DEVELOPMENT OF REGULATORY PRINCIPLES FOR MULTI-AXLE SEMITRAILERS

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ABSTRACT

Current truck weight regulations in the provinces of Ontario and Quebec allow more weight to be carried within a particular dimension if more axles are used, or the axles are more widely spaced. The consequence has been the emergence of a wide variety of configurations of multi-axle semitrailer, designed to carry high payload weights, and usually equipped with at least one airlift axle that is customarily lifted when turns are made.

The stability and control, pavement, and bridge loading characteristics of fourteen tractor-semitrailer combinations having various arrangements of 3 to 6 semitrailer axles, 6 to 9 total axles, have been evaluated. Performance criteria similar to those developed in the CCMTA/RTAC Vehicle Weights and Dimensions Study were used for stability and control. These vehicles were evaluated with fixed liftable axles both down and raised, and with self-steering axles having properties representative of automotive and turntable steer mechanisms.

This led to four axle configuration controls for semitrailers :
1/ One fixed axle unit per semitrailer;
2/ No more than one liftable axle unit;
3/ That liftable axle should be ahead of the fixed axle unit;
4/ The liftable axle should be self-steering.

Stringent specification of the liftable self-steering axle deployment and control logic will be necessary to ensure that the axle is down and properly loaded when the vehicle load so requires. The self-steering axle may also be locked at highway speed. Specification and development of controls for these requirements appears to be technically feasible.

This has allowed the province of Quebec to propose amendment to their special permit program for 7-axle tractor-semitrailer combinations. It might also serve as a basis for more subtle proposed changes to the regulations of the province of Ontario.

INTRODUCTION

Current truck weight regulations in the provinces of Ontario and Quebec, which make up central Canada, allow more weight to be carried within a particular dimension if more axles are used, or the axles are more widely spaced. The dimensional controls on axle spacing are based almost entirely on considerations of bridge loading. A wide variety of multi-axle semitrailer configurations have emerged that are designed to carry heavy payloads. Their widely spaced axles provide considerable resistance to low-speed turning, which poses a threat of tractor jackknife on a wet and slippery pavement. Industry has addressed this difficulty by equipping these semitrailers with liftable axles, which are customarily raised when turns are made. They sometimes remain raised while cruising along the highway. Not only does this overload the remaining axles, it also substantially reduces resistance to rollover. A disproportionate number of axle overload offences also arise from vehicles equipped with liftable axles. The liftable axle may be set at an arbitrary load, which often results in an improper distribution of load among the axle units even though the gross weight is within limits. These axle overloads pose a threat to bridge deck structures and the main longitudinal members of short span bridges, and are also considered to be a major contributor to rutting and other damage to the provincial highway systems [1].

The CCMTA/RTAC Vehicle Weights and Dimensions Study examined only two multi-axle semitrailers, and concluded that widely spaced axles degraded their stability and control properties, particularly while turning [2,3]. Study of a semitrailer equipped with a self-steering belly axle and a fixed dual axle unit showed little difference in stability and control characteristics from a semitrailer having only the fixed dual axle unit [4]. Axle units not sharing load equally were judged more damaging to pavements than axle units that shared load equally. The Vehicle Weights and Dimensions Study therefore recommended in its regulatory principles that liftable or self-steering axles not be considered for the proposed vehicle configurations [5,6].

The multi-axle semitrailer equipped with liftable axles plays a major part in the efficiency of the transportation system supporting the industries of Ontario and Quebec. It is not practical at this time to consider an outright ban on liftable axles. Even curtailment of allowable loads would be a severe blow to the provincial economies concerned. The technical portion of the Weights and Dimensions Study did not cover the range of configuration or weight of multi-axle semitrailers in use in Ontario and Quebec, but it did provide a methodology for evaluating stability and control of vehicles in an objective manner. A first step, therefore, was to apply this methodology to investigate the range of these vehicles in more detail to determine whether there were some configurations and equipment options that might provide potential for development. This study would also be expected to reveal some configurations that should be discouraged.

This paper presents findings of a technical study of the stability and control characteristics of tractor-semitrailers having multi-axle semitrailers of various axle configurations with either liftable or self-steering axles, and the highway implications of these various vehicles [7]. Simple regulatory principles are proposed for configuration of such vehicles. The contrasting regulatory options available to the provinces of Ontario and Quebec to implement these principles are outlined.

VEHICLE CONFIGURATIONS

Fourteen specific tractor-semitrailer vehicle configurations, having from six to nine axles in total, were selected to represent the fleet of heavy haul vehicles in use in either in Ontario, or Quebec, or both. Each vehicle was named to describe its configuration and the semitrailer axle arrangement. The first two characters, SN, indicate the vehicle is a tractor-semitrailer with N axles. The remainder describes the semitrailer axle arrangement, from front to rear, as follows :

- A - liftable single axle unit
- A2 - liftable dual axle unit
- D - fixed dual axle unit
- Q - fixed four axle unit
- T - fixed triple axle unit

Configuration S6AD represents a 6-axle tractor-semitrailer, where the semitrailer has a single liftable axle ahead of a fixed dual axle unit

Each vehicle used the same generic tractor of conventional cab behind engine design with a 1.52 m (60 in) spread tandem drive axle and the fifth wheel 0.15 m (6 in) ahead of centre. The 5.33 m (210 in) wheelbase was chosen to generate a high gross weight according to Ontario regulations. It weighed 9800 kg (21609 lb), and the front axle rating was 5443 kg (12000 lb).

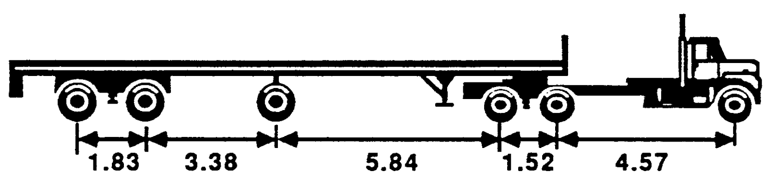
Each semitrailer was a 14.63 m (48 ft) long flatbed with a 0.91 m (36 in) kingpin setback. Fixed axles were assumed to have a typical leaf spring suspension, and liftable axles were assumed to have a typical air suspension. The gross weight of 6-axle tractor-semitrailers was limited by sum of axle loads, but for all others the axle spacings were chosen so that the gross weight was limited by Ontario regulations. Each vehicle with the same number of axles had the same tare weight, nearly the same gross weight, and hence nearly the same payload weight. Payload was distributed uniformly along the full length of each semitrailer to load the drive axles of the tractor to 17900 kg (39462 lb). The liftable axles were given a specific load, and semitrailer axle spacings were adjusted to balance the payload. Payload density was chosen so that the payload centre of gravity was

2.81 m (110.5 in) above the ground for all vehicles. This represents a commodity such as lumber.

This process created one representative of each a particular class of vehicle, but may not be exactly what is used to haul any specific commodity. It provided vehicles that were directly comparable to each other. It would be expected that trends that arise from the study will generally be applicable to vehicles whose configuration is close to those defined.

The two 6-axle tractor-semitrailers selected are shown in Figure 1. Configuration S6AD is very widely used in Ontario, Quebec and the maritime provinces. Configuration S6DA places the liftable axle behind the fixed axles, and is rare. These vehicles had a gross weight of 52262 kg (115216 lb), typical for both Ontario and Quebec, though these two provinces have slightly different axle spacing and axle load requirements.

Configuration S6AD



Configuration S6DA

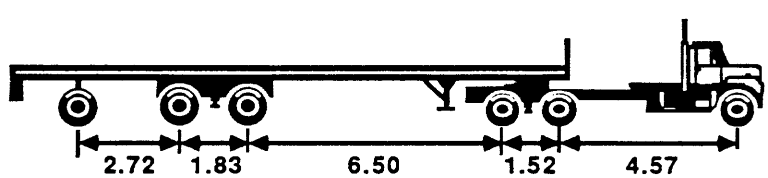
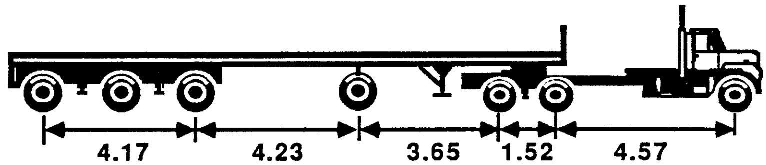
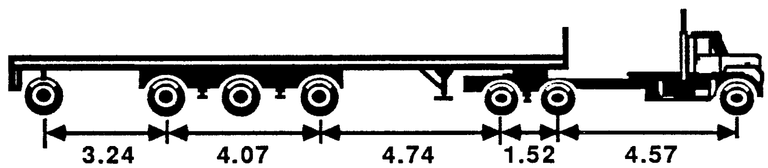


Figure 1/ 6-Axle Tractor-Semitrailers

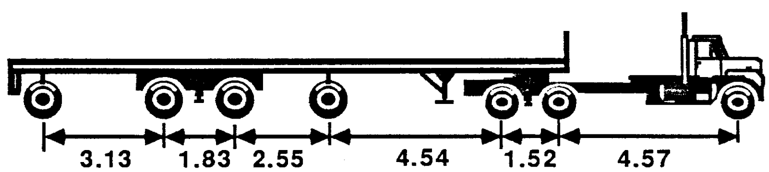
Configuration S7AT



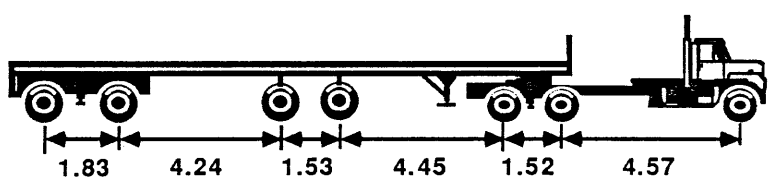
Configuration S7TA



Configuration S7ADA



Configuration S7A2D



Configuration S7AAD

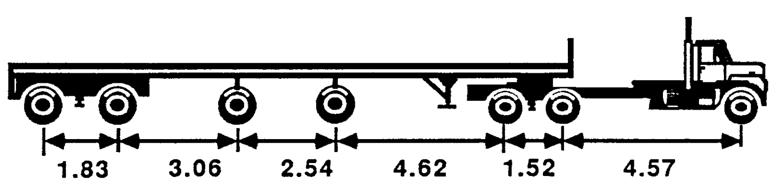
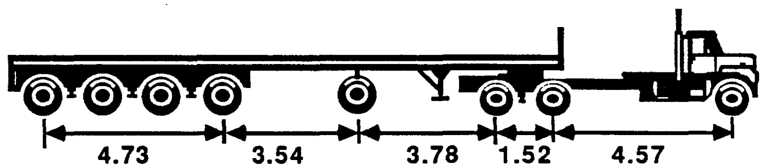
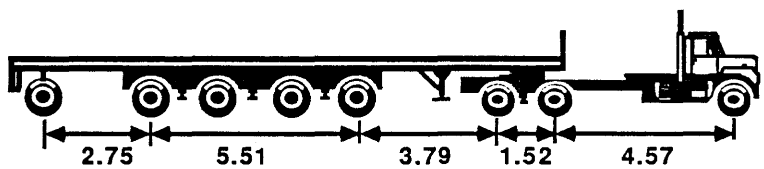


Figure 2/ 7-Axle Tractor-Semitrailers

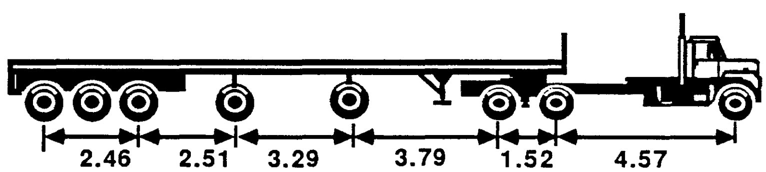
Configuration S8AQ



Configuration S8QA



Configuration S8AAT



Configuration S8ATA

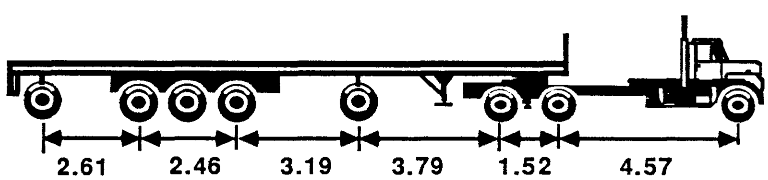
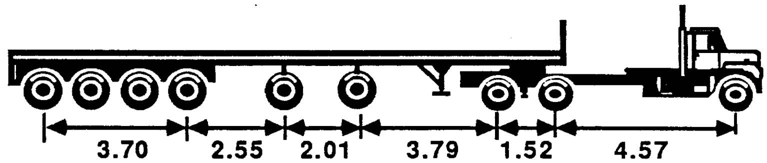
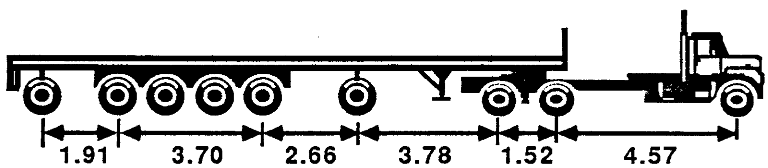


Figure 3/ 8-Axle Tractor-Semitrailers

Configuration S9AAQ



Configuration S9AQA



Configuration S9AATA

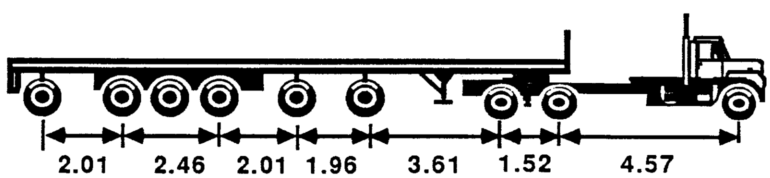


Figure 4/ 9-Axle Tractor-Semitrailers

The five 7-axle tractor-semitrailers selected are shown in Figure 2. Configuration S7AT is widely used for heavy haul. Configuration S7TA places the liftable axle aft of the fixed axle unit, and is rare. These combinations both had gross weights of 58109 kg (128107 lb). Their gross weight in Ontario ranges from 57000 to 58500 kg (125662 to 128969 lb). Configurations S7ADA, S7AAD and S7A2D, with a fixed dual axle unit and two liftable axles, have considerable diversity in axle spacings. They all had gross weights of 58200 kg (128307 lb), but may operate in Ontario at gross weights up to 60100 kg (132496 lb) with a longer wheelbase tractor. In Quebec, those 7-axle tractor-semitrailers carrying general freight can operate freely at typical gross weights up to about 53500 kg (117946 lb). Slightly higher weights are available for unprocessed wood. However, since 1986 they have been allowed to operate up to the Ontario gross weight limit by annual special permit.

The four 8-axle tractor-semitrailers selected are shown in Figure 3. The 5-axle semitrailer became practical in Ontario after maximum semitrailer length increased from 14 to 14.65 m (45.9 to 48 ft) in 1984, which allowed space to add the fifth axle without reducing allowable gross weight. It is not recognized in Quebec. Configuration S8AQ may arise from Michigan influences. Configuration S8QA may be unknown, but is included for completeness. Configuration S8AAT, with two liftable axles and a fixed triple axle unit is common throughout Ontario. Configuration S8ATA, with a liftable axle both ahead and behind a fixed triple axle unit, has recently become quite popular for heavy haul in Ontario. All these vehicles operate in Ontario at gross weights up to 61500 kg (135582 lb). They all had gross weights of 58600 kg (129189 lb).

The three 9-axle tractor-semitrailers selected are shown in Figure 4. All exist only as compromises between the regulations of Michigan and Ontario, and may operate in Ontario at gross weights up to 61500 kg (135582 kg). They also all had gross weights of 58600 kg (129189 lb)

STABILITY AND CONTROL EVALUATION

Computer Simulation Methodology

A mainframe version of the yaw/roll program in use at Ontario Ministry of Transportation [8] was used for stability and control analysis of the various vehicle configurations. This has been used extensively in previous simulation studies, and has been shown to provide reasonable agreement with tests [9], including some of multi-axle semitrailers [10].

Seven measures were used to characterize vehicle performance. These were based on definitions and performance levels from the CCMTA/RTAC Vehicle Weights and Dimensions Study [5].

A/ **Static Roll Threshold** is the tractor lateral acceleration at which a vehicle will just roll over in a steady turn. The recommended minimum roll threshold was 0.4 g [5].

B/ **High-Speed Offtracking** is the lateral offset between the path of the steer axle of the tractor and the path of the last axle of the vehicle in a moderate steady turn of 0.2 g lateral acceleration. The recommended maximum high-speed offtracking was 0.46 m (18 in) [5].

C/ **Load Transfer Ratio** is the fractional change in load between left- and right-hand side tires in an evasive manoeuvre. It indicates how close the vehicle came to lifting off all of the tires on one side. The recommended maximum load transfer ratio was 0.6 [5].

D/ **Transient High-Speed Offtracking** is the peak overshoot in lateral position of the last axle from the path of the tractor front axle in an manoeuvre, an indication of potential intrusion into an adjacent lane of traffic. The recommended maximum transient high-speed offtracking was 0.8 m (31.5 in) [5].

E/ **Friction Demand** is a measure of the resistance of multiple trailer axles to travel around a tight-radius turn such as at an intersection, and describes the minimum level of tire-pavement friction necessary at the tractor drive axles for the vehicle to make a turn without tractor jackknife. The recommended maximum friction demand was 0.1 [5].

F/ **Low-Speed Offtracking** is the extent of inboard offtracking of the rearmost trailer from the tractor front axle in a 90 degree right-hand intersection turn. The recommended maximum low-speed offtracking was that arising from a 4.8 m (190 in) wheelbase tractor drawing a 12.5 m (41 ft) wheelbase semitrailer in the same turn.

G/ **Effective Overhang Ratio** is the distance from the turn centre to the rear of the trailer, divided by the semitrailer wheelbase. The recommended maximum effective overhang ratio was 0.35 for a semitrailer with one fixed axle unit [5]. This controls outswing into an adjacent lane in a 90 degree right-hand intersection turn. Because all semitrailers had unequally loaded and unequally spaced axles, the turn centre was determined during the simulation to compute the effective overhang ratio.

Measures A and B were obtained from a high-speed turn made at 100 km/h; measures C and D from a high-speed evasive manoeuvre made at 100 km/h, and measures E, F and G from a 90 degree right-hand turn, made at 8.8 km/h, and of radius 14 m (45.93 ft) at the centre of the tractor left front wheel. A vehicle path was defined for each manoeuvre, and a driver model was used to cause the vehicle to follow that path. This methodology is the same as that used in the CCMTA/RTAC Vehicle Weights and Dimensions Study [2,4].

The vehicle component properties were selected from the data files produced during the CCMTA/RTAC Vehicle Weights and Dimensions Study [4]. A wide range of alternative equipment is in use. Since this study is a comparison of vehicle characteristics, selection of equipment is of lesser importance because any uniform change in equipment would not be expected to change the relative ranking of vehicles.

Results for Fixed Liftable Axles

Table 1 presents values for performance measures for all tractor-semitrailer configurations with fixed liftable axles.

Semitrailer high-speed offtracking in the steady circular turn at 0.2 g lateral acceleration was outboard of the path of the tractor, and ranged from 0.454 to 0.658 m (1.49 to 2.16 ft). The range is small because each semitrailer has about the same effective wheelbase. Configuration S9AATA met the performance criterion of 0.46 m (18 in), but the remaining vehicles all failed to meet it because of the relatively short effective semitrailer wheelbase, and large total spread axle spread.

Roll thresholds ranged from 0.310 g for S6DA to 0.394 g for S8AAT and S9AATA. The roll threshold generally increased with the number of axles. The 6-axle vehicles have quite a high payload. As each axle is added, the increment in payload decreases relative to the increment in roll resistance. When the ninth axle is added there is a decrease in payload. No vehicle met the performance criterion, a minimum roll threshold of 0.4 g [5]. However, if they had been loaded with freight at a uniform density of 545 kg/cu m (34 lb/cu ft), as was used in the Vehicle Weights and Dimensions Study [2], they would have met or been closer to the proposed performance criterion.

The load transfer ratio and transient offtracking measures obtained from the evasive manoeuvre were rather similar for all configurations. This is because all semitrailers have about the same effective wheelbase, as discussed above. S7TA has the highest load transfer ratio (0.695) and transient offtracking (0.838 m). S9AATA has the lowest load transfer ratio (0.607) and transient offtracking (0.597 m). All vehicles exceeded the proposed maximum load transfer ratio of 0.60 slightly, and all except S7TA were within the proposed transient offtracking performance criterion of 0.8 m (31.5 in) [5].

Low-speed offtracking in the low-speed right-hand turn was less in all cases than for a 14.63 m (48 ft) semitrailer with a dual axle unit and a 12.5 m (41 ft) wheelbase. The friction demand of all the vehicles was much higher than the maximum of 0.1 [5]. It was moderate for the two 6-axle vehicles. It was rather

Table 1/ Performance measures with fixed liftable axles

Vehicle	H-S Ot (m)	Roll Thr (g)	Ld Tr Ratio	Trans Ot (m)	Fric Dmnd	Eff Ovhng
	<0.46	>0.40	<0.60	<0.80	<0.1	<0.35
S6AD	0.551	0.329	0.648	0.704	0.25	0.347
S6DA	0.582	0.310			0.21	0.420
S7AT	0.588	0.354	0.673	0.796	0.56	0.327
S7TA	0.658	0.319	0.695	0.838	0.48	0.456
S7ADA	0.573	0.348	0.648	0.747	0.45	0.430
S7A2D	0.539	0.369	0.650	0.722	0.57	0.287
S7AAD	0.542	0.368	0.678	0.747	0.53	0.360
S8AQ	0.514	0.379	0.646	0.692	0.52	0.350
S8QA	0.579	0.361	0.644	0.768	0.61	0.425
S8AAT	0.475	0.394	0.636	0.634	0.53	0.314
S8ATA	0.536	0.363	0.646	0.722	0.50	0.420
S9AAQ	0.478	0.392	0.619	0.646	0.58	0.360
S9AQA	0.481	0.391	0.624	0.640	0.48	0.420
S9AATA	0.454	0.394	0.607	0.597	0.45	0.397

Table 2/ Performance measures with liftable axles raised

Vehicle	H-S Ot (m)	Roll Thr (g)	Ld Tr Ratio	Trans Ot (m)	Fric Dmnd
	<0.46	>0.40	<0.60	<0.80	<0.1
S6AD	0.740	0.289	0.634	0.789	0.04
S6DA	0.789	0.231			0.10
S7AT	0.710	0.326	0.638	0.786	0.13
S7TA					0.45
S7ADA			0.734	0.991	0.08
S7A2D					
S7AAD	0.889	0.285	0.659	0.878	0.03
S8AQ	0.597	0.361	0.615	0.689	0.16
S8QA	0.609	0.274			0.80
S8AAT	0.694	0.339	0.625	0.738	0.04
S8ATA	0.685	0.282	0.687	0.841	0.09
S9AAQ	0.569	0.367			0.09
S9AQA	0.557	0.330	0.647	0.728	0.17
S9AATA	0.670	0.298	0.655	0.792	0.07

uniformly high for all other vehicles, because the tires most distant from the turn centre of the semitrailer had passed their maximum sideforce capability so additional slip did not generate significant additional sideforce. None of the vehicles with more than three axles on the semitrailer would be able to negotiate a right-hand turn on a wet and slippery road without raising some or all of its liftable axles to avoid tractor jackknife. The effective overhang ratio was large for all vehicles, because the spread of the axles reduced the wheelbase. Only three vehicles, S6AD, S7AT and S7A2D had an effective overhang ratio less than the maximum of 0.35 [5].

Each of the multi-axle semitrailers, with all liftable axles down, failed to meet at least one of the performance criteria by a significant margin. Some failed more than one criterion.

Results for Raised Liftable Axles

It was assumed that all liftable axles would be raised for operational reasons at some time. Table 2 presents values for performance measures for all tractor-semitrailer configurations with liftable axles raised. It should be compared with Table 1.

High-speed offtracking increased, because the number of axles providing lateral force was reduced. The roll threshold decreased because the number of axles resisting rollover was reduced. There was a small increase in both load transfer ratio and transient offtracking in the high speed evasive manoeuvre.

Friction demand in the low-speed right-hand turn was reduced from a high of 0.58 to less than 0.17, for all configurations except S7TA and S8QA. Raising the liftable axle at the rear of these vehicles significantly reduced the tractor drive axle load, so the friction demand for the vehicle increased even though the moment needed to turn the semitrailer had decreased.

Raising the liftable axles reduced the friction demand while turning for most vehicles. It also seriously degraded resistance to rollover, and created axle overloads.

Results for Self-steering Axles

Each liftable axle was replaced with a self-steering axle that was steered by the frictional torque generated at the tire-road interface when the vehicle changed direction. A typical automotive steer self-steering axle, having moderate centering force and high Coulomb friction in the steer mechanism, was used. The results are presented in Table 3, and again should be compared with Table 1.

The self-steering axle reduced the friction demand in the low-speed right-hand turn, generally to about half of the value with the fixed liftable axle. The friction demand of configurations S6AD and S6DA were reduced from 0.25 and 0.21 to

Table 3/ Performance measures with self-steering axles

Vehicle	H-S Ot (m)	Roll Thr (g)	Ld Tr Ratio	Trans Ot (m)	Fric Dmnd	Eff Ovhng
	<0.46	>0.40	<0.60	<0.80	<0.1	<0.35
S6AD	0.603	0.349	0.606	0.692	0.10	0.270
S6DA	0.731	0.315	0.608	0.832	0.11	0.630
S7AT	0.615	0.361	0.641	0.756	0.32	0.268
S7TA	0.725	0.313	0.655	0.845	0.30	0.637
S7ADA	0.591	0.355	0.621	0.725	0.33	0.370
S7A2D	0.612	0.373			0.26	0.193
S7AAD	0.643	0.403	0.606	0.728	0.23	0.188
S8AQ	0.524	0.393			0.33	0.300
S8QA	0.658	0.337	0.657	0.905	0.39	0.650
S8AAT	0.509	0.410	0.598	0.619	0.28	0.213
S8ATA	0.630	0.352			0.24	0.477
S9AAQ	0.512	0.403			0.36	0.266
S9AQA	0.505	0.399	0.620	0.667	0.32	0.460
S9AATA	0.484	0.391			0.31	0.440

Table 4/ Performance measures for free-castering self-steering axles

Vehicle	H-S Ot (m)	Roll Thr (g)	Ld Tr Ratio	Trans Ot (m)	Fric Dmnd	Eff Ovhng
	<0.46	>0.40	<0.60	<0.80	<0.1	<0.35
S6AD	0.740	0.381	0.573	0.725	0.06	0.245
S6DA	1.027	0.329			0.06	0.680
S7AT	0.704	0.408	0.596	0.744	0.19	0.244
S7TA	0.911	0.326			0.20	0.756
S7ADA	0.633	0.388			0.24	0.337
S7A2D						
S7AAD	0.993	0.479	0.540	0.805	0.08	0.144
S8AQ	0.557	0.416	0.584	0.643	0.22	0.307
S8QA	0.832	0.333			0.30	0.764
S8AAT	0.719	0.458			0.08	0.175
S8ATA	1.002	0.368	0.564	1.003	0.08	0.510
S9AAQ	0.588	0.438	0.543	0.655	0.14	0.232
S9AQA	0.676	0.394	0.573	0.808	0.15	0.488
S9AATA	0.710	0.438	0.529	0.814	0.08	0.425

the acceptable levels of 0.10 and 0.11 respectively. Reductions for the other vehicles were large, but they all remained substantially in excess of the proposed criterion of 0.10. Any vehicle with a self-steering axle behind its fixed axle unit exceeded the maximum effective overhang ratio of 0.35, whereas all vehicles with their fixed axle unit at the rear met this performance criterion.

When the self-steering mechanism was made nearly free-castering, with low centering force and low Coulomb friction, it became representative of a turntable steer axle. The results are presented in Table 4. The roll threshold and high-speed offtracking in the high-speed circular turn both generally increased over the corresponding self-steering configurations. There was a further significant improvement in friction demand for all vehicles.

Stability and Control Conclusions

The differences arising between vehicles during the high-speed turn and the evasive manoeuvre were not dramatic. This does not mean these differences are unimportant, just that the differences arising from the low-speed right-hand turn served to categorize the vehicles.

Figure 5 compares the effective overhang ratio performance for all vehicles, with fixed liftable axles, self-steering axles and free-castering self-steering axles. Vehicles S6DA, S7TA, S7ADA, S8QA, S8ATA, S9AQA and S9AATA, all of which had a liftable or self-steering axle aft of the fixed axle unit, failed to meet the effective overhang ratio criterion for all three axle types.

Figure 6 compares the friction demand performance for all vehicles, with fixed liftable axles, self-steering axles and free-castering self-steering axles. All vehicles with a fixed liftable axle failed to meet the friction demand criterion by a wide margin, because of the wide spread between the first and last axles. With self-steering axles having nominal properties, of those vehicles that met the effective overhang ratio criterion, only S6AD also met the friction demand criterion. With free-castering self-steering axles, S7AAD, and S8AAT also met the friction demand criterion. It is presumed that S7A2D would also meet the criterion. S7AT would have met the criterion with a triple axle unit of smaller spread, though that would reduce its allowable gross weight.

Figure 7 compares the roll threshold for all vehicles, with fixed liftable axles both down and raised, self-steering axles and free-castering self-steering axles. The roll threshold improves as the self-steering resistance is reduced to free-castering, as does the load transfer ratio, whereas high-speed and transient offtracking are both degraded. It is a matter for consideration whether self-steering axles on these vehicles should be locked when they operate at high speed.

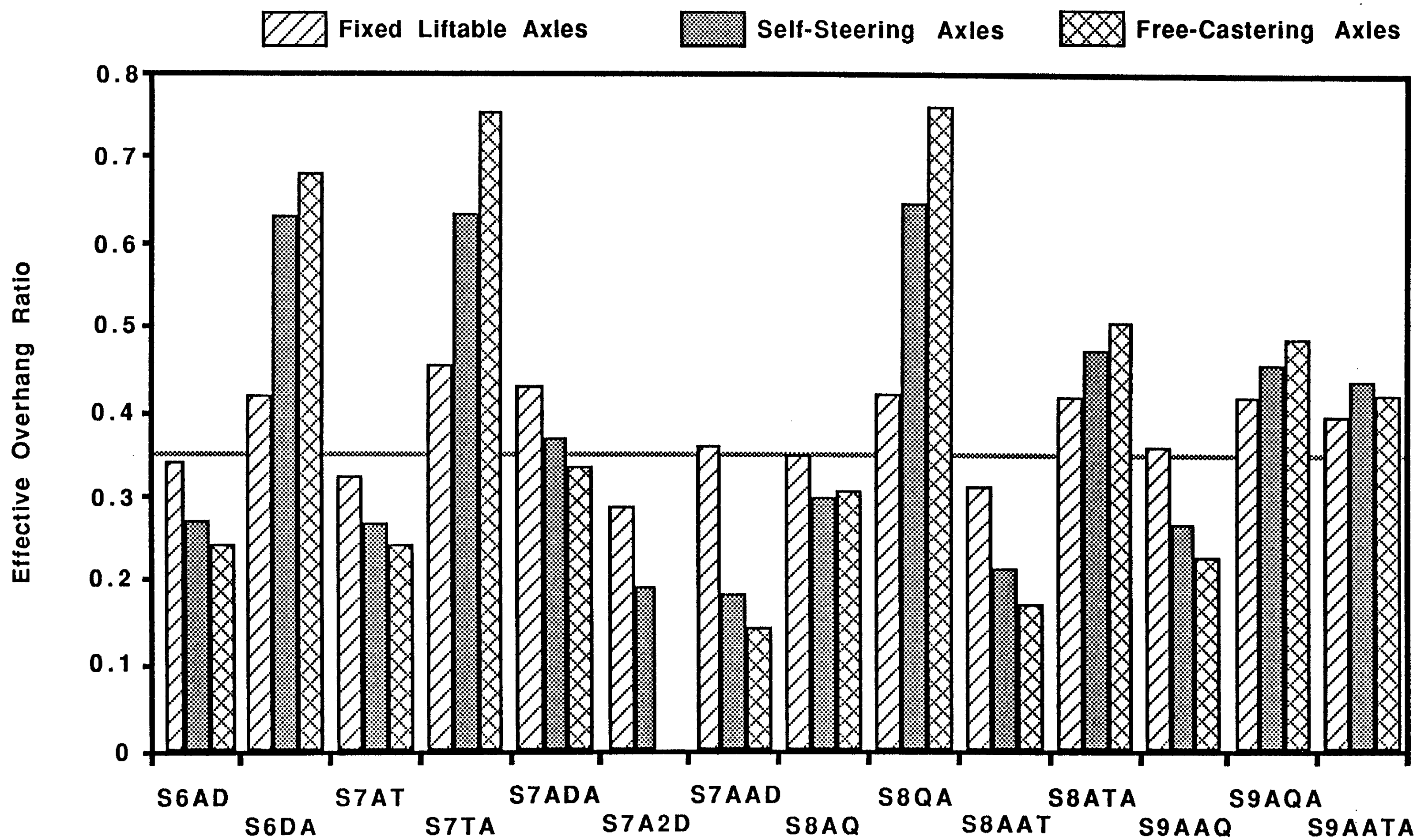


Figure 5/ Effective Overhang Ratio – 14 m Right-hand Turn

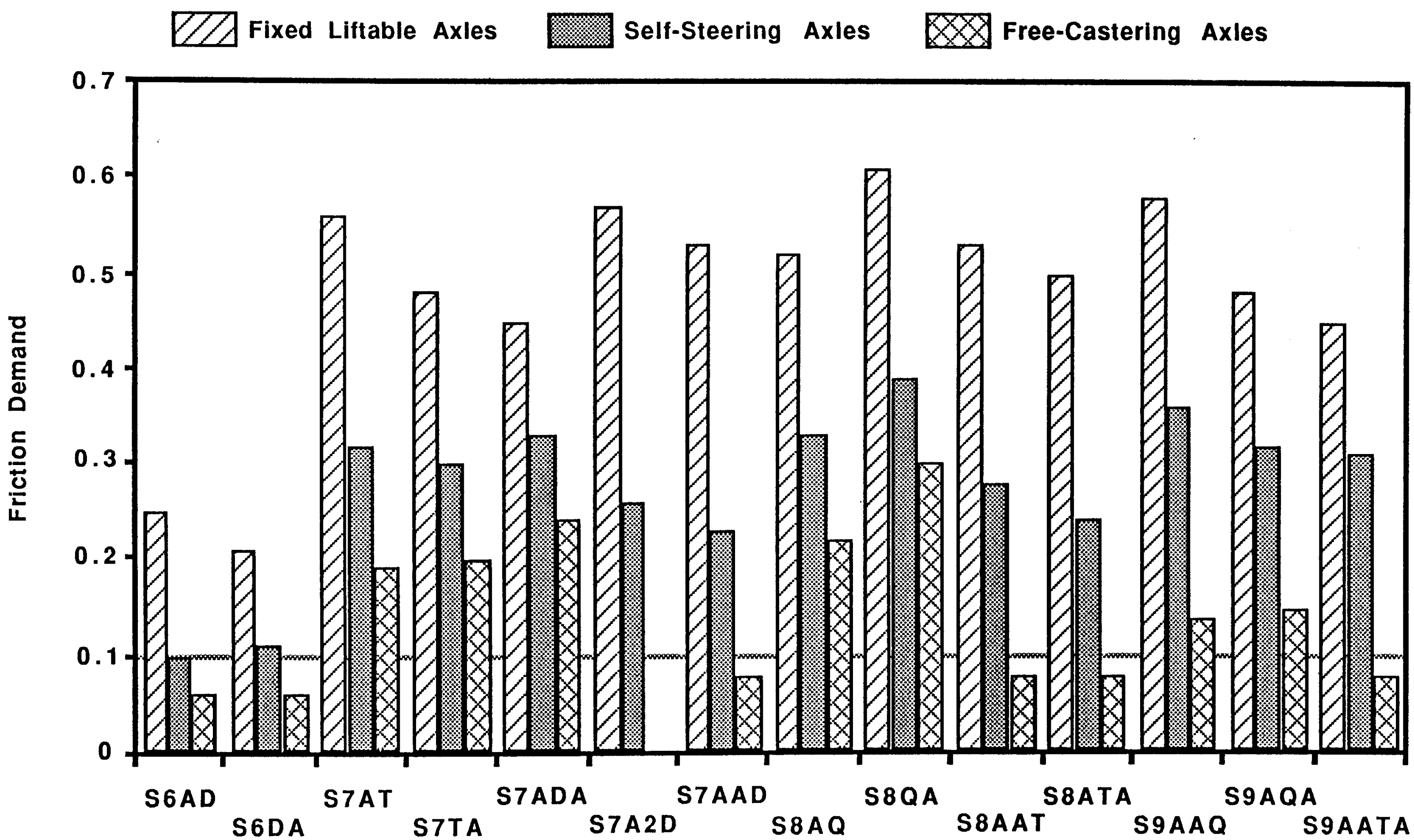


Figure 6/ Friction Demand – 14 m Right-hand Turn

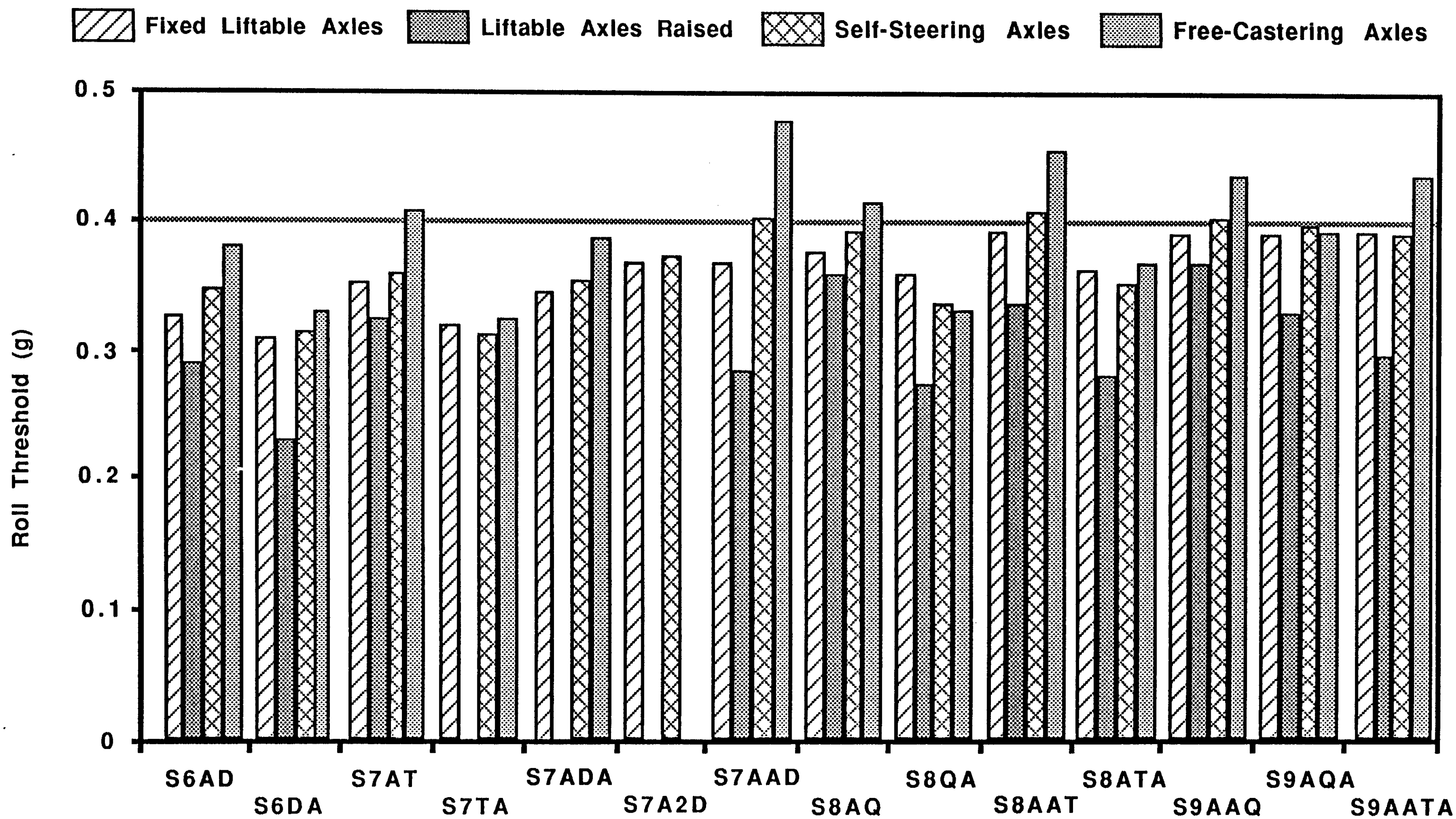


Figure 7/ Roll Threshold – High-speed Steady Turn

HIGHWAY CONSIDERATIONS

Pavement Loading

Pavement loading impact was evaluated in terms of equivalent single axle loads (ESAL's) of 8165 kg (18000 lb) using the following axle unit load equivalency values [3] :

Steer axle, single tires	5000 kg
Single axle unit, dual tires	10000 kg
Dual axle unit, dual tires	17000 kg
Triple and four axle units, dual tires	24000 kg

Table 5 compares the number of ESAL's with liftable axles down and raised. The number of ESAL's increases with an increase in the number of axle units. Configuration S7AAD generates more ESAL's than S7AT because it has one more axle unit. The number of ESAL's generally decreases with an increase in total number of axles, because each axle added to these vehicles adds less payload. There is a dramatic increase in the number of ESAL's when liftable axles are raised, ranging from 50% for S7AT to 296% for S7ADA. The highest increases in ESAL's arise for configurations such as S6DA, S7ADA and S7A2D, whose drive axles and/or trailer axles become most heavily overloaded. When the liftable axles of configuration S8ATA are down, they generate a significant portion of the ESAL's and the underloaded triple axle unit is hardly significant. However, when the liftable axles are raised the triple axle unit is heavily overloaded, but not so overloaded as axle units of some other vehicles, so that its increase in ESAL's is relatively modest.

Bridge Loading

Bridge loading impact was evaluated using the Ontario Bridge Formula (OBF) [11]. The axle unit and gross weights in the Ontario regulations are based upon the OBF, but do not exactly correspond to it [12], because of some generosity when the formula was transformed into tables. Table 6 shows that the gross weight of the vehicles with liftable axles down exceeded the allowable OBF load by as much as 6.4%.

Raising the liftable axles caused the allowable OBF loads to be exceeded by some very large amounts. Entries flagged with an asterisk show where the load exceeded that specified in the Ontario Highway Bridge Design Code for design and evaluation of bridges [13]. When the liftable axle on any vehicle with no liftable axle ahead of the fixed trailer axles was raised, the tractor drive axles were drastically unloaded. The trailer axle loads all exceeded the design load level by 4-6 t, and there was also a significant excess of gross weight over the OBF. All vehicles with fixed axles behind all trailer liftable axles exhibited significant excesses of the OBF for both drive and trailer axles when their liftable axles are raised, but actually conformed slightly better to the OBF for gross weight than with the liftable axles down. The remaining vehicles have liftable

Table 5/ Pavement Loading

Vehicle	ESAL's/Vehicle for Liftable Axles		
	Down	Up	% Change
S6AD	10.77	17.96	66.6
S6DA	10.77	31.67	193.9
S7AT	9.91	14.93	50.6
S7TA	9.64	19.73	104.8
S7ADA	10.32	40.85	296.0
S7AAD	10.93	25.97	137.6
S7A2D	10.11	25.97	156.9
S8AQ	10.33	15.57	50.8
S8QA	10.49	23.74	126.3
S8ATA	8.12	15.61	92.1
S8AAT	9.02	17.90	98.4
S9AQA	8.13	15.51	90.7
S9AAQ	8.01	16.36	104.2
S9AATA	7.00	15.10	115.7

Table 6/ Bridge Loading

Vehicle	Exceedance of OBF Load (percent)			
	Liftable Axle Position			
	Down	Up		
	Gross	Gross	Drive	Trailer
S6AD	-7.7	-13.0	22.0	30.8
S6DA	-6.1	13.6	-23.1	73.6 *
S7AT	2.6	-3.9	32.5	13.5
S7TA	5.5	27.4 *	-33.5	62.7 *
S7ADA	5.1	20.0	-2.4	84.8 *
S7AAD	5.5	-4.4	47.9	37.1
S7A2D	5.2	-4.2	48.9	36.1
S8AQ	5.7	0.2	30.0	14.3
S8QA	6.4	26.3 *	-39.6	47.2 *
S8ATA	6.3	18.6	3.4	84.5 *
S8AAT	6.0	0.3	52.0	44.2
S9AQA	5.5	14.1	3.5	51.9 *
S9AAQ	5.6	-1.2	37.2	25.8
S9AATA	5.6	11.7	14.7	73.9 *

axles disposed on either side of a fixed axle unit. When all liftable axles are raised, almost the entire load was assumed by the fixed trailer axles. The trailer axle loads exceeded the design load by 6.46 t for the popular S8ATA vehicle, and there was also a significant excess of gross weight over the OBF.

FORMULATION OF REGULATORY PRINCIPLES

The CCMTA/RTAC Vehicle Weights and Dimensions Study recommended that a semitrailer be permitted only one axle unit, either single, dual or triple, and limited the spread of the dual and triple axle units [5,6]. It recommended further that no province need permit liftable axles. These recommendations, based upon considerations of friction demand in a tight turn, pavement damage, and the potential for abuse or misuse of the lift feature, reinforced the prior stance of those provinces that did not tolerate liftable axles. They would, however, severely limit the gross weight available on tractor-semitrailers operating in Ontario and Quebec.

The high axle and gross loads currently allowed in Ontario and Quebec are considered to contribute to the industrial economies of both provinces. It is clear, though, that the provinces face an increasing cost for highway rehabilitation if the high loads continue and abuse of the liftable axle is unchecked. It therefore appears necessary to develop some compromise whereby the application of liftable axles would be carefully controlled, so that current load levels could remain but abuse would not be possible.

The two determining performance measures were friction demand and effective overhang ratio. For all other measures there were generally only small differences between vehicles, and where the measures were not met, the failure was not judged to be serious. The gain in stability performance and highway loading by controlling vehicle configuration so that liftable axles would always be down when they needed to be down far outweighed any concern that vehicles did not quite meet some performance measures.

The only vehicles that met both the friction demand and effective overhang ratio measures were :

1/ S6AD with a nominal or free-castering self-steering axle;
2/ S7AAD with free-castering self-steering axles;
3/ S7A2D with free-castering self-steering axles;
4/ S8AAT with free-castering self-steering axles; and
5/ S7AT with a free-castering self-steering axle and reduced triple axle unit spread.

There is little experience with self-steering axles on semitrailers at this time. Indeed, this was one of the reasons that they were not recommended by the CCMTA/RTAC Vehicle Weights and Dimensions Study [5,6]. Two self-steering axles, such as would be required for configurations S7AAD, S7A2D and S8AAT, would add considerable mechanical and dynamic complexity to these vehicles. While a development and demonstration program of reasonable duration might address concerns for single self-steering axles, two self-steering axles are considered an inappropriate risk at this time. Linking the steering of these two axles might be an option, but that has not been examined.

Review of the computer simulation results, and analysis of design and operation of multi-axle semitrailers, led easily to the following regulatory principles :

Vehicle Configuration

1/ There shall be one fixed axle unit per semitrailer.
2/ There shall be no more than one liftable axle unit per semitrailer.
3/ The liftable axle unit shall be ahead of the fixed axle unit.

Liftable Axles

1/ The liftable axle may be raised when not required to carry load.
2/ The liftable axle shall share load properly with the fixed axles at all times when required to carry load.
3/ The liftable axle shall control its own load within some specified tolerance on a roadway of specified undulation.
4/ The liftable axle shall control its own load within some specified tolerance over some specified time period and for some specified variation in its energy source.
5/ The liftable axle shall be self-steering.
6/ The liftable axle shall lift when reverse gear is selected.
7/ The driver may occasionally unload the liftable axle for a short period when traction is poor, though option to do this shall be strictly limited.
8/ The liftable axle control device shall be proof against tampering, misuse and abuse.

Self-steering Axles

1/ Steer centering force requirements should be specified, following those recently developed for the C-dolly [14].
2/ The steering mechanism may lock when speed exceeds (say) 50 km/h, and should unlock when speed diminishes below 30 km/h.
3/ The self-steering axle shall lift when reverse gear is selected.

These controls may not be complete, and further development of the logic and requirements may be necessary. Their essence is to allow the driver control of liftable axle deployment only in emergency conditions. Development of devices that implement these controls appears within the capability of current technology, though meeting the demanding reliability and environmental conditions of trucking community may be challenging. The provinces of Ontario and Quebec, supported by the Transportation Development Centre of Transport Canada, have started a development project to address this need.

Previous work has shown that the stability and control performance of a self-steering axle in the belly axle position of a three axle semitrailer is quite satisfactory [4,15]. There is no doubt that the self-steering axle is more complicated, expensive, and requires more maintenance than a fixed axle. But then, the liftable belly axle also causes significantly more wear and tear on body structure and tires than for a semitrailer with just one axle unit. The issue of whether self-steering axles can be made to work would appear to depend to a large extent on the incentive to make them work.

IMPLEMENTATION OF REGULATORY PRINCIPLES

Ontario

The current law and regulations of Ontario has few direct controls on vehicle configuration [12], so a wide range of vehicle configurations are seen on the highways. The Memorandum of Understanding on Vehicle Weights and Dimensions restricted the tractor-semitrailer to six axles [6]. This gave a substantial gross weight advantage to 7- and 8-axle B-trains, so they became the vehicles of choice for movement of heavy payloads. In Ontario at present, the 7- and 8-axle B-train has no gross weight advantage over the 7- and 8-axle tractor-semitrailer. Tractor-semitrailers are therefore generally preferred for haul of most heavy commodities.

Implementation of the Memorandum of Understanding in Ontario will provide both 7- and 8-axle B-trains with a gross weight advantage of about 2000 kg (4409 lb) over tractor-semitrailers. Other measures under consideration may widen the B-train's gross weight advantage by at least another 1000 kg (2205 lb). The B-train should then begin to supplant the multi-axle semitrailer by a process of natural selection, at least for those shipments that are not in long pieces.

An understanding of intention to adopt the regulatory principles outlined in the preceding section would allow industry the lead time to prepare for the controls envisaged. Therefore, when appropriate liftable axle load control devices are developed, and experience has been gained with self-steering axles, a requirement for this equipment, and the vehicle configuration controls of one fixed axle unit per semitrailer, and no more than one liftable axle unit ahead of the fixed axle unit, may be implemented.

Quebec

The current law and regulations of Quebec specifies vehicle configurations directly [16]. It therefore has a somewhat narrower range of configurations than Ontario, as well as an absence of semitrailers with five or more axles. Recently the Ministere des Transports took steps to encourage the use of privileged configurations. It has proposed to introduce into its regulations two new configurations of 4-axle semitrailer, each composed of a liftable axle ahead of a fixed triple axle unit. These will both be allowed an additional 2000 kg (4409 lb) over the 30000 kg (66138 lb) currently allowed on other configurations of 4-axle semitrailer, for a gross weight limited to 55500 kg (122355 lb). This recognizes that the current gross weights, those allowed by Ontario's regulations, are a little generous.

Again, when appropriate liftable axle load control devices are developed, and experience has been gained with self-steering axles, then a requirement for this equipment might be implemented for new vehicles.

CONCLUSIONS

The stability and control, pavement, and bridge loading characteristics of fourteen tractor-semitrailer combinations having various arrangements of 3 to 6 trailer axles, 6 to 9 total axles, have been evaluated. Performance criteria similar to those developed in the CCMTA/RTAC Vehicle Weights and Dimensions Study were used for stability and control. These vehicles were evaluated with fixed liftable axles, and with self-steering axles having properties representative of automotive and turntable steer mechanisms.

No tractor-semitrailer having one or more fixed liftable axles, and six or more axles total so arranged that the highest gross weight can be carried for the number of axles provided, can meet all the performance criteria with the liftable axle down. When liftable axles are raised to meet these criteria, the roll threshold is seriously degraded, and axle and gross weights rise to a level that threatens serious damage to the highway system.

One vehicle configuration meets the performance criteria when its liftable axle is also made self-steering. This is the common 6-axle tractor-semitrailer having a semitrailer with a single axle (belly axle) located ahead of a fixed dual axle unit. The 7-axle tractor-semitrailer having a semitrailer with a single liftable self-steering axle located forward of a fixed triple axle unit comes acceptably close to meeting the criteria.

These findings lead easily to the vehicle configuration controls that there should be only one fixed axle unit per semitrailer, no more than one liftable axle unit, that liftable axle should be ahead of the fixed axle unit, and should be self-steering. Stringent specification of the liftable self-steering axle deployment and control logic will be necessary to ensure that the axle is down and properly loaded when the vehicle load so requires. The self-steering axle may also be locked at highway speed. Specification and development of controls for these requirements appears to be technically feasible.

The province of Ontario cannot easily implement these regulatory principles into its current law and regulations, though other measures are expected to encourage alternatives to many multi-axle semitrailer configurations. It will be easier for the province of Quebec to implement the regulatory principles on vehicle configuration because the appropriate vehicle configurations can easily be placed into the regulations. Complete implementation by both provinces will be practical when a joint project to develop liftable axle load control devices, and gain experience with self-steering axles, has been completed.

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