

A FIELD OPERATIONAL TEST OF A ROLL STABILITY ADVISOR FOR HEAVY TRUCKS

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ABSTRACT

A field operational test was conducted to evaluate the potential of a roll advisor and control device for reducing the occurrence of rollover crashes of heavy commercial vehicles. The test platform was six, five-axle tractor-semitrailer combination vehicles operating over a twelve-month period in the Midwestern region of the United States. Data were gathered for approximately 770,000 kilometers of travel, split evenly between driving with and without the advisory system. Presented in this paper are: the structure and operation of the test; data content and gathering techniques; overall exposure results; and the main analysis methods used to evaluate the device.

The partners in the research included:

- University of Michigan Research Institute (UMTRI)—an independent organization responsible for all aspects of the field operational test and data collection,
- Freightliner LLC—a heavy vehicle manufacturer in the United States,
- Meritor WABCO—a system supplier for commercial vehicle control,
- Praxair Corporation—a supplier of atmospheric, process and specialty gases, and
- United States Department of Transportation Intelligent Vehicle Initiative program.

INTRODUCTION

The purpose of this paper is to discuss the mechanics of a field operational test (FOT) designed to evaluate the influence of a prototype heavy-truck Roll Stability Advisor & Control (RA&C) device on the lateral driving performance of a relatively limited group of professional drivers. This paper presents the structure and operation of the FOT, overall exposure of the fleet to lend legitimacy to the objective of the research and the main analysis methods used to gain insight into the influence of RA&C device and heavy-vehicle driving in general. The research in its entirety is covered in UMTRI's final report (Winkler, 2002) and in more specific publications that address: the lateral performance of truck drivers (Winkler, 2004) and the influence of the RA&C device on driver performance (Sullivan, 2004).

THE TEST METHOD

The experimental design

The RA&C FOT was essentially a human behavioral experiment. The central question of that experiment was: Does an RA&C device alter driving behavior in a manner to improve safety; specifically, does it reduce the risk of rollover crashes? To answer this question an experiment was conducted that consisted of an initial, baseline period (phase 1) in which the driving performance of the subject drivers was observed without the RA&C device, followed by a similar period of time (phase 2) in which the device was implemented and the performance of the same drivers was observed.

Under this serial form of experiment, each driver was thought of as an “experimental unit” that is measured once without treatment and again with treatment. Comparisons of driving behavior were then made between the treated and untreated conditions. However, this form of experiment has drawbacks, namely that it simply can not be undertaken - within the constraints of real commercial trucking and a one-year time window - without introducing confounding influences. In a perfect experimental design, all factors other than the absence or presence of RA&C (the treatment) that might affect driving performance would be maintained

constant across the two phases of observations so that changes observed could be unambiguously attributed to RA&C only. Unfortunately, that was not practical in a field test that takes place in the midst of a real commercial trucking operation. Clearly, projected over a single year; weather, day-light, product demand, driving routes, drivers themselves, traffic conditions, etc., are going to vary. There are two acceptable choices when dealing with potential confounds: control them or measure and account for them. Since the former was not possible, the latter was undertaken. To maximize the likelihood of observing an effect of RA&C, many sources of variability were measured and considered in the analyses of the performance data.

The prototype RA and C device

RA&C is a composite system whose primary elements are Roll Stability Advisor (RSA), Roll Stability Control (RSC), and Hard Braking Event Detection (HBED). Each of these systems provides advisory messages to the driver via the Driver Message Center (DMC) which is shown in figure 1. RSC also provided for active slowing of the vehicle via the electronic engine controller. The physical device was incorporated as part of the ABS controller in a black box mounted on the inside of the right-frame rail near the fifth wheel. Three levels of RSA advisories were defined to communicate increasing severity with increasing potential for rollover. Increasing severity associated with the three levels of risk was communicated through the wording of the message, the length of display time, and the duration of an audible alert. The text messages are displayed on two alternating screens: the first presents the qualitative advisory on risk, the second a quantitative advisory for reduced speed. The speed reduction was a calculated variable based on the observed speed and lateral acceleration during the turn. The RSC is an active control system intended to prevent rollover. When the RA&C system perceives an exceptionally high risk of rollover, it sends a signal to the engine's electronic control unit to reduce engine power and, if deemed appropriate, to apply the engine brake. RSC control was also accompanied by an advisory message and audible alert.

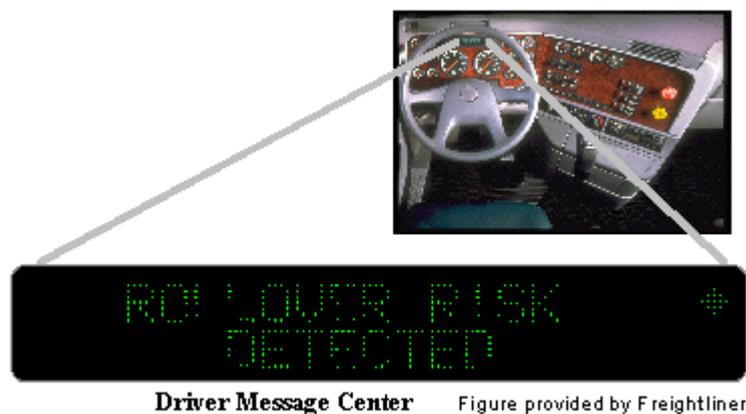


Figure 1. Location and appearance of the driver message center.

The fleet, facility and drivers

The FOT fleet included six new Freightliner Century Class tractors and eight cryogenic-liquid nitrogen trailers. The general practice during the FOT was to “marry” tractors and trailers. That is, unlike many fleets where power units and trailers are interchanged regularly, in this test a tractor and trailer were likely to stay coupled for extended periods and normally were not switched unless a unit was removed from service. Three of the FOT vehicles are shown in figure 2.

The fleet was dispatched, loaded and maintained from a distribution and production facility located in La Porte, Indiana which is in northwest Indiana approximately 10 miles south of the Indiana/Michigan state line. Onsite were all the services and facilities necessary to maintain and operate the fleet, including a maintenance shop, fueling station, weigh scale, driver amenities, and the infrastructure for extracting gases from the atmosphere. A plan-view of the facility is shown in figure 3.



Figure 2. The FOT vehicles.

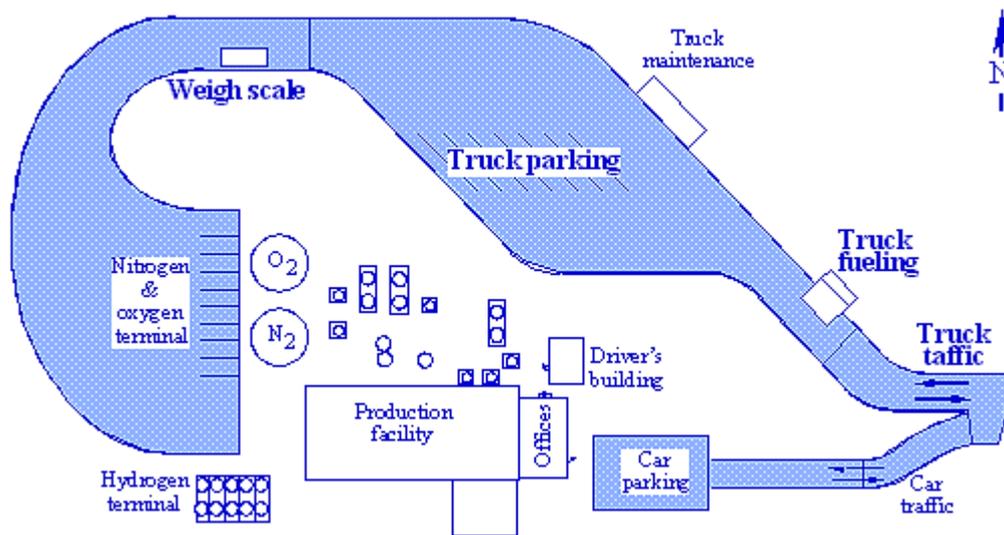


Figure 3. Praxair's La Porte, Indiana production and distribution facility.

At the outset, 23 drivers were involved in the FOT. However, primarily due to layoffs associated with the economic downturn of 2001, nine of these drivers left the program substantially before its completion. Thus, the FOT ended with fourteen subjects with relatively consistent driving exposure throughout the study. This set of drivers was referred to as “comparable” drivers. The excluded or “non-comparable” drivers were not included in the final analyses but their driving data were used in the identification and classification of roadway curves that became the foundation of making meaningful comparisons between phase 1 and phase 2 for each of the comparable drivers.

At the start of the field test drivers ranged in age from 37 to 56 years with a median age for the group of 47.5 years. Their truck driving experience ranged from a minimum of eight years to a maximum of 33 with a median experience of 22 years. Specific experience with tankers ranged from three to 23 years (median: 8.5).

The data acquisition system

The primary electronic component responsible for the success of the FOT was the DAS computer. This system was the core of the test. Foremost, it interfaced with sensors and data buses to gather, process, and log the measures necessary for the documentation of the vehicle motions and driver performance. A picture of the DAS, as installed in each FOT tractor, is shown in figure 4. The main components of the DAS were a 266 MHz CPU with 128 MB of random access memory and a 320 MB flash hard drive.

By design, the DAS was transparent to the driver in that it did not require any external manual control and was fully automated in terms of start-up, shut-down, networking, file creation/deletion, and transfer.



Figure 4. Installed UMTRI on-board data acquisition system.

Typically, the DAS on the test vehicle was on when the vehicle was on and off when the vehicle was off, booting up when the ignition was turned on and shutting down in an orderly fashion when the ignition was turned off. The DAS reads and processes all the data channels whenever the vehicle ignition was on. The control logic to handle these tasks is shown in figure 5. The figure shows the various paths the DAS logic follows to ensure proper functioning and to minimize the potential for lost data, either through corrupted files or interrupted processes.

The most common path in figure 5 starts with an ignition-on event that initiates boot-up of the DAS computer. After boot-up, a trip counter is incremented, variables are initialized, and new files are opened for the trip. In most cases, this is followed by an ignition-off event, offsite of the La Porte terminal (i.e., upload is false), which causes the DAS to write and close relevant files, complete shutdown procedures, and turn itself off. However, if the ignition-off event occurs within the parking area of the La Porte terminal, as determined by the GPS, the DAS begins an upload procedure that closes all relevant files, starts the networking services, searches and connects to the La Porte data server, and uploads new files to the server. Following the upload, the DAS deletes selected files from its memory using a list generated by querying a database that resides on the La Porte server. Then, if the ignition is still off, the DAS begins shutdown procedures and turns itself off.

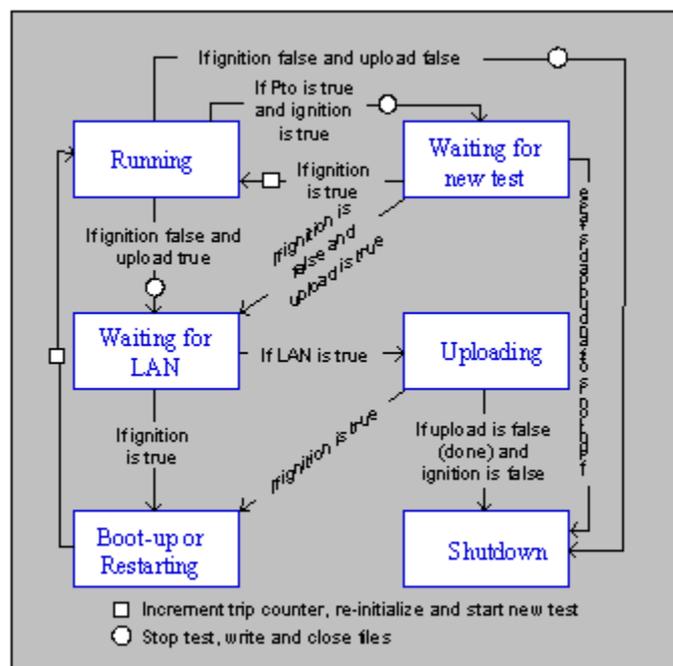


Figure 5. Control modes and logic for the FOT DAS.

The logic gets more complicated when the ignition comes on during the time when the DAS is either connecting or uploading to the server. (These upload events can take many minutes.) If this occurs the current process is interrupted, the operating mode changes to restart, and a new test is started.

There was one exception to the ignition-cycle event that starts a new trip on the DAS. When deliveries were made, off-loading product was done by running a pump powered by the tractor power-take-off (Pto). To operate the Pto the tractors had to be running, and since there was a general desire to segregate trips by load condition, a special rule was added to the DAS control logic that would start a new test if the Pto was on for more than 15 minutes (near the minimum time required to off-load product).

Although not shown in the DAS logic, a fail safe mode was programmed into the system. In the event that the DAS computer malfunctioned and could not shut-down properly, power to the computer would automatically be shut off after 20 minutes. This prevented both the DAS battery and the vehicle batteries from being inadvertently drained if the vehicle was parked for a long time with the DAS computer running and locked up.

The DAS also had a maintenance mode of operation. When a special key was inserted on the bottom of the DAS, the computer started in manual control mode. This mode was for updating and troubleshooting tasks required during the FOT. Since all elements of the data collection system were on the same network vis-à-vis the wireless and lease-line, updating and maintaining the DAS computer could be, and usually was, accomplished remotely from UMTRI in Ann Arbor, Michigan. This offsite control of the on-board computers was enormously beneficial in that it reduced the number of trips to La Porte and, more importantly, minimized interruption to Praxair's business.

SUMMARY OF DRIVING EXPOSURE

The six vehicles of the FOT fleet were phased into service from early November, 2000 through late February, 2001. All six operated in the FOT through the end of November of 2001. During that time, data were collected for approximately 10,000 hours of vehicle service. The vehicles were in motion during approximately 9800 of those service hours. The analyses of the rollover device derived from about 9640 hours of service with the difference principally accounted for by some data having been lost to irrecoverable instrument problems.

Figure 6 indicates that once all six vehicles were in service, travel distance was accumulated at a rather steady rate despite the economic downturn of the latter half of 2001. The total distance accumulated was a bit over 772,000 km and was split rather evenly between phase 1 and phase 2 (49 to 51 percent, respectively). The figure also indicates that about 74 percent of this total distance was covered with the vehicles operating under cruise control and about 11 percent with windshield wipers on (a surrogate for poor weather).

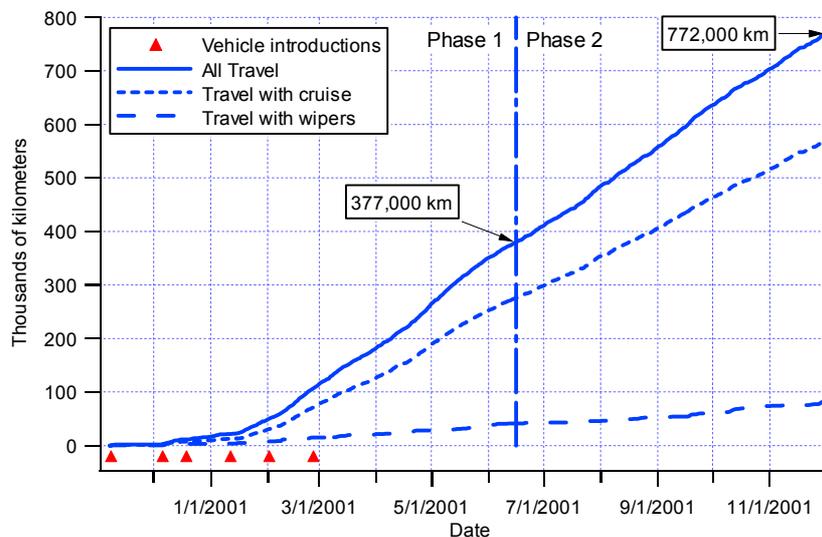


Figure 6. Accumulation of FOT travel distance in time.

The distances represented in figure 6 were accumulated in a total of 9042 FOT trips, a trip being defined primarily for data-collection purposes as the period from ignition-on to ignition-off. Figure 7 shows a histogram of the number of trips by trip distance. The figure includes an insert with an expanded histogram of just the trips of distances under 5 km. The figure shows that a great many of the FOT trips (more than 60 percent) were very short - probably just short moves from one point to another in parking lots and work yards. In fact, the “distance” of quite a few trips was actually zero. The insert shows that the count of trips drops radically at distances greater than about 0.7 km, implying that real trips are those which exceed this distance.

The quality of the data collected on trips less than 0.1 km was problematic (primarily due to the GPS startup issues) and potentially misleading. However, rollover events do occur in parking lots and work yards, so the inclusion of short trip data were important and although the trip distance histogram suggests using a 0.7 km threshold, analyses of this device were generally based on trips whose distance exceeded 0.1 km.

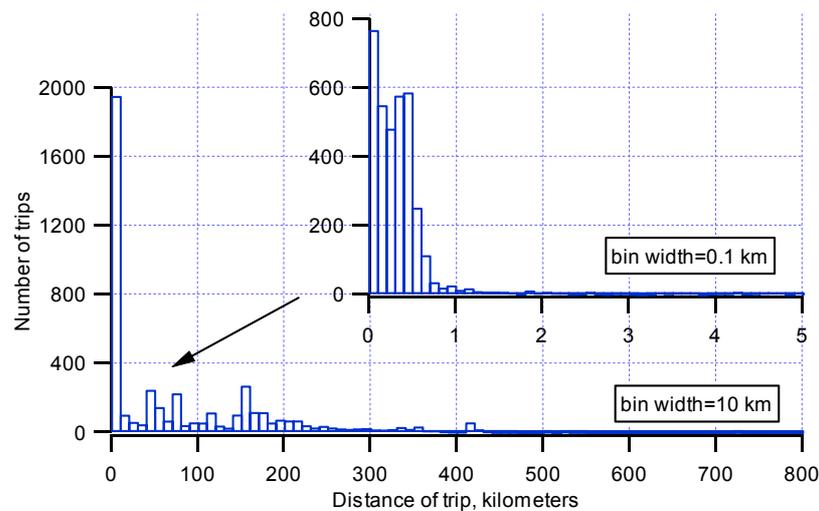


Figure 7. Histogram of trip distances.

A more complete breakdown by phase of the FOT exposure is shown in Table 1. The table indicates that most of these exposure measures are rather well balanced between phase 1 and phase 2. Perhaps the most significant differences between the two phases are the increase in percentage of travel time in daylight. This, of course, results from the arrangement of the study within the calendar year. Also of significance is the difference in the amount of good weather between the two phases and in the distribution of load. All these changes, weather, load and ambient light level have a measurable effect on driving behavior and thus could confound any difference in performance between the two phases that may otherwise be attributed to the rollover device. Hence, considerable effort was made to control for these variables in the analyses comparing driver lateral performance between phase 1 and 2.

An additional difference between phase 1 and phase 2 exposure of importance is the mix of delivery points. While the average distance to delivery points and the average distance of delivery legs were rather constant across phase, it is known that there were changes in the actual mix of delivery points as individual customer demand changed between phases. This is a subtle but important consideration in terms of comparing broadly-based performance metrics. For example, changes in overall lateral acceleration performance that may be attributed to the rollover device are confounded by the route exposure distributions from phase 1 and 2. Without controlling for these route changes comparisons for a group of drivers or an individual driver could be misleading in terms of attributing the change to the rollover device alone.

Table 1. Phase 1 and 2 exposure comparison.

	<i>Phase 1</i>	<i>Phase 2</i>	<i>Change</i>
Total distance	376,857 km	395,276 km	18,419 km
<u>Average distances</u>			
of trips > 0.1 km	95.1 km	91.6 km	-3.4 km
of trips > 0.7 km	137 km	133 km	-4 km
of leg of delivery tour	136 km	136 km	0 km
La Porte to delivery point	166 km	166 km	0 km
<u>Road type</u>			
Percent of travel in phase on: freeway	65.0%	64.0%	-1.0%
highway	16.0%	16.4%	0.5%
arterial	9.1%	9.6%	0.5%
local/regional	7.4%	7.5%	0.1%
access roads	2.5%	2.5%	0.0%
<u>Day/night</u> ¹			
Percent of travel time in daylight	63%	67%	4%
<u>Weather</u>			
Percent of travel time in good ² weather	82%	84%	2%
<u>Loading</u>			
Average Mass, metric ton	26.1	25.8	-0.3
Percent of time: empty ³	37.1%	38.7%	2%
Partial ⁴	14.5%	11.9%	-3%
Full ⁵	48.0%	49.0%	1%
<u>Speed</u>			
Average speed in motion, kph	78.6	78.9	0.3
Percent of time: 3 to 27 kph	9.7%	9.4%	-0.3%
28 to 57 kph	7.6%	7.2%	-0.4%
58 to 87 kph	14.7%	14.4%	-0.3%
88 to 112 kph	68.1%	68.9%	0.9%
<u>Curves</u>			
Percent of travel time in curves ⁶	9.4%	9.1%	-0.3%

¹ “Night” when the sun was 6 or more degrees below the horizon

² “Good” when wiper use was less than 1% and visibility was greater than 2 km

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 “Curve” when path radius was less than 1 km for 3 seconds or more

ANALYSIS METHODS

The two main analysis methods used in the evaluation of the device were the correction and derivation of lateral acceleration and the identification and coding of curves. These processes formed the bases by which the authors feel a meaningful evaluation of the effectiveness of the device could be made. Highlights of the two methods are covered below.

Lateral acceleration

The primary objective measure for evaluating driver behavior and the potential influence of the RA&C device, at least as it pertains to reducing likelihood of rollover, is the lateral-acceleration behavior of the vehicle as it is driven by the individual drivers participating in the FOT. This section defines the term “lateral acceleration” as used in the research, and describes the analysis methods used to correct the primary lateral acceleration signal as well as derive several different measures of lateral-acceleration at different locations on the FOT vehicle.

For the work presented here, the definition of lateral acceleration is somewhat different from the formal definition according to the International Organization for Standardization (ISO, 1991) and the Society of Automotive Engineers (SAE, 1978). Those definitions do not account well for the influence of cross slope of road surface, which the authors recognize must be considered in a manner appropriate for evaluating vehicle rollover. Therefore, lateral acceleration is defined as the component of vehicle acceleration, including (or with the addition of) the component of gravitational acceleration, perpendicular to the longitudinal axis of the vehicle, at a specified point in the vehicle and in a plane parallel to the road surface.

The primary measurement of lateral acceleration was obtained by an accelerometer mounted laterally at the center of the front axle of the tractor. The choice of this location was a direct result of the observation made above regarding the appeal of determining lateral acceleration parallel to the roadway surface for purposes of

the analysis of rollover. Because of suspension and frame properties, and the fact that payloads are carried toward the rear of the vehicle, the front suspensions of commercial vehicles typically suffer very little roll moment. Consequently, the solid front axle typically remains rather parallel to the road surface even during severe turning where chassis and drive axles may roll appreciably. (This applies to frequencies associated with yaw and roll motions, not to higher frequencies associated with ride disturbances and road roughness.)

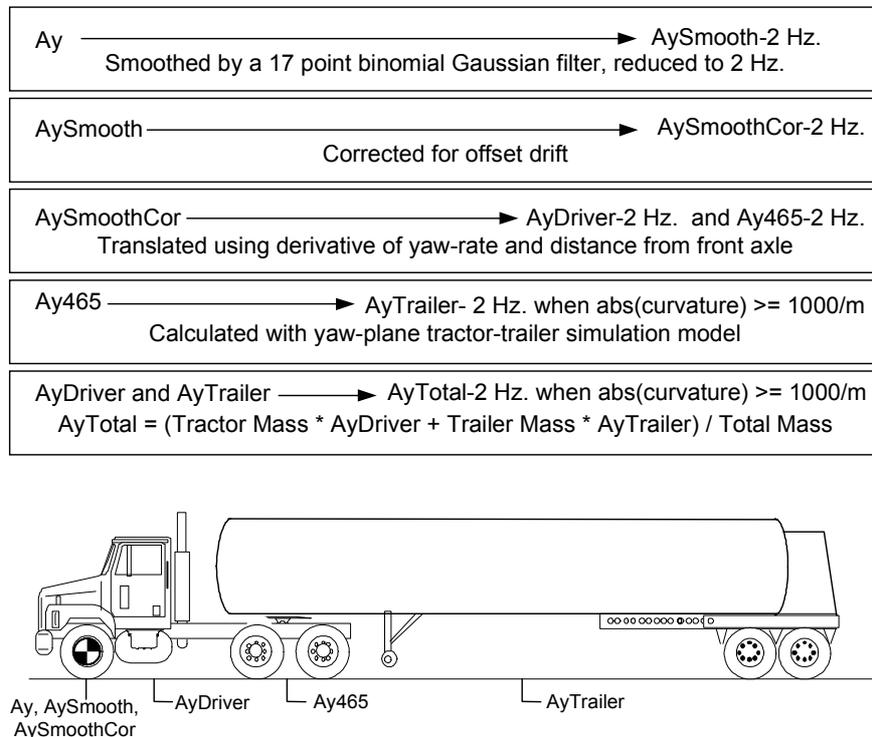


Figure 8. Locations of calculated lateral accelerations.

Ultimately, six different estimates of lateral acceleration were derived from the primary Ay measure.¹ They are shown below in figure 8. Also included in the figure is a brief indication of the numerical methods used to generate them along with the progression from which they were produced. The two primary signals used in evaluating the RA&C device were AyDriver and AyTotal. AyDriver is an estimate of the lateral acceleration at the longitudinal position of the driver’s seat and represents what the driver “feels” when maneuvering through curves and turns. AyTotal, however, estimates the actual rollover risk of the entire vehicle. That is, tractors and trailers do not roll independently of one another but rather are coupled in roll by the fifth-wheel. Hence, evaluation of rollover risk should be based on the overall lateral-acceleration experience of both the tractor and trailer, with the relative mass being the appropriate weighting function.

Finally, absolute levels of lateral acceleration do not always reflect the relative risk associated with rolling over because the rollover threshold in heavy vehicles is strongly related to load condition. For this reason, the comparative analysis was also done using the ratio of AyTotal to the corresponding estimated static rollover threshold as measured by tilt-table experiments for a given load condition. The resulting ratio, called rollover ratio is a number from 0 to 1 that represents the available rollover margin of the vehicle in its current load condition. A rollover ratio of 0.5 indicates that the lateral-acceleration experienced by the combination reached half of the available rollover margin; a rollover ratio of 1 means rollover is imminent.

Accurate estimates of lateral acceleration formed the bases for producing meaningful results in this research and a significant effort was made to correct biases, drifts and errors in this signal. The most important of these corrections was the removal of long-term drift in the zero-offset of the signals from each tractor over the duration of the FOT. The final method used to correct for offset-drift was to determine an appropriate zero correction factor based on the relationship of average measure lateral acceleration and the average cross

¹ Note that since they all are based initially on Ay, all are estimates of lateral acceleration parallel to the roadway, i.e., including the influence of gravity due to roadway cross-slope but not subject to the influence of chassis roll.

slope for long straight sections of good quality roadway. Implementing the approach required identifying a set of roadway segments that individually met the physical requirements (straightness, limited access, no signals, minimal grade, smooth surface, etc.) and as a group were numerous and well distributed such that each FOT vehicle would encounter a site frequently. In total, 18 well-distributed sites were selected based on an analysis that showed that nearly 80 percent of all FOT travel time was within 1 hour one of these eighteen sites and 98 percent of all time was within four hours of a site.

To measure the cross slope of each site a passenger vehicle was specially instrumented with accelerometers, inclinometers, and a DAS. A technician then traveled to each site, calibrated the instruments, and followed a specific protocol to make repeated measurements in both directions and in all lanes of multilane roadways. The results from these tests were repeatable and consistent showing an average of the standard deviations for tests at each site was less than 0.00093 g. Final calculations showed an average cross slope for all roads (right-most lane only of multilane roads) was 0.017 g.

For the entire FOT database, a total of 15,337 passes were identified for the 18 sites. A quality assessment of each pass was made based on statistical analysis of signals including speed, yaw-rate, heading angle, lateral acceleration, and lane offset position. Final offset correction values were then calculated and used to adjust the corresponding tractor lateral acceleration data that occurred closest in time to the offset correction. Three independent sites were then selected to validate the correction process by averaging the corrected and non-corrected lateral acceleration signals for each site pass. Figure 9 shows the result for north-bound direction of one of the three sites. The figure shows a reduction in the standard deviation of lateral acceleration from 0.019 g to 0.0045 g for uncorrected and corrected signals, respectively. Visually, the figure shows a considerable reduction in the scatter of the uncorrected lateral acceleration data.

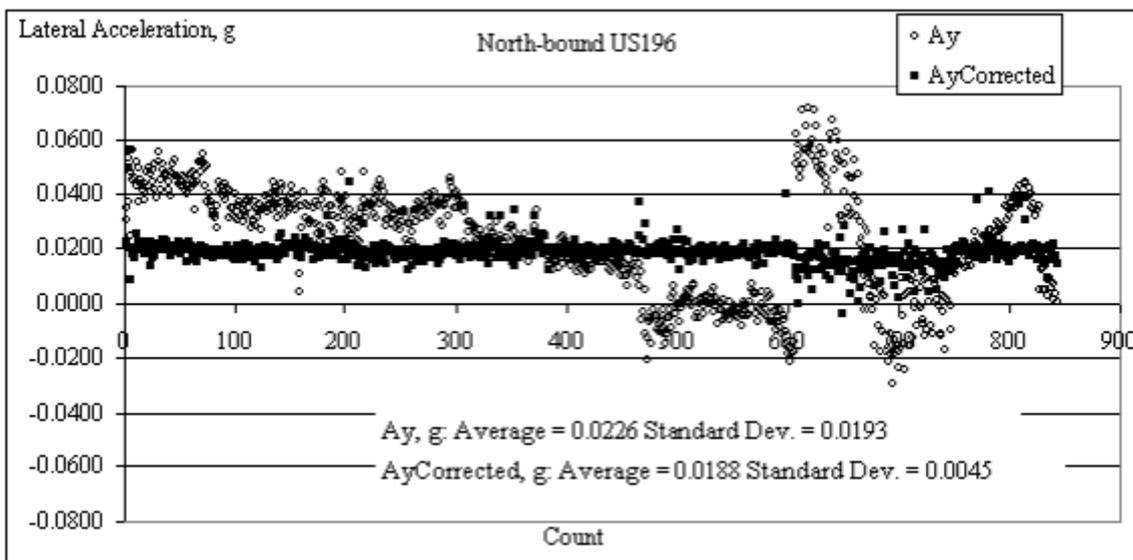


Figure 9. Distribution of corrected and uncorrected lateral acceleration at a validation site.

Curve identification and performance metrics

A major element in trying to quantify the influence of the RA&C device on driver behavior has to derive from comparable measures of vehicle performance over discrete sections of roadway that involve turning and, hence, lateral acceleration. Moreover, the statistical quality of a finding depends on the number of observations and the ability to control for confounding variables that may also influence on driver behavior. It is these considerations that make the consistent identification and processing of events on curves in the RA&C database critically important. Also, it is recognized by the authors that curves must be identified and characterized using the underlying geometrical and geographical properties of the curves themselves, as opposed to using the vehicle performance data to identify areas of perceived rollover risk. Use of measures of the dependent variable (the performance data) to select curves for evaluation would create a linkage between the dependent and independent variable potentially undermining the driver performance/device analysis.

The first step in the curve-analysis process was to build a table of events that explicitly identified all the time that the FOT vehicles were “in curves”. The condition that identified a “curve” was an absolute curvature $\geq 1.0 \text{ km}^{-1}$ (i.e., a curve with a radius $\leq 1 \text{ km}$) continuously for at least 3 seconds. Based on this definition over 330,000 turn events were identified for the entire FOT. Next, a computationally intensive process was developed that used geometric triangulation and statistics such as, change in heading, distance traveled and turn direction, as well as, start and end geographical characteristics like heading angle and location to make groupings of similar turn events. A curve was then defined by calculating the average characteristics of the individual passes contained in each group. This process resulted in over 24,000 uniquely identified curves in the geographical region covered during the FOT. Finally, the entire FOT database was searched again to specifically identify the start and end times of each pass of each vehicle over every curve.

An example of a curve is shown in figure 10. The left side of the figure shows the GPS points from all 167 passes along with the symbols, circles in this case, that show the start (0,0) and end (78,-230) gates of the curve. This figure is representative of the general quality of the curves with respect to the consistency and general scatter of the GPS data. The right side of the figure shows the curve location on the map.²

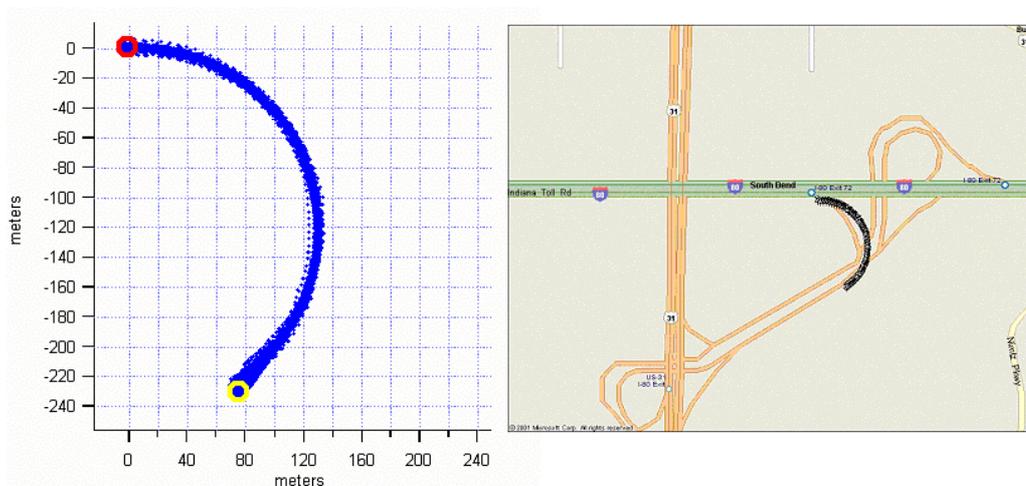


Figure 10. Example curve with 167 passes.

Ultimately, the curve analysis methods produced a subset of data containing over fifty different metrics to characterize the vehicle, driver, road, environmental conditions for the each pass over each curve for entire FOT. These statistics were then used in a series of multifactor analyses to evaluate the effect of the rollover device on lateral performance. The results of these analyses are discussed in the paper by Sullivan (2004). In short, the findings showed that no statistically-significant, main effect of the general presence of RA&C on turning behavior of drivers could be established. However, in a separate analysis, individual RA&C advisories/actions were seen to have a statistically-significant ($p \leq 0.05$) influence on turning performance in that performance in more severe turns directly following an advisory was more conservative than performance in similar turns preceding an advisory. In other words, there was some evidence to suggest that upon be advised by the device drivers were more conservative in subsequent curves in terms of their lateral performance behavior.

SUMMARY

This paper presents an overview of the structure and operation of an FOT designed to evaluate the potential of a roll advisor and control device for reducing the occurrence of rollover crashes of heavy commercial vehicles. It discusses the test methodology, the device being tested, and data collection architecture. Overall exposure results are summarized to lend credence to the entire research effort. Finally, analysis methods to characterize the numerical processes used to measure the lateral performance behavior of the driver are presented along with a discussion of the technique used to account for the confounding effect of route

² Clearly, the GPS points representing the actual path of the curve do not align well with the road segments shown on the map. This is due to location inaccuracies in the map program, since the overall quality of the GPS points is supported by the repeatability shown in the left-side representation of the curve.

changes that occurred during the FOT. Although not directly covered in this paper, the authors concluded the prototype-RA&C device showed no statistically-significant, main effect, on turning behavior of drivers could be established.

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