OBSERVATIONS ON THE LATERAL PERFORMANCE OF TRUCK DRIVERS

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ABSTRACT

UMTRI, in partnership with Freightliner, Meritor WABCO, and Praxair Corporation, and with funding from the US DOT Intelligent Vehicle Initiative, conducted a year-long field operational test (FOT) of an early version of Freightliner/Meritor WABCO's Roll Stability Advisor and Control (RA&C). While the primary intent of the study was to evaluate this device, this paper provides an example of the “collateral value” that such undertakings can yield.

The FOT followed six tractor-semitrailer combinations hauling liquid nitrogen in actual commercial service. The vehicles were tracked for a full year, during which they were driven by 23 drivers in a slip-seat operation. Total travel exceeded 700,000 kilometers and reached nearly 10,000 hours.

The vehicles were heavily instrumented, and data were recorded full time while the vehicles were in use. Data representing 92% of all travel during the year were successfully recorded. Raw data from the vehicles amounted to some 25 GB and grew to 65 GB with post processing and analysis.

This large and very rich database provides a new, high-fidelity view of the driving process yielding value well beyond the original interest of the research. This paper examines the influences of speed, load condition, and individual driving style on lateral performance through the use of histograms of lateral acceleration and rollover ratio. Interesting asymmetries in lateral performance are presented. Other factors seen to have statistically significant influences on lateral performance were weather, lighting, and direction of turn.

INTRODUCTION

This paper presents general observations on the turning performance and lateral-acceleration experience of truck drivers during their everyday experience in an actual commercial trucking operation. Six vehicles operated by 23 drivers were followed for one year in a naturalistic Field Operational Test (FOT) funded by the US Department of Transportation through its Intelligent Vehicle Initiative. T FOT investigated the influence of a prototype Roll Stability Advisor & Control (RA&C) system (Winkler, Sullivan, Bogard, Goodsell, Hagan, 2002).

The RA&C studied was jointly developed by Freightliner and Meritor WABCO and was installed on six Freightliner, Century Class tractors for the FOT. These vehicles were used, in combination with cryogenic-tanker semitrailers, as part of the normal operations of the Praxair Corporation for delivery of liquid nitrogen to customers serviced by the Praxair facility in La Porte, Indiana, USA. The test tractors were instrumented extensively and monitored for a full year. The raw data base from the vehicles amounted to some 25 gb and grew to 65 gb with post processing and analysis. A companion paper presented at this symposium provides a detailed description of the FOT (Bogard, Winkler, Sullivan, Hagan 2004).

The primary purpose of the FOT was to examine the influence of RA&C on driver performance. A second companion paper provides analyses and results in this regard (Sullivan, Winkler, Bogard, Hagan, 2004).

For purposes of this paper, it is adequate to note that the influence of RA&C was sufficiently small that we believe the results herein were not materially influenced by the use of RA&C during portions of the FOT.[1]

THE FOT FLEET, DRIVERS, AND EXPOSURE

The FOT monitored six, 5-axle tractor-semitrailer combinations (figure 1) hauling liquid nitrogen in normal service from the Praxair facility in La Porte, Indiana, USA. The total fleet at this facility was composed of eighteen similar vehicles with some variation with season and economic conditions.

Figure 1. Three of the FOT vehicles.

Data gathering was fully automated. Purpose-built data acquisition systems (DAS) on board the tractors booted automatically when the ignition came on and shut down when the ignition was switched off. (In the parlance of the FOT, such a cycle constituted one “trip.”) When a vehicle was shut down within a known (by GPS) parking area at the terminal, the DAS automatically transferred data via wireless Ethernet to a server installed by UMTRI at the Praxair terminal.

The great majority of all travel by the FOT fleet was accomplished in day trips from La Porte . The service area (see figure 2) covered substantial portions of several states and had a good mix of urban and rural as well as limited-access and secondary roads. The large majority of travel was over rather flat terrain. In total, data were gathered for approximately 770,000 km or 9800 hours of travel.[2] Other metrics describing exposure appear in table 1.

The La Porte facility operated three shifts, seven days a week, in a so-called slip-seat operation in which drivers were not assigned specific vehicles. Under these procedures, twenty-two individuals drove the FOT vehicles an appreciable distance over the 13-month period of data gathering (November, 2000 through November 2001). These drivers formed a rather mature group, ranging in age from 37 to 56 years, and each had from 8 to 33 years of driving experience. Fourteen of the drivers each contributed between 30,000 and 50,000 kilometers; one drove more than 50,000 kilometers. The other seven, largely due to layoffs, drove less than 30,000 km each in FOT vehicles. Overall, FOT driving was about 40 percent of all the driving of this group during the period of the study.

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[1] RA&C is a system in continuing development. Indeed, development took place before and during and continued after the data-gathering portion of this project. Therefore, it is important to note that observations concerning RA&C in this and the companion papers address only the one, specific version of RA&C that was installed in the FOT vehicles during the period of the study. Changes and improvements made to RA&C since that time can not be addressed.

[2] Extremely short “trips” (less than 0.1 km) were often problematic as the DAS would have inadequate time to boot. All such trips were exclude from the data analyses to avoid excessive processing difficulties.

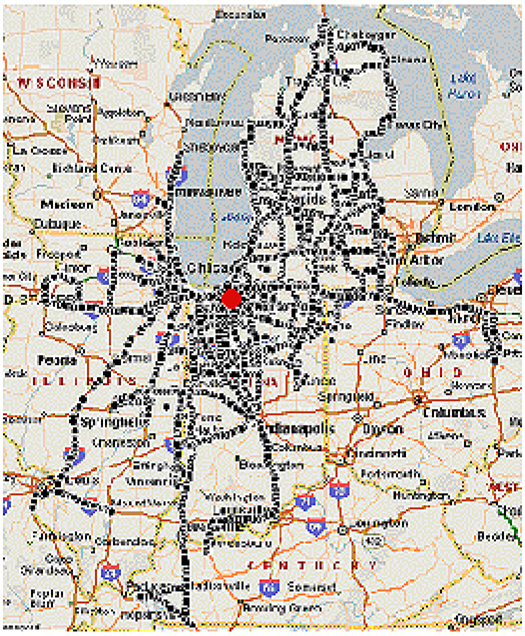

Figure 2. La Porte (●) and the FOT routes (■).

Table 1. Some descriptors of exposure of the FOT fleet.

Time	total	12,190 hour	
	in motion	9800 hour	
	in turns[1]	900 hours	
Distance	total	772,100 km	
	with cruise control on	571,100 km	
	in good weather[2]	689,100 km	
	average leg of delivery trip	136 km	
Road type [% by distance]	freeway	65%	
	highway	16%	
	arterial	9%	
	local/regional	7%	
	access roads	3%	
Loading [% by time]	empty[3]	38%	
	partial[4]	13%	
	full[5]	49%	
Speed	average in motion	79 kph	
[% by time]		in motion	in turns[1]
	3 to 27 kph	10%	50%
	28 to 57 kph	7%	17%
	58 to 87 kph	15%	15%
	88 to 112 kph	69%	15%
Lighting [% by time]	daylight : dark[6]	65% : 35%	
Weather [% by time]	good : bad [2]	83% : 17%	

1 “In a turn” when path radius was less than 1 km for 3 seconds or more.
2 “Good” when wiper use was less than 1% and visibility was greater than 2km.
3 “Empty” when total mass was less than 17 metric tones.
4 “Partial” when total mass was between 17 and 33 metric tones.
5 “Full” when total mass was greater than 33 metric tones.
6 “Dark” when the sun was 6 or more degrees below the horizon.

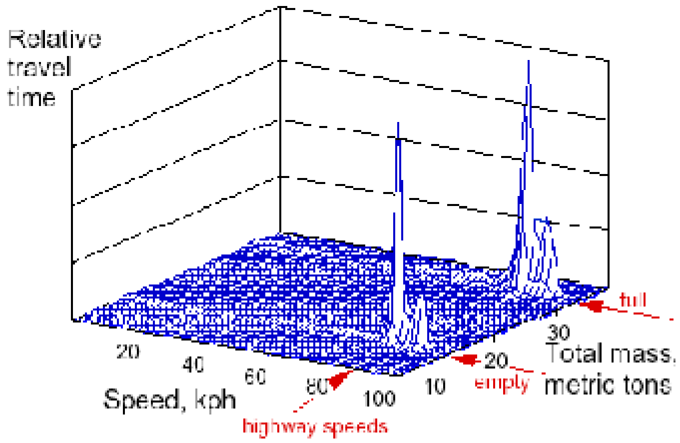

Figure 3. Histogram of travel time by speed and load.

Figure 3 is a histogram of travel time of the FOT vehicles by speed and load. The figure displays (or implies) some of the same information presented in table 1. That is, the figure clearly shows that the great majority of travel time was spent at highway speeds (and presumably on freeways and highways) and that travel time was largely split between the fully loaded and the empty conditions. Moreover, the figure also shows that the speed profiles in the empty and in the loaded conditions were quite similar. One can surmise—and, indeed, it was so—that, typically, these vehicles left the terminal fully loaded, traveled by highway to another town or location where the majority of product was off loaded to one or more closely-located customers, and then returned to the terminal essentially empty.

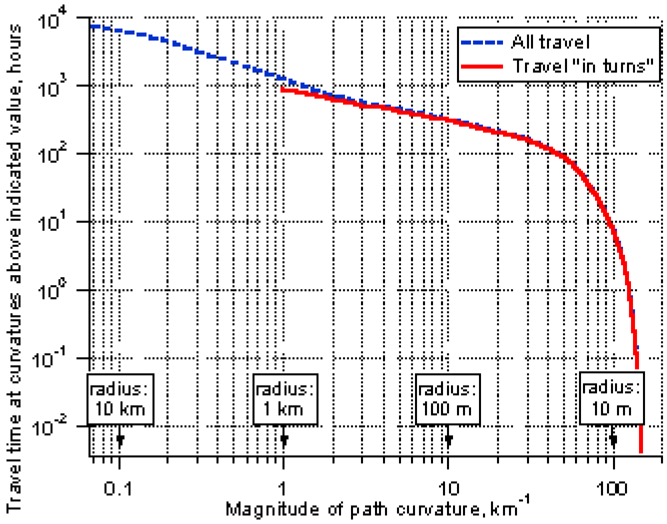

Figure 4. Cumulative histogram of path curvature.

Figure 4 elucidates the exposure of the FOT fleet to curves and turns. The figure presents two cumulative histograms of path curvature (i.e., the inverse of path radius) of the tractor. Both axes are in logarithmic scale. The magnitude (absolute value) of path curvature appears on the abscissa with orders of magnitude of path radii also indicated. The ordinate shows travel time (hours) spent at path curvatures at or above the indicated value. Of the two data plots, the dotted curve is for all travel. The solid curve is for time spent in turns, were in a turn is defined as traveling at a radius of 1 kilometer or less (curvature ≥ 1 km^{-1}) for three or more seconds.

Since all travel must take place at a magnitude of path curvature greater than absolute zero, the plot for all travel begins at the far left near 9800 hours (i.e., all time in motion).[3] By definition, the plot for travel in turns begins where curvature equals 1 km^{-1} and, at this point, has a value of about 900 hours (all time in turns). The two plots are nearly identical for radii of 500 m or less, implying that the definition of in a turn is reasonable and also that "straight" travel is largely composed of "wandering" at radii of 500 m or more. It is also of interest that something on the order of 1 percent of turning takes place at radii on the order of the length of the vehicle or less (i.e., radii of $\leq$ 20 m or curvature $\geq$ 50 km^{-1}).[4]

OBSERVATIONS ON LATERAL PERFORMANCE

Lateral performance measures

Two primary measures of lateral performance form the basis for the discussion that follows. These are (1) lateral acceleration at the driver's position and (2) rollover ratio. The former is seen as a direct measure the driver's performance and/or experience. The latter is seen as a measure of the actual rollover risk incurred as a result of that performance/experience. Lateral acceleration at the center of gravity (c.g.) of the trailer also receives some consideration because of its importance in determining rollover ratio.

The definition of "lateral acceleration" as used herein is somewhat different than the formal definitions given in ISO, 1991, and SAE, 1978. Those definitions do not account well for the influence of the cross slope of the roadway on the potential for rollover.

Hence, the definition used herein is:

- lateral acceleration: the component of acceleration that is perpendicular to the longitudinal axis of the vehicle at a specified position in the vehicle and is in a plane parallel to the road surface, including (or with the addition of) the component of gravitational acceleration in the same direction.

The polarity convention herein is similar to that of the ISO definition, i.e., positive accelerations are to the left, typically resulting from left turns and, for this definition, roadways sloping downward to the right. In the FOT, lateral acceleration at the driver's position was determined for all travel time using calculations based on signals from sensors for lateral acceleration (at the front axle), forward speed, and tractor yaw rate. For details, see (Bogard, et al., 2004) and (Winkler, et al., 2002).

Rollover ratio is the ratio of the current lateral acceleration of the vehicle to its steady-state rollover threshold.

This concept applies easily when lateral acceleration is uniform over the length of the vehicle. However, for real vehicles in real maneuvers-and especially articulated vehicles in tight-radius, low-speed maneuvers - this condition does not generally hold. In the FOT, rollover ratio was calculated as the ratio of the weighted average of the lateral accelerations of the tractor and the trailer (at their respective centers of gravity) to the rollover threshold. The weighting factors were the tractor and trailer masses, and the rollover threshold was determined from tilt-table tests of an FOT vehicle. Because of the complexity of the calculations and the large volume of data, rollover ratio was determined only for the 900 hours of travel in turns. Again, for details see (Bogard, et al., 2004) and (Winkler, et al., 2002).

Lateral performance in all travel—observations on load, speed, and asymmetries

Figure 5 presents a cumulative histogram of the magnitude (absolute value) of lateral acceleration at the driver's position for all travel time of the FOT fleet. Magnitude of acceleration is shown on the abscissa and the fraction of travel time spent above the indicated acceleration is shown on the ordinate, which is in logarithmic scale. The data are segregated by loading condition, and each of the plots (i.e., for full, partial, or

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[3] The value at the far left is less than of 9800 hours, in part because the logarithmic horizontal scale can not be shown all the way to zero. In general, histograms herein are based on slightly less than all the data implied by table 1 because of minor deletions generally made to avoid excessive calculation difficulties.

[4] At first thought, 1 percent may seem high, but this reduces to roughly 1 to 2 minutes per shift. This figure does seem reasonable as the total time for tight turning accumulated at the terminal, in customers' work yards and parking lots, and in turning at intersections.

empty loading) are individually normalized such that each plot begins at an ordinate value of 1 at zero acceleration.

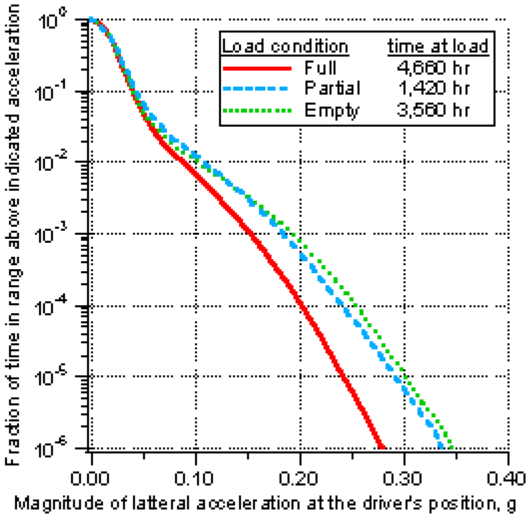

Figure 5. Cumulative histograms of lateral acceleration for three load conditions.

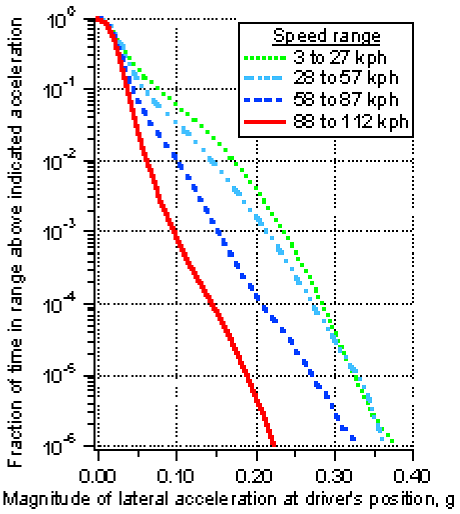

Figure 6. Cumulative histograms of lateral acceleration for four speed ranges.

Beginning at the left-hand side of the figure, the data plots indicate that, regardless of loading condition, about 90 percent of travel time is at lateral accelerations less than about 0.04 g, and about 99 percent is at accelerations less than 0.10 g. However, just in this range, a clear distinction between loading conditions begins to appear, such that the figure clearly indicates a tendency for drivers to spend greater portions of driving time at higher accelerations when the vehicle is empty or partially loaded than when the vehicle is fully loaded. For example, the FOT vehicles were ten times more likely to exceed 0.2 g when empty than when loaded. That is, when empty, 0.2 g was exceeded during 0.1 percent of travel time, but when loaded, this level was exceeded during just 0.01 percent of travel. Since essentially the same road network was negotiated in empty and loaded conditions, it appears that drivers attempted to compensated for the lower stability of their vehicles when loaded by driving more conservatively.

Figure 6 is a cumulative histogram of the same form as figure 5, but with the data segregated by speed rather than by load. The figure clearly shows a tendency for driving at more elevated accelerations at lower speeds than at higher speeds. The distinction begins at very low magnitudes. The probability of exceeding 0.1g is already roughly 100 times greater at low speeds than at high speeds. The ratio grows to roughly 1000 to 1 for accelerations exceeding 0.2 g. Three potential explanations for this behavior come to mind. The first is that it has been observed for some time that drivers (at least passenger-car drivers) tend to generate higher lateral accelerations in turns at low speeds than in turns at high speeds, e.g., Ritchie (1968) and Reymond (2001). Another is that truck drivers may well understand that, in low-speed maneuvering, the semitrailer typically experiences lower lateral accelerations than the tractor due to the mechanisms of transient, low-speed off-tracking. (See the following discussion.) Finally, the simple matter of opportunity may be important. That is, well-designed, high-speed roadways offer very little opportunity for turning at high magnitudes of lateral acceleration.

Figure 7 presents a histogram of lateral acceleration at the driver’s position with the data again segregated by speed. While this graph derives from the same data source as figure 5, here the polarity of lateral acceleration is preserved and the presentation is a simple histogram (i.e., not cumulative). Thus, the abscissa spans both positive and negative values of acceleration, and the ordinate displays fraction of time at the indicated acceleration. The ordinate is in logarithmic scale. The data are sufficiently plentiful to allow quite narrow bins (0.01 g) so that the plots are presented as continuous curves rather than column graphs. The data are normalized as a single group (not for each individual speed range as in figure 6) such that the area under all four curves sum to a total of 1 and the curves reflect the relative amount of time spent in each speed range as well as the distribution of acceleration in the range.

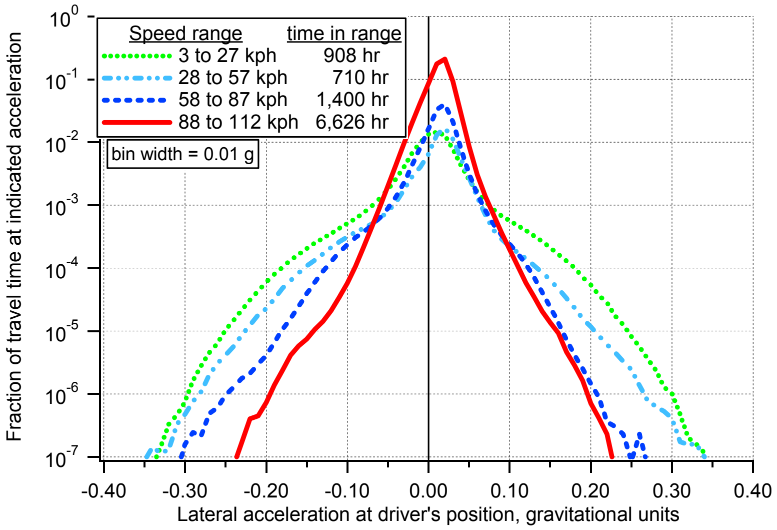

Figure 7. Histograms of lateral acceleration for four speed ranges.

Figure 7 highlights some interesting asymmetries of lateral-acceleration experience. Most obviously, the most-likely values of lateral acceleration (accelerations at the peaks of the curves) are small, positive values. This is clearly a result of the cross slope intentionally built into straight roadways for the purpose of drainage. Finer binning of the data than shown here, reveals that the most-likely value of lateral acceleration in each of the three higher speed ranges is 0.0175 g, indicating that the representative cross slope of the roads traveled by the FOT fleet was 1.75 percent downward to the right. In the lowest speed range, the most likely value is 0.0125 g and, in addition, the histogram is less peaked. Both of these properties likely result from the fact that a substantial portion of the time spent at low speeds is in parking lots and work yards where cross slope may be generally less and is certainly more randomly displayed with respect to the vehicle's path.

There are other asymmetries of interest in figure 7. Note, for instance, the fractional values for the 58 to 87 kph speed range (dark blue, dashed) at values of ±0.2 g. In left turns (positive acceleration), the ordinate value is about 1.5e-6 but in right turns it is 4.1e-6—a 2.7-to-1 bias toward right turns for this magnitude of lateral acceleration. Asymmetries of this type are made more apparent in figure 8. This graph presents an asymmetry parameter (AsymP) on the ordinate and the magnitude of acceleration on the abscissa, where:

$$\mathrm{AsymP} = f_a / (f_a + f_{-a}) - 0.5, \tag{1}$$

and f_a and f_{-a} are the ordinate values from the plots in figure 7 at accelerations of ±a, respectively. If, at a particular magnitude of acceleration, the plot of figure 7 is symmetric, then AsymP for that magnitude is zero. The parameter can range from 0.5 (all left and no right turns) to -0.5 (all right and no left turns).

Looking first at the plot of figure 8 for turning at all speeds (solid black), the influence of cross slope is apparent from the positive peak at about 0.02 g. As magnitude of acceleration increases from there, the value of AsymP descends to zero (symmetric turning) at about 0.1 g. But above 0.1 g, there is a clear bias for turns to the right. Surely one source for this is the bias toward right-hand turns in the entrance, exit, and especially the interchange ramps for limited-access highways in the US. (For example, and exchange from a north-bound to an east-bound road is almost always characterized by a (roughly) 90-degree right turn, but an exchange from north-bound to west-bound often involves a 270-degree right turn rather than a 90-degree left turn.) Another potential source of the asymmetry is turning at intersections. Although the display of left turns and right turns is probably balanced in number, intersection turns to the right demand shorter path radii than those to the left and, therefore, may tend toward higher accelerations. These hypotheses appear to be supported by the plots for individual speed ranges in figure 8. The two intermediate ranges (dashed, dark and light blue) show decided right-turn bias at higher accelerations. The higher speed range of these two is especially characteristic of ramp speeds. The lowest speed range (dashed green), characteristic of speeds in tight intersection turns shows a modest right-turn bias for higher accelerations. Finally, for the highest speed range (highway speeds in dashed red), AsymP shows the left-turn (rather, right cross-slope) bias prevailing at lower accelerations but descending only to zero (symmetric turning) for higher accelerations. This is as would be expected for on-highway travel.

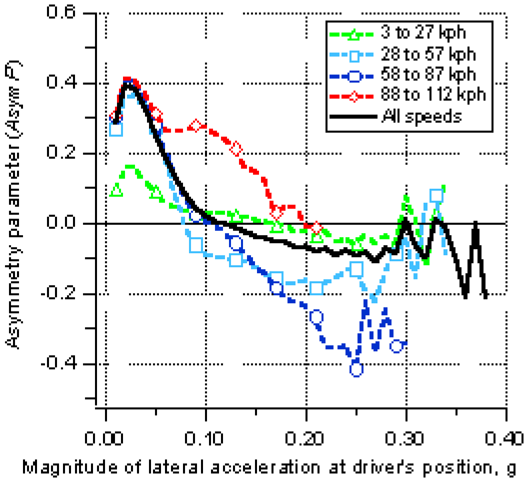

Figure 8. The asymmetry of lateral-acceleration experience by speed.

Lateral performance in turns—influences of load and speed on the risk of rollover

From the data of figure 5, above, it was apparent that the FOT vehicles spent a smaller portion of travel time at elevated lateral accelerations when fully loaded than when partially loaded or empty. Further, it was suggested that the drivers may be attempting to compensate for the reduced roll stability of the full vehicle by using a more conservative driving style.

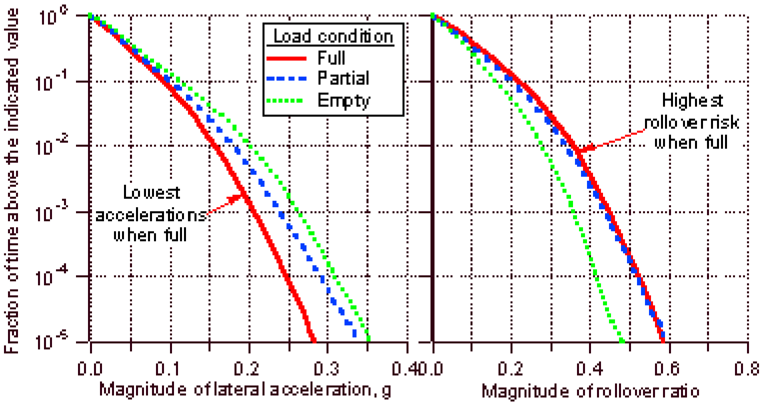

Figure 9. Cumulative histograms comparing lateral acceleration and rollover ratio in turns by load.

Figure 9 examines this subject further. This figure presents two sets of cumulative histograms. The left-hand graph contains histograms of lateral acceleration at the drivers position for driving in turns, segregated by load. (Figure 5 was similar but was for all driving.) The right-hand graph presents cumulative histograms of rollover ratio for driving in turns, also segregated by load. The influence of load on lateral-acceleration experience shown in this figure is essentially as it was seen to be in figure 5, but the influence of load on rollover ratio (rollover risk) is reverse. That is, the vehicles spent larger portions of time in turning operating at elevated rollover ratio when full or partially loaded than they did when empty. If the relationship between load and lateral acceleration did, indeed, result from drivers' attempts to compensate for the low stability of loaded vehicles, figure 9 demonstrates that those attempts were not fully compensatory: the risk of rollover was still greatest for the full vehicles and nearly as great for the partially loaded vehicles.

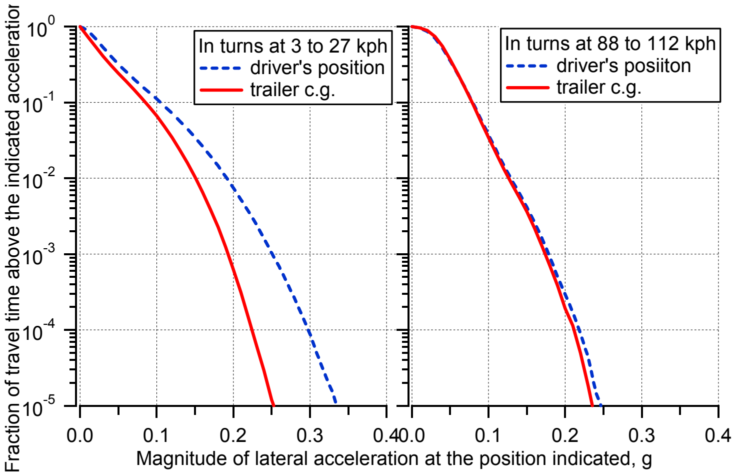

Figure 10. Cumulative histograms of lateral accelerations of tractors and trailers in turns at low and high speeds.

Also, in the previous discussion related to figure 6, it was noted that "in low-speed maneuvering, the semitrailer typically experiences lower lateral accelerations than the tractor due to the mechanisms of transient, low-speed off-tracking," and it was speculated that drivers may account for this somewhat in their driving strategies. Whether they do or not, there is, in fact, some influence of off tracking on rollover-ratio experience. Figure 10 illustrates the extent of this influence by comparing the lateral acceleration experience of the tractor and the trailer. The figure shows histograms for acceleration at the driver's position (which is quite near the longitudinal position of the c.g. of the tractor) and at the position of the c.g. of the trailer for the lowest speed range (3 to 27 kph) and for the highest speed range (88 to 112 kph). As should be expected, the off-tracking influence is strong in the low-speed range, reducing the magnitude of accelerations experienced by the trailer substantially. Also as expected, the influence is virtually nil at high speeds. However, as the time spent in turns in the 3-to-27 kph range is about half of all time spent in turns (see table 1), the off-tracking mechanism has a noticeable influence on the overall experience of rollover ratio. That net influence is illustrated in figure 11. In this figure, the left-hand graph presents the cumulative histograms of lateral acceleration for all driving in curves, segregated by speed. The right-hand graph presents histograms of rollover ratio for the same driving, also segregated by speed. It can be readily seen that the relative spread between histograms for the speed ranges is quite a bit less for rollover ratio than for acceleration at the driver's position. This of course is a result of the strong influence of trailer acceleration on rollover ratio and the reduction of trailer acceleration at low speeds due to off tracking.

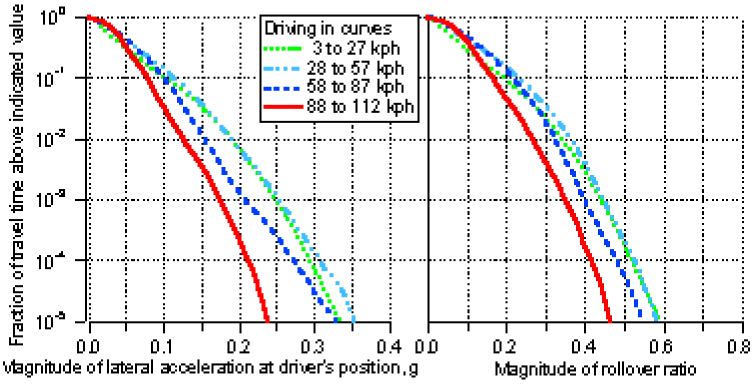

Figure 11. Cumulative histograms comparing lateral acceleration and rollover ratio in turns by speed.

Lateral performance of individual drivers

The strongest influence on lateral performance observed in all the FOT data was the influence of individual driving style. That influence is illustrated in figure 12 where individual histograms of lateral acceleration at the driver's position are presented for 22 drivers of the FOT. The histograms in the left-hand graph are for all driving with fully loaded vehicles; the histograms on the right are for all driving in empty vehicles.

From the figure it can be seen that one driver (bold, green, dotted curve) stands out from the group and displays what is clearly the most conservative driving style.

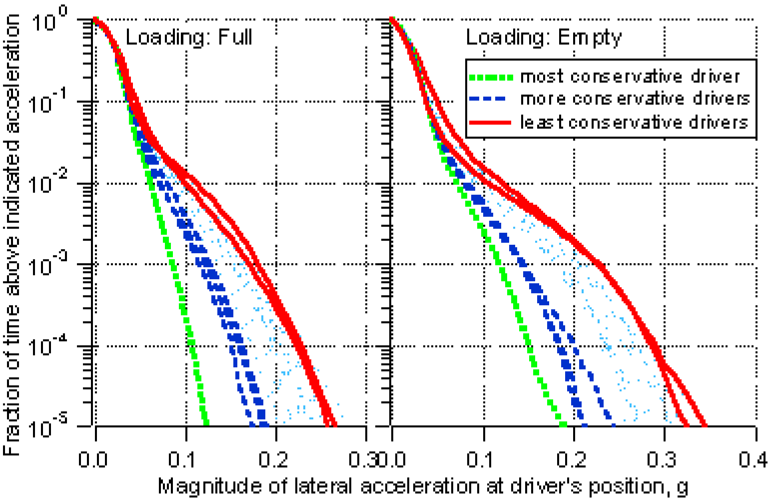

Figure 12. Individual cumulative histograms of lateral acceleration for 22 drivers for fully loaded and empty conditions.

This individual participated throughout the full year of the study. The figure shows that during that year he virtually never exceeded 0.15g in lateral acceleration when his vehicle was full, nor 0.2g when his vehicle was empty. The performance of the other 21 drivers more-or-less group together. Of these, three (bold, blue, dashed curves) define the more conservative boundary of driving styles among the group while two others (bold, red, solid curves) define the least conservative boundary. Overall, the range of performance among the individuals is remarkably large. For example, consider the probability of an individual exceeding a given lateral acceleration threshold: in this case, 0.15g with a full vehicle (but, if more data were available, perhaps the rollover threshold of the full vehicle). Considering just the 21 drivers of “the group” (i.e., disregarding the one most conservative driver), the two least conservative drivers (red) exceeded 0.15g in the full condition at a fractional value in the range of 2.7e-3. The 3 more conservative drivers (dark blue) exceeded 0.15g when loaded at a fractional value of about 1.8e-4. Thus, the least conservative drivers were some 15 times more likely to exceed 0.15g with a full vehicle than the more conservative drivers. Making a similar comparison for empty vehicles, the least conservative drivers were about 75 times more likely to exceed 0.2g than are the more conservative drivers. If similar comparisons are made between the least conservative drivers (red) and the one most conservative driver (green), the ratios increase more or less by an order of magnitude. Also note that, in general, these ratios tend to increase as the acceleration threshold of interest increases. Projecting these observations out to the range of the rollover threshold (0.375 g for the full vehicle), they would suggest that, over long periods and for large populations, rollover rates for drivers who operate like our least conservative drivers would be on the order of 1000 times the rate for drivers like our more conservative drivers.[5]

Other factors influencing lateral performance

The preceding discussion has presented observations on the influence of various factors on the lateral performance of the FOT fleet based on characteristics observable in histograms of lateral acceleration and rollover ratio. The FOT data were also subject to multi-factor analyses which examined the influence of several factors on turning performance in a statistically rigorous manner. These analyses served to confirm two of the primary observations herein in that they showed individual driving style and load condition to be the two strongest, statistically-significant factors influence turning performance. These same analyses revealed that lighting (daylight versus darkness, see table 1), weather (good versus bad, see table 1) and direction of turn (right versus left) all were statistically significant factors in turning performance of the FOT fleet. The data showed that lateral acceleration and rollover ratio were higher in daylight than in darkness,

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[5] Also, recall that the FOT drivers were, in general, a mature and experienced group. It is likely that the range of driving styles over the entire driver population is even larger than what is seen here.

were higher in good weather than in bad, and were higher in right turns than in left turns. Figure 13 illustrates the relative strength of these effects on rollover ratio. For details see (Sullivan, et al., 2004) and (Winkler, et al., 2002).

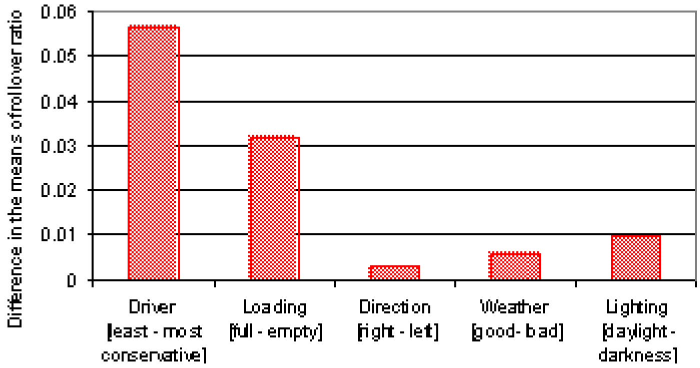

Figure 13. Relative strengths of the influences of several factors on rollover ratio in turns.

SUMMARY

This paper has presented observations on the lateral performance of truck drivers as gleaned from data collected in a year-long field test of six tractor-semitrailer combinations in real commercial service. Some 23 drivers were involved with 22 driving a substantial distance in the test. A description of the operating environment of the test fleet was provided through a set of general exposure metrics. The influences of speed, load condition, and individual driving style on lateral performance were elucidated through the use of histograms of lateral acceleration and rollover ratio. Interesting asymmetries in lateral performance were presented. The range of performance observed between the individual drivers was seen to be remarkably large, and this factor was found to have the strongest influence on lateral performance among those factors examined. Other factors having a statistically significant influence on lateral performance were load condition, weather, lighting, and direction of turn.

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