LATERAL FORCES ON HEAVY TRUCKS – CONTRIBUTIONS FROM WIND

Dr. Frank Wilson
Dr. Eric Hildebrand
Transportation Group
University of New Brunswick
Canada
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ABSTRACT

A tractor semi-trailer unit equipped with on-board instrumentation that measured speed, lateral accelerations, and the roll angle of the vehicle was driven around a test site (inter-change ramp) under varying wind conditions. A portable weather station was installed in the centre of the test track. The rollover threshold of the truck was calculated based on the characteristics of the vehicle and then compared with the lateral accelerations measured on the test vehicle. An analysis of the data indicated that there existed significant differences in lateral accelerations under scenarios of varying wind speeds, verifying that wind can contribute to rollover. An analysis of the rollover threshold revealed that the lateral accelerations experienced by the truck were often greater than the rollover threshold for brief periods of time. The time periods were not sufficiently long enough to cause rollover of the vehicle.

The research demonstrated that the technique developed on this project could be used to determine the safe speed for heavy trucks operating on specific sections of the roadway.

INTRODUCTION

The main objective of this research was to determine how lateral forces are affected by wind as a heavy truck traverses a highway curve or interchange loop-ramp. The procedure developed for this research was unique compared with other procedures for testing lateral accelerations or forces in that a truck was maneuvered around a curve a number of times, under varying wind conditions and vehicle speeds. The design of this experiment was such that a statistical analysis of the vehicle's dynamic responses could be carried out based on various wind conditions. The experiment also demonstrated a new approach for determining the maximum safe speed for trucks on highway curves based on the geometric characteristics and wind conditions.

TRUCK ACCIDENT CHARACTERISTICS

Commercial trucks make up a significant portion of the traffic stream on many highways in North America. In the United States in 1999, there were nearly eight million registered heavy vehicles, which accounted for 3.5 percent of the registered vehicle fleet. In addition, the average miles traveled per truck (26,014 miles) was more than double the average mileage for passenger vehicle (11,888 miles) in 1999 (1). In terms of safety, four percent of the 11 million accidents in the United States in 2001 were caused by commercial trucks. In total, trucks accounted for eight percent of all vehicles involved in fatal crashes, but only four percent of vehicles involved in injury and property damage only crashes (1). These figures suggest that while truck accidents occur less frequently than other types of vehicles, many of these accidents are more severe.

Large trucks were involved in 18,000 rollover events in the United States, of which, 622 were fatal crashes (1). Eleven thousand of the rollover events resulted in injury, indicating that the injury occurrence in a rollover is high (61%) compared to total truck accidents (21%). Combination trucks accounted for 11,000 of all heavy truck crashes while single-unit trucks accounted for 7,000 crashes (1).

In Canada, there are fewer heavy vehicles than in the United States. In 2000, there were approximately 661,000 heavy trucks (straight trucks and combination trucks with weights greater than 4,500kg) (2), of which, 528 were involved in fatal collisions. This represents about

12 percent of all fatalities on the road (2). In total, truck rollovers account for 13 to 38 percent of all truck accidents, and of these, between 40 and 60 percent occur on highway interchange ramps (3).

BACKGROUND

Variables that contribute to truck rollovers can be divided into four categories – vehicle characteristics, highway features, environmental and human factors. In many cases, truck rollovers are caused by excessive speed as trucks negotiate short radius curves on highway ramps. Hildebrand and Wilson (4) studied in detail 53 heavy freight vehicle collisions between 1993 and 1996 in New Brunswick. In 15 cases, rollover was the initial factor in the incident and more than a third of these occurred on highway ramps. Excessive speed was the main contributing factor causing five of the accidents, and in the sixth case, speed and load shift combined to cause the accident. Other vehicle characteristics, besides speed, that affect a vehicle's rollover threshold include the height to the center of gravity, type of suspension, and track width. Highway features that commonly contribute to rollover accidents include posted speed limits, curve radii and lengths, super-elevation, and deceleration lane widths. Human factors encompass the characteristics of the driver's control of the vehicle. Environmental factors include wind force and direction as well as rain, snow, ice, etc.

The effect of wind on the stability of heavy vehicles is an important safety consideration and the primary focus of this research project. For the most part, limited research has been undertaken on this topic, although it has been noted to be a critical safety factor in areas with frequent high winds, or in areas prone to strong gusts. In Atlantic Canada, the Confederation Bridge between New Brunswick and Prince Edward Island, the "Wreckhouse" area in western Newfoundland and the Tantramar Marshes in New Brunswick are three examples of areas where wind often plays a critical role in the stability and safety of heavy vehicles. These areas are frequently closed to truck traffic due to wind conditions. Two of these sites are in close proximity to the study area for this research project.

When a truck negotiates the curves or ramps on a highway, wind may play a considerable role in causing the vehicle to rollover at lower speeds than expected, or it may be responsible for preventing rollover when it might have occurred at higher speeds. In the case of a truck traveling around a curve, a strong gust of wind from the inward side (coming from the centre of the curve) may provide the extra force required at the critical moment to cause the overturning forces to exceed the resisting forces, resulting in rollover. On the other hand, a gust of wind from the outward side (coming from outside of the curve) may provide a counter-force that helps resist the overturning forces.

There are many mathematical models and computer simulations that are used to estimate the dynamic responses and rollover thresholds of heavy vehicles. These include the:

- PHASE-4 computer program developed by the Texas Transportation Institute and the Texas State Department of Highways and Public Transportation (5).
- University of Michigan Transportation Research Institute (UMTRI) model (6).
- Linear yaw plane model (7).
- TBS model (7).
- Static roll model (7).

Most of the previous research has involved modeling or tilt-table tests. This study was directed to obtain over-the-road measured results. This provided a means for researchers to compare actual field condition data with the theoretical results.

Figueredo (8) designed a data acquisition system to collect field data on lateral acceleration experienced by the vehicle, roll angle of the trailer, and the vehicle speed. The purpose of this project was to equip a five-axle-tractor-semi-trailer with instrumentation that would measure the dynamic forces exerted on a vehicle in transit, and to use this data to determine the lateral forces experienced by the vehicle while moving around a curve. The testing process took place over 1,110 km of highway between Moncton, New Brunswick and North Sydney, Nova Scotia. From this study, it was found that:

- the Data Acquisition System (DAS) provided an acceptable method of collecting dynamic characteristics of a heavy vehicle while in motion.
- that it provided a high level of accuracy of the

recorded data.
- the data can be used to determine the dynamic stability of a vehicle in motion.

METHODOLOGY

In order to measure the dynamic forces acting on a heavy vehicle while in motion, several pieces of equipment were required. Figuereo's (8) Data Acquisition System (DAS) was used to collect data on lateral forces experienced by the vehicle, roll angle of the trailer, and vehicle speed. Wind conditions (i.e. speed and direction) were measured using a weather station that was positioned near the test ramp.

The Data Acquisition System DAS-P1000 uses a set of sensors and a central processing unit to collect the dynamic response characteristics of the tractor-semi-trailer while in motion. Its features include:

- central processing unit.
- three tri-axial accelerometers.
- steering wheel optical sensor.
- roll angle sensor.

The three tri-axial accelerometers measured the lateral, vertical, and longitudinal accelerations on the truck while in motion. One was placed at the top of the rear of the trailer, another near the fifth-wheel assembly, and the third in the cab of the truck. The steering wheel optical sensor provided a measure of the steering angle of the truck at any given instant and was attached to the steering column. The radar gun was used to collect the actual speed data of the truck, and was placed in the cab of the truck, aimed towards the road. The roll angle sensor located on the roof on the centerline of the rear of the trailer measured the vertical displacement of the top of the truck, which was used to measure the roll angle of the trailer. The central processing unit was a PC-based system that collected the data at 1/5 second intervals.

The weather station was used to measure the wind speed and direction near the ramp. A simple vane-and-cup anemometer was used, and combined with a data logger, measured the wind speed and direction at 1 second intervals.

The site selected for this research was near Moncton, New Brunswick, at the interchange between Route 2 (Trans Canada Highway) and Route 15. The eastbound-to-northbound ramp was utilized for vehicle testing as shown in Figure 1. The vehicle was instrumented, and testing took place between October 2003 and March 2004. A total of 54 test runs were completed over four separate days. The same vehicle was used for all of the runs to normalize for the effects of vehicle characteristics on lateral acceleration. The driver was required to follow the yellow edge line as closely as possible to control for human factors as the vehicle traveled along the ramp. The testing occurred over several months because of the need to coordinate the availability of all personnel with the days when the wind conditions satisfied the testing criteria and roads were clear of ice and snow.

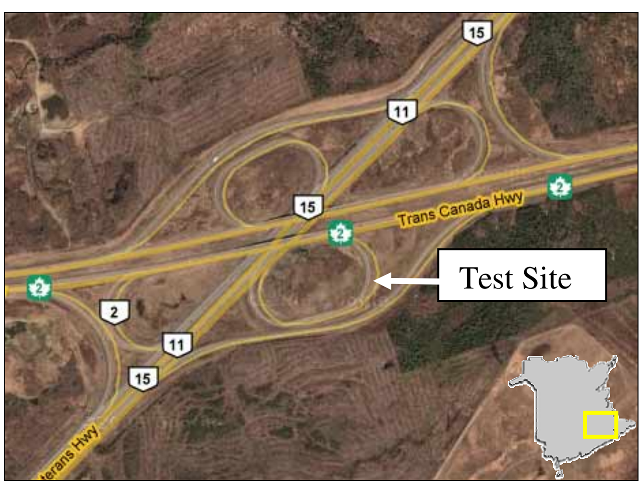

Figure 1. Loop ramp test site.

There are a number of reasons why this location was selected as the test site. First, the ramp has a history of rollover accidents, which was approximately two times the rate on adjacent ramps in the area. Anecdotal evidence indicates that the ramp can be challenging for trucks to maneuver because of its configuration. The ramp has two curves connected by a tangent. The curve at the entry to the ramp has a radius of 90m and a length of 314m. A tangent with a length of 108m follows this curve. The second curve at the end of the tangent has a radius of 80m and a length of 182m. While traveling along the first curve, an unfamiliar driver is generally cautious, and traverses the curve at a reasonable speed. On the subsequent tangent, the driver tends to accelerate, assuming the controlling curve has passed. Additionally, the tangent consists of a small down grade, which may add to the vehicle speed. When the driver enters the second curve, the speed is often greater than the speed through the first curve. This second curve has slightly smaller radius than the first, which causes an increased chance of vehicle rollover. The speed posted at the beginning of the first curve was 50 km/h. After the testing was completed, the speed posted at the beginning of the ramp was reduced to 40 km/h. A second posting of 40 km/h was posted at the mid-point of the tangent.

The second reason this ramp was chosen was because of the openness of the area. The area around the interchange is relatively clear of obstructions such as trees or buildings. In addition, the openness of the area results in sustained high winds that can be measured and used in determination of the effect of wind on truck rollover. The openness also allowed for an unobstructed view of the entire site.

TESTING

The trials were performed to determine the impact of lateral forces exerted by the wind on a heavy vehicle as it traveled around a highway ramp. A summary of the testing times and weather can be found in Table 1. Results were reported for 50 out of the 54 test runs because data were not accurate from four of the test runs due to instrumentation errors.

Table 1.
Testing Conditions

	Date	Number of Runs	Wind Condition
Day 1	November 15, 2003	14	Calm (≤8.8 km/h)
Day 2	November 16, 2003	5	Calm (≤8.8 km/h)
Day 3	December 11, 2003	12	Moderate (8.8 to 19.0 km/h)
Day 4	March 25, 2004	19	Strong (≥19.0 km/h)

The trials were made at varying speeds, with attempts to hold truck speeds constant at 35, 45, and 55 km/hr. However, the actual speeds of each run varied somewhat as the curves were traversed.

ANALYSIS

Data on the dynamic behavior of the truck was collected for each trial run. In order to study rollover potential, the lateral accelerations were examined. A typical lateral acceleration plot is shown in Figure 2.

The elements of Figure 2 are as follows:

A – The truck enters the curve to the right and the lateral accelerations to the left begin to increase.

B – The average maximum lateral acceleration peaks.

C – On the tangent, the lateral acceleration begins to decrease as the truck exits the curve and lateral acceleration approaches base conditions.

D – On the second curve, the lateral accelerations once again begin to rise and reach a peak value.

E – At the end of the second curve, a small peak in lateral accelerations can be experienced, most likely due to a combination of speed increase and the “sudden snap” noted by drivers.

F – When the truck enters Highway 15 North, the lateral accelerations begin to recede.

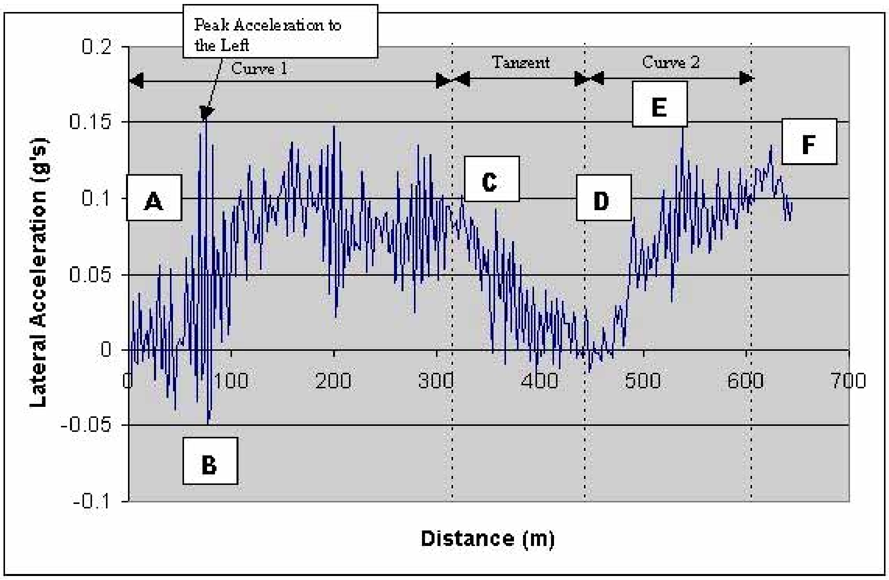

Figure 2. Lateral accelerations through test site.

Each run was analyzed by determining the peak lateral accelerations the trailer and the truck experienced. To determine the contribution of the wind forces on lateral accelerations, each run was categorized based on vehicle speed and wind speed. The average peak lateral accelerations for the runs in each group were calculated and a comparison made between the different groups. The lateral accelerations (Ax) in bold text in Table 2 indicate the average maximum lateral acceleration recorded by each accelerometer for the various wind and truck speeds. The second row (Vt) in each group of vehicle speeds represents the average truck speed for the group. The third row (Vw) represents the average wind speed for the group. The final row (N) indicates the number of observations in the group. Each observation corresponds with a ramp run, and was sorted based on the position on the ramp, i.e. curve 1 or curve 2.

TABLE 2.
Lateral Accelerations

Vehicle Speeds (km/h)	Test Results	Curve 1			Curve 2		
		Wind Speed (km/h)			Wind Speed (km/h)		
		0-8.8	**8.9-18.9**	**>19.0**	**0-8.8**	**8.9-18.9**	**>19.0**
<42	**Ax (g's)**	**0.157**	**0.222**	**0.291**	**0.187**	**0.229**	**0.281**
	Vt (km/h)	35.7	39.7	38.8	36.4	39.0	39.8
	Vw (km/h)	4.6	14.1	21.6	5.3	16.1	23.1
	N	5	5	4	5	3	4
42-49	**Ax (g's)**	**0.233**	**0.264**	**0.362**	**0.269**	**0.327**	**0.370**
	Vt (km/h)	44.1	45.7	46.1	44.1	47.8	46.8
	Vw (km/h)	3.0	14.1	21.4	3.6	16.2	21.3
	N	5	2	10	7	7	5
>49	**Ax (g's)**	**0.306**	**0.331**	**0.409**	**0.337**	**0.366**	**0.397**
	Vt (km/h)	51.4	53.9	51.4	52.6	54.8	52.1
	Vw (km/h)	3.6	15.5	21.2	3.9	15.7	21.4
	N	6	7	6	6	6	7

where:
Ax = equals lateral force on vehicle (g's).
V_t = average speed of test vehicle (kph).
V_w = average speed of wind (kph).
N = number of runs in sample.

Figures 3 and 4 illustrate the trends in the lateral accelerations on curves one and two, respectively, by classes of wind speed. Each series plotted represents varying vehicle speed.

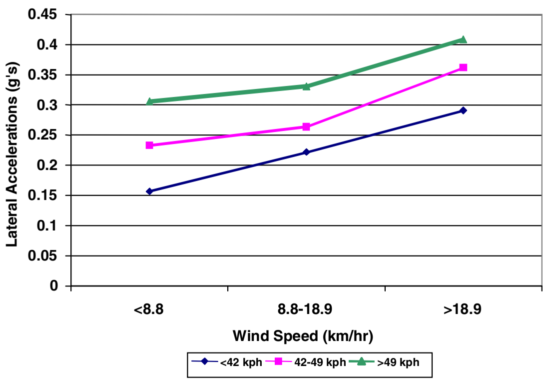

Figure 3. Maximum lateral accelerations by wind speed on curve 1.

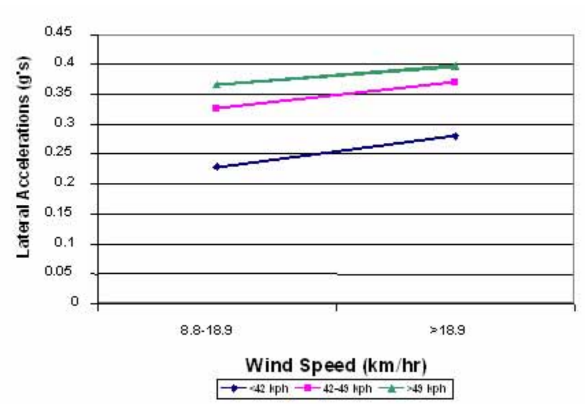

Figure 4. Maximum lateral accelerations by wind speed on curve 2.

The lateral accelerations were compared statistically to determine if wind speed and vehicle speed have an effect on the lateral forces measured. The Student's t-test for the comparison of means assuming unequal variances was used for the analysis. A summary of the tests for significance results is presented in Table 3.

Table 3.
Tests of Significance for Trailer Accelerometer

Vehicle Speed (kph)	Wind Speed Class (kph)	Significant Difference?	
		Curve 1	Curve 2
<42	0-8.8 vs. 8.9-18.9	Yes	Yes
	8.9-18.9 vs.> 19.0	Yes	Yes
42-49	0-8.8 vs. 8.9-18.9	Yes	Yes
	8.9-18.9 vs.> 19.0	Yes	Yes
>49	0-8.8 vs. 8.9-18.9	Yes	Yes
	8.9-18.9 vs.> 19.0	Yes	Yes

For each vehicle speed category, the low and middle wind speeds and the middle and high wind speeds were compared. For each curve and for each vehicle speed, it was determined at the 95 percent confidence level that as wind speed increased so did the lateral accelerations.

The roll threshold for the truck was also calculated using the static roll model and compared to the peak lateral accelerations experienced by the truck. Table 4 lists the values for the determination of the rollover threshold for this truck.

The truck rollover threshold varies between 0.47 and 0.54 g's for the test unit, depending on superelevation development and trailer roll angle. The maximum average lateral accelerations found to occur on the truck were 0.409 g's and 0.397 g's for curve 1 and curve 2. This indicates that the empty unit experienced lateral forces that were 86 and 74 percent of the rollover threshold for the vehicle.

Table 4.
Rollover Threshold

Values for Static Roll Model Calculation	Curve 1	Curve 2
Track Width (m)	2.0	2.0
Maximum roll angle of the trailer (degree)	20	11
Lateral shift of the centre of gravity of the trailer (m)	0.44	0.24
Height of Centre of Gravity of Truck (m)	2.0	2.0
Roll Centre Height (m)	0.78	0.78
Maximum Superelevation	0.07	0.08
Rollover Threshold (g's)	0.473	0.539

During the testing, there were individual lateral force events that actually resulted in the rollover threshold being exceeded. The results for day 4, run 3 (D4R3) are shown in Figure 5. The plot of peak accelerations shows two events that exceeded the calculated rollover threshold (with lateral accelerations of 0.582 g's and 0.492 g's compared to the rollover threshold of 0.473g's). These events were spikes in the lateral accelerations and may have been caused by a strong gust of wind or other external road factors. Baker and Reynolds (9) estimated that in order for rollover to occur, the rollover threshold must be exceeded for more than 0.5 seconds (10). The duration of these peaks were short enough (<0.2 seconds) that the vehicle did not enter a roll condition before the vehicle experienced forces below the roll threshold. However, the results show that wind gusts of a longer duration could have caused the vehicle to roll.

CONCLUSIONS

This research investigated the impact that wind has on heavy truck rollover. It was found that wind does compound the lateral forces experienced by a truck, even when the wind speed is not extreme. The additional lateral forces results in net changes to effective lateral accelerations thereby compromising roll stability of the unit.

The maximum wind speed observed during these tests was approximately 28 kph, which was not perceptible to the driver. In strong winds, when a driver can feel the wind blowing against the truck, the lateral forces would be expected to be much higher. By investigating how a seemingly imperceptible wind increase can increase the lateral forces experienced by a truck, design guidelines and speed signing can be adjusted to improve the safety of vehicles operating on highway curves and ramps. This research confirmed that the procedures developed in this project, using an improved data acquisition system, could be adopted to evaluate wind forces on heavy trucks. The tests developed as part of this research could be used to recommend speed advisories on interchange ramps and other curves on a highway system.

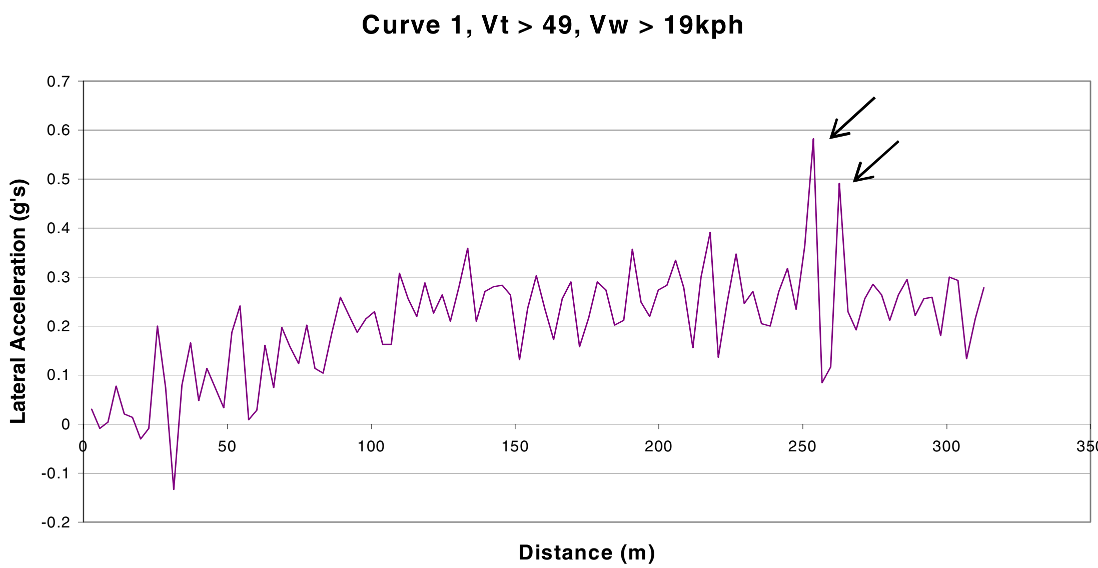

Figure 5. Lateral Accelerations for Test on Day 4, Run 3.

RECOMMENDATIONS

From the research it was found that similar methods could be utilized to further the understanding of the impact of wind forces on truck rollover. Lateral accelerations could be measured on trucks in other high-risk areas, such as Prince Edward Island's Confederation Bridge, using a data acquisition system similar to the one developed in this study. The impact of wind speeds could then be determined by combining the results of the dynamic characteristics of the truck with wind data from weather stations. Results such as those presented in Table 2 and Figures 2 and 3, would assist operators in better managing traffic in these high-risk areas. If further testing of this type is considered, it is recommended that the data acquisition system on the truck be improved by adding:

- A GPS unit to log the truck position, speed and direction.
- An on-board anemometer to measure wind speed and direction.
- Pressure sensors to measure the wind force on the sides of the truck.

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