Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Rearward Amplification Suppression (RAMS)		5. Report Date December 2000
		6. Performing Organization Code
7. Author(s) C. MacAdam, M. Hagan, P. Fancher, C. Winkler, R. Ervin, J. Zhou, and S. Bogard		8. Performing Organization Report No. UMTRI-2000-47
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, Michigan 48109		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFH61-96-C-00038
12. Sponsoring Agency Name and Address Federal Highway Administration U. S. Department of Transportation Washington, D. C. 20590		13. Type of Report and Period Covered Final 4/15/99 - 9/15/00
		14. Sponsoring Agency Code
15. Supplementary Notes Technical Contacts: J. Britell (DOT)		

16. Abstract

The basic goal of this work was to develop and demonstrate an automatic brake control system that could intervene — only when needed — to help suppress unwanted trailer oscillations (commonly referred to as 'rearward amplification') in large combination vehicles (typically double and triple trailer combinations). The system would only be enabled for highway speed conditions greater than 50 mph. If possible, the system would be so simple that it 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 (Rearward Amplification Suppression) system.

Another aspect of this work was the perceived 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 on a "trailer-only" system. Further, if the outcome of this study 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 US DOT) to evaluate the RAMS system in actual practice.

Key findings from the work include: A particular "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. None of the RAMS systems examined within the study was seen to provide directional stability benefits on very low friction surfaces (e.g., wet jennite, ice/snow, etc.). A "safe harbor" — in terms of rearward amplification tendencies — exists for most combination vehicles at speeds below 45 mph. Consequently, the speed reduction that accompanies a RAMS intervention provides a beneficial byproduct of increased directional damping to the vehicle as it slows down.

17. Key Words trucks, stability, rollover, doubles, triples, rearward amplification, combination vehicles, directional stability, differential braking, roll response, control algorithm, damping, trailers		18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) None	20. Security Classif. (of this page) None	21. No. of Pages 90	22. Price

Final Technical Report
for
Task Order No. 7

(Contract No. DTFH61-96-C-00038)

Rearward Amplification Suppression (RAMS)

UMTRI-2000-47

C. MacAdam
M. Hagan
P. Fancher
C. Winkler
R. Ervin
J. Zhou
S. Bogard

The University of Michigan
Transportation Research Institute

December 2000

[This page blank]

Table of Contents

List of Figures

Acknowledgements

The authors gratefully acknowledge the help of the Haldex Corporation and its representative Mr. Dave Englebert for providing test vehicle equipment in the form of a tractor, two trailers, dolly, and associated EBS components to implement the RAMS functionality.

Mr. Dick Hoover of VRTC and his staff also provided a third trailer and dolly combination as well as support staff services for all testing conducted at VRTC during the project work.

Mr. Jim Britell served as the Contract Officer's Technical Representative.

Acronyms commonly used in the report include:

VRTC - referring to the Vehicle Research and Test Center facility in East Liberty, Ohio.

ABS - anti-lock brake system.

EBS - electronically controlled air-actuated brakes.

Executive Summary

The basic goal of this work was to develop and demonstrate an automatic brake control system that could intervene — only when needed — to help suppress unwanted trailer oscillations (commonly referred to as 'rearward amplification') in large combination vehicles (typically double and triple trailer combinations). The system would only be enabled for highway speed conditions greater than 50 mph. If possible, the system would be so simple that it 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 **Am**plification **S**uppression) system.

To the extent that even more effective (and complex) RAMS systems could also be identified for future vehicle designs that would support such RAMS requirements, they also were included within this study, though as a secondary or back-up system offering to the "trailer-only" system.

Another aspect of this work was the perceived 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 on a "trailer-only" system. Further, if the outcome of this study 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 US DOT) to evaluate the RAMS system in actual practice.

Key findings from the work are:

- A particular *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. The system is characterized by the following features:
  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) 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
  4) 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)

- A more future-looking *Full-Vehicle RAMS System* (requiring more complex communication links from the tractor unit to the last dolly) has also been developed and shown to provide a further 15-20% benefit in rearward amplification performance over the best trailer-only system.

- None of the RAMS systems examined within the study was seen to provide directional stability benefits on very low friction surfaces (e.g., wet jennite, ice/snow, etc.). Trailer-swing instabilities were very common with or without a RAMS system active.

- Forward speed is a powerful influence on the development of rearward amplification in combination vehicles, particularly above 50 mph. Consequently, the speed reduction that accompanies a RAMS intervention braking sequence provides a beneficial byproduct of increased directional damping to the vehicle as it slows down. A 'safe harbor' — in terms of rearward amplification tendencies — exists for most combination vehicles at speeds below 45 mph.

- 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.

- Simple brake control strategies that do not utilize intelligent *differential* (left side / right side) braking are shown to be largely ineffective at reducing rearward amplification. A simple strategy of merely reducing vehicle speed through conventional braking alone is not sufficient to producing notable reductions in rearward amplification (i.e., absent any accompanying yaw damping influences along the way to lower speed levels).

The primary recommendation from this study pertains to encouragement of a practical, in-use evaluation of the recommended trailer-only system. Namely, it is recommended that,

- A subsequent field trial of the trailer-only system be undertaken to help evaluate in-practice experiences with different hardware configurations as well as potential safety benefits. A trailer or subsystem manufacturer, operating in possible partnership with the U.S. DOT, could equip a targeted fleet of semitrailer and dolly units with the recommended trailer-only system. On-board data storage, triggered by RAMS activation events, could be used to subsequently evaluate the performance of the RAMS system, the types of maneuvering events activating the system, and the likely safety benefits provided by the system operation.

  Other practical in-use issues, such as mixing of RAMS and non-RAMS trailer units within a vehicle train, could perhaps also be addressed within such a field trial, but may be more helpful following an initial trial of 'pure' RAMS-enabled trains in order to more cleanly evaluate their full potential (i.e., absent results and questions pertaining to mixed-train RAMS configurations).

1.0 Introduction

This document constitutes a final reporting of findings for Task Order No. 7 entitled "Rearward Amplification Suppression (RAMS)," under Contract No. DTFH61-96-C-00038. The basic goal of this work was to develop and demonstrate an automatic brake control system that could intervene — only when needed — to help suppress unwanted trailer oscillations in large combination vehicles (typically double and triple trailer combinations). The system would only be enabled for highway speed conditions greater than 50 mph. If possible, the system would be so simple that it could be provided on a trailer-by-trailer basis. That is, the proposed RAMS 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 system.

To the extent that even more effective (and complex) RAMS systems could also be identified for future vehicle designs that would support such RAMS requirements, they also were included within this study, though as a secondary or back-up system offering to the "trailer-only" system. (Each of the different systems and their accompanying shorthand terminology such as "trailer-only," as used here and elsewhere within the report, is defined more precisely in the first portion of Section 2 under *Terminology.*)

Another aspect of this work was the perceived 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 on a "trailer-only" system. Further, if the outcome of this study 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 US DOT) to evaluate the RAMS system in actual practice.

The report is organized by the following principal sections that follow this Section 1 Introduction — Section 2: Rearward Amplification and the RAMS Concept; Section 3: Test Vehicle and Instrumentation; Section 4: RAMS Algorithm Development / Simulation Study; Section 5: Vehicle Testing at VRTC; Section 6: Vehicle Test Results; and Section 7: Conclusions and Recommendations. References and Appendices A, B, and C conclude the report.

Section 2 describes the basic rearward amplification phenomena (sometimes called "crack-the-whip") normally present in large combination vehicles. These phenomena lead to ever-increasing lateral accelerations and roll responses for the more rearward trailers, thereby increasing the chances of rollover in those units. An example illustration of the potential benefits — of employing even a simple RAMS system — is included in this section to demonstrate the final product and motivation for this research study.

Section 3 describes the test vehicles (triples combination and doubles combination) and the vehicle instrumentation.

Section 4 discusses the development of the various RAMS algorithms included in the study and the use of computer simulation within the development process.

Section 5 describes the vehicle tests conducted at the VRTC test facility in Ohio. It includes discussion of the different operating conditions, vehicle configurations, and example time history responses illustrating key test runs.

Section 6 provides a presentation and discussion of the test results.

Section 7 offers conclusions and recommendations on the project work.

References and Appendices follow Section 7. Appendix A contains the Vehicle Specification document which is intended to provide information to other parties wishing to implement a RAMS functionality. Appendix B contains vehicle parameters used to simulate the test vehicle within the initial design stages. Appendix C contains supporting figures from the computer simulation analyses.

Finally, it should be noted that this report is, in part, an update and continuation of the work begun under the previous 'smart truck' project reported on in reference [1]. Since the data describing many of the same test vehicle components (suspension data, inertial vehicle properties, etc.) are fully documented in that report, this report relies on reference data from that initial report without duplication here. Appendix B of this report does contain a set of nominal reference data from an UMTRI computer simulation model describing the triples baseline vehicle used in this study. Appendix A also provides a copy of the Functional Specifications document that fully describes the recommended "trailer-only" algorithm and its implementation as well as specifications for the best of the "full-vehicle" algorithms.

Again, terminology such as "trailer-only" or "full-vehicle" are defined in Section 2 under *Terminology*.

2.0 Rearward Amplification and the RAMS Concept

The basic problem present in many large combination vehicles (e.g., doubles and triples utilizing 28-ft trailers) when travelling at highway speeds above 50 mph, is the so-called 'rearward amplification' phenomena — commonly described as a crack-the-whip response. At these speeds, if the tractor unit performs a lane-change or obstacle avoidance maneuver requiring some level of lateral acceleration, each successive trailer in the train combination develops a successively higher lateral acceleration response. If the level of lateral acceleration developed by the rearmost trailer is large enough, rollover of that trailer unit can occur.

- The Basic RAMS Concept -

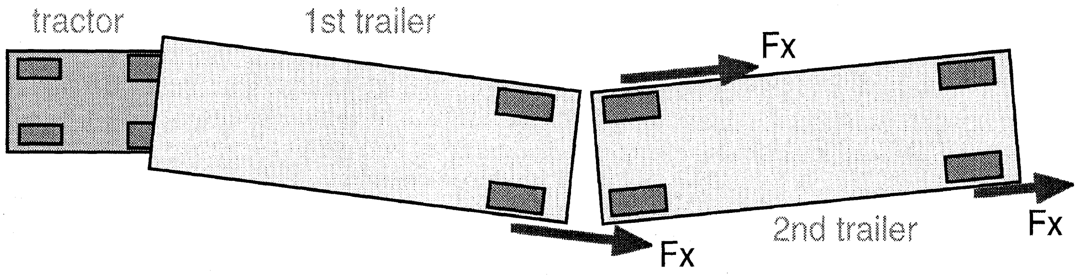
- **Application of Intelligent Braking to Left and Right Sides of Trailer/Dolly Axles in order to Damp out Excessive Trailer Yaw Motions**

Why?

- **To Help Attenuate "Rearward Amplification" Tendencies in Combination Vehicles that Lead to Rollover of Rear-most Trailers**

The motivation then for a rearward amplification suppression (or RAMS) concept is the potential for intelligent intervention by an available control system to damp out unwanted and excessive trailer oscillations as they begin to develop on such vehicles. Since steering control of individual wheels or axles is not available as a control intervention option on commercial trucks, the next best and available control source is the brake system. By applying intelligent differential (side-to-side) braking at different axle locations along the vehicle train during a rearward amplification event, significant damping control can be applied to help attenuate excessive trailer oscillations as they begin to develop. See Figure 2-1. This of course requires a means for sensing the development of unwanted trailer motions and a coordinated application of individual brake pressures to different wheel locations so as to provide a beneficial damping affect.

RAMS Implemented with Braking Forces ->



Use of side-to-side braking forces (Fx), to help diminish excessive trailer oscillations in combination vehicles

Timing and magnitude of braking forces determined by sensed motion of trailers and a RAMS control algorithm

Figure 2-1. Use of Tire Brake Forces to Damp Out Unwanted Trailer Motions.

This sensing and control response combination is frequently referred to within this report as a 'RAMS algorithm.' That is, a sensed motion signal (yaw rate measurement, lateral acceleration measurement, etc.) is required as an input to the algorithm's decision-making component. Then, based upon the characteristics of the sensed signal and a rule used by the decision-making component, brake pressures may be applied to certain wheel locations on the vehicle train in order to help attenuate the unwanted motion responses. Brake pressure applied at individual wheel locations by the algorithm cause corresponding tire brake forces to develop at those same wheels. These tire forces — and their respective moment arms that locate them with respect to each corresponding trailer mass center — produce moments that resist excessive yaw rotational motions by the trailer body. This basic yaw damping mechanism is the primary control strategy employed in most of the RAMS algorithms that are described in more detail in later sections.

2.1 Terminology

Before discussing the various RAMS control algorithms and their features, it is important that certain terms used throughout the report to refer to different algorithms are defined in sufficient detail that no confusion exists as to their meaning. These terms include the expressions: *trailer-only, trailer-to-trailer, and full-vehicle*, usually used in combination with 'algorithm' to refer to a particular class of algorithms examined within the study. These expressions are defined as follows:

Trailer-Only — This expression is meant to lump each semitrailer and its corresponding dolly together (sometimes referred to as a 'full-trailer,' or simply 'trailer'). In this context, a RAMS algorithm that is a *trailer-only* algorithm can only sense motion signals and issue brake control commands for a single semitrailer+dolly pair on the vehicle train. It can not utilize information from other units (e.g., the preceding semitrailer or the tractor unit) or issue commands to brakes located on other semitrailers or dollies other than its own. It does require a sensor and control link between the semitrailer to its associated dolly unit, thereby placing some modest burden on a trailer or subsytem manufacturer wishing to implement a RAMS functionality.

Trailer-to-trailer — This expression means that trailer-to-trailer communication is possible. It assumes that communication links are provided between adjoining trailers and would be desirable for such RAMS algorithms that depend on advanced motion information available from a preceding trailer in the vehicle train. Trailer-to-trailer algorithms are similar to trailer-only algorithms, except that they can utilize sensor information from an adjoining trailer (as well as their own). This scheme allows for some anticipation or quickening within these control algorithms to potentially improve their performance over a trailer-only algorithm. It does introduce more complexity since it requires communication links between adjacent semitrailers and their associated dolly units.

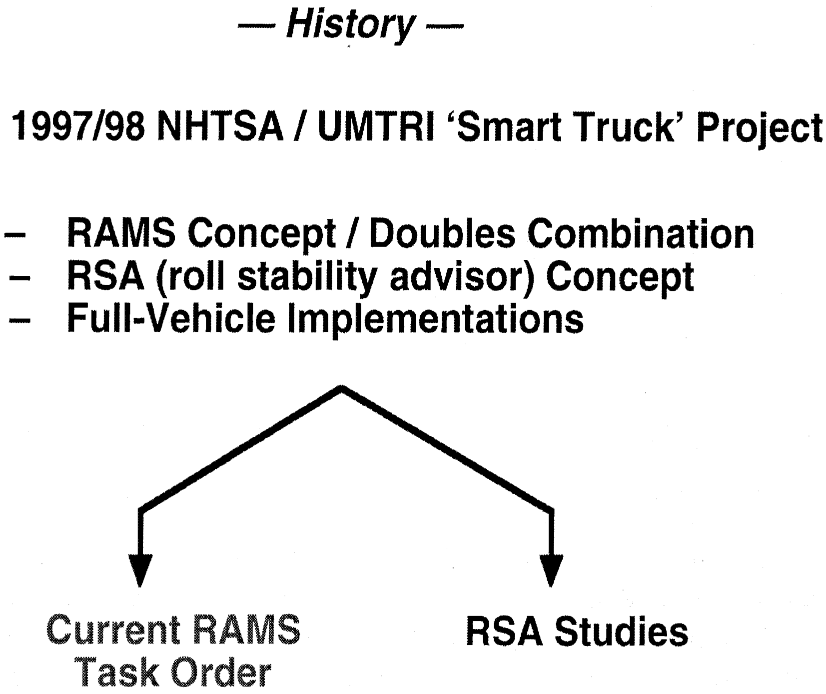
Full-vehicle — Refers to an unrestricted flow of information and control activity about the vehicle. For example, a rearmost axle pressure command signal could depend upon and be controlled by how the tractor unit is moving as well as how other trailer units on the vehicle are moving. It requires the most complete communication links in order to allow unrestricted access from any unit to any other unit on the vehicle train, including the tractor unit. Accordingly, this class of RAMS systems is considered more applicable to future vehicles that may commonly support vehicle-wide communication and data exchange.

Clearly, the trailer-only class of algorithms is the simplest to implement since it depends only on the sensed motion of each semitrailer — the primary mass element in any semitrailer-dolly pair. It does require communication between the semitrailer unit and its dolly since the primary mass motion being sensed and controlled (semitrailer) will, in strong measure, depend upon the tire forces provided by its associated dolly (in addition to its own semitrailer tires). Because of the simpler communication requirements for the trailer-only algorithms, their implementation by a subsytem manufacturer wishing to implement a RAMS functionality is clearly the least burdensome of the three classes outlined above. In practice, some coordination and attention to matching of RAMS-enabled semitrailers to RAMS-enabled dolly units will be required to provide maximum benefit.

Cases in which trailer-only RAMS systems are mixed and matched arbitrarily within a vehicle train provide reduced benefit and some of these potential scenarios are discussed briefly in Section 7. Operating rules and conditions for more complex and futuristic systems, such as the full-vehicle class of algorithms, will largely depend on whether or not adoption of certain EBS standards or communication standards eventually penetrate sufficient portions of the trucking fleet.

2.2 The Prior RAMS Study

The initial project work that led to this task order was begun in 1997 under the project entitled "Two Active Systems for Enhancing Dynamic Stability in Heavy Truck Operations " [1] in which both a RAMS functionality and a roll stability advisor (RSA) concept were jointly examined. The findings from that so-called 'smart truck' project indicated that both types of stability enhancement concepts were feasible and worth pursuing. That led to subsequent funding from FHWA/NHTSA for this project and for support of several subsequent RSA studies currently ongoing.



— History —

1997/98 NHTSA / UMTRI 'Smart Truck' Project

- **RAMS Concept / Doubles Combination**
- **RSA (roll stability advisor) Concept**
- **Full-Vehicle Implementations**

Current RAMS Task Order

RSA Studies

Figure 2-2. Recent History of RAMS Research at UMTRI.

Under that initial work, the RAMS systems that were being implemented were essentially full-vehicle algorithms. That is, control algorithms developed under that work had access to all sensor signals on any part of the vehicle, including the tractor. The recommended algorithm from that first study, in fact, used tractor steering angle and tractor yaw rate as part of its control algorithm for operating the brakes on the dolly unit. In addition, the first study utilized a doubles combination to test out these basic concepts.

One of the primary motivations for this current study was to see if a simpler RAMS algorithm could be developed that did not have to communicate with as many different vehicle units within the train. This led to the emphasis upon trailer-only systems within this work. The basic idea behind the trailer-only notion was minimal dependence upon other units, hoping that a RAMS functionality could be developed on a trailer-by-trailer basis. That is, sensing and control functions would be local to each trailer, thereby removing the need to communicate across trailer units and certainly independent of the tractor unit.

This motivation primarily stemmed from an understanding that truck/trailer fleets and subsytem manufacturers would have a much simpler task at beginning to implement any sort of RAMS functionality if it was begun in its simplest form. If an EBS/RAMS functionality is to develop and begin to penetrate the market, it would likely do so in a gradual manner and depend upon the perceived benefits that accrue to the truck operator by its adoption over time.

To add to the drama of this task order, the implementation of the proposed RAMS work was extended from a doubles combination to a triples combination. The addition of one additional dolly and semitrailer to the mix amounted to raising the bar another 30% or so in terms of the level of additional rearward amplification developed at the last trailer location. Thus, this task order began with the understanding that a triples combination would be the primary baseline target vehicle *and* that the algorithm design emphasis would principally focus on more restricted RAMS systems that depend only on local sensing of trailer motions for its operation. See Figures 2-3 and 2-4 for illustrations of all the sensor/processor communication paths in the original vs. current RAMS implementations.

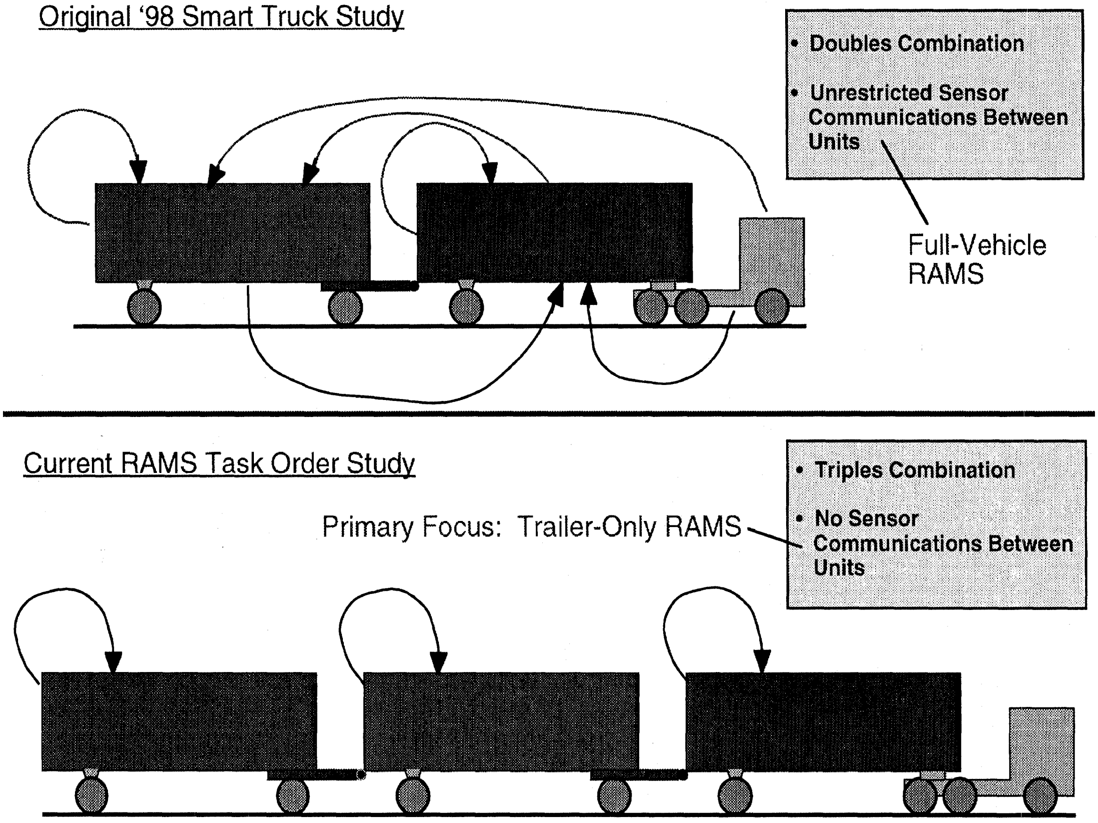


Figure 2-3. Extension of Initial RAMS Study to Include a Triples Combination and Focus Primarily Upon Trailer-Only Systems.

In the event that a trailer-only RAMS system could not be developed under this work, the task order also provided for study and development of a more complex full-vehicle system that could utilize information from other vehicle units in order to help boost the control performance of the system to a suitable level. Consequently, this project does include some work aimed at a more futuristic class of RAMS systems that are assumed to be capable of utilizing information from anywhere on the vehicle (full-vehicle algorithms) and that may have impact in future years when truck communication systems or EBS systems are more standardized and far more common. In addition, inclusion of a set of full-vehicle systems within this study does provide a reference level of performance against which to measure the performance achieved by several of the simpler trailer-only or trailer-to-trailer algorithms that are, by definition, restricted to lower performance regimes due to their restricted use of sensor information.

– Current RAMS Task Order –

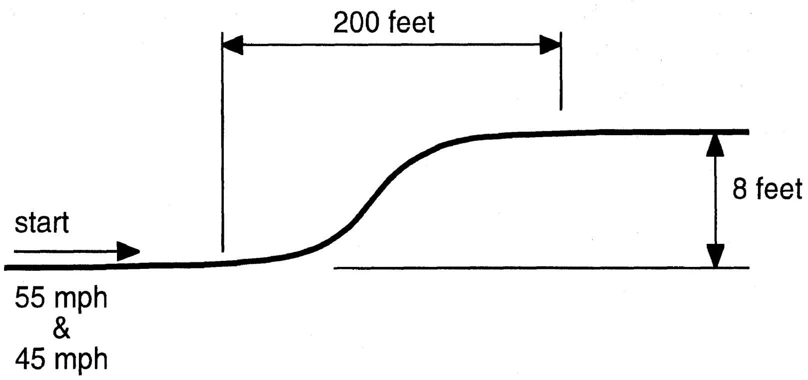
- **Primary Focus on Trailer-Only RAMS System**
- **Extends RAMS to Triples Combinations**
- **Provides Full-Vehicle RAMS System as Back-Up & Example of More Future-Looking EBS Concepts**

Figure 2-4. Summary of Key Elements of the Current Project Work.

2.3 Rearward Amplification — A Triples Combination Example

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 2-5 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 [1].

Lane-Change (Obstacle Avoidance) Test Maneuver Used to Excite Rearward Amplification and to Evaluate RAMS Effectiveness



- **Road Surface Markers Allow Driver to Steer Along Path**
- **Results in Tractor Lateral Accel Levels of About 0.15 - 0.20 g's, Depending on Driver Steering Behavior**

Figure 2-5. Lane-Change Path Used to Excite a Rearward Amplification Response.

This 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 travelling at 55 mph. Because of the inherent dynamics of most large combination vehicles operating at these speeds, each subsequent trailer in the vehicle train will experience ever-higher peak levels of lateral acceleration than its preceding unit. This amplification of lateral acceleration response and the accompanying path and roll responses of each trailer at rearward locations is referred to as rearward amplification. Figure 2-6 shows a representative test track example of rearward amplification collected under this project work for the baseline triples combination (described further in Section 3) travelling at an initial speed of about 55 mph with a payload height of 92 inches above ground.

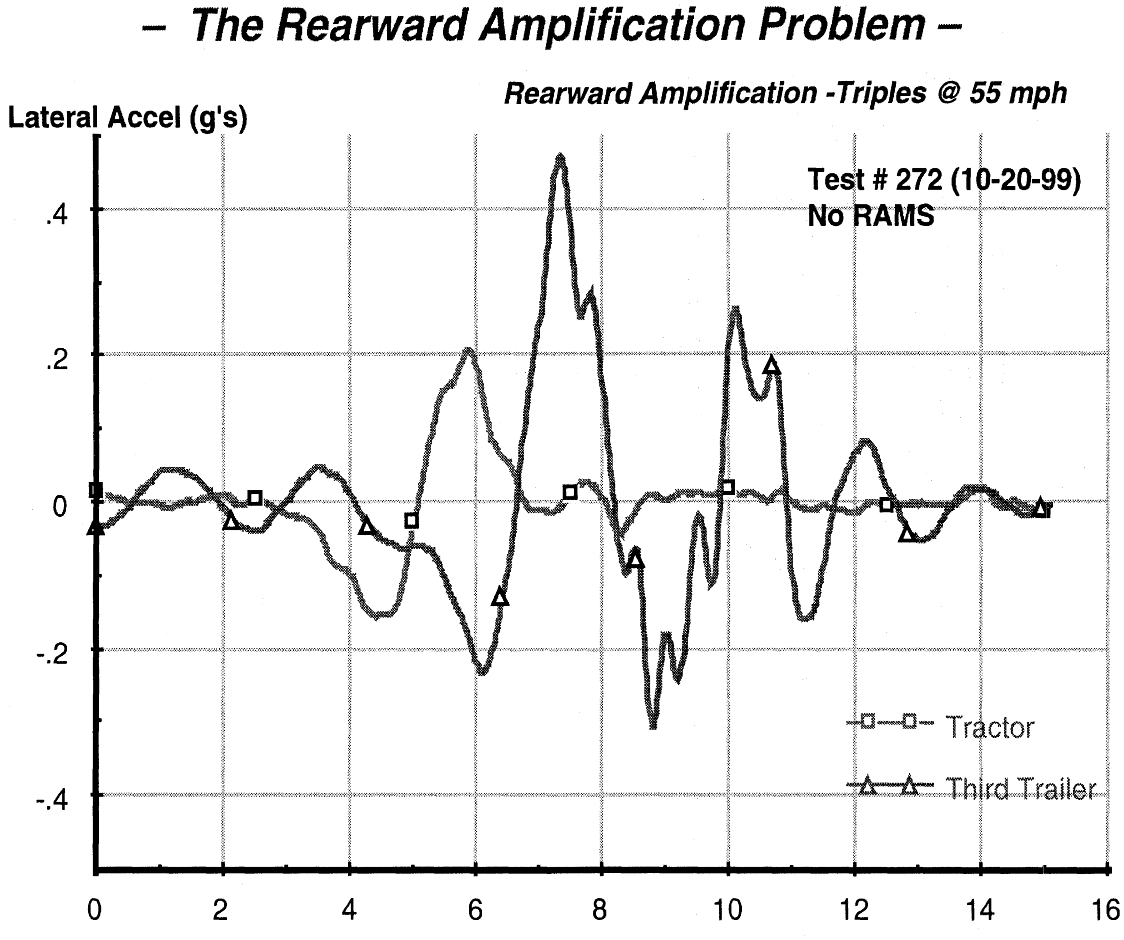
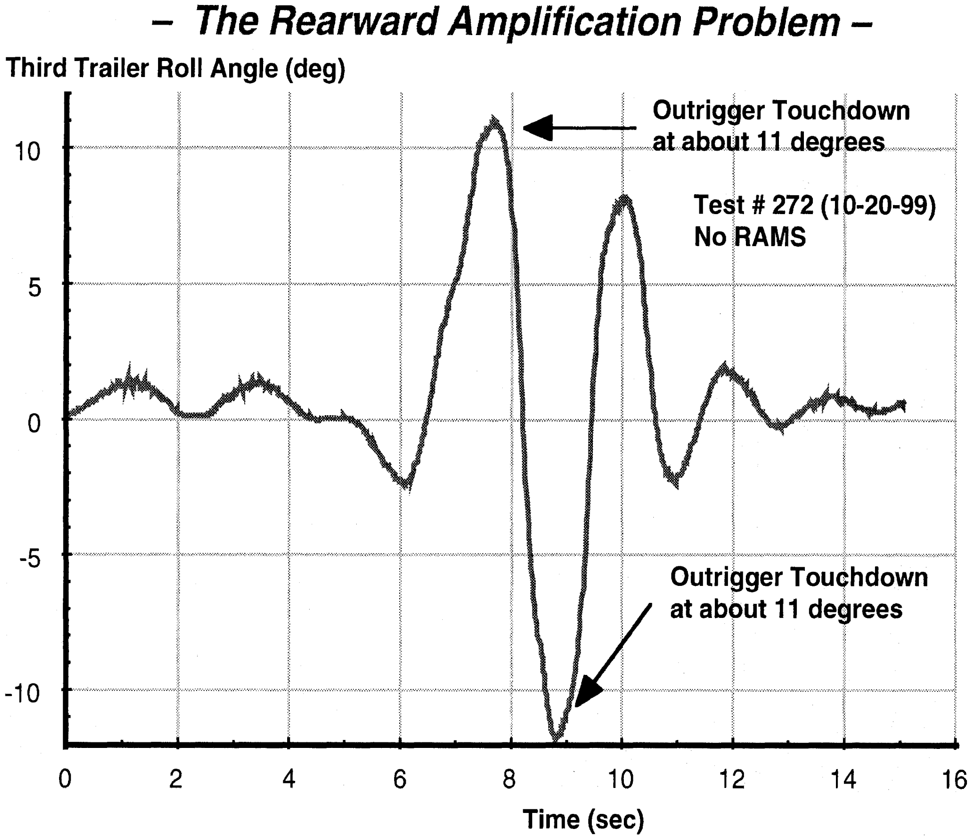


Figure 2-6. Rearward Amplification of Lateral Accelerations (tractor unit vs. third trailer of a triples combination) – Test Run #272.

Because of the elevated levels of lateral acceleration experienced by the rearmost trailer, it is also susceptible to amplified path and roll responses. If the rearward amplification level is large enough, rollover of the last unit is possible. In fact, this particular test run does provoke a rollover of the third trailer as shown by the roll angle response recorded in Figure 2-7. Outriggers mounted on the last two trailers touch down at about 11 degrees of roll, thereby catching the trailer and preventing it from rolling completely over. In general, roll angles greater than about 6 degrees or so for vehicles of this type will usually result in a rollover event.



Outrigger Touchdown at about 11 degrees

Test # 272 (10-20-99) No RAMS

Outrigger Touchdown at about 11 degrees

Figure 2-7. Rollover Response Recorded for the Third Trailer in Test Run #272.

To illustrate the benefit that even a simple trailer-only RAMS system can have on helping to stabilize rearmost trailers under identical operating conditions, Figure 2-8 shows a sample result of corresponding measurements for the same combination vehicle equipped with a trailer-only RAMS system developed under this work. (Details of its implementation are described in subsequent sections of the report and Appendix A.) Figure 2-8 shows the lateral acceleration responses for the tractor and the third trailer as before.

Despite even somewhat larger peak lateral acceleration levels for the tractor unit in this run, the peak lateral acceleration of the third trailer has been reduced from about 0.5 g's down to approximately 0.33 g's. The normalized ratios of last trailer and tractor lateral acceleration levels (third trailer peak normalized by tractor average peak values) indicate a reduction in rearward amplification from about 2.7 down to 1.65, an approximate 40% reduction.

Furthermore, and more importantly, the unstable roll response for the non-RAMS triple in Figure 2-7 has now been brought under control by the trailer-only RAMS system and reduced to less than 4 degrees of peak roll angle, as seen in Figure 2-9. A direct comparison of the two roll angle measurements plotted on the same graph are seen in Figure 2-10.

Lastly, it should be noted that forward speed has a profound effect on the development of unwanted rearward amplification tendencies in combination vehicles above about 45 mph. Speeds below 45 mph act as a type of 'safe harbor' with regard to rearward amplification tendencies in most large combination vehicles. Since one of the beneficial byproducts of a RAMS intervention is a loss of vehicle speed due to the application of selected brakes during the RAMS activation, the resulting loss of vehicle speed provides further benefit from the natural increase in vehicle yaw damping that occurs for such vehicles at lower speeds. As a result, the arming or enabling of any RAMS system can be greatly simplified in practice by only allowing it to operate for speeds above 45-50 mph. This of course eliminates a large portion of operating conditions for which RAMS needs to be potentially operational and vigilant. As will be described in later sections, this speed-dependent enabling of RAMS is one of the basic features that is recommended as part of the RAMS functional specifications.

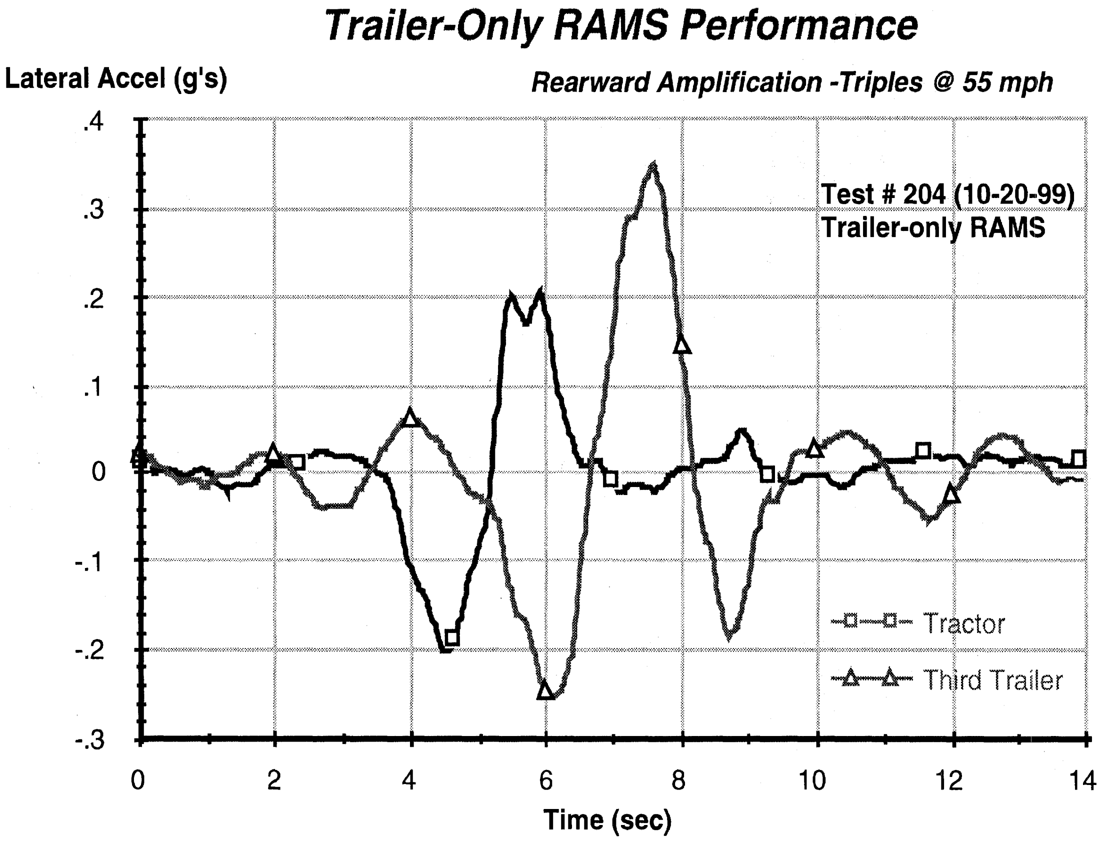


Figure 2-8. Rearward Amplification of Lateral Accelerations (tractor unit vs. third trailer) Equipped with a Trailer-Only RAMS System – Test Run #204.

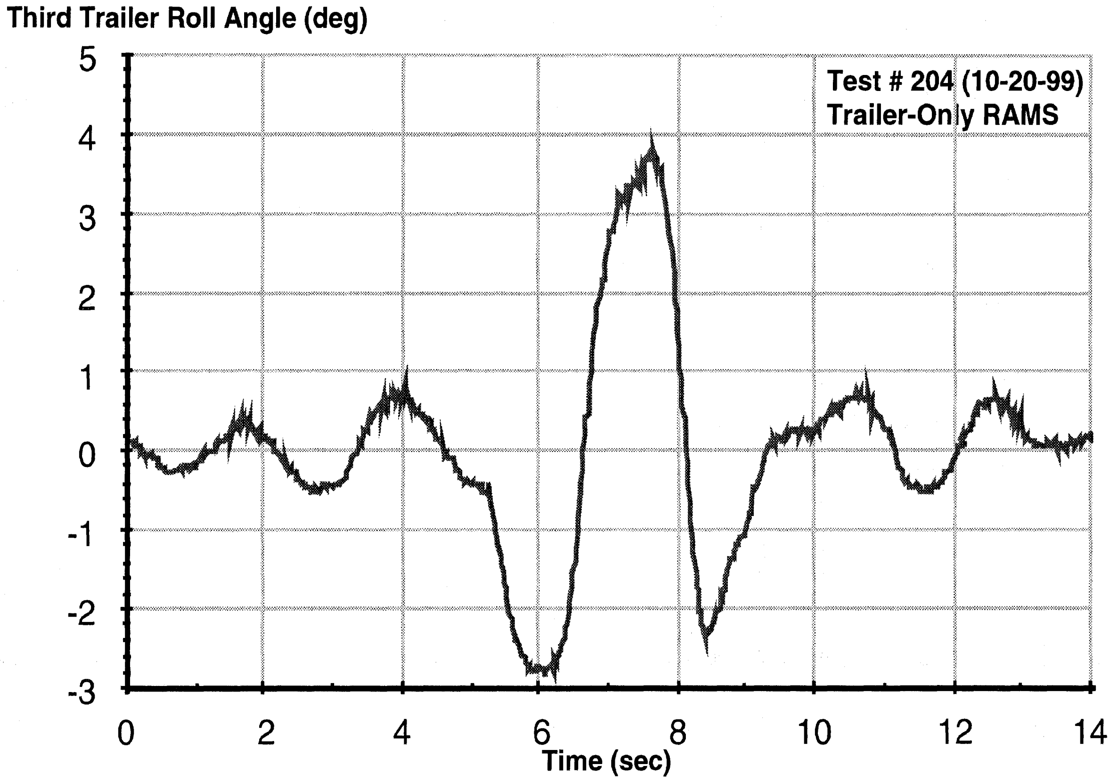


Figure 2-9. Stable Roll Response for the Third Trailer Using the Trailer-Only RAMS System – Test Run #204.

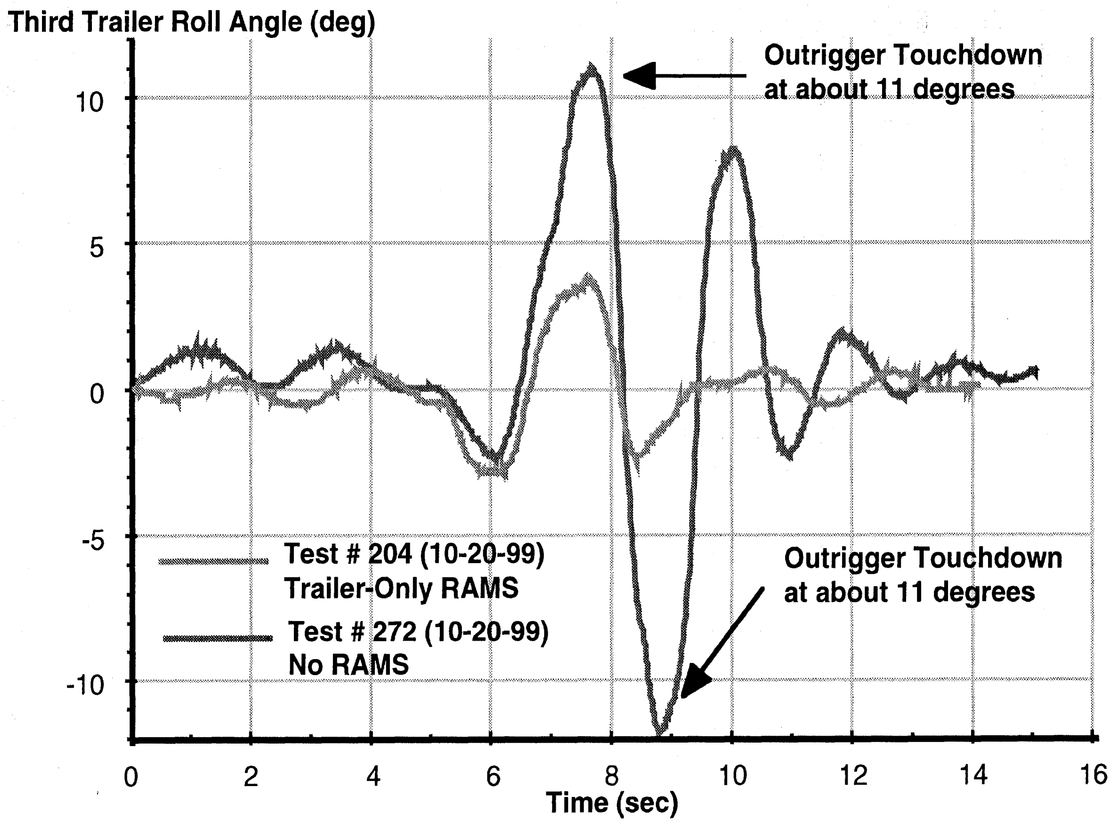


Figure 2-10. Comparison of the Measured Roll Response for the Third Trailer. No-RAMS vs. the Trailer-Only RAMS System – Test Runs #272 and #204.

3.0 Test Vehicle and Instrumentation

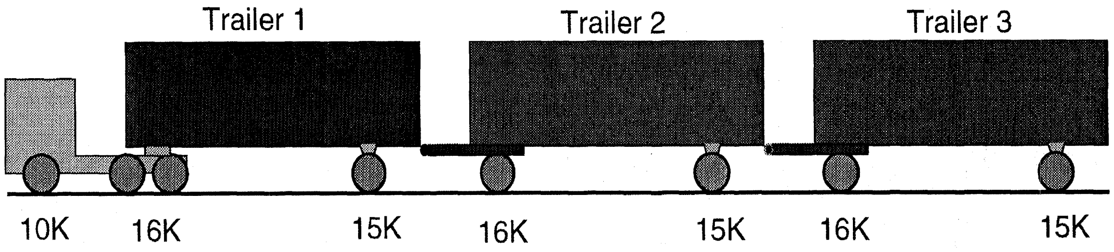
The baseline test vehicle used in this study was a triples combination utilizing 28-ft trailers. The power unit was a 3-axle tractor having an approximate 20-ft wheelbase. When fully loaded, all axles but the tractor steer axle carried about 15,000 to 16,000 lbs of load. Figure 3-1 describes the basic configuration for the triples combination.

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



Distribution of Axle Loads

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 3-1. The Baseline Triples Combination Vehicle Used in the RAMS Testing.

Haldex Corporation supplied the tractor unit, two semitrailers and one dolly. Each of these units was equipped with air suspensions. The first semitrailer and first dolly were supplied by VRTC / NHTSA and were equipped with multi-leaf steel suspensions. The last two trailers were also equipped with outriggers to prevent rollover of those units. When fully loaded the gross vehicle weight was approximately 103,000 lbs. 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. The most common payload height was 88 inches above ground. Payload height was fixed in the first semitrailer at about 70 inches above ground.

Testing of a doubles combination was accomplished by disconnecting the last semitrailer and dolly from the baseline triples configuration. The doubles tests were primarily used to trouble-shoot and verify proper operation of the RAMS hardware and each of the RAMS algorithms prior to any triples testing. The doubles tests also allowed for a direct comparison with test results obtained from the initial smart truck project [1] that also used a doubles configuration within its test program.

Figure 3-2 lists the primary data channels and instrumentation on the test vehicle. 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). Lateral accelerometers were also mounted in the nose/floor area of each semitrailer and on the dolly tongue near its pintle hook connection. These latter accelerometers were used in conjunction with certain RAMS algorithms that attempted to utilize trailer-mounted and dolly-mounted lateral acceleration signals within their algorithm design.

Instrumentation & Data Collection

- **Forward Speed (optical 5th wheel on tractor)**
- **Lateral Accel of Tractor & Last Trailer (stable platform)**
- **Yaw Rates of Tractor, Each Semi, and Each Dolly**
- **Lateral Acceleration of Tractor, Each Semi (nose), and Each Dolly**
- **Roll Angle of Last Trailer (stable platform in last trailer)**
- **All Wheel Speeds (ABS units)**
- **All Brake Pressures (EBS units)**
- **Tractor Steering Wheel Angle (rotary potentiometer)**

Figure 3-2. Vehicle Instrumentation / Data Collection.

Yaw rate gyros were also mounted on each articulating unit of the vehicle train and included the tractor, each semitrailer, and each dolly unit. As above, the yaw rate signals were also employed as motion sensors for several of the different RAMS algorithms examined in the study.

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 for each (non-tractor) wheel location were provided by the EBS / Haldex hardware mounted on each semitrailer and dolly (transducers located at the valving manifold output lines leading to each brake chamber). All rotational wheel speeds were also provided by the ABS / Haldex units mounted at each wheel/brake location.

Figures 3-3 and 3-4 show photographs of the test vehicle operating under dry and wet test track conditions.

Figure 3-3. Baseline Triples Configuration Used in RAMS Testing.

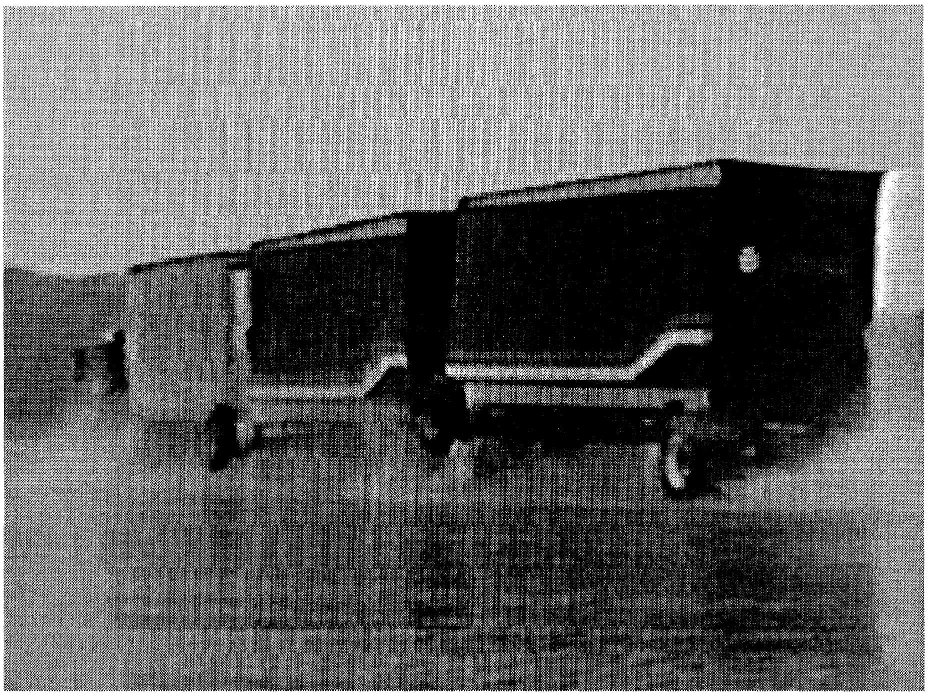


Figure 3-4 Baseline Triples Configuration Used in RAMS Testing – Heavy Rain Conditions on Asphalt Surface.

4.0 RAMS Algorithm Development / Simulation Study

As noted in the Introduction, a major goal of this project work was the development of a trailer-only RAMS algorithm that would be simple enough to implement by subsystem manufacturers while also delivering significant stability improvements to the rearmost trailers of doubles and triples combinations. At the same time, development of a full-vehicle RAMS algorithm, primarily with more future-looking vehicles in mind, was also included within the study. This wide range of potential RAMS algorithms could be either (a) relatively simple to implement but might suffer from poor control performance due to dependence upon only local (trailer-only) vehicle response measurements, or (b) more complex full-vehicle algorithms that are more difficult to implement in practice but could potentially achieve superior performance due to their unrestricted access to vehicle response variables anywhere on the vehicle train.

To address this broad set of algorithm possibilities, a computer simulation study was undertaken to examine a wide range of algorithm designs. These different designs included the possibility for using different sensor signals, different types of rules for detecting rearward amplification events that likely required control intervention, and different control actuation strategies for applying brake pressures to specific wheel locations in order to achieve beneficial yaw damping effects. Consequently, the design of a RAMS algorithm involved three basic ingredients — 1) a sensor signal, or signal set, upon which to operate and make decisions, 2) a decision-making component that would determine if a rearward amplification event was occurring and what to do about it, and 3) a corresponding control component that would issue brake pressure commands to selected brakes to cause a reduction (or desired regulation) of the sensed motion variable(s) being monitored by the RAMS system. Various choices are of course present in this design procedure and have to do with which motion variables to monitor, what the rules are for triggering a RAMS intervention, which gain coefficients to select, which brakes to apply during an intervention sequence, and how pressure should be applied to each brake. All of these types of questions were part of the initial algorithm design process and are depicted in general form in Figure 4-1.

Various possibilities for sensor signals seen in Figure 4-1 include (a) yaw rate measurements of semitrailers, dollies, and the tractor, (b) lateral acceleration signals of these same units, and (c) combinations of such signals such as their differences or sums. The decision-making element depicted in Figure 4-1 would contain rules about how to detect when a rearward amplification event was beginning to occur based upon sensor signal levels (e.g., yaw rate or lateral acceleration exceeding a certain threshold value, etc.) and if so, how much brake pressure to apply, perhaps based upon the level of the sensor signal. The third portion of Figure 4-1 considers the important question of which brakes to apply the pressure to in order to effect the best damping performance from the RAMS algorithm. The brake selection process can be complicated because it is not always obvious which set of brakes will provide the most damping benefit. The basic choices are: (1) apply brake pressure to the outside wheels in a turn, (2) apply brake pressure to the inside wheels, or (3) apply pressure diagonally to an outside wheel and an inside wheel. These choices will usually depend on the characteristics of the suspensions and how much so-called compliance-steer and roll-steer is exhibited by the suspension when braking forces are applied to one side of an axle or another. These types of brake-selection strategies are discussed in more detail in portions of the Functional Specifications document contained in Appendix A.

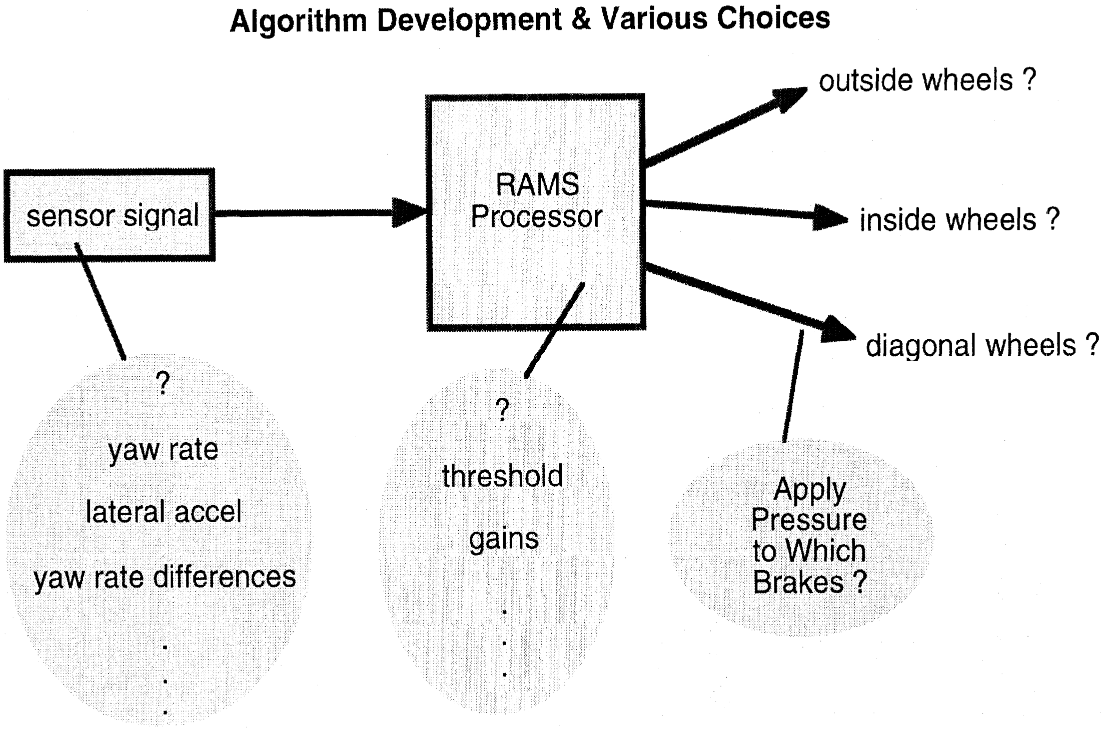


Figure 4-1. Considerations in the Development of a RAMS Algorithm.

In order to help sort out the influence of these different features, a computer simulation of the baseline triples vehicle [2] and a generalized computer model capable of representing each of the different RAMS design possibilities were developed and integrated as a single analysis tool. By exercising the vehicle model in conjunction with the generalized RAMS model, numerous combinations of vehicle and algorithm designs could be efficiently examined to help identify promising algorithm candidates. Those algorithms identified within this initial modelling and simulation activity as having the greatest chance of success were then programmed into the test vehicle software for use in the subsequent test program at VRTC. The array of algorithm choices covered both trailer-only algorithms, trailer-to-trailer algorithms, and more complex full-vehicle algorithms — most of which could be selected on-the-fly as the test vehicle conducted a particular series of tests. This "play-book" approach to the test program added significant efficiency to the testing activity, allowing rapid collection and review of data as the testing proceeded. It also helped minimize much of the common "trial and error" methodologies that can frequently bog down test program activities. In almost all cases, basic predictions by the computer simulation tool — as to likely performance benefits of specific RAMS algorithms — were confirmed by the test results.

The basic algorithm selection process emphasized those points identified in Figure 4-2, namely (a) identification of the most promising RAMS algorithms, (b) desire to program the best-of-the-lot into the test vehicle, (c) particular emphasis and attention paid to the class of trailer-only algorithms, and (d) full-vehicle algorithms viewed as a potential back-up algorithm in the event the trailer-only algorithms provided insufficient performance enhancements in test results. These also provided a benchmark of best-you-can-do performance against which to measure all other candidate algorithms.

– RAMS Algorithm Selection Process –

- **Those algorithms seen in initial simulation analyses to be the most effective at reducing rearward amplification**
- **Best algorithms included in the test program at VRTC and programmed into the test vehicle for easy activation / modification**
- **Emphasis on trailer-only algorithms**
- **Full-vehicle algorithms provided an alternate back-up algorithm (if needed) as well as a 'best-you-can-do' performance benchmark**

Figure 4-2. Principal Considerations in Selecting the Various RAMS Algorithms.

The specific details of the various RAMS algorithms, as categorized into three distinct classes, are outlined in Figure 4-3. The three classes are 1) trailer-only algorithms, 2) trailer-to-trailer algorithms, and 3) full vehicle algorithms. As noted in the Terminology discussion of subsection 2.1, each class is associated primarily with sensor information assumed available to the algorithm. That is, (a) trailer-only algorithms are restricted to sensor signals associated with the semitrailer and dolly pair (sometimes referred to as 'trailer' or 'full-trailer') for which it has control authority, (b) trailer-to-trailer algorithms that are similar to trailer-only algorithms, but also allow for communication between any two adjoining semitrailers in order to access additional sensor information from the adjoining trailer (typically as part of an anticipatory strategy in which a following-trailer RAMS controller previews upcoming motion ahead of it by using sensor information from the preceding trailer), and (c) full-vehicle algorithms that permit full communication and sharing of motion information for control purposes — the unrestricted case. This latter category, and to some extent the trailer-to-trailer category, are seen currently as being more futuristic control strategies for RAMS because of their additional complexity and present lack of practical support within the typical truck/trailer hardware environment. Consequently, the emphasis upon developing the simplest RAMS system in which only minimal communication links are required — between any semitrailer and its associated dolly — was seen as providing the best opportunity for a practical implementation of RAMS at the present time.

Different RAMS Control Algorithms

- Trailer-Only Algorithms
  - **yaw rate sensor on semitrailer**
  - **lateral accelerometer in nose of semitrailer**
  - **yaw rate sensors on semitrailer and on dolly (unit-by-unit)**
  - **lateral accelerometers on semitrailer and on dolly**

  - *diagonal wheel braking*
  - *same-side wheel braking*

- Trailer-to-Trailer Algorithms (assumes trailer-to-trailer communication)
  - **sum of semitrailer yaw rates as sensor signal (quickened yaw rate signal)**
  - **difference of semitrailer yaw rates (articulation rate damping)**

  - *diagonal wheel braking*
  - *same-side wheel braking*

- Full-Vehicle Algorithms (assumes complete tractor to last trailer communication)
  - **mixes of resident semitrailer yaw rate and yaw rates from semis ahead in train**
  - **semitrailer yaw rate damping for semi axle; yaw rate difference (articulation rate damping) on dolly axle**
  - **semitrailer yaw rate damping for semi axle; quickened yaw rate difference (quickened articulation rate damping) on dolly axle using tractor yaw rate as lead unit**

  - *diagonal wheel braking*
  - *same-side wheel braking*

Figure 4-3. Three Classes of RAMS Algorithms, Associated Sensor Inputs, and Corresponding Brake-Selection Options.

Figure 4-3 also lists the primary sensor signals and brake-selection strategies considered for the three basic classes of algorithms. For example, under Trailer-Only Algorithms, yaw rate of the semitrailer was one sensor signal possibility. So also was lateral acceleration of the semitrailer as measured at the semitrailer nose (to include anticipatory motion information available at that location when the semitrailer first starts to turn). Likewise yaw rates of the semitrailer and of the dolly unit alone were also considered. And, lastly lateral acceleration signals of the semitrailer nose location and of the dolly-pintle hitch location (again for anticipatory reasons) alone were also considered as other potential sensor inputs to the trailer-only class of RAMS algorithms.

In addition to the sensor signal considerations, brake-selection strategies were also on the menu of algorithm choices. Brakes could be activated in a same-side manner (outside wheel locations during turning, or inside wheels) or in a diagonal manner (dolly outside wheel and semitrailer inside wheel during turning, or vice versa). Consequently, numerous combinations of sensor signal inputs and brake-selection strategies were possible and needed to be evaluated using the simulation tool.

This same basic approach was also applied to the other two classes of algorithms and their associated set of input sensor signals and brake-selection options. However, with the trailer-to-trailer algorithms, and more so with the full-vehicle algorithms, the number of sensor choices increases further (by definition of additional sensor access around the vehicle). Consequently, sensor signal choices were bounded for these two algorithm classes by selection of signals that were thought to be of likely benefit, rather than a shot-gun approach that considered all sensor signals available.

4.1 RAMS Processing Module

With regard to the processing module within the RAMS algorithm, the basic rule ultimately used for detection and activation of a rearward amplification event was a simple threshold crossing by the sensor input signal. That is, a dead-zone region exists in which sensor signals lying within this region are ignored and have no effect. (The sensor signal, in general, is selected to act as a surrogate or indicator of the level of motion present in the vehicle, and thereby hopefully associated, at least indirectly, to a rearward amplification experience.) For excursions by the sensor 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, if semitrailer yaw rate is the designated sensor signal, and a threshold value of 2.2 degrees per second (0.04 radians/sec) is specified, 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 4-4 shows such an example corresponding to test run #202. (Brake pressure traces corresponding to the indicated firing points noted here are seen in Figure 5-5 of the next section.)

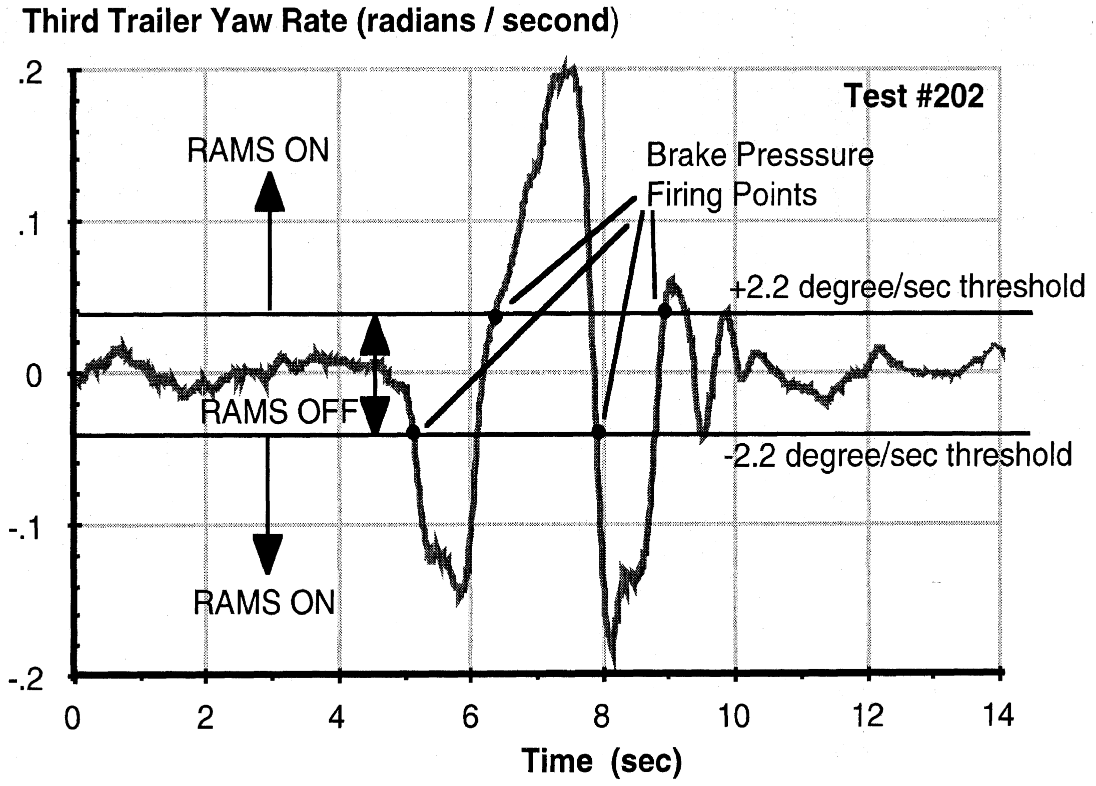


Figure 4-4. RAMS Activation Determined by Magnitude of Sensor Signal.

The 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 a certain speed such as 50 mph or so. 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.

4.2 Trailer-Only Algorithms and the Diagonal Braking Strategy

The simulation runs conducted for the trailer-only class of RAMS algorithm possibilities indicated that simple yaw rate damping (or certain lateral acceleration) strategies were very effective at attenuating rearward amplification, provided that the correct brakes were involved in the control actuation. In fact, the simulation and associated analyses indicated that a *diagonal* braking scheme was the most beneficial scheme to achieving significant yaw damping. As indicated in Figure 4-5, 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 so-called brake-steer compliance within typical truck/trailer suspensions. 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. See Figure 4-6. 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. Consequently, as depicted in Figure 4-7, 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. (Appendix A discusses these basic inter-relationships in more detail with some of the same accompanying figures.)

– RAMS Trailer-Only Algorithm –

The Diagonal Braking Strategy

- **Utilizes diagonal wheel locations (e.g., dolly right-side and semi left-side brakes)**

Why?

- **To take advantage of suspension brake-steer compliance in order to 'steer' each axle and thereby generate *lateral* tire forces for yaw damping purposes**

Figure 4-5. Diagonal Braking Advantage in RAMS Trailer-Only Algorithm.

Brake-Steer Compliance Mechanism

1: RAMS brake pressure applied to one one side of axle

2: Longitudinal tire force results

3: Axle steers in response to asymmetric loading and the bushing compliances in the suspension

4: Lateral tire forces generated

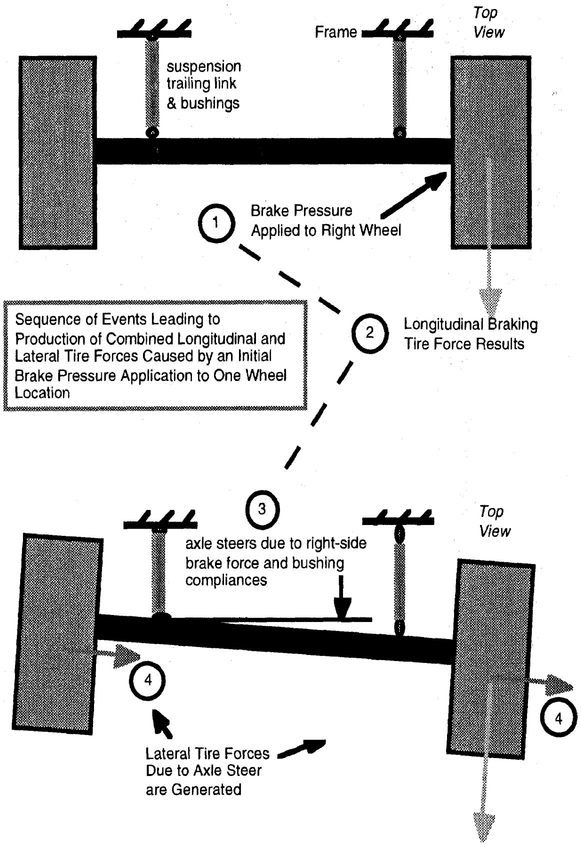


Figure 4-6. Brake-Steer Compliance Mechanism.

The Contribution of Both Lateral and Longitudinal Tire Forces Generated by RAMS Towards a Corrective Yaw Moment Acting on the Trailer.

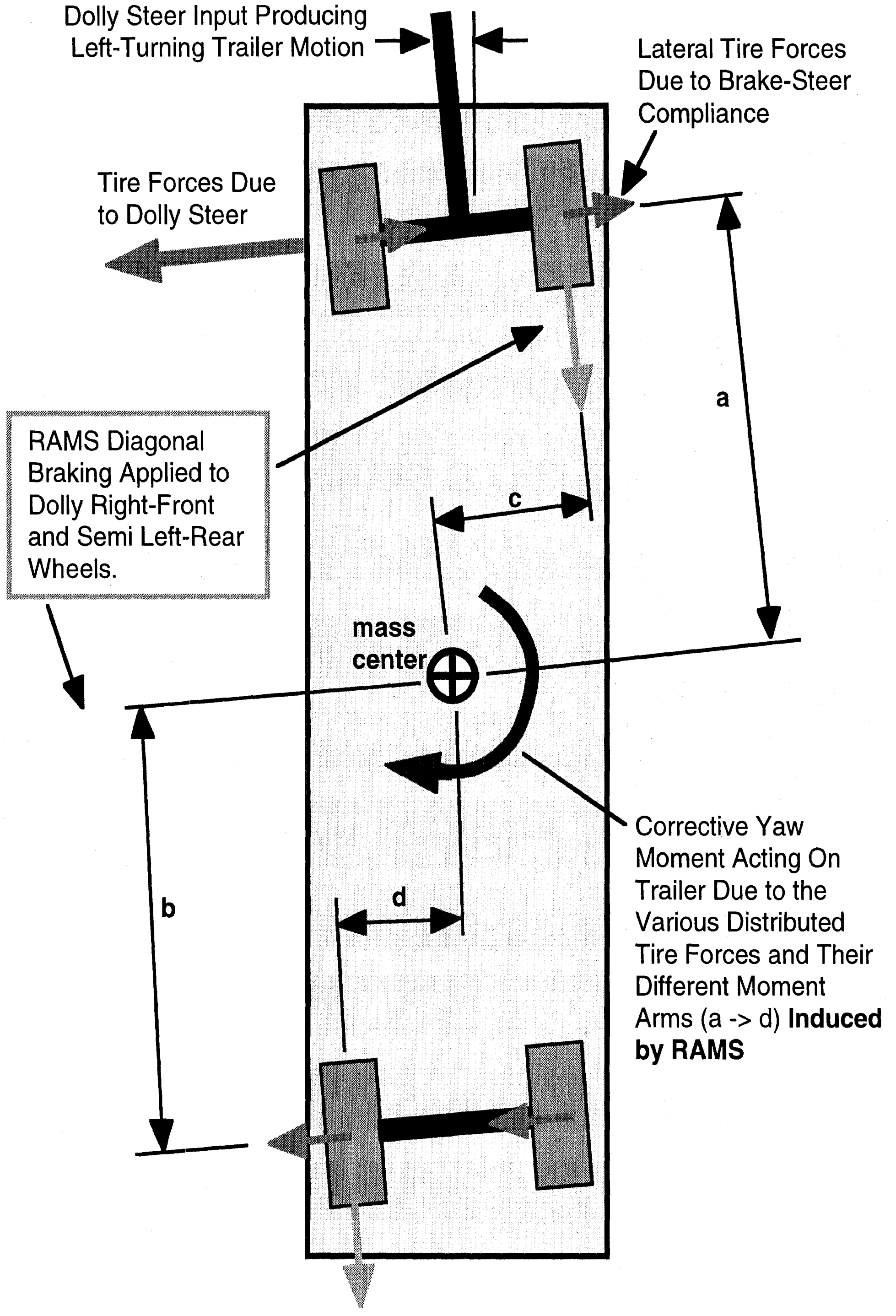


Figure 4-7. Corrective Yaw Damping Moment from Trailer-Only RAMS System Employing Diagonal Braking.

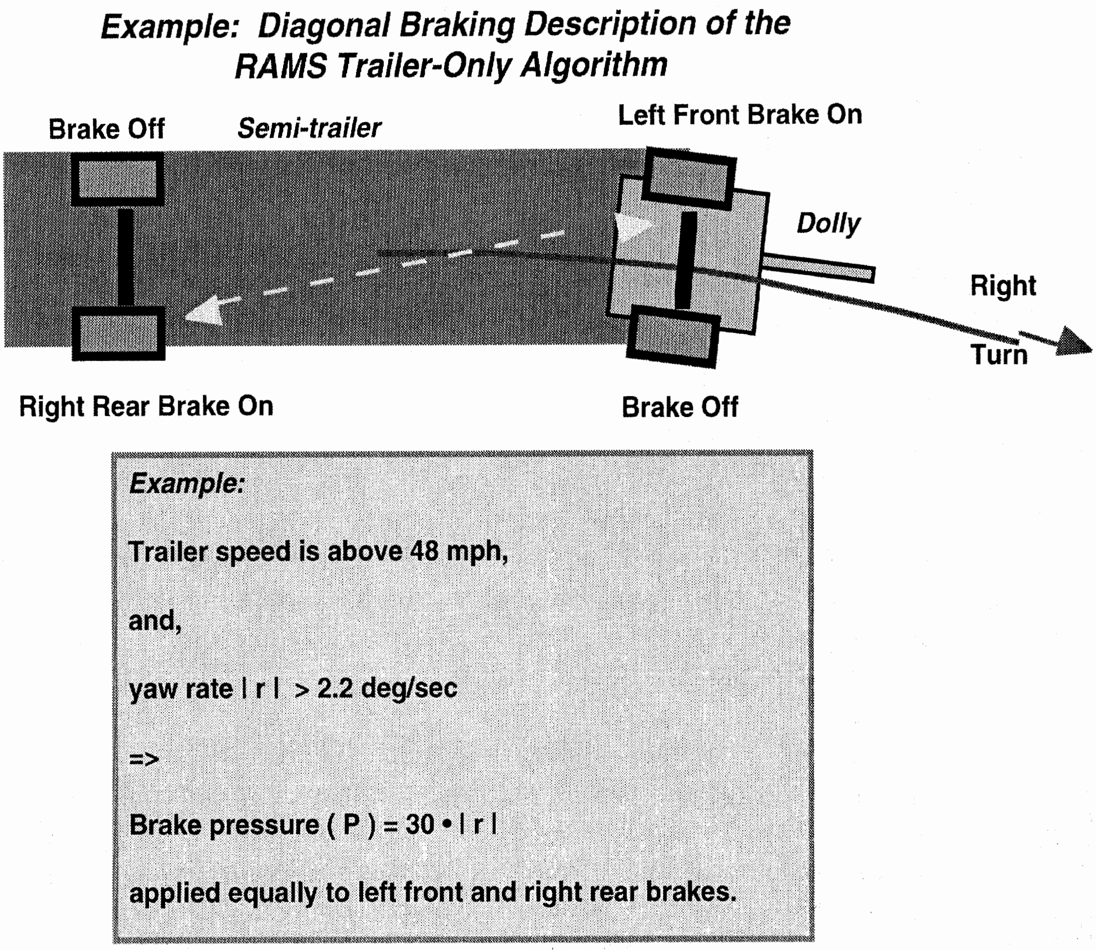
As a result of these simulation runs and analyses for the trailer-only class of algorithms, both yaw rate damping employing the described diagonal brake strategy and a similar algorithm that uses lateral acceleration signals from the nose location of the semitrailer, were brought forward as the most promising trailer-only algorithms to utilize and evaluate within the full vehicle tests at VRTC.

A summary of the 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 Figure 4-8. A corresponding simple example depicting its operation at the start of a turning maneuver is seen in Figure 4-9. Here, 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) and a brake gain of 30 psi per degree/second of yaw rate. Figure 4-10 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.

- RAMS Trailer-Only Algorithm -

- **Utilizes semi-trailer yaw rate as the only sensor signal (per semi/dolly combo)**
- **Employs 'diagonal' braking strategy**
- **System only activated for vehicle (trailer) speed > 48 mph**
- **Braking applied when semi yaw rate exceeds threshold of 2.2 degrees/second (corresponds 0.1 g's at 55 mph)**

Figure 4-8. Summary Features of a Trailer-Only RAMS Algorithm Utilizing Semitrailer Yaw Rate as its Sensor Signal.



Example:

Trailer speed is above 48 mph,

and,

yaw rate | r | > 2.2 deg/sec

=>

Brake pressure (P) = 30 • | r |

applied equally to left front and right rear brakes.

Figure 4-9. Example Operation of a Trailer-Only Algorithm Utilizing Semitrailer Yaw Rate as its Sensor Signal.

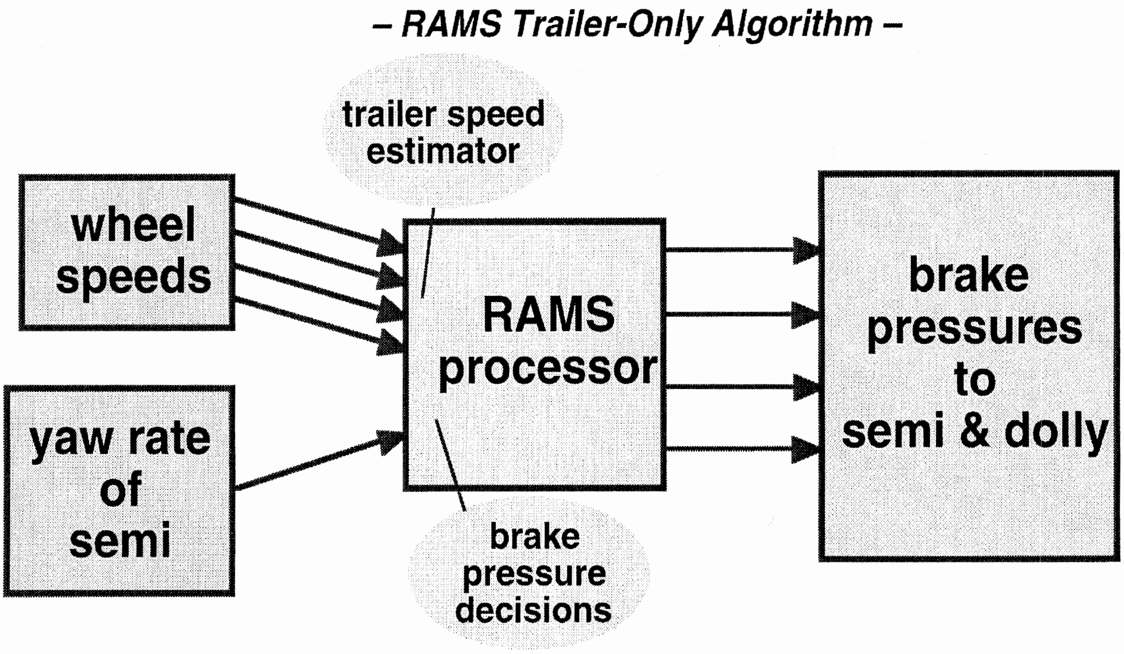


Figure 4-10. Use of ABS Wheel Speed Signals to Estimate Forward Speed and Semitrailer Yaw Rate to Activate RAMS Braking.

4.3 Trailer-to-Trailer Algorithms

With regard to the trailer-to-trailer class of RAMS algorithms, two basic algorithms were identified as also being potentially effective. These two algorithms used the *sum* or the *difference* of yaw rates from two adjoining trailers as their basic sensor input to the algorithm. The first trailer-to-trailer algorithm used the sum of yaw rates from the host trailer and its preceding trailer to control brakes pressures on the host trailer. The idea is similar to the simpler trailer-only yaw rate damping scheme, but attempts to anticipate the beginning of the host trailer yaw rate by adding in the yaw rate of the preceding trailer as a preview device. This scheme also employed diagonal braking similar to that used for the trailer-only algorithms and was indicated as a good candidate to examine within the test program.

The other promising trailer-to-trailer algorithm identified within the simulation study utilized the *difference* in two adjoining trailer yaw rates (i.e., articulation rate) as the basic sensor signal. This algorithm was similar to the other trailer-to-trailer algorithm but instead utilized braking on the inside wheels of the host trailer whenever turning occurred.

4.4 Full-Vehicle Algorithms

The full-vehicle RAMS algorithms that were examined within the simulation study started with the same algorithm utilized in the previous smart truck project [1] for a doubles combination. It was extended under this project to a triples combination. This algorithm was far more complex than any of the trailer-only algorithms described above. For example, operation of the dolly brakes depended upon steering inputs from the tractor driver, yaw rate signals from the tractor and semitrailer, and time-delay calculations for some of these signals. Simulation of these rules appeared to provide similar beneficial performance for the triples, however full evaluation of its performance was reserved for the test program in light of the emphasis within this project on the simpler trailer-only algorithms.

Other full-vehicle algorithms that were simulated included mixtures of features from the initial full-vehicle doubles algorithm and portions of the more recent trailer-only algorithms that relied on simple yaw rate damping concepts. Several examples of these were also programmed into the test vehicle for their evaluation on the test track.

5.0 Vehicle Tests at VRTC

Following the installation of instrumentation and RAMS hardware on the test vehicle at UMTRI, testing was begun at the Vehicle Research and Test Center facility (VRTC) near Columbus, Ohio. By this time, most of the RAMS algorithms that had performed well within the simulation analyses were also programmed into the on-board vehicle computer system for evaluation within the testing program. The on-board software was designed to allow for rapid selection of different RAMS algorithms on-the-fly during a testing sequence in order to increase efficiency. This allowed for a rapid coverage of the key algorithms that were identified within the simulation analyses. As testing continued and other variations of the basic algorithms were considered, the test vehicle could be re-programmed during testing stoppages to implement these alternate concepts. This overall arrangement produced a good mixture of flexibility and efficiency for the RAMS data collection activities.

Figure 5-1 outlines the basic set of vehicle configurations, their payload arrangements, and surface conditions used in the RAMS testing. For each vehicle and surface combination, a fairly complete set of RAMS algorithms was tested, including several repeats at all 55 mph speed conditions. Each test configuration usually started with a single test run conducted at 45 mph in order to verify the basic system operation intended for the algorithm (i.e., presence of brake pressures at designated wheels, correct signal polarities, timing and sequencing of brake pressures along the vehicle train, etc.). Speed was then increased to 55 mph and several repeat tests were usually conducted at that speed for the same algorithm.

The basic test procedure utilized the closed-loop lane-change maneuver described earlier in Figure 2-5. Test speeds were either 45 or 55 mph on the dry and wet asphalt surface.

A test speed of 38 mph was used on the wetted jennite surface. The VRTC facility limits maximum speeds to 40 mph on the wet jennite surface area for safety reasons. Consequently, RAMS testing on this low friction surface was limited. Accordingly, the system feature that normally inactivates RAMS for speeds below 48 mph was **disabled** for these special tests in order to evaluate whether or not any potential benefit accrues from RAMS operation under very low friction surface conditions.

RAMS testing began with the doubles configuration and the payload located at the lowest 70-inch height. All payload height variations occurred in the last two trailers of the triple, or the last trailer of the double. The first semitrailer load was always fixed at a height of 70 inches above ground (All payload height measurements are denoted with respect to ground unless otherwise indicated). The doubles testing started with several non-RAMS tests to obtain representative baseline response information for the nominal vehicle without any RAMS stability enhancements. RAMS testing then began for each of the RAMS algorithms, always starting with a 45 mph run followed by three 55 mph runs. Following the complete set of RAMS algorithm tests for the doubles combination in its low payload configuration (70 inches), the triples configuration was then assembled and testing continued.

Test Matrix / Summary

- **Doubles Testing:** **Low c.g. (70" payload height) / 45 & 55 mph speeds High friction surface conditions**
- **Triples Testing:** **Low & High c.g.'s (70", 88", 92") / 45 & 55 mph speeds / High friction surface, dry and heavy rain conditions**
- **Triples Testing:** **Low Friction Surface Tests (wetted jennite) / 38 mph / Low c.g. payload location**
- **Most Configurations Evaluated with:**
  - **No-Rams**
  - **Multiple Trailer-Only RAMS Algorithms**
  - **Multiple Trailer-to-Trailer RAMS Algorithms**
  - **Multiple Full-Vehicle RAMS Algorithms**

Figure 5-1. Summary of the Basic Vehicle Configurations and Surface Conditions.

The triples testing also started in the low payload configuration of 70 inches. As with the doubles, several non-RAMS tests were conducted to obtain representative response data for that baseline configuration. Test sequences at 45 mph and 55 mph as before were then conducted for each of the RAMS algorithms. At these lower payload heights, no unusual roll responses were observed, even without the RAMS active.

The next sequence of tests was conducted with the payload in the last two trailers raised to a height of 88 inches above ground. In this configuration at 45 mph, the rearward amplification phenomena were largely absent and the last trailer of the triples combination was relatively stable in its roll response. However when speed was increased to 55 mph for this same configuration, the last trailer of the triples combination was easily rolled onto its outriggers in both directions.

At this point, the RAMS algorithm testing then recommenced. Most of the selected algorithms provided improvement to the roll stability response of the rearmost trailers. Results of these tests are summarized in the next Section 6. However a representative set of time history plots for the triples configuration can be seen in Figures 5-2 through 5-6 corresponding to the non-RAMS triple and the same vehicle equipped with one of the trailer-only RAMS systems.

The set of plots seen in Figures 5-2 correspond 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 phenomena are 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 2 to 3 times larger than the corresponding tractor values in both of these vehicle response plots. (As noted above, at a speed of 45 mph, the rearward amplification phenomena are largely absent, indicating a 'safe harbor' effect with regard to vehicle speed, as well as a strong sensitivity to speeds above 45 mph.)

The time history results seen in Figure 5-3 correspond to the same vehicle and test conditions, but with a trailer-only RAMS system active and utilizing semitrailer yaw rate as the sensor feedback signal. Diagonal braking is also employed as part of the RAMS strategy. As seen in Figure 5-3, 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 5-2 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 2.0 for the triple.

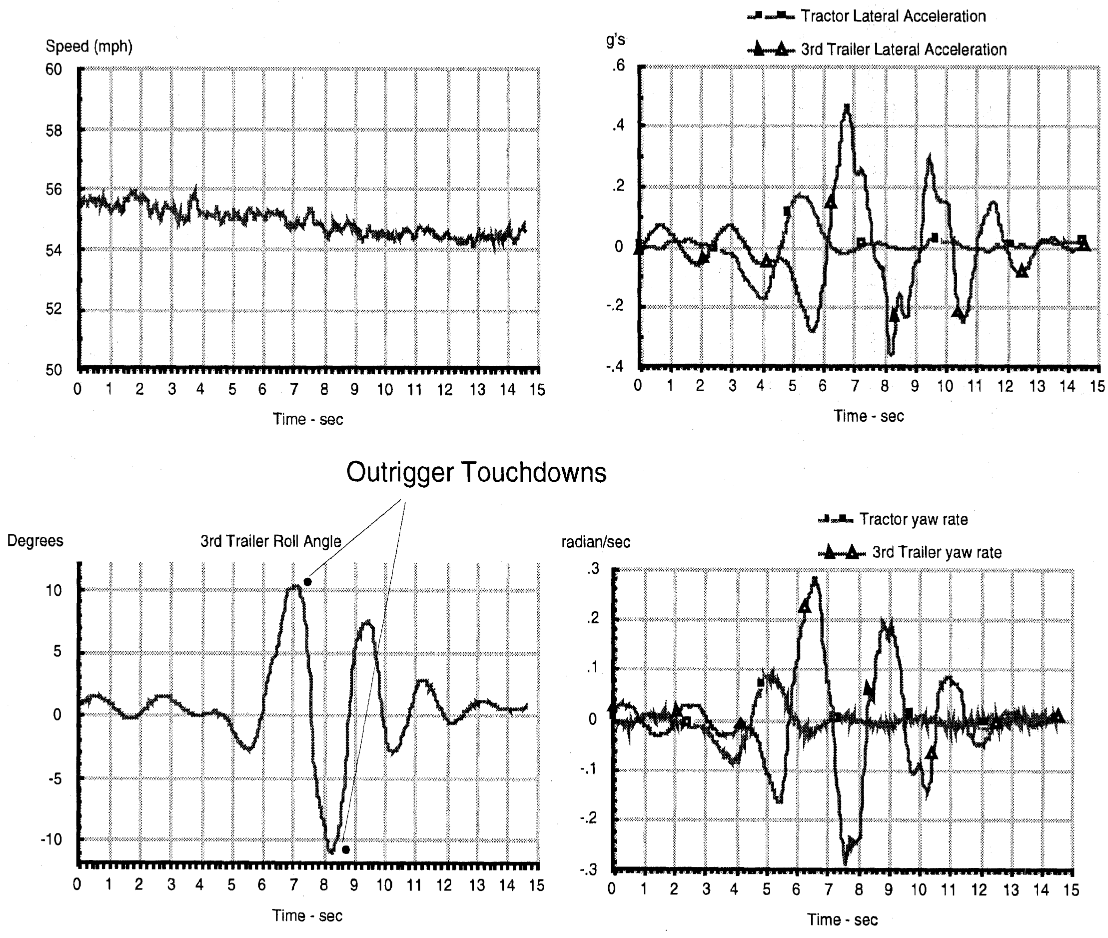


Figure 5-2. Representative Non-RAMS Test Result for the Triples Combination at 55 mph and an 88-inch Payload Height.

Figures 5-4 and 5-5 contain time history measurements of brake pressures from the last two trailers in the same RAMS test run #202. Brake pressure recordings on the second trailer seen in Figure 5-4, show that at a time of about 4.5 seconds, pressures are first applied to the right dolly and left semitrailer wheels. A short time afterwards, at about 6.0 seconds, brake pressures are then applied to the left dolly and the right semitrailer wheels of the second trailer. The opposite diagonal wheels are commanded to zero pressure. One more pressure application occurs for the right side dolly and left side semitrailer wheels at a time of about 7.5 seconds. This back and forth diagonal brake pressure sequence at each trailer helps to damp out excessive yaw motions in the trailer.

A similar sequence of diagonal alternating pressures is seen in Figure 5-5 corresponding to the last trailer of the triples combination.

If a particular wheel location is undergoing a lightened load when the RAMS system commands pressure to that wheel and a wheel lockup begins to occur — as commonly occurs on the semitrailer wheels — the antilock brake system will intervene and dump brake pressure for that wheel, thereby overriding the commanded RAMS brake pressure request. This is a desirable feature of RAMS and should always be enabled so that any installed ABS system has the final control authority over the wheel in such situations. Some examples of this overriding ABS behavior appear in Figures 5-4 and 5-5 for the rear semitrailer wheel locations. (Occasionally the ABS system would unexpectedly lock out the RAMS command for a short period of time following an ABS override. An example of this occurred in test #202 for the third trailer right-side brake at the time value of 6 seconds where a RAMS command was issued to that brake, but was ignored due to an ABS lock-out.)

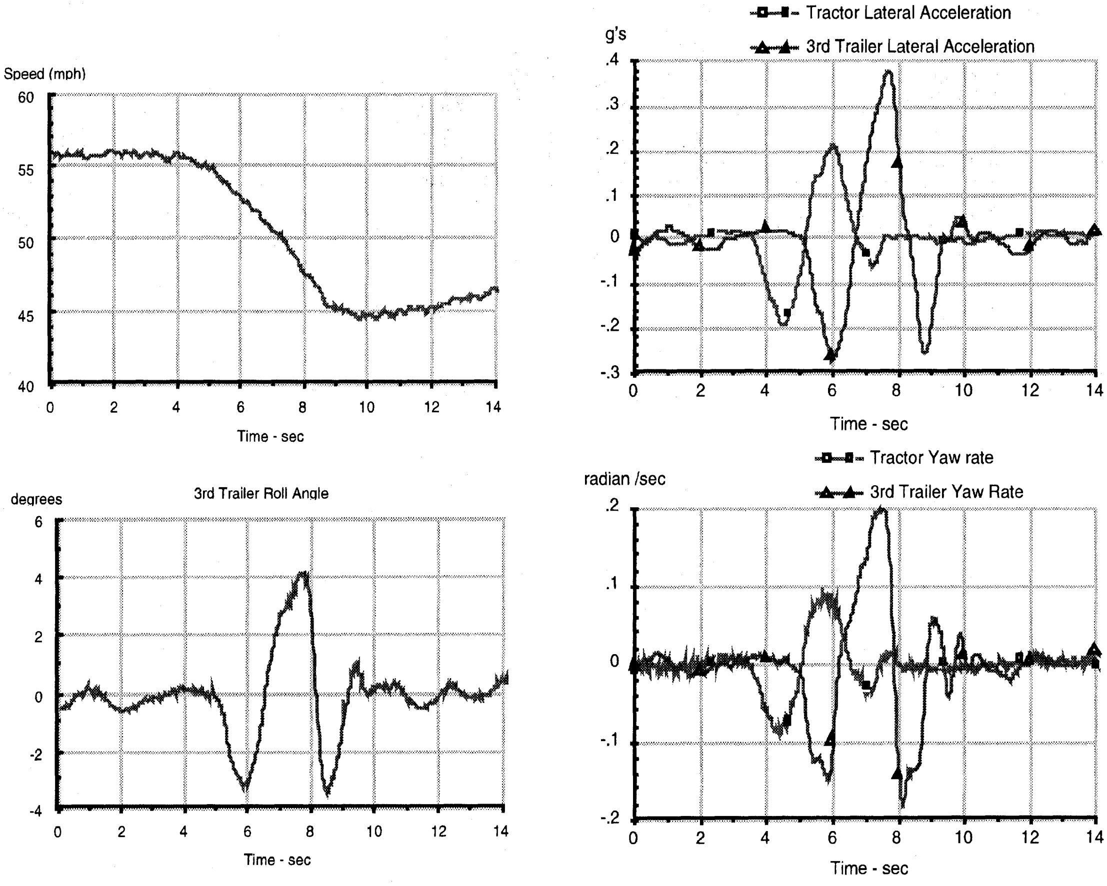


Figure 5-3. Representative Trailer-Only RAMS Test Result for the Triples Combination at 55 mph and an 88-inch Payload Height.

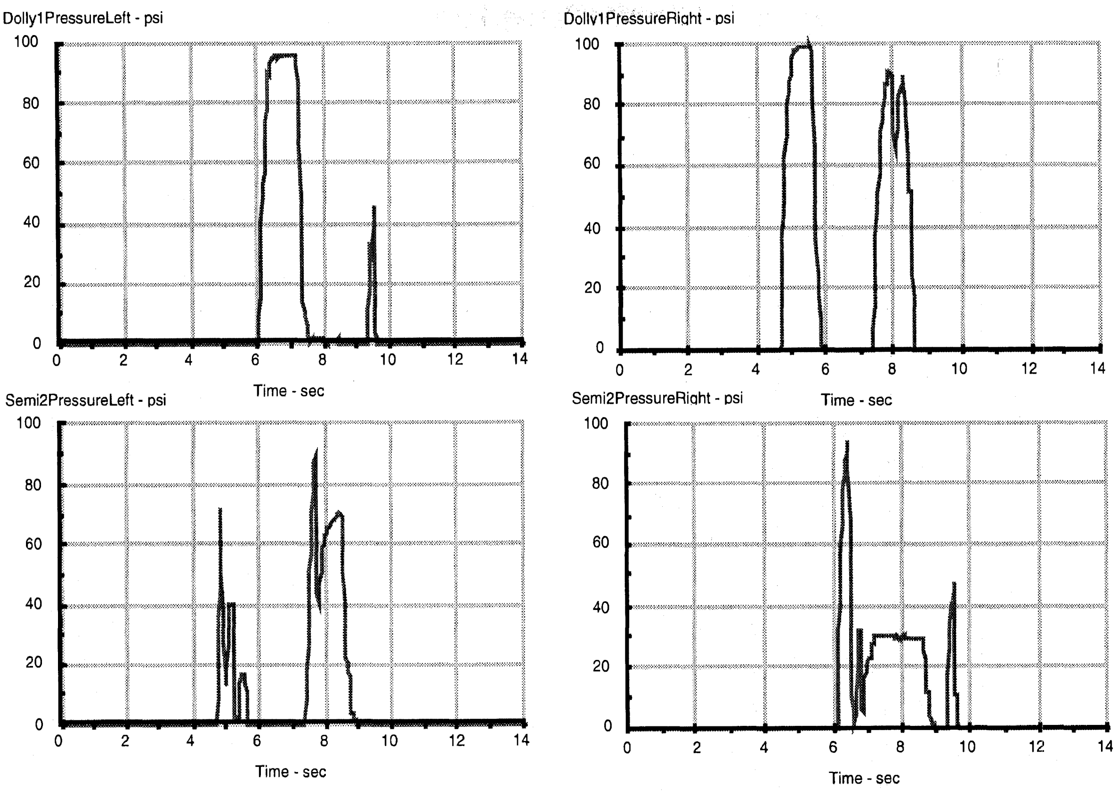


Figure 5-4. RAMS Brake Pressures Applied to the Dolly and Semitrailer Wheels (left & right side wheels) of the Second Trailer (Test #202).

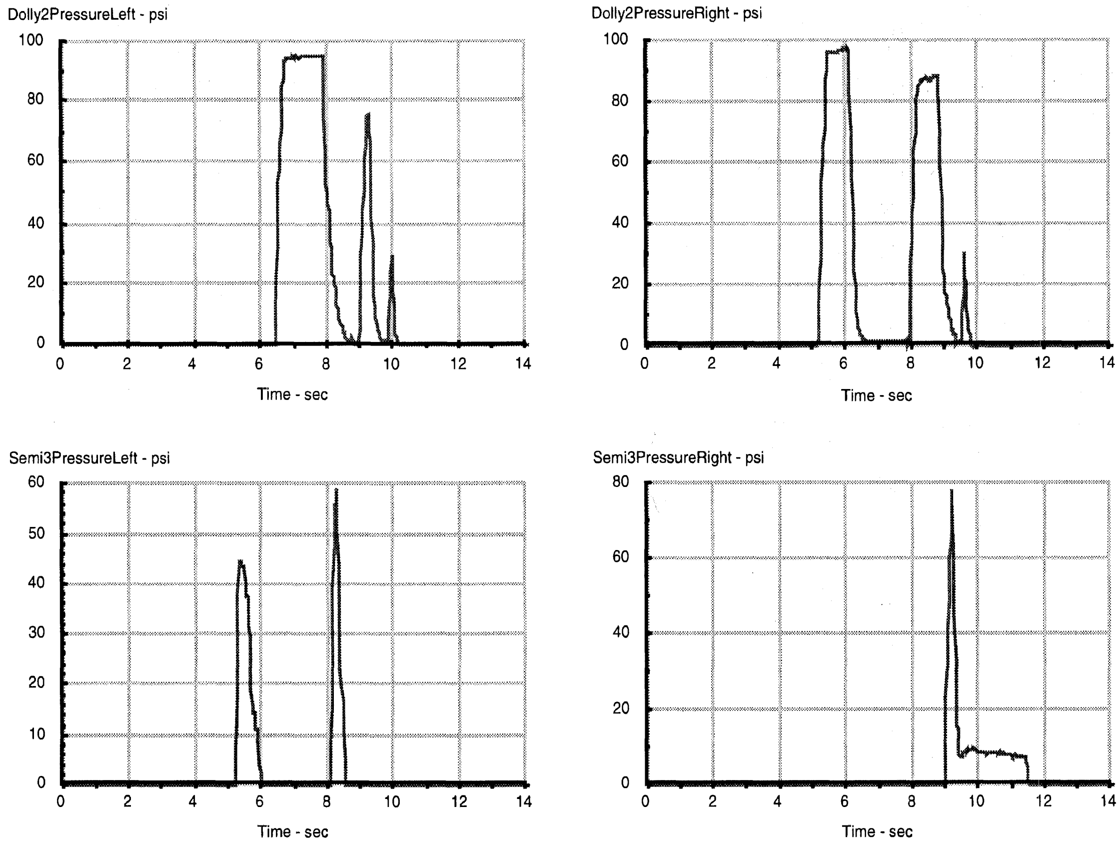


Figure 5-5. RAMS Brake Pressures Applied to the Dolly and Semitrailer Wheels (left & right side wheels) of the Third Trailer (Test #202).

A clearer example of the diagonal braking scheme and an ABS overriding intervention at the semitrailer wheel locations is perhaps provided in Figure 5-6 from test run #204. As seen in Figure 5-6, the ABS interrupts the first requested RAMS brake pressure command at the semitrailer wheels on both the left and the right wheels. The second brake pressure request at the semitrailer left side wheel is not interrupted (trailer is undergoing less load transfer by this time and becoming stabilized) and identical brake pressures traces (double pulses proportional to semitrailer yaw rate variations measured by its yaw rate sensor) are seen towards the end of the run at the left semitrailer wheel and the right dolly wheel. These latter pressure modulation traces that are identical reflect the operating nature of the diagonal braking scheme when no ABS interruptions occur.

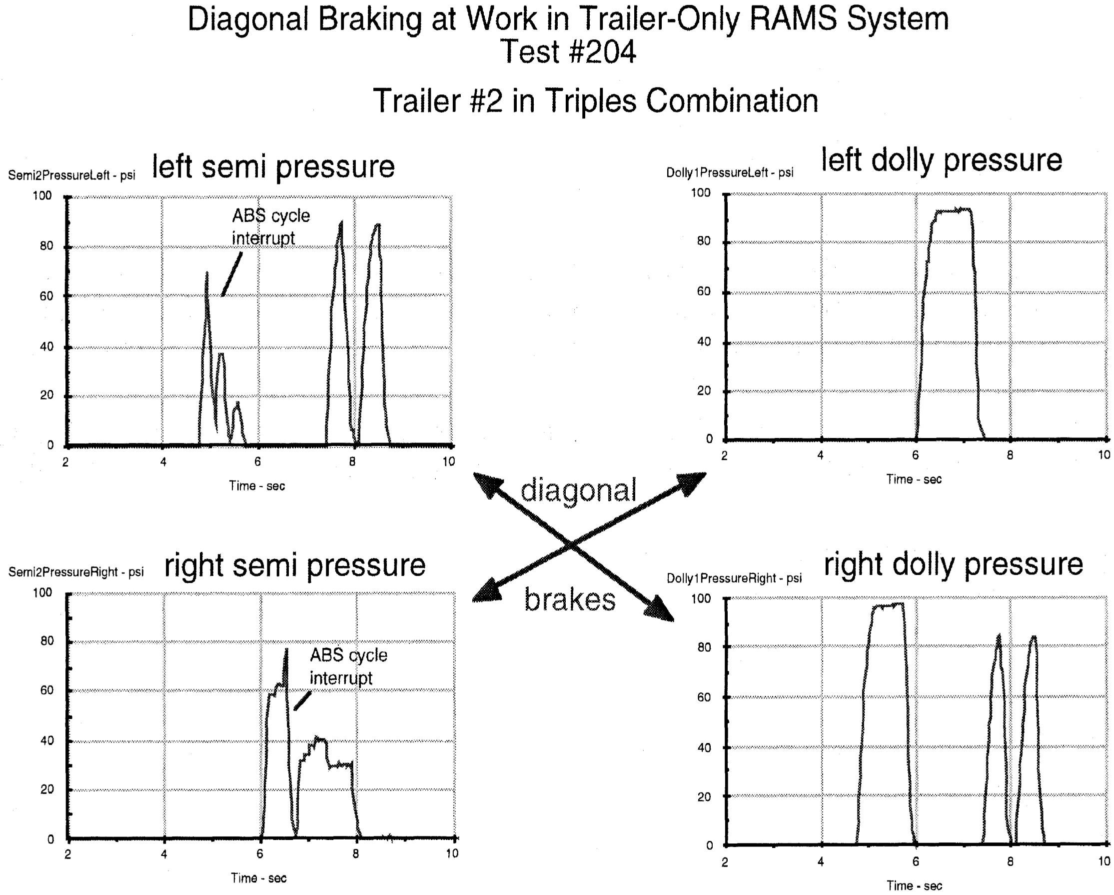


Figure 5-6. Diagonal Braking Feature Present in the Trailer-Only Algorithm with ABS System Interruptions. Second Trailer Brake Pressures for Test #204.

5.1 Road Surface Friction Influence

RAMS testing was conducted under three different surface conditions. These included (a) the dry asphalt VRTC skid pad, (b) the same asphalt surface but under heavy rain conditions, and (c) the wetted jennite low friction test surface at VRTC. On the asphalt surface, the RAMS systems performed well and generally very similarly under both dry and wet conditions, despite many of the tests being conducted during heavy rain and standing water.

On the wetted jennite surface, for which the tire/road friction level was reduced to a range of 0.35 – 0.20 (depending on longitudinal slip and locked-wheel state of the tire), RAMS test results were significantly different. (Test speeds on this low friction surface were limited to speeds below 40 mph for safety reasons — as noted above at the start of Section 5. The RAMS feature that inactivates system operation for speeds less than 48 mph was accordingly disabled in order to conduct this test sequence.) Under these low friction surface conditions, the primary instability is *trailer swing* due to the diminishment of available lateral tire forces, not trailer rollover. That is, as the tractor unit performs a lane-change or obstacle avoidance maneuver, the subsequent motion of following trailers undergoing similar motions will begin to exceed the available tire/road friction available from the wetted jennite surface and begin to slide laterally. This lateral sliding further compounds the lateral motion requirements for subsequent trailer and dolly tires. The net result is normally a series of left and right articulating trailer swings by the last trailer unit towards the middle and end of the lane-change maneuver. Some trailer swings can be large enough so as to encroach well into adjacent travel lanes.

This basic behavior was observed only on the very low friction jennite surface. It occurred with and without RAMS active, but was clearly amplified by the activation of RAMS. Under these low friction conditions, RAMS activation of course exercises various brakes along the vehicle train as part of its control strategy, thereby introducing longitudinal wheel slip as a confounding influence that attenuates the production of lateral tire force capabilities. This further reduces the amount of lateral tire force available and causes an additional degradation in the directional control of each trailer, leading to further trailer swing when RAMS is active.

No improvement in trailer directional behavior was observed for any of the RAMS-enabled configurations over the non-RAMS configuration when operating on the wetted jennite surface. This result of course was the direct opposite of all testing observations for the higher friction dry and wet asphalt conditions. In fact, the best-performing full-vehicle RAMS systems on the dry asphalt surface tended to be the worst performers on the wetted jennite. This again relates directly to the effective utilization of tire braking forces by RAMS and the availability of such forces when operating on mid- and high friction surfaces. Under low friction conditions where tire lock-ups occur more frequently and aggressively, the level of available longitudinal and lateral tire forces is sharply reduced due to the higher wheel slip conditions prevailing on these surfaces, thereby lessening the role that such tire forces play as normal stabilizing influences or as intervening control force influences.

5.2 Payload Height Variations

RAMS testing was conducted on the triples combination for payload heights (above ground) of 70 inches, 88 inches, and 92 inches. All payload height variations occurred only in the last two trailers of the triple. The first semitrailer payload height was fixed at 70 inches. The doubles combination was tested only with a payload height of 70 inches since it was primarily used to check out and verify the correct operation of the different RAMS control algorithms and associated hardware prior to the start of triples testing.

At the payload height of 70 inches, both the doubles and triples configurations exhibited good roll stability in their rearmost trailer units with or without RAMS activated.

At a payload height of 88 inches and the non-RAMS configuration, the third trailer of the triples combination was easily rolled during the lane-change test at 55 mph. At this same test speed, use of most any RAMS system (trailer-only, trailer-to-trailer, and full-vehicle algorithms) was helpful in stabilizing the rearmost trailer, though to varying degrees as indicated by the results seen in the next section. At 45 mph little rearward amplification was present in the non-RAMS vehicle and the third trailer roll response was stable.

The same general observations noted here for the 88 inch payload height also applied to the 92 inch payload height configurations. The primary difference was perhaps a modest reduction in overall roll stability, though nothing especially noteworthy.

6.0 Vehicle Test Results

The test results and charts presented in this section utilize two basic performance measures of rearward amplification to illustrate and document the performance obtained from each of the different RAMS algorithms relative to each other and to the non-RAMS baseline configuration.

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 normalized by 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. For example, for a rearward amplification gain value of 2.0, the peak lateral acceleration of the last trailer would be expected to be twice the average of the peak lateral acceleration level experienced by the tractor unit — during the defined lane change test maneuver.

The first set of results seen in Figure 6-1 and 6-2 correspond to these two performance measures for the triples combination operating on the dry asphalt test surface with a payload height of 88 inches at 55 mph. Figure 6-1 shows the last trailer roll gain measure versus several different RAMS algorithms. (The non-RAMS rollover cases are bounded by the maximum value of 60 — indicative of outrigger touchdowns — on this and similar graphs of this section.) The algorithms are grouped according to whether they fall into trailer-only, trailer-to-trailer, or full-vehicle classifications. Each bar represents the average of 3 to 5 test run repeats. Figure 6-2 shows the corresponding results for the rearward amplification gain performance measure.

As indicated in Figure 6-1, 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 trailer-to-trailer algorithm classification, the 'yaw rate difference' algorithm is the best with a value of 18.5. And in the full-vehicle classification the 'yaw tractor difference' algorithm is the best of the lot — and of all algorithms examined — indicating a value of about 18.0. A similar but less discriminatory trend is seen in Figure 6-2 for the corresponding rearward amplification performance measure. The functional specifications required for implementing the best trailer-only algorithm ('yaw rate') and the best full-vehicle algorithm ('yaw tractor difference') are contained in Appendix A.

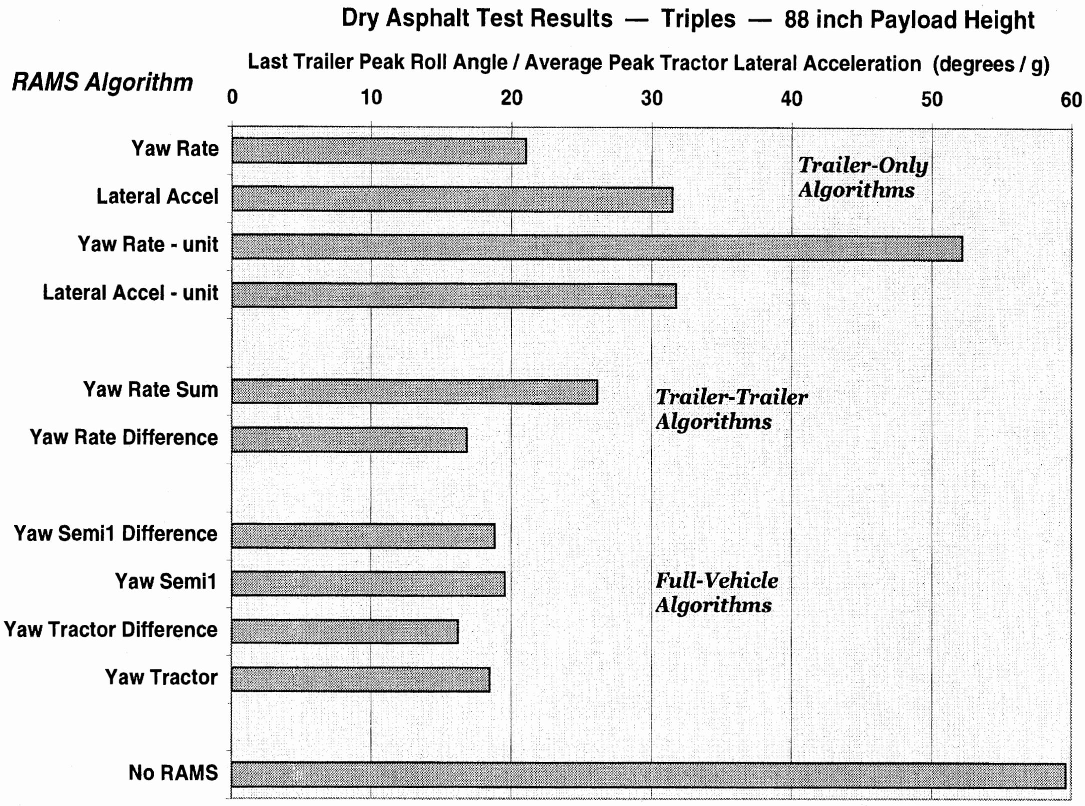


Figure 6-1. Last Trailer Roll Gain Performance Measure.

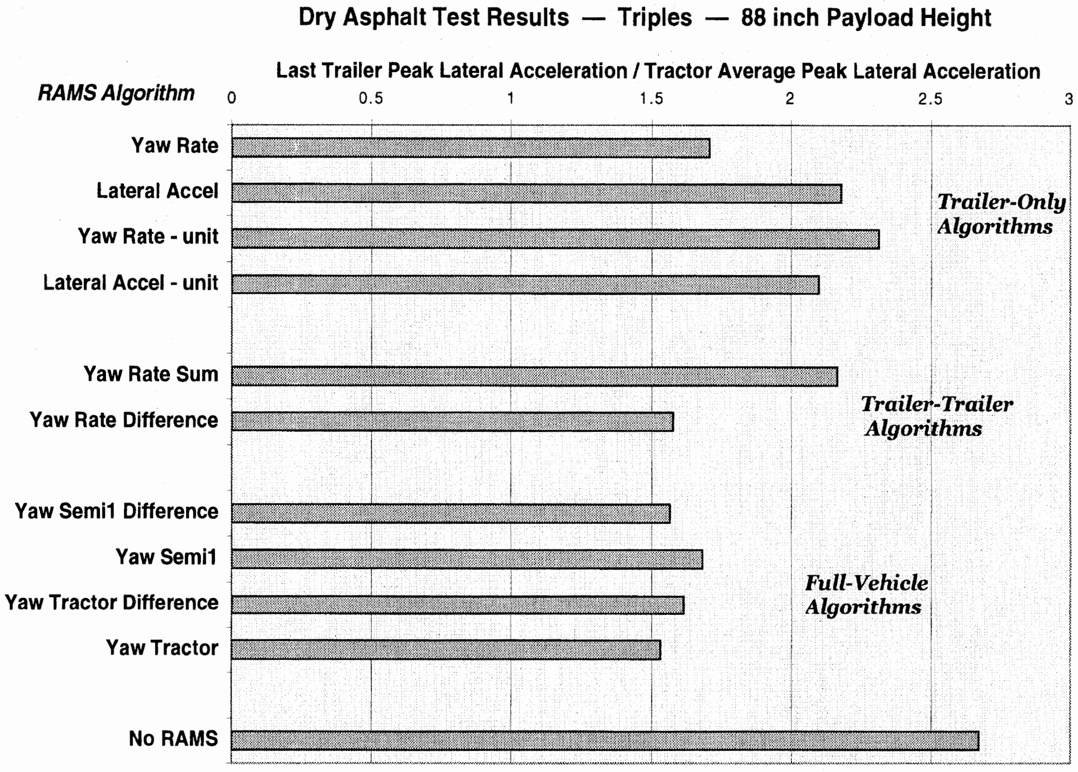


Figure 6-2. Rearward Amplification Gain Performance Measure.

Also seen in Figures 6-1 and 6-2 are results for 'yaw rate - unit' and lateral acceleration - unit' algorithms under the trailer-only algorithm classification. These two algorithms are true unit-by-unit algorithms in the sense that yaw rate gyros or lateral accelerometers mounted on the semitrailer and on the dolly unit directly controlled their own unit's brakes. That is, the dolly-mounted gyro measurement controlled the dolly brakes and the semitrailer gyro measurement controlled the semitrailer brakes. Unfortunately, neither of these concepts demonstrated any performance similar to the 'yaw rate' trailer-only algorithm. Reasons for this likely relate to timing issues. That is, the yaw rate response of the dolly, though similar to that of the semitrailer, is advanced in time from the semitrailer response. Since the semitrailer is the principal mass and its motion should be of primary concern for the RAMS control system, responding to the dolly unit yaw rate response, as though it were the semitrailer, is likely ill-timed and a poor surrogate in this application. Other issues such as an increased noise environment for the dolly transducer measurement may have also played a role in this poorer performance.

Figures 6-3 and 6-4 contain a subset of results for the same triples configuration operating now with a 92-inch payload height at 55 mph. The same basic observations apply for this configuration and further confirm the test results measured with the 88-inch payload configuration.

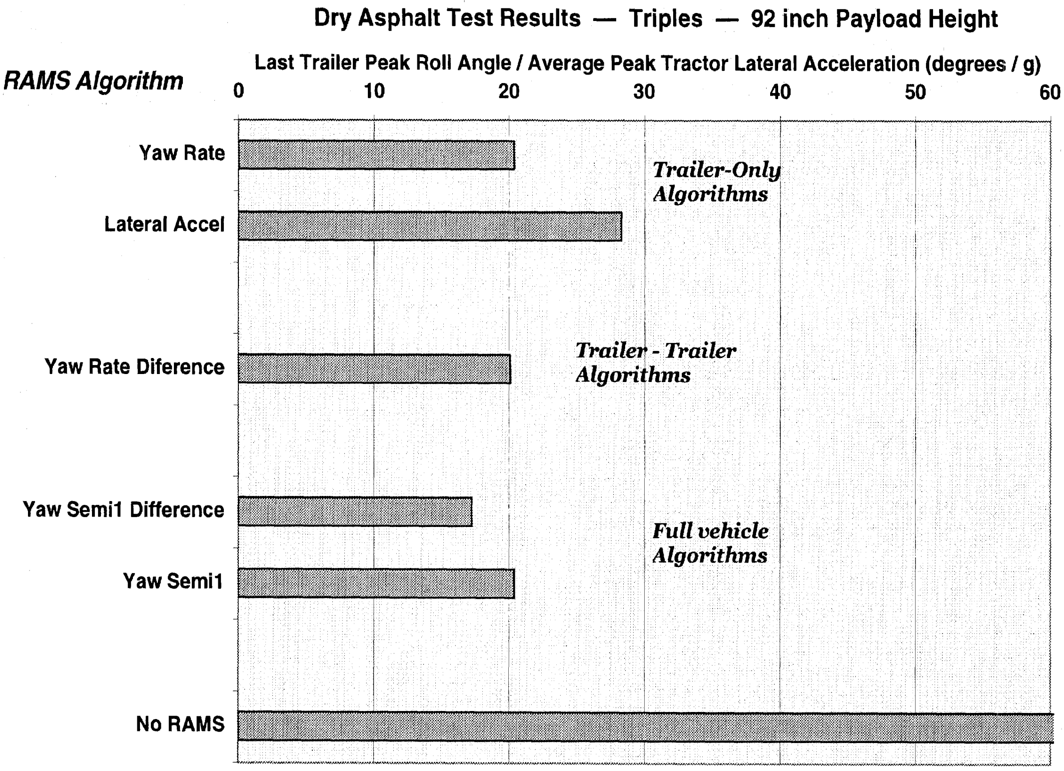


Figure 6-3. Last Trailer Roll Gain Performance Measure.

Test results for the last trailer roll gain performance measure obtained on the wet asphalt surface during heavy rain conditions is seen in Figure 6-5. The same basic trend observed on the dry asphalt surface was also maintained under these wet conditions. Again, the best performing trailer--only algorithm was the 'yaw rate' system. For the trailer-to-trailer algorithm classification the 'yaw rate difference' system was best. No full-vehicle algorithms were tested during the wet asphalt series due to time constraints caused by instrumentation and weather delays. However, based upon the results obtained for the other algorithms and their similarity to the dry asphalt results, similar trends in beneficial performance would be expected from the full-vehicle systems under these wet asphalt conditions.

Results for the rearward amplification gain performance measure are not available for the wet asphalt test condition due to an intermittent electrical connector problem affecting the last trailer's lateral accelerometer measurement that occurred during the wet test series.

A special series of wet asphalt tests labeled as 'simple braking' algorithms is also seen in Figure 6-5. These algorithms applied *all* brakes on the trailer units (instead of utilizing differential side-to-side diagonal braking) to see if a simple-minded approach of slowing the vehicle down during a rearward amplification event would provide the same benefit as the differential braking algorithms that attempted to damp trailer yaw motions while slowing the vehicle. The results indicate that this approach does not work very well, though it is somewhat better than the worst case non-RAMS configuration.

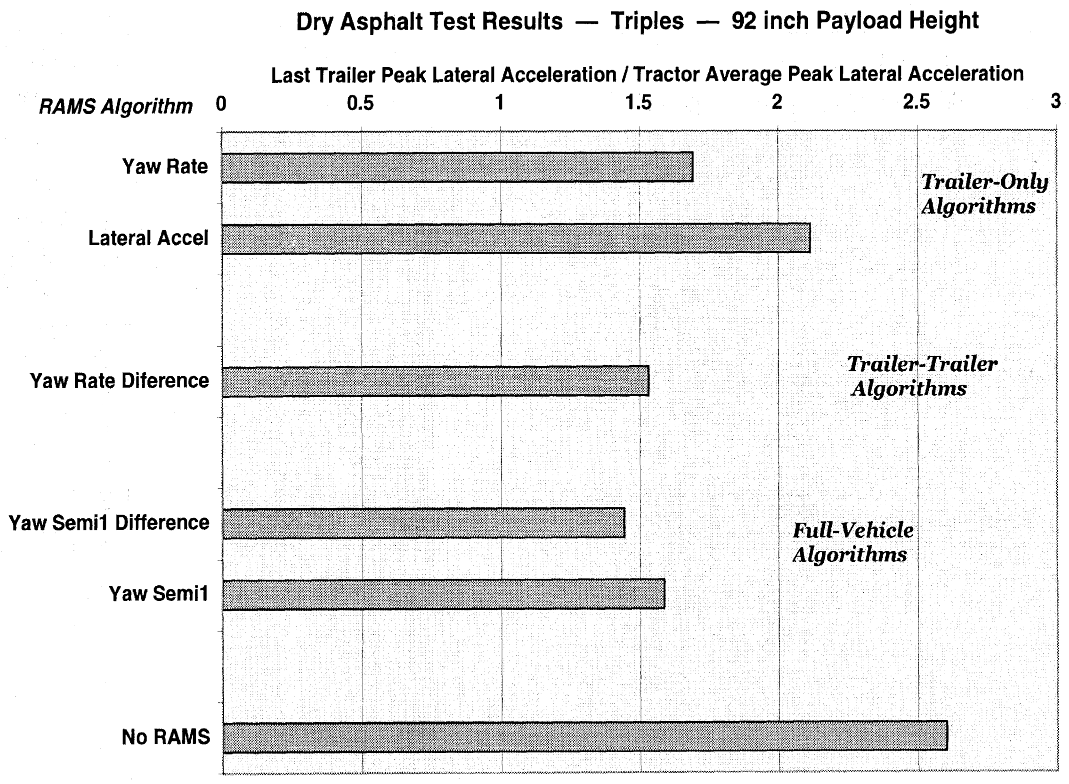


Figure 6-4. Rearward Amplification Gain Performance Measure.

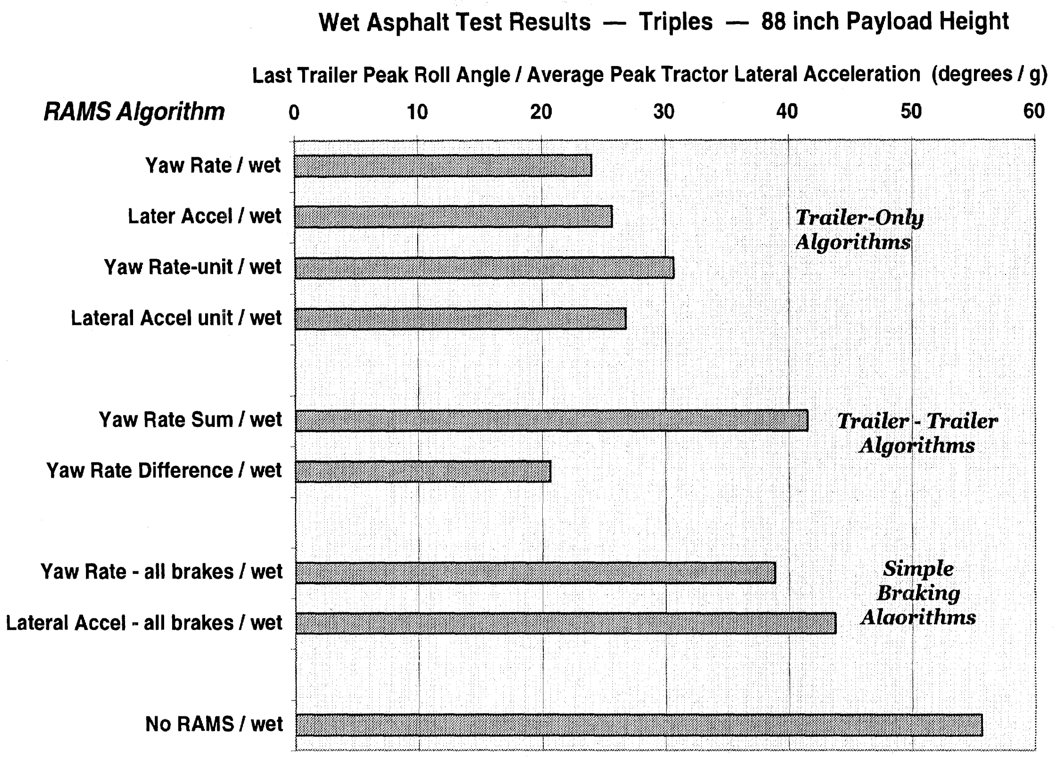


Figure 6-5. Last Trailer Roll Gain Performance Measure.

Lastly, Figures 6-6 and 6-7 show a subset of results for four different RAMS systems with the triples combination operating in its lowest payload height configuration — 70 inches. These results are presented primarily as a simple indicator of the strong sensitivity of the trailer roll gain performance measure to the influence of payload height. Like forward speed, payload height plays a powerful role in affecting the level of last trailer roll gain exhibited by a combination vehicle.

Interestingly, the lateral acceleration gain performance seen in Figure 6-7 for the same four different RAMS systems is largely unaffected by payload height when contrasted to corresponding results seen in Figure 6-2 for the 88 inch payload height condition. This may be due in part to the use of the stabilized platform in the last trailer on which is mounted the last trailer's lateral accelerometer and thereby free of most roll-related influences. The other contributor to this observation is, of course, the intervention and control activity of the RAMS systems which act in a compensating manner to limit the level of lateral acceleration amplification present in the vehicle train, regardless of the payload height.

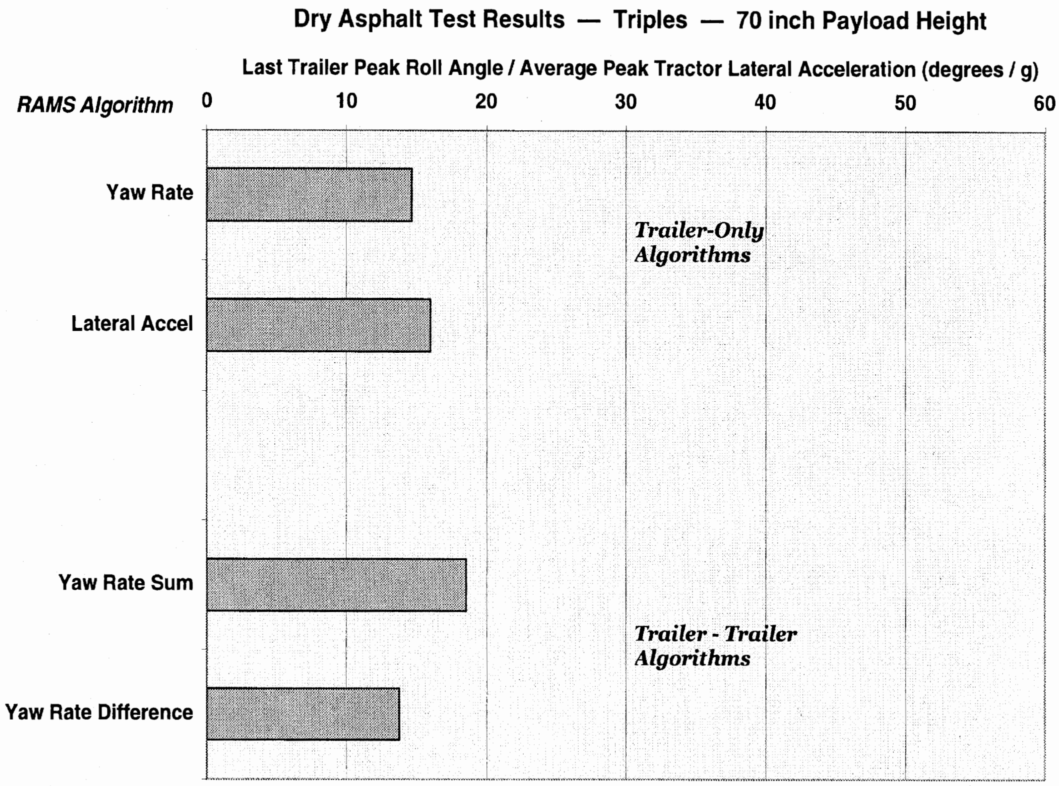


Figure 6-6. Last Trailer Roll Gain Performance Measure.

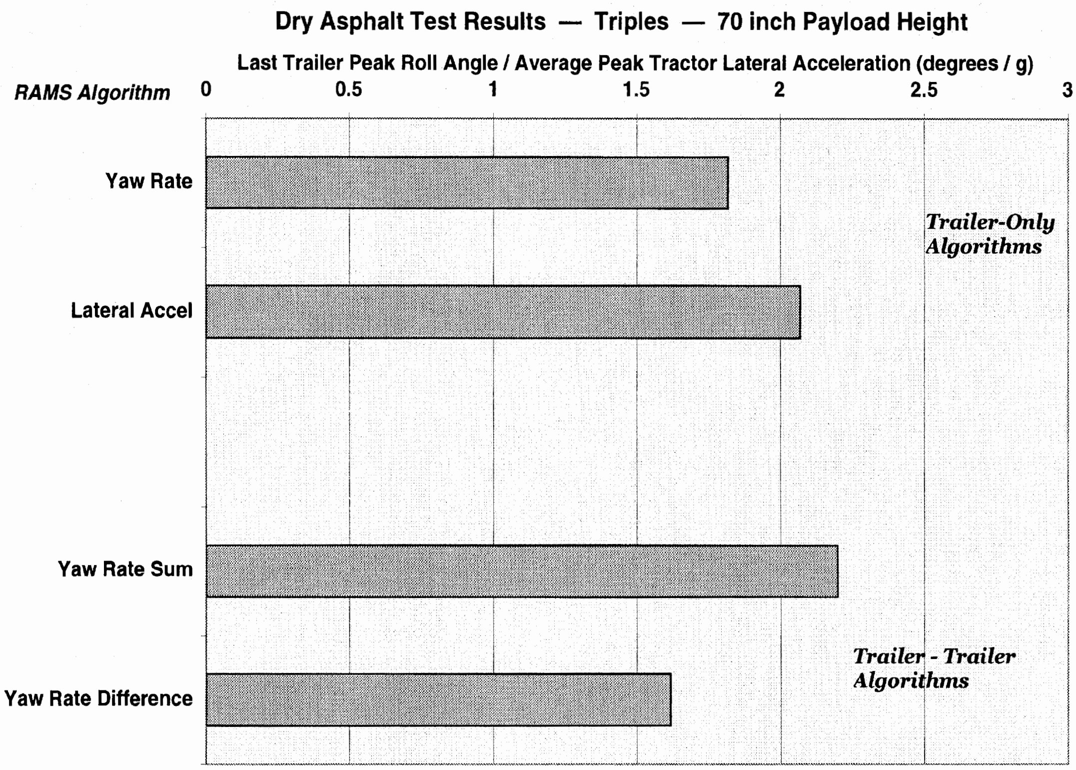


Figure 6-7. Rearward Amplification Gain Performance Measure.

Lastly, questions regarding the likely operation of the recommended trailer-only RAMS system along freeway connector sites or similar highway scenarios — where sustained turning is required at elevated highway speeds — was addressed briefly through computer simulation. If turning requirements are large enough at such sites so as to cause trailer yaw rates to momentarily exceed the RAMS activation threshold, some 'firing' of the RAMS system could occur during entry into and out of such curves.

To examine this possibility, a very aggressive highway curve geometry (straight section — to fixed radius curve — to straight section) was specified within the UMTRI computer simulation and the triples combination was then run along this hypothetical road geometry to evaluate the behavior of the RAMS system. The results indicated that even for a highway curve geometry having twice the curvature that is likely to ever be encountered on an interstate freeway system, the RAMS system was activated only briefly upon entry into the curve, and briefly upon exit from the curve. The total loss of vehicle speed as a result of the RAMS firing was less than 2 mph. Appendix C contains plots in Figure C-1 of simulation time histories for the required driver steering response needed to negotiate the specified curve, corresponding lateral acceleration of the tractor unit and last trailer, and forward speed of the vehicle.

This particular curve (1000 ft radius) and speed of travel (55 mph) produce an approximate 0.2 g requirement in terms of lateral acceleration. As seen in Figure C-1, both the tractor unit and the last trailer reflect this requirement with the last trailer exhibiting very little overshoot or rearward amplification of lateral acceleration. The primary reason for this relatively tame response from the last trailer under this scenario is due to the lower frequency steering input provided by the simulated driver. As noted previously, rapidity of steering input is a key ingredient in the development of rearward amplification events during highway driving with combination vehicles. (The test track lane-change maneuver described earlier in Figure 2-5 elicits rapid steering responses from the tractor driver by virtue of the specified path, thereby provoking the intended rearward amplification phenomena as part of the designated test procedure.)

Consequently, the likelihood of unwanted or accidental activation of a RAMS system during routine highway curve negotiations is estimated to be very low. In rare cases where a tractor driver may however enter such a curve at excessive speed so as to cause the RAMS system to activate, the resulting braking and accompanying damping provided by the RAMS system would provide benefit in terms of lower speed and improved directional control.

7.0 Conclusions and Recommendations

Several observations and conclusions can be made regarding the results obtained under this research study. They are:

- A particular *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. Details of the system are provided in Appendix A, but the 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) 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
  4) 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)

- A more future-looking *Full-Vehicle RAMS System* (requiring more complex communication links from the tractor unit to the last dolly) has also been developed and shown to provide a further 15-20% benefit in rearward amplification performance over the best trailer-only system. Details of this system are also provided in Appendix A.

- Certain other RAMS systems, such as the trailer-to-trailer classification that share sensor information only between adjoining trailer units, have also been shown to be very effective at reducing rearward amplification tendencies. These systems do require some additional intra-vehicle communication links (beyond that needed for the simplest trailer-only system) and therefore fall midway, in terms of communication complexity, between the trailer-only and the full-vehicle class of algorithms.

- None of the RAMS systems examined within the study was seen to provide directional stability benefits on very low friction surfaces (e.g., wet jennite, ice/snow, etc.). Trailer-swing instabilities were very common with or without a RAMS system active. However, activation of any RAMS system further aggravated the trailer swing tendencies. In fact, those full-vehicle RAMS algorithms that performed the best under dry and wet asphalt operating conditions, demonstrated the poorest performance under the very low friction test conditions.

- Activation of a RAMS system should not be permitted under very low friction operating conditions. While the probability of this is not likely since most vehicles would not be operating at speeds in excess of 50 mph under such conditions, some provision for a manual or automatic override and lock-out for RAMS should be considered for these very rare situations.

- Forward speed is a powerful influence on the development of rearward amplification in combination vehicles, particularly above 50 mph. Consequently, the speed reduction that accompanies a RAMS intervention braking sequence provides a beneficial byproduct of increased directional damping to the vehicle as it slows down. A 'safe harbor' — in terms of rearward amplification tendencies — exists for most combination vehicles at speeds below 45 mph.

- 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.

- Simple brake control strategies that do not utilize intelligent *differential* (left side / right side) braking are shown to be largely ineffective at reducing rearward amplification. A simple strategy of merely reducing vehicle speed through conventional braking alone is not sufficient to producing notable reductions in rearward amplification (i.e., absent any accompanying yaw damping influences along the way toward lower speed levels).

- Though not tested or evaluated directly within this study, mixing of RAMS-enabled and conventional non-RAMS trailers within a vehicle train would be expected to provide some partial benefit in reducing rearward amplification. This assumes that the RAMS-enabled trailers within the train are trailer-only systems that depend only upon sensing their own motions.

The primary recommendation from this study pertains to encouragement of a practical, in-use evaluation of the recommended trailer-only system. Namely that,

- A subsequent field trial of the trailer-only system is recommended to help evaluate in-practice experiences with different hardware configurations as well as potential safety benefits. A trailer or subsystem manufacturer, operating in possible partnership with the U.S. DOT, could equip a targeted fleet of semitrailer and dolly units with the recommended trailer-only system. On-board data storage, triggered by RAMS activation events, could be used to subsequently evaluate the performance of the RAMS system, the types of maneuvering events activating the system, and the likely safety benefits provided by the system operation.

  Other practical in-use issues, such as mixing of RAMS and non-RAMS trailer units within a vehicle train, could perhaps also be addressed within such a field trial, but may be more helpful following an initial trial of 'pure' RAMS-enabled trains in order to more cleanly evaluate their full potential (i.e., absent results and questions pertaining to mixed train RAMS configurations).

References

1. Ervin, R. et al., “Two Active Systems for Enhancing Dynamic Stability in Heavy Truck Operations,” NHTSA / FHWA Contract DTNH22-95-H-07002, Final Technical Report, UMTRI-98-39, July 1998.

2. MacAdam, C. et al., "A Computerized Model for Simulating the Braking and Steering Dynamics of Heavy Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations, Users' Manual--PHASE 4," HSRI, Univ. of Mich., Report. No. UM-HSRI-80-58, September 1980.

Appendix A — Functional Specifications Document

This appendix A contains a stand-alone document entitled *Functional Specifications* that describes the detailed features of the recommended *trailer-only* RAMS system. It also contains a detailed description of the more future-looking *full vehicle* RAMS system within its Appendix II.

Note: The sub-appendices associated with (and appearing at the end of) this stand-alone Functional Specifications document (Appendix A) are labeled as Roman numeral appendices I, II, and III.

Rearward Amplification Suppression (RAMS)

Functional Specifications

1.0 Introduction

This document defines the functional specifications of the proposed trailer-only RAMS brake control algorithm so that a practical implementation of the algorithm can be achieved by truck/trailer subsystem manufacturers following these guidelines. Since the primary thrust of this task order is to address a trailer-only system capable of being more readily implemented in today's trucking market and within any follow-on field operational trials, the specification issues related to more futuristic smart truck concepts (that could include an entire vehicle train) are contained separately in Appendix II to avoid potential confusion.

The primary sensor used by the proposed trailer-only system is a yaw rate transducer mounted on each trailer and used by the RAMS algorithm to control the side-to-side (differential) braking at the semi-trailer axle, as well as at its associated dolly axle. Based on this yaw rate signal, the RAMS algorithm applies brake pressures at selected wheels (semi and dolly) to help damp out unwanted trailer yaw oscillations. (The proposed algorithm can also be implemented using lateral accelerometers, if need be, though at a cost of reduced performance due to trailer roll influences on any body-mounted accelerometer signals.)

Unless otherwise noted, it is assumed that one yaw rate sensor (per semi-trailer), located anywhere on the semi-trailer body, is being used to provide control information to the algorithm.

The document is organized by the following sections:

- *Basic Vehicle Equipment Assumptions*
- *Trailer-Only Algorithm Description*
- *Accuracy and Sampling Rate Requirements*
- *Operating Environment Issues*
- *Appendix I – Trailer-Only Algorithm / Technical Details*
- *Appendix II – Full-Vehicle EBS / RAMS Algorithm Summary*
- *Appendix III – Miscellaneous Supporting Figures*

Appendix I provides additional technical discussion on the concept of the trailer-only algorithm and its utilization of suspension brake-steer compliance for generating lateral tire forces as part of the yaw damping control strategy.

Appendix II outlines the specification requirements for a more complex EBS RAMS control system that assumes communication and data links along the complete vehicle train, including tractor information.

— The Trailer-Only RAMS System —

2.0 Basic Vehicle Equipment Assumptions

Certain basic assumptions about the vehicle hardware available on each semi-trailer and dolly unit are noted. These assumptions apply to each semi-trailer and dolly **pair** that appear in the vehicle train as well as to the first semi-trailer following the tractor power unit. No tractor involvement is assumed. Application of the more general semi/dolly pair specification to the first semi-trailer unit involves only its semi-trailer wheels.

ABS System — First, it is assumed that each wheel of the semi-trailer and dolly is equipped with a fully operational ABS brake controller. The ABS system will over-ride and intervene during any RAMS command sequence when an imminent wheel-lock is about to occur at any particular wheel location. That is, the ABS unit always has final control authority at each wheel location, regardless of what the proposed RAMS system may be requesting. It is also assumed that the ABS system is an "independent wheel" controller (versus, for example, a "select-low" or "average-wheel" axle system), meaning that it is responsible for controlling the brake pressure at individual wheel locations, independent of simultaneous wheel slip experiences at adjoining wheel locations.

RAMS Valving Mechanism — Aside from providing a separate RAMS valving mechanism (as performed in this ad hoc research study) modification/integration of existing ABS system components to accept RAMS command signals would provide a more logical approach, assuming the ABS pressure modulation capabilities are suitable. This of course is in keeping with a more integrated EBS approach and would likely be preferable to separate RAMS and ABS valving mechanisms and their associated components. The details of this implementation of course lie with the subsystem manufacturer. The terminology EBS/ABS is intended to encapsulate this concept within an electro-mechanical "box" associated with each wheel location (semi-trailer or dolly).

Vehicle Speed Estimation — The proposed RAMS algorithm uses forward speed as one of the primary means to arm/enable/disable the RAMS system. As noted in a later section, the recommended minimum speed for RAMS activation is 48 mph. Consequently, some means for estimating forward speed of each trailer unit is needed for this functionality.

It is assumed that the process of estimating forward speed of the vehicle (trailer) can be performed by processing ABS wheel speed sensor signals. It may be that the ABS unit already possesses a reliable method for estimating vehicle speed. Absent that capability, various techniques can be used to obtain a vehicle speed estimate from the four available wheel speeds being monitored by the ABS units on each trailer.

One simple method is to select the maximum wheel speed from each of the four wheel speed sensors and use that value (or a trailing window average of such samples) as the estimate of forward vehicle speed at each instant in time. This of course assumes that not all four brakes (semi and dolly) are being aggressively exercised simultaneously. Since the proposed RAMS system utilizes a "diagonal" braking scheme, in which only diagonal pairs of brakes are being exercised at the same time (e.g., dolly right-side brake and semi-trailer left-side brake), the likelihood of obtaining a free-rolling wheel is normally present with this method.

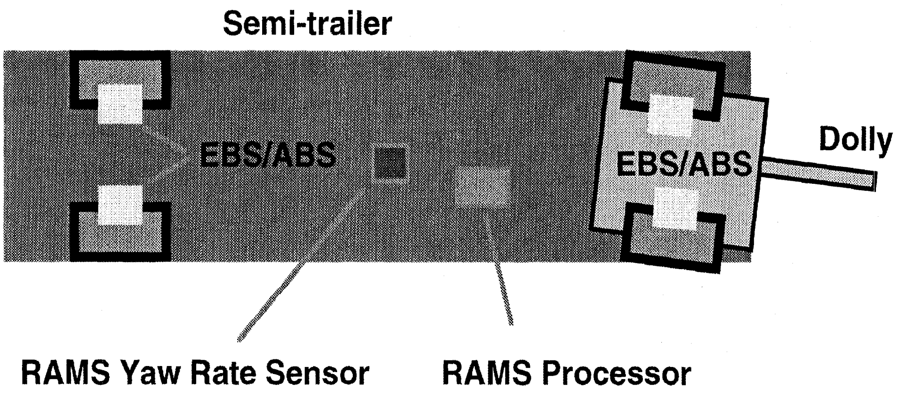
It would also be advisable to average such forward speed estimates over the last N samples to help minimize potential noise effects. Depending on the sampling rate used, N should be selected to provide a trailing window average of perhaps 0.5 seconds or so. (A sampling rate of 50 Hz would therefore suggest N = 25).

Yaw Rate Sensor — The trailer-only RAMS algorithm relies upon yaw rate from the semi-trailer. Consequently, a yaw rate transducer is assumed mounted somewhere on the body of the semi-trailer to provide this information to the algorithm.

RAMS Computer Module — A computer module or processing unit is assumed to be available for performing the necessary RAMS algorithm computations and accepting semi-trailer yaw rate and forward speed estimates as continuous input signals. The outputs of the computer module are four pressure command signals — two for the left/right semi-trailer wheels and two for the corresponding left/right dolly wheel locations.

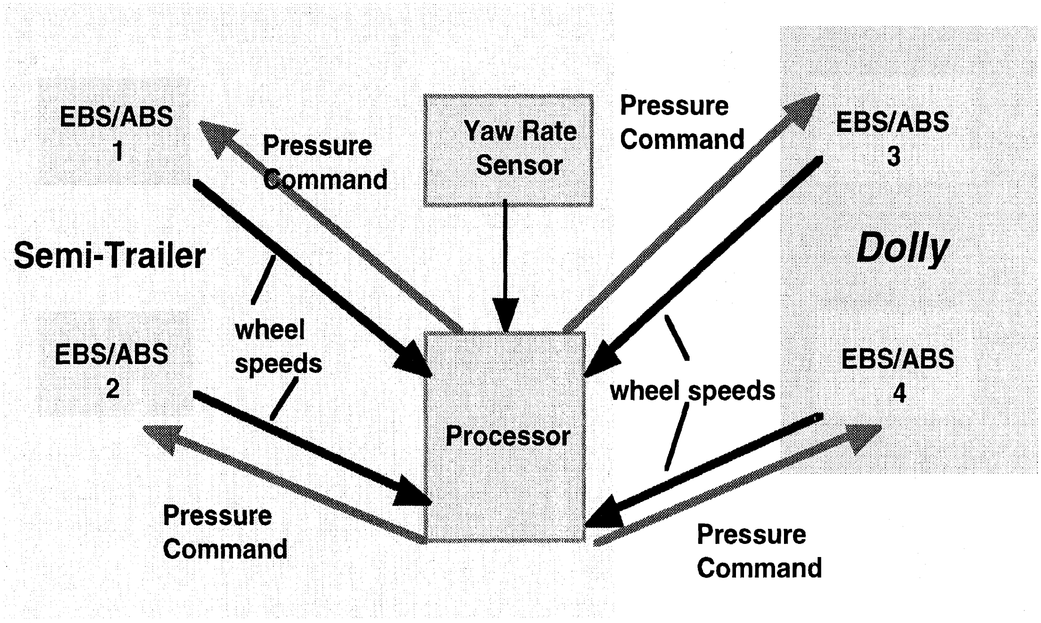
Fig 1 summarizes these basic equipment requirements.

Figure 1. Basic Equipment Assumed Available on Each Semi-trailer & Associated Dolly.



Sensor/Processor Communication Requirements — The trailer-only RAMS algorithm relies upon yaw rate from the semi-trailer body and four wheel speed sensor signals provided by the ABS system as input signals. The output of the RAMS processor are four command signals sent to each of the wheel brake pressure controllers (EBS/ABS valving units). Consequently, input/output communication links are required between the RAMS processor (likely located on the semi-trailer) and the four EBS/ABS locations on the semi-trailer and the dolly. Figure 2 summarizes these communication links.

Figure 2. Communication Links Between the RAMS Processor, the Yaw Rate Sensor, and the Four Wheel Locations (Trailer-Only System).



3.0 RAMS Algorithm Description

The RAMS algorithm is simple in concept and easily implemented. The algorithm acts as a basic yaw rate damper on trailer yaw motions that exceed a certain threshold. It utilizes side-to-side (differential) braking to generate appropriate longitudinal and lateral tire forces to damp out excessive trailer yaw motions. Lateral tire forces — deriving from suspension brake-steer compliance effects caused, in turn, by differential longitudinal brake forces — are a key ingredient of the yaw damping strategy. A more complete description of the brake-steer compliance mechanism and the resulting tire forces is provided in Appendix I.

The algorithm operates according to the following basic rules:

(1) Vehicle speed must be above 48 mph for the RAMS system to be enabled. If vehicle speed falls below this activation threshold, the system should revert to its normal non-RAMS state. If vehicle speed falls below the 48 mph threshold while RAMS is active, the RAMS system should still be disabled.

(2) For vehicle speeds above 48 mph, if the trailer yaw rate signal deviates by more than 2.2 degrees/second away from a defined reference signal, r0, brake pressure is applied to diagonal wheel locations according to the following equations:

$$\text{If } |r - r0| > 2.2, \qquad P = 30 \bullet |r - r0| \tag{1}$$
$$\text{otherwise,} \qquad P = 0 \tag{2}$$

where,

P	is the RAMS commanded brake pressure (units of psi)
r	is the trailer yaw rate measurement (units of degrees/second)
r0	is a reference signal defined as a 3-second trailing window average of the yaw rate measurement, r. (units of degrees per second)

The threshold value of 2.2 deg/sec of yaw rate corresponds to about 0.1 g's of lateral acceleration at a speed of 55 mph.

Yaw rate, r, is positive if the vehicle is turning to the right.

Brake pressure, P, is always positive or zero, and saturates at the supply pressure Pmax (typically 100-120 psi).

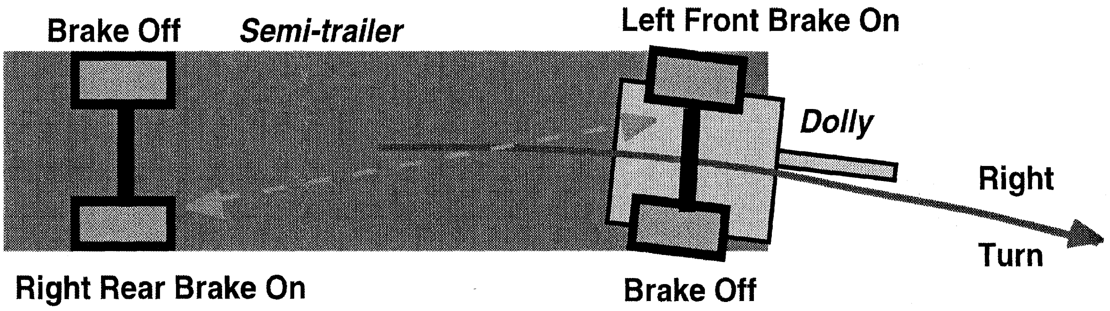
The diagonal wheel locations to which brake pressures are applied are defined according to the following convention:

A RAMS activation for a *positive* yaw rate, r, causes brake pressure — defined by equation (1) — to be applied simultaneously and equally to the dolly left-side brake ***and*** to the semi-trailer right-side brake; a RAMS activation for *negative* yaw rate (left turning motion) causes the corresponding brake pressure to be applied to the dolly right-side brake ***and*** the semi-trailer left-side brake. The diagonal brake pair not being commanded by equation (1) in the aforementioned rule during a RAMS activation should be commanded to zero pressure. That is, brake pressure is only applied to diagonal wheel locations (dolly/semi), and, brake pressure can only be applied to one diagonal wheel pair at any given time. See the example in Figure 3 below.

The yaw rate reference signal, r0:

The yaw rate reference signal, r0, defined as a 3-second moving average of the yaw rate measurement, r, is normally close to zero for most straight-line driving. For highway curves and connector transitions, r0, provides a time-lagged reference yaw rate signal, applicable to that particular curve, against which to measure significant trailer yaw rate deviations. Sudden vehicle transitions into or out of such curves may cause a momentary activation of the RAMS system, but the reference signal will prevent unwanted activations of the RAMS system along the curve during otherwise normal turning. (If r0 was always defined to be zero, as is suitable for straight-line running conditions, some highway curves could impose sufficient steady-state yaw rate requirements that the RAMS system would be activated unnecessarily. The non-zero time-lagged reference signal minimizes the potential for these types of unwanted RAMS activations during extended travel along curves.)

Figure 3. Diagonal Braking Description of the RAMS Trailer-Only Algorithm.



> *Example:*
>
> Trailer speed is above 48 mph,
>
> $r0 = 0$
>
> and,
>
> yaw rate deviation $|r - r0| > 2.2$ deg/sec
>
> =>
>
> Brake pressure (P) = $30 \cdot |r - r0|$
>
> applied equally to left front and right rear brakes.

4.0 Accuracy and Sampling Rate Issues

The proposed RAMS system assumes that the following signals are accurate to at least these levels:

• yaw rate	+/- 0.1 degrees / second
• vehicle speed estimate	+/- 1 mph

An analog RAMS yaw rate sensor scaled to +/- 5 degrees/second and having an accuracy of 1 or 2 percent would provide the minimum level of desired accuracy. An A/D converter with at least 8 bits (+/- 128) of resolution would likewise be required.

Sampling Rate

Sampling rates for the trailer yaw rate measurement used in the RAMS algorithm should be at least 50 HZ. Computer simulations have indicated a reduction in performance for slower sampling. Figure III-1 in Appendix III illustrates this observation.

Yaw Rate Threshold Crossings

To help minimize false firings or "sputtering" of the brake system due to intermittent noise-induced transgressions of the yaw rate threshold that activates the RAMS system (i.e., momentary deviations of more than 2.2 degrees/second away from the r0 reference signal), at least three successive yaw rate samples above (or below) the threshold should be confirmed prior to activating (or disabling) the RAMS pressure command signals defined by equations (1) and (2). Figures III-2, III-3, and III-4 in Appendix III help to further describe these different conditions.

5.0 Operating Environment Issues

It is assumed that the RAMS system durability and ruggedness requirements should be comparable to that provided for by other heavy vehicle trailer components such as ABS system computer modules, cabling, and associated wheel sensor mechanical elements. To the extent that integration of RAMS functionality and other EBS components can be implemented (e.g., within EBS/ABS packages), further cost and efficiency benefits would likely accrue.

Signal Conditioning

Analog conditioning of the yaw rate sensor signals with at least a second-order butterworth filter having a break-point (cut-off frequency) of 5 to 10 Hz is recommended to help attenuate normal operating environment noise and vibration effects.

Low Friction Surface Conditions

RAMS functions should be disabled under prevailing low tire/road friction operating conditions (ice, snow, wetted jennite surfaces, etc.). VRTC vehicle tests and simulation results both indicate poor performance from all RAMS control schemes operating under these conditions. The principal reason is due to excessive braking activity and the corresponding diminishment of lateral tire force capabilities associated with the attendant high wheel slip conditions. Although it would be unusual for normal operating speeds to be above the minimum 48 mph RAMS enabling speed under such low friction operating conditions, some provision for a disabling safeguard may be required for this special set of circumstances.

This low friction caveat does not however apply to heavy rain falling on otherwise high friction surfaces. Vehicle tests conducted at VRTC during heavy rain conditions on the asphalt test surface still demonstrated effective and beneficial performance of the RAMS system in suppressing rearward amplification tendencies.

Appendix I. Technical Details Regarding the RAMS Trailer-Only Algorithm and the Brake-Steer Compliance Mechanism.

Trailer yaw damping forces can be provided not only by longitudinal brake forces on one side of the vehicle or the other, but also by simultaneous lateral tire forces caused by suspension compliance-steering of an axle in response to longitudinal braking forces. Figure I-1 helps to illustrate this point. The sequence of events are: 1) brake pressure applied to a particular wheel location by the algorithm, 2) longitudinal tire force is generated at that wheel, 3) the longitudinal tire force steers (or "twists") the axle assembly because of suspension bushing compliances, 4) the "steered" axle then generates lateral tire forces at both sides of the suspension. Consequently, application of brake pressure to a single wheel location will generate 1) a longitudinal tire force at that wheel location, and 2) a reactionary lateral tire force at that wheel location and at its opposite (side) wheel counterpart — due to suspension brake-steer compliance effects. The goal then is to intelligently utilize these coincident tire forces (longitudinal and lateral) that are simultaneously present to maximize the level of yaw damping applied to the trailer.

Attempts at utilizing yaw rate damping commonly ignore the significant effects of suspension brake-steer compliance and thereby often under- or over-estimate the net yaw damping effect. In the case of long trailers, the lateral tire forces can be significant because of the lengthy moment arm accompanying the lateral tire force component as part of the basic yaw damping mechanism. Longitudinal (braking) tire forces may commonly be larger in magnitude, but because the length of their moment arm is considerably shorter, the contribution of longitudinal tire forces towards the total applied yaw moment acting on the trailer can be less influential than the moment provided by lateral tire force contributions.

As depicted in Figure I-2, the various tire forces that are generated by a diagonal differential braking scheme can be fairly complex. Figure I-2 helps to illustrate that even though lateral tire forces deriving from brake-steer compliance effects may be modest in magnitude relative to longitudinal braking forces, their significantly longer moment arms, **a** and **b**, allow them to contribute significantly to the corrective yaw moment applied to the trailer. In Figure I-2, the trailer is turning to the left due to the applied dolly steer angle input, but its motion is being resisted by a corrective yaw moment deriving from the RAMS diagonal braking algorithm that applies brake pressure to the right-front (dolly) and left-rear (semi) wheel locations. Lateral brake-steer compliance tire forces are generated in response to the RAMS brake pressure applications and play a major role in contributing towards the corrective yaw damping moment.

Although diagrams like Figure I-2 apply to relatively simple tire force relationships that exist at the very beginning of a RAMS intervention, events can change dramatically once side-to-side load transfers, wheel lock-ups, and ABS interventions begin to occur. Consequently, numerical simulation of these more complex dynamic phenomena and nonlinear interactions is required to help design and evaluate RAMS control algorithms over a broader range of operating conditions. Experimental data obtained from subsequent track testing with a triples combination at VRTC helped to further evaluate and refine the basic algorithm(s) provided within this specification.

Figure I-1. Longitudinal and Lateral Tire Forces Induced by an Application of Brake Pressure at One Wheel Location.

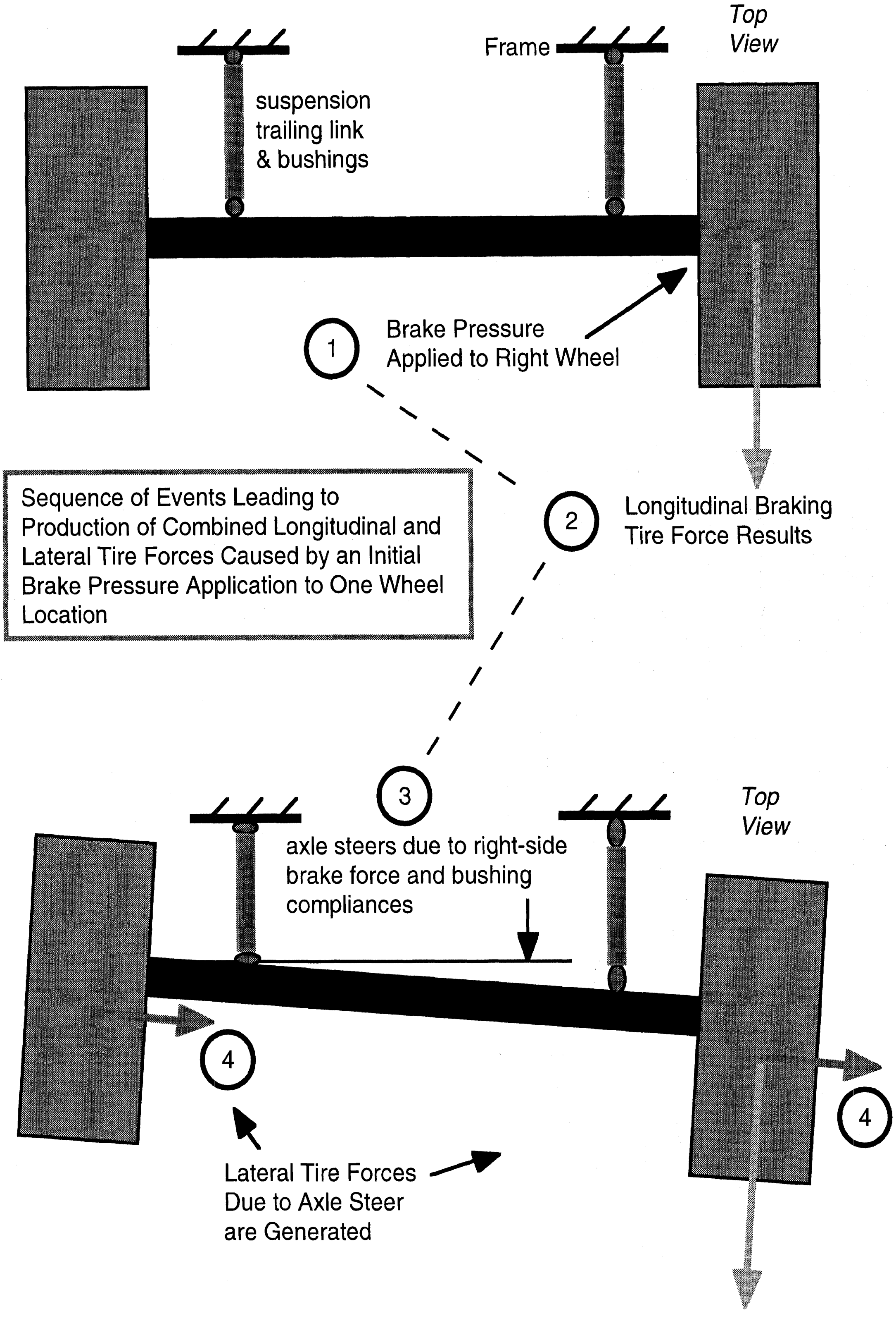
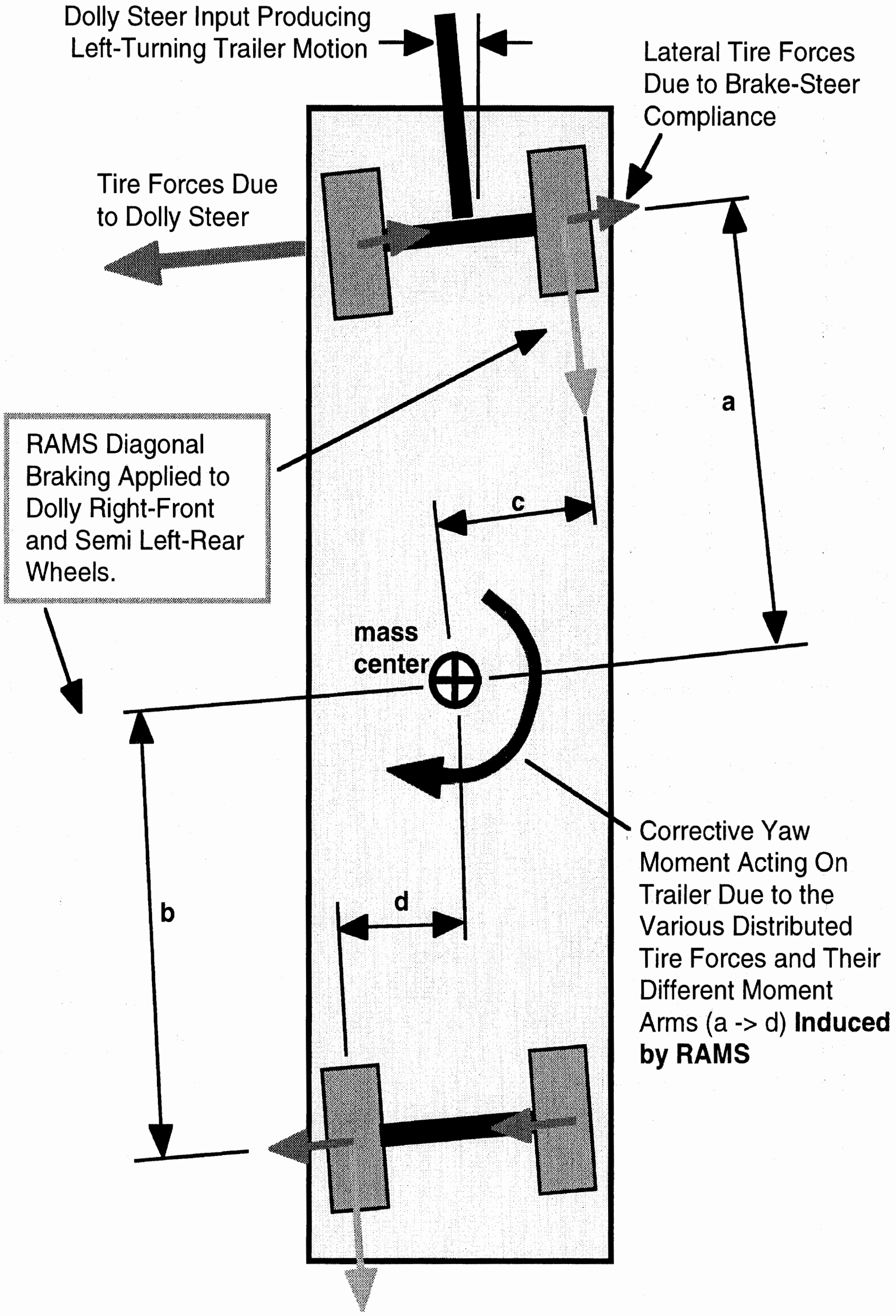


Figure I-2. The Contribution of Both Lateral and Longitudinal Tire Forces Generated by RAMS Towards a Corrective Yaw Moment Acting on the Trailer.



The designer of a RAMS control product should recognize from this discussion of compliance-steer effects that system performance is intimately connected to the specific compliance properties of the installed suspension(s). Thus it seems advisable, and perhaps essential, that the RAMS-EBS-ABS control package be matched to the specific suspension systems that accompany it.

Appendix II. Technical Summary of a Full-Vehicle RAMS Algorithm.

A more complex RAMS algorithm that can be used to further enhance the damping performance achievable by doubles or triples combination vehicles is outlined in this Appendix. This summary specification assumes trailer-to-trailer and tractor communication links that allow sharing of sensor information along the length of the vehicle train, as may occur more commonly in future vehicle configurations.

The intended control strategy here is to generate simple yaw rate damping at each semi-trailer axle in the same manner used by the full-trailer brake-steer compliance algorithm. It also utilizes "time-advanced" articulation rate damping at the dolly axles. The "time-advancement" concept uses tractor yaw rate, in place of each preceding semi-trailer yaw rate, to quicken the onset of braking at each dolly.

Evaluation of this algorithm during the recent vehicle tests at VRTC indicated some improvement in damping characteristics beyond the trailer-only algorithm. A summary of its specification, similar to that defined in Section 3 for the trailer-only system, is provided below for a seven-axle triples combination vehicle (two-axle tractor pulling three semi-trailers, all equipped with single axle suspensions, including two single-axle dollies). The same specification applies to a doubles combination, but the last two rules (axles 6 and 7, below) would be deleted.

Specifications for a Full-Vehicle RAMS Algorithm

The algorithm operates according to the following basic rules:

(1) As for the trailer-only system, vehicle speed must be above 48 mph for the RAMS system to be enabled. If vehicle speed falls below this activation threshold, the system should revert to its normal non-RAMS state. If vehicle speed falls below the 48 mph threshold while RAMS is active, the RAMS system should still be disabled.

(2) For vehicle speeds above 48 mph, if the semi-trailer yaw rate or yaw rate differences defined below, deviate by more than 2.2 degrees/second away from a corresponding reference signal, r_0, brake pressure is applied to specific axle/wheel locations according to the following rules:

Axle 3 (first semi-trailer axle):

If $|r2 - r2_0| > 2.2$, $P3 = 30 \cdot |r2 - r2_0|$ (B-1)

otherwise, $P3 = 0$ (B-2)

where,

P3 is the RAMS commanded brake pressure to the first semi-trailer axle (psi)
(If $r2 > 0$, as in a right turn, P3 is applied to the right semi-trailer brake and zero pressure applied to the left brake; if $r2 < 0$, as in a

	left turn, P3 is applied to the left semi-trailer brake and zero pressure applied to the right brake).
r2	is the first semi-trailer yaw rate measurement (degrees/second)
$r2_0$	is a reference signal defined as a 3-second trailing window average of the semi-trailer yaw rate measurement, r2. (degrees per second)

Yaw rate, r, is positive if the vehicle is turning to the right.

All axle brake pressures, Pi (i =3,7), are always positive or zero, and saturate at the supply pressure Pmax (typically 100-120 psi).

Axle 4 (first dolly axle):

If $|r1\text{-}r3 - r13_0| > 2.2$, $P4 = 30 \bullet |r1\text{-}r3 - r13_0|$ (B-3)
otherwise, $P4 = 0$ (B-4)

where,

P4	is the RAMS commanded brake pressure at the first dolly axle (psi) [If (r1-r3) > 0, as at the start of a right turn, P4 is applied to the right dolly brake and zero pressure applied to the left brake; if (r1-r3) < 0, as at the start of a left turn, P4 is applied to the left dolly brake and zero pressure applied to the right brake].
r1	is the tractor unit yaw rate measurement (degrees/second)
r3	is the <u>second</u> semi-trailer yaw rate measurement (degrees/second)
$r13_0$	is a reference signal defined as a 3-second trailing window average of the difference in tractor and second semi-trailer yaw rate measurements, r1-r3 (degrees per second).

Axle 5 (second semi-trailer axle):

If $|r3 - r3_0| > 2.2$, $P5 = 30 \bullet |r3 - r3_0|$ (B-5)
otherwise, $P5 = 0$ (B-6)

where,

P5	is the RAMS commanded brake pressure to the <u>second</u> semi-trailer axle (psi) (If r3 > 0 as in a right turn, P5 is applied to the right semi-trailer brake and zero pressure applied to the left brake; if r3 < 0, as in a left turn, P5 is applied to the left semi-trailer brake and zero pressure applied to the right brake).
r3	is the second semi-trailer yaw rate measurement (degrees/second)
$r3_0$	is a reference signal defined as a 3-second trailing window average of the semi-trailer yaw rate measurement, r3 (degrees per second).

Axle 6 (second dolly axle):

If $|r1\text{-}r4 - r14_0| > 2.2$, $P6 = 30 \bullet |r1\text{-}r4 - r14_0|$ (B-7)
otherwise, $P6 = 0$ (B-8)

where,

P6	is the RAMS commanded brake pressure to the <u>second</u> dolly axle (psi) [If (r1-r4) > 0, as at the start of a right turn, P6 is applied to the right dolly brake and zero pressure applied to the left brake; if (r1-r4) < 0, as at the start of a left turn, P6 is applied to the left dolly brake and zero pressure applied to the right brake).
r1	is the tractor unit yaw rate measurement (degrees/second)
r4	is the <u>third</u> semi-trailer yaw rate measurement (degrees/second)
$r14_0$	is a reference signal defined as a 3-second trailing window average of the difference in tractor and third semi-trailer yaw rate measurements, r1-r4 (degrees per second).

Axle 7 (third semi-trailer axle):

If $|r4 - r4_0| > 2.2$, $P7 = 30 \bullet |r4 - r4_0|$ (B-9)
otherwise, $P7 = 0$ (B-10)

where,

P7	is the RAMS commanded brake pressure to the <u>third</u> semi-trailer axle (psi) (If r4 > 0, as in a right turn, P7 is applied to the right semi-trailer brake and zero pressure applied to the left brake; if r4 < 0, as in a left turn, P7 is applied to the left semi-trailer brake and zero pressure applied to the right brake).
r4	is the <u>third</u> semi-trailer yaw rate measurement (degrees/second)
$r4_0$	is a reference signal defined as a 3-second trailing window average of the semi-trailer yaw rate measurement, r4 (degrees per second).

The reference signals, $r1_0$ -> $r4_0$, noted here are defined and utilized in the same manner indicated above in Section 3 for the trailer-only system.

The same sampling rate, accuracy values, and equipment "hardness" requirements identified above in Sections 4 and 5 also apply here to the full vehicle RAMS specification.

Appendix III. Miscellaneous Supporting Figures.

Several supporting figures appear in this appendix and are referenced in the main text.

Figure III-1. Influence of Sensor Sampling Rate on RAMS Trailer-Only Performance.

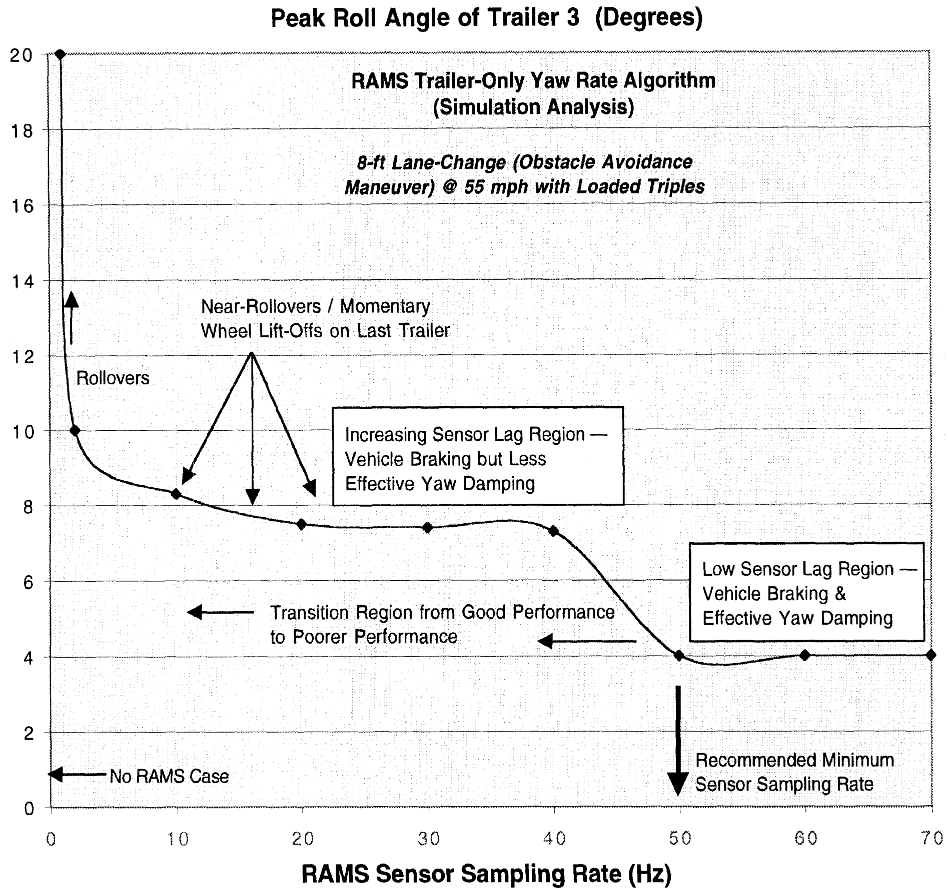


Figure III-2. Example of Random-Like Sensor Signal (Sensor Noise + Small Vehicle Motions) Occurring During Straight-line Running Conditions.

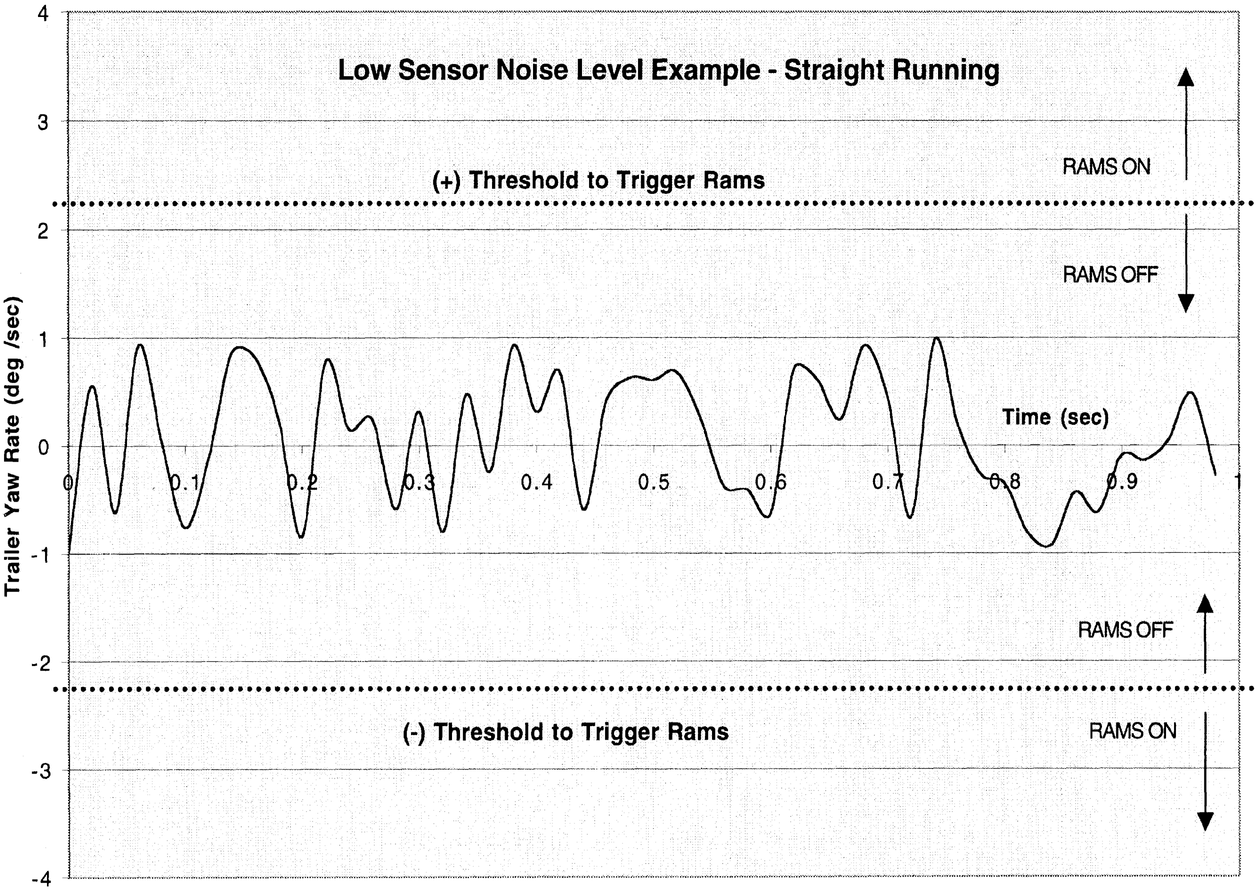


Figure III-3. Hypothetical Illustration of Sensor Noise Large Enough To Intermittently Trigger the RAMS System During Straight-line Running

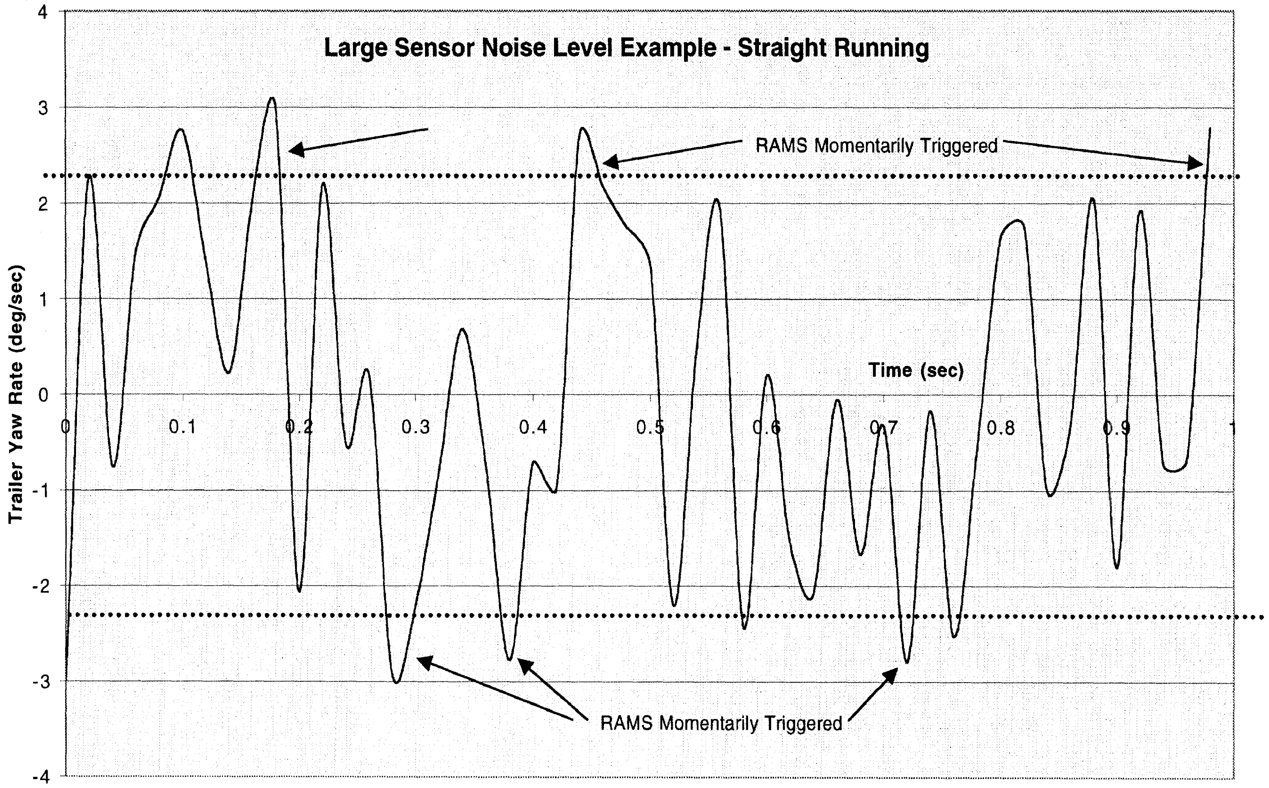
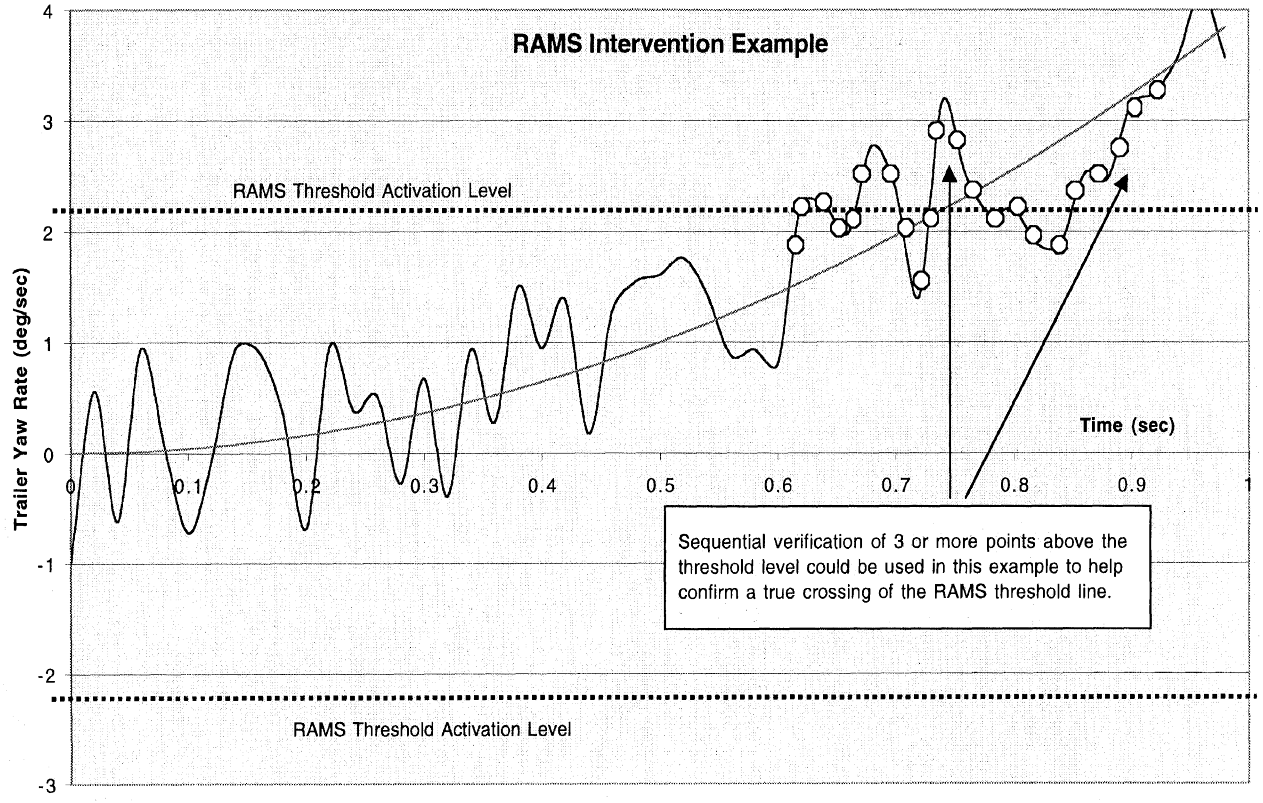


Figure III-4. Verification of Three or More Sequential Threshold Crossings by the Trailer Yaw Rate Signal.



Sequential verification of 3 or more points above the threshold level could be used in this example to help confirm a true crossing of the RAMS threshold line.

Appendix B - Program Listing of the Vehicle Parameters Used in the UMTRI Simulation Analyses

This appendix contains a computer program listing (UMTRI Phase 4 model) of the vehicle parameters used to characterize the triple trailer combination vehicle used in the simulation study.

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  1

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   SIMULATION OPERATION PARAMETERS:
--------------------------------

0        VEHICLE CONFIGURATION (NUMBER OF TRAILERS - ENTER 0 FOR A STRAIGHT TRUCK)                                 3
INITIAL VELOCITY (FT/SEC)                                                                              81.00
STEER TABLE (NUMBER OF LINES):  POSITIVE -STEER ANGLE TABLE, NEGATIVE - PATH FOLLOWER TABLE               -4
0                  CLOSED-LOOP PATH FOLLOWING MODE
0                  X-Y PATH COORDINATES :
0                                                                                         X         Y

0                                                                                      (FEET)    (FEET)
.00         .00
100.00        .00
225.00      -8.00
9999.00      -8.00

DRIVER TRANSPORT LAG (SEC) :               .20
END OF PREVIEW INTERVAL (SEC) :           1.00

0        TREADLE PRESSURE TABLE (NUMBER OF LINES)                                                                  3
TABLE ENTRIES:                                                    TIME (SEC)    PRESSURE (PSI)
----------    --------------
.00             .00
.50             .00
9.90             .00

MAXIMUM SIMULATION TIME (SEC)                                                                           8.01
TIME INCREMENT OF OUTPUT (SEC)                                                                           .10
0        ROAD KEY =  0 : FLAT ROAD.
0        OUTPUT PAGE OPTION KEYS:  0 DELETES PAGES
------------------------------------------
SPRUNG MASS    SPRUNG MASS    SPRUNG MASS   TIRE FORCES   BRAKE SUMMARY    LATERAL        UNSPRUNG MASS      TEMP
POSITION       VELOCITY       ACCELERATION     PAGES          PAGES          PAGES              PAGES         PAGES

1              1              1              1              1            1                1                0
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  2

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRACTOR PARAMETERS
------------------

WHEELBASE - DISTANCE FROM FRONT AXLE TO CENTER OF REAR SUSPENSION (IN)                              120.00
BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)                                                 10700.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                                   8800.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                                             44.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                 20000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                                                85000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                                  85000.00
PAYLOAD WEIGHT (LB)                                                                                    .00
*** ZERO ENTRY INDICATES NO PAYLOAD ***
*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***
FIFTH WHEEL LOCATION (IN. AHEAD OF REAR SUSP. CENTER)                                                 1.73
FIFTH WHEEL HEIGHT ABOVE GROUND (IN)                                                                 48.00
TRACTOR FRAME STIFFNESS (IN-LB/DEG)                                                               50000.00
TRACTOR FRAME TORSIONAL AXIS HEIGHT ABOVE GROUND (IN)                                                36.00
0   TRACTOR FRONT SUSPENSION AND AXLE PARAMETERS                                           LEFT SIDE           RIGHT SIDE
----------------------------------------------                                         ---------           ----------

SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                            -119.00              -119.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                        .00                  .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                         .00                  .00
------------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                     3719.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                            23.00
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                      .00
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                      1500.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                                 32.00
TRACK WIDTH (IN)                                                                                 80.00
UNSPRUNG WEIGHT (LB)                                                                           1200.00
STEERING GEAR RATIO (DEG STEERING WHEEL/DEG ROAD WHEEL)                                          28.00
STEERING STIFFNESS (IN-LB/DEG)                                                                11000.00
TIE ROD STIFFNESS (IN-LB/DEG)                                                                 11000.00
MECHANICAL TRAIL (IN)                                                                             1.00
TORSIONAL WRAP-UP STIFFNESS (IN-LB/IN)                                                       150000.00
LATERAL OFFSET OF STEERING AXIS (IN)                                                              3.00
0   TRACTOR FRONT TIRES AND WHEELS                                                         LEFT SIDE           RIGHT SIDE
------------------------------                                                         ---------           ----------

CORNERING STIFFNESS  (LB/DEG/TIRE)                                                     -1.00                -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                                 -2.00                -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                           .00                  .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                   -1600.00             -1600.00
*** NEGATIVE ALIGNING MOMENT ENTRY ***
*** ALIGNING MOMENT CURVE FIT PARAMETERS:  (    .0000    .0000   5.0000    .8000)  (   .0000    .0000   5.0000    .8000)
TIRE SPRING RATE (LB/IN/TIRE)                                                        4500.00              4500.00
TIRE LOADED RADIUS (IN)                                                                19.50                19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                          103.00               103.00
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.      INPUT PAGE NO.  3

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRACTOR REAR SUSPENSION  AND AXLE PARAMETERS                                         LEFT SIDE           RIGHT SIDE
---------------------------------------------                                        ---------           ----------


SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM            0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                          -131.00             -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                      .00                 .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                       .00                 .00
-----------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                       30.40
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                -.10
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                95000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                            29.62
TRACK WIDTH (IN)                                                                            72.00
UNSPRUNG WEIGHT (LB)                                                                      1750.00
0   TRACTOR REAR TIRES  AND WHEELS                                                   LEFT SIDE           RIGHT SIDE
-----------------------------                                                        ---------           ----------


0        DUAL TIRE SEPARATION (IN)                                                           13.00               13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                                   -1.00               -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                               -2.00               -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                         .00                 .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                   600.00              600.00
TIRE SPRING RATE (LB/IN/TIRE)                                                      4500.00             4500.00
TIRE LOADED RADIUS (IN)                                                              19.50               19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                        115.00              115.00
1
0   TRACTOR FRONT BRAKES                                                             LEFT SIDE           RIGHT SIDE
--------------------                                                                 ---------           ----------

0        TIME LAG (SEC)                                                                      .0500               .0500
RISE TIME (SEC)                                                                      .2000               .2000
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                                   1000.0000           1000.0000
BRAKE HYSTERESIS KEY: 0 ENTRY INDICATES BRAKE HYSTERESIS OPTION NOT IN USE ON VEHICLE TRAIN                   0
BRAKE PROPORTIONING KEY: 0 ENTRY INDICATES BRAKE PROPORTIONING OPTION NOT IN USE ON VEHICLE TRAIN             0
0   TRACTOR REAR BRAKES                                                              LEFT SIDE           RIGHT SIDE
--------------------                                                                 ---------           ----------

0        TIME LAG (SEC)                                                                      .0500               .0500
RISE TIME (SEC)                                                                      .2000               .2000
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                                   1500.0000           1500.0000
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.         INPUT PAGE NO.  4

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRAILER NO. 1 PARAMETERS
------------------------

WHEELBASE - DISTANCE FROM KINGPIN TO CENTER OFREAR SUSPENSION (IN)                                  259.00
BASE VEHICLE KINGPIN STATIC LOAD (LB)                                                              5000.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                                   6700.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                                             70.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                 53000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                                               258000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                                 230000.00
PAYLOAD WEIGHT (LB)                                                                               14500.00
PAYLOAD DISTANCE AHEAD OF REAR SUSPENSION CENTER(IN)                                            109.00
PAYLOAD CG HEIGHT (IN. ABOVE GROUND)                                                             60.00
PAYLOAD ROLL MOMENT OF INERTIA(IN-LB-SEC**2)                                                  38000.00
PAYLOAD PITCH MOMENT OF INERTIA(IN-LB-SEC**2)                                                365000.00
PAYLOAD YAW MOMENT OF INERTIA(IN-LB-SEC**2)                                                  365000.00
LOCATION OF PINTLE HOOK (IN BEHIND REAR SUSP. CENTER)                                                36.00
HEIGHT OF PINTLE HOOK (IN ABOVE GROUND)                                                              32.00
0   TRAILER NO. 1 REAR SUSPENSION  AND AXLE PARAMETERS                                     LEFT SIDE            RIGHT SIDE
----------------------------------------------                                         ---------            ----------

SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM             0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                            -131.00              -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                        .00                  .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                         .00                  .00
-----------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                     4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                            24.80
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                      .14
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                    106000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                                 37.25
TRACK WIDTH (IN)                                                                                 72.00
UNSPRUNG WEIGHT (LB)                                                                           1750.00
0   TRAILER NO. 1 REAR TIRES  AND WHEELS                                                   LEFT SIDE            RIGHT SIDE
-------------------------------                                                        ---------            ----------

0        DUAL TIRE SEPARATION (IN)                                                              13.00                13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                                     -1.00                -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                                 -2.00                -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                            .00                  .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                     600.00               600.00
TIRE SPRING RATE (LB/IN/TIRE)                                                        4500.00              4500.00
TIRE LOADED RADIUS (IN)                                                                19.50                19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                          115.00               115.00
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  5

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;



0   TRAILER NO. 1 REAR BRAKES                                                            LEFT SIDE           RIGHT SIDE
--------------------                                                                 ---------           ----------

0        TIME LAG (SEC)                                                                       .0300               .0300
RISE TIME (SEC)                                                                      .1500               .1500
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                                   1500.0000           1500.0000
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  6

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRAILER NO. 2 PARAMETERS
------------------------

DOLLY KEY: 1 = CONVERTER DOLLY, 2 = FIXED DOLLY                                                          1
DISTANCE FROM DOLLY SUSPENSION TO PINTLE HOOK (IN)                                                   80.00
TURNTABLE LOCATION (IN AHEAD OF SUSP. CENTER)                                                          .00
TURNTABLE HEIGHT ABOVE GROUND (IN)                                                                   48.00
WHEELBASE - DISTANCE FROM CENTER OF FRONT SUSP. TO CENTER OF REAR SUSP. (IN)                        259.00
BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)                                                  8000.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                                   7600.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                                             70.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                 53000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                                               258000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                                 230000.00
PAYLOAD WEIGHT (LB)                                                                               15500.00
PAYLOAD DISTANCE AHEAD OF REAR SUSPENSION CENTER(IN)                                           129.50
PAYLOAD CG HEIGHT (IN. ABOVE GROUND)                                                           102.00
PAYLOAD ROLL MOMENT OF INERTIA(IN-LB-SEC**2)                                                 38000.00
PAYLOAD PITCH MOMENT OF INERTIA(IN-LB-SEC**2)                                               365000.00
PAYLOAD YAW MOMENT OF INERTIA(IN-LB-SEC**2)                                                 365000.00
LOCATION OF PINTLE HOOK (IN BEHIND REAR SUSP. CENTER)                                                36.00
HEIGHT OF PINTLE HOOK (IN ABOVE GROUND)                                                              32.00
0   TRAILER NO. 2 FRONT SUSPENSION AND AXLE PARAMETERS                                    LEFT SIDE           RIGHT SIDE
---------------------------------------------                                         ---------           ----------

SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM           0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                           -131.00              -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                       .00                  .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                        .00                  .00
-----------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                    4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                           24.80
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                     .14
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                   106000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                                37.25
TRACK WIDTH (IN)                                                                                72.00
UNSPRUNG WEIGHT (LB)                                                                          1750.00
0   TRAILER NO. 2 FRONT TIRES AND WHEELS                                                  LEFT SIDE           RIGHT SIDE
-------------------------------                                                       ---------           ----------

0        DUAL TIRE SEPARATION (IN)                                                             13.00               13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                                    -1.00               -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                                -2.00               -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                          .00                 .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                    600.00              600.00
TIRE SPRING RATE (LB/IN/TIRE)                                                       4500.00             4500.00
TIRE LOADED RADIUS (IN)                                                               19.50               19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                         115.00              115.00
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  7

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRAILER NO. 2 REAR SUSPENSION  AND AXLE PARAMETERS                                   LEFT SIDE           RIGHT SIDE
    -----------------------------------------                                         ---------           ----------

SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM           0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                          -131.00              -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                      .00                  .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                       .00                  .00
-----------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                   4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                          24.80
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                    .14
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                  106000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                               37.25
TRACK WIDTH (IN)                                                                               72.00
UNSPRUNG WEIGHT (LB)                                                                         1750.00
0   TRAILER NO. 2 REAR TIRES  AND WHEELS                                                 LEFT SIDE           RIGHT SIDE
------------------------------                                                        ---------           ----------

0        DUAL TIRE SEPARATION (IN)                                                            13.00               13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                                   -1.00               -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                               -2.00               -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                         .00                 .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                   600.00              600.00
TIRE SPRING RATE (LB/IN/TIRE)                                                      4500.00             4500.00
TIRE LOADED RADIUS (IN)                                                              19.50               19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                        115.00              115.00
0   TRAILER NO. 2 FRONT BRAKES                                                           LEFT SIDE           RIGHT SIDE
--------------------                                                                  ---------           ----------

0        TIME LAG (SEC)                                                                       .0300               .0300
RISE TIME (SEC)                                                                      .1500               .1500
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                                   1500.0000           1500.0000
0   TRAILER NO. 2 REAR BRAKES                                                            LEFT SIDE           RIGHT SIDE
--------------------                                                                  ---------           ----------

0        TIME LAG (SEC)                                                                       .0300               .0300
RISE TIME (SEC)                                                                      .1500               .1500
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                                   1500.0000           1500.0000
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.       INPUT PAGE NO.  8

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRAILER NO. 3 PARAMETERS
------------------------

DOLLY KEY: 1 = CONVERTER DOLLY, 2 = FIXED DOLLY                                                          1
DISTANCE FROM DOLLY SUSPENSION TO PINTLE HOOK (IN)                                                   80.00
TURNTABLE LOCATION (IN AHEAD OF SUSP. CENTER)                                                          .00
TURNTABLE HEIGHT ABOVE GROUND (IN)                                                                   48.00
WHEELBASE - DISTANCE FROM CENTER OF FRONT SUSP. TO CENTER OF REAR SUSP. (IN)                        259.00
BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)                                                  8500.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)                                                   7600.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)                                                             70.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                 53000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)                                               258000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)                                                 230000.00
PAYLOAD WEIGHT (LB)                                                                               15500.00
PAYLOAD DISTANCE AHEAD OF REAR SUSPENSION CENTER(IN)                                           129.50
PAYLOAD CG HEIGHT (IN. ABOVE GROUND)                                                           102.00
PAYLOAD ROLL MOMENT OF INERTIA(IN-LB-SEC**2)                                                 38000.00
PAYLOAD PITCH MOMENT OF INERTIA(IN-LB-SEC**2)                                               365000.00
PAYLOAD YAW MOMENT OF INERTIA(IN-LB-SEC**2)                                                 365000.00
0   TRAILER NO. 3 FRONT SUSPENSION AND AXLE PARAMETERS                                   LEFT SIDE           RIGHT SIDE
---------------------------------------------                                         ---------           ----------

SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM            0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                                          -131.00              -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                                       .00                  .00
COULOMB FRICTION (LB/SIDE/AXLE)                                                        .00                  .00
-----------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                                   4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                                          24.80
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                                    .14
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                                  106000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                               37.25
TRACK WIDTH (IN)                                                                               72.00
UNSPRUNG WEIGHT (LB)                                                                         1750.00
0   TRAILER NO. 3 FRONT TIRES AND WHEELS                                                 LEFT SIDE           RIGHT SIDE
-------------------------------                                                       ---------           ----------

0        DUAL TIRE SEPARATION (IN)                                                             13.00               13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                                    -1.00               -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                                -2.00               -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                                          .00                 .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                                    600.00              600.00
TIRE SPRING RATE (LB/IN/TIRE)                                                       4500.00             4500.00
TIRE LOADED RADIUS (IN)                                                               19.50               19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                                         115.00              115.00
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.      INPUT PAGE NO.  9

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0   TRAILER NO. 3 REAR SUSPENSION  AND AXLE PARAMETERS                      LEFT SIDE        RIGHT SIDE
--------------------------------------                                   ---------        ----------

SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM         0
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)                             -131.00           -131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)                         .00               .00
COULOMB FRICTION (LB/SIDE/AXLE)                                          .00               .00
------------------------------
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)                                    4500.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)                                           24.80
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)                                     .14
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)                                   106000.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)                                37.25
TRACK WIDTH (IN)                                                                72.00
UNSPRUNG WEIGHT (LB)                                                          1750.00
0   TRAILER NO. 3 REAR TIRES  AND WHEELS                                    LEFT SIDE        RIGHT SIDE
------------------------                                                 ---------        ----------

0       DUAL TIRE SEPARATION (IN)                                              13.00            13.00
CORNERING STIFFNESS  (LB/DEG/TIRE)                                      -1.00            -1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
LONGITUDINAL STIFFNESS  (LB/SLIP/TIRE)                                  -2.00            -2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***
CAMBER STIFFNESS (LB/DEG/TIRE)                                            .00              .00
ALIGNING MOMENT  (IN-LB/DEG/TIRE)                                      600.00           600.00
TIRE SPRING RATE (LB/IN/TIRE)                                         4500.00          4500.00
TIRE LOADED RADIUS (IN)                                                 19.50            19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)                           115.00           115.00
0   TRAILER NO. 3 FRONT BRAKES                                              LEFT SIDE        RIGHT SIDE
-----------------                                                        ---------        ----------

0       TIME LAG (SEC)                                                         .0300            .0300
RISE TIME (SEC)                                                         .1500            .1500
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                      1500.0000        1500.0000
0   TRAILER NO. 3 REAR BRAKES                                               LEFT SIDE        RIGHT SIDE
-----------------                                                        ---------        ----------

0       TIME LAG (SEC)                                                         .0300            .0300
RISE TIME (SEC)                                                         .1500            .1500
BRAKE TORQUE (IN-LB/PSI/BRAKE)                                      1500.0000        1500.0000
0       ANTILOCK KEY:  1 INDICATES ANTILOCK WILL BE USED                                       -1
0   RAMSKEY: 0  (0 => off, 1 => on)   RAMS Gain: 1.33     V-off (f/s):  44.0    rear %: 1.00     threshold: 3.00    rmslmx:  .20    rmtau:  .00
fxstr: .00000656
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.        SUMMARY PAGE

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;
0TRAILER NO. 3          PAYLOAD =   15500.000 LBS.                                   EMPTY              LOADED

DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)                   138.750             133.648
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)                             70.000              87.651
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     53000.000          109437.773
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                   258000.000          642978.375
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     230000.000          596540.562


0TRAILER NO. 2          PAYLOAD =   15500.000 LBS.                                   EMPTY              LOADED

DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)                   133.781             131.377
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)                             70.000              87.971
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     53000.000          109026.875
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                   258000.000          641349.500
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     230000.000          595322.625


0TRAILER NO. 1          PAYLOAD =   14500.000 LBS.                                   EMPTY              LOADED

DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)                   130.151             117.607
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)                             70.000              64.070
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     53000.000           92528.703
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                   258000.000          631367.438
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)                     230000.000          601838.750


0 TRACTOR          PAYLOAD =         .000 LBS                                        EMPTY              LOADED

DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO REAR SUSPENSION (IN)                    68.882              68.882
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO GROUND (IN)                             44.000              44.000
ROLL MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)                     20000.000           20000.000
PITCH MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)                    85000.000           85000.000
YAW MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)                      85000.000           85000.000


0THE STATIC LOADS ON THE AXLES ARE:
AXLE NUMBER       LOAD
NS(1,1,1)      10860.059
NS(1,2,1)      19742.258
NS(2,2,1)      15097.685
NS(3,1,1)      15750.001
NS(3,2,1)      15349.999
NS(4,1,1)      16250.000
NS(4,2,1)      15350.000
---------------
TOTAL       108400.000
0THE TRACTOR TOTAL MASS CENTER IS        54.154 INCHES BEHIND THE FRONT AXLE
THE TOTAL YAW MOMENT OF INERTIA IS   122387.969 IN-LB-SEC**2

0THE FIRST TRAILER TOTAL MASS CENTER IS       149.248 INCHES BEHIND THE KINGPIN
THE TOTAL YAW MOMENT OF INERTIA IS   664857.750 IN-LB-SEC**2

0THE SECOND TRAILER TOTAL MASS CENTER IS       127.834 INCHES BEHIND THE TURNTABLE CENTER
THE TOTAL YAW MOMENT OF INERTIA IS   756412.875 IN-LB-SEC**2

0THE THIRD TRAILER TOTAL MASS CENTER IS       125.812 INCHES BEHIND THE TURNTABLE CENTER
THE TOTAL YAW MOMENT OF INERTIA IS   757741.250 IN-LB-SEC**2
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0        SPRING TABLES
-------------
NO. OF LINES                  FORCE (LB)          DEFLECTION (IN)                     TABLE NO.
------------                  ----------          ---------------                     ---------

0                   4                                                                                -119.00
-20000.00               -20.00
.00                  .00
9250.00                 7.20
25000.00                 7.50
(SPRING COMPRESSION ENVELOPE)
0
0

-20000.00               -20.00
.00                  .00
8040.00                 7.20
25000.00                 7.50
(SPRING EXTENSION ENVELOPE)
0    SUSPENSION DEFLECTION CONSTANTS =    .08000 INCHES COMPRESSION,          .08000 INCHES EXTENSION.
0SPRING STATIC EQUILIBRIUM CONDITION:   4830.03 LB,       4.02 INCHES.           UNIT 1  SUSP 1  AXLE 1
0                  10                                                                                -131.00
-10000.00                  .00
3464.00                 1.74
6088.00                 3.65
8529.00                 5.23
10786.00                 6.35
12434.00                 6.99
15180.00                 7.86
18658.00                 8.74
20000.00                 8.96
25000.00                10.00
(SPRING COMPRESSION ENVELOPE)
0
0

-10000.00                  .00
3281.00                 1.86
4929.00                 3.41
6576.00                 4.91
8041.00                 5.95
9627.00                 6.79
11885.00                 7.63
13898.00                 8.16
17986.00                 8.94
20000.00                 9.12
(SPRING EXTENSION ENVELOPE)
0    SUSPENSION DEFLECTION CONSTANTS =    .10000 INCHES COMPRESSION,          .10000 INCHES EXTENSION.
0SPRING STATIC EQUILIBRIUM CONDITION:   8996.13 LB,       5.94 INCHES.           UNIT 1  SUSP 2  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   6673.84 LB,       4.43 INCHES.           UNIT 2  SUSP 2  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   7000.00 LB,       4.68 INCHES.           UNIT 3  SUSP 1  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   6800.00 LB,       4.53 INCHES.           UNIT 3  SUSP 2  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   7250.00 LB,       4.87 INCHES.           UNIT 4  SUSP 1  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   6800.00 LB,       4.53 INCHES.           UNIT 4  SUSP 2  AXLE 1
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0        MU-Y VS ALPHA TABLES
---------------------

NO. OF LOADS   NO. OF VELOCITIES                                                            TABLE NO.
------------   -----------------                                                            ---------
3              1                                                                            -1
VELOCITY = 66.00 FT/SEC  LOAD =    3000.00 LB
ALPHA (DEG)          MU - Y
-----------          ------

.00             .00
1.00             .18
2.00             .33
4.00             .57
6.00             .71
12.00             .83

VELOCITY = 66.00 FT/SEC  LOAD =    6000.00 LB
ALPHA (DEG)          MU - Y
-----------          ------

.00             .00
1.00             .14
2.00             .25
4.00             .46
6.00             .58
12.00             .69

VELOCITY = 66.00 FT/SEC  LOAD =    9000.00 LB
ALPHA (DEG)          MU - Y
-----------          ------

.00             .00
1.00             .11
2.00             .19
4.00             .38
6.00             .52
12.00             .69

0        ROLL-OFF TABLE
--------------

0                                   SLIP
ALPHA         .00         .04         .10         .50        1.00
0                   .00       1.00        1.00         .90         .30         .10
0                  4.00       1.00        1.00         .90         .30         .10
0                  8.00       1.00        1.00         .90         .35         .13
0                 12.00       1.00        1.00         .90         .42         .17
0                 16.00       1.00        1.00         .90         .48         .22
```

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.

RAMS Seven-Axle Triple / 27-ft Trailers; Air Suspens; 8-ft Lane-Change; 55 mph;


0       MU-X VS. SLIP TABLES
--------------------

NO. OF LOADS   NO. OF VELOCITIES                                             TABLE NO.
------------   -----------------                                             ---------
3              1                                                             -2
VELOCITY =  66.00 FT/SEC LOAD =     3000.00 LB
SLIP                 MU - X
----                 ------

.00             .00
.10             .68
.20             .80
.30             .77
1.00             .55

VELOCITY =  66.00 FT/SEC LOAD =     6000.00 LB
SLIP                 MU - X
----                 ------

.00             .00
.10             .59
.20             .75
.30             .73
1.00             .50

VELOCITY =  66.00 FT/SEC LOAD =     9000.00 LB
SLIP                 MU - X
----                 ------

.00             .00
.10             .44
.20             .70
.30             .69
1.00             .45

0       ROLL-OFF TABLE
--------------

0                                   SLIP
ALPHA          .00          .04          .10          .50          1.00
0                    .00         1.00         1.00         1.00         1.00         1.00
0                   4.00         1.00         1.00         1.00         1.00         1.00
0                   8.00          .75          .75          .75          .95         1.00
0                  12.00          .50          .50          .60          .90          .95
0                  16.00          .40          .40          .45          .85          .95

Stop Time =    8.01
```

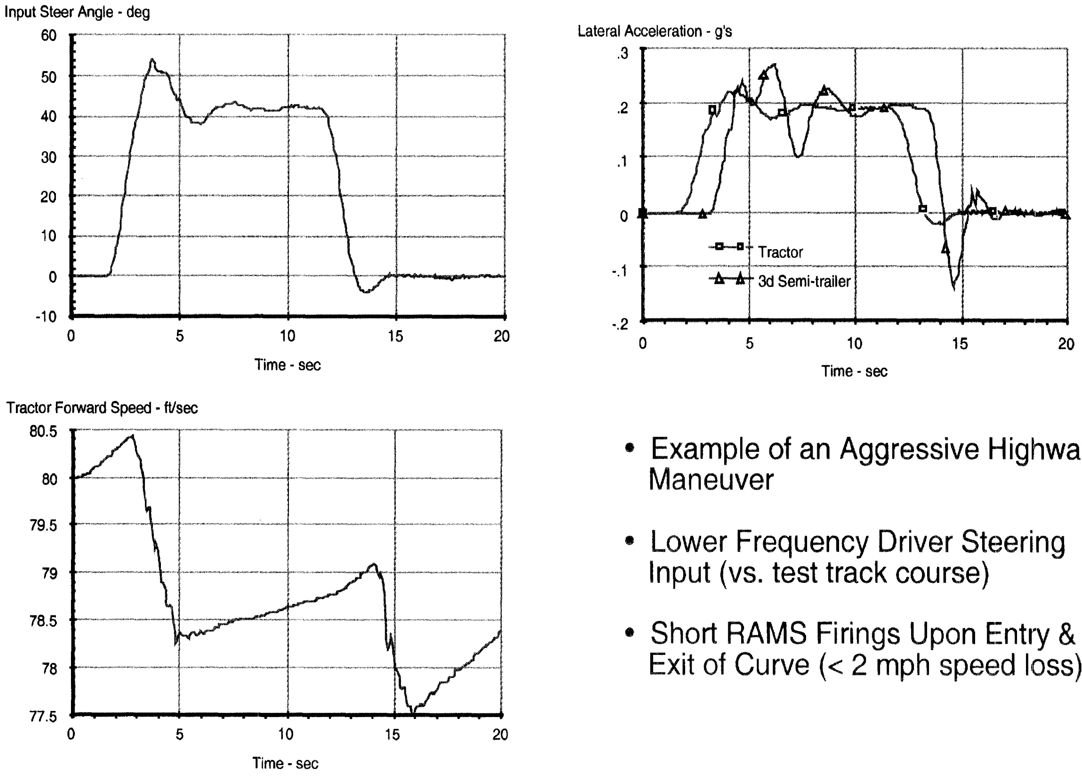
Appendix C - Supporting Computer Simulation Figures

This appendix contains miscellaneous supporting figures from the RAMS computer simulation analyses as referred to in the report text.

Figure C-1 corresponds to results from the simulation study showing predicted vehicle responses for entry and exit of a fixed radius highway curve.

Figures C-2 and C-3 each show an animation sequence corresponding to the baseline vehicle response with and without RAMS active. Figure C-2 shows the stable vehicle response achieved with the "Trailer-Only" RAMS system in operation. Figure C-3 shows the vehicle response with no RAMS system active, resulting in rollover of the last trailer (last frame of Figure C-3). All frames seen in Figures C-2 and C-3 are at 0.70 second intervals. The speed is 55 mph and the vehicle is conducting the baseline 8-ft lane change test maneuver described in the report.

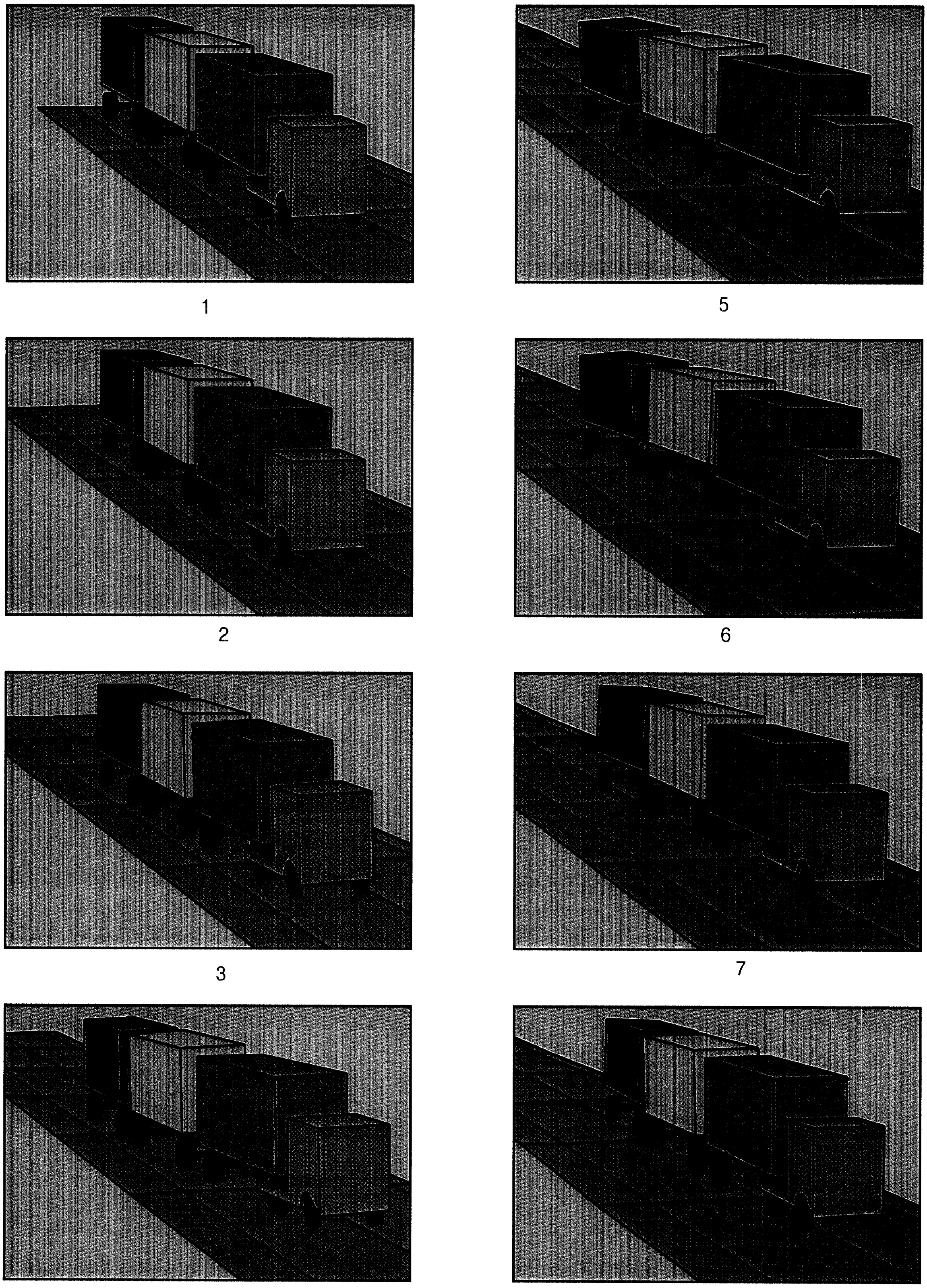
RAMS Seven-Axle Triple / 27-ft Trailers; 1000-ft Radius Curve; 55 mph; Loaded; - Simulation Run.



- Example of an Aggressive Highway Maneuver
- Lower Frequency Driver Steering Input (vs. test track course)
- Short RAMS Firings Upon Entry & Exit of Curve (< 2 mph speed loss)

Figure C-1. Simulated Curve Negotiation and RAMS Activation.

Figure C-2. Computer Animation Sequence Illustrating the Simulated Tripes Response for the Trailer-Only RAMS System. Rapid 8-ft Lane-Change.



Start

1

2

3

4

5

6

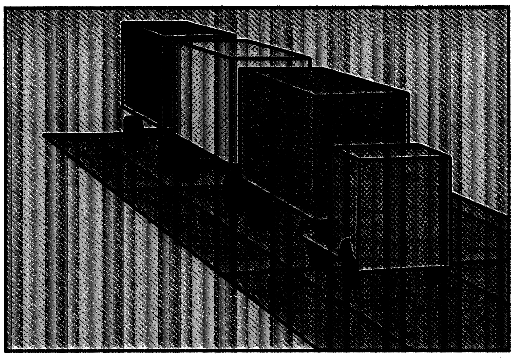
7

8

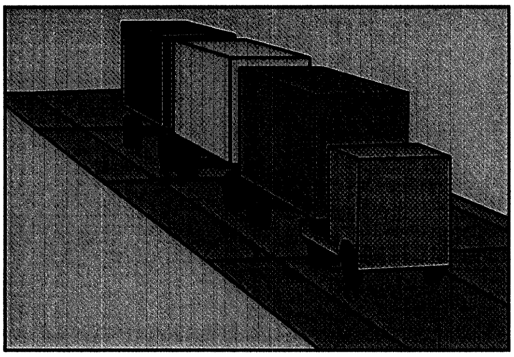
End

Figure C-3. Computer Animation Sequence Illustrating the Simulated Tripes Response for the Non-RAMS Configuration. (Last Trailer Rollover) Rapid 8-ft Lane-Change.

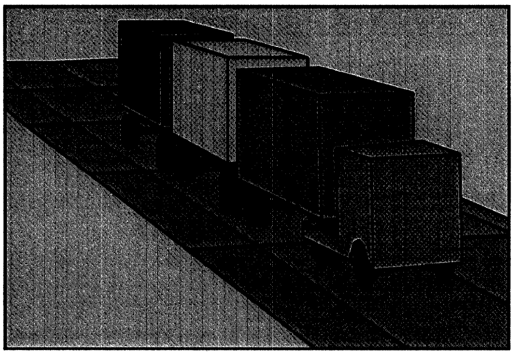
Start



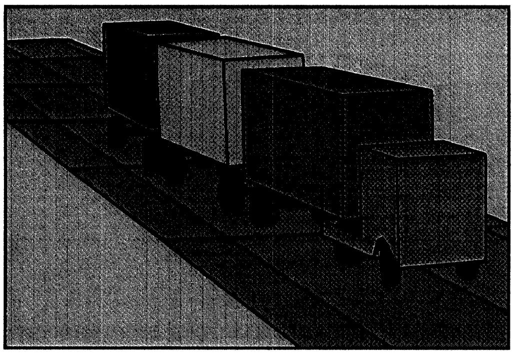
1



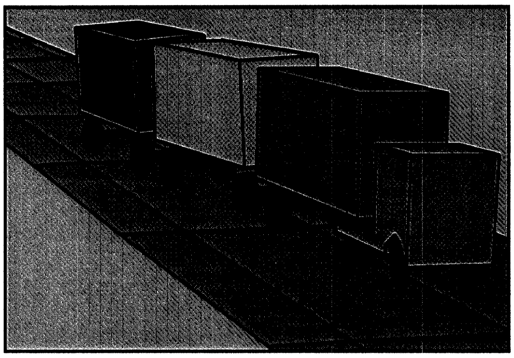
2



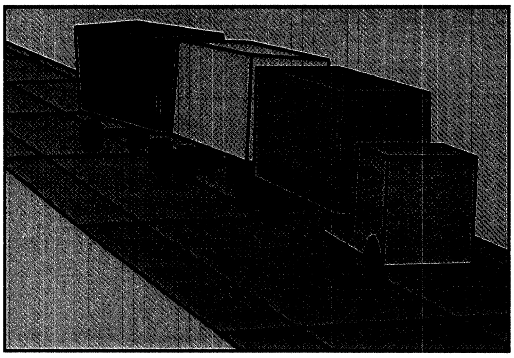
3



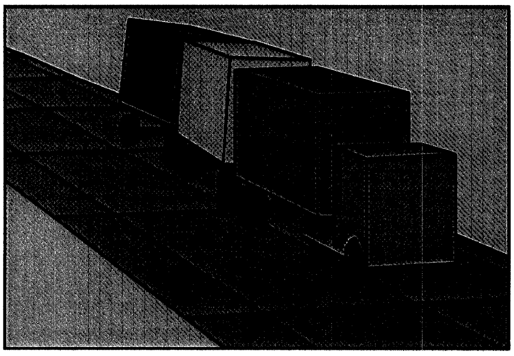
4



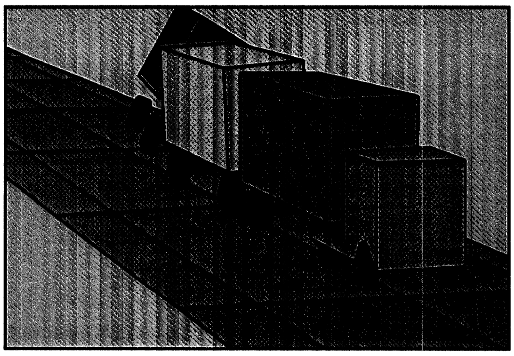
5



6



7



8

End