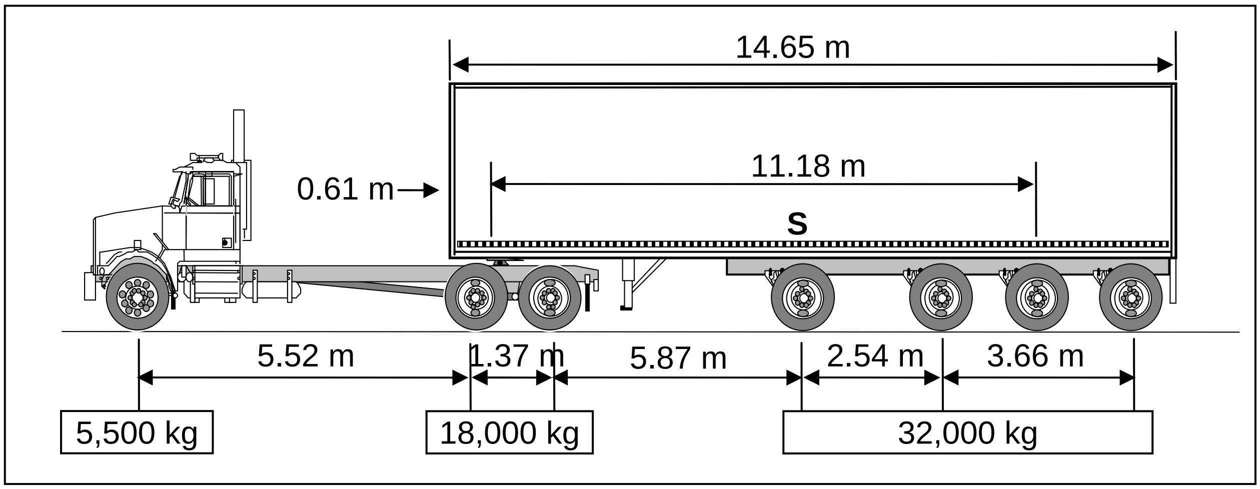
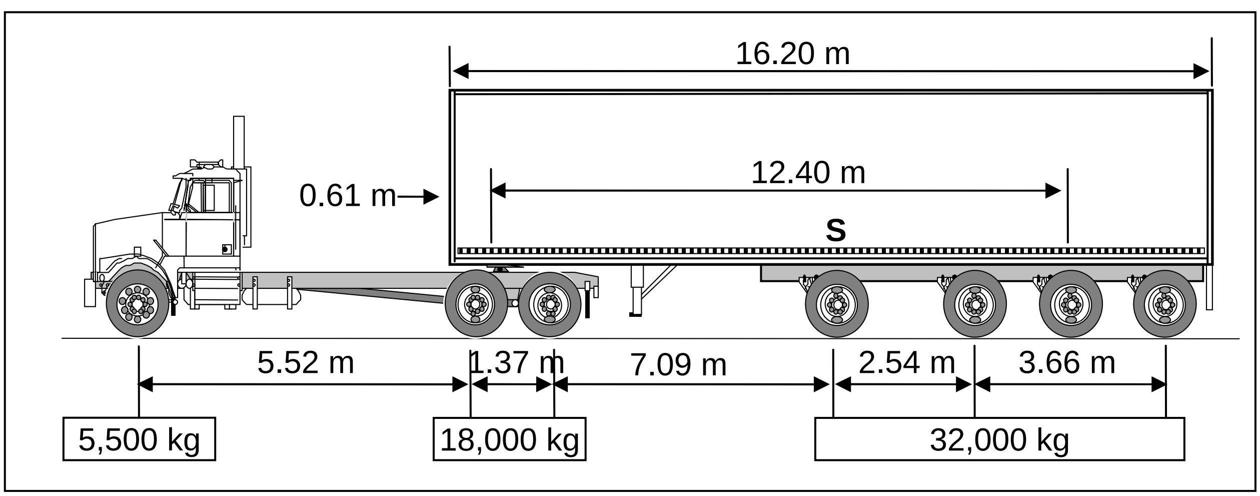


Figure 15: 53' Self-steer Quad Van



These dimensions respect the minimum inter-axle spacing of 5.50 m (217 in) used by Ontario [4] and Québec. The tare weight of a self-steer quad semitrailer was 8,164 kg (18,000 lb). Each fixed axle was assumed to weigh 680 kg (1,500 lb) and the self-steering axle was assumed to weigh 952 kg (2,100 lb). Moments of inertia for the semitrailers were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7]. The allowable gross weight for each configuration was 55,500 kg (122,355 kg).

The simulation used a single tire on the self-steering axle. It is not particularly relevant for dynamic performance of the vehicle whether a single tire or dual tires are used, or the size of the tire. The wheels of a self-steering axle simply align themselves with the local direction of travel against the resistance provided by the stiffness and friction of the self-steering system. A self-steering axle on a self-steer quad semitrailer generates negligible side-force on the trailer, and also is located close to the centre of gravity of the trailer, so also generates negligible yaw moment. Any choice of tire size or arrangement allows the axle to steer properly, and the lateral force capacity of the tires will only be challenged if the steer bottoms in a tight turn. The choice of tire size and arrangement is much more significant to geometric clearances within the self-steering system, which determine the maximum self-steer angle, and to management of the vehicle within a carrier's fleet.

It appears preferable to use a self-steering axle with the minimum practical centring stiffness to reduce friction demand, and with the minimum practical single axle spacing to reduce self-steer angle. The minimum practical centring stiffness is that which is just sufficient to cause the steer to centre when the axle is raised. The analysis used measured self-steer characteristics of a self-steering axle set up for low centring force [13].

5.2.3 Load Distribution

Each self-steer quad semitrailer was considered as a van loaded with general freight of uniform density over the entire length of the semitrailer, except for the rearmost 0.30 m (12 in). The maximum payload used was 37,648 kg (83,000 lb), which resulted in a gross weight of 55,157 kg (121,600 lb). Runs were also made at 75% of maximum payload weight, which resulted in a gross weight of 45,145 kg (99,526 lb). A payload less than 75% of the capacity of a typical self-steer quad could be carried by a tridem semitrailer, and the operator would usually raise the self-steer axle, so the semitrailer would effectively become a tridem semitrailer, which is already a legal vehicle so does not need to be considered. Each payload was also considered with a height of 0.61, 1.22, 1.83 or 2.44 m (24, 48, 72 or 96 in).

5.3 Results and Discussion

Table 42 presents the static roll threshold for the various load cases, payload levels and payload centre of gravity heights. Trailer length had no significant effect on static roll threshold, since the payload weight and height was the same for each vehicle. Vehicle speed also had no significant effect on static roll threshold.

Table 43 and Table 44 show the high-speed offtracking, load transfer ratio and transient offtracking for 16.20 m (53 ft) and 14.65 m (48 ft) semitrailers respectively for both payload levels, all payload heights, and speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). Load level is the percentage of the nominal payload. **CG** is the payload height; **X** corresponds to a payload height of 2.44 m (96 in), **H** to a payload height of 1.83 m (72 in), **M** to a payload height of 1.22 m (48 in), and **L** to a payload height of 0.61 m (24 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with payload height and speed.

Figure 16, Figure 17 and Figure 18 show the high-speed offtracking, load transfer ratio and transient offtracking respectively, for 100% payload, all payload heights, and all speeds. The horizontal green line in each Figure indicates the performance standard, so a data point below this line meets the standard. Each performance measure increases with payload height and speed. This configuration exceeds the high-speed offtracking performance standard for the highest payload heights and speeds, but by a matter of only about 0.10 m (4 in). This level of deviation has been accepted by Ontario and Québec in their specifications for self-steer quad semitrailers. Following the discussion in Section 3.7.4, high-speed offtracking not expected to be an issue for operation on freeways, and would be expected to be within the performance standard for operation on other roads with a speed limit lower than 90 km/h (55.9 mi/h). There is little difference in high-speed offtracking performance between 14.65 and 16.20 m (48 and 53 ft) semitrailers. In contrast, the load transfer ratio and transient offtracking of 14.65 m (48 ft) semitrailers is consistently higher than for 16.20 m (53 ft) semitrailers, due to their shorter wheelbase, but all configurations meet these performance standards even for the highest speed and payload height.

The low-speed offtracking was about 4.85 m (191 in) for a 14.65 m (48 ft) semitrailer, and 5.55 m (218 in) for a 16.20 m (53 ft) semitrailer, with no significant rear outswing, which meet the performance standard of 5.60 m (220 in). Friction demand was between 0.17 and 0.23, which is typical for a self-steer quad semitrailer. While this exceeds the original performance standard of 0.1, this performance measure is no longer considered a safety warrant, as discussed in Section 2.1.3 above.

Table 42: Static Roll Thresholds for Self-steer Quad Semitrailers

Payload Height (m)	Static Roll Threshold (>0.35 g)			
	100% Payload		75% Payload	
	53 ft	48 ft	53 ft	48 ft
2.44	0.383	0.383	0.401	0.402
1.83	0.441	0.445	0.458	0.459
1.22	0.519	0.523	0.533	0.534
0.61	0.618	0.622	0.614	0.620

Table 43: High-speed Performance Measures for 16.20 m (53 ft) Self-steer Quads

Load Level	CG	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
100%	X	0.449	**0.508**	**0.552**	0.506	0.545	0.573	0.507	0.627	0.730
100%	H	0.422	**0.481**	**0.522**	0.432	0.462	0.505	0.474	0.587	0.705
100%	M	0.398	0.458	**0.500**	0.363	0.396	0.417	0.446	0.540	0.652
100%	L	0.383	0.441	**0.484**	0.301	0.328	0.351	0.425	0.528	0.625
75%	X	0.359	0.413	0.454	0.465	0.516	0.549	0.434	0.543	0.640
75%	H	0.351	0.405	0.447	0.399	0.443	0.479	0.415	0.519	0.614
75%	M	0.344	0.396	0.439	0.338	0.378	0.413	0.399	0.500	0.599
75%	L	0.337	0.389	0.432	0.284	0.319	0.346	0.387	0.486	0.583

Table 44: High-speed Performance Measures for 14.65 m (48 ft) Self-steer Quads

Load Level	CG	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
100%	X	0.457	**0.504**	**0.544**	0.536	0.576	**0.603**	0.561	0.677	0.777
100%	H	0.433	**0.479**	**0.515**	0.456	0.495	0.528	0.527	0.640	0.750
100%	M	0.410	0.458	**0.493**	0.386	0.421	0.445	0.497	0.600	0.701
100%	L	0.396	0.445	**0.482**	0.321	0.345	0.365	0.472	0.567	0.665
75%	X	0.372	0.415	0.449	0.495	0.544	0.582	0.482	0.591	0.684
75%	H	0.365	0.408	0.442	0.425	0.468	0.506	0.460	0.566	0.656
75%	M	0.358	0.399	0.436	0.360	0.402	0.433	0.441	0.543	0.638
75%	L	0.352	0.394	0.428	0.303	0.340	0.365	0.428	0.529	0.622

Figure 16: High-speed Offtracking for Self-steer Quad Semitrailer

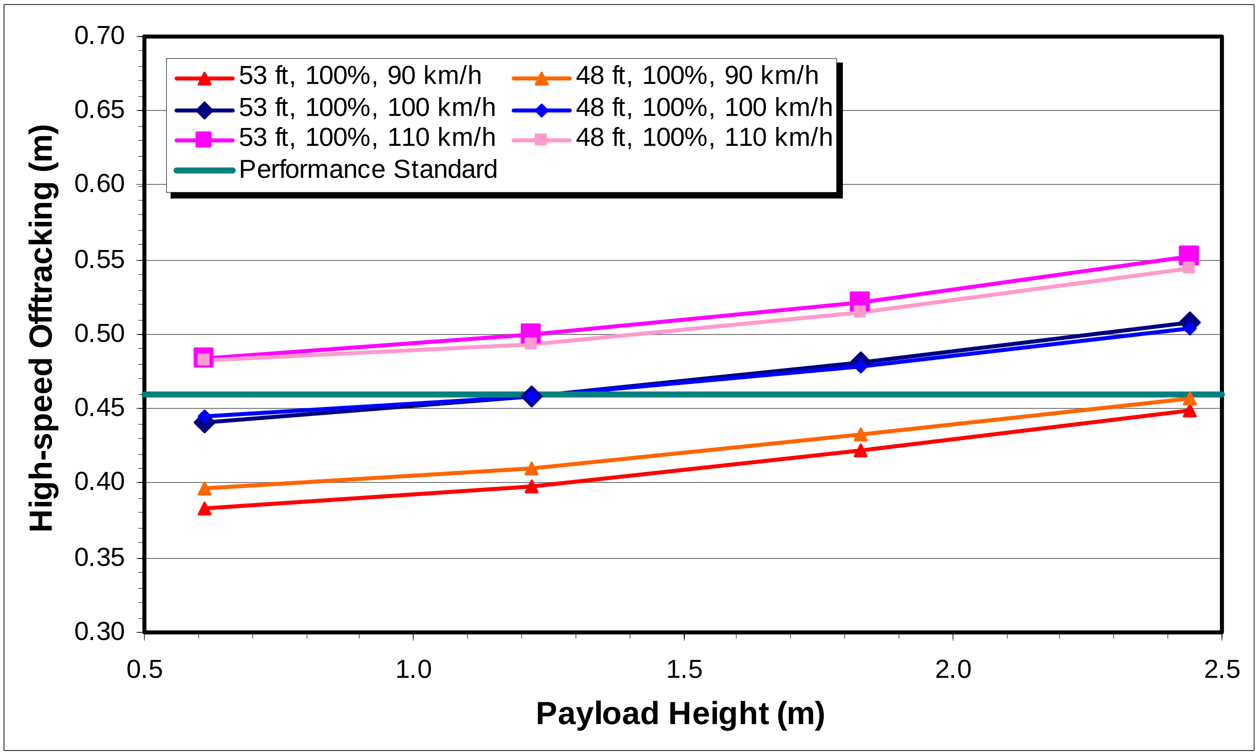


Figure 17: Load Transfer Ratio for Self-steer Quad Semitrailer

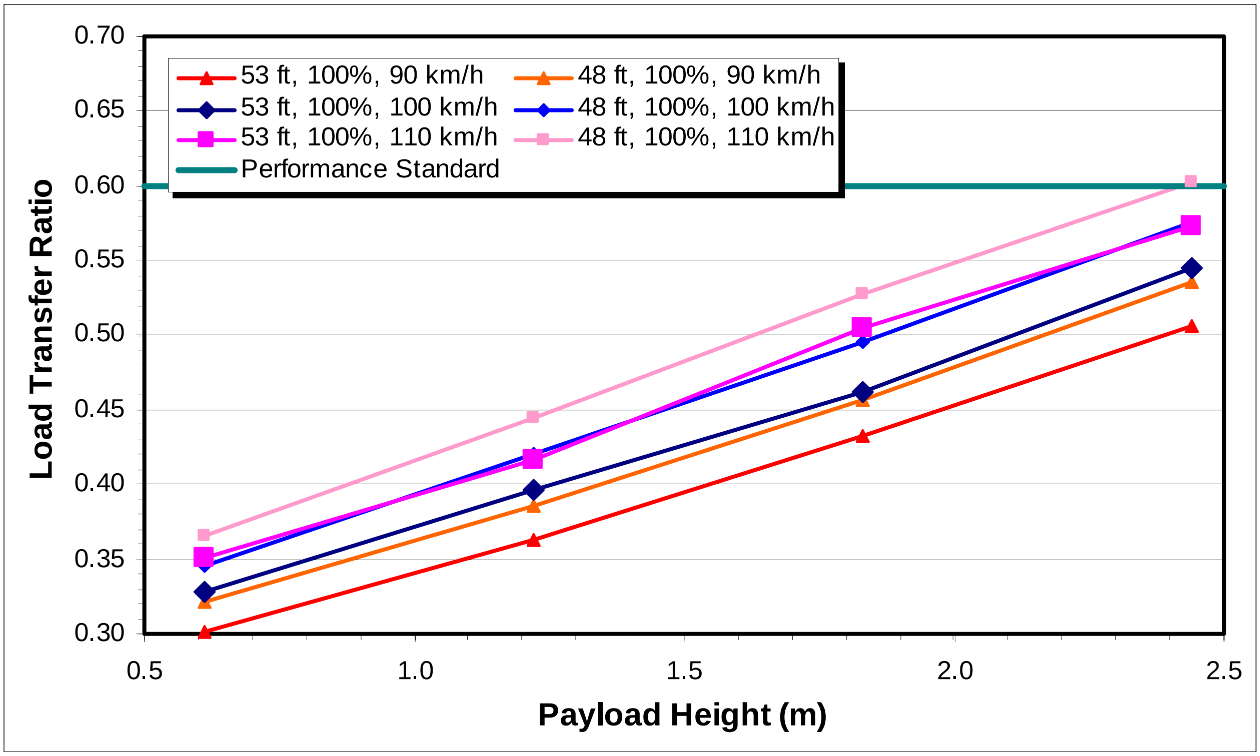
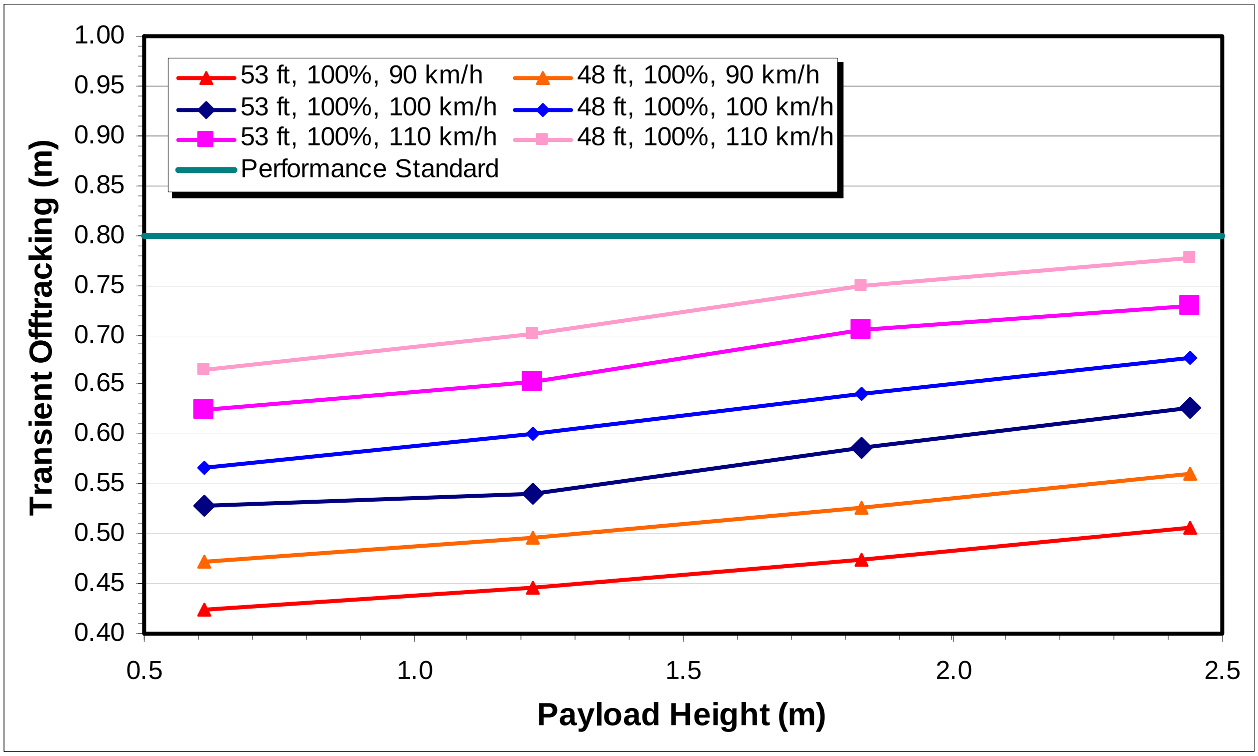


Figure 18: Transient Offtracking for Self-steer Quad Semitrailer



There is little difference in dynamic performance between 14.65 and 16.20 m (53 ft) self-steer quad semitrailers. The semitrailer length is largely a function of body style. A van needs to be 16.20 m (53 ft) long so that it is available for backhauls that would normally travel in a 16.20 m (53 ft) tandem or tridem semitrailer, at the payload weight appropriate to those semitrailers. Chip vans and trailers that carry municipal waste also need to be 16.20 m (53 ft) long, to maximize the payload volume based on the typical range of density for those payloads. Other body styles that carry dense or bulk commodities, or heavy loads, like flatbeds, tankers and log trucks, lose payload weight due to the additional tare weight if they are longer than the minimum length necessary for inter-axle spacings to achieve the maximum allowable gross weight. In practice, most of these are 14.65 m (48 ft) long.

6. SELF-STEER QUAD TANKER

6.1 Tank Truck Rollover

6.1.1 Performance Standards

Rollover is the critical issue for tank trucks. Transport Canada's Dangerous Goods Directorate (TDG) maintains a database of incidents and spills that have arisen during transportation of dangerous goods. This database has 1,874 reported crashes of highway vehicles carrying dangerous goods from 1990 to 1998, and 810 of these, or 43%, included rollover of a vehicle carrying dangerous goods [23]. Transport Canada's database of all crashes shows that less than 5% of all heavy truck crashes involve rollover of the truck, but these crashes are responsible for about a quarter of all the truck driver fatalities [24]. The TDG accident database showed that 83% of the vehicles that rolled over were tank trucks [23]. Thus, tank trucks appear to be significantly over-represented in crashes that include a rollover. Prior results show that the proportion of rollovers in single vehicle crashes increases exponentially as the roll threshold of the vehicle diminishes [9]. So, improvement in the roll resistance of tank trucks would be expected to reduce the incidence of rollover, and consequently, the risk of spill, fire or explosion, risk to driver's lives, and risk to the public.

The M.o.U. is founded on performance standards, and these include a preferred minimum static roll threshold of 0.40 g [5]. This standard has never been directly enforced, so legal vehicles configured and loaded in conformity with provincial rules based on the M.o.U. can, and do, operate with a static roll threshold less than 0.40 g. Provinces have, however, used this value when considering applications for a special permit for vehicles outside their rules.

New Zealand has narrow winding roads and short length limits, which have resulted in some rather high vehicles, so there was a serious problem with rollover. New Zealand therefore imposed an operational minimum static roll threshold of 0.35 g on all vehicles [10]. This required a vehicle that could not meet the static roll threshold with its normal full payload to be operated at a lesser payload so that it did meet the roll threshold. New vehicles are now designed so that they meet this requirement. New Zealand also has a minimum static roll threshold of 0.45 g for tank trucks, but their 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. Australia is developing a system that will allow operation of a vehicle outside its rules provided the vehicle meets a set of performance-based standards [11]. A minimum static roll threshold of 0.35 g has been proposed for vehicles carrying general freight, with a minimum of 0.40 g for tank trucks. The European countries now have a minimum static roll threshold for tank trucks, which is 0.40 g based on a tilt test, or 0.42 g based on a specified calculation procedure [12].

It is clear that the European countries, Australia and New Zealand consider that tank trucks should be held to a higher static roll threshold than other vehicles. It is also clear that design features commonly used in Canadian tank trucks results in a high payload centre of gravity, which leads directly to a low roll threshold [25], and a high rate of rollover [23], [9]. It is also clear that vehicles can be designed with a lower payload centre of gravity than is customary, and this can result in a static roll threshold that exceeds 0.40 g [25]. TDG is currently considering approaches that could improve the rollover stability of tank trucks used for highway transportation of dangerous goods. At this point, it is not known what direction TDG will take. This work proceeded on the basis of determining a maximum centre of gravity height that should ensure the static roll threshold for a self-steer quad tank truck will be greater than 0.40 g.

6.1.2 Fuel Tanker

A fuel tanker is required to meet the TC 407 specification [26]. A fuel tanker used for delivery to gas stations invariably has a tank with a modified oval cross-section that is divided into several compartments along its length. The tank is typically sized so that all compartments would be full for a full load of gasoline. A compartment loaded with diesel fuel is typically about 84% full by volume, reflecting the greater density of diesel fuel over gasoline. This results in a small amount of lateral movement (slosh) of the fluid contents as a consequence of sprung mass roll and lateral acceleration, which reduces the static roll threshold of the vehicle. The lowest static rollover threshold for a vehicle with a modified oval tank may occur when the tank is between about 40 and 60% full by volume and the vehicle is loaded to its allowable gross weight [9]. The supply cycle for gas stations is usually managed so that each compartment is entirely emptied at a gas station, so the vehicle rarely travels with a partially full compartment, except to the extent that compartments are loaded with diesel fuel. If a compartment is partially loaded, the vehicle will usually be below its allowable gross weight. So, in normal operation, the lowest static rollover threshold for a fuel tanker used for delivery to gas stations would normally be when the vehicle is fully loaded with diesel fuel to its allowable gross weight.

6.1.3 Compressed Gas Tanker

A compressed gas tanker must meet the TC 331 specification if it is designed to carry propane or similar natural gases, which are in a liquid state at air temperatures, or the TC 341 specification if it is designed to carry compressed gases like oxygen, nitrogen or carbon dioxide, which require cryogenic cooling to keep the gas in a liquid state [26]. These gases are carried in heavy tanks with a circular cross-section. The lowest static rollover threshold for a vehicle with a circular tank occurs when the tank is full by volume and the vehicle is loaded to its allowable gross weight [9].

6.1.4 General Fluid Tanker

Most tankers that carry liquids other than fuel and compressed gases are general purpose vehicles and meet the TC 407 specification [26]. These liquids are carried in a clean-bore tank with a circular cross-section, i.e. there are no compartments. These tanks are often partially filled with a commodity that is denser than that which would fill the tank, and load the vehicle to its allowable gross weight. In this case, even though substantial fluid movement (slosh) may be possible, the roll threshold is higher than with the same weight of fluid filling the tank. The lowest rollover threshold for a vehicle with a circular tank occurs when the tank is full by volume and the vehicle is loaded to its allowable gross weight [9].

6.2 Vehicle Configurations

This work used the same generic tandem drive tractor as described in Section 5.2.1, but with a 4.83 m (190 in) wheelbase. The tractor does not need any longer wheelbase, because the vehicle will be for local use, so will generally not require a sleeper. The tractor was considered to weigh 7,257, 8,164 or 9,072 kg (16,000, 18,000 or 20,000 lb). Tractor wheelbase is not a significant factor in the principal dynamic performance measures considered here, which relate to trailers.

Figure 19 shows the dimensions for a typical self-steer quad semitrailer tanker with a 14.65 m (48 ft) length, as defined by Ontario and Québec rules. Figure 20 shows the same vehicle in a 16.20 m (53 ft) length. The symbol **S** indicates the liftable self-

Figure 19: 48' Self-steer Quad Tanker

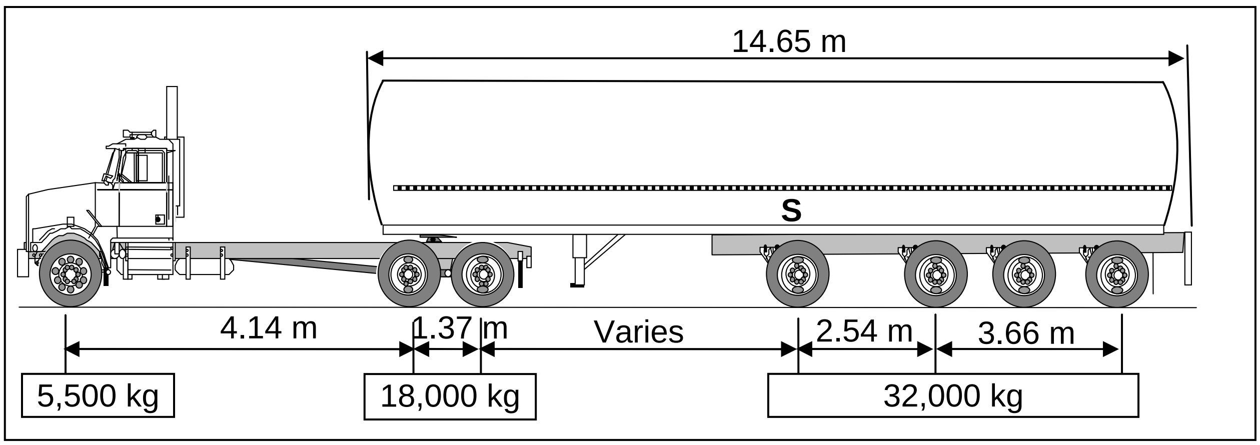
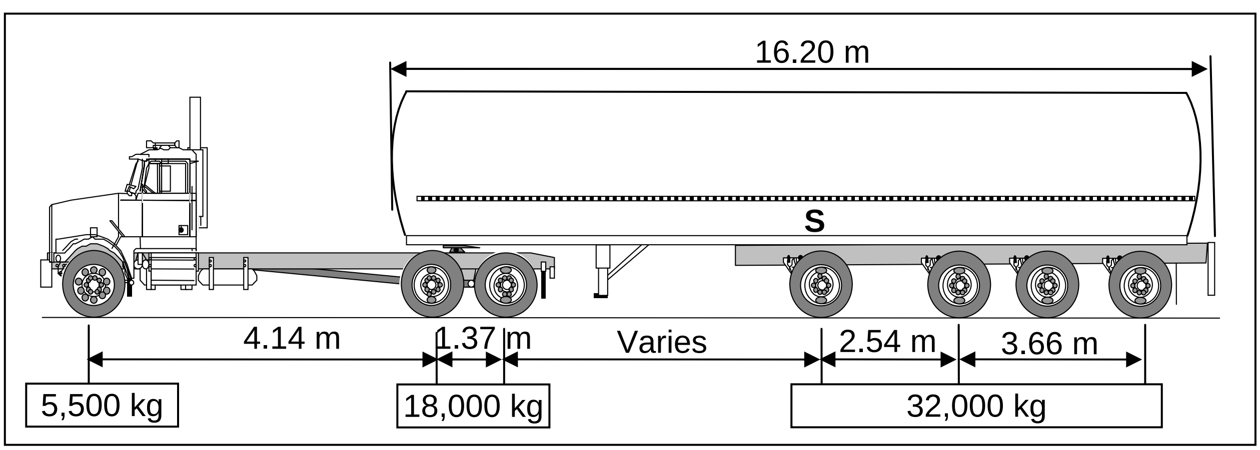


Figure 20: 53' Self-steer Quad Tanker



steering axle. The kingpin setback was 0.46 m (18 in) for each semitrailer. Each fixed axle was assumed to weigh 680 kg (1,500 lb) and the self-steering axle was assumed to weigh 952 kg (2,100 lb). The semitrailers were assumed fitted with a self-steering axle with a low centring force, as described in Section 5.2.2. While a tank semitrailer may have the same length as a van, the cargo-carrying portion of a tanker is shorter than the cargo-carrying portion of a van. The load length was assumed 0.61 m (24 in) less than the semitrailer length. The wheelbase of a self-steer quad tank semitrailer therefore is a little shorter than that of a self-steer quad van, and varied with the tractor tare weight. The 14.65 m (48 ft) semitrailer wheelbase was 10.97, 11.18 or 11.38 m (432, 440 or 448 in) for heavy, medium and light tractors respectively, and the 16.20 m (53 ft) semitrailer wheelbase was 12.19, 12.39 or 12.50 m (480, 488 or 492 in) for heavy, medium and light tractors respectively.

The tanks for the different types of tanker have significantly different weights, but the combined weight of the tank and a full payload is constant regardless of the type of tank. The maximum weight of the tank and contents is the allowable gross weight of the vehicle, less the tare weight of the tractor with full fuel and driver, less the weight of the semitrailer running gear. The allowable gross weight is 55,500 kg (122,355 lb). The total weight of the semitrailer axles and their fixed suspension components is fixed at about 3,900 kg (8,600 lb). Consider that a tractor might weigh 7,257, 8,164 or 9,072 kg (16,000, 18,000 or 20,000 lb). Then the combined weight of tank and contents could be 44,343, 43,436 or 42,538 kg (97,755, 95,755 or 93,755 lb). The maximum legal height is 4.15 m (162 in), but all tanks with manholes at the top must have rollover protection devices, which reduces the maximum possible height for this type of tank. A common fifth wheel height is 1.22 m (48 in), and the minimum practical thickness for an upper coupler plate is about 0.10 m (4 in), so the practical bottom of a tank is 1.32 m (52 in) above the ground. These give a maximum possible tank height of 2.79 m (110 in). Most (but not all) cargo tanks are symmetric about a horizontal axis at the mid-point between the upper and lower parts of the shell. So, for such a symmetric tank, the centre of the tank would be 2.72 m (107 in) above the ground. If the smallest tank is circular with a diameter of 1.22 m (48 in), this would have its centre about 1.93 m (76 in) above the ground. Assume that the vertical location of the centre of gravity of an empty tank, including frame rails, suspension sub-frame, rollover protection devices, valves, pumps and other plumbing, cabinets, landing gear, ladders and walkways, fenders, and all other attachments, is close to its centre. Then if the tank is completely full, the vertical location of the combined centre of gravity of tank and contents is also close to its centre. The combined centre of gravity of tank and contents therefore could vary from about 1.93 to 2.72 m (76 to 107 in) above the ground.

Runs were made for the three weights of tank and contents identified above, each for a range of centre of gravity heights for tank and contents from 1.90 to 2.67 m (75 to 105 in), in steps of 0.25 m (10 in). This allowed the maximum centre of gravity height to be determined to ensure a roll threshold of at least 0.40 g.

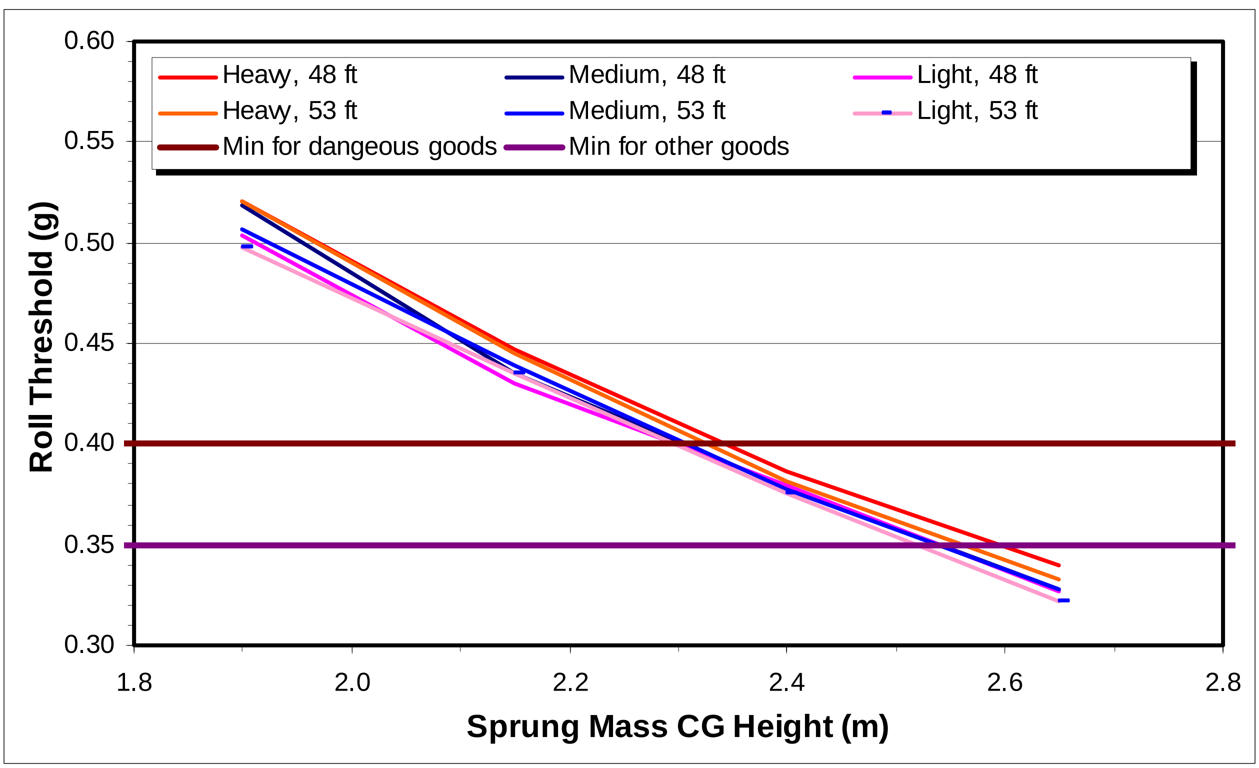
6.3 Results and Discussion

Table 45 shows the static roll thresholds for the sprung weights from heavy, medium and light weight tractors (**H**, **M** and **L**) for 14.65 and 16.20 m (48 and 53 ft) semitrailers, and the various sprung weight centre of gravity heights. These results are also shown in Figure 21. There is little difference between 14.65 and 16.20 m (48 and 53 ft) semitrailers of the same weight and centre of gravity height. However, for product of a given density, a 16.20 m (53 ft) semitrailer would have a lower centre of gravity than a 14.65 m (48 ft) semitrailer. The static roll thresholds diminish slightly as the tractor gets lighter, because weight saved on the tractor becomes additional payload. Figure 21 suggests a static roll threshold of 0.40 g should be achieved for a sprung mass centre of

Table 45: Static Roll Thresholds for Self-steer Quad Tankers

Sprung Weight CG Height (m)	Static Roll Threshold (>0.40 g)					
	14.65 m (48 ft)			16.20 m (53 ft)		
	H	M	L	H	M	L
2.65	**0.340**	**0.332**	**0.327**	**0.336**	**0.330**	**0.324**
2.40	**0.390**	**0.385**	**0.379**	**0.386**	**0.383**	**0.379**
2.15	0.453	0.444	0.435	0.452	0.445	0.439
1.90	0.531	0.525	0.515	0.528	0.520	0.510

Figure 21: Static Roll Threshold for Self-steer Quad Tankers



gravity no more than 2.30 m (90 in) above the ground. This is suggested as an interim requirement pending a regulatory requirement from TDG, as discussed above. Recent tilt tests identified some vehicles that certainly met this requirement, but still had a roll threshold below 0.40 g [25]. This criterion should ensure that any new vehicles would have a moderate centre of gravity, less than the 2.50 to 2.60 m (98 to 102 in) of some existing tank trucks with low roll thresholds.

Any requirement should probably be phrased as “for the critical (maximum) payload, either demonstrate a static roll threshold above 0.40 g by test, or the combined centre of gravity of the sprung mass and payload shall be as low as possible, but not more than 2.30 m above the ground”.

One of the vehicles in the recent test program was a four-axle semitrailer fuel tanker of a different axle configuration than the self-steer quad [25]. The tank had a capacity of 47,700 l (10,494 Imp gal), and there was an additional 11,000 l (2,420 Imp gal) tank on the tractor. The geometric centre of the rear of the trailer tank was 2.06 m (81 in) above the ground, and the vehicle had a roll threshold of 0.42 g. The centre of gravity of the sprung mass with the tank full to capacity was probably a little below its geometric centre.

Even if these vehicles would have a higher static roll threshold than existing vehicles, they can still be rolled over. Therefore, additionally, a requirement should be considered for both tractor and semitrailer to be equipped with an electronic roll stability system. This is a relatively inexpensive enhancement to an antilock brake system that is now commercially available. It can provide a significant improvement in roll resistance for a vehicle on the roadway by selectively applying brakes to slow the vehicle when the logic perceives that a potential rollover is approaching. It is probably less useful when a vehicle runs off the road.

Table 46 and Table 47 show the high-speed offtracking, load transfer ratio and transient offtracking for 14.65 m (48 ft) and 16.20 m (53 ft) semitrailers respectively, for heavy, medium and light weight tractors (**H**, **M** and **L**), all centre of gravity heights, and speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). **CG** is the loaded sprung mass centre of gravity height; **X** corresponds to 2.65 m (104 in), **H** to 2.40 m (94 in), **M** to 2.15 m (84 in), and **L** to 1.90 m (74 in). Values that do not meet their performance standard are highlighted in bold face. Each performance measure increases with sprung mass centre of gravity height, payload weight, and speed. The same comments made in Section 5.3 also apply to these results.

Table 46: High-speed Performance Measures for 14.65 m (48 ft) Tankers

PU Weight	CG	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
H	X	0.434	0.441	**0.465**	**0.640**	**0.687**	**0.693**	0.574	0.697	0.775
H	H	0.402	0.453	0.446	0.553	0.584	**0.605**	0.515	0.618	0.725
H	M	0.386	0.432	**0.464**	0.477	0.502	0.537	0.475	0.575	0.657
H	L	0.367	0.411	0.443	0.409	0.429	0.454	0.449	0.535	0.625
M	X	0.439	0.485	**0.473**	**0.649**	**0.680**	**0.705**	0.579	0.685	0.783
M	H	0.474	0.456	**0.492**	0.557	0.592	**0.612**	0.525	0.632	0.730
M	M	0.386	0.433	**0.467**	0.479	0.516	0.535	0.482	0.593	0.684
M	L	0.367	0.412	0.445	0.409	0.431	0.456	0.450	0.544	0.627
L	X	0.443	**0.492**	**0.527**	**0.658**	**0.697**	**0.705**	0.592	0.719	**0.807**
L	H	0.412	**0.460**	**0.497**	0.566	**0.600**	**0.640**	0.543	0.650	0.778
L	M	0.388	0.431	**0.470**	0.485	0.513	0.537	0.500	0.600	0.695
L	L	0.367	0.414	0.447	0.415	0.440	0.472	0.470	0.566	0.676

Table 47: High-speed Performance Measures for 16.20 m (53 ft) Tankers

PU Weight	CG	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
H	X	0.434	**0.486**	**0.481**	**0.611**	**0.637**	**0.674**	0.519	0.623	0.735
H	H	0.404	0.456	**0.494**	0.521	0.564	0.594	0.465	0.581	0.688
H	M	0.382	0.425	**0.469**	0.449	0.490	0.501	0.426	0.540	0.624
H	L	0.360	0.411	0.448	0.385	0.411	0.433	0.401	0.484	0.579
M	X	0.437	**0.492**	**0.530**	**0.610**	**0.649**	**0.665**	0.509	0.636	0.736
M	H	0.406	**0.460**	**0.464**	0.528	0.570	0.585	0.472	0.593	0.676
M	M	0.381	0.433	**0.474**	0.455	0.483	0.506	0.436	0.534	0.631
M	L	0.359	0.412	0.450	0.387	0.413	0.433	0.404	0.491	0.588
L	X	0.444	**0.500**	**0.540**	**0.624**	**0.658**	**0.676**	0.538	0.657	0.753
L	H	0.410	**0.465**	**0.507**	0.542	0.566	**0.613**	0.494	0.604	0.729
L	M	0.384	0.438	**0.479**	0.458	0.497	0.512	0.445	0.572	0.653
L	L	0.363	0.414	0.454	0.395	0.418	0.441	0.425	0.522	0.621

7. TRIDEM-DRIVE TRACTOR-SEMITRAILERS

7.1 Vehicle Configurations

A tridem drive tractor pulling a van semitrailer in a 14.65 m (48 ft) or 16.20 m (53 ft) length, as follows:

1. Single axle semitrailer;
2. Tandem semitrailer;
3. Tridem semitrailer;
4. Self-steer quad semitrailer; or a
5. Tandem-tandem B-train log trailer.

7.1.1 Tractor

This work used a generic tridem drive tractor with a 6.80 m (267 in) wheelbase, a 2.80 m (110 in) drive axle spread, and a fifth wheel 0.46 m (18 in) ahead of the centre of the drive tandem. The drive axles had a track width of 2.54 m (100 in). The tractor had a tare weight of 10,886 kg (24,000 lb). This tractor is compatible with that recently introduced into regulation in Ontario [4], and with tractors allowed by B.C. [27] and Alberta [28]. The front axle was assumed to weigh 680 kg (1,500 lb), with a rating of at least 7,257 kg (16,000 lb), and a tare load of 5,896 kg (13,000 lb). Each drive axle was assumed to weigh 1,134 kg (2,500 lb). Moments of inertia were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7].

7.1.2 Semitrailers

This work used the same generic 14.65 and 16.2 m (48 and 53 ft) tandem and tridem van semitrailers as described in Section 3.1.2, and the same generic 14.65 and 16.2 m (48 and 53 ft) self-steer quad semitrailers as described in Section 5.2.2. The single-axle semitrailer used the same box structure as a tandem semitrailer, simply with one axle removed. The wheelbase of these semitrailers was limited to a maximum of 12.00 m (472 in) to compensate for the greater wheelbase of the tractor, which is compatible with the regulation in Ontario [4], and slightly less than allowed under permit by Quebec for a tractor with a wheelbase up to 6.80 m (268 in) [29].

While the semitrailers, as stated above, had the same physical properties as used previously, semitrailers designed for use with a tandem drive tractor are not compatible with a tridem drive tractor. The tridem drive axle group is about twice the spread of a tandem drive axle group, and the fifth wheel needs to be further forward to get the required front axle load. A trailer with frame rails needs a gooseneck about 1.65 m (65 in) or so longer to be compatible with a tridem drive tractor, and any trailer needs its landing gear set rearwards by a corresponding amount.

7.1.3 Load Distribution

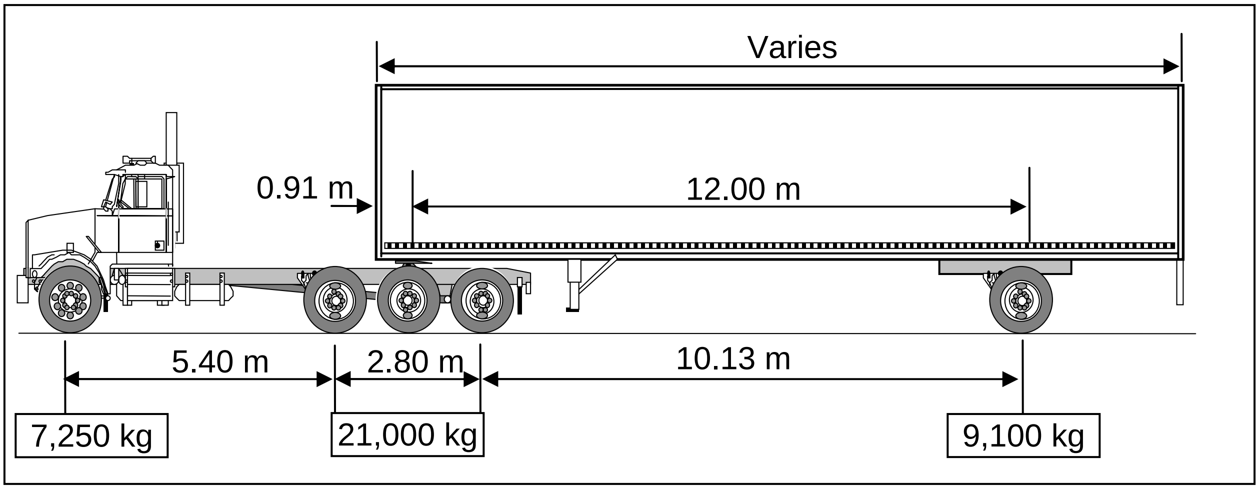
Each semitrailer was considered as a van loaded with a solid block of general freight of uniform density butted against the front of the semitrailer. The maximum wheelbase of 12.00 m (472 in) resulted in a semitrailer axle overload when the payload was distributed along the entire length of the semitrailer, so the payload was restricted to a length that balanced the axle loads. Runs were also made at 50% and 75% of maximum payload weight for tridem and self-steer quad semitrailers. The payload was considered with a height of 2.44 m (96 in) for single and tandem axle semitrailers, and with a height of 1.22, 1.83 or 2.44 m (48, 72 or 96 in) for tridem and self-steer quad semitrailers.

7.2 Tridem Drive Tractor and Single Axle Semitrailer

7.2.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 22. The allowable gross weight was 37,350 kg (82,341 lb), which allowed a maximum payload of 20,411 kg (44,000 lb) at a length of only 8.23 m (324 in). The payload length had to be limited to avoid overloading the semitrailer axle.

Figure 22: Tridem Drive Tractor and Single Axle Semitrailer



7.2.2 Results and Discussion

This configuration was run only with the maximum payload of 20,411 kg (44,000 lb) and a payload height of 2.44 m (96 in) for 14.65 and 16.20 m (48 and 53 ft) semitrailers, at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). No partial payload weights or lower payload heights were considered.

The static roll threshold was 0.405 g. The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 48. All performance measures increased with speed, but even at 110 km/h (68.3 mi/h), were all well within their performance standards. Differences in performance measures for the two semitrailer lengths were insignificant.

The lateral friction utilization was about 0.69, well within the performance standard of 0.80, principally because the front axle weight is 34% of the drive tridem weight, well above the minimum of 27% required by Alberta [28] and Ontario [4]. Low-speed offtracking was 5.73 m (225 in), as the vehicle was at the extreme wheelbase for both tractor and semitrailer. Other low-speed performance measures were all well within the performance standards.

Table 48: High-speed Performance Measures for Single-axle Semitrailers

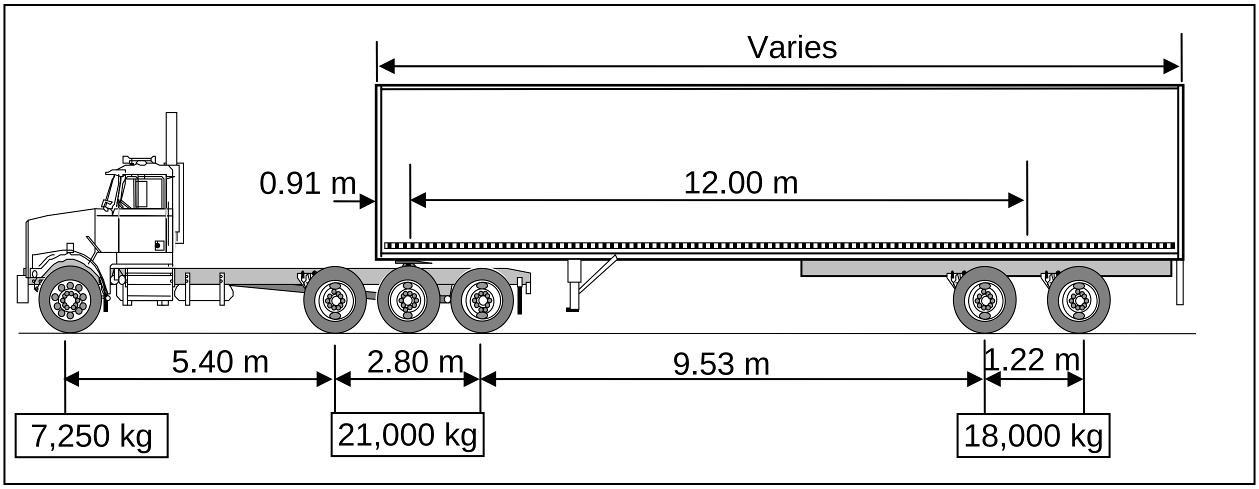
Length (ft)	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
53	H	0.318	0.374	0.414	0.496	0.536	0.571	0.376	0.481	0.587
48	H	0.313	0.370	0.410	0.500	0.539	0.573	0.370	0.476	0.579

7.3 Tridem Drive Tractor and Tandem Semitrailer

7.3.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 23. The allowable gross weight was 46,250 kg (101,962 lb), which allowed a maximum payload of 28,123 kg (62,000 lb) at a length of only 13.31 m (524 in). The payload length had to be limited to avoid overloading the semitrailer axle group.

Figure 23: Tridem Drive Tractor and Tandem Semitrailer



7.3.2 Results and Discussion

This configuration was also run only with the maximum payload of 28,123 kg (62,000 lb) and a payload height of 2.44 m (96 in) for 14.65 and 16.20 m (48 and 53 ft) semitrailers, at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). No partial payloads were considered.

The static roll threshold was 0.390 g. The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 49. All performance measures all increased with speed, but even at 110 km/h (68.3 mi/h), were all well within their performance standards. Differences in performance measures for the two semitrailer lengths were insignificant.

The lateral friction utilization was about 0.69, well within the performance standard of 0.80, principally because the front axle weight is 34% of the drive tridem weight, well above the minimum of 27% required by Alberta [28] and Ontario [4]. Low-speed offtracking was about 5.73 m (225 in), as the vehicle was at the extreme wheelbase for both tractor and semitrailer. Other low-speed performance measures were all well within the performance standards.

Table 49: High-speed Performance Measures for Tandem-axle Semitrailers

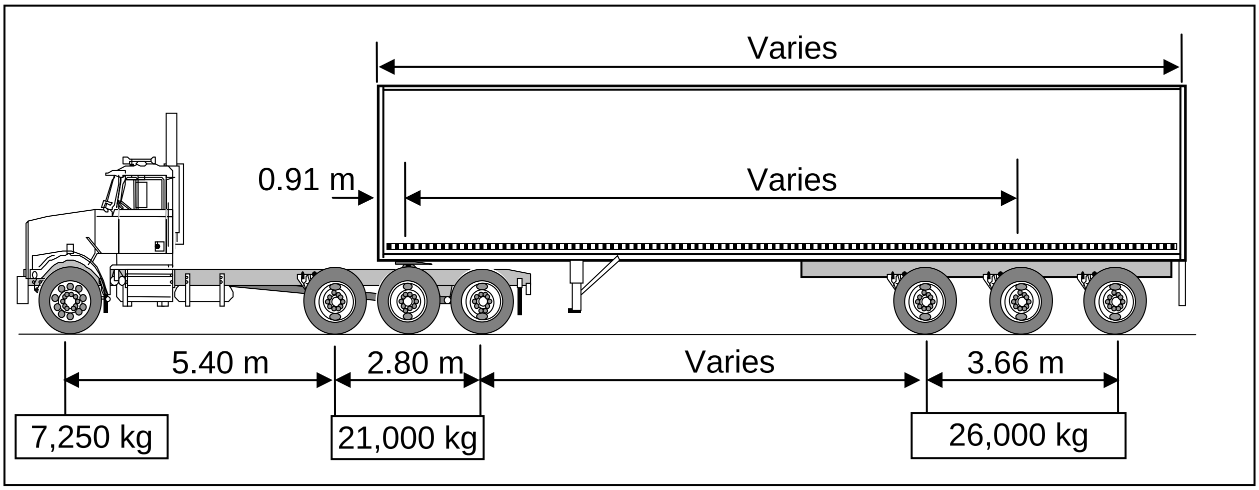
Length (ft)	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
53	H	0.338	0.393	0.435	0.471	0.513	0.551	0.371	0.473	0.569
48	H	0.336	0.392	0.433	0.472	0.513	0.551	0.367	0.469	0.564

7.4 Tridem Drive Tractor and Tridem Semitrailer

7.4.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 24. The allowable gross weight was 54,250 kg (119,600 lb), which allowed a maximum payload of 35,380 kg (78,000 lb). The wheelbase was 12.00 m (472 in) for a 16.20 m (53 ft) semitrailer, and 10.87 m (428 in) for a 14.65 m (48 ft) semitrailer. The payload length was 15.54 m (612 in) for a 16.20 m (53 ft) semitrailer, and 14.32 m (564 in) for a 14.65 m (48 ft) semitrailer

Figure 24: Tridem Drive Tractor and Tridem Semitrailer



7.4.2 Results and Discussion

This configuration was run with the maximum payload of 35,380 kg (78,000 lb), and at 50 and 75% of that payload, for payload heights of 1.22, 1.83 and 2.44 m (48, 72 and 96 in), for 14.65 and 16.20 m (48 and 53 ft) semitrailers. It was run at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h).

The static roll thresholds are shown in Table 50.

The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 51 and Table 52 for 16.20 m (53 ft) and 14.65 m (48 ft) semitrailers respectively, for all load levels and payload heights. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in), and **L** to a payload height of 1.22 m (48 in). Differences in performance measures for the two semitrailer lengths were insignificant. All performance measures increased with speed, payload weight and payload height. Load transfer ratio and transient offtracking were within their performance standards for all load conditions and speeds. High-speed offtracking exceeded its performance standard for the highest payload weight and height at 110 km/h (68.3 mi/h). However, this speed should only be reached on a freeway, when high-speed offtracking should not be an issue, as discussed in Section 3.7.4 above.

The lateral friction utilization was about 0.60 and about 0.75, depending on the payload weight. This is well within the performance standard of 0.80, principally because the front axle weight varies from about 33 to 47% of the drive tridem weight, well above the minimum of 27% required by Alberta [28] and Ontario [4]. Low-speed offtracking was about 5.66 m (223 in) for 16.20 m (53 ft) semitrailers, as the vehicle was at the extreme wheelbase for both tractor and semitrailer, and 5.09 m (200 in) for 14.65 m (48 ft) semitrailers. Other low-speed performance measures were all well within the performance standards.

Table 50: Static Roll Threshold for Tridem Semitrailers

Payload Height	Static Roll Threshold (>0.35 g)					
	100% Payload		75% Payload		50% Payload	
(m)	53 ft	48 ft	53 ft	48 ft	53 ft	48 ft
2.44	0.386	0.388	0.420	0.422	0.469	0.469
1.83	0.448	0.448	0.481	0.482	0.519	0.520
1.22	0.521	0.522	0.549	0.552	0.580	0.579

Table 51: High-speed Performance Measures for 16.20 m (53 ft) Tridem Semitrailers

Load Level	CG	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
100%	H	0.368	0.425	**0.467**	0.466	0.512	0.553	0.395	0.506	0.608
100%	M	0.346	0.403	0.444	0.388	0.428	0.466	0.363	0.465	0.563
100%	L	0.330	0.386	0.428	0.325	0.360	0.392	0.339	0.434	0.529
75%	H	0.299	0.354	0.397	0.417	0.461	0.500	0.324	0.416	0.505
75%	M	0.288	0.345	0.387	0.356	0.396	0.433	0.309	0.398	0.482
75%	L	0.281	0.339	0.380	0.301	0.336	0.369	0.297	0.384	0.465
50%	H	0.261	0.317	0.359	0.348	0.388	0.426	0.269	0.355	0.435
50%	M	0.254	0.310	0.351	0.305	0.341	0.375	0.261	0.344	0.423
50%	L	0.248	0.305	0.345	0.265	0.298	0.328	0.253	0.335	0.412

Table 52: High-speed Performance Measures for 14.65 m (48 ft) Tridem Semitrailers

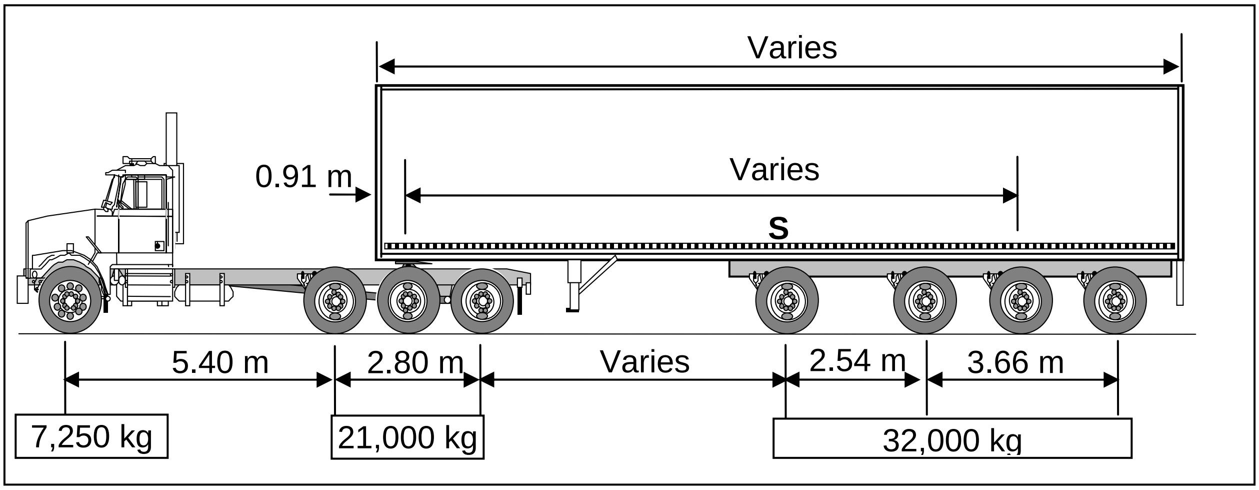
Load Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
100%	H	0.376	0.423	**0.459**	0.490	0.536	0.578	0.433	0.539	0.643
100%	M	0.355	0.402	0.439	0.408	0.450	0.487	0.398	0.499	0.593
100%	L	0.340	0.387	0.423	0.341	0.378	0.410	0.371	0.468	0.555
75%	H	0.311	0.358	0.394	0.437	0.482	0.522	0.354	0.447	0.532
75%	M	0.302	0.348	0.384	0.374	0.416	0.452	0.337	0.426	0.508
75%	L	0.296	0.342	0.378	0.316	0.353	0.386	0.325	0.411	0.492
50%	H	0.277	0.322	0.358	0.365	0.407	0.445	0.297	0.381	0.463
50%	M	0.270	0.315	0.351	0.320	0.358	0.392	0.287	0.369	0.449
50%	L	0.264	0.310	0.346	0.279	0.313	0.344	0.279	0.359	0.437

7.5 Tridem Drive Tractor and Self-steer Quad Semitrailer

7.5.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 25, using a self-steer quad semitrailer as defined under Ontario rules [4]. The symbol **S** indicates the self-steering axle. The allowable gross weight was 60,250 kg (132,827 lb). The wheelbase was 12.00 m (472 in) for a 16.20 m (53 ft) semitrailer, for an inter-axle spacing of 5.77 m (227 in), and 11.18 m (440 in) for a 14.65 m (48 ft) semitrailer, for an inter-axle spacing of 4.95 m (195 in). The maximum payload was 39,462 kg (87,000 lb) at a length of 15.39 m (606 in) for a 16.20 m (53 ft) semitrailer, and 13.26 m (522 in) for a 14.65 m (48 ft) semitrailer.

Figure 25: Tridem Drive Tractor and Self-steer Quad Semitrailer



7.5.2 Results and Discussion

This configuration was run with the maximum payload of 39,462 kg (87,000 lb), and at 50 and 75% of that payload, for payload heights of 1.22, 1.83 and 2.44 m (48, 72 and 96 in), for 14.65 and 16.20 m (48 and 53 ft) semitrailers, at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h).

The static roll thresholds are shown in Table 53.

The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 54 and Table 55 for 16.20 m (53 ft) and 14.65 m (48 ft) semitrailers respectively, for all load levels and payload heights. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in), and **L** to a payload height of 1.22 m (48 in). Differences in performance measures for the two semitrailer lengths were insignificant. All performance measures increased with speed, payload weight and payload height. Load transfer ratio and transient offtracking were within their performance standards for all load conditions and speeds. High-speed offtracking exceeded its performance standard for the highest payload weight and height at 100 and 110 km/h (62.1 and 68.3 mi/h). However, these speeds should only be reached on a freeway, when high-speed offtracking should not be an issue, as discussed in Section 3.7.4 above.

The lateral friction utilization was about 0.60 and about 0.78, depending on the payload weight. These are within the performance standard of 0.80, principally because the front axle weight varies from about 34 to 48% of the drive tridem weight, well above the minimum of 27% required by Alberta [28] and Ontario [4]. Low-speed offtracking was 5.71 m (225 in) for 16.20 m (53 ft) semitrailers, as the vehicle was at the extreme wheelbase for both tractor and semitrailer, and 5.20 m (205 in) for 14.65 m (48 ft) semitrailers. Other low-speed performance measures were all well within the performance standards.

Table 53: Static Roll Threshold for Self-steer Quad Semitrailers

Payload Height	Static Roll Threshold (>0.35 g)					
	100% Payload		75% Payload		50% Payload	
(m)	53 ft	48 ft	53 ft	48 ft	53 ft	48 ft
2.44	0.401	0.399	0.429	0.429	0.479	0.480
1.83	0.457	0.462	0.492	0.487	0.537	0.539
1.22	0.539	0.536	0.569	0.567	0.610	0.608

Table 54: High-speed Performance Measures for 16.20 m (53 ft) Self-steer Quad Semitrailers

Load Level	CG	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
100%	H	0.418	**0.477**	**0.520**	0.478	0.516	0.560	0.467	0.575	0.700
100%	M	0.393	0.453	**0.496**	0.404	0.437	0.477	0.432	0.542	0.656
100%	L	0.378	0.434	**0.478**	0.339	0.374	0.402	0.408	0.516	0.614
75%	H	0.344	0.397	0.442	0.426	0.475	0.510	0.393	0.493	0.593
75%	M	0.336	0.389	0.433	0.365	0.409	0.447	0.377	0.476	0.573
75%	L	0.331	0.381	0.425	0.312	0.350	0.382	0.365	0.461	0.557
50%	H	0.312	0.358	0.392	0.357	0.402	0.444	0.337	0.430	0.518
50%	M	0.306	0.352	0.386	0.315	0.355	0.392	0.327	0.418	0.503
50%	L	0.301	0.346	0.380	0.275	0.311	0.344	0.319	0.408	0.492

Table 55: High-speed Performance Measures for 14.65 m (48 ft) Self-steer Quad Semitrailers

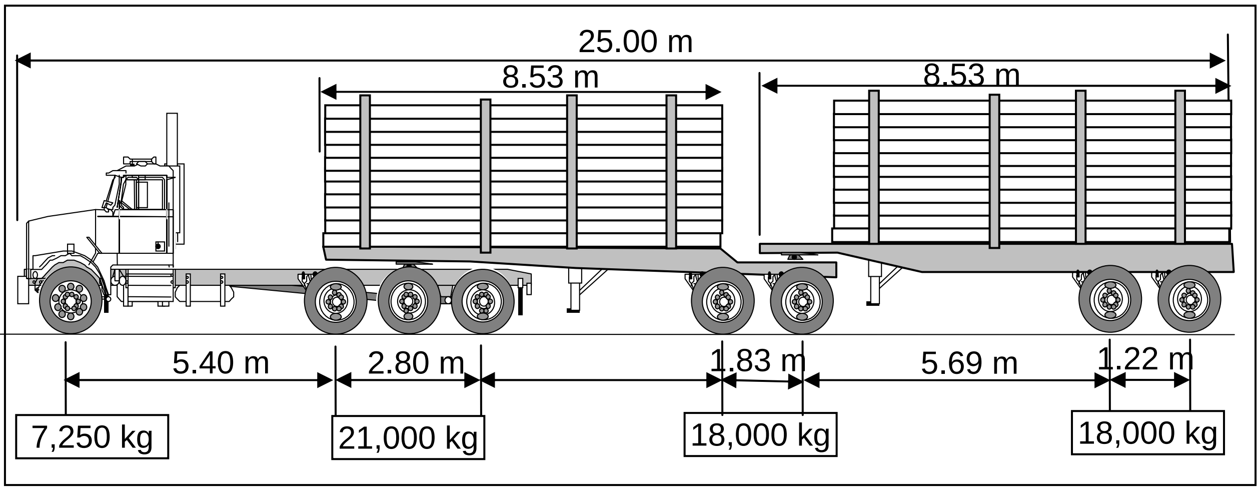
Load Level	CG	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
		90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
100%	H	0.419	**0.471**	**0.510**	0.490	0.522	0.552	0.477	0.578	0.682
100%	M	0.397	0.447	**0.499**	0.414	0.445	0.471	0.442	0.541	0.638
100%	L	0.381	0.431	**0.470**	0.346	0.379	0.398	0.418	0.515	0.603
75%	H	0.353	0.396	0.437	0.438	0.484	0.522	0.404	0.504	0.595
75%	M	0.345	0.389	0.433	0.375	0.419	0.455	0.388	0.485	0.573
75%	L	0.339	0.380	0.420	0.321	0.359	0.390	0.375	0.469	0.555
50%	H	0.322	0.360	0.391	0.368	0.413	0.454	0.349	0.439	0.524
50%	M	0.316	0.354	0.385	0.325	0.365	0.401	0.338	0.426	0.510
50%	L	0.310	0.348	0.380	0.284	0.319	0.351	0.329	0.415	0.498

7.6 Tridem Drive Tractor and Tandem-tandem B-train Log Trailer

7.6.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 26. Each trailer had a bed length of 8.53 m (28 ft), which with a minimum lead trailer inter-axle spacing of 5.50 m (217 in), and a minimum pup trailer wheelbase of 6.25 m (248 in), just allows the vehicle within an overall length of 25.0 m (82 ft). The allowable gross weight was 62,500 kg (137,787 lb), which allowed a maximum payload of 41,730 kg (92,000 lb), split equally between the two trailers. The lead trailer used a kingpin setback of 1.57 m (62 in), and the pup trailer used a kingpin setback of 0.30 m (12 in). The load was 7.92 m (26 ft) long on each trailer, which was the greatest length possible without overloading the centre tandem axle group. The load on the lead trailer was set fully forward to load the fifth wheel, and the load on the pup trailer was set fully rearward to load the pup tandem.

Figure 26: Tridem Drive Tractor and Tandem-tandem B-train Log Trailer



7.6.2 Results and Discussion

This configuration was run only with the maximum payload of 41,730 kg (92,000 lb), and at 50 and 75% of that payload, for payload heights of 1.22, 1.83 and 2.44 m (48, 72 and 96 in), at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h).

Logs found in eastern Canada have a block density of 500-750 kg/cu m (31-47 lb/cu ft), depending on the species of tree. This analysis used a 7.92 m (26 ft) long block of load on each trailer, which would have a height from 1.43 to 2.17 m (56 to 86 in) for this range of density. A load only 7.31 m (24 ft) long could have a height up to 2.36 m (93 in), while any longer load would have a lower height.

The static roll thresholds are shown in Table 56. Using the typical lower log density of 500 kg/cu m (31 lb/cu ft), and a 7.92 m (26 ft) long block of load on each trailer, as described above, and interpolating in Table 56, the static roll threshold would be about 0.366 g for the highest load of logs likely within the allowable gross weight.

The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 57, for all load levels and payload centre of gravity heights. **CG** is the payload height; **H** corresponds to a payload height of 2.44 m (96 in), **M** to a payload height of 1.83 m (72 in), and **L** to a payload height of 1.22 m (48 in). All performance measures increased with speed, payload weight, and payload height. High-speed offtracking exceeds the performance standard by up to 0.11 m (4 in) at 110 km/h (68.3 mi/h), but this will probably be satisfactory if operations at speeds of 100 km/h (62.1 mi/h) and more only occur on freeways. The load transfer ratio is essentially satisfactory, for the highest likely payload height of 2.17 m (86 in), as discussed above. It is fairly difficult to roll a B-train over in a lane change manoeuvre, because the two trailers roll out-of-phase with each other in the manoeuvre, so that load transfer of one offsets that of the other. Transient offtracking increases significantly with speed. It should be satisfactory at 100 km/h (62.1 mi/h), but exceeds the performance standard at 110 km/h (68.3 mi/h).

The dynamic performance of this configuration can be moderated by controlling both payload height and speed. The payload height on a log truck can be limited by limiting the height of the log bunks above the deck of the trailer. If such a limit should be considered, it should take account of the typical diameter of logs that are shipped, crowning of the load required for cargo securement, and any drop in the trailer frame. It may be appropriate to consider a speed limit of 100 km/h (62.1 mi/h) for this configuration for operation on freeways.

The lateral friction utilization was between about 0.59 and about 0.71, depending on the payload weight. These are within the performance standard of 0.80, principally because the front axle weight varies from about 34 to 48% of the drive tridem weight, well above the minimum of 27% required by Alberta [28] and Ontario [4]. Low-speed offtracking was 5.00 m (197 in), and other low-speed performance measures were all also well within their performance standards.

Table 56: Static Roll Threshold for Tandem-tandem B-train Log Trailer

Payload Height (m)	Static Roll Threshold (>0.35 g)		
	100% Payload	75% Payload	50% Payload
2.44	**0.334**	0.371	0.429
1.83	0.392	0.431	0.494
1.22	0.475	0.513	0.550

Table 57: High-speed Performance Measures for Tandem-tandem B-train

Load Level	CG	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
100%	H	**0.491**	**0.540**	**0.576**	0.544	**0.621**	**0.691**	0.670	**0.819**	**0.955**
100%	M	**0.467**	**0.516**	**0.552**	0.454	0.517	0.581	0.621	0.766	**0.899**
100%	L	0.447	**0.496**	**0.531**	0.378	0.429	0.480	0.583	0.719	**0.851**
75%	H	0.446	**0.495**	**0.532**	0.469	0.532	0.598	0.587	0.725	**0.856**
75%	M	0.430	**0.479**	**0.515**	0.401	0.456	0.507	0.560	0.691	**0.821**
75%	L	0.416	**0.465**	**0.501**	0.341	0.389	0.435	0.535	0.664	0.790
50%	H	0.408	0.457	**0.493**	0.387	0.444	0.499	0.516	0.645	0.769
50%	M	0.397	0.446	**0.482**	0.341	0.390	0.437	0.500	0.626	0.746
50%	L	0.388	0.436	**0.472**	0.297	0.339	0.381	0.485	0.609	0.725

8. TRIDEM-DRIVE STRAIGHT TRUCK

8.1 Vehicle Configurations

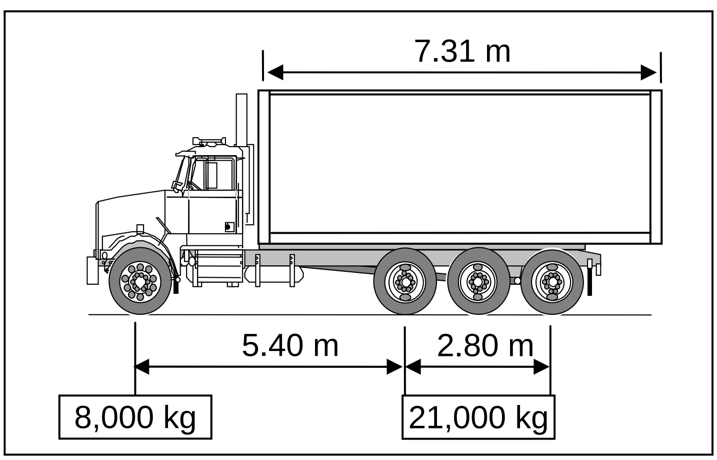
A generic tridem drive straight truck was configured with the following key properties:

1. Front axle setback of 1.22 m (48 in);
2. Bumper-to-back of cab (BBC) dimension of 2.90 m (114 in);
3. Front axle rated at 9,072 kg (20,000 lb);
4. 445 mm (18 in) wide front axle tires;
5. Tare weight of 13,381 kg (29,500 lb);
6. Tare front axle weight of 5,896 kg (13,000 lb);
7. Wheelbase of 6.60 m (260 in);
8. Tridem drive axle spread of 2.80 m (110 in);
9. Track width of 2.44 m (96 in) or 2.54 m (100 in); and
10. Load box length of 7.31 m (24 ft).

The dimensions are compatible with those of British Columbia [27] and Alberta [28]. Note that Alberta requires a track width of at least 2.50 m (98 in), while B.C. does not, so both were evaluated. The vehicle used the minimum wheelbase of 6.60 m (260 in), because it results in the lightest vehicle, and also because the front axle tends to get overloaded as the wheelbase increases for an end dump application. Other body styles with some rear overhang are much easier to load, but again there would not seem much need for a longer wheelbase except for a vehicle completed as a specialized piece of equipment.

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 27. The front axle was assumed to be rated at 9.072 kg (20,000 lb) [2], and could be loaded to this weight, but the vehicle was evaluated at a gross weight of 29,000 kg (63,933 lb).

Figure 27: Tridem Drive Straight Truck



A generic body was used, with a deck height of 1.42 m (56 in), and the vehicle was loaded with 15,422 kg (34,000 lb) of payload of uniform density. Runs were also made for 75% and 50% of this payload. Payload was considered with a height of 1.22, 1.83, 2.44 or 2.69 m (48, 72, 96 or 106 in). The latter represents the highest possible payload with a 1.42 m (56 in) deck height and an overall height of 4.15 m (162 in).

8.2 Results and Discussion

The static roll threshold for vehicles with wide- and narrow-track axles and the various payload levels and heights is presented in Table 58, and the load transfer ratio is presented in Table 59. Wide track axles demonstrate a clear benefit. This is consistent with the regulation in Alberta [28]. Other high-speed performance measures were designed primarily for trailers, so are not relevant to a single unit vehicle, and are not presented. It may be prudent to limit use of these vehicles to more dense payloads, and exclude high payloads like logs and waste.

The lateral friction utilization is between 0.60 and 0.70, well within the performance standard of 0.80, principally because the front axle weight is between 37 and 48% of the drive tridem weight, well above the minimum of 25% required by British Columbia [27] and Alberta [28]. Other low-speed performance measures meet the performance standards.

Table 58: Static Roll Threshold for Tridem Drive Straight Trucks

Payload Height (m)	Static Roll Threshold (>0.35 g)					
	Wide Track Axles			Narrow Track Axles		
	100%	75%	50%	100%	75%	50%
2.69	0.375	0.409	0.465	0.352	0.383	0.438
2.44	0.395	0.428	0.481	0.375	0.405	0.456
1.83	0.448	0.481	0.529	0.427	0.456	0.501
1.22	0.516	0.539	0.591	0.490	0.510	0.558

Table 59: Load Transfer Ratio for Tridem Drive Straight Trucks

Payload Height (m)	Load Transfer Ratio (<0.60)					
	Wide Track Axles			Narrow Track Axles		
	100%	75%	50%	100%	75%	50%
2.69	**0.677**	0.522	0.423	**0.736**	0.567	0.454
2.44	**0.621**	0.485	0.406	**0.669**	0.524	0.432
1.83	0.517	0.428	0.369	0.552	0.455	0.391
1.22	0.435	0.377	0.331	0.464	0.400	0.351

9. TRIDEM-DRIVE TRUCK-TRAILER COMBINATIONS

9.1 Vehicle Configurations

A tridem drive straight truck was configured to pull each of the following trailer configurations:

1. A tandem axle pony trailer; or
2. A tridem axle pony trailer.

Each trailer was configured either as a gravel dump or a log truck.

9.1.1 The Tridem Drive Truck

A generic tridem drive straight truck was configured with the same properties as described in Section 8.1, but only with wide-track axles. In addition, the truck was fitted with a towing hitch with a nominal hitch offset of 2.11 m (83 in) from the centre of the drive tridem, assuming 1.40 m (55 in) for half the tridem spread, plus 0.71 m (28 in) to the rear of the vehicle. Experience with tridem drive log trucks in British Columbia and Alberta suggests the minimum practical hitch offset is about 2.28 m (90 in). A vehicle was also considered with a hitch offset of 2.60 m (102 in), which is the maximum allowed by Alberta [28]. British Columbia restricts hitch offset to a maximum of 2.50 m (98 in) [27].

9.1.2 The Pony Trailers

The tandem axle pony trailer had a 4.72 m (15 ft 6 in) box length, a 1.22 m (48 in) spread tandem axle with a leaf spring suspension, and the M.o.U. minimum wheelbase of 6.25 m (246 in). The trailer had a tare weight of 5,670 kg (12,500 lb).

The tridem axle pony trailer also had a 4.72 m (15 ft 6 in) box length, a 2.44 m (96 in) spread tridem axle with a leaf spring suspension, and a wheelbase of 6.56 m (258 in), because the minimum tridem-tridem inter-axle spacing of 6.00 m (236 in) governed. The trailer had a tare weight of 6,577 kg (14,500 lb).

The same tare weight was used for the structure and load box of each pony trailer.

9.1.3 Loading

These truck-trailer combinations are most likely to haul materials related to construction, like sand, gravel or asphalt, to maintenance, like road salt, or logs. Asphalt has a density around 1,760 kg/cu m (110 lb/cu ft). Gravel has a density around 1,603-1,924 kg/cu m (100-120 lb/cu ft). Road salt has a density around 1,282 kg/cu m (80 lb/cu ft). Dump trucks were run using payload densities of 1,282 kg/cu m (80 lb/cu ft) and 1,760 kg/cu m (110 lb/cu ft). Logs found in eastern Canada have a block density of 500-750 kg/cu m (31-47 lb/cu ft), depending on the species of tree. Log trucks were run using payload densities of 500 kg/cu m (31 lb/cu ft) and 750 kg/cu m (47 lb/cu ft).

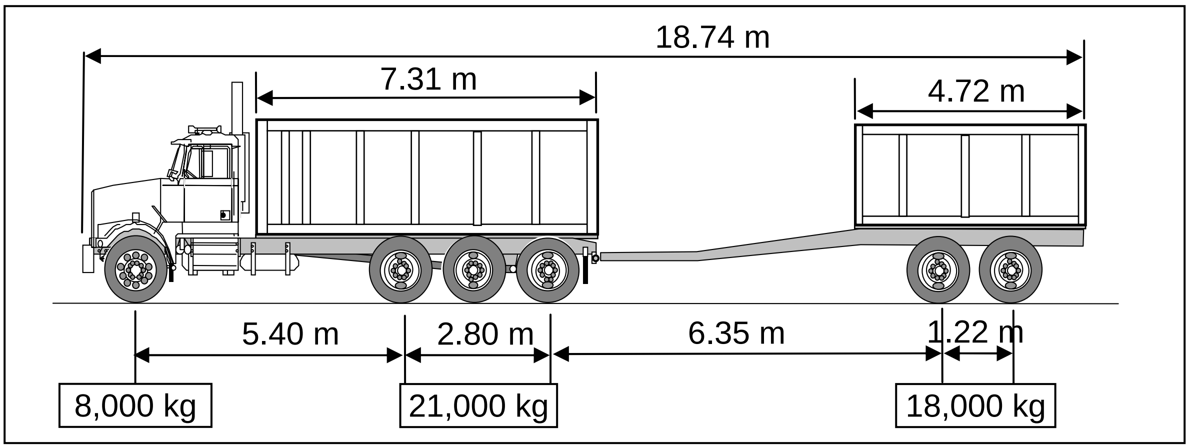
The payload was selected as an even number of thousands of pounds that brought the vehicle just below its allowable maximum gross weight and each allowable axle weight, with the maximum possible payload on the truck, and the balance on the trailer.

9.2 Tridem Drive Truck and Tandem Pony Trailer

9.2.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 28. The pony trailer has a box length of 4.72 m (15 ft 6 in), but with the minimum wheelbase of 6.25 m (246 in), it has a tandem-to-tridem inter-axle spacing greater than the minimum of 5.50 m (217 in). This combination was evaluated at a gross weight of 45,813 kg (101,000 lb), with a payload of 14,515 kg (32,000 lb) on the truck and 12,247 kg (27,000 lb) on the trailer, at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). No partial payloads were considered. The truck payload was lower than for the straight truck considered above due to the trailer weight transferred to the truck.

Figure 28: Tridem Drive Straight Truck and Tandem Pony Trailer



9.2.2 Results and Discussion

The static roll thresholds for payloads with a density of 500, 750, 1,282 and 1,760 kg/cu m (31, 47, 80 and 110 lb/cu ft) are presented in Table 60, for the two hitch offsets considered. Neither hitch offset nor speed affects the static roll threshold. In each case, the trailer rolls over before the truck.

The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 61 for a 2.11 m (83 in) hitch offset, and Table 62 for a 2.60 m (102 in) hitch offset. The pony trailer is presumed to roll over for a load transfer ratio of 1, indicated by "**Roll**" in the appropriate cells for load transfer ratio and transient offtracking. Each performance measure increases with speed, and is lower for the lower hitch offset. The high-speed offtracking performance standard is exceeded by no more than about 0.03 m (1 in) for each hitch offset, at a speed of 100 km/h (62.1 mi/h) or more. This should not be an issue for operation on a freeway, as discussed in Section 3.7.4. The transient offtracking performance standard is exceeded by up to 0.12 m (5 in) at 110 km/h (68.3 mi/h). The load transfer ratio performance standard of

0.60 is exceeded for all densities and speeds except one.

The lateral friction utilization is about 0.65, well within the performance standard of 0.80, because the front axle weight is 35.5% of the drive tridem weight, well above the minimum of 25% required by British Columbia [27] and Alberta [28]. Other low-speed performance measures are all well within their respective performance standards.

Table 60: Static Roll Threshold for Tridem Drive Truck and Tandem Pony Trailer

Payload Density (lb/cu ft)	Trailer Payload Height	Static Roll Threshold (>0.35 g) Hitch Offset 2.11 m	Static Roll Threshold (>0.35 g) Hitch Offset 2.60 m
31	2.14 m (84.3 in)	0.451	0.448
47	1.41 m (55.6 in)	0.550	0.549
80	0.83 m (32.7 in)	0.611	0.612
110	0.60 m (23.8 in)	0.635	0.638

Table 61: Performance Measures for 2.11 m Hitch Offset

Payload Density (lb/cu ft)	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
31	0.439	**0.463**	**0.482**	**0.892**	**0.992**	**Roll**	0.685	0.782	**Roll**
47	0.424	0.450	**0.464**	**0.757**	**0.817**	**0.881**	0.640	0.752	**0.862**
80	0.415	0.438	0.454	**0.635**	**0.693**	**0.749**	0.596	0.706	**0.805**
110	0.411	0.434	0.452	0.593	**0.648**	**0.710**	0.580	0.689	0.783

Table 62: Performance Measures for 2.60 m Hitch Offset

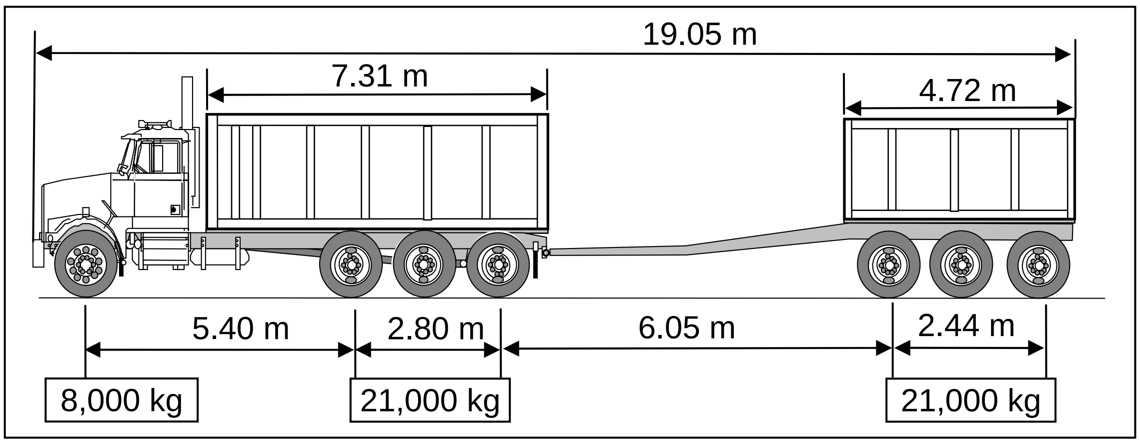
Payload Density (lb/cu ft)	High-speed Offtracking (<0.46 m)			Load Transfer Ratio (<0.60)			Transient Offtracking (<0.80 m)		
	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h	100 km/h	110 km/h
31	**0.464**	**0.483**	**0.496**	**0.904**	**Roll**	**Roll**	0.722	**Roll**	**Roll**
47	0.447	**0.471**	**0.489**	**0.790**	**0.850**	**0.940**	0.684	**0.804**	**0.922**
80	0.436	**0.460**	**0.476**	**0.663**	**0.722**	**0.776**	0.638	0.753	**0.863**
110	0.434	0.454	**0.472**	**0.619**	**0.676**	**0.734**	0.621	0.735	**0.841**

9.3 Tridem Drive Truck and Tridem Pony Trailer

9.3.1 Vehicle Configuration

The vehicle configuration, dimensions and allowable axle group weights are shown in Figure 29. The pony trailer has a box length of 4.72 m (15 ft 6 in). It has a wheelbase of 7.22 m (284 in), which is about the minimum possible with the minimum tridem-to-tridem inter-axle spacing of 6.00 m (236 in). This combination was evaluated at a gross weight of 49,215 kg (108,500 lb), with a payload of 14,515 kg (32,000 lb) on the truck and 14,741 kg (32,500 lb) on the trailer, at speeds of 90, 100 and 110 km/h (55.9, 62.1 and 68.3 mi/h). No partial payloads were considered. The truck payload was lower than for the straight truck considered above due to the trailer weight transferred to the truck.

Figure 29: Tridem Drive Straight Truck and Tridem Pony Trailer



9.3.2 Results and Discussion

The static roll thresholds for payloads with a density of 500, 750, 1,282 and 1,760 kg/cu m (31, 47, 80 and 110 lb/cu ft) are presented in Table 63, for the two hitch offsets considered. Neither hitch offset nor speed affects the static roll threshold. In each case, the trailer rolls over before the truck.

The high-speed offtracking, load transfer ratio and transient offtracking performance measures are shown in Table 64 for a 2.11 m (83 in) hitch offset, and Table 65 for a 2.60 m (102 in) hitch offset. The pony trailer is presumed to roll over for a load transfer ratio of 1, indicated by "**Roll**" in the appropriate cells for load transfer ratio and transient offtracking. Each performance measure increases with speed, and is lower for the lower hitch offset. The high-speed offtracking performance standard is exceeded by no more than about 0.05 m (2 in) for each hitch offset, at a speed of 100 km/h (62.1 mi/h) or more. This should not be an issue for operation on a freeway, as discussed in Section 3.7.4. The transient offtracking performance standard is exceeded by up to

0.10 m (4 in) at 110 km/h (68.3 mi/h). The load transfer ratio performance standard of 0.60 is exceeded for all densities and speeds except for 1,760 kg/cu m (110 lb/cu ft) at 90 km/h (55.9 mi/h), which covers asphalt and aggregates.

The lateral friction utilization is about 0.65, well within the performance standard of 0.80, because the front axle weight is about 35% of the drive tridem weight, well above the minimum of 25% required by British Columbia [27] and Alberta [28]. Other low-speed performance measures are all well within the respective performance standards.

Table 63: Static Roll Threshold for Tridem Drive Truck and Tridem Pony Trailer

Payload Density (lb/cu ft)	Trailer Payload Height	Static Roll Threshold (>0.35 g)	
		Hitch Offset	
		2.11 m	2.60 m
31	2.58 m (101.5 in)	0.365	0.366
47	1.70 m (66.9 in)	0.547	0.549
80	1.00 m (39.3 in)	0.608	0.615
110	0.73 m (28.6 in)	0.636	0.635

Table 64: Performance Measures for 2.11 m Hitch Offset

Payload Density (lb/cu ft)	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
31	0.440	**0.464**	**0.483**	**0.878**	**0.993**	**Roll**	0.665	0.765	**Roll**
47	0.428	0.448	**0.469**	**0.746**	**0.816**	**0.881**	0.621	0.732	**0.840**
80	0.420	0.441	**0.462**	**0.617**	**0.681**	**0.735**	0.579	0.688	0.785
110	0.417	0.438	0.459	0.570	**0.632**	**0.684**	0.566	0.674	0.767

Table 65: Performance Measures for 2.60 m Hitch Offset

Payload Density (lb/cu ft)	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
31	**0.462**	**0.486**	**0.505**	**0.903**	**Roll**	**Roll**	0.703	**Roll**	**Roll**
47	0.450	**0.472**	**0.489**	**0.776**	**0.853**	**0.926**	0.665	0.782	**0.900**
80	0.442	**0.463**	**0.484**	**0.644**	**0.711**	**0.773**	0.621	0.734	**0.841**
110	0.440	**0.460**	**0.481**	0.597	**0.661**	**0.715**	0.607	0.719	**0.821**

9.4 Discussion

These results are generally similar to those of the prior study of tandem and tridem pony trailers towed by twin-steer straight trucks [18]. This is not surprising, because the performance measures are designed primarily for trailers, and the response of a trailer does not depend greatly on the vehicle that tows it, because the path of the towing vehicle is prescribed for each manoeuvre, as described in Section 2.1.

It is important that the hitch offset should be the minimum possible. A tridem drive truck requires a greater hitch offset than the 1.80 m (71 in) specified for single and tandem drive trucks, because the spacing from the centre to rearmost drive axle immediately uses up 1.40 m (55 in), and the tire radius accounts for another 0.50 m (20 in). Experience with tridem drive log trucks in British Columbia and Alberta suggests the minimum practical hitch offset is about 2.28 m (90 in). Alberta has a significantly greater hitch offset allowance because many of the tridem drive trucks are actually a piece of equipment, and vehicle features like hoists and landing legs occupy space that would otherwise be available for the pintle hook.

The tridem pony trailer configuration was evaluated with a box length of 4.72 m (15 ft 6 in), which is quite suitable for commodities like asphalt and gravel. The trailer could support a 7.31 m (24 ft) box, which might be more suitable for logs. A load of this length would have the same effect as an increase in density of 500 kg/cu m (31 lb/cu ft) to 750 kg/cu m (47 lb/cu ft), or of 750 kg/cu m (47 lb/cu ft) to 1,125 kg/cu m (70 lb/cu ft), in Table 63, Table 64 and Table 65. The effect on performance of this change may be determined by interpolation for density from Table 63, Table 64 and Table 65. Effectively, using the longer box length for a commodity with a modest density like logs would result in similar dynamic performance to a denser commodity like road salt, asphalt or gravel in the shorter box.

10. EFFECT OF WIND ON VAN SEMITRAILERS

10.1 Vehicle Configurations

This analysis estimated the effect of a steady wind, and a gust superimposed on a steady wind, on rollover and offtracking of the following combinations:

1. 16.20 m (53 ft) tandem semitrailer; or
2. Twin 16.20 m (53 ft) tandem semitrailer LCV configuration.

10.2 Method of Analysis

Aerodynamic data from the literature was previously processed to give side force and moment coefficients about the centre of gravity of a wind tunnel model [30], [31]. From these data, the position of the centre of pressure of the model trailer was computed assuming a uniform distribution of pressure over the entire side area of the vehicle. The aerodynamic force then is composed of the side force coefficient, applied at a specified location on the trailer. The final piece of aerodynamic data is the gust factor, which multiplies the wind speed to represent a maximum likely gust. The gust was considered as an increase in wind speed of 20-30% of the steady wind speed for a period of 2-4 s.

There are two ways that wind may affect the performance of a vehicle, rollover and offtracking. The risk of rollover may be evaluated by the load transfer ratio performance measure. The load transfer ratio performance standard of 0.60 means that the wheels on one side of the vehicle carry 20% of the vehicle's weight, with 80% carried by the wheels on the other side. This leaves quite a slender margin for the driver to manoeuvre without lifting wheels in a curve. Wind may also cause trailers to offtrack, also known as dogtracking. In this case, the appropriate performance standard is that for high-speed offtracking, where 0.46 m (18 in) of offtracking of the rearmost axle of a 2.59 m (102 in) wide vehicle allows it within 0.08 m (3 in) of the edge of a 3.66 m (144 in) wide lane with the tractor centred in the lane.

A standard run used the driver model to cause the vehicle to follow a straight path at a specified speed. The wind began immediately, at its specified speed, and the simulation ran for 15 s to allow the vehicle responses to reach a steady state. At this point, the wind speed was increased instantaneously by the gust factor for 4 s, when the gust was removed, and the simulation ran for another 1 s, unless it had already been terminated by rollover. When the run was completed, the results were scanned and the following four performance measures were computed:

1. The average load transfer ratio for 2 s immediately prior to the gust;
2. The average offtracking of the rearmost axle from the front axle for the same period;
3. The maximum load transfer ratio during the gust; and
4. The maximum offtracking of the rearmost axle from the front axle during the gust.

10.3 16.20 m (53 ft) Semitrailers

10.3.1 Vehicle Configuration

The tractor and semitrailer were the same as used in the LCV configurations described in Section 3.1.2. The 16.20 m (53 ft) semitrailer had a tandem axle with a middle wheelbase of 11.89 m (488 in).

The vehicles were considered empty, and with a payload in increments of 2,268 kg (5,000 lb) up to a total of 11,340 kg (25,000 lb), distributed uniformly over the forward 15.85 m (52 ft) of the semitrailer, and with a payload height of 1.22 m (48 in).

10.3.2 Results and Discussion

Table 66 presents the load transfer ratio of an empty 16.2 m (53 ft) semitrailer induced by steady or gusting winds. Values in bold indicate that the performance measure exceeded the performance standard of 0.60, and **Roll** indicates the vehicle rolled over. Load transfer ratio increases with wind speed, and for a given wind speed, diminishes with vehicle speed. Travel may be feasible in a steady non-gusting wind up to about 75 km/h (46.6 mi/h), but becomes risky at about 50 km/h (31 mi/h) in a strongly gusting wind. These values would be lower for stationary or slow-moving vehicles. The results in Table 66 are plotted in Figure 30, in two groups of four lines. For each group, the upper line is for a vehicle speed of 40 km/h (24.8 mi/h), and subsequent lines follow in order to the lowest line for a vehicle speed of 100 km/h (62.1 mi/h).

Table 67 presents load transfer ratio for the same vehicle traveling at 40 km/h (24.8 mi/h) induced by steady or gusting winds for various weights of payload in the trailer. It requires a payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) to achieve a significant increase in the resistance to wind-induced rollover. Payload centre of gravity height appeared to have little influence on wind-induced load transfer ratio.

Table 68 presents offtracking of an empty 16.2 m (53 ft) semitrailer induced by steady or gusting winds. **Roll** indicates the vehicle rolled over. Wind-induced offtracking increases with wind speed, and for a given wind speed, diminishes with vehicle speed. Offtracking increases rapidly for stronger winds, and clearly becomes an issue for a steady wind speed over 75 km/h (46.6 mi/h), or at about 50 km/h (31 mi/h) in a strongly gusting wind. Coincidentally, these are the same speeds at which rollover becomes a concern. These results are plotted in Figure 31, in the same format as Figure 30.

Table 69 presents offtracking for the same vehicle traveling at 40 km/h (24.8 mi/h) induced by steady or gusting winds for various weights of payload in the trailer. It requires a payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) to achieve a significant reduction in wind-induced offtracking.

A single axle 16.20 m (53 ft) semitrailer would be more sensitive to wind than the tandem axle semitrailer considered here, but such vehicles are quite rare.

Table 66: Wind-induced Load Transfer Ratio, Empty Semitrailer

Vehicle Speed (km/h)	Wind-induced Load Transfer Ratio (<0.60)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	**50**	**60**	**70**	**80**	**40**	**50**	**60**	**70**	**80**
40	0.145	0.233	0.343	0.472	**0.625**	0.305	0.546	**0.857**	**0.973**	**Roll**
60	0.134	0.218	0.326	0.452	0.598	0.223	0.415	**0.674**	**0.848**	**Roll**
80	0.126	0.206	0.308	0.433	0.577	0.183	0.333	0.545	**0.739**	**Roll**
100	0.121	0.197	0.294	0.412	0.550	0.158	0.286	0.459	**0.643**	**Roll**

Table 67: Wind-induced Load Transfer Ratio, Loaded Semitrailer

Payload (lb)	Wind-induced Load Transfer Ratio (<0.60)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	**50**	**60**	**70**	**80**	**40**	**50**	**60**	**70**	**80**
0	0.145	0.233	0.343	0.472	**0.625**	0.305	0.546	**0.857**	**0.973**	**Roll**
5000	0.119	0.191	0.280	0.387	0.512	0.250	0.447	**0.699**	**0.788**	**Roll**
10000	0.100	0.162	0.238	0.328	0.434	0.212	0.379	0.592	**0.668**	**Roll**
15000	0.087	0.141	0.207	0.285	0.377	0.185	0.330	0.515	0.582	**Roll**
20000	0.077	0.125	0.183	0.253	0.334	0.164	0.292	0.457	0.516	**0.893**
25000	0.070	0.112	0.165	0.227	0.301	0.148	0.262	0.411	0.464	**0.802**

Figure 30: Wind-induced Load Transfer Ratio, Empty Semitrailer

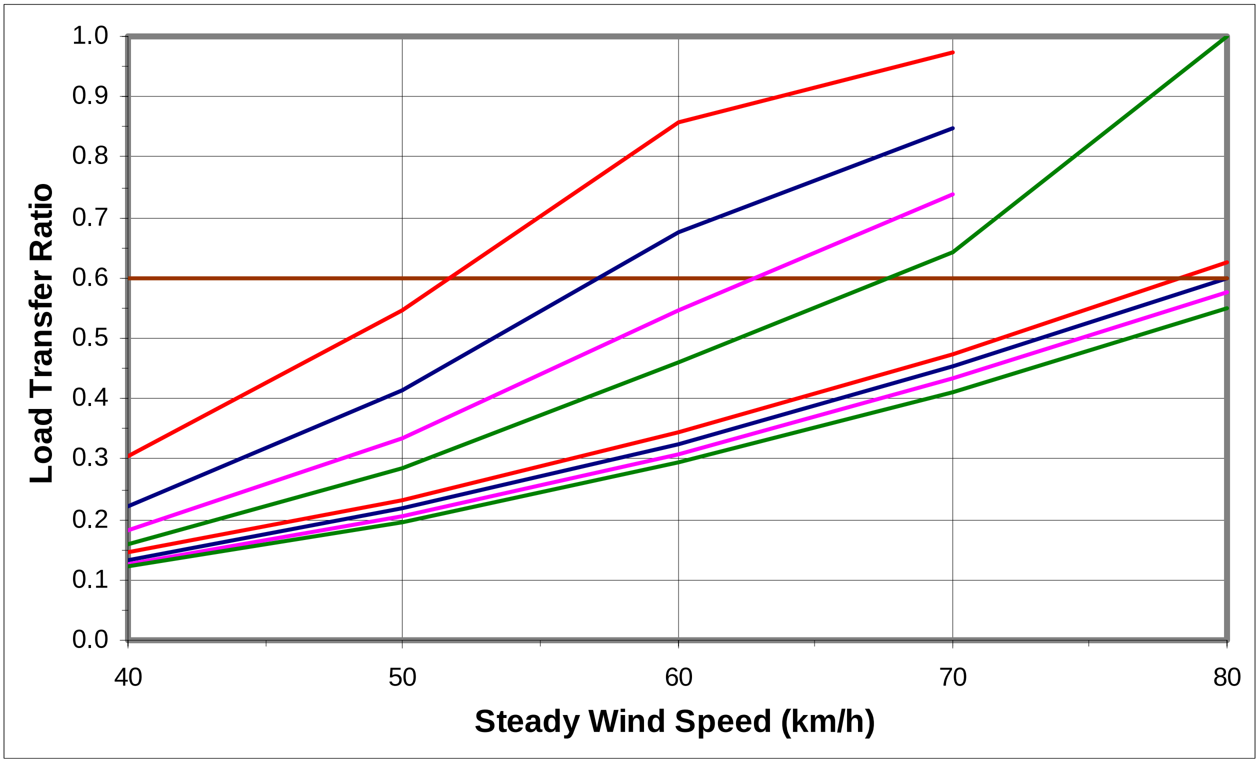


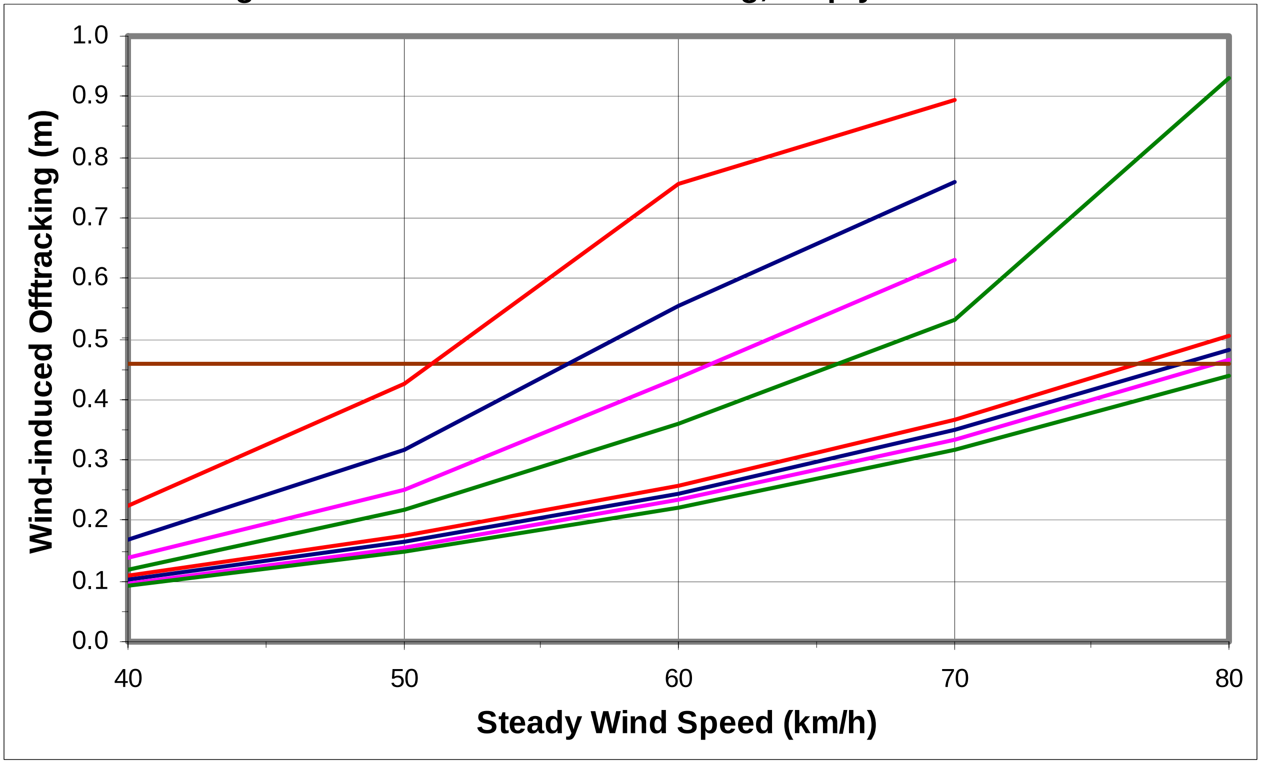
Table 68: Wind-induced Offtracking, Empty Semitrailer

Vehicle Speed (km/h)	Wind-induced Offtracking (<0.46 m)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	50	60	70	80	40	50	60	70	80
40	0.109	0.175	0.258	0.366	**0.506**	0.226	0.427	**0.756**	**0.895**	**Roll**
60	0.101	0.164	0.245	0.350	**0.483**	0.168	0.316	**0.554**	**0.759**	**Roll**
80	0.096	0.155	0.233	0.333	**0.464**	0.138	0.251	0.436	**0.630**	**Roll**
100	0.092	0.150	0.222	0.317	0.440	0.120	0.217	0.361	**0.531**	**Roll**

Table 69: Wind-induced Offtracking, Loaded Semitrailer

Payload (lb)	Wind-induced Offtracking (<0.46 m)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	50	60	70	80	40	50	60	70	80
0	0.109	0.175	0.258	0.366	**0.506**	0.226	0.427	**0.756**	**0.895**	**Roll**
5000	0.086	0.138	0.205	0.286	0.394	0.179	0.331	**0.560**	**0.664**	**Roll**
10000	0.072	0.117	0.175	0.244	0.326	0.153	0.278	**0.464**	**0.535**	**Roll**
15000	0.064	0.103	0.153	0.214	0.285	0.134	0.244	0.398	0.459	**Roll**
20000	0.058	0.094	0.138	0.192	0.255	0.121	0.219	0.350	0.403	**0.793**
25000	0.054	0.086	0.127	0.176	0.234	0.111	0.201	0.315	0.360	**0.697**

Figure 31: Wind-induced Offtracking, Empty Semitrailer



Tridem and self-steer quad 16.20 m (53 ft) semitrailers would be slightly less sensitive to wind than tandem semitrailers when empty, or carrying the same payload weight.

10.4 LCV Configurations

10.4.1 Vehicle Configuration

These vehicles were the same LCV configurations as described in Section 3.1.2. Each 16.20 m (53 ft) semitrailer had a tandem axle with a middle wheelbase of 11.89 m (488 in).

Each semitrailer was considered empty, and with a payload in increments of 2,268 kg (5,000 lb) up to a total of 11,340 kg (25,000 lb), distributed uniformly over the forward 15.85 m (52 ft) of the semitrailer, and with a payload height of 1.22 m (48 in).

10.4.2 Results and Discussion

Table 70 presents the load transfer ratio of an empty LCV induced by steady or gusting winds, in the same format as Table 66. Load transfer ratio increases with wind speed, and for a given wind speed, diminishes with vehicle speed. Travel may be feasible in a steady non-gusting wind up to about 75 km/h (46.6 mi/h), but becomes risky at about 50 km/h (28 mi/h) in a strongly gusting wind. These are the same results as for tractor-semitrailers, though in all cases it is the second trailer that rolls over first. The results in Table 70 are plotted in Figure 32, in two groups of four lines. For each group, the upper line is for a vehicle speed of 40 km/h (24.8 mi/h), and subsequent lines follow in order to the lowest line for a vehicle speed of 100 km/h (62.1 mi/h).

Table 71 presents load transfer ratio for the same vehicle traveling at 40 km/h (24.8 mi/h) induced by steady or gusting winds for various weights of payload in each trailer. It requires a payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) in each trailer to achieve a significant increase in the resistance to wind-induced rollover.

Table 72 presents offtracking of an LCV induced by steady or gusting winds, in the same format as Table 68. Offtracking increases rapidly for stronger winds, and clearly becomes an issue for a steady wind speed between 50 and 60 km/h (31 and 37.3 mi/h), or over 40 km/h (24.8 mi/h) in a strongly gusting wind. Wind-induced offtracking is therefore the critical performance measure for LCV’s. These results are plotted in Figure 33, in the same format as Figure 30. Wind-induced offtracking of an LCV is greater than for a 16.20 m (53 ft) semitrailer, because the wind causes offtracking of the first semitrailer as discussed above, then causes additional offtracking of the second semitrailer.

Table 73 presents offtracking for the same vehicle traveling at 40 km/h (24.8 mi/h) induced by steady or gusting winds for various weights of payload in each trailer. It requires a payload of 6,800 to 11,300 kg (15,000 to 25,000 lb) in each trailer to achieve a significant reduction in wind-induced offtracking.

Table 70: Wind-induced Load Transfer Ratio, Empty LCV

Vehicle Speed (km/h)	Wind-induced Load Transfer Ratio (<0.60)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	**50**	**60**	**70**	**80**	**40**	**50**	**60**	**70**	**80**
40	0.157	0.253	0.372	0.513	**0.678**	0.333	0.596	**0.921**	**Roll**	**Roll**
60	0.146	0.237	0.354	0.492	**0.650**	0.244	0.452	**0.735**	**0.917**	**Roll**
80	0.137	0.224	0.335	0.470	**0.626**	0.198	0.361	0.589	**0.801**	**Roll**
100	0.132	0.215	0.320	0.449	0.598	0.172	0.312	0.498	**0.694**	**Roll**

Table 71: Wind-induced Load Transfer Ratio, Loaded LCV

Payload (lb)	Wind-induced Load Transfer Ratio (<0.60)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	**50**	**60**	**70**	**80**	**40**	**50**	**60**	**70**	**80**
0	0.157	0.253	0.372	0.513	**0.678**	0.333	0.596	**0.921**	**Roll**	**Roll**
5000	0.125	0.202	0.296	0.408	0.539	0.266	0.474	**0.743**	**0.842**	**Roll**
10000	0.104	0.167	0.246	0.339	0.449	0.221	0.395	**0.618**	**0.697**	**Roll**
15000	0.089	0.144	0.211	0.291	0.385	0.189	0.339	0.532	**0.600**	**Roll**
20000	0.078	0.126	0.185	0.255	0.338	0.168	0.298	0.466	0.526	**0.928**
25000	0.070	0.113	0.165	0.228	0.302	0.149	0.266	0.417	0.470	**0.819**

Figure 32: Wind-induced Load Transfer Ratio, Empty LCV

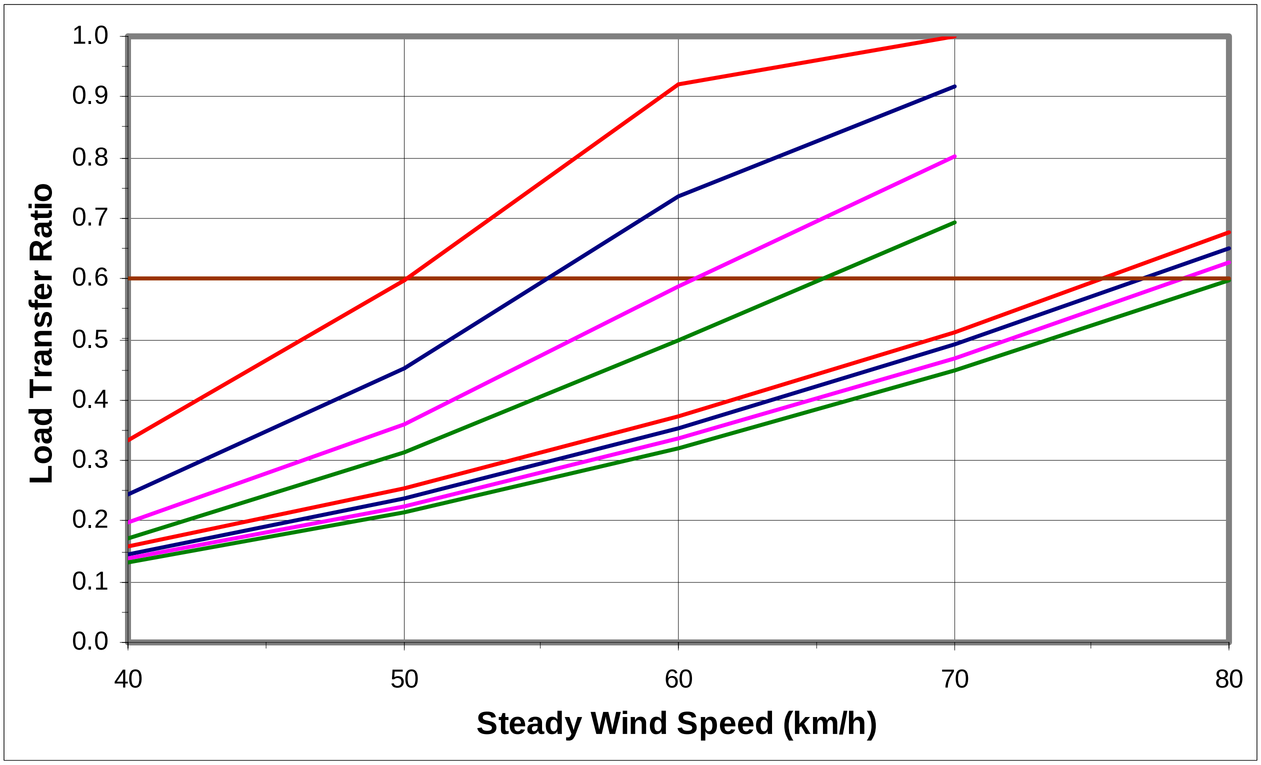


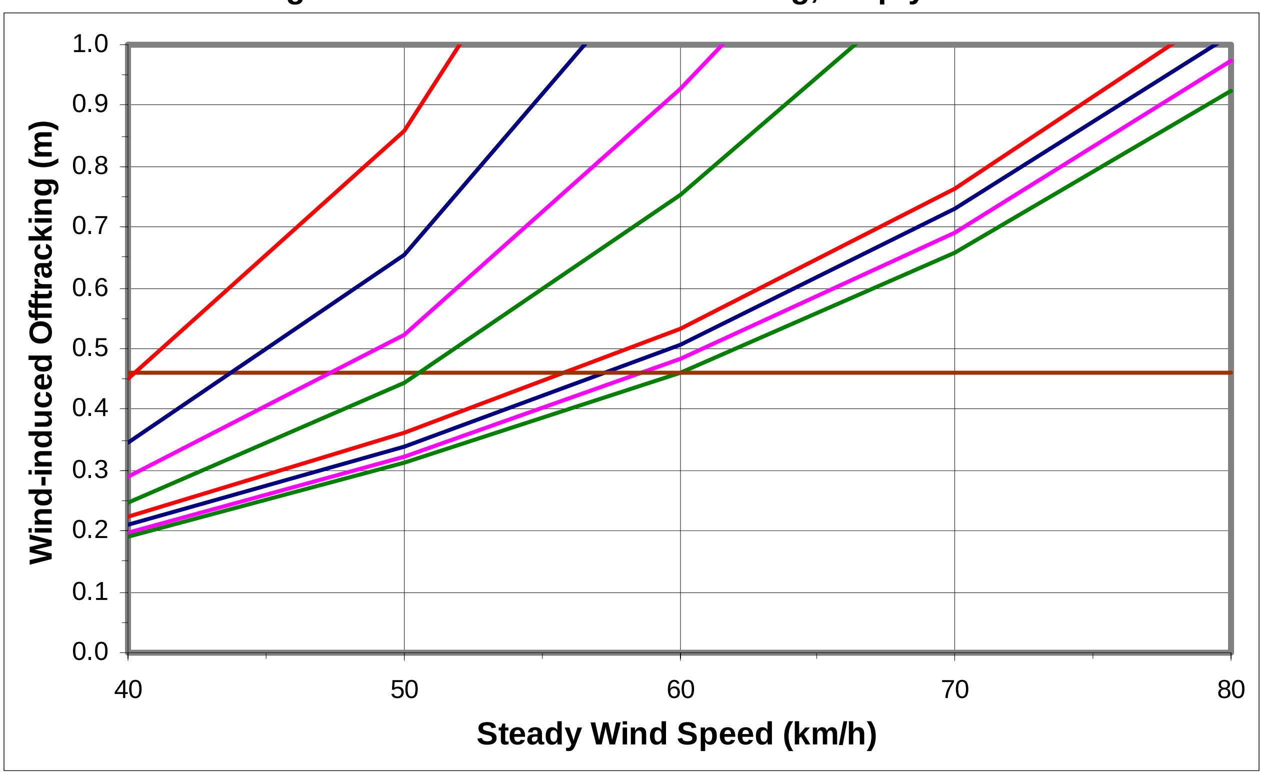
Table 72: Wind-induced Offtracking, Empty LCV

Vehicle Speed (km/h)	Wind-induced Offtracking (<0.46 m)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	50	60	70	80	40	50	60	70	80
40	0.225	0.362	**0.532**	**0.764**	**1.067**	0.450	**0.858**	**1.567**	**Roll**	**Roll**
60	0.209	0.338	**0.507**	**0.729**	**1.017**	0.347	**0.655**	**1.185**	**1.655**	**Roll**
80	0.199	0.322	**0.482**	**0.692**	**0.975**	0.288	**0.522**	**0.928**	**1.402**	**Roll**
100	0.191	0.311	**0.461**	**0.658**	**0.924**	0.247	0.445	**0.752**	**1.141**	**Roll**

Table 73: Wind-induced Offtracking, Loaded LCV

Payload (lb)	Wind-induced Offtracking (<0.46 m)									
	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
	40	50	60	70	80	40	50	60	70	80
0	0.225	0.362	**0.532**	**0.764**	**1.067**	0.450	**0.858**	**1.567**	**Roll**	**Roll**
5000	0.174	0.280	0.415	**0.581**	**0.810**	0.349	**0.648**	**1.114**	**1.337**	**Roll**
10000	0.145	0.235	0.350	**0.489**	**0.657**	0.294	**0.535**	**0.906**	**1.055**	**Roll**
15000	0.127	0.205	0.304	0.424	**0.568**	0.255	**0.464**	**0.767**	**0.893**	**Roll**
20000	0.115	0.185	0.273	0.378	**0.505**	0.230	0.414	**0.667**	**0.776**	**1.545**
25000	0.105	0.170	0.250	0.346	**0.460**	0.211	0.378	**0.596**	**0.688**	**1.341**

Figure 33: Wind-induced Offtracking, Empty LCV



11. CONCLUSIONS

11.1 Scope

This work has assessed the dynamic performance of:

1. Long combination vehicles (LCV's) for general freight;
2. LCV's for international containers;
3. Self-steer quad semitrailers for general freight;
4. Self-steer quad semitrailers for bulk liquids;
5. Tridem drive tractor-semitrailers;
6. Tridem drive straight trucks; and
7. Tridem drive truck-trailer combinations.

It also includes a brief assessment of the effect of wind on rollover of tractor-semitrailers and LCV's.

11.2 Dynamic Performance of LCV's for General Freight

Any of the LCV configurations with a typical tandem semitrailer payload weight up to about 20,411 kg (45,000 lb), and up to 2.44 m (96 in) in height, would be expected to have a static roll threshold close to or higher than 0.40 g. Higher payload weight on the lead semitrailer, with a height over 1.83 m (72 in), results in a static roll threshold for the tractor-semitrailer between 0.35 and 0.40 g. A static roll threshold over 0.40 g can be achieved either by limiting payload weight to about 20,411 kg (45,000 lb), or by limiting payload height to 1.83 m (72 in) if the payload weight exceeds 20,411 kg (45,000 lb).

The load transfer ratio and transient offtracking each approach or exceed their respective performance standards for the heaviest vehicles with the highest payloads when operated at 100 km/h. The results suggest there may be a trade-off between limiting speed and limiting payload height and/or weight. A speed limit of 90 km/h (55.9 mi/h) would be appropriate to ensure moderate load transfer ratio and transient offtracking, combined with the payload limits described above.

The high-speed offtracking of some LCV configurations may exceed the performance standard for some payload conditions using the standard method of evaluation. However, in practice, if LCV's are restricted to operation only on freeways at 90 km/h (55.9 mi/h), curves will have a much larger radius than that used in the standard method of evaluation, so the lateral acceleration should always be much less than 0.20 g, and the performance standard should never be approached. It may also be appropriate to limit speed to control high-speed offtracking on access routes which have curves with a radius between about 250 and 400 m (820 and 1,312 ft).

It is known that traffic moving below the legal speed limit on freeways is a concern to some road safety authorities. However, there are a number of trucking companies that voluntarily operate at around 90 km/h (55.9 mi/h) to conserve fuel. It is also evident that certain classes of vehicle, like mobile cranes, certain heavy haul vehicles, and convoys of military vehicles, consistently operate on freeways at a speed less than 100 km/h (62.1 mi/h).

These vehicles exceed both low-speed offtracking and rear outswing performance standards by a wide margin, but this should not be an issue since these vehicles will presumably operate under a route-specific permit that only allows them to go where they can make the turns.

When there is a difference in weight between the two trailers, the high-speed dynamic performance is better when the heavier of the two is the lead trailer. There is no apparent reason from the point of view of dynamic performance why the rear trailer, or both trailers, should not be empty.

If existing trailers are modified to add a pintle hook and air supplies for the pup trailer, the work should be done to objective standards, preferably by the original manufacturer of the trailer, or another company properly qualified to do the work. The airbrake timing of the modified trailer, and of an entire combination, should be checked.

11.3 Dynamic Performance of LCV’s for International Containers

The roll threshold for tractor-semitrailers, and these vehicles, carrying high-cube containers loaded to their rating and with a high payload, is poor. All configurations exceed the load transfer ratio and transient offtracking performance standards, even with a moderate payload height, and at 90 km/h (55.6 mi/h). Most configurations exceed the high-speed offtracking performance standard, but this will also not be an issue for permit operation at 90 km/h (55.9 mi/h) on freeways, as discussed above for LCV’s.

11.4 Dynamic Performance of Self-steer Quad Semitrailers for General Freight

Self-steer quad semitrailers exceed the high-speed offtracking performance standard for the highest payload heights and speeds, but only by about 0.10 m (4 in) at 110 km/h (68.3 mi/h). This level of deviation has been accepted by Ontario and Québec in their specifications for self-steer quad semitrailers. These vehicles should not exceed the performance standard if they only operate on freeways at speeds over 90 km/h (55.9 mi/h). There is little difference in high-speed offtracking performance between 14.65 and 16.20 m (48 and 53 ft) semitrailers. In contrast, the load transfer ratio and transient offtracking of 14.65 m (48 ft) semitrailers is consistently higher than for 16.20 m (53 ft) semitrailers, due to their shorter wheelbase, but all configurations meet these performance standards. All configurations also meet all low-speed performance standards.

The length of a self-steer quad semitrailer depends largely on the body style of the semitrailer. A van needs to be 16.20 m (53 ft) long so that it is available for backhauls that would normally travel in a 16.20 m (53 ft) tandem or tridem semitrailer, at a payload weight appropriate to those semitrailers. Other body styles, like flatbeds, tankers and log trucks, that carry dense or bulk commodities, or heavy loads, lose payload due to the additional tare weight if they are longer than the minimum length necessary for inter-axle spacings. In practice, most of these are 14.65 m (48 ft) long.

11.5 Dynamic Performance of Self-steer Quad Tankers

Tank trucks have a significantly higher rate of rollover than the truck fleet as a whole. European countries now have a minimum static roll threshold of 0.40 g for tank trucks, and Australia is considering the same value. This would be an appropriate standard for consideration. Any requirement should probably be phrased as “for the critical (maximum) payload, either demonstrate a static roll threshold above 0.40 g by test, or the combined centre of gravity of the sprung mass and payload shall be as low as possible, but not more than 2.30 m above the ground”. It would also be appropriate to require that both tractor and semitrailer should each be equipped with an electronic roll stability system. Other aspects of dynamic performance of self-steer quad tankers are essentially the same as for general freight vehicles.

11.6 Dynamic Performance of Tridem Drive Tractor-semitrailers

A tridem drive tractor with a single axle, tandem, tridem or self-steer quad semitrailer meets all the performance standards when loaded to its allowable gross weight with a high payload, except for high-speed offtracking for a self-steer quad. However, this should not be an issue if these vehicles only operate on freeways at speeds over 90 km/h (55.9 mi/h). The semitrailer wheelbase must be limited to 12.00 m (616 in) to meet the low-speed offtracking performance standard. When a tridem drive tractor pulls a tandem-tandem B-train log hauler, the high-speed offtracking and transient offtracking fail the performance standard at 110 km/h (68.3 mi/h). High-speed offtracking is not a significant issue for operation on freeways, but transient offtracking is. The low allowable load on the tridem drive axle group ensures that the lateral friction utilization performance standard is met.

11.7 Dynamic Performance of Tridem Drive Straight Trucks

A tridem drive straight truck needs wide-track axles to achieve a satisfactory static roll threshold and load transfer ratio, though it still exceeds the performance standards for these for the heaviest and highest payloads. The low allowable load on the tridem drive axle group ensures that the lateral friction utilization performance standard is met.

11.8 Dynamic Performance of Tridem Drive Truck-trailer Combinations

These vehicles fail the load transfer ratio performance standard for essentially any commodities they might haul, though performance is best for dense loads like asphalt and aggregates. A tridem pony trailer should have as long a box as possible to minimize the payload height. The hitch offset should be the minimum possible.

11.9 Effect of Wind on Van Semitrailers

A strong wind may blow over a vehicle with a large exposed face, like a 16.20 m (53 ft) van semitrailer, or an LCV composed of two such semitrailers, and may also cause the semitrailers to offtrack. It is appropriate to use the load transfer ratio performance measure to assess rollover, and the high-speed offtracking performance measure to assess wind-induced offtracking.

Load transfer ratio and offtracking both increase with wind speed, and for a given wind speed, both diminish with vehicle speed. The critical case is for a pure side wind, at 90 deg to the direction of travel of the vehicle.

An empty tractor-tandem semitrailer reaches both the load transfer ratio and offtracking performance standards when a steady non-gusting wind reaches about 75 km/h (46.6 mi/h), or the steady component of a strongly gusting wind reaches about 50 km/h (31 mi/h). These values are lower for stationary or slow-moving vehicles. It requires a payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) to achieve a significant increase in the resistance to wind-induced rollover and offtracking.

An empty LCV with tandem semitrailers reaches the load transfer ratio performance standard when a steady non-gusting wind reaches about 75 km/h (46.6 mi/h), or the steady component of a strongly gusting wind reaches about 50 km/h (31 mi/h). These are the same values as for a tractor-semitrailer, though the second trailer always blew over before the tractor and lead semitrailer. An empty LCV reaches the offtracking performance standard when a steady non-gusting wind reaches about 55 km/h (34.2 mi/h), or the steady component of a strongly gusting wind reaches about 40 km/h (24.8 mi/h). A payload of 4,500 to 6,800 kg (10,000 to 15,000 lb) in each trailer provides a significant increase in the resistance to wind-induced rollover, but there is little improvement in wind-induced offtracking until there is a payload of 11,340 kg (25,000 lb) in each trailer. This allows travel while the steady component of a strongly gusting wind does not exceed about 55 km/h (34.2 mi/h).

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