INFLUENCE OF A ROLL-STABILITY ADVISOR ON TURNING PERFORMANCE OF TRUCK DRIVERS

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ABSTRACT

The influence of a rollover advisory system on a driver's lateral performance was investigated in a field operational test in which baseline driving (prior to the introduction of the advisory system) was compared to driving following the advisory system's introduction. Using a multifactor analysis approach, vehicle load state (empty vs. full), weather conditions, ambient light level, and turn direction were all found to reliably influence the driving performance of each driver. Notably, the magnitude of these environmental factors were somewhat dwarfed by the magnitude of variation between drivers. No main effect of the advisory system on overall lateral performance was found, although there was some suggestion that the influence of the advisory system may be restricted to situations when rollover risk is greatest: in clear weather, on high-severity curves, during right turns. In a more restricted analysis, a driver's curve performance 250 km before and after an advisory was compared. Drivers exhibited reliably lower rollover ratios after a rollover advisory was issued, suggesting that an advisory may affect performance in the interval directly following the advisory.

INTRODUCTION

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

The system whose influence was studied was an early prototype version of RA&C, jointly developed by Freightliner and Meritor WABCO. This version of RA&C 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 recorded 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). A second companion paper describes the exposure of the fleet (i.e., travel time and distance, loading, speed, road type, day/night, weather, etc.) and characterizes the overall lateral performance of the fleet and of individual drivers (Winkler, Sullivan, Bogard, & Hagan, 2004).

THE RA AND C SYSTEM[1]

The RA&C studied in the field test was a composite system whose primary elements were Roll Stability Advisor (RSA), Roll Stability Control (RSC), and Hard Braking Event Detection (HBED). Each of these

[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 test vehicles during the period of the study (Winkler, et al., 2003; Bogard, et al., 2004). Changes and improvements made to RA&C since that time can not be addressed.

systems provided advisory messages to the driver via a Driver Message Center (see Figure 1). Advisory messages were accompanied by an audible tone.

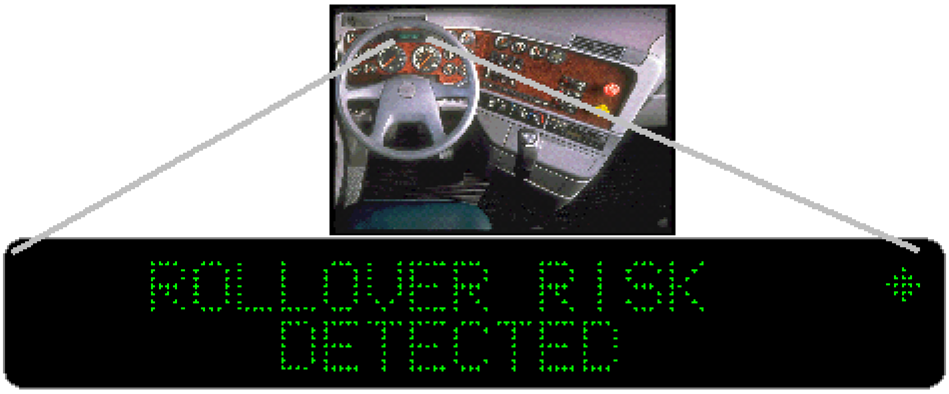

Figure 1. The driver message center. (Figure provided by Freightliner.)

- RSA was an in-cab training aid that presented an advisory message to the driver whenever the system observed conditions judged to have presented a significant risk of rollover. The intent of RSA was to modify driver performance through training; RSA was not a rollover-warning device. Accordingly, RSA messages were not delivered immediately upon detecting a risk of rollover but were delivered a short time after the risk had subsided. There were three levels of RSA advisories that communicated increasing severity with increasing risk of rollover. Increasing severity was implied through the wording of the message, the length of display time, and the duration of the audible alert.
- RSC was an active control system intended to prevent rollover. When RA&C detected an exceptionally high risk of rollover, it sent 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 was delivered simultaneously with RSC control.
- HBED, like RSA, was a training aid that advised the driver when an unusual braking event had been detected. There were three levels of HBED advisories.

THE OPERATIONAL ENVIRONMENT

The RA&C field test took place within the naturalistic context of everyday operations of the facilities of Praxair Corporation in La Porte, Indiana. Six, five-axle tractor-semitrailer vehicles, each composed of a Freightliner Century Class, day-cab tractor hauling a Praxair cryogenic, liquid-nitrogen semitrailer, made up the test fleet. Twenty-three individuals drove the test vehicles during the field test in a so-called slip-seat operation. Operations took place primarily in northern Indiana, northwest Illinois, and throughout the lower peninsula of Michigan. The field test began in November, 2000, and ran through November, 2001. During that time data were 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 travel was on freeways.

RA&C was activated in June of 2001. Total travel time and distance were split rather evenly between the two phases of the experiment. Most other physical-exposure variables were reasonably well balanced across phases with some notable exceptions. Phase 1, as would be expected, had more travel in bad weather and more in darkness. The average length of a trip remained nearly equal from phase to phase, but the mix of delivery points changed due to market influences. Most importantly, the mix of drivers changed between phases. Some drivers left the study altogether, and among the fourteen drivers who participated in both phases and whose driving was used in the analyses, the relative amount of travel by the more conservative and the less conservative drivers changed slightly.

THE EXPERIMENT[2]

The RA&C FOT was primarily a human-factors experiment that addressed the questions of whether or not the introduction of RA&C brought about objectively identifiable changes in either (1) drivers' behavior in negotiating turns or (2) the actual risk of rollover incurred during turns.

These questions were addressed primarily through multifactor analyses in which the basic comparison made was between an individual's performance before the system was activated (during phase 1), and that same individual's performance after the system was activated (during phase 2). Separate measures were used to characterize turning behavior and actual risk of rollover. Results from comparisons between individuals were pooled to determine overall statistical reliability across individuals. Several other factors were also included in the analyses to help isolate the effects resulting from the presence of the RA&C.

Notably, the method specifically addressed the system's effect driver-by-driver, not its effect on the aggregate behavior of the fleet or even the aggregate behavior of a subgroup of drivers. As is pointed out in Winkler, et al., 2004, the difference in turning performance among drivers was very large. Thus, a substantial change in the aggregate behavior of the fleet could take place due to a change in the mix of drivers (because of layoffs or new hires) or even due to just a change in the proportional contributions of specific individuals. And, of course, changes in the mix of other situational factors such as routing, loading condition, weather, light condition, turn direction, and curve severity could produce observable changes in aggregate performance. To conclude that RA&C modified driver performance, it was necessary to observe a relatively consistent influence on individual drivers operating in similar driving situations.

Before describing the results of the analyses, a brief review of major components of the experimental design is presented.

The subjects

Twenty-three drivers participated in the field test. They 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).

Data from fourteen drivers, called the comparable drives, were included in the final analyses. These individuals participated throughout the entire study. (Eight individuals left the driver pool during the course of the study. One driver was also excluded from the analysis because of comparatively small amount of driving distance.) The fourteen comparable drivers averaged 41,400 kilometers during the field test. During phase 2, these fourteen drivers received a total of 278 RA&C messages, or an average of about 20 messages per driver. The types of messages were distributed as shown in Table 1.

Table 1. Counts of RA&C messages received by the fourteen comparable drivers.

RSA 1	*RSA 2*	*RSA 3*	*RSC*	*RSA/RSC total*	*HBED 1*	*HBED 2*	*HBED 3*	*Grand Total*
174	50	5	24	253	25	0	0	278

The dependent variables: AyDSM and RRSM

In the analyses whose results are presented here, the dependent measures used to characterize (1) driver performance in turns and (2) actual rollover risk in turns were the maximum sustained values of lateral acceleration at the driver's position (AyDriverSustMax or AyDSM) and of rollover ratio (RollOverRatioSustMax or RRSM), respectively.[3] These variables are explained in detail in Winkler, et al., 2002.

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[2]This section briefly presents the primary elements of the filed test experiment. These subjects are addressed in more detail in Winkler, et al. (2002) and in the two companion papers, Bogard, et al. (2004), and Winkler, et al. (2004).

[3]Analyses were also performed using other forms of lateral acceleration and rollover ratio as well as more speculative dependent measures including curve-entry speed, deceleration rate, and braking behavior. Results were either null or essentially the same as reported here (Winkler, et al., 2002).

We note here:

- Since rollover was the primary concern and since the cross slope of the road influences rollover, "lateral" acceleration herein is considered to be the component of vehicle acceleration perpendicular to the longitudinal axis of the vehicle and parallel to the road surface, including the component of gravity parallel to the road surface.
- Rollover ratio is the ratio of the composite lateral acceleration of the vehicle (i.e., the weighted average of lateral acceleration of the centers of gravity of tractor and trailer) to static rollover threshold of the vehicle (as loaded).[4] A lateral acceleration of zero implies a rollover ratio of zero; a lateral acceleration equal to the rollover threshold of the vehicle implies a rollover ratio of unity.

In the analyses, AyDSM is used to ask the question "Was driving behavior altered by the RA&C?" RRSM is used to ask the question "Does the presence of RA&C reduce the actual risk of rollover." These measures were determined for each pass made by the 14 comparable drivers through a set of some 1726 curves.[5] To be included in this set, it was necessary that the particular curve be traversed multiple times by multiple drivers in both phase 1 and phase 2 of the study.

The independent variables

The principal independent variable in this study was the absence or presence of RA&C expressed in the analyses as the influence of Phase. That is, Phase 1 refers to the initial period of driving without RA&C and Phase 2 to the subsequent period of driving with RA&C active. To permit adequate "learning" or "break-in" exposure to the RA&C, the first 5000 kilometers of phase-2 driving for each driver were excluded from the basic analysis. This number was selected based on inspection of normalized advisory rates among drivers.

Several others factors that were considered likely to influence driving behavior in turns were also included in the analysis. These factors include seasonal influences that could be expected to function as confounds of the primary variable, phase, and non-seasonal factors expected to influence turning behavior.

The factors were:

- Weather: good or bad. Good weather required more than 2 km visibility and wiper use of less than 1 percent during 15 minutes before and 15 minutes after the turn.
- Lighting: day or night. Lighting was considered "night" when the sun was 6 or more degrees below the horizon.
- Load: empty or full. The vehicle was considered empty when total mass was less than 17 metric ton and full when total mass exceeded 33 metric ton. (Partial loading, i.e., between full and empty, was not included as less than 15 percent of all driving took place in this state.)
- Direction of turn: left or right. This variable was included because the data showed a substantial bias favoring turns to the right as well as more severe turning to the right.
- Curve severity: four quartiles. Curves were binned into four quartiles of severity. Severity was determined separately for lateral acceleration and rollover ratio. In both cases, the measure of severity derived from the mean value from all passes through that curve by the non comparable drivers (i.e., drivers not in the analyses) during phase 1 (i.e., before RA&C was introduced). Severity was determined separately for the full and empty conditions. (Curves taken often when full tended to be different than those taken often when empty.) Curve severity was considered an important factor since it seemed likely that it could affect the amount of influence RA&C might have on driving behavior. That is, one can readily imagine that RA&C might exert greater influence on curves of high severity than on curves of low severity. Moreover, the changes in seasonal and market influences between phases were known to produce some change in the mix of routes such that it was possible that the aggregate severity of turning could well have been greater in one phase than another. Thus, the severity of each curve used in the analyses was determined, and curves were then pooled into four quartiles.

Exploratory statistics versus testing of explicit hypotheses

Finally, the reader should be aware that the statistical tests undertaken and, in part, reported herein were an exploratory effort to discover relationships between variables in the data. This deviates from the more

[4]Rollover threshold was determined by tilt-table tests of one of the test vehicles.

[5]More than 6000 individual curves with a total of more than 184,000 passes, were initially identified in the data set.

rigorous use of statistics wherein specific targeted hypotheses are formulated well before data are collected and only those hypotheses are examined. Instead, for this field test, much of the investigation was driven by what was found by examining the data. Thus, much of the analysis is effectively post hoc in nature. In general, formal post hoc analysis methods require use of a Bonferroni adjustment in establishing the significance criteria and, consequently, typically hold data to stricter criteria than the 5 percent (0.05) criterion used here. Consequently, results reported herein should be viewed primarily as evidence suggestive of trends and, perhaps, as guidance for future investigation.

INFLUENCE OF RA AND C ON PERFORMANCE IN CURVES

This analysis related measured performance of comparable drivers on curved sections of roadway (the dependent variables) to levels of the independent variables using a repeated-measures analysis of variance. The resulting F-ratios, calculated for each factor, indicate the magnitude of association between each factor and the dependent variable. The data set employed was that for comparable drivers, in ranked curves, with empty or full vehicles, and without cruise control engaged.

Light level was excluded from the first analysis because of a large number of empty cells (i.e., with no observations) for driving in darkness. In a second analysis, only the factors light condition, load, and phase were retained and data were collapsed over the remaining factors in order to pool sufficient data to obtain estimates for each driver in the dark.

Main effects

Main effects on both measures of turning performance, AyDSM and RRSM, were observed for weather, load, turn direction, light condition and curve severity, but no significant main effect of phase (i.e., RA&C) was observed. Table 2 summarizes the statistics for main effects as derived from the two analyses (i.e., excluding and including lighting condition). Figure 1 illustrates the magnitude of the effects of load, turn direction, weather, light conditions, and phase on driving performance.[6] For comparison, the figure also illustrates the size of the difference between the least and most conservative driver.

Table 2. Summary of statistics for main effects on observed RRSM and AyDSM.

	Statistics for AyDSM			*Statistics for RRSM*		
Factor	*F*	*df*	*p*	*F*	*Df*	*P*
1. Lighting condition excluded						
Weather	64.41	1,13	< .0001	89.92	1,13	< .0001
Load	43.68	1,13	< .0001	115.81	1,13	< .0001
Turn Direction	10.61	1,13	.006	4.94	1,13	<.05
Curve Quartile	417.92	3,39	< .0001	389.00	3,39	< .0001
Phase	1.0	1,13	.335	0.01	1,13	.927
2. Lighting condition included						
Light conditions	8.24	1,12	.017	11.38	1,12	.006
Load	163.11	1,12	<.0001	88.60	1,12	<.001
Phase	1.80	1,12	.209	2.09	1,12	.174

As the figure shows, except for individual driving style, the largest effect on turning performance was found between driving a fully loaded trailer and an empty trailer. In particular, we note that although drivers reduced the magnitude of lateral acceleration generated when driving a full tanker, this was insufficient to compensate for the increased rollover risk as measured by RRSM. While drivers appear to be attuned to the differences in vehicle stability created by changes in load, this awareness may not be sufficiently precise to fully mitigate the added risk.

[6] Although a strong main effect of curve quartile is also found, it is less interesting since the curves were sorted into those quartiles based on the *AyDSM* and *RRSM* performance measures of the non-comparable drivers. The meaning of the main effect is simply that the drivers in the experimental group performed like the non-comparable drivers on these curves.

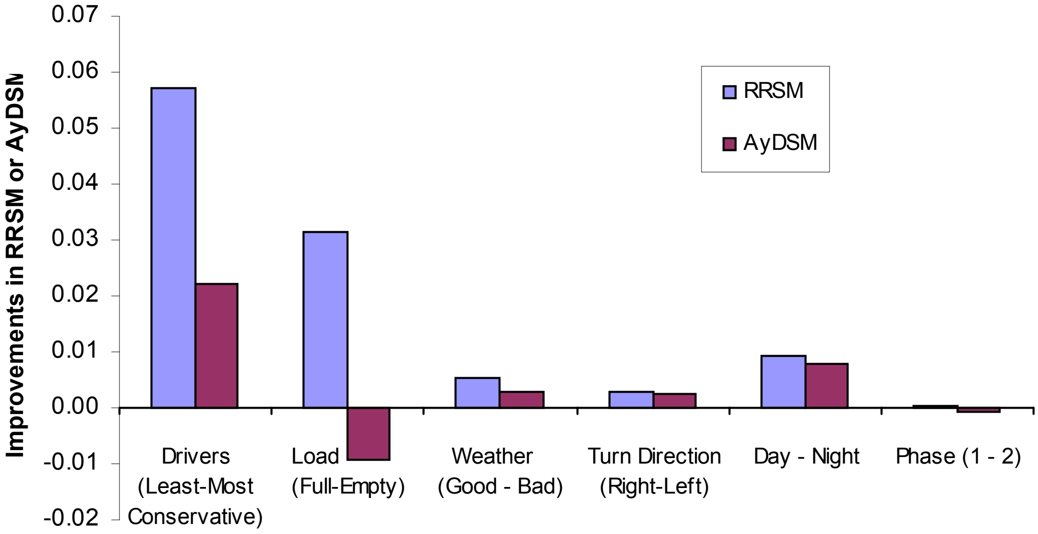

Figure 1. Comparison of the main effects of the various factors on AyDSM and RRSM.

Unlike load, the effects of weather, turn direction and light conditions on AyDSM and RRSM were of the same polarity: measures of AyDSM and RRSM were lower in good weather than in bad weather; they were lower in left turns than in right turns; and they were lower in darkness than in light. Perhaps drivers use added caution in bad weather resulting in the traversal of curves at lower speeds. The reduced forward preview in dark conditions may likewise encourage added caution. However, it is less clear why right turns appeared to produce modestly higher measures of AyDSM and RRSM. Perhaps drivers' perception of lateral force or lateral rollover risk is affected in an asymmetric fashion.

Figure 1 shows virtually no difference between phase 1 and phase 2 driving performance, suggesting that if such an influence exists, it is likely far smaller than the effects produces by the other factors.

These differences due to various physical factors are all somewhat dwarfed by the magnitude of the difference between the least and most conservative of the drivers.

Interaction effects

It would be a mistake to exclusively search for an influence of the RA&C in the main effects since this assumes that the RA&C exerts its influence uniformly under all conditions. Instead, it is plausible to consider that the device's influence might interact with a variety of conditions. For example, the influence of bad weather on a driver's performance may completely overshadow any effect of the RA&C so that all bad-weather performance is maximally conservative regardless of the presence of the device. Likewise, a driver may adopt a maximally conservative driving strategy under fully loaded conditions. Consequently, the RA&C advisory system may only be influential in certain "enabling" circumstances—circumstances in which other reasons for driving conservatively do not overshadow the influence of the device.

Table 3. Significant and marginal two and three-way interactions observed for RRSM.

Two-way Interactions	*F*	*df*	*p*
Weather by Curve Quartile	14.36	3,39	<.0001
Load by Curve Quartile	33.77	3,39	<.0001
Turn Direction by Curve Quartile	5.48	3,39	.012
Three-way Interactions			
Load by Turn Direction by Curve Quartile	18.55	3,39	<.0001
Phase by Turn Direction by Curve Quartile	4.06	3,39	.023
Phase by Weather by Curve Quartile	3.34	3,39	.043
Phase by Weather by Turn Direction	4.97	1,13	.044

There is a weak suggestion among some of the three-way interaction effects that a phase effect might exist under certain circumstances, although the magnitude of the effect is slight. For example, in Table 3 there appears to be an effect of phase coupled with turn direction and curve quartile suggesting that the strength of the RA&C effect is greatest on right turns for the most severe turns. In fact, many of the interactions with curve quartile reasonably suggest that we are most likely to observe changes on the most severe right-hand curves during good weather. An example of a three-way interaction is shown in Figure 2. One interpretation of this plot is that the RA&C device has no influence on driving in bad weather conditions, and even in good weather, its influence is strongest in only the most severe curves. The overall pattern of interactions fit an expected pattern: that the introduction of RA&C induces performance that reduces rollover risk where rollover risk would otherwise tend to be high, i.e., in more severe curves (higher quartiles and right-hand turns) during good weather. Having made that observation, it should also be noted that the evidence is not all that strong. The sizes of the observed reductions are not large, and the probabilities that the observations are significant are not sufficiently strong to overcome a Bonferroni adjustment for post-hoc tests. (Appropriate p values would have to be an order of magnitude smaller than they are in Table 3.) Indeed, given the relatively modest degree of exposure many of the drivers had to the RA&C (nine of the drivers received 10 or fewer advisories; five received fewer than 3 advisories), it is surprising that the any effect is observed and advisable to be cautious in drawing firm conclusions about the system's efficacy.

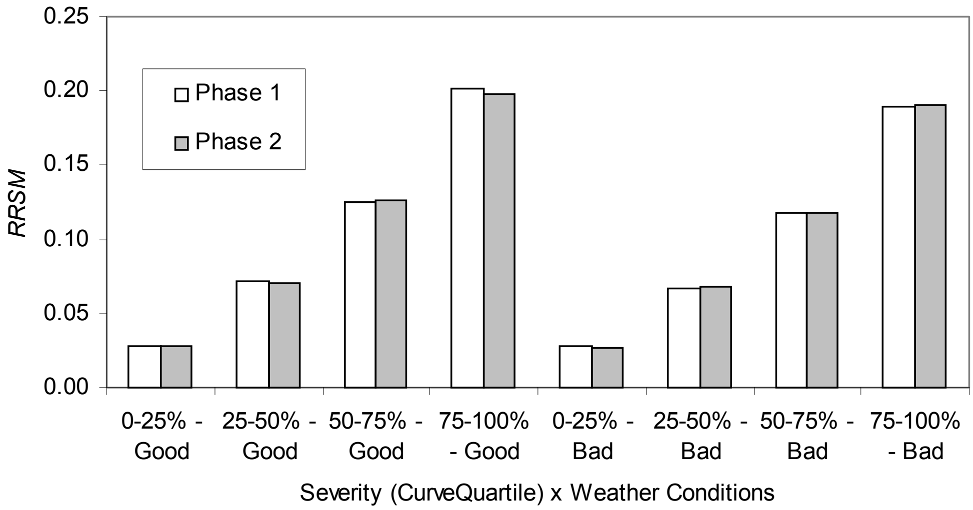

Figure 2. Three-way interaction between phase, weather, and curve severity.

Curve performance before and after advisories

A secondary analysis examined the curve performance of drivers as indexed by RRSM and AyDSM before and after an RA&C advisory message was received. That is, given that a driver receives an advisory, is driving performance altered in near proximity to when the advisory is issued.

To do this analysis, each curve on which an advisory occurred was identified. Subsequently, curve performance in three distance ranges (250, 500, and 750 km) preceding and following each advisory were evaluated. The change in performance across these two ranges was then analyzed. The range from 1 km before to 1 km after the advisory was always excluded from this analysis. Only performance on higher-severity curves (i.e., in the third and fourth RRSM quartile) and in good weather was used. Only 12 of the drivers were included in the analysis because two drivers received no advisories throughout the study.

Main effects of load and advisory exposure (before/after) were observed for both AyDSM and RRSM; no interaction between load and time of exposure was observed. Driving performance appeared to be more moderate in the 250 km following an advisory. The mean reduction was approximately 0.005 g across all drivers; the mean reduction in RRSM was 0.009 across all drivers ($F_{1,10} = 14.85$, $p < .003$). Similar results were obtained in analyses of the 500 km intervals and the 750 km intervals with the mean reductions shown in Figure 3. The figure shows that the influence of the advisory is diminished as the analysis interval widens around the advisory. This result was the most reliable effect found for the RA&C system.

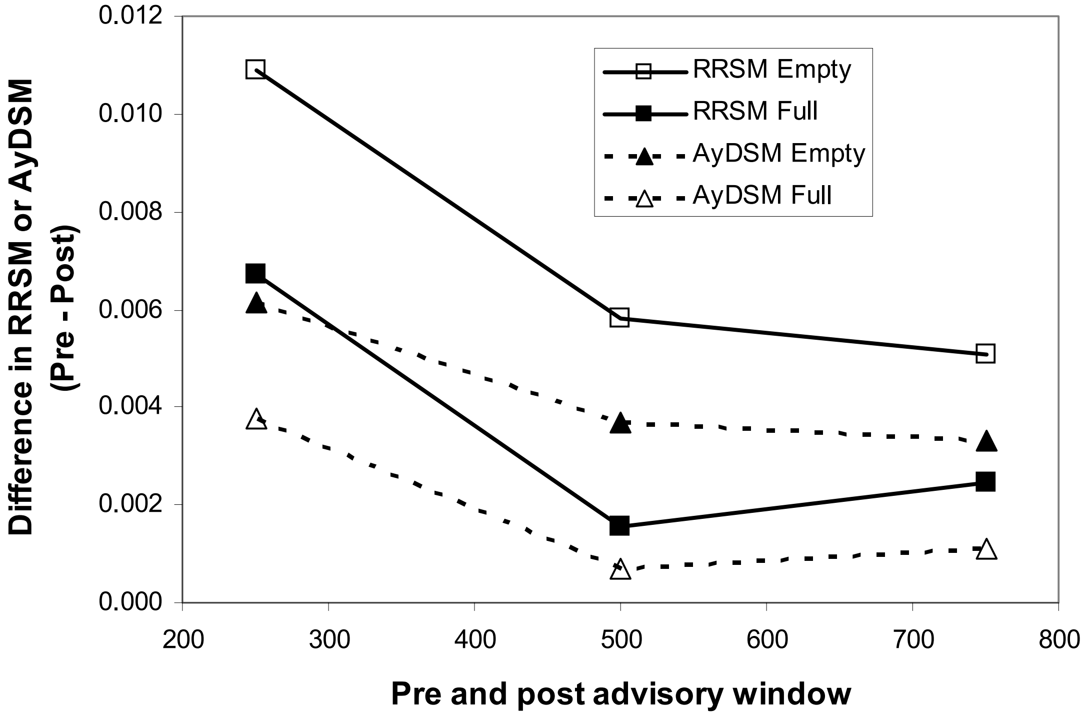

Figure 3. Reduction in RRSM and AyDSM following an RA&C advisory.

SUMMARY

This paper describes an investigation of the influence of a Roll Advisory and Control system (RA&C) on drivers' lateral performance in a real-world field operational test. An analysis approach was employed in which driving performance was compared within drivers, controlling for variation between drivers. In addition, the analysis tracked and controlled several environmental factors like vehicle load state (empty vs. full), weather conditions, ambient light level, and turn direction. These factors were all found to reliably influence the driving performance of each driver. Notably, the magnitude of these environmental factors were somewhat dwarfed by the magnitude of variation between drivers.

No main effect of the advisory system on overall lateral performance was found, although it seems plausible that the advisory system would exhibit its strongest influence in conditions in which rollover risk tends to be high: in clear weather, on high-severity curves, and during right turns. Some modest interaction effects were found that were consistent with this expectation. A secondary analysis revealed a more robust, albeit localized, influence of the advisory system on driving performance immediately after delivery of an advisory message. Thus while the evidence for a broad influence of the RA&C on driving behavior is weak, there is some evidence that drivers alter their performance in the short term in response to an advisory.

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