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Intelligent Vehicle Initiative (IVI) Field Operational Test Program

Final Report

Volume 1 of 4

Freightliner Trucks Field Operational Test: The Freightliner/Meritor Wabco Roll Stability Advisor and Control at Praxair

By

Scott D. Smith
Executive Engineer, Government Technical Affairs
Freightliner LLC
4747 N. Channel Avenue
Portland, Oregon 97217

For

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FREIGHTLINER® LLC
A DaimlerChrysler Company

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1.0 BACKGROUND

Rollover is one of the most significant factors in heavy truck accidents on America's roadways. Accidents involving heavy trucks can tie up traffic for hours, and do serious damage to roads and related infrastructure. Rollover crashes account for 14% of fatal and 9% of injury crashes, with approximately one half the truck drivers killed each year losing their lives in rollovers[1].

FIGURE 1: HEAVY TRUCK ROLLLOVER ACCIDENT

As part of the Department of Transportation's Intelligent Vehicle Initiative, Freightliner LLC was awarded a Cooperative Agreement in 1999 for a three-year test of a Roll Advisor and Control System. The overall project agreement included 4 main topics: The development and analysis of a *Roll Advisor and Control System* (RA&C) was primary, and directly related to it was the development of a driver interface. A second, and separate system was included on the vehicles to evaluate current *Lane Guidance* technology. Separate studies were conducted, using the same Global Positioning Satellite data collected for Roll Advisor, to develop and refine *3D Road Mapping* techniques, and this led to the evaluation of the effectiveness of a predictive *Roll Warning* technology.

2.0 INTRODUCTION

For the field test, Freightliner partnered with DaimlerChrysler Research and Technology of North America, Meritor WABCO, Praxair, and the University of Michigan Transportation Research Institute. Each partner had specific responsibilities associated with the various topics covered in this field test.

[1] Winkler, C.B.; Bogard, S.E.; Ervin, R.D.; Horsman, A.; Blower, D.; Mink, C.; Karamihas, S. 1993. Evaluation of innovative converter dollies. Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Federal Highway Administration, Washington, D.C. Report No. UMTRI-93-41-1/FHWA/MC-94/019 (3 volumes).

Meritor WABCO engineers collaborated with DaimlerChrysler Research and Technology of North America and Freightliner's Department of Engineering and Technology to develop and refine the RA & C software and hardware. Praxair was the Freightliner customer that operated the vehicles used for data collection during their normal business operations from a terminal in LaPorte, Indiana, as such neither Meritor WABCO or Praxair had final reporting responsibility.

Freightliner, as the prime contractor to the DOT, had the overall project management responsibility. The remaining partners each had specific task responsibilities and reporting requirements; the full reports on their respective activities are included as stand-alone Volumes II-IV of this final report. Volume I represents a summary of the overall project and highlights of the most relevant findings contained in the reports of the other partners. Volume II from The University of Michigan Transportation Research Institute (UMTRI) includes the details related to the RA&C FOT, vehicle instrumentation, data collection and analysis of the system. Volume III from Daimler Chrysler Research & Technology North America’s Vehicle System Technology Center (VSTC), contains details of Human Factors interface development as related to the RA&C system, Theoretical Rollover Warning Effectiveness, and evaluation of the Lane Guidance system performance. Volume IV is the final report from Daimler Chrysler Research & Technology North America (RTNA) of Palo Alto, California covering the specifics of their work regarding a technique for developing more accurate digital maps for roadway geometry.

3.0 ROLL ADVISOR AND CONTROL

(Reference Volume II for details)

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 a Driver Message Center. Advisory messages are accompanied by an audible tone.

RSA is an in-cab training aid that presents an advisory message to the driver whenever the system observes conditions judged to have presented a significant risk of rollover. The intent of RSA is to modify driver performance through training; RSA is not a rollover-warning device. Accordingly, RSA messages are not delivered immediately upon detecting a risk of rollover but are delivered a short time after the risk has subsided. There are three levels of RSA advisories.

RSC is an active control system intended to prevent rollover. When RSC detects 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 retarder. An advisory message is delivered simultaneously with RSC control.

HBED, like RSA, is a training aid that advises the driver when an unusual braking event has been detected. There are three levels of HBED advisories.

As described above, RA&C is a composite system including RSA, RSC, and HBED functions. The influences of RA&C on driver behavior observed in this study can only be ascribed to the *entire* system. A separate analysis on trip and leg performance data, examined the change in turning performance that followed soon after RA&C advisories. Turn performance in relatively severe turns coming within a prescribed distance following advisories was compared to performance in similar situations before advisories.

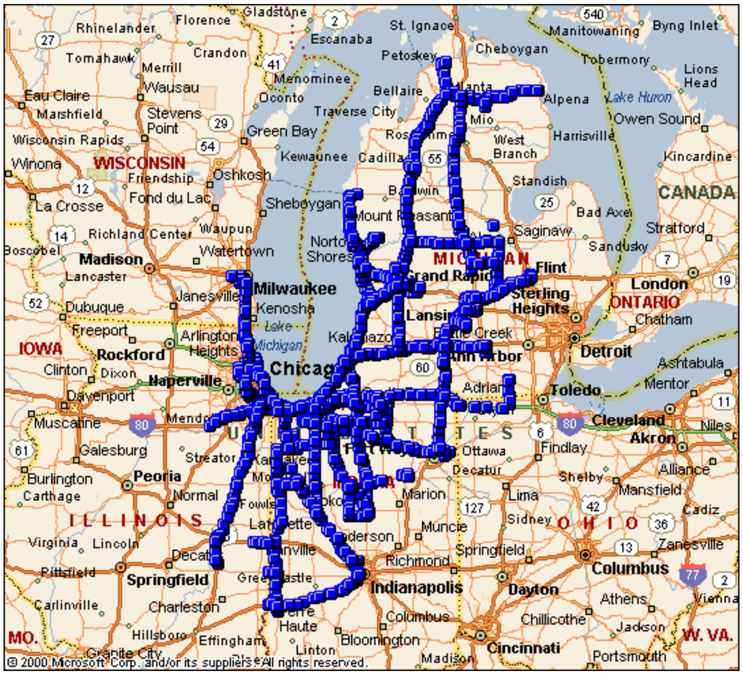
The primary intent for the FOT was to answer if a Roll Advisory System can influence driver behavior and reduce rollover accidents as explained in the previous section. The Freightliner Roll Advisor and Control system utilizes the network of ABS sensors installed on the truck wheels, each sending data to the Electronic Control Unit mounted on the tractor frame rail. Accelerometers in the ECU measure lateral acceleration of the truck, and proprietary software estimates the vehicle mass and center of gravity, then compares this information with pre-defined test data to determine when a rollover would occur. If a potentially hazardous maneuver is detected, the system alerts the driver by sounding an audible tone in the cab, and based on the level of rollover risk detected, one of three predetermined messages suggesting a specific reduction in speed is displayed on Freightliner's proprietary Driver Message Center located in the center of the dash. At the highest level of risk where rollover is imminent, the control feature of the system activates the engine brake, and interrupts fuel flow to reduce the vehicle's speed.

Six, five-axle tractor-trailer vehicles, each consisting of a Freightliner Century Class day-cab tractor hauling a Praxair cryogenic, liquid-nitrogen semi trailer, made up the test fleet as shown in Figure 2.

FIGURE 2: FRIEGHTLINER CENTURY CLASS S/T

Praxair took delivery of the six specially equipped Freightliner Century Class S/T tractors in September of 2000. The tractors were put into regular service, delivering products from Praxair's terminal in Laporte, Indiana to customers in Indiana, Michigan, and Illinois as shown in Figure 3.

FIGURE 3: ROUTES

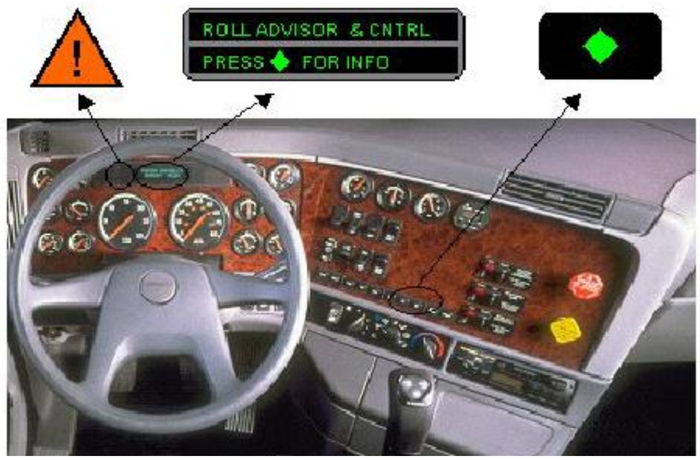


The field test began in November 2000, and ran through November 2001. During that time data was collected on approximately 770,000 kilometers and 10,000 hours of travel. Most fleet travel was in the fully loaded or empty condition, and most was at highway speeds. About 65 percent of the travel was on freeways.

The University of Michigan's Transportation Research Institute, (UMTRI), oversaw the collection and analysis of data during the field operational test. Prior to the field test, UMTRI conducted a series of controlled tests profiling the system's operation to establish a "baseline" against which field test data would be compared. Full vehicle maneuvers on a closed test track were conducted to profile the system software, and full vehicle tilt table tests were performed to determine the rollover threshold of the combination vehicles. UMTRI also designed, fabricated, and installed the test instrumentation. On board the vehicles, data was collected describing the motion, location, and operating state of the vehicle, control inputs of the driver, ambient conditions, and the functioning of the Roll Advisor and Control System. Throughout the two phases of the FOT, UMTRI conducted driver interviews to assess attitudes toward a system like this, and determined whether drivers perceived benefits of the system, as they became more familiar with its functionality.

The field operational test was designed to determine if a Roll Advisor System could influence driver behavior and reduce rollover accidents, by communicating rollover risk and recommending corrective action to the driver. A carefully constructed human interface with a specific messaging scheme was developed to communicate in a manner that was acceptable to the drivers. Drivers found the Freightliner Driver Message Center to be simple to understand and indicated that the messages were clear, legibly presented, and produced minimal distraction while driving.

FIGURE 4: DRIVER MESSAGE CENTER



During Phase I, the first six months of the yearlong data collection period, UMTRI collected baseline data of driver and system performance, with no advisories displayed to the driver. The turning behavior of drivers was examined on the basis of two measures: lateral acceleration at the driver's position, which was taken as a measure of the driver's own experience, and rollover ratio, which is a measure of the actual risk of rollover. Rollover ratio ranges from zero to one hundred percent. A value of one hundred percent indicates impending rollover.

The advisor display functions were activated in phase 2 of the test, and data was collected for an additional 6 months. There were 379 advisory messages issued by the RA&C Systems during the second phase of the FOT. See Table 1, Roll Advisory & Control Events.

TABLE 1: ROLL ADVISORY & CONTROL EVENTS

RSA Level 1	241
RSA Level 2	65
RSA Level 3	6
RSC	29
Total RSA/C	*341*
HBED	*38*
TOTAL	**379**

The 294 RSA/C episodes were not evenly distributed among the drivers. RA&C advisories and control actions were strongly associated with a few individual drivers. Two of the 19 drivers who participated in Phase 2 accounted for 39 percent of all the RSA/C episodes (including 43 percent of all RSA/C messages) but only 12 percent of Phase 2 travel. The top driver had 69 episodes and the second highest had 45 episodes. Five other drivers experienced from 19 to 23 episodes each. These top 7 drivers accounted for 75% of all the episodes. On the other hand, six drivers had none or only one RSA/C episode. See Table 2, RA&C Advisories By Driver.

TABLE 2: RA&C ADVISORIES BY DRIVER

Driver	% of Episodes
Top 2 drivers	39%
Top 7 drivers	75%
6 drivers	0 to 0.3%

Table 3, RA& C Episode Counts by Type of Curve shows the episode counts and classifications of curves, which took place. As can be seen from Table 3, RA&C episodes were concentrated on freeway ramps and intersection turns. Two locations referred to as hotspots stood out: 90 Degree right turn intersection and 270 Degree right turn freeway onramp. Five others had 10 or more episodes.

TABLE 3: RA&C EPISODE COUNTS BY TYPE OF CURVE

		Counts of episodes in:		
Curve type	*Description*	*curves with > 1 episode*	*curves with 1 episode*	*all curves with episodes*
1	Freeway on-ramp	4	13	17
2	Freeway on-ramp, 270 deg	48	4	52
3	Freeway off-ramp	5	8	13
4	Freeway off-ramp, 270 deg	2	2	4
5	Freeway connector ramp	11	2	13
6	Highway intersection	18	3	21
7	Urban intersection	23	25	48
8	Intersection onto or off of freeway ramp	32	16	48
9	Curve in urban street	28	14	42
10	Urban street on-ramp	3	0	3
11	Highway on-ramp	2	1	3
12	Curve in highway	3	12	15
13	Construction lane shift	2	0	2
14	Highway turn to Praxair lot	7	2	9
15	Parking lot	0	2	2

The two locations that stood out were referred to as hotspots: Figure 5, Hotspot #1 Location of greatest number of RA&C episodes Gary Avenue West to Cline Ave North, Gary, Indiana and Figure 6, Hotspot #2 Location of 2nd greatest number of RA&C episodes on ramp from US 31 North to I-80 West near South Bend, Indiana.

FIGURE 5: HOTSPOT #1
LOCATION GARY AVENUE WEST TO CLINE AVE NORTH, GARY, INDIANA

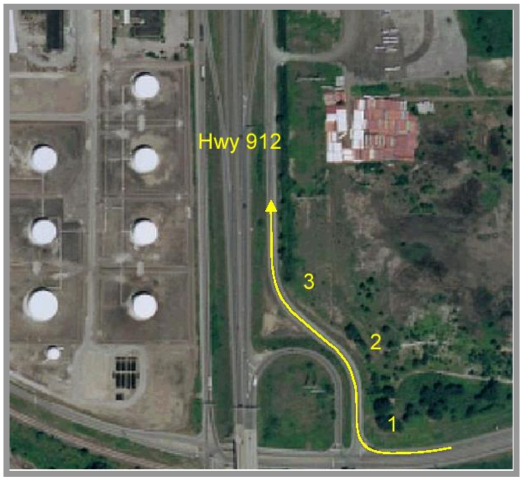
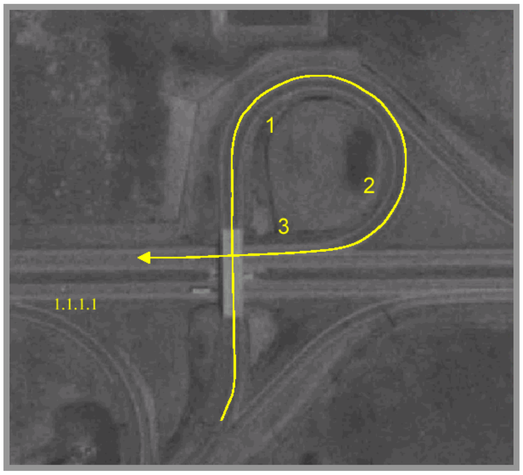


FIGURE 6: HOTSPOT #2
LOCATION US 31 NORTH TO I-80 WEST NEAR SOUTH BEND, INDIANA



Judged in terms of the driver's lateral acceleration experience, turning performance was more conservative with loaded vehicles than with empty vehicles, suggesting that drivers are aware that loaded vehicles are less stable and that they attempt to compensate for that lower stability with a more cautious driving style. Subjective data gathered through interviews and periodic surveys of the drivers support this view.

The simplest analysis of the data examined the change in overall turning behavior of the comparable drivers from phase 1 (without RA&C active) to phase 2 (with RA&C active). The analysis did show a small, but statistically significant change in high-acceleration turning between phases that suggests a lower risk of rollover in phase 2. However, this analysis may not have accounted for all the factors, other than the presence of Roll Advisor and Control, which might have also changed between phase 1 & 2.

For these reasons, multi-factor statistical analyses were also undertaken that did account for other factors. In addition to phase, these analyses considered load, weather, lighting, and curve severity. In these analyses, no statistically significant main effect (i.e., overall effect) of RA&C could be found, but certain significant interaction effects that suggest a positive influence of RA&C in opportune situations were found. For example, small but significant reductions in rollover ratio in phase 2 (with RA&C) were found in the most severe turns where weather was clear and, therefore, not a factor, and also in the most acute turns, found to be to the right.

A separate analysis examined the change in turning performance that followed soon after RA&C advisories. Turning performance in relatively severe turns coming within a prescribed distance following advisories was compared to performance in similar situations before advisories. Results showed that behavior in severe turns was significantly more conservative following advisories, especially within the first 250 km.

In other words, a simple analysis comparing driver behavior in the two phases showed a slightly lower risk of rollover when advisor alerts were activated during phase II. More complex analyses showed less risk in the most severe turns, with significantly more conservative turning behavior within the first 250 km following an advisory alert.

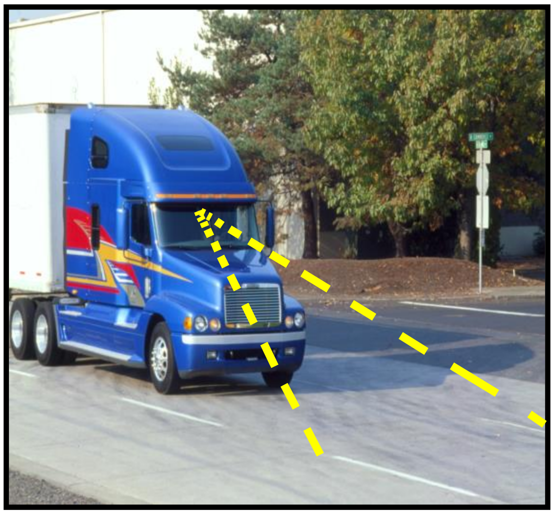
4.0 LANE GUIDANCE SYSTEM

(Reference Volume III for details)

Beyond the primary Roll Advisor and Control aspect of the field operational test, the project also gathered large quantities of data on other technology. Single incident road departure incidents represent the most serious crash problem based upon National Highway Accident Data Analysis (source: DOT). Many are fatigue related accidents. For Car/Truck fatal accidents, 19% are caused by a car failing to stay in its lane and 11% are caused by a truck failing to stay in its lane (source: Center for National Truck Statistics – UMTRI).

Test vehicles were also equipped with a Lane Guidance System. Lane Guidance System is designed to reduce road departure incidents. It utilizes a camera mounted behind the windshield. This camera "reads" the lane markers, and can alert a driver with a tone if the vehicle begins to leave the lane unintentionally. During this FOT the Lane Guidance was not visible to the operator of the truck and tone disabled in order to collect data on the system to evaluate it’s effectiveness of tracking lane markings during different conditions.

FIGURE 7: LANE GUIDANCE SYSTEM



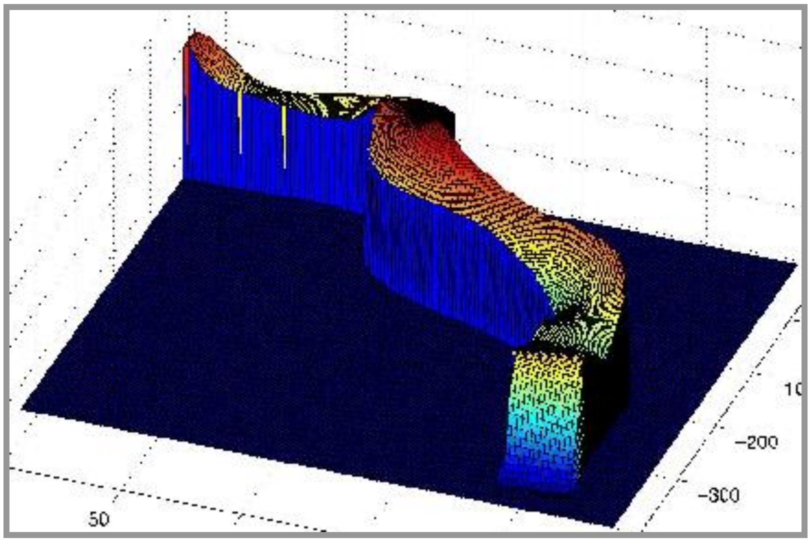
Taking the tracking performance data of tractors between February 1, 2001 and May 18, 2001, the overall tracking performance was 83%. Tracking performance is defined as the % of time the system recognizes, i.e. "tracks", either a left or right-hand lane marker. Above 60 kph tracking was 87%. Best tracking occurred from 80 to 100 kph at 96%. Tracking peaked at 97% with cruise control on and speeds greater than 90 kph. The system tracked lane markers slightly better at night than during the day. The result of this performance evaluation showed that the Lane guidance system performs best when the driver is potentially least attentive, during the night and early morning hours with cruise control engaged at highway speeds, and during dry conditions. For more detail see Volume III, Section 4.4, Performance Evaluation.

5.0 ROAD GEOMETRY MAPPING

(Reference Volume IV for details)

Data was also collected to facilitate more detailed 3D road mapping, techniques with the ultimate goal of a predictive roll warning and avoidance system. Such predictive technologies could warn a driver prior to a curve if the situation is dangerous and ideally slow down the truck in advance. Future safety applications such as this will require detailed foreknowledge of the road ahead. Curvature, gradient, super elevation, and typical speeds are critical parameters that current navigation systems do not provide. The DaimlerChrysler Research and Technology Center in Palo Alto builds precise maps with these parameters from large quantities of global positioning satellite data.

FIGURE 8: 3-D MAP OF HOTSPOT #1: LOCATION OF GREATEST NUMBER OF RA&C EPISODES: GARY AVENUE WEST TO CLINE AVENUE NORTH, GARY, INDIANA



Road mapping/geometry used FOT data to refine processes and algorithms to create highly accurate 3D maps from large collections of less accurate positioning data. Maps can have errors up to 15 meters with Driving errors contributing typically 10-30 centimeters on maps. The maps can calculate accurate position to within a few centimeters. Road mapping/geometry analysis included: vehicle speed analysis, detailed analysis of two FOT "Hotspots", Multi-body dynamic simulations of a tractor-trailer, and demonstrations of a predictive algorithm base upon FOT data (both three dimensional road map data and driver performance).

Road Maps were generated to within one-centimeter accuracy from FOT Data. It may be possible to project speed and lateral acceleration with as few as ten passes. Rollover prediction 10 seconds in advance was demonstrated with 1/3 second accuracy when compared to an actual event recorded during the FOT. It was determined that it is possible to provide enough advance warning to avoid dangerous situations. Better prediction may be possible with more sophisticated model refinements.

6.0 ROLL WARNING EFFECTIVENESS

(Reference Volume III for details)

The intention of Rollover Warning Effectiveness was to answer the question: What information is necessary to accurately predict combination vehicle rollover? Information gained through this analysis can be used to better understand the requirements for a predictive system. First, a vehicle speed analysis is presented based on the FOT data for the two geographical locations that produced the most RSA advisories during Phase II, referred to as Hotspots and originally identified by UMTRI. Then, a detailed dynamic analysis of these two hotspots is performed. This is achieved by applying multi-body dynamics simulations to the Praxair tractor-trailer combination to better understand the physical behavior of the combination vehicle and the driver input that produced each maneuver within the limits of the road geometry. The simulation results are then used to produce vehicle-specific and maneuver-specific dynamic rollover characteristics that accurately capture the essential elements of vehicle rollover.

7.0 SUMMARY OF RESULTS

RA&C episodes were concentrated on freeway ramps and intersection turns. Two locations stood out (hotspots): 90 Degree right turn intersection and 270 Degree right turn freeway onramp. Furthermore, RA&C demonstrated small but statistically significant influence on the driving behavior of RA&C, with acceptance of both fleet management and the drivers.

The FOT has demonstrated that RA&C has the ability to modify behavior and, thus can influence driver behavior and reduce rollover accidents; however, it cannot prevent all rollovers, or replace good driver judgment.

The picture seems to be generally encouraging with respect to the potential of RA&C-like devices, particularly in light of the fact that the subject device evolved and was improved upon during and as a result of this FOT. The drivers who participated were a rather mature and experienced group. Subjectively, the drivers appeared to embrace the utility of RA&C but, at the same time, reported that it had only “some or little” influence on their driving. However, they thought the system would work well with inexperienced drivers. Some of the driver comments were: system simple to understand, messages were clear and legible, minimal distraction while driving, system did not account for loading and such capability would enhance value of system, too sensitive, and generally encouraging potential for RA&C technology.

Freightliner and Meritor WABCO have made modification to the RA&C system outside of the FOT. The modification improved the mass estimator, thresholds for advisory and control, and service brake activation on the tractor-trailer was added as an additional feature to prevent rollover.

While quantitative results of Roll Advisor and Control were not overwhelmingly dramatic, there was statistical significance on driving behavior. RA&C is currently available on a limited basis with plans to offer the system in additional product applications. Freightliner has built additional vehicles for Praxair and other customers with RA&C since the FOT was completed.

Best tracking performance 96.3% occurred for vehicle speeds in the range of 80 to 100 kph. The Lane Guidance system proved to be 87-96% accurate in tracking at vehicle speeds of 60 to 100 kilometers per hour. The lane guidance system performs best when the driver is potentially least attentive, during the night and early morning hours with cruise control engaged at highway speeds, and during dry conditions. Lane guidance is currently available to customers in several commercial truck applications.

Proprietary analysis of the GPS data collected during the FOT resulted in three-dimensional maps many times more accurate than currently available data. Road Maps were generated to within one-centimeter accuracy from FOT Data. Furthermore, the predictive techniques evaluated using this data, as compared to actual Roll Control events, proved to be reliable in predicting a rollover 10 seconds before it actually occurred, with less than 1/3 of a second deviation. Thus, it is possible to provide enough advance warning to avoid dangerous situations with this technique. Better prediction may be possible with more sophisticated model refinements. It may also be possible to project speed and lateral acceleration with only ten passes. Predictive Technologies including advanced road mapping is still being developed with the anticipation of commercial applications in the near future.

8.0 CONCLUSIONS & RECOMMENDATIONS

Federally funded field tests such as this create a true partnership between government and industry helping to improve the safety and efficiency of America's transportation system. The large volume of data collected provided the information necessary for a thorough analysis. However, this large database offers very significant potential value for further studies. The exponential improvement in mapping accuracy and its future application in preventive technology is just one example.

Because of the nature of the FOT methodology necessary to evaluate the potential benefits of the RA&C, modifications and improvements to the systems were necessarily not allowed. Unfortunately, this also does not allow the opportunity within this program to evaluate the incremental benefit from improvements to the system. The controlled environment does not allow for a broader scale analysis of the safety benefits in a greater variety of applications. For these reasons some the Freightliner team would recommend the following:

- Capture Praxair Management Feedback on System Value to correlate to driver studies
- Broader scale deployment of the technology to other Truck/Trailer combinations; other regions of country; and to a less experienced driver set
- Collect and analyze additional Data in Praxair Fleet Operations at LaPorte, Indiana used in the FOT with system improvements in place.
- Advance the Predictive Technology for Roll Warning and Control to On-Vehicle Testing

The FOT provided greater understanding of potential benefits to the safety of U.S. highways through accelerated deployment of Roll Advisory & Control Technology. The OEM, supplier, and customer partners in the test firmly believe the project has been a tremendously valuable exercise. They see significant potential benefits to the safety of America's roadways, minimizing inconvenience to motorists from rollover accidents and the costs in terms of damage to the nation's infrastructure, to say nothing of fewer injuries and deaths.