Stability and Control Analysis of Tandem-Tandem Trucks and Truck-Trailer Combinations

Prepared for

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1. Introduction

The national Memorandum of Understanding on Vehicle Weights and Dimensions ("the M.o.U.") initially covered tractor-semitrailers and A-, B- and C-train doubles [1]. While the M.o.U. was being implemented, the provinces were asked about other vehicles, and they expressed a desire that these should be regulated using the same criteria as the vehicles then covered by the M.o.U. The most common of these other vehicles were straight trucks and truck-trailer combinations, so a study was conducted of the dynamic performance of these vehicles [2]. The single-single and single-tandem were the only straight trucks that met all performance standards. All other configurations had various performance deficiencies that would preclude them from consideration, so the only truck-trailer combinations considered were those hauled using a single-tandem straight truck. As a consequence of this study, and some tests [3], straight truck, truck-pony trailer and truck-full trailer combinations were added to the M.o.U. in 1991.

A four-axle straight truck with a tandem steer axle and a tandem drive axle has been widely used in Quebec for a long time, primarily for garbage, as a dump truck, and as a flatbed for construction materials. It is allowed 16,000 kg (35,273 lb) on the front tandem and 18,000 kg (39,683 lb) on the drive tandem with the gross weight limited at 32,000 kg (70,547 lb), or less if the inter-axle spacing is less than 3.0 m (118 in). A gross weight of 34,000 kg (74,956 lb) is allowed until the end of 1999 for dump trucks hauling construction and road maintenance payloads. The tandem-tandem truck may also tow a pony trailer or full trailer, and the trailer is not required to meet the dimensional limits of the M.o.U. The tandem-tandem truck is also used as a ready-mix concrete truck in most provinces, either by permit or regulation. While there are other specialised tandem-tandem trucks in some provinces, they are not common anywhere except Quebec. There are now a number of these trucks in use as dump trucks in Nova Scotia. The province has some questions regarding both configuration of these vehicles, and their suitability for towing trailers.

The principal reason the previous study [2] did not recommend the tandem-tandem straight truck for consideration was that it potentially had a low rollover threshold for typical uses. However, Nova Scotia is considering their use, primarily as end dump trucks for such materials as gravel, asphalt and salt. The payload centre of gravity height would then be quite well controlled by the high density of the payload. These trucks may also be required to pull trailers. Since the previous study considered the truck unsuitable for general use as a single unit, and merely towing a trailer would not rectify any of those deficiencies, the tandem-tandem truck-trailer combination was not investigated [2]. The trailer configuration rules from that study were based on trailer responses while towed by a single-tandem truck. However, the truck is not considered to have a strong effect on trailer response.

This study examines the dynamic performance of tandem-tandem straight trucks and truck-trailer combinations, in comparison with single-tandem straight trucks and truck-trailer combinations with the dimensions of the M.o.U. and Nova Scotia loads. It is conducted by computer simulation using the same methodology as the earlier study [2].

2. Vehicle Configurations

2.1 The Baseline Three-axle Truck

This is a study of tandem-tandem trucks and truck-trailers. However, the M.o.U. is based on the performance of a single-tandem truck, so a generic three-axle dump truck was configured for comparative purposes with the following key properties:

- front axle rated at 9,072 kg (20,000 lb);
- 445 mm (18 in) wide front axle tires;
- tare weight of 9,979 kg (22,000 lb);
- tare front axle weight of 5,443 kg (12,000 lb);
- 4.83 m (190 in) wheelbase;
- 1.37 m (54 in) spread tandem drive axle;
- 4.88 m (16 ft) long load box; and
- hitch offset of 1.52 m (60 in).

The truck axle and gross weights are as shown in Tables 1 and 2, below.

2.2 The Tandem-Tandem Trucks

Generic tandem-tandem straight trucks were configured with the following key properties:

- true tandem front axle with each axle rated at 9,072 kg (20,000 lb);
- 445 mm (18 in) wide front axle tires;
- 1.52 m (60 in) spread tandem front axle;
- tare weight of 13,608 kg (30,000 lb);
- tare tandem front axle weight of 7,257 kg (16,000 lb);
- inter-axle spacing of 3.05 m (120 in), 3.30 m (130 in) or 3.66 m (144 in);
- 1.37 m (54 in) spread tandem drive axle;
- load box length of 5.64 m (18 ft 6 in), 6.10 m (20 ft) or 6.55 m (21 ft 6 in); and
- hitch offset of 1.52 m (60 in).

The baseline tandem-tandem straight truck configuration was considered a 3.30 m (130 in) inter-axle spacing with a 6.10 m (20 ft) load box.

The truck axle and gross weights are as shown in Tables 1 and 2, below.

2.3 The Trailers

Four trailers were configured with the M.o.U. minimum wheelbase of 6.25 m (246 in):

- Single axle pony trailer, with 4.72 m (15 ft 6 in) long load box;
- Tandem axle pony trailer, with the same load box and 1.25 m (49 in) spread tandem;

- Tridem axle pony trailer, with the same box and 2.44 m (96 in) spread tridem; and
- Two-axle full trailer, with a 7.32 m (24 ft) long frame, a 4.72 m (15 ft 6 in) long load box centred on the frame, and a 3.66 m (144 in) long drawbar.

The same tare weight was used for the structure and load box of each pony trailer, regardless of the number of axles, to simplify the analysis. The weight changes and the effect on the loaded centre of gravity height are small, because a change in structure or load box weight between trailers is compensated by a change in payload weight. Further, the comparison is not between pony trailers, it is between single-tandem and tandem-tandem trucks pulling the same trailer.

Each trailer was pulled by the baseline single-tandem straight truck, as shown in Figure 1, and by the tandem-tandem straight trucks, as shown in Figure 2. Table 1 lists the truck-trailer configurations, axle loads and gross weights based on the registered axle weights. Note that when the tandem-tandem straight truck pulls a trailer with two or more axles, the combination is limited to a maximum gross registered weight of 50,000 kg (110,230 lb), and in this configuration, the tandem front axle weight is limited to 14,000 kg (30,864 lb). Table 2 shows the axle and gross weights when the Nova Scotia tolerance of 500 kg (1,102 lb) per axle is included. Figures 1 and 2 also show the axle and gross weights of the truck-trailer combinations for both sets of loads.

2.4 Loading

The tandem-tandem trucks and any trailers they may pull will haul materials related to highway construction and maintenance, like gravel, asphalt and road salt. Asphalt has a density around 1,760 kg/cu m (110 lb/cu ft). Gravel has a density around 1,603-1924 kg/cu m (100-120 lb/cu ft). Road salt has a density around 1,282 kg/cu m (80 lb/cu ft). The lowest density results in the highest centre of gravity for a particular weight of payload, so the analysis was conducted using a payload density of 1,282 kg/cu m (80 lb/cu ft), representing road salt. The earlier study used a payload density of 2,242 kg/cu m (140 lb/cu ft) to represent gravel, which was expected to be the most common commodity that would be hauled by truck-trailer combinations [2]. It was a little on the high side, however.

The vehicle payload was configured as an even number of thousands of pounds that brought the vehicle just below its allowable maximum gross weight and each allowable axle weight. However, truck-trailer combinations were limited to a gross weight of 50,000 kg (110,230 lb), and in this case, the tandem-tandem truck front axle load was reduced as shown in Tables 1 and 2. The payload was loaded in a solid block from the front of the box continuously for that length that balanced the axle loads. It is common for dump trucks with high front axle load capacity to require a forward load bias in order to comply with axle load regulations. This loading scheme maximized the payload weight and height. The payloads are considered typical, in the sense that the payload is at the high end of the practical range for an operator trying to stay within gross and axle weights, and the centre of gravity of the load is also at the high end. Together, these tend to give results close to the lower limit for vehicle dynamic performance.

Table 1/ Axle and Gross Weights of Trucks and Truck-trailer Combinations

Truck	Trailer	Front axle (kg)	Drive (kg)	Trailer (kg)	Gross (kg)
3-axle	None	8,000	18,000		26,000
3-axle	Single pony	8,000	18,000	9,000	35,000
3-axle	Tandem pony	8,000	18,000	18,000	44,000
3-axle	Tridem pony	8,000	18,000	20,500	46,500
3-axle	Full	8,000	18,000	18,000	44,000
4-axle	None	16,000	18,000		34,000
4-axle	Single pony	16,000	18,000	9,000	43,000
4-axle	Tandem pony	14,000	18,000	18,000	50,000
4-axle	Tridem pony	14,000	18,000	18,000	50,000
4-axle	Full	14,000	18,000	18,000	50,000

Table 2/ Axle and Gross Weights of Trucks and Truck-trailer Combinations with Tolerances

Truck	Trailer	Front axle (kg)	Drive (kg)	Trailer (kg)	Gross (kg)
3-axle	None	8,500	19,000		27,500
3-axle	Single pony	8,500	19,000	9,500	37,000
3-axle	Tandem pony	8,500	19,000	19,000	46,500
3-axle	Tridem pony	8,500	19,000	22,000	49,500
3-axle	Full	8,500	19,000	19,000	46,500
4-axle	None	17,000	19,000		36,000
4-axle	Single pony	17,000	19,000	9,500	45,500
4-axle	Tandem pony	15,000	19,000	19,000	53,000
4-axle	Tridem pony	15,000	19,000	19,500	53,500
4-axle	Full	15,000	19,000	19,000	53,000

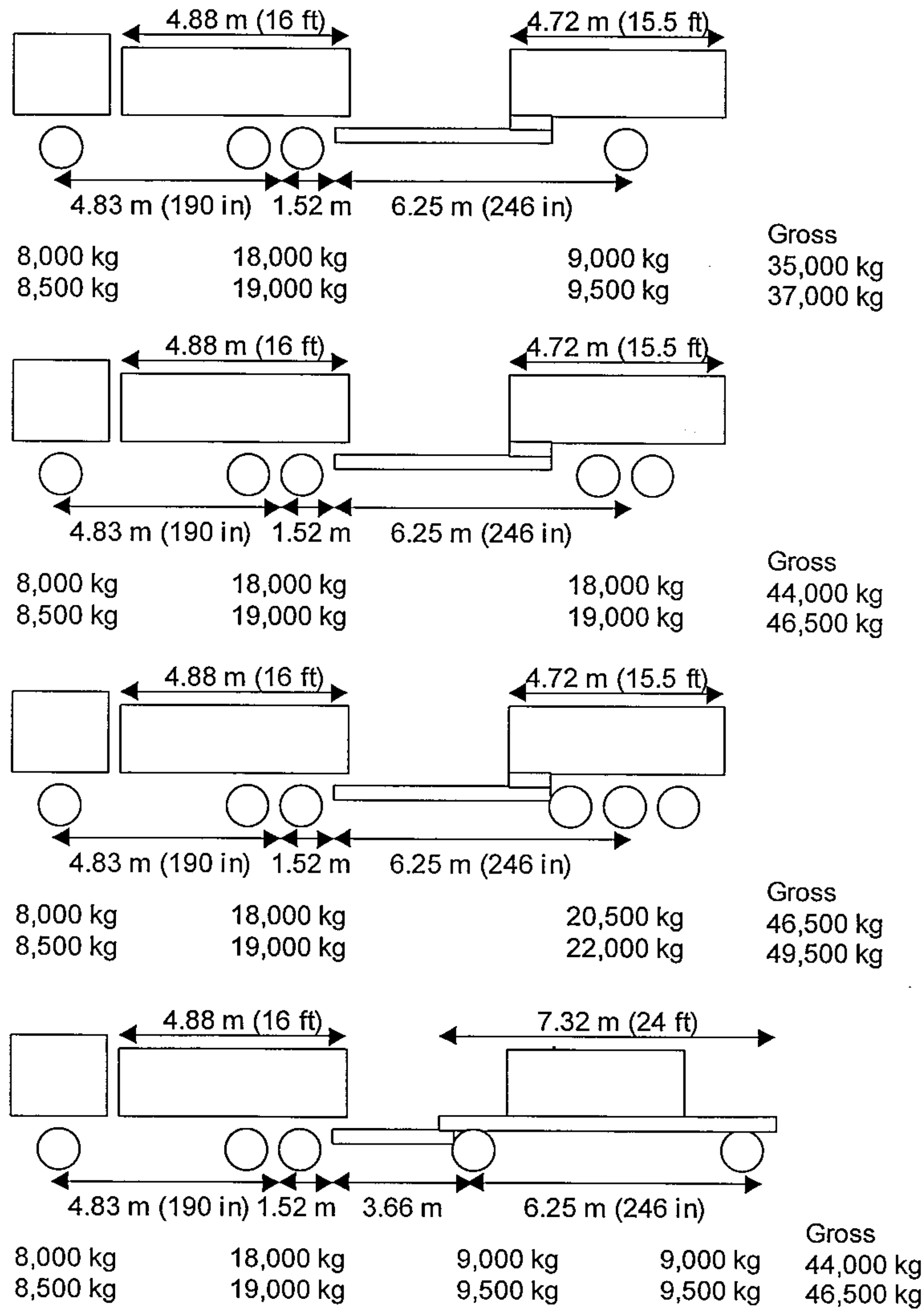

Figure 1/ Single-Tandem Truck-Trailer Combinations

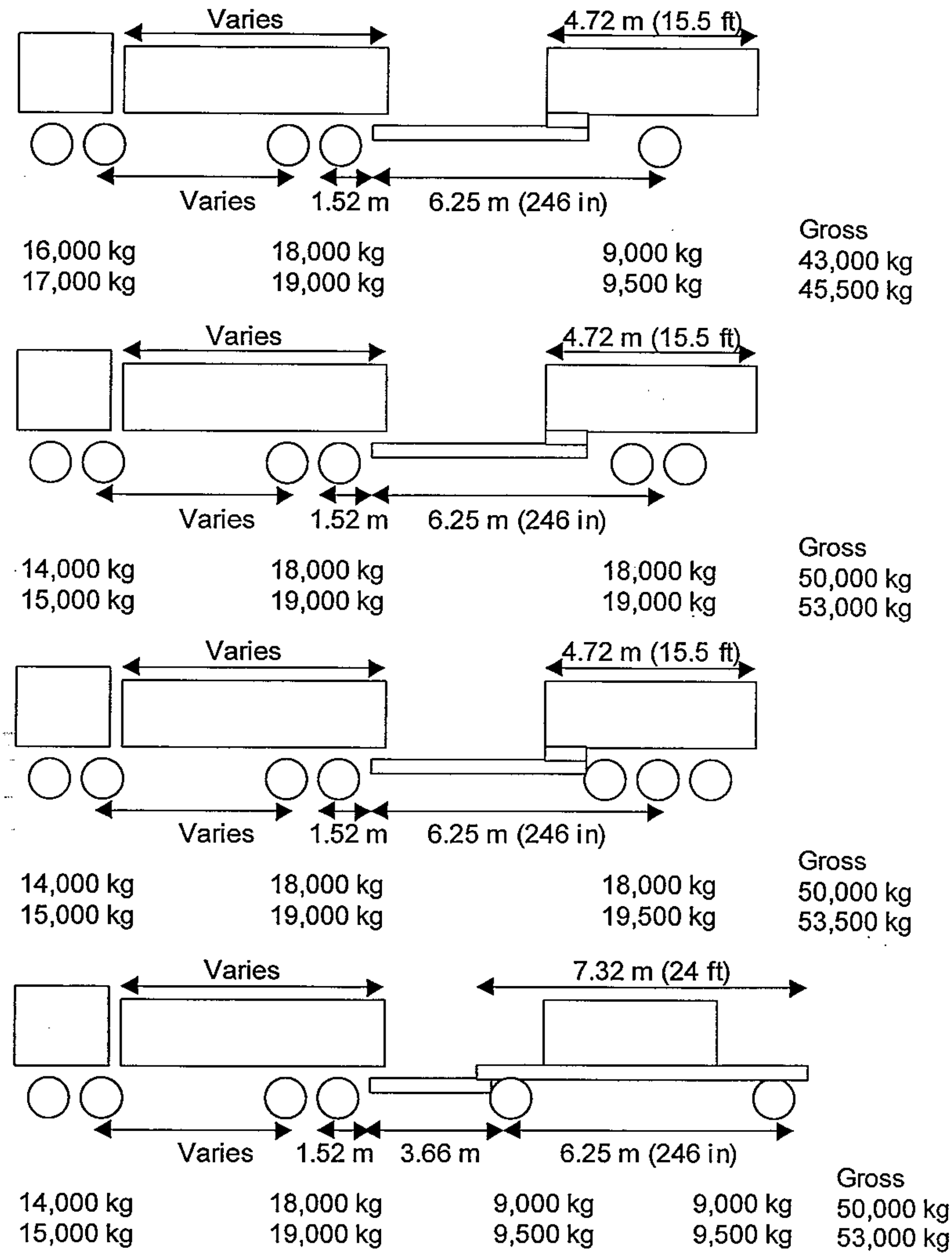

Figure 2/ Tandem-Tandem Truck-Trailer Combinations

3. Stability and Control Simulation Methodology

3.1 Simulation Program

The analysis was conducted by computer simulation, using a version of the yaw/roll program. This was originally developed at the University of Michigan Transportation Research Institute (UMTRI), as a means to assess the lateral/directional stability and control of various vehicle configurations [4]. This program has been used extensively in previous simulation studies, and has been shown to provide reasonable agreement with test results for a wide range of vehicles [5], including those of this study [3]. It was used for most simulations conducted during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6], which formed the basis for the M.o.U. and much recent regulation. It was also used in the study that resulted in straight trucks and truck-trailer combinations being added to the M.o.U. [2].

The yaw/roll program is a dynamic simulation of moderate complexity that represents the combined lateral, yaw and roll response of a heavy articulated vehicle to a steering input. The model can represent combinations with up to six vehicle units and eleven axles, with up to six axles on any vehicle unit. Up to five axles (besides the front axle) at any location may be self-steering or forced steering. Fifth wheel, turntable, pintle hook, C-dolly and other couplings allow A-train, B-train and C-train combinations, and others. The steering input can be defined at the hand steering wheel, the road wheels, or can be obtained from a driver model that steers to follow a specified path on the ground as closely as possible. The program does not represent longitudinal tire forces needed for drive and brake torque, so is restricted to constant longitudinal velocity. It is also restricted to a smooth, flat surface of uniform frictional characteristics.

3.2 Performance Measures and Performance Standards

A performance measure is a response of a system to a standardised input. The input must be standardised so that the same response can be compared for different vehicles. A performance standard is the criterion or boundary between acceptable and unsatisfactory performance. Evaluating vehicle performance consists of three steps:

- Subject the vehicle to a standardised input;
- Evaluate the performance measure; then
- Compare the performance measure to the performance standard.

Six performance measures were used to characterise vehicle performance, based on those developed in the CCMTA/RTAC Vehicle Weights and Dimensions Study [6]. The performance measures were obtained from three manoeuvres run with the yaw/roll model that provided the necessary responses. The driver model was used to cause the front axle of the vehicle to follow a path defined for each manoeuvre. The driver model parameters were set to represent an alert driver, so the specified path is followed as accurately as possible. The program includes algorithms to scan the responses and compute the performance measures after each run.

High-speed Offtracking and **Rollover Threshold** are obtained from a turn made at 100 km/h (62.1 mi/h). The turn starts with a short tangent segment, followed by a spiral entry into a curve of radius 393.3 m (1290.3 ft), which corresponds to a lateral acceleration of 0.2 g. The turn is maintained until 10 s after the start of the run, to allow a steady state condition to be achieved, then steering wheel angle is increased steadily at 2 deg/s until the vehicle rolls over.

- **High-Speed Offtracking** is the lateral offset, in meters, between the path of the steer axle of the power unit and the path of the rearmost axle of the vehicle in a steady turn of 0.2 g lateral acceleration. Since the driver guides the power unit along a desired path, there is a potential safety hazard if the tires of the rearmost axle follow a more outboard path that might intersect a curb or other roadside obstacle, or intrude into an adjacent lane of traffic. High-speed offtracking should not exceed 0.46 m (18 in) outboard of the path of the power unit in a 0.2 g turn.

- **Rollover Threshold** is the power unit 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 accidents in highway service. The static rollover threshold should preferably not be less than 0.4 g.

Load Transfer Ratio and **Transient High-speed Offtracking** are obtained from a high-speed lane change made at 100 km/h (62.1 mi/h). The path is a side-step of 2.11 m (6.92 ft), which corresponds to a single cycle sinusoidal lateral acceleration of 0.15 g and 3.0 s period at the power unit front axle. This manoeuvre is sufficiently gentle that it does not result in rollover for multi-trailer combinations. The period corresponds to that at which the greatest response occurred for most trucks in the simulations for the CCMTA/RTAC Vehicle Weights and Dimensions Study [6], but is not necessarily the period at which greatest response would actually occur for any particular vehicle. The two measures are not particularly strongly dependent upon steer period for tractor-semitrailers, whereas they usually are for truck-trailer and multi-trailer combinations.

- **Load Transfer Ratio** is the fractional change in load between left-hand and right-hand side tires of a vehicle in an obstacle avoidance manoeuvre. It indicates how close the vehicle came to lifting off all the tires on one side, a precursor to rollover. The load transfer ratio should not exceed 0.6, which corresponds to an 80-20% left-right split in wheel loads. A load transfer ratio of 1.0 corresponds to all wheels on one side of the rearmost roll unit lifting off.

- **Transient High-Speed Offtracking** is the peak overshoot, in meters, in the lateral position of the rearmost axle from the path of the power unit front axle in an obstacle avoidance manoeuvre. It is an indication of potential to sideswipe a vehicle in an adjacent lane, or for rollover if the rearmost axle should strike a curb. This measure quantifies the "tail-wagging" response of a multiply articulated vehicle to a rapid steer input. Transient offtracking should not exceed 0.8 m (31.5 in).

Low-speed Offtracking and **Friction Demand** are obtained from a 90 degree right-hand turn made with the left front wheel of the power unit following a 14 m (45.93 ft) radius curve at 8.8 km/h (5.5 mi/h). This radius was used for the previous truck-trailer study, as it tends to be more representative of actual vehicle turning [2] than the 10.97 m (36 ft) radius used in the CCMTA/RTAC Vehicle Weights and Dimensions Study [6]. It is also the radius that was used to develop the current MTO geometric design standard for an open throat intersection (T-junction) that must accommodate significant numbers of turns by large trucks. It may not be the tightest turn possible for these vehicles. The low-speed offtracking performance standard was originally set at 6 m (19.7 ft) for a turn with 10.97 m (36 ft) radius [6]. However, not all vehicles can make such a tight turn. A more realistic performance measure is that the vehicle being evaluated should offtrack no worse than the largest vehicle allowed by the M.o.U., a 6.2 m (244 in) wheelbase tractor with a 12.5 m (492 in) wheelbase semitrailer, in a turn that the vehicle being evaluated is able to make.

- **Low-Speed Offtracking** is the extent of inboard offtracking of the rearmost axle from the power unit's front axle in a typical 90 degree right-hand turn at an intersection. This property is relevant to the "fit" of the vehicle on the road system, and has implications for safety as well as abuse of roadside appurtenances. Low-speed offtracking should be no greater than for the largest vehicle allowed by the M.o.U., a 6.2 m (244 in) wheelbase tractor with a 12.5 m (492 in) wheelbase semitrailer.

- **Friction Demand** is a measure of the resistance of multiple axles to travel around a tight-radius turn, such as at an intersection. It results in a "demand" for tire side force at the power unit's drive axles. When the pavement friction level is low, a vehicle whose friction demand exceeds that which is available will produce a jackknife-type response of the power unit. The friction demand measure describes the minimum level of 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 0.1.

3.3 Data

The absolute accuracy of a vehicle simulation depends critically both on how well the model represents the vehicle system, and how accurately the data for the vehicle components (e.g. tires, springs, etc) is known. Previous work has addressed the accuracy of the models [4, 5]. 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.

Data for vehicle components were drawn from the CCMTA/RTAC Vehicle Weights and Dimensions Study, and other representative data for the vehicles being considered.

4. Stability and Control Results

4.1 Performance Measures for Straight Trucks

Table 3 presents the performance measures arising from all manoeuvres for the baseline single-tandem straight truck, and the tandem-tandem straight trucks. Table 3 also shows the performance standards, for comparison. Where the performance of a vehicle does not meet the performance standard, the performance measure is highlighted in bold.

The first row of Table 3 is considered the baseline vehicle, a "typical" three-axle straight truck that meets the M.o.U. at Nova Scotia allowable weights.

Table 3 implicitly includes the effect of varying load box length for the tandem-tandem trucks. Load was distributed so that each vehicle was loaded within its axle weight limits, so in all cases the load was biased to the front of the load box. The only difference from varying load box length was the amount of empty space at the rear of the box. Since the axle weights and payload centre of gravity height were the same for all three load box lengths for each inter-axle spacing, the vehicle responses were the same. In practical terms, the load box length will vary with inter-axle spacing, front axle setback and the bumper to back of cab (BBC) dimension. If the load box is not properly matched in length and location to the axle capacities available, the maximum allowable weight less the tare, a uniformly distributed load or a randomly distributed load will invariably result in an axle overload, usually to the drive tandem.

Table 3/ Performance Measures for Straight Trucks

Truck (1)	Inter-axle (m)	Load (2)	High-speed Offtrack (m)	Static Roll (g)	Load Transfer Ratio	Trans't Offtrack (m)	Low-speed Offtrack (m)	Friction Demand
			<0.46	>0.40	<0.60	<0.80	<5.63	<0.10
ST		N	0.22	0.48	0.51	0.26	0.89	0.01
ST		T	0.23	0.48	0.51	0.28	0.89	0.01
TT	3.05	N	0.25	0.41	**0.60**	0.24	1.06	0.01
TT	3.30	N	0.26	0.42	0.59	0.25	1.16	0.01
TT	3.66	N	0.27	0.42	0.56	0.26	1.30	0.01
TT	3.05	T	0.26	**0.38**	**0.66**	0.27	1.06	0.01
TT	3.30	T	0.27	**0.39**	**0.63**	0.28	1.16	0.01
TT	3.66	T	0.28	0.40	0.59	0.29	1.30	0.01

Notes: (1) ST=single-tandem, TT=tandem-tandem
(2) N=normal axle loads, T=normal axle loads plus tolerance

Table 3 shows that all configurations meet all three offtracking performance measures, and friction demand. These measures are designed for combination vehicles, and any single unit vehicle should automatically meet them. The principal problems are with rollover threshold and load transfer ratio. The results clearly show the rollover threshold is lower for tandem-tandem trucks compared to single-tandem trucks, and that load transfer ratios are higher. This is because the tandem-tandem truck has a higher payload, and a higher payload centre of gravity, because in most cases the payload must be pushed to the front of the load box for proper weight distribution to the axles. The additional front axle of the tandem-tandem truck adds little to the rollover resistance, as the suspension is soft for driver ride. Thus, the tandem-tandem truck is marginal with the salt payload at normal weights, and fails both performance standards with an inter-axle spacing of 3.05 m (120 in) and 3.30 m (130 in). This is not due directly to the inter-axle spacing, it is because the payload must be pushed more to the front of the load box to achieve the proper front tandem axle weight, which increases the payload centre of gravity height. Simply loading with asphalt at 1,763 kg/cu m (110 lb/cu ft) increased the rollover threshold of a tandem-tandem truck with a 3.30 m (130 in) inter-axle spacing and weight tolerance from 0.39 to 0.46 g, and reduced the load transfer ratio from 0.63 to 0.51. The tandem-tandem trucks will meet all performance standards when loaded with gravel or asphalt.

If tandem-tandem trucks can be configured so that the load box is loaded uniformly along its entire length to get the proper weight on the front axle, they should meet all the performance standards for the gravel, asphalt and road salt payloads considered.

Any payload with a density much less than 1282 kb/cu m (80 lb/cu ft) will raise the payload centre of gravity for a tandem-tandem truck so that the vehicle always fails the rollover and load transfer ratio performance standards. The previous study concluded there would be no way to ensure a higher rollover resistance for future tandem-tandem trucks, and did not expect that provinces would be able to restrict the types of payload they might carry. The study therefore recommended the tandem-tandem truck not be considered for the M.o.U. [2]. For this study, if the tandem-tandem trucks are restricted to use as end dumps for construction and maintenance materials like gravel, asphalt and road salt, then they meet the performance standards at normal weights, and are very close with tolerances included. However, they will fail these performance standards if they are included under the general regulations, and end up carrying less dense commodities like logs and garbage.

4.2 Performance Measures for Truck-trailer Combinations

Table 4 presents the performance measures arising from all manoeuvres for the baseline single-tandem straight truck, and the tandem-tandem straight trucks, pulling a single, tandem or tridem axle pony trailer, or a 2-axle full trailer. It is in the same format as Table 3. Again, where the performance of a vehicle does not meet the performance standard, the performance measure is highlighted in bold. The tandem-tandem truck in this part of the analysis used a 3.30 m (130 in) inter-axle spacing and a 6.10 m (20 ft) long load box, reportedly the most common configuration.

Table 4/ Performance Measures for Truck-Trailer Combinations

Truck (1)	Trailer (2)	Load (3)	High-speed Offtrack (m)	Static Roll (g)	Load Transfer Ratio	Trans't Offtrack (m)	Low-speed Offtrack (m)	Friction Demand
			<0.46	>0.40	<0.60	<0.80	<5.63	<0.10
ST	PT1	N	0.42	0.48	**0.72**	0.64	2.22	0.01
ST	PT1	T	0.44	0.48	**0.74**	0.69	2.22	0.02
ST	PT2	N	0.42	0.49	**0.83**	0.76	2.16	0.07
ST	PT2	T	**0.49**	0.49	**0.93**	0.81	2.16	0.07
ST	PT3	N	0.42	0.49	**0.82**	0.74	2.07	**0.19**
ST	PT3	T	0.44	0.48	**0.83**	0.79	2.07	**0.19**
ST	FT	N	**0.54**	0.49	**0.80**	**0.94**	2.65	0.01
ST	FT	T	**0.56**	0.48	**0.81**	**1.00**	2.65	0.01
TT	PT1	N	0.45	0.41	**0.69**	0.61	2.46	0.01
TT	PT1	T	**0.47**	**0.39**	**0.72**	0.66	2.46	0.01
TT	PT2	N	**0.48**	0.46	**0.81**	0.73	2.40	0.06
TT	PT2	T	**0.48**	0.45	**0.85**	0.77	2.40	0.06
TT	PT3	N	0.46	0.42	**0.71**	0.63	2.34	**0.15**
TT	PT3	T	**0.48**	0.43	**0.77**	0.69	2.33	**0.15**
TT	FT	N	**0.55**	0.45	**0.77**	**0.89**	2.88	0.01
TT	FT	T	**0.58**	0.43	**0.80**	**0.96**	2.88	0.01

Notes: (1) ST=single-tandem, TT=tandem-tandem
(2) PTn= pony trailer with n axles, FT= 2-axle full trailer
(3) N=normal axle loads, T=normal axle loads plus tolerance

The rollover threshold in Table 4 is that of the truck, which always rolled over before the trailer in a truck-trailer combination. However, the load transfer ratio is that of the trailer, which always exceeded the load transfer ratio of the truck. The single-tandem truck fails high-speed offtracking for the tandem pony trailer with tolerances; high-speed offtracking and transient offtracking for the full trailer at both weights; friction demand for the tridem pony trailer at both weights; and load transfer ratio for all trailers at both weights. This is primarily because this study uses Nova Scotia's axle loads with a payload density of 1282 kg/cu m (80 lb/cu ft), whereas the previous study used M.o.U. axle loads and a payload density of 2,244 kg/cu m (140 lb/cu ft) [2]. With higher axle loads and a lower payload density, it is not surprising the vehicles evaluated in this study do not perform quite as well as those configured for the M.o.U. from the previous study [2]. Simply loading with asphalt at 1,763 kg/cu m (110 lb/cu ft) reduces the load transfer ratio from 0.85 to 0.83 for a tandem-tandem truck pulling a tandem pony trailer when weight tolerance is included.

The tandem-tandem truck fails high-speed offtracking for all trailers except the single and tridem pony trailer at normal weights. It fails transient offtracking for the full trailer at both weights. It fails friction demand for the tridem pony trailer at both weights. It fails load transfer ratio for all trailers at both weights. On the other hand, limiting the gross weight at normal loads to 50,000 kg (110,230 lb) by cutting the front tandem from 16,000 kg (35,273 lb) to 14,000 kg (30,864 lb) improves the truck rollover threshold.

Table 4 shows that the performance of a particular trailer pulled by a tandem-tandem truck is not very different than when it is pulled by a single-tandem truck. In general, high-speed offtracking is slightly worse for the tandem-tandem, and load transfer ratio, transient offtracking and friction demand are slightly better. Overall, the results are quite close. The power units are quite close in dimensions, and make the same manoeuvres, so it is reasonable to expect that the trailer responses would be fairly similar. This suggests that, to the extent that a tandem-tandem truck is considered acceptable as a single unit, then it should be equally acceptable pulling any M.o.U. trailer that a single-tandem truck would pull.

4.3 Load Distribution for Tandem-Tandem Truck-Trailer Combinations

The normal gross weight of tandem-tandem truck-trailer combinations is limited to 50,000 kg (110,230 lb) by cutting the front tandem from 16,000 kg (35,273 lb) to 14,000 kg (30,864 lb). This helps with axle weight distribution, to the extent that it is necessary to bias the payload to the front of the load box. However, it also means that the truck must be loaded differently, depending on whether it is towing a trailer or not. The other issue is that these trailers are fairly responsive, as seen in Table 4. If the truck is loaded in the same way, regardless of whether it tows a trailer, and the trailer axle weight is reduced, this reduces the trailer payload centre of gravity height, which tends to reduce trailer responses.

Table 5 compares the performance of the tandem-tandem truck pulling a tandem or tridem pony trailer or the full trailer at normal weights. The rows are in pairs. The first row of a pair, labelled R in column 3, is from Table 4 with the truck front axle tandem at 14,000 kg (30,864 lb). The second row of a pair, labelled N in column 3, is the same vehicle with the front axle at 16,000 kg (35,273 lb) and the trailer weight reduced by 2,000 kg (4,410 lb).

For each trailer, transferring weight from the trailer to the truck improves those performance measures governed by trailer characteristics. The truck rollover threshold does drop but only to the same value as if it were being driven without a trailer. There seem to be three choices, discussed below.

In the first case where the truck front axle load is reduced by 2,000 kg (4,410 lb), as proposed, the truck rollover threshold is improved at the expense of trailer response. This would be selected in a situation where these vehicles would travel infrequently on divided highways or at speeds approaching 100 km/h (62 mi/h), and truck rollover might be more likely. It does lead to two different payload weights for the truck, depending on whether it pulls a trailer or not. This complication could lead to gross weight overloads.

Table 5/ Performance Measures for Truck-Trailer Combinations Reduced Trailer Axle Weights

Truck (1)	Trailer (2)	Load (3)	High-speed Offtrack (m)	Static Roll (g)	Load Transfer Ratio	Trans't Offtrack (m)	Low-speed Offtrack (m)	Friction Demand
			<0.46	>0.40	<0.60	<0.80	<5.63	<0.10
TT	PT2	R	**0.48**	0.46	**0.81**	0.73	2.40	0.06
TT	PT2	N	0.46	0.42	**0.73**	0.64	2.41	0.05
TT	PT3	R	0.46	0.42	**0.71**	0.63	2.34	**0.15**
TT	PT3	N	0.45	0.43	**0.66**	0.60	2.36	**0.13**
TT	FT	R	**0.55**	0.45	**0.77**	**0.89**	2.88	0.01
TT	FT	N	**0.53**	0.42	**0.71**	0.79	2.87	0.01

Notes: (1) ST=single-tandem, TT=tandem-tandem
(2) PTn= pony trailer with n axles, FT= 2-axle full trailer
(3) R=reduced truck front axle load, N=normal truck front axle load

In the second case, where the truck front axle weight is maintained and the trailer axle load is reduced by 2,000 kg (4,410 lb), the truck is loaded the same and rolls at the same lateral acceleration, regardless of whether it pulls a trailer or not. This reduces trailer responses, which might be preferred where these vehicles would travel frequently on divided highways or at speeds approaching 100 km/h (62 mi/h), and high-speed lane changes might occur.

Alternatively, truck and trailer axle loads could be maintained, but the gross weight could be limited at 50,000 kg kg (110,230 lb). This creates some margin for error in load distribution, as now the gross weight is less than the sum of allowable axle loads. It could be beneficial for trucks where the load must be biased to the front of the load box to get the full 16,000 kg (35,273 lb) on the front tandem. The operator could then load the truck and trailer according to preference, possibly somewhere between the two limits. Performance would then be somewhere between the limits shown in Table 5.

5. Discussion

5.1 Previous Rollover Tests

Tandem-tandem straight trucks are widely used in Quebec, and a series of tilt tests compared the rollover characteristics of single-tandem and tandem-tandem trucks [7]. Table 6, adapted from [7], summarizes the rollover thresholds of four dump trucks, some for more than one load case.

Table 6/ Measured Rollover Thresholds of Dump Trucks

Vehicle Type	Vehicle	Average Rollover Threshold (g)
Single-tandem	2a	0.46
Single-tandem	3	0.49
Tandem-tandem	5	0.44
Tandem-tandem	7a	0.44
Tandem-tandem	7b	0.48

The gross weights of the single-tandem trucks were about the same, and the gross weights of the tandem-tandem trucks were about the same, as well. The 4-axle dump trucks used a somewhat longer load box than the 3-axle vehicles, so there was little increase in centre of gravity height. The values from this test confirm the analysis done here for dump trucks.

5.2 Vehicle Manufacture

Over the last ten years or so, Quebec has made a number of changes to regulations and policies that have been specifically targeted at the dump truck industry. Axle weight regulation has been re-introduced. Dump trucks are now being built with a load box of sufficient length and properly located so that a uniformly distributed payload of maximum weight results in axle weights that comply with the regulation.

Other issues relate to the original manufacture of tandem-tandem straight trucks. Many were in fact conversions of trucks originally manufactured with a single front axle. When the second axle was added, it often used an independent air suspension. If the axle was not actually liftable, the driver still had the capability to unload the axle. This reportedly gave some advantages in manoeuvring off-road in soft ground. However, the leading front axle would be greatly overloaded in this situation. In some cases, the steering of the second axle was simply linked to the steering of the original axle, so the original steering box was significantly under-rated for the new requirement. Quebec now allows a front axle weight of only 15,000 kg (33,069 lb) when the front axles are not a true tandem. This has essentially eliminated conversions, and ensures that any new vehicle is manufactured as a tandem-tandem, with a true tandem front axle.

5.3 Load Distribution

The gravel, asphalt or road salt payloads for tandem-tandem straight trucks are bulk commodities that flow when being loaded, so need to be distributed uniformly over the length of the load box. The load box is often not correctly positioned relative to the wheelbase, so a uniformly distributed payload usually results in an axle overload on the drive tandem, as shown on the left in Figure 3. The payload must be biased to the front of the load box to correct this, as shown on the right in Figure 3, where the axle loads require 0.97 m (38 in) empty at the back of the box. It is difficult to bias the load reliably, especially if the vehicle is loaded in two scoops by a loader with a bucket almost as wide as the load box is long. When the payload is biased, it elevates the payload centre of gravity. Figure 4 shows that if the inter-axle spacing is extended to 4.14 m (163 in), a uniformly distributed payload balances the axle loads. This example simply illustrates the issue. It is only resolved if the operator, dealer and final stage vehicle manufacturer (who adds the load box) make sure the proper inter-axle spacing is specified, so that a uniformly distributed load results in the allowable axle loads for the particular load box length and location. If the vehicle is not built right, it will invariably have axle overloads.

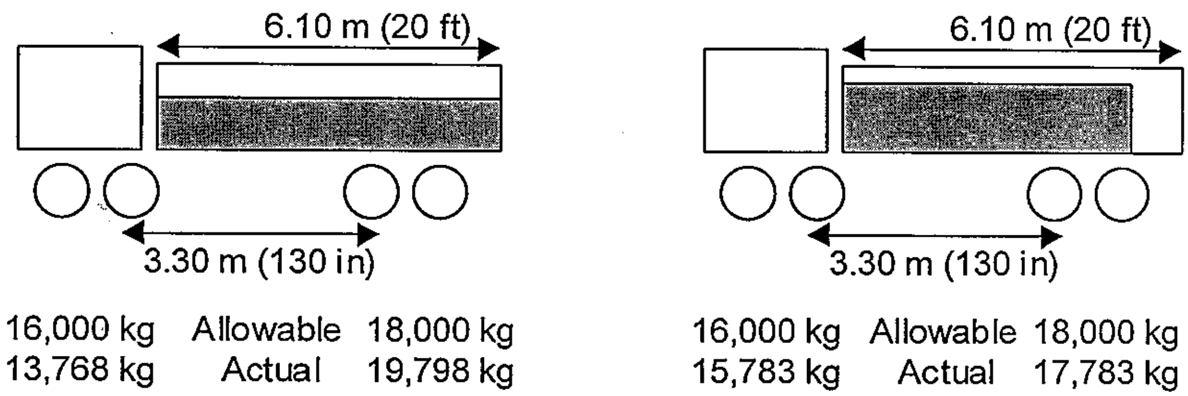

Figure 3/ Effect of Load Distribution on Axle Loads

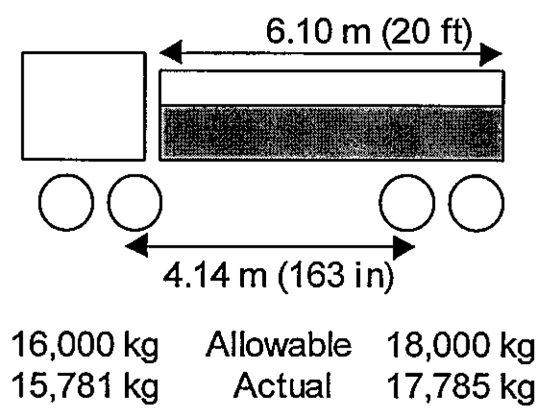

Figure 4/ Effect of Inter-axle Spacing on Axle Loads

6. Summary

This report has examined the dynamic performance of tandem-tandem straight trucks, as single unit vehicles and pulling trailers configured in accordance with the Memorandum of Understanding on Vehicle Weights and Dimensions ("the M.o.U."). The performance of these vehicles has been compared to a single-tandem truck, alone and pulling the same trailers. The vehicles were loaded with road salt, the material with the lowest density commonly carried by this class of vehicle. Payload weights and weight distributions used were those from current regulations in Nova Scotia, including accumulation of axle weight tolerances into a gross weight tolerance.

The principal factor is rollover. A tandem-tandem truck accrues a higher payload than a single-tandem truck, in about the same wheelbase and practical box length. It has a higher centre of gravity but little additional rollover resistance, so has a lower rollover threshold and higher load transfer ratio than the single-tandem truck. These both get worse when tolerances are included. They also both get worse when the inter-axle spacing is reduced, primarily because the load must be pushed further ahead in the load box to get the required front axle load. This increases the centre of gravity height.

In all cases the power unit in a truck-trailer combination had a lower roll threshold than the trailer, and the trailer had a higher load transfer ratio than the power unit. The high-speed offtracking, load transfer ratio and transient offtracking all increased when weight tolerance was included, while the other performance measures were unaffected. The tandem-tandem truck-trailers generally had slightly higher high-speed offtracking and low-speed offtracking than the single-tandem truck-trailers, and slightly lower load transfer ratio, transient offtracking and friction demand. On balance, the differences in trailer response when pulled by a single-tandem truck or tandem-tandem truck are small. So, if a tandem-tandem truck is considered suitable to operate as a single unit, there appears no reason it should not pull any M.o.U. trailer that a single-tandem truck would be allowed to pull.

The tandem-tandem truck-trailers are limited to a gross weight of 50,000 kg (110,230 lb). The baseline case evaluated reduces the front axle load from 16,000 to 14,000 kg (35,273 to 30,864 lb). Trailer responses are reduced if the truck front axle load is maintained but the trailer load is reduced. There are pros and cons to each scenario. Alternatively, normal axle loads could be maintained, and gross weight limited, to allow the operator some flexibility in loading.

There are some important issues in configuration, manufacture and use of tandem-tandem trucks. When an existing truck has been converted by adding an axle, the two steering axles may not form a true tandem, and the steering system may be overloaded. A truck originally manufactured as a tandem-tandem avoids this. It is probably difficult for many of the shorter trucks to operate without frequent drive tandem overloads. New trucks need to be configured with sufficient inter-axle spacing (or wheelbase) and a sufficiently long box that the front tandem load can be achieved with a payload uniformly distributed over the entire length of the load box.

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