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A Simple Differential Brake Control Algorithm for Attenuating Rearward Amplification in Doubles and Triples Combination Vehicles

C. MacADAM*
M. HAGAN

SUMMARY

A simple brake control algorithm useful for attenuating rearward amplification tendencies in doubles and triples combination trucks is described. The basic goal was to first design, and then to demonstrate through experimental testing, an automatic brake control system that could intervene — only when needed — to help suppress unwanted trailer yaw oscillations (commonly referred to as 'rearward amplification') in large combination vehicles (typically doubles and triples combinations in the U.S.). The system would only be enabled for highway speed operating conditions, and if possible, so simple that the system could be provided on a trailer-by-trailer basis. That is, the proposed system, when implemented on a particular trailer within a combination vehicle train, would not have to depend upon sensor information from units ahead of it or behind it in order to function properly and yet provide significant benefit. The primary focus therefore of this work was on the development and demonstration of a so-called "trailer-only" RAMS (**R**earward **A**mplification **S**uppression) system [1].

1. INTRODUCTION

A principal aspect of the algorithm development and associated control system [1] was the practical need to "keep it simple," thereby facilitating the implementation and potential adoption of a RAMS functionality (and its associated vehicle outfitting) by the truck and trailer user community. Thus, the emphasis here is on a "trailer-only" system. Furthermore, if the outcome of this work was successful at demonstrating the effectiveness of a practical and simple-to-implement RAMS system, then it was deemed likely that a follow-on field trial of the proposed system could be executed by a third party subsystem manufacturer (perhaps in partnership with the U.S. Department of Transportation) to evaluate the RAMS system in actual practice.

Key features of the described system are:

- the system is only enabled for vehicle speeds in excess of 21.5 m/sec (48 mph)
- it requires a single yaw rate transducer mounted on each semitrailer in order to provide sufficient control information to the algorithm
- information from each semitrailer yaw rate transducer allows the trailer-only RAMS algorithm to control brakes on its own semitrailer and on its associated dolly
- a communication link is required between each semitrailer and its own dolly unit (to monitor dolly wheel speeds and provide pressure commands to the dolly brakes)

* University of Michigan Transportation Research Institute

Emphasis is also placed on the importance of capitalizing on brake-steer compliance effects present in most heavy truck suspensions. These effects can provide beneficial *lateral* tire force components that further enhance and augment the usual trailer yaw damping moments associated with longitudinal braking forces accompanying differential brake control interventions.

The following Figure 1 shows a representative experimental result comparing roll angle measurements for a standard, no-RAMS triple combination vehicle (shown as test #272) and the same vehicle equipped with the newly developed trailer-only RAMS system (test #204) described in this paper. The roll responses correspond to a rapid 8-ft single lane-change maneuver conducted at 55 mph. Rollover of the standard, no-RAMS trailer configuration is only prevented by frame-mounted outriggers that contact the ground at a roll angle of about 11 degrees.

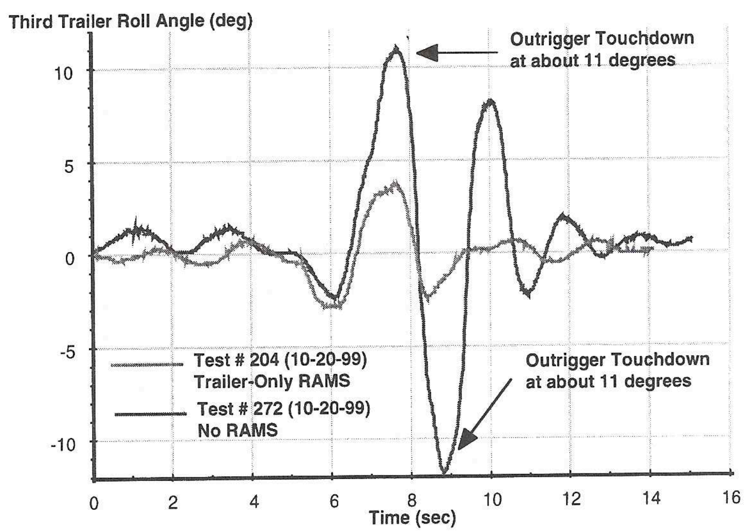


Figure 1. Comparison of the Measured Roll Response for the Third Trailer. No-RAMS vs. the Trailer-Only RAMS System – Test Runs #272 and #204.

2. BASIC VEHICLE CONFIGURATION

The baseline test vehicle used in this study was a triples combination utilizing 28-ft trailers. Haldex Corporation supplied the tractor unit, two semitrailers and one dolly. The U.S. Department of Transportation provided the remaining trailer and testing facility. The power unit was a 3-axle tractor having an approximate 20-ft wheelbase. When fully loaded, all axles but the tractor steer axle carried about 15,000 to 16,000 lbs of load. Figure 2 describes the basic configuration for the triples combination.

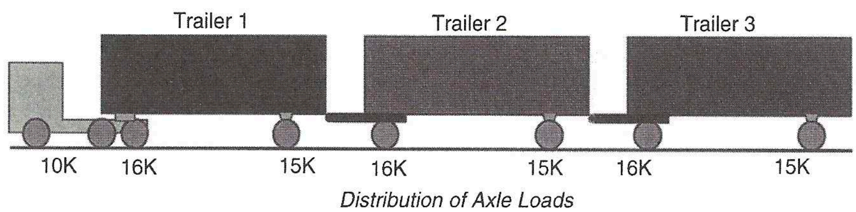
Air or steel leaf spring suspensions were present at the various axle locations. The last two trailers were also equipped with outriggers to prevent rollover of those units during testing. Payload heights were varied vertically in the last two trailers by means of adjustable load racks. Payloads were typically located in the range of 70 inches to 92 inches above ground for all tests. Payload height was fixed in the first semitrailer at about 70 inches above ground.

The Baseline Triples Description Used in the RAMS Testing

103 K Gross Weight

92" Payload Height in Trailers 2 and 3

70" Payload Height in Trailer 1



Trailers 2 & 3 and Dolly 2 Equipped with Air Suspensions

Trailer 1 and Dolly 1 Equipped with Steel Suspensions

Air Suspension on Tractor Rear

Trailers 2 and 3 Equipped with Roll Stabilization Outriggers

Figure 2. The Baseline Triples Combination Vehicle Used in the RAMS Testing.

The test vehicle was equipped with a variety of instrumentation for measuring performance. Forward speed was measured using an optical fifth wheel mounted on the tractor frame. Lateral accelerometers mounted on the tractor steering axle and on a Humphrey stabilized platform in the last trailer provided horizontal-plane measurements of lateral acceleration, thereby allowing calculation of normalized rearward amplification values (absent trailer roll influences). Yaw rate gyros were also mounted on each articulating unit of the vehicle train and included the tractor, each semitrailer, and each dolly unit. Roll angle information for the last trailer in the vehicle train was obtained from the stabilized platform located approximately in the mid-center region of the trailer. Driver steering wheel displacement was also measured by a rotary potentiometer mounted on the tractor steering column. Brake line pressures and wheel speeds for each wheel location were provided by the Haldex electronic brake control system hardware mounted on the vehicle. Figure 3 shows a photograph of the test vehicle.

3. TEST MANEUVER USED TO EVALUATE PERFORMANCE

A standard test procedure used to excite rearward amplification responses in combination vehicles requires a truck driver to perform a brisk 8-foot lane-change, or obstacle avoidance maneuver, at speeds typically above 50 mph. A path similar to that depicted in Figure 4 is laid out on a test course with markers and the truck driver attempts to track it as well as possible. The specific path description and definition can be found in reference [2].

Execution of this maneuver usually results in the tractor unit experiencing peak lateral acceleration levels (similar in shape to a single sine wave) in the range of 0.15 to 0.20 g's when traveling at 55 mph. Because of the inherent dynamics of these types of large combination vehicles operating at highway speeds, each subsequent trailer in the vehicle train will experience ever-higher peak levels of lateral acceleration than its preceding unit, normally producing a rearward amplification gain of more than 2.5 for the rearmost third trailer. For tractor peak lateral acceleration levels in the vicinity of 0.15 to 0.20 g's, this gain factor produces sufficient lateral acceleration at the last trailer so as to precipitate a last trailer rollover, particularly for loaded trailers having elevated mass centers.

Figure 3. Baseline Triples Configuration Used in RAMS Testing.

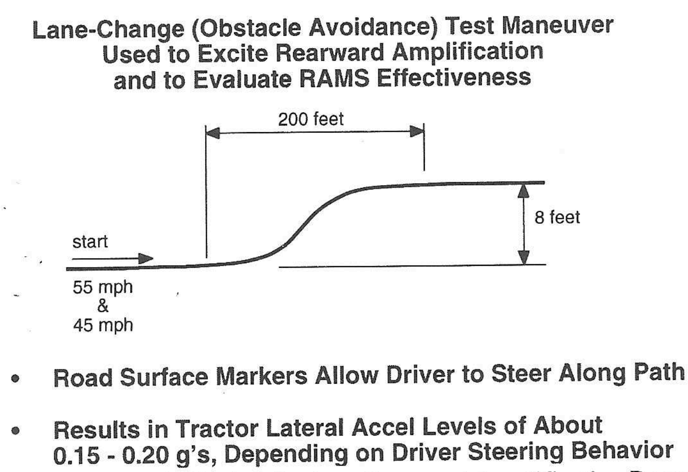


Figure 4. Lane-Change Path Used to Excite a Rearward Amplification Response.

4. CONTROL ALGORITHM AND ASSOCIATED SYSTEM

A variety of algorithm designs were considered and tested via computer simulation [3] and track testing within the study [1]. This paper reports on the best of the simple "trailer-only" algorithms examined in the overall study [1]. The basic rule ultimately used for detection and activation of a rearward amplification event was a simple threshold crossing by each semitrailer yaw rate signal. That is, a dead-zone region exists in which the yaw rate signal lying within this region is ignored and has no effect. (The yaw rate signal acts as an indicator of the level of motion present in the vehicle, and thereby is associated, at least indirectly, to a rearward amplification experience.) For excursions by the yaw rate signal beyond a specified threshold level, specific semitrailer and dolly brakes are then applied in proportion to the level of the sensor signal. For example, using a threshold value of 2.2 degrees per second (0.04 radians/sec), absolute values of semitrailer yaw rate less than 2.2 degrees per second will have no effect and the RAMS system is not active. However, if the semitrailer yaw rate signal exceeds the 2.2 degree per second threshold, brake pressures are applied to selected semitrailer and dolly wheels in proportion to the magnitude of the yaw rate sensor signal. Figure 5 shows such an example corresponding to test run #202.

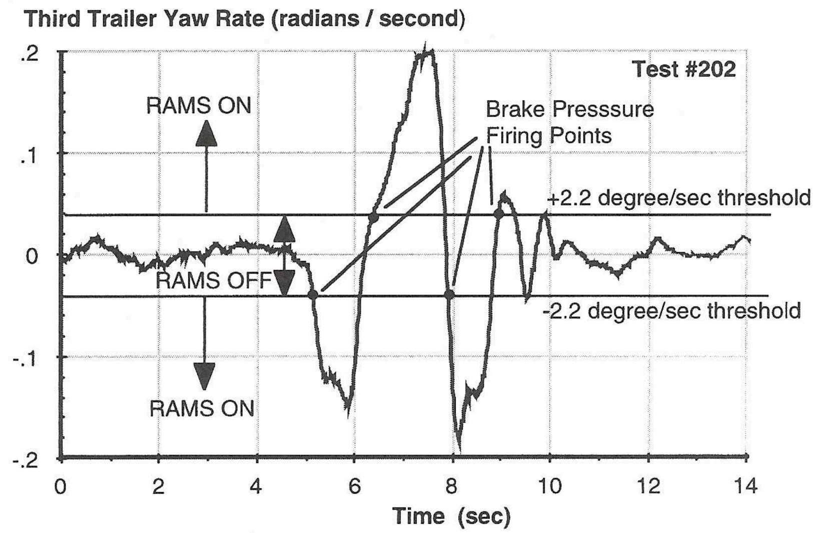


Figure 5. RAMS Activation Determined by Magnitude of Trailer Yaw Rate Signal.

Brake-Steer Compliance Effects

An important aspect of the RAMS design was to identify which brakes on the semitrailer/dolly combination should be activated during a rearward amplification event. Since the goal of the brake actuation was to achieve maximum yaw rate damping and initial analyses indicated that brake-steer effects present in most heavy truck suspensions undergoing side-to-side (differential) braking would be significant, a *diagonal* braking scheme was indicated to be the most effective means for achieving the desired result. The best diagonal braking design was to activate the dolly outside brake and the semitrailer inside brake during a RAMS intervention. The opposite diagonal brakes are simultaneously commanded to zero pressure. Figures 6 and 7 help to illustrate this basic mechanism and the influence of *lateral* as well as longitudinal tire forces on the associated semitrailer yaw moment.

As indicated in Figure 6, reasons for the effectiveness of the diagonal braking scheme — in which commanded brake pressure is applied to the dolly outside wheel during turning and the semitrailer inside wheel (with the opposing pair of wheels commanded to zero pressure) — are directly related to the presence of brake-steer compliance within the suspension. The brake-steer effect causes the axle on either the semitrailer or the dolly to be steered, relative to its mounting, towards that side of the vehicle on which a brake is being applied. The brake force applied on only one side of an axle allows a twisting of the axle due to bushing compliances present in the suspension linkages — typically a degree or more depending on the level of brake force applied. This modest level of axle steer produces accompanying *lateral* tire forces that then enter the picture as additional yaw damping influences that also contribute to the net moment acting on the trailer.

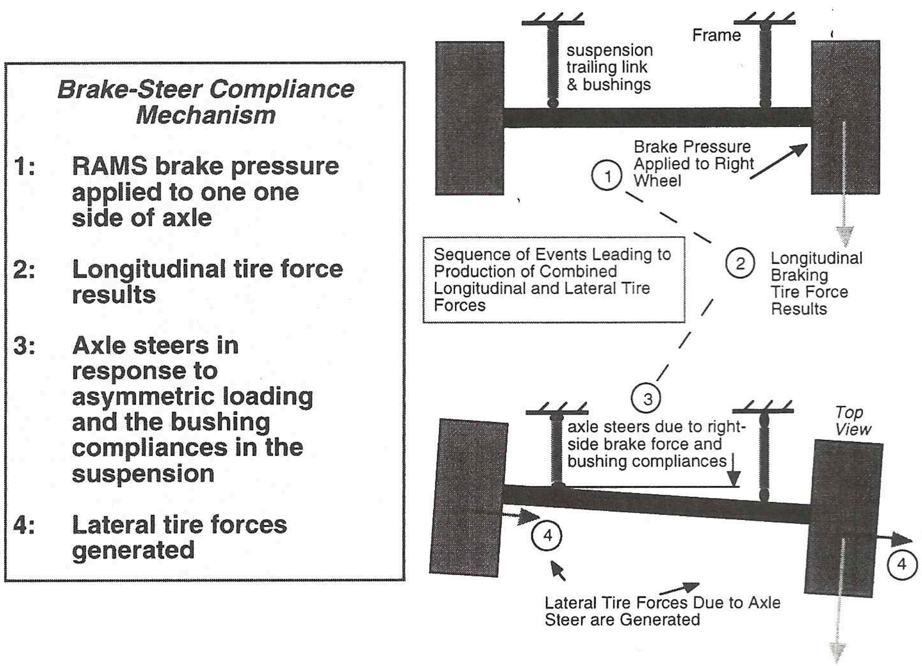


Figure 6. Brake-Steer Compliance Mechanism.

Consequently, as depicted in Figure 7, the complete yaw damping moment that acts on a trailer during a RAMS intervention is dependent upon not only the longitudinal tire forces produced by the asymmetric side-to-side brake pressure applications, but also by the lateral tire forces produced by the brake-steer mechanism responding, in turn, to those brake forces.

The RAMS processing module also takes into account the forward travel speed of the vehicle and only allows activation by the RAMS system for travel speeds above 48 mph. This feature of course recognizes the fact that rearward amplification in combination vehicles is only a problem at higher speeds, thereby only allowing arming or activation of the RAMS system under these operating conditions.

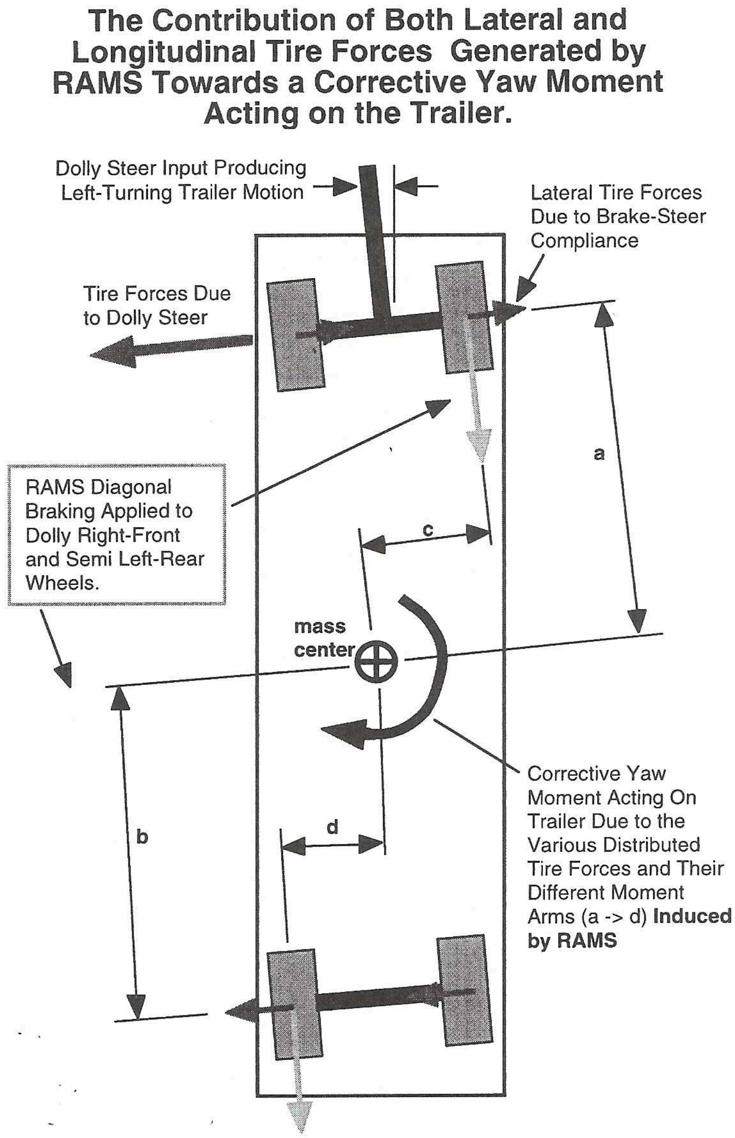


Figure 7. Corrective Yaw Damping Moment from Trailer-Only RAMS System Employing Diagonal Braking.

A summary of the simplified trailer-only algorithm that utilizes semitrailer yaw rate as the sensor signal and that is activated only for vehicle speeds above 48 mph is seen in Figures 8 and 9. As noted in the summary example, the specified threshold for RAMS activation is 2.2 degrees per second of yaw rate (corresponding to 0.1 g's of lateral acceleration at a speed of 55 mph). A brake gain of 30 psi per degree/second of yaw rate is also specified. Figure 9 shows the communication links that are required in order to process individual wheel speed signals from the ABS units to estimate forward vehicle speed and from the semitrailer yaw rate gyro to determine whether or not RAMS braking should be activated.

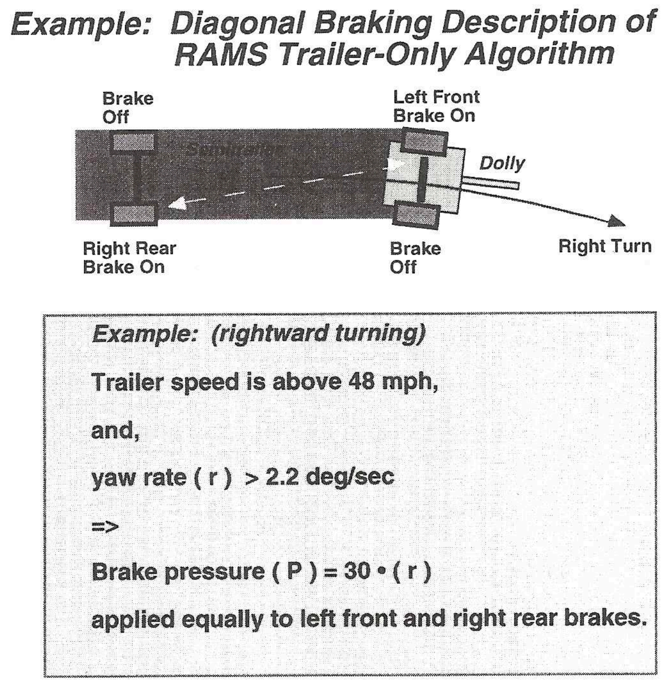


Figure 8. Example Operation of a Trailer-Only Algorithm Utilizing Semitrailer Yaw Rate as its Sensor Signal.

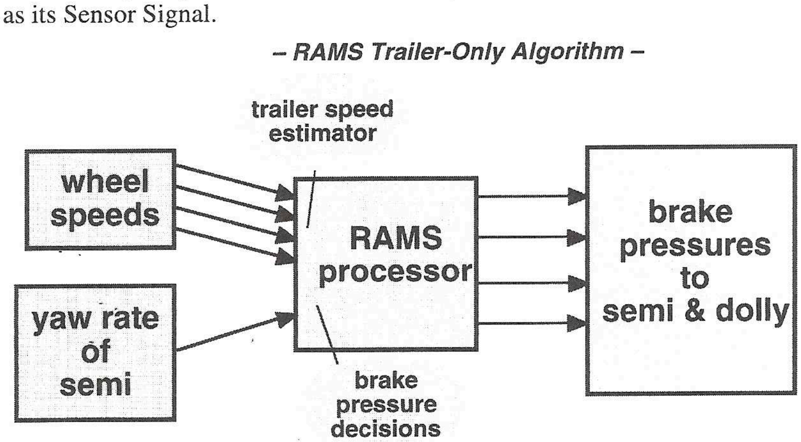


Figure 9. Use of ABS Wheel Speed Signals to Estimate Forward Speed and Semitrailer Yaw Rate to Activate RAMS Braking.

5. EXAMPLE RESULTS

The set of plots seen in Figure 10 corresponds to the non-RAMS triple with a payload height of 88 inches above ground (test #253). Rollover of the last trailer easily occurs in this run, as indicated by the outrigger touchdown at roll angle values around plus and minus 10 degrees. Initial speed is just above 55 mph. The rearward amplification phenomenon is clearly evident in the other lateral acceleration and yaw rate responses for the tractor unit and the last (3rd) trailer unit. Peak values achieved by the last trailer unit are more than 2.7 times larger than the corresponding tractor values in both of these vehicle response plots. (At a speed of 45 mph, the rearward amplification phenomenon is largely absent, indicating a 'safe harbor' effect with regard to vehicle speed, as well as a strong sensitivity to speeds above 45 mph.) Plots utilize the SAE sign convention, except for roll angle, which has an opposite polarity.

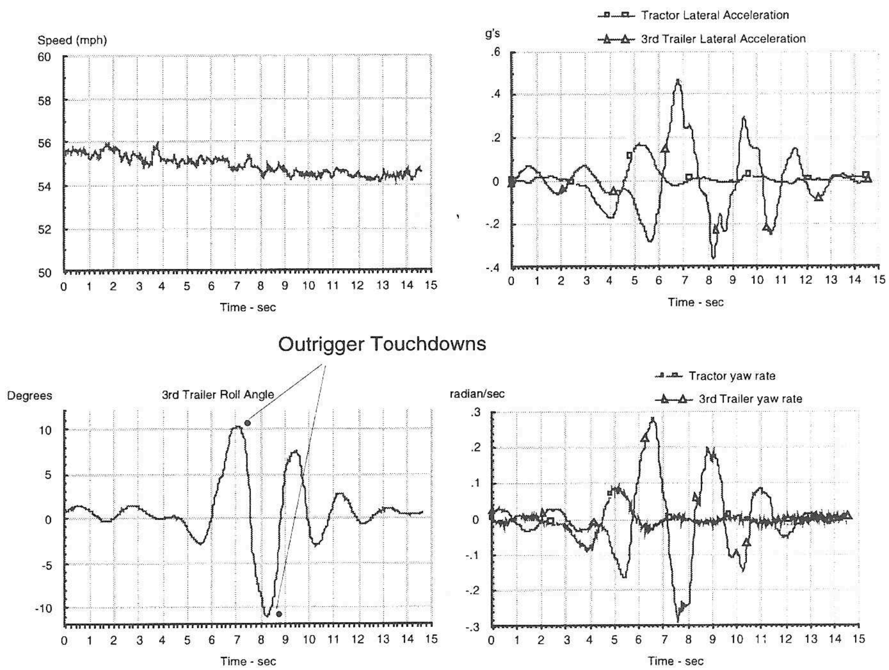


Figure 10. Representative Non-RAMS Test Result for the Triples Combination at 55 mph and an 88-inch Payload Height.

The time history results seen in Figure 11 correspond to the same vehicle and test conditions, but with the simplified trailer-only RAMS system now active and utilizing diagonal braking. As seen in Figure 11, vehicle speed falls off during the course of the run due to the RAMS system intervention that causes various diagonal sets of brakes to be applied intermittently at different trailer wheel locations (i.e., semitrailer and associated dolly pairs). The speed loss in this particular test run was about 10 mph, though 7 mph was probably a more commonly observed figure. Also seen in this figure is the corresponding roll response of the last trailer indicating a sharp reduction in peak value down to about 4 degrees of roll angle. Tractor and 3rd trailer lateral acceleration and yaw rate responses are also seen in this figure, corresponding to the same plots seen in Figure 10 for the non-RAMS configuration. The amount of rearward amplification, as reflected by the ratio of peak response values, has now been reduced to levels below 1.8.

The test results from the RAMS study [1] utilized two basic performance measures of rearward amplification to illustrate and document the performance obtained from the RAMS algorithm relative to the non-RAMS baseline configuration.

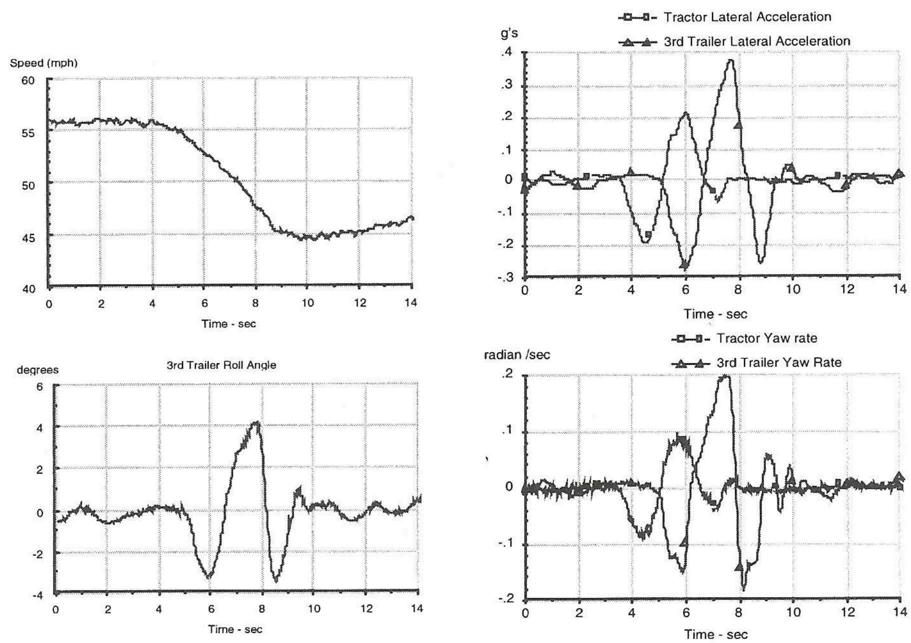


Figure 11. Representative Trailer-Only RAMS Test Result for the Triples Combination at 55 mph and an 88-inch Payload Height.

The first performance measure — *last trailer roll gain* — is defined as the peak roll angle achieved by the last trailer (during the defined test maneuver) normalized by the average peak lateral acceleration of the tractor unit (units of degrees per g). It indicates how sensitive the last trailer peak roll angle is to the level of average peak lateral acceleration generated by the tractor unit. For example a gain value for this performance index of 20 would suggest that the peak roll angle for the last trailer in the defined test maneuver would be 20 times the average peak tractor lateral acceleration of the tractor. Therefore, a tractor unit generating plus and minus lateral acceleration values of 0.18 g's in the test maneuver would be expected to produce a peak roll response at the last trailer of (20 x 0.18) = 3.6 degrees. This particular performance measure was found to correlate very well with the reaction of observers at the test track, as well as with the recorded videotape footage of individual vehicle tests afterwards.

The other performance measure used to characterize the rearward amplification is the traditional *rearward amplification gain* measure. This performance measure is simply the ratio of the peak lateral acceleration achieved by the last trailer unit to the average peak lateral acceleration level of the tractor unit. Like the last trailer roll gain measure, it is a measure of the sensitivity of the peak lateral acceleration developed by the last trailer relative to its lead tractor unit.

Figures 12 and 13 show results for these two performance measures for the triples combination operating on the dry asphalt test surface with a payload height of 88 inches. Figure 12 shows the last trailer roll gain measure versus several different RAMS algorithms examined in the overall study [1]. (The non-RAMS rollover cases are bounded by the maximum value of 60 — indicative of outrigger touchdowns — on this graph.) The algorithms are grouped according to whether they fall into trailer-only, trailer-to-trailer, or full-vehicle classifications [1] — each classification representing a more complicated algorithm and associated communication requirement along the vehicle. Each bar represents the average of 3 to 5 test run repeats. Figure 13 shows the corresponding results for the traditional rearward amplification gain performance measure involving the ratio of last unit to leading unit peak lateral accelerations. The simplified trailer-only algorithm described in this paper corresponds to the top bar in each graph labeled as 'Yaw Rate.'

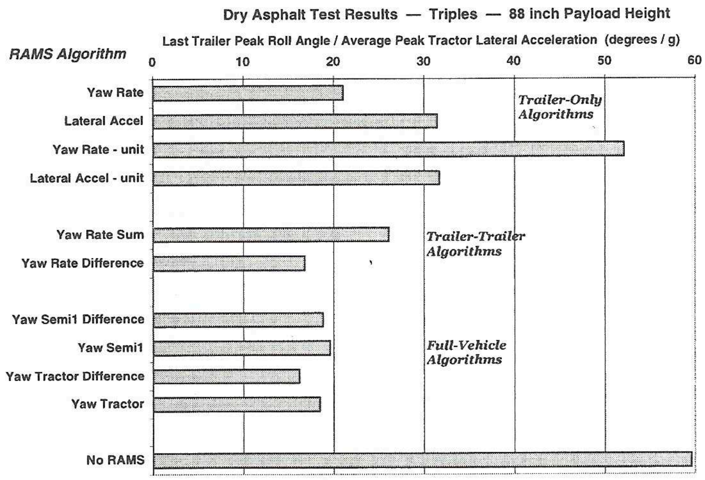


Figure 12. Last Trailer Roll Gain Performance Measure. Simplified Semitrailer Yaw Rate Algorithm ('Yaw Rate') vs. Other More Comprehensive Algorithms Examined Within the RAMS Study [1].

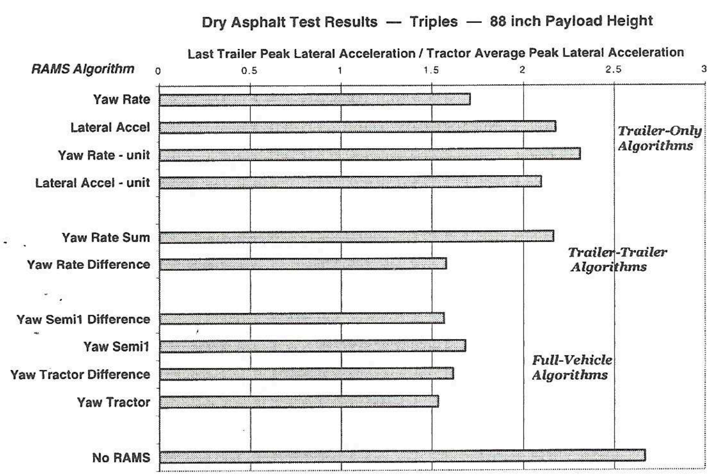


Figure 13. Traditional Rearward Amplification Gain Performance Measure Corresponding to Those Seen in Figure 12.

As indicated in Figure 12, the best RAMS algorithm (lower value) for the trailer-only algorithm classification is the 'Yaw Rate' algorithm with a value of 21.5. In the more complicated 'trailer-to-trailer' classification and 'full-vehicle' classification (described in reference [1]), the very best algorithm achieved a value of about 17.0. A similar but less discriminatory trend is seen in Figure 13 for the corresponding traditional rearward amplification performance measure. For the simplified trailer-only yaw rate algorithm, the traditional rearward amplification gain is seen to be reduced from 2.7 to 1.7, when compared to the unassisted no-RAMS configuration

Similar beneficial results were also achieved under heavy rain conditions on the same asphalt surface. However, one scenario under which no RAMS system was able to improve operating performance was for very low surface friction conditions (wetted jennite test surface, or presumably similar ice/snow conditions, with friction coefficients in the range of 0.1 to 0.3). Under such very low friction conditions where tire lock-ups occur more frequently and aggressively, the level of available longitudinal and lateral tire forces are sharply reduced due to the higher wheel slip conditions and limited friction of these surfaces, thereby lessening the role that such tire forces play as normal stabilizing influences or as intervening control force influences.

6. CONCLUSIONS

- A simplified *Trailer-Only RAMS System* has been developed and shown to be highly effective at reducing rearward amplification in double and triple trailer combinations on both dry (and wet) high friction surfaces. Key features characterizing its operation are:

1) the system is only enabled for vehicle speeds in excess of 48 mph
2) it requires a single yaw rate transducer mounted on each semitrailer in order to provide sufficient control information to the algorithm
3) each semitrailer yaw rate transducer allows the trailer-only RAMS algorithm to control brakes on its own semitrailer and on its associated dolly
4) communication is required between each semitrailer and its own dolly unit (to monitor dolly wheel speeds and provide pressure commands to the dolly brakes)

- Use of a diagonal braking scheme to take advantage of suspension brake-steer compliance effects has been shown to be particularly helpful in developing an effective trailer-only RAMS algorithm. The principal effect of the brake-steer mechanism is to introduce beneficial *lateral* tire forces, as well as braking tire forces, to provide increased yaw damping to each trailer during a RAMS intervention.
- Forward speed is a powerful influence on the development of rearward amplification in combination vehicles, particularly above 50 mph. The speed reduction that accompanies a RAMS intervention braking event provides a beneficial byproduct of increased directional damping to the vehicle as it slows down.
- No RAMS system examined within the study [1] was seen to provide directional stability benefits on very low friction surfaces (e.g., wet jennite, ice/snow, etc.). Activation of any RAMS system further aggravated trailer swing tendencies under these very low friction conditions.

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THE DYNAMICS OF VEHICLES ON ROADS AND ON TRACKS

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