THE EFFECT OF WIND ON HEAVY VEHICLES

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Abstract

There are certain areas of Canada, including a number of elevated bridges, which are beset by strong winds. Local authorities are aware that empty and lightly loaded van semi-trailers may be blown over by a strong wind, so they have protocols to halt truck movement in a strong wind. This paper considers the effect of wind on various truck configurations common in Canada.

Keywords: Heavy Vehicles, Freight transport, Wind, Rollover.

Résumé

Certains secteurs du Canada, y compris des ponts de grande hauteur, sont exposés à des vents forts. Les autorités locales sont conscientes que des poids lourds à semi-remorques vides et des camionnette faiblement chargées pourraient être renversés par un vent fort, donc elles ont des protocoles pour arrêter les camions en cas de vent fort. Cet article étudie l'effet de vent sur diverses configurations de camions communes au Canada.

Mots-clés: poids lourds, transport de marchandises, vent.

1. Introduction

There are certain areas of Canada, including a number of elevated bridges, which experience strong winds. At many of these locations, the ten-year return period for mean hourly wind speed may exceed 86 km/h. Local authorities are aware that empty and lightly loaded van semi-trailers may be blown over by a strong wind, so they have protocols to halt truck movement in strong winds. This analysis considers in more general terms the effect of wind on various truck configurations common in Canada.

2. Preliminary Analysis

Empty vehicles with the fewest axles for their particular configuration appeared the most likely to suffer wind-induced rollover. A preliminary analysis included:

- 3-, 4- and 5-axle tractor-semi-trailers, with a 16.20 m semi-trailer;
- 5- and 6-axle A-train doubles, with two 8.53 single axle trailers;
- 5- and 6-axle B-train doubles, with two 9.22 m trailers; and
- 9-axle A-train double, with two 16.20 m tandem trailers.

The 5-axle tractor-semi-trailer is the most common configuration in Canada, at over 50% of the entire truck fleet. Each of the other configurations is less than 1% of the fleet.

2.1 Method of Analysis

This analysis used the author's version of the Yaw/Roll model (Gillespie and MacAdam, 1982), modified to apply a wind input to a vehicle during a run. The driver model was used to cause the vehicle to follow a straight path at 100 km/h with a wind blowing at 90 degrees to the vehicle. The wind was applied at the centre of the exposed area of each vehicle unit, with a lateral drag coefficient of 2.0 for trailers, 1.5 for tractors, to reflect their rounded surface, and zero for converter dollies. The wind speed was increased at a rate of 4.4 km/h/s until a vehicle rolled over.

2.2 Results and Discussion

Table 1 shows the responses by vehicle configuration. The first column gives the vehicle configuration. The second column gives the wind speed at rollover. The last three columns give the rear axle offtracking at wind speeds of 44, 55 and 66 km/h.

Table 1 – Wind responses by configuration.

Vehicle Configuration		Wind Speed at Rollover (km/h)	Rear axle offtracking (m)		
			44 km/h	55 km/h	66 km/h
Semi	11S1	73.7	0.238	0.408	0.658
Semi	11S2	79.0	0.198	0.323	0.506
Semi	12S2	84.3	0.186	0.311	0.475
A-train	11S1-11	81.2	0.204	0.326	0.497
A-train	12S1-11	81.2	0.195	0.311	0.475
B-train	12S2S1	89.5	0.122	0.283	0.421
B-train	11S2S1	89.1	0.189	0.302	0.454

It is clear from Table 1 that wind-induced rollover may occur for wind speeds well within a ten year return period for many locations across Canada. The possibility that vehicles may be blown over is therefore not a rare and unusual occurrence.

The results for the 5-axle tractor-semi-trailer must be considered the baseline, as it is the most common configuration in Canada. Both 3- and 4-axle tractor-semi-trailers rolled over at lower wind speeds, and had greater offtracking, than the 5-axle tractor-semi-trailer. However, these vehicles are quite rare. The trend for an increase in wind speed necessary to cause rollover with an increase in the number of axles suggests that tractor-semi-trailers with more than five axles, which are widely used in Canada, will be less critical than the 5-axle tractor-semi-trailer.

Only the second trailer rolled over for the A-trains, so a single or tandem drive tractor made no difference as the tractor and lead trailer always remained standing. The A-trains were close in performance to the 5-axle tractor-semi-trailer, and are also relatively rare.

The entire vehicle rolled over for both B-trains. The wind speed at rollover for both B-trains was higher than for the tractor-semi-trailers, and the wind-induced offtracking was significantly less, so this vehicle is clearly less critical than a 5-axle tractor-semi-trailer. More common B-trains have more axles, so should be even less critical.

3. Detailed Analysis

The 5-axle tractor-semi-trailer with a 16.20 m tandem semi-trailer shown in Figure 1 is the most common single vehicle, and should serve as a baseline for analysis, as discussed above. The Turnpike Double, shown in Figure 2, is a 9-axle A-train double with the same 16.20 m tandem trailers as considered for the 5-axle tractor-semi-trailer. This configuration operates under a special permit in several provinces in Canada, and also in several states in the U.S. It is a configuration of some current interest in Canada, and also for this analysis, as it has the largest surface area of any configuration on the highway.

These vehicles were considered empty, and with a payload in increments of 2,268 kg up to 11,340 kg, distributed uniformly over all but the rearmost 0.30 m of the length of each trailer, and with a payload height of 1.22 m.
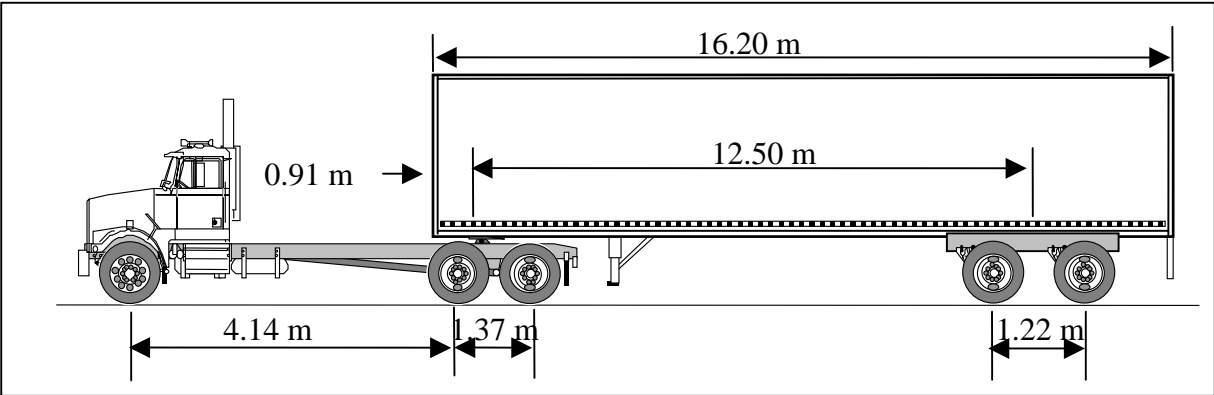

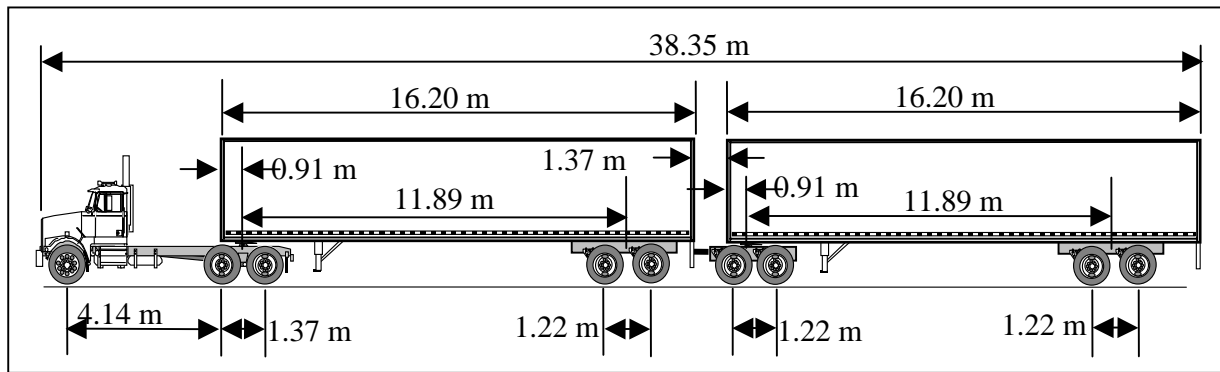**Figure 1** – 16.20 m Tandem Van Semi-trailer.

Figure 2 – Turnpike Double with Twin 16.20 m Tandem Van Semi-trailers.

3.1 Method of Analysis

The wind model for this analysis was composed of wind blowing at a steady speed, and a gust factor, which multiplied the wind speed to represent a maximum likely gust. The gust was considered as a step increase in the steady wind speed, for a period of 2-4 s. The magnitude of the gust depended on both wind speed and vehicle speed.

Aerodynamic data from the literature were processed to give side force and moment coefficients about the centre of gravity of a wind tunnel model (Coleman and Baker, 1994, and Baker and Humphreys, 1996). The centre of pressure of the model trailer was computed from these data, assuming a uniform distribution of pressure over the entire side area of the vehicle. The aerodynamic force then was composed of the side force coefficient, applied at a specified location on a vehicle.

Wind may affect the performance of a vehicle by causing it to roll over, or by causing offtracking of trailing units of an articulated vehicle.

The risk of wind-induced rollover was evaluated by the load transfer ratio performance measure, which was originally developed as a measure of the risk of rollover of a vehicle unit in an evasive manoeuvre (Ervin and Guy, 1986). This evaluates the difference in axle loads between one side and the other for a vehicle, or that part likely to roll over. 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 (CCMTA/RTAC Vehicle Weights and Dimensions Study Implementation Planning Committee, 1987). This leaves a rather slender margin for a driver to manoeuvre without lifting wheels.

Wind-induced offtracking, also known as dogtracking, was evaluated by the high-speed offtracking performance measure, which was originally developed as a measure of the likelihood that the rearmost axle of a vehicle making a high-speed turn would strike a curb and provoke rollover, or enter the space of another vehicle (Ervin and Guy, 1986). The high-speed offtracking performance standard of 0.46 m allows the rearmost axle of a 2.59 m wide vehicle within 0.08 m of the edge of a 3.66 m wide lane with the tractor centred in the lane (CCMTA/RTAC Vehicle Weights and Dimensions Study Implementation Planning Committee, 1987).

This analysis also used the author's version of the Yaw/Roll model (Gillespie and MacAdam, 1982). The driver model was used 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 to reach a steady state. At this point, the wind speed was increased instantaneously by the gust factor. The gust continued for 4 s, and then 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:

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

3.2 5-axle Tractor-semi-trailer

Table 2 presents the load transfer ratio of an empty 16.2 m semi-trailer induced by both a steady and a gusting wind. Values in bold indicate that the performance measure exceeded the performance standard of 0.60, and **Roll** indicates the vehicle rolled over. The load transfer ratio increased with wind speed, and for a given wind speed, diminished with vehicle speed. The results suggest that travel may be feasible in a steady wind up to about 75 km/h, but becomes risky at a speed over 50 km/h in a strongly gusting wind. These values would be lower for a more slowly-moving vehicle. The results in Table 2 are plotted in Figure 3. The lower group of four lines represents the response to a steady wind, and the upper group represents the response to a gust. The vehicle speed is labeled for each line in the upper group of four lines, and the lines in the lower group are in the same order, 40 km/h at the top and 100 km/h at the bottom.

Table 3 presents offtracking of an empty 16.2 m semi-trailer induced by both a steady and a gusting wind. Values in bold indicate that the performance measure exceeded the performance standard of 0.46 m, and **Roll** indicates the vehicle rolled over. Wind-induced offtracking increased with wind speed, and for a given wind speed, diminished with vehicle speed. Offtracking increased rapidly for stronger winds, and clearly became an issue for a steady wind speed over 75 km/h, or at about 50 km/h for a strongly gusting wind. Coincidentally, these are the same speeds at which rollover became a concern. These results are plotted in Figure 4, in the same format as Figure 3.

The weight of payload in a vehicle was expected to increase its resistance to wind-induced rollover and offtracking. The vehicle was therefore run again while traveling at 40 km/h, with a payload weight in increments of 2,268 kg, up to a total of 11,340 kg.

Table 4 and Table 5 present the load transfer ratio and offtracking induced by both a steady and a gusting wind in the same format as Table 2 and Table 3 respectively, for the same vehicle traveling at 40 km/h with various weights of payload in the trailer. It requires a payload of 4,500 to 6,800 kg to achieve a significant increase in the resistance to wind-induced rollover or a significant reduction in wind-induced offtracking. Payload centre of gravity height appeared to have little influence on these performance measures. Carriers generally try and carry a payload, and only about 15% of these vehicles travel with a payload less than about 6,800 kg.

Table 2 – Wind-induced Load Transfer Ratio of Empty Semi-trailer**.**

Vehicle Speed (km/h)	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 3 – Wind-induced Offtracking of Empty Semi-trailer.

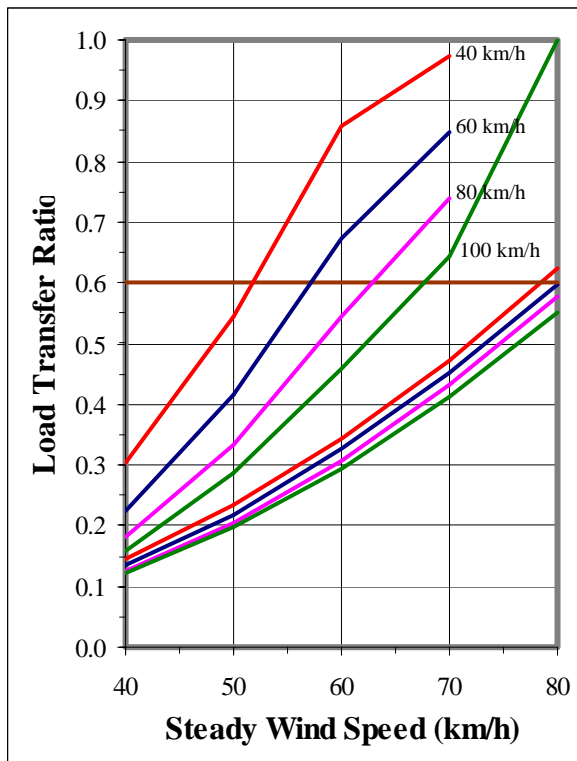| Vehicle Speed (km/h)	Steady Wind Speed (km/h)					Gusting Wind, Steady Speed (km/h)				
	40	**50**	**60**	**70**	**80**	**40**	**50**	**60**	**70**	**80**
40	0.109	0.175	0.258	0.366	**0.506**	0.226	0.427	**0.756**	**0.895**	**Roll**
60	0.101	0.164	0.245	0.350	**0.483**	0.168	0.316	**0.554**	**0.759**	**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**

Figure 3 – Wind-induced Load Transfer Ratio of Empty Semi-trailer.
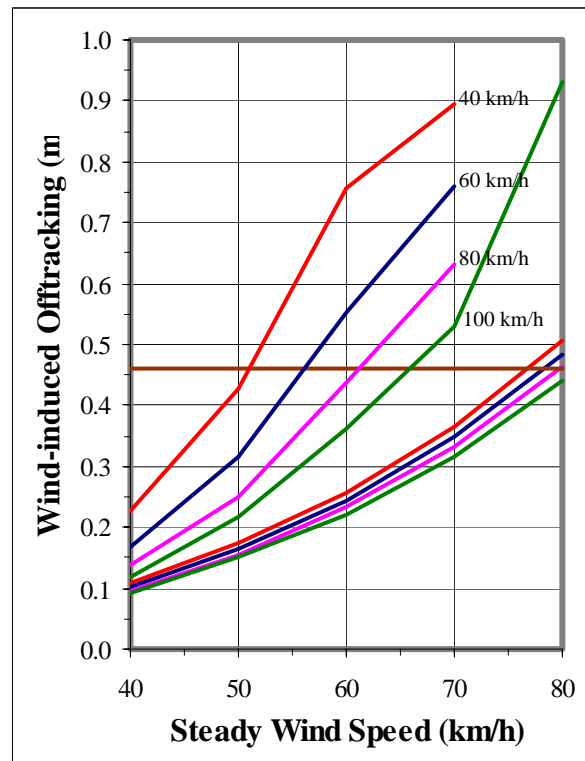
Figure 4 – Wind-induced Offtracking of Empty Semi-trailer.

Table 4 – Effect of Payload on Wind-induced Load Transfer Ratio of Semi-trailer.

Payload	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
(lb)	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**
5,000	0.119	0.191	0.280	0.387	0.512	0.250	0.447	**0.699**	**0.788**	**Roll**
10,000	0.100	0.162	0.238	0.328	0.434	0.212	0.379	0.592	**0.668**	**Roll**
15,000	0.087	0.141	0.207	0.285	0.377	0.185	0.330	0.515	0.582	**Roll**
20,000	0.077	0.125	0.183	0.253	0.334	0.164	0.292	0.457	0.516	**0.893**
25,000	0.070	0.112	0.165	0.227	0.301	0.148	0.262	0.411	0.464	**0.802**

Table 5 – Effect of Payload on Wind-induced Offtracking of Semi-trailer.

Payload	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
(lb)	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**
5,000	0.086	0.138	0.205	0.286	0.394	0.179	0.331	**0.560**	**0.664**	**Roll**
10,000	0.072	0.117	0.175	0.244	0.326	0.153	0.278	**0.464**	**0.535**	**Roll**
15,000	0.064	0.103	0.153	0.214	0.285	0.134	0.244	0.398	0.459	**Roll**
20,000	0.058	0.094	0.138	0.192	0.255	0.121	0.219	0.350	0.403	**0.793**
25,000	0.054	0.086	0.127	0.176	0.234	0.111	0.201	0.315	0.360	**0.697**

3.3 Turnpike Double

This vehicle was composed of the same tractor as used for the 5-axle tractor-semi-trailer, with two of the same trailers, and a tandem axle converter dolly.

Table 6 presents the load transfer ratio of an empty Turnpike Double induced by both a steady and a gusting wind, in the same format as Table 2. The load transfer ratio increased with wind speed, and for a given wind speed, diminished with vehicle speed. Travel may be feasible in a steady wind up to about 75 km/h, but becomes risky at about 50 km/h in a strongly gusting wind. These are the same results as for the 5-axle tractor- semi-trailer, though in all cases the second trailer rolled over and the tractor and lead trailer remained standing. The results in Table 6 are plotted in Figure 5, in the same format as Figure 3.

Table 7 presents offtracking of an empty Turnpike Double induced by both a steady and a gusting wind, in the same format as Table 3. Wind-induced offtracking increased with wind speed, and for a given wind speed, diminished with vehicle speed. Offtracking increased rapidly for stronger winds, and clearly became an issue for a steady wind speed over 50 km/h, or over 40 km/h for a strongly gusting wind. Offtracking is significantly larger than for the 5-axle tractor-semi-trailer, because offtracking of the rear trailer is superimposed on offtracking developed by the lead semi-trailer. These results are plotted in Figure 6, in the same format as Figure 4.

The weight of payload in the Turnpike Double was expected to increase its resistance to wind-induced rollover and offtracking.

Table 8 and Table 9, in the same format as Table 4 and Table 5 respectively, present the load transfer ratio and offtracking induced by both a steady and a gusting wind for the same vehicle traveling at 40 km/h with various weights of payload in each trailer. It required a

payload of 4,500 to 6,800 kg in each trailer to achieve a significant increase in the resistance to rollover in a gusting wind, and even 6,800 to 11,300 kg in each trailer only achieved a modest reduction in wind-induced offtracking. About 40% of trips by 5-axle tractor-semi-trailers are with less than 11,300 kg of payload.

Table 6 – Wind-induced Load Transfer Ratio of Empty Turnpike Double.

Vehicle Speed (km/h)	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 7 – Wind-induced Offtracking of Empty Turnpike Double.

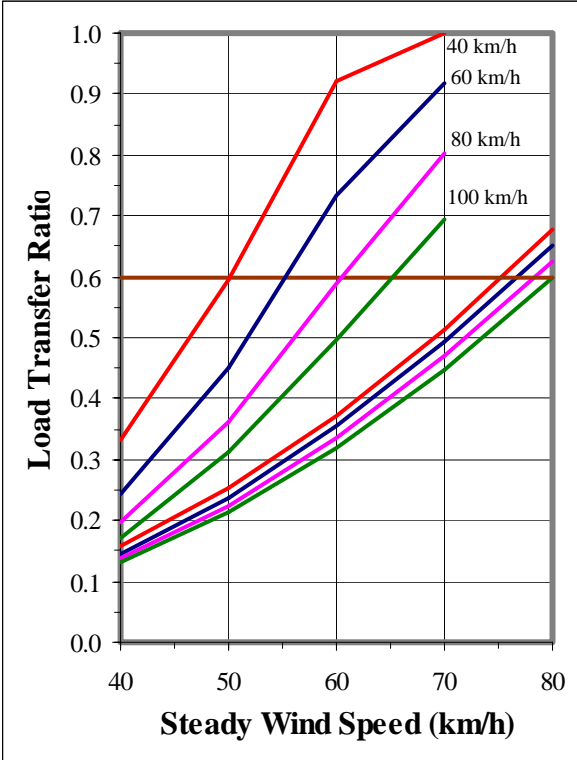| Vehicle Speed (km/h)	Steady Wind Speed (km/h)					Gusting Wind, Steady Speed (km/h)				
	40	50	60	70	80	40	50	60	70	80
40	0.225	0.362	**0.532**	**0.764**	**1.067**	0.450	**0.858**	**1.567**	**2.196**	**Roll**
60	0.209	0.338	**0.507**	**0.729**	**1.017**	0.347	**0.655**	**1.185**	**1.655**	**Roll**
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**

Figure 5 – Wind-induced Load Transfer Ratio of Empty Turnpike Double.
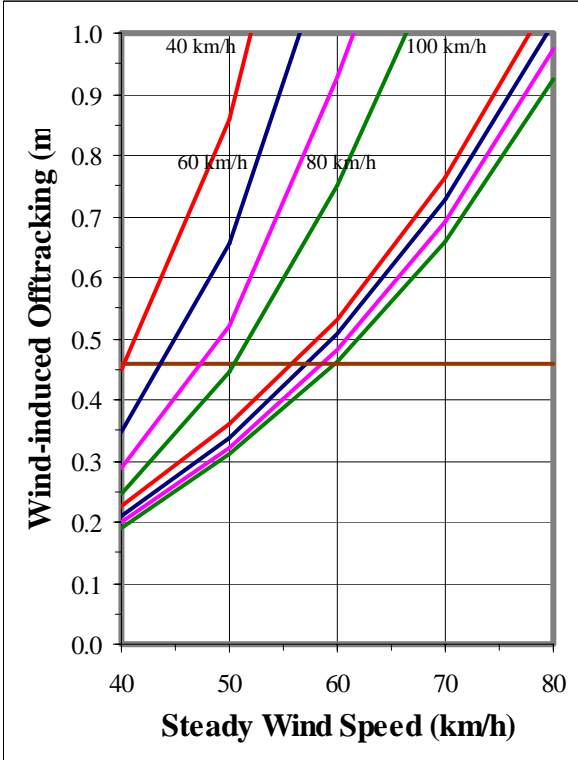
Figure 6 – Wind-induced Offtracking of Empty Turnpike Double.

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Table 8 – Effect of Payload on Load Transfer Ratio of Turnpike Double.

Payload	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
(lb)	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**
5,000	0.125	0.202	0.296	0.408	0.539	0.266	0.474	**0.743**	**0.842**	**Roll**
10,000	0.104	0.167	0.246	0.339	0.449	0.221	0.395	**0.618**	**0.697**	**Roll**
15,000	0.089	0.144	0.211	0.291	0.385	0.189	0.339	0.532	**0.600**	**Roll**
20,000	0.078	0.126	0.185	0.255	0.338	0.168	0.298	0.466	0.526	**0.928**
25,000	0.070	0.113	0.165	0.228	0.302	0.149	0.266	0.417	0.470	**0.819**

Table 9 – Effect of Payload on Wind-induced Offtracking of Turnpike Double.

Payload	Steady Wind Speed (km/h)					Gusting Wind Steady Speed (km/h)				
(lb)	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	2.196	**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

4. Conclusions

This paper has evaluated the effect of wind on truck configurations common in Canada. The load transfer ratio and high-speed offtracking performance standards are suitable for evaluation of wind-induced rollover and offtracking, respectively. Wind-induced load transfer ratio and offtracking both increase with wind speed, and for a given wind speed, and diminish with vehicle speed, for all vehicles. Wind-induced rollover occurs at wind speeds well within the ten-year return period for wind at many locations all across Canada.

The critical vehicle is a 5-axle tractor-semi-trailer with a 16.20 m tandem semi-trailer, which is over 50% of the truck fleet in Canada. Travel may be feasible in a steady wind up to about 75 km/h, but becomes risky over 50 km/h in a strongly gusting wind. A payload of 4,500 to 6,800 kg is required for 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. The same results apply for a Turnpike Double, a 9-axle A-train with twin 16.20 m semi-trailers.

Wind-induced offtracking for a 5-axle tractor-semi-trailer increased rapidly for stronger winds, and clearly becomes an issue for a steady wind speed over 75 km/h, or at about 50 km/h in a strongly gusting wind. Coincidentally, these are the same speeds at which rollover becomes a concern. It also required a payload of 4,500 to 6,800 kg to achieve a significant reduction in wind-induced offtracking. Wind-induced offtracking becomes an issue for a Turnpike Double for a steady wind speed over 50 km/h, or over 40 km/h for a strongly gusting wind. Wind-induced offtracking of this vehicle is greater than for a 16.20 m semi-trailer because the wind causes offtracking of the first semi-trailer, then causes

additional offtracking of the second semi-trailer. It requires a payload of 6,800 to 11,300 kg in each trailer to achieve a modest reduction in wind-induced offtracking.

About 15% of trips by 5-axle tractor-semi-trailers are with less than 6,800 kg of payload, and about 40% are with less than 11,300 kg of payload. This mitigates significantly the effect of wind for most trips.

Drivers of 3- and 4-axle tractor semi-trailers with a 16.20 m semi-trailer, and 5- and 6-axle A-train doubles, should be particularly cautious when traveling empty or lightly loaded in strong and gusting winds, as these configurations are somewhat more sensitive to wind-induced rollover and offtracking than the common 5-axle tractor-semi-trailer. Tractor-semi-trailers with more than five axles, and B-trains, are less sensitive to wind than the common 5-axle tractor-semi-trailer.

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