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NHTSA's Heavy Duty Vehicle Brake Research Program Report Number 11-- Evaluation of Stopping Performance of Trailer Antilock Brake Systems

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16. Abstract

In order to better understand the functioning of antilock brake systems on pneumatically braked trailers, a series of tests were conducted to evaluate different ABS control strategies, performance variations among systems supplied by different manufacturers, and the operation of ABS on double and triple trailer combinations.

The testing showed that there was relatively little difference in the stopping capability of the vehicle with the various control strategies and with the various manufacturers' systems. The only exception to this was in the case of a split coefficient surface or a maneuver where there was significant weight transfer from on side of the vehicle to the other. In these two situations, the systems which use axle control strategies had longer stopping distances than those using individual wheel or side-by-side control.

These results held true for the doubles and triples combinations as well. Additionally, it was found that the stopping capability of doubles and triples combinations was particularly enhanced with ABS on the trailers and dollies compared to having ABS on just the tractor in the case of mixed loads, where some of the trailers in the combination are loaded and some are not.

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TECHNICAL SUMMARY

Report Title: NHTSA's Heavy Duty Vehicle Brake Research Program Report Number 11 - Evaluation of Stopping Performance of Trailer Antilock Brake Systems	Date: November 1995
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Since the mid-1980s, the use of antilock brake systems (ABS) on heavy vehicles has increased substantially, particularly on truck tractors. In order to better understand the functioning of antilock brake systems on pneumatically braked trailers, a series of tests were conducted to evaluate different control strategies, performance variations among systems supplied by four manufacturers, and operation of ABSs on double and triple trailer combinations.

The tests comparing control strategies were conducted using a tandem axle trailer equipped to allow rapid changeover from one control strategy to another. The control strategies evaluated included 4S/3M, 4S/2M side-by-side and axle control, 2S/2M and 2S/1M. Various surfaces having a range of coefficient of friction levels and various maneuvers were used for the comparisons. In general, the results showed that there was relatively little difference in vehicle performance with the various control strategies, with the exception of the case where the air pressure necessary for lockup is significantly different from one side of the vehicle to the other. This can occur on a split coefficient surface (i.e., different coefficient levels in the two wheel tracks) or in a curve where the lateral force developed is sufficient to cause a significant amount of weight transfer from one side of the vehicle to the other. In these cases, the stopping distances for the systems which use individual wheel or side-by-side control strategies are shorter than those which use axle control strategies.

For the tests to evaluate performance variations between systems by different manufactures, a tandem axle trailer equipped to allow rapid changeover was again used. As was seen with the comparison of control strategies, these tests showed relatively little difference in the stopping capability of the vehicle with the various systems. The only exception again being a difference seen between the axle control and side-by-side control systems for split coefficient of friction surfaces.

The tests of double and triple trailer combinations were conducted using single axle trailers and dollies equipped with 2S/2M and 2S/1M ABSs. In general, the results seen for the single trailer held true for the doubles and triples combinations as well, in that relatively little difference was seen in the performance of the 2S/2M and 2S/1M systems except in the split coefficient of friction case. Additionally, it was found that mixing of the different operational modes in the combination did not have a negative effect on the vehicle's stopping performance capability, and that, in a number of cases, having ABS on the dollies as well as the trailers resulted in significant improvements in the stopping capability of the combination compared to having ABS on the trailers only. Also, it was found that the stopping capability of doubles and triples combinations was particularly enhanced by having ABS on the trailers and dollies in the case of mixed loads, where some of the trailers in the combination are loaded and some are not.

NHTSA's Heavy Duty Vehicle Brake Research Program

Report Number 11 – Evaluation of Stopping Performance of

Trailer Antilock Brake Systems

1.0 Introduction

The report which follows is the eleventh in a series of reports on NHTSA's Heavy Duty Vehicle Brake Research Program. It presents the results of tests to evaluate Antilock Brake Systems (ABS) on air braked trailers. For a general discussion on the background and scope of the Agency's long range Heavy Duty Vehicle Brake Research Program, the reader is referred to Reference 1. Research findings previously published on other subjects related to heavy vehicle braking are included in References 1 through 11.

In 1970 NHTSA proposed a set of heavy truck braking requirements which, while not mandating the use of antilock brake systems (ABSs), were difficult to meet without an ABS. These requirements, contained in the Federal Motor Vehicle Safety Standards (FMVSS) 121, were challenged in the courts and eventually set aside. The court decision effectively stopped the development of ABSs in this country during the late 1970s and early 1980s. Development of these systems continued in Europe during this period, however, and in the mid 1980s, U.S. interest increased in the European systems. Since the mid-1980s, the use of ABS on heavy vehicles has increased substantially, particularly on truck tractors.

In order to better understand the functioning of antilock brake systems on pneumatically braked trailers, a series of tests were conducted by the National Highway Traffic Safety Administrations's Vehicle Research and Test Center (VRTC), located on the facilities of the Transportation Research Center, Inc (TRC) in East Liberty, Ohio. These tests included evaluations of different control strategies, performance variations among systems supplied by four manufacturers, and operation of ABSs on doubles and triples combinations.

2.0 Background

The purpose of an antilock brake system is to control the pressure applied to a brake or a group of brakes to reduce the possibility of lockup on some of the wheels. A locked wheel produces longitudinal forces which are below the maximum force possible with a rolling wheel and is capable of producing relatively low lateral forces. For these two reasons, an ABS can reduce stopping distances and improve the lateral stability of the vehicle compared to the same vehicle with one or more wheels locked.

In general, an ABS controls the lockup of wheels by sensing the speed of the wheel, making some decision about the possibility of wheel lockup based on the wheel speed and other information and, if necessary, adjusting the pressure at the brake. These functions are most often performed by separate components in the system, namely the wheel speed sensors to determine wheel speed, the electronic control unit (ECU) to analyze the wheel speed information and determine the appropriate actions, and the modulator to adjust the brake pressure in response to signals from the ECU. These basic components work together to reduce the possibility of wheel lockup and enhance the stability of the vehicle.

Various configurations are possible using the same basic components to change the operational characteristics and complexities of the system. With a tandem axle trailer for example, the most complex system would be one that has a sensor and modulator on each of the four wheels. Such a system, referred to as individual wheel control, would require four sensors and four modulators. A less complicated system might use two sensors, one each on one wheel of the tandem sets on both sides of the vehicle, with a single modulator adjusting the pressure of all four brakes together. This type of system, referred to as tandem control, would have the fewest components, but would not be capable of controlling the pressures of the individual wheels to account for possible differences in the surface under the two wheel paths. Other systems might have two sensors and one modulator on each axle, known as axle control, or sensors and modulators on each side of the vehicle, known as side-by-side control.

In addition to possible variations in the hardware configuration, the performance of the system can be affected by the control logic programed into the ECU. For example, in the case of an axle or side-by-side configuration, the control logic determines how the system responds to the various wheel speed sensor inputs. The system may use select low logic where the pressure is controlled based on the first wheel to lock, select high logic where the pressure is controlled based on the last wheel to lock, or some modified control logic.

As stated above, the purpose of the antilock system is to control wheel lockup. By controlling wheel lockup, directional stability of the vehicle is maintained, and in many cases the stopping performance is improved. Maintaining vehicle directional stability allows the driver to steer around obstacles as necessary and/or to keep the vehicle within a lane or path without spinning or sliding across other lanes of traffic.

The amount of reduction in stopping distance is dependent upon, among other things, the difference between the peak rolling and the sliding tire-to-road coefficients of friction and the vehicle's brake balance. If the difference between the peak and sliding coefficients of friction is small, then little stopping performance improvement will be seen with an antilock brake system compared to a stop with all wheels locked.

If the driver is modulating the brakes to avoid wheel lockup, brake balance is an important factor in the stopping performance improvement possible with ABS. Brake balance can be understood as the percentage of braking on a given axle relative to the percentage of dynamic weight on that axle. With good brake balance, the braking percentage and dynamic weight percentage are nearly the same and the forces at all axles can be near their maximum level without locking. Poor brake balance occurs when one or more axles exert too much braking for the dynamic weight on those axles while the other axles exert too little braking for their dynamic weight. This means that the overbraked axle will lock at a lower brake pressures than the underbraked axles. This lower pressure means that the brake forces on the other axles are below their maximum. Vehicles with poor brake balance will benefit more from an ABS than ones with proper brake balance since the driver of a vehicle with proper brake balance can modulate the brakes more easily, keeping all wheels near their peak force, than can a driver of a vehicle with poor brake balance.

In general, heavy vehicles exhibit relatively good brake balance when fully loaded but poor balance when empty. This is due to the difficulty in finding a compromise brake balance level for such extremes in load conditions.

The stopping distance performance tests described below were conducted by a trained test driver on a test track making multiple attempts to obtain the best possible stopping distance. As such, comparisons of stopping distances with and without ABS cannot be directly related to those of typical drivers in a panic situation.

3.0 Tandem Axle Trailer Performance

Tests to evaluate the performance of ABS on a tandem axle trailer were conducted using a 42 foot tandem axle flat-bed trailer with a four-spring suspension. These tests were conducted using an ABS which could be arranged in any of several control configurations to compare the performance of those various configurations. Additional tests were conducted with ABSs from four manufacturers installed on the trailer as described below. In all of the testing, comparisons were made to having no ABS on the trailer.

3.1 Test Conditions - Tandem Axle Trailer Tests

For both sets of tests on the tandem axle trailer, stops were made both with the trailer empty and with it loaded. For the loaded tests, weights were added to the trailer so that each axle in the combination was as near as possible to its gross axle weight rating (GAWR) and the combination was as near as possible to 80000 lb. The tests were conducted on different surfaces with each of the systems and with no trailer ABS. The truck tractor towing the trailer had an operational ABS during all of the testing to minimize the effect the truck tractor had on the results.

The test surfaces used for these tests are shown in Table 1 along with the peak friction coefficient (PFC) for the surface. The PFC was measured using ASTM E1337 "Standard Test Method for Determining Longitudinal Peak Braking Coefficient of Paved Surfaces Using a Standard Reference Test Tire – E1136."

Table 1 – Test Surfaces and PFC

Surface	PFC*
Wet Epoxy	0.20
Wet Jennite	0.25
Wet Polished Concrete	0.55
Wet Smooth Concrete	0.80
Wet Asphalt	0.85
Dry Concrete	0.90

* PFC = Peak Friction Coefficient

The epoxy and Jennite surfaces are both coatings over an asphalt surface and are only tested when wet. The epoxy is similar to an icy roadway and the Jennite approximates a well-polished secondary roadway with tar on the surface. The split surface tests were conducted with one side of the vehicle on either the epoxy or Jennite surface and the other on wet asphalt. This would be similar to a situation where the road had ice under one wheel track and was wet but not icy in the other wheel track. Both the polished and smooth concrete surfaces are concrete surfaces which have been polished using a grinder. These two surfaces would be similar to roadways worn smooth by traffic. The dry concrete surface is representative of primary roadways in good condition.

On the epoxy and the Jennite surfaces and for some of the tests on wet asphalt, the stops were made in a straight lane and also on a 500 foot radius curve. The 500 foot radius curve is representative of a relatively tight freeway entrance or exit ramp. On the three concrete surfaces, only straight-line stops were made.

For the tests comparing ABS control strategies, the ABS was supplied by one manufacturer and changes were made in the control strategies by changing the ECU module and, where necessary, connections to sensor and modulator leads. The pneumatic plumbing changes were made by means of a series of shutoff valves to route the air to the appropriate valves and brake chambers. The configurations tested included two sensors and one modulator (2S/1M), two sensors and two modulators (2S/2M), four sensors and two modulators (4S/2M), and four sensors and three modulators (4S/3M). The 4S/2M configuration was divided into side-by-side (two sensors and one modulator for the two wheels on each side of the vehicle) and axle control (two sensors and one modulator for each axle). The axle control systems (2S/1M, 4S/2M axle control) used a select low logic, meaning that the pressure was controlled by the wheel tending to lock first.

The 2S/1M system was installed with the sensors on the front axle of the tandem and the modulator controlling all of the brakes. This is a typical installation for a trailer with a four-spring suspension. The 2S/2M system was configured with a sensor on each front wheel and a modulator controlling the two wheels on one side of the vehicle, referred to as side-by-side control. The 4S/2M configurations had the sensors at each wheel and the modulators were either on each axle for axle control or on each side for side-by-side control. The 4S/3M configuration had sensors at each wheel with individual modulators for the wheels on the front axle of the tandem and a single modulator for the two wheels on the rear axle of the tandem.

For the tests with four manufacturers' ABSs, all four systems were installed on the trailer at the same time to allow immediate changeover from one system to another. This changeover of systems was accomplished by plumbing the trailer using high-flow quick disconnect junctions so that the air lines could simply be disconnected from one system and connected to another. (Earlier testing has shown that high-flow quick disconnect junctions do not affect system performance.) Likewise, the wiring was run into a junction box with connectors for ease of system changeover. Provisions were also made to allow operation without ABS for comparison.

The four ABSs included two systems with two sensors and one modulator valve (2S/1M) and two systems with four sensors and two modulator valves (4S/2M). For the two 2S/1M systems, the sensors were installed in the forward axle and for the two 4S/2M systems, each modulator controlled one axle.

3.2 Test Results - Tandem Axle Trailer Tests

The results of the tandem axle trailer tests are summarized in the following sections of the report with all of the results given in Appendices at the end of the report. The results are presented graphically with bars representing the range in stable stopping distance from the shortest to the longest stop with ABS operational on both the truck tractor and on the trailer. Horizontal lines are also shown for each test condition which represent the shortest and the longest stable stopping distances with ABS on the truck tractor only. In determining which stop was the shortest, only stops for which directional control was maintained were included. This means that for the stops in a curve, the vehicle remained within the lane, and for the straight line stops, no more than one wheel per axle locked. For all of the tests with ABS operational on the trailer, the vehicle remained within the lane and did not lock any wheels, so the results shown are for all stops made.

For the tests where ABS was operational on all axles, the tests were conducted by making three stops using a rapid full treadle application of the brake. For the tests with ABS disabled on the trailer, the tests were performed by making driver-modulated best effort stops with six stops being made in each condition. It should be noted again that these results are for a trained test driver who is not faced with an emergency situation.

3.2.1 Tests Comparing Control Strategies

The tests comparing control strategies for trailer systems were conducted on a number of different surfaces both loaded and empty. For simplification, only the results for some of the surfaces will be given in the following sections. The results for all of the tests are given in Appendix A.

The graphs below and in Appendix A have each of the control strategies listed along the bottom of the graphs. In the graphs, the two 4S/2M systems are differentiated as either Mar for axle control or SBS for side-by-side control.

The results for the straight line stops on the wet Jennite are shown in Figure

1. This figure shows that for the loaded case, the shortest stops with ABS on the trailer were generally the same as the shortest stop without ABS on the trailer. As noted above, the brake system of a tractor / trailer combination is balanced for a loaded vehicle, hence, even with no ABS on the trailer, the test driver was able to modulate the brakes to achieve stopping distances similar to those with ABS. The longest stop with no ABS on the trailer was significantly longer than the longest stops with ABS, indicating that the driver was able to achieve stopping distances comparable to that with ABS on at least one stop but was not able to consistently stop in that distance as was true with ABS. With the vehicle unloaded, the stopping distances with ABS were significantly shorter than without. This again is due to the fact that the brake system is balanced for the loaded vehicle, making the empty vehicle prone to lock wheels at low pressures and making it impossible for the driver to modulate the brakes so as to achieve optimal stopping performance.

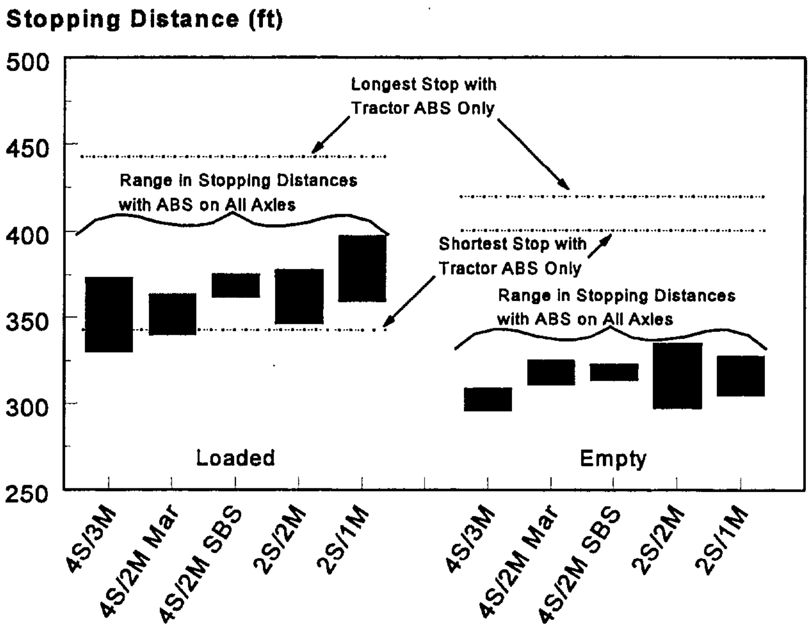

Figure 1 – Comparison of Control Strategies for 35 mph Straight Line Stops on the Wet Jennite

Comparison of the results for the different control strategies shown in Figure 1 show relatively little difference for the various methods of control. This is as would be expected for straight line stops on a uniform surface. While more sensors and modulators can, in general, keep more of the wheels near peak braking performance, a straight line stop on a uniform surface should not require different braking levels at the various wheels.

The results for the tests on the wet Jennite curve are shown in Figure 2. This figure shows that the stopping distances, both with the vehicle loaded and empty, were shorter with the ABS operational on the trailer than with ABS on the truck tractor only. The stopping distance improvement with ABS is more pronounced for the empty case than the loaded case. The improvement in stopping performance with ABS in both load conditions is an indication of the enhanced stability of the combination with ABS. Even though the brake balance for the loaded vehicle is good, it is still difficult for the driver to maintain control of the vehicle on the slippery curve without ABS.

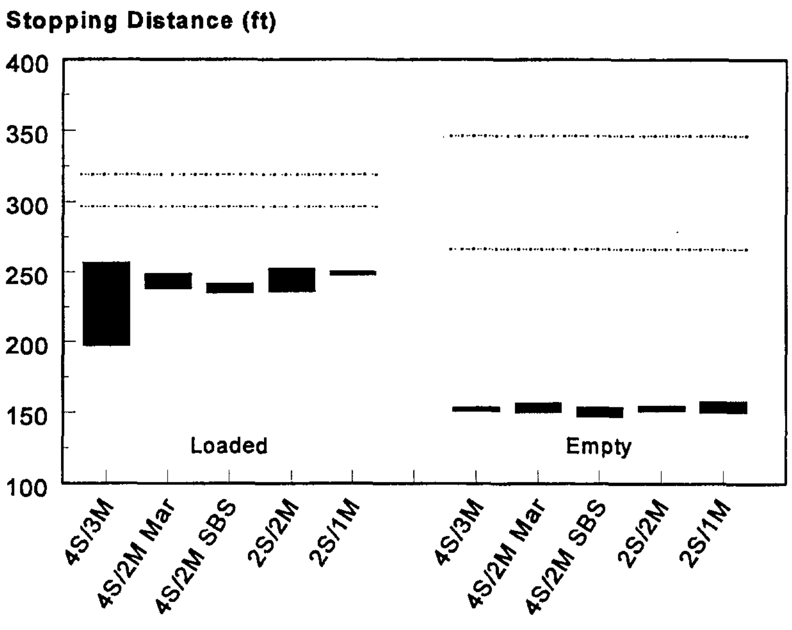

Figure 2 — Comparison of Control Strategies for 30 mph Stops on the Wet Jennite Curve

Comparing the different control strategies, Figure 2 shows that the different methods of control resulted in stopping distances which were approximately the same. While some differences might have been expected between the systems which use axle control and those which use individual wheel control or side-by-side control due to weight transfer from the wheels on the inside of the curve to the wheels on the outside, apparently there was not enough lateral weight transfer at this speed to affect the ABS performance.

The results of the tests conducted on the split coefficient surface are shown in Figure 3. Of particular interest in this plot is the comparison of the different control strategies, especially for the loaded vehicle. Note that the stopping distances for the 4S/2M Mar and the 2S/1M control strategies resulted in significantly longer stopping distances than did the other control methods. This is due to the fact that these two systems were axle control systems that used select low logic. This means that the pressure to the brakes on both sides of the vehicle were controlled by the wheel on the side which tended to lock first (the low coefficient side). This results in the wheels on the higher coefficient side of the vehicle being at a pressure below the optimum for that surface. The systems which control the wheels on the individual sides of the vehicle independently control the pressures appropriately for the surface coefficient on each side of the vehicle, hence the wheel on the high coefficient side of the vehicle is generating higher forces resulting in shorter stopping distances. This trend of the axle control systems having longer stopping distances than the individual wheel or side-by-side control systems was more apparent for the loaded vehicle than the empty vehicle. For the empty vehicle, the overbraking of the lightly loaded wheels means that the pressure at which the wheels tend to lock even on the high coefficient side of the vehicle was not significantly higher than that of the low coefficient side, hence, relatively little advantage is gained by having higher pressures on one side of the vehicle than the other.

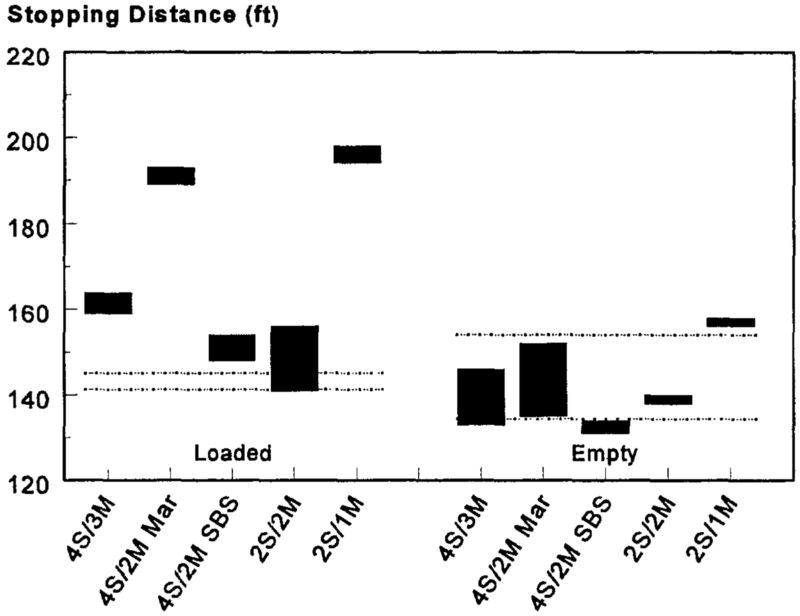

Figure 3 – Comparison of Control Strategies for 35 mph Stops on the Split Coefficient Surface

Looking at the stopping distances shown in Figure 3 it can be seen that, in general, the driver was able to stop the vehicle with ABS on the truck tractor only in as short or shorter distances than with the ABS operational on the trailer. This was done by allowing the wheels on the low coefficient surface to lock while modulating the pressure to control the wheels on the high coefficient surface. For this combination of surfaces, this method resulted in shorter stopping distances than with the wheels on both sides of the vehicle rolling, as is the case with the ABS. For other combinations of surfaces, this method of allowing one wheel to lock while modulating the other wheel may not result in the best stopping performance.

Another test condition which showed significant differences in the performance of the various control strategies was the wet asphalt curve. These results are shown in Figure 4. Again, it can be seen that for the loaded tests, the two axle control systems (4S/2M Mar and 2S/1M) had longer stopping distances than did the other control methods. The reasons for this are the same as those discussed above for the split coefficient surface tests. As the vehicle goes around the curve, weight shifts from the inside wheels to the outside wheels resulting in the inside, more lightly loaded wheel having a tendency to lock at lower pressures than the outside, more heavily loaded wheel. As with the split coefficient condition, this results in the select low systems reducing pressure to both sides of the vehicle while the systems which control each side independently can adjust the pressure appropriately for the weight on each wheel. Also, as was seen for the split coefficient condition, the difference is more pronounced in the loaded condition than in the empty condition.

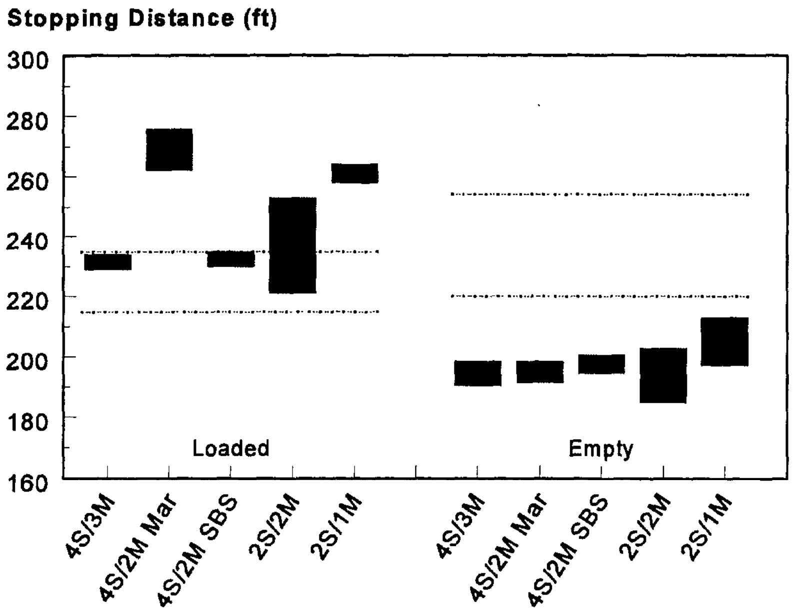

Figure 4 – Comparison of Control Strategies for 50 mph Stops on the Wet Asphalt Curve

For the asphalt curve, the shortest stopping distance with ABS on the truck tractor only was shorter than the stopping distance with ABS on both the truck tractor and the trailer in the loaded configuration. With the vehicle empty, however, the stopping performance with ABS on all axles was better than with ABS on the truck tractor only. As discussed above, this is due to the brake system being balanced for the loaded vehicle and overbraked for the empty vehicle. This effect is particularly pronounced on high coefficient of friction surfaces. With the vehicle loaded on a high coefficient surface, the driver can apply full or nearly full pressure to the brakes without locking the wheels. This means that the ABS will either not cycle, resulting in no effect on stopping distance, or may cycle briefly if it senses impending lockup, reducing the pressure and slightly increasing stopping distance. The ABS does, however, allow control of the vehicle to be maintained if some of the wheels should approach lockup.

The results of the remainder of the tests comparing control strategies will not be presented here but are given in Appendix A. These results generally show the same trends discussed above, with the addition of ABS on the trailer causing stopping distances to either improve or, at least, remain the same as with ABS on the truck tractor only. Generally, the improvements in stopping capability were more pronounced for the empty vehicle and particularly for the low coefficient of friction surfaces. The differences in the control strategies were generally small for the uniform coefficient straight line tests, while the axle control systems had longer stopping distances for the split coefficient surfaces and on maneuvers where weight is transferred from one side of the vehicle to the other. In all cases, the ABS allowed the vehicle to be stopped in a stable, controlled fashion with a full application of the brakes.

An additional set of tests was conducted where the brakes were applied on one uniform coefficient surface and, during the stop, the vehicle transitioned to another uniform coefficient surface. The tests were run in both directions so that the transition was from a high coefficient (high co) surface to a low coefficient (low co) surface and from a low to a high coefficient surface. This type of test ensures that the system can recognize the change in surface coefficient and react appropriately.

To illustrate the system reaction to the transition, the vehicle speed, the wheel speed for one wheel and chamber pressure for one brake are shown in Figure 5 for a representative high to low transition and in Figure 6 for a low to high transition. The vehicle speed in both of these plots shows a change in slope at the point of the surface transition. A similar change in slope can be seen for the wheel speed, although not as pronounced. The chamber pressure shows a change in the average pressure level and the frequency of cycling just after the transition as the system responds to the change in surface friction.

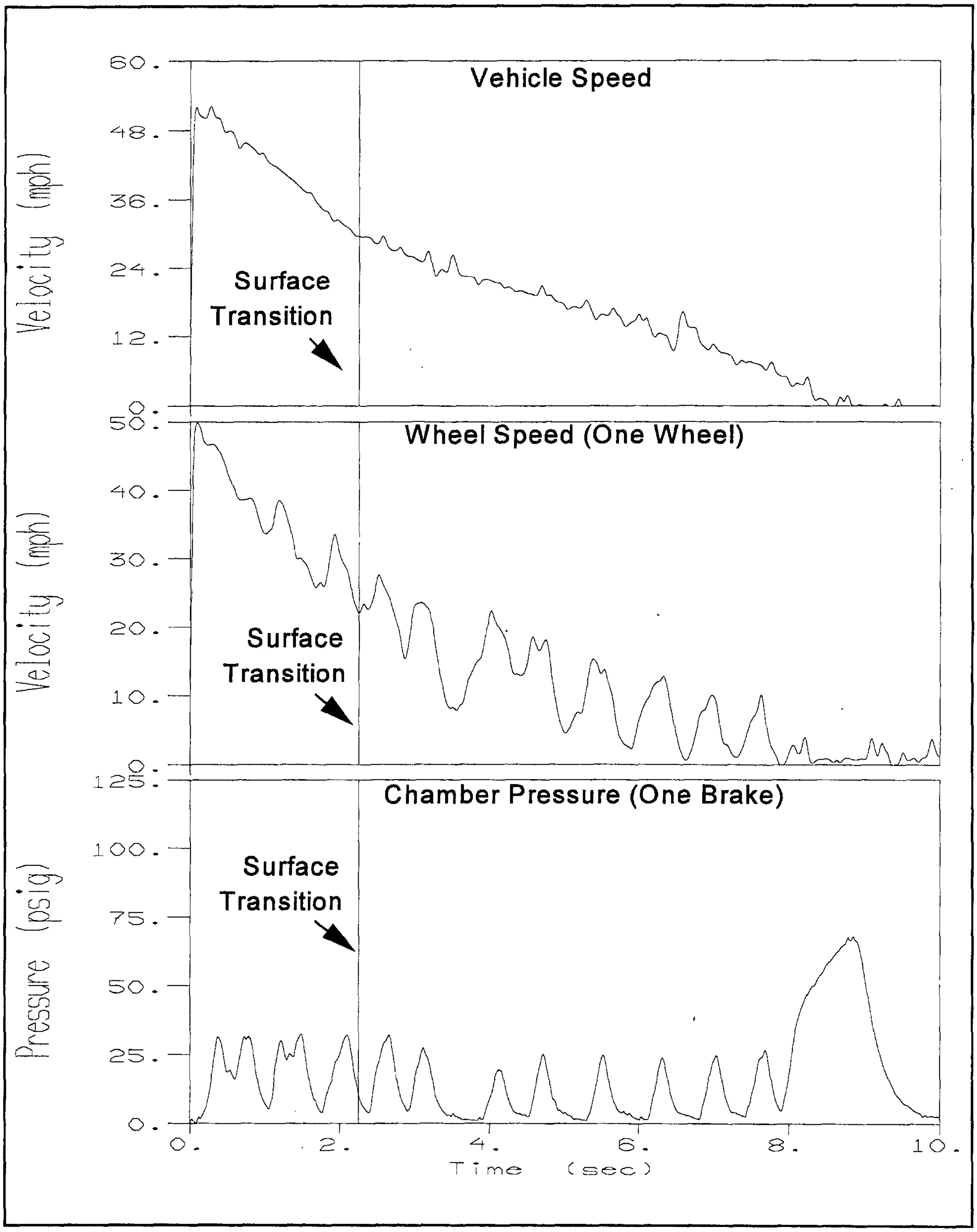

Figure 5 – Example of Data for a High Co to Low Co Surface Transition Test

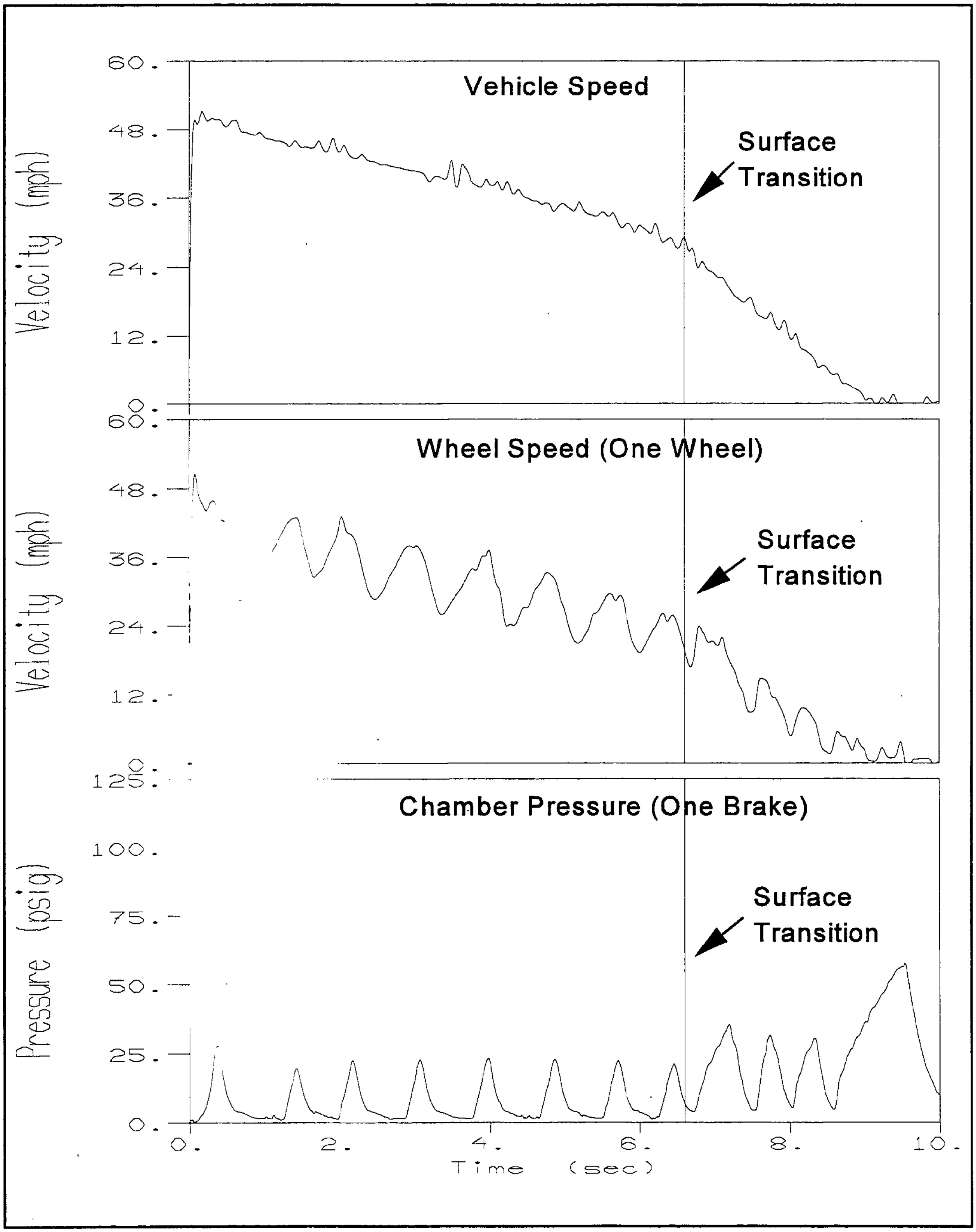

Figure 6 – Example of Data for a Low Co to High Co Surface Transition Test

The transition test requires the driver to initiate the stop at the appropriate speed and location to allow the transition to be made at a given speed. This is difficult to do consistently on multiple stops, so the conditions for each stop are slightly different, making comparisons of system performance difficult. It can only be noted that none of the system configurations allowed any of the wheels to lockup and that all of the configurations increased or reduced the pressure at the brakes appropriately after the surface transition.

3.2.2 Tests with Systems from Different Manufacturers

The results of the tests using systems from different manufacturers will again be shown as plots with bars indicating the range of stopping distance with ABS on all axles and horizontal lines showing the range in performance with ABS on the truck tractor only. Results of tests of particular interest will be shown below with all of the results shown in Appendix B. The different manufacturers' systems will be referred to by letters with the two 4S/2M systems being labeled A and B and the two 2S/2M systems being referred to as systems C and D.

Figure 7 shows the results for the tests on the wet Jennite curve. As with the results seen above, having ABS on the trailer improved the stopping distance performance compared to ABS on the truck tractor only. The stopping distance performance improvement is particularly pronounced for the empty trailer tests where the stopping distances went from over 350 feet with truck tractor ABS only to under 150 feet with ABS on the trailer. Figure 7 also shows that there was relatively little difference in the performance of the different manufacturer's systems.

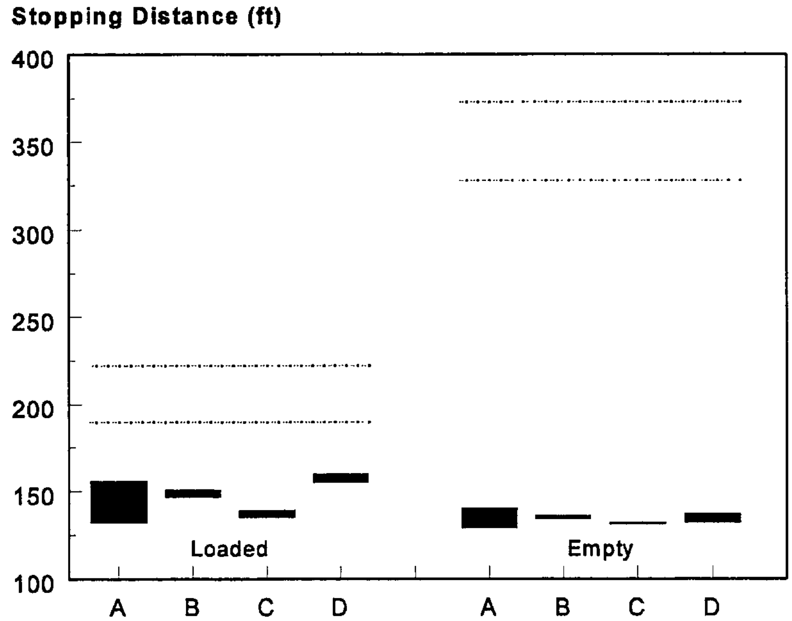

Figure 7 – 25 mph Stopping Distances on Wet Jennite Curve with Four Manufacturers' ABSs

The results for the split coefficient surface are shown in Figure 8. These results show the effect of the side-by-side control logic used by systems A and B versus the axle control logic used by systems C and D. As described above, the axle control logic results in longer stopping distances due to the pressure being controlled based on the low coefficient surface which underbrakes the wheels on the high coefficient surface.

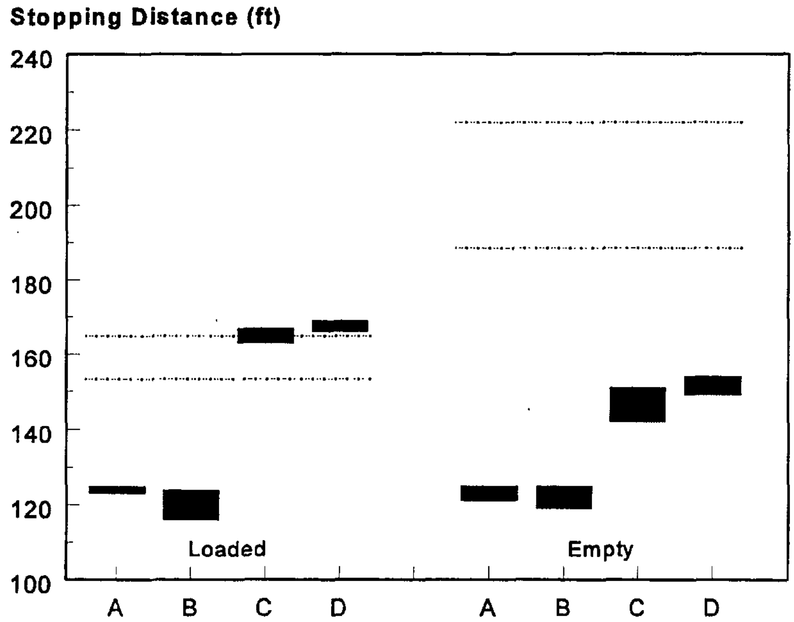

Figure 8 – 30 mph Stopping Distances on Split Coefficient with Four Manufacturers' ABSs

The remainder of the tests with the four manufacturers' systems (shown in Appendix B) show that the stopping distances were shorter with ABS on the trailers than they were with ABS on the truck tractor only, with the only exception being the two axle control systems during the loaded tests on the split coefficient surface. The results also show essentially no difference between the performance of the different manufacturers' systems, again with the exception of the tests on the split coefficient surface.

4.0 Doubles and Triples Combinations

The use of doubles and triples combinations has increased in recent years. The use of ABSs on these combinations raises some additional questions beyond those of a single trailer. The issue of providing sufficient electrical power to the ABS is more difficult for double and triple trailer combinations due to the additional length and multiple connectors. These issues were discussed in Reference 11. Other questions unique to doubles and triples combinations are whether each of the units in the combination (i.e. trailers and dollies) need to have ABS and the effects of mixed ABS operational modes or mixed loading throughout the combination.

4.1 Test Conditions – Doubles and Triples Combinations

For the doubles and triples tests, three 27 foot single axle trailers and two single axle A-dollies were equipped with ABSs which could be configured as either two sensors with two modulators (2S/2M) or two sensors with one modulator (2S/1M) using select low logic. The plumbing and wiring were configured as described above to allow easy changeover from one system to the other or to a standard brake system with no ABS.

The tests were conducted comparing the performance of the combinations with ABS on all of the units and with ABS on only the trailers but not on the dollies. These tests were conducted using both 2S/2M and 2S/1M configurations. Tests were also conducted mixing the control strategies (2S/2M and 2S/1M) on the trailers and dollies. In all cases, the truck tractor towing the combination had an operational ABS to minimize any effects of the performance of the truck tractor on the results.

Tests were also conducted to evaluate the effect of mixed loading of the trailers. The mixed loading tests were conducted with some of the trailers in the combination loaded while the remainder of the trailers in the combination were empty. The loading of trailers was accomplished by adding weights such that the trailer axle and the axle supporting the front of the trailer (i.e. the truck tractor drive for the front trailer or the dolly for the back trailers) was as near as possible to its GAWR.

The test surfaces used were those listed in Table 1.

4.2 Test Results - Doubles and Triples Combinations

A selected set of the results for the tests on the triples combination will be shown in this section with the results of all of the tests shown in Appendix C. As above, the results are shown as a bar indicating the range in stopping distance with ABS operational on the trailers. Lines are also shown indicating the range in stopping distances with ABS on the truck tractor only. The tests for which each of the units (i.e., trailers and dollies) in the combination was equipped with ABS were performed by making a rapid full treadle application. The test conditions for which ABS was not operational on all of the units (i.e., truck tractor only, or truck tractor and trailers but not dollies) were performed with the driver modulating the brakes to get the best possible stopping distance. The best distance was defined as the shortest stop with less than one wheel per axle locked for the straight line tests or the shortest stop within the lane for the stops in a curve. In those cases where a full treadle application was used, three stops were made for each test condition and in the cases where the driver modulated the brakes, six stops were made for each test condition.

In these graphs, labeling along the bottom of each graph indicates the operational mode of the ABS on the trailers. Those labeled "2S/2M" means that all axles had 2S/2M, similarly, those labeled "2S/1M" indicates all axles having 2S/1M. The results labeled as "2S/2M Off" or "2S/1M Off" indicate the tests where the trailers had either 2S/2M or 2S/1M and the dolly ABS was not operational. The tests with mixed operational modes are shown as "Mix 1" and "Mix 2". For the doubles combination, Mix 1 was with the first trailer and the dolly being equipped with 2S/2M and the second trailer having a 2S/1M system. Mix 2 was with the first trailer having a 2S/1M system and the dolly and second trailer having a 2S/2M system. For the triples combination, Mix 1 represents having 2S/2M on the first and last trailers and both dollies and 2S/1M on the second trailer. Mix 2 was with a 2S/1M system on the first and last trailer and a 2S/2M system on the second trailer and both dollies.

The results of the triples straight line stops on wet Jennite are shown in Figure 9. These results show that with the vehicle loaded, the range in performance with ABS on some of the units in the combination was generally within the range of performance for ABS on the truck tractor only except with 2S/2M on all of the trailers and dollies, where the range was somewhat shorter than for the truck tractor only configuration. The results of the empty tests, however, show an improvement with ABS in all of the test configurations compared to ABS on the truck tractor only, with the greatest improvement coming with 2S/2M on all of the towed units. These results again show the effect of brake balance on stopping distance performance improvement with ABS. The loaded results show little, if any, performance improvement, while the tests with the empty vehicle show significant improvement.

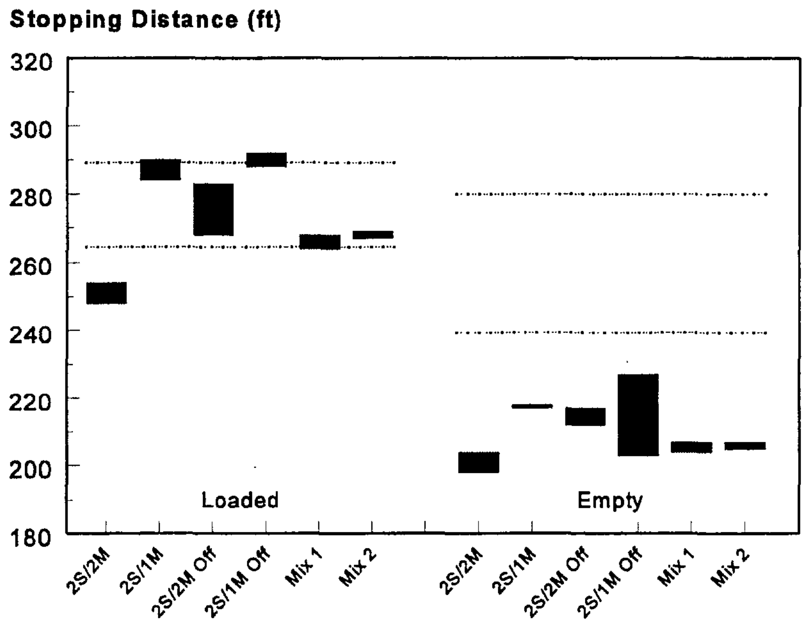

Figure 9 — 30 mph Straight Line Stopping Distances on Wet Jennite for Triples Combination

For the triples on the wet Jennite curve, the stopping distance results are shown in Figure 10. From these results it can be seen that in both the loaded and empty configurations, having ABS on all axles improved the stopping distance performance over having ABS on the truck tractor only. It can also be seen that having ABS on the truck tractor and the trailers but not on the dollies resulted in longer stopping distances than with ABS on all axles, particularly with the vehicle empty. This is due to the driver having to modulate the brakes to maintain control of the dollies, thus eliminating some of the advantage gained by having ABS on the truck tractor and trailers.

A comparison of Figure 9 and Figure 10 indicates that the combination's stopping distances were longer for the straight line tests than for the stops in a curve. This may seem to be counterintuitive since it would be expected that straight line stopping distances would be shorter than stops in a curve. It is believed that the differences in the stopping distances for the two groups of tests are due to local differences in the coefficient of friction for the areas where these two sets of tests were conducted.

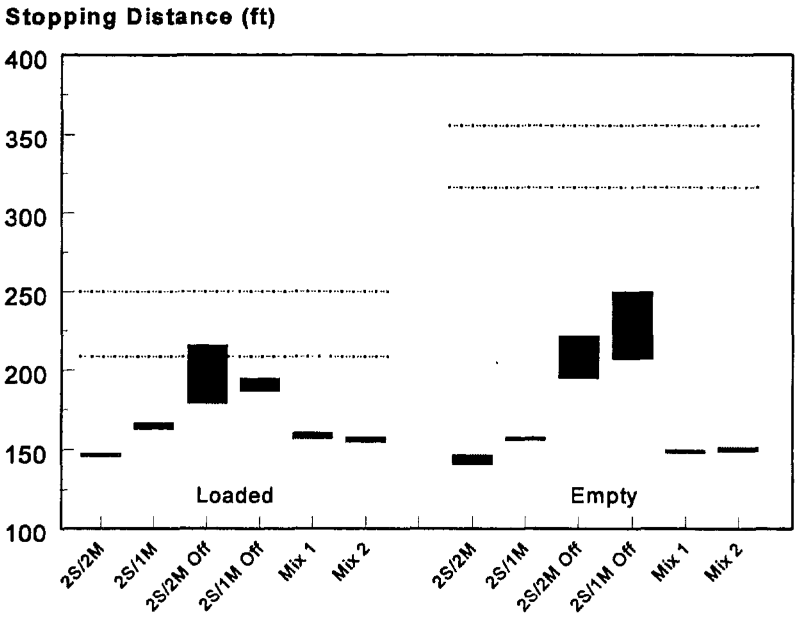

Figure 10 – 30 mph Stopping Distances on Wet Jennite Curve for Triples Combination

The stopping distance results for the triples tests on the split coefficient surface are shown in Figure 11. As was seen for the single trailer results, using axle control logic (2S/1M) resulted in longer stopping distances than using individual wheel control (2S/2M). This was true both with ABS on all units in the combination and with ABS on the trailers only but not on the dollies. Some effect of this is also seen in the case of mixing the systems on the trailers, where the use of 2S/2M on two of the three trailers (Mix 1) produced shorter stopping distances than did the use of 2S/1M on two of the three (Mix 2).

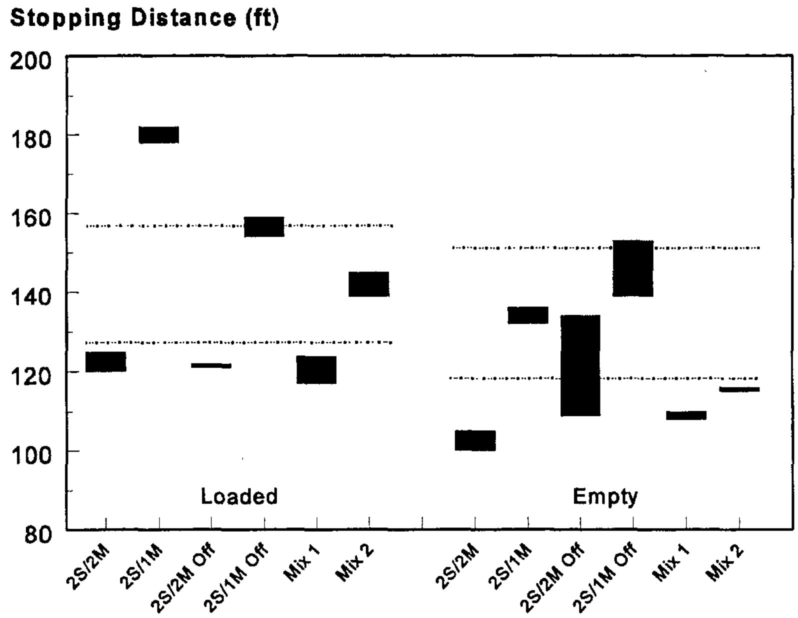

Figure 11 — 30 mph Stopping Distances on Split Coefficient Surface with Triples Combination

The tests on the other surfaces and the tests with the doubles combination (shown in Appendix C) all show the general trends seen in the results described above. The stopping distances generally show improvement with ABS on the trailers over ABS on the truck tractor only, particularly for the empty vehicle condition. Having ABS on the truck tractor and trailers only, with no ABS on the dollies, generally resulted in stopping distances which were longer than with ABS on all units of the combination and in some cases were as long as or longer than with ABS on the truck tractor only. The mix of ABS modes (2S/2M and 2S/1M) on the trailers did not result in any significant degradation in stopping performance.

To look at the issue of mixed loading of the trailers in the combination, tests were run on the doubles with the front trailer loaded and the rear trailer empty, on the triples with the front two trailers loaded and the rear trailer empty, and with the front trailer loaded and the rear two empty. The tests were conducted on the wet Jennite curve and on the dry concrete. The results of these tests are shown in Figure 12 and Figure 13 respectively. Both 2S/2M and 2S/1M systems were tested. These figures shows that for these loading conditions there was a significant stopping distance improvement with the ABS on the trailers and dolly or dollies compared to ABS on the truck tractor alone. This was particularly true for the tests on wet Jennite. The improvement in stopping distance for these loading conditions is due to the fact that the lightly loaded trailers tended to lockup easily, requiring that lower brake pressures be used to maintain control of the combination. With the relatively low brake pressures necessary for the lightly loaded trailers, the heavily loaded trailers were well below their optimum brake force level. With ABS, however, the braking forces on all of the trailers and dollies were at or near their peak force level.

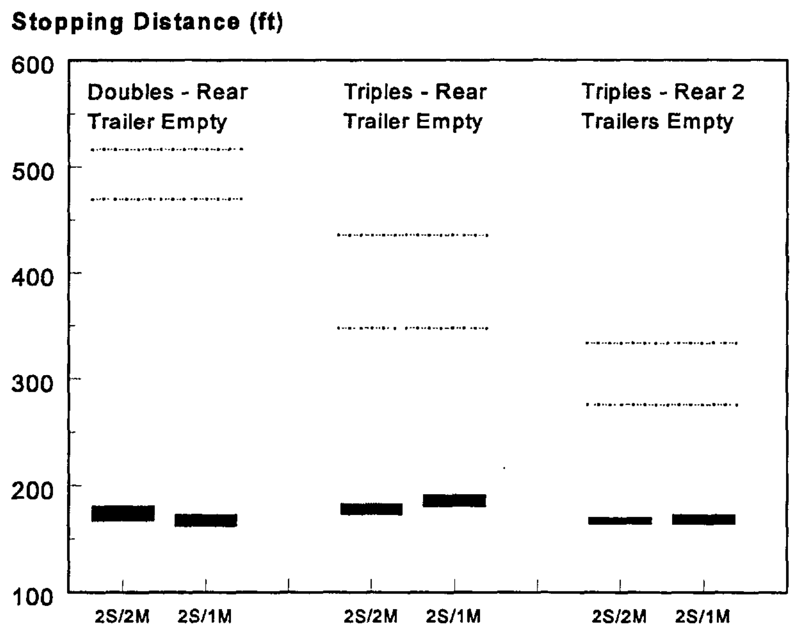

Figure 12 — 30 mph Stopping Distances on Wet Jennite for Mixed Loading Tests

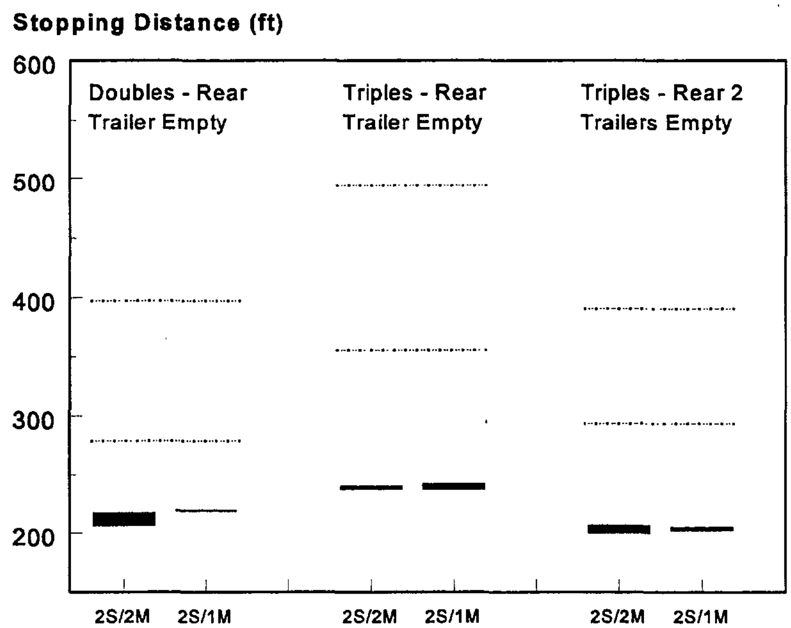

Figure 13 – 55 mph Stopping Distances on Dry Concrete for Mixed Loading Tests

5.0 Summary and Conclusions

Tests were conducted to evaluate the stopping performance of antilock brake systems on trailers. The tests included a single tandem axle trailer and double and triple trailer combinations. Comparisons were made of different ABS operational configurations and of systems supplied by different manufacturers measuring controlled stopping capability.

In general, the results of these tests showed that the difference in having an antilock brake system versus not having one was much greater than differences in the control strategy or ABS manufacturer design. The only condition where significant differences between control strategies could be seen was on a split coefficient surface or in a curve where high lateral forces were developed.

Additionally, on doubles and triples combinations it was found that in most of the test conditions the presence of ABS on the dollies as well as on the trailers resulted in an improvement in the stopping distances. It was also found that mixing the ABS control strategies on the various units throughout the combination did not significantly affect vehicle performance. Finally, it was found that having ABS on a combination with mixed loading(i.e., some of the trailers loaded and some empty) significantly improves the stable stopping capability of the combination.

6.0 References

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9. Flick, Mark A., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 9 -- Stopping Distances of 1988 Heavy Vehicles," Vehicle Research and Test Center, Report Number DOT HS 807 531, February 1990.

10 Clarke, R.M., Radlinski, R.W., and Knipling, R.R., "Improved Brake Systems for Commercial Motor Vehicles," National Highway Traffic Safety Administration, Report Number DOT HS 807 706, April 1991.

11. Flick, Mark A., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 10 -- Evaluation of Trailer Antilock Braking Systems Electrical Powering," Vehicle Research and Test Center, Report Number DOT HS 808 249, March 1995.

Appendix A

Results for Control Strategies Comparisons

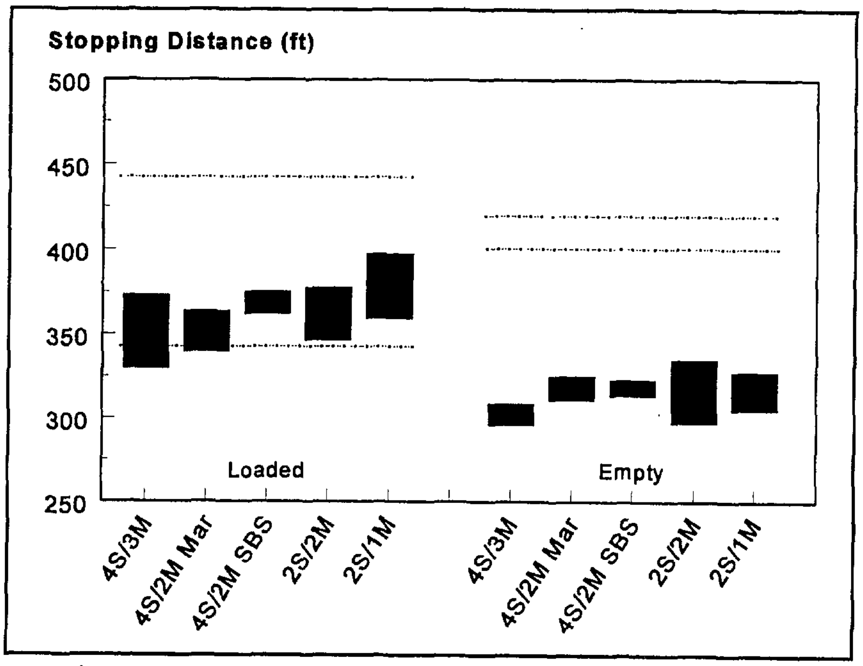

Figure A1 – 35 mph Stops on Wet Jennite Straight Line

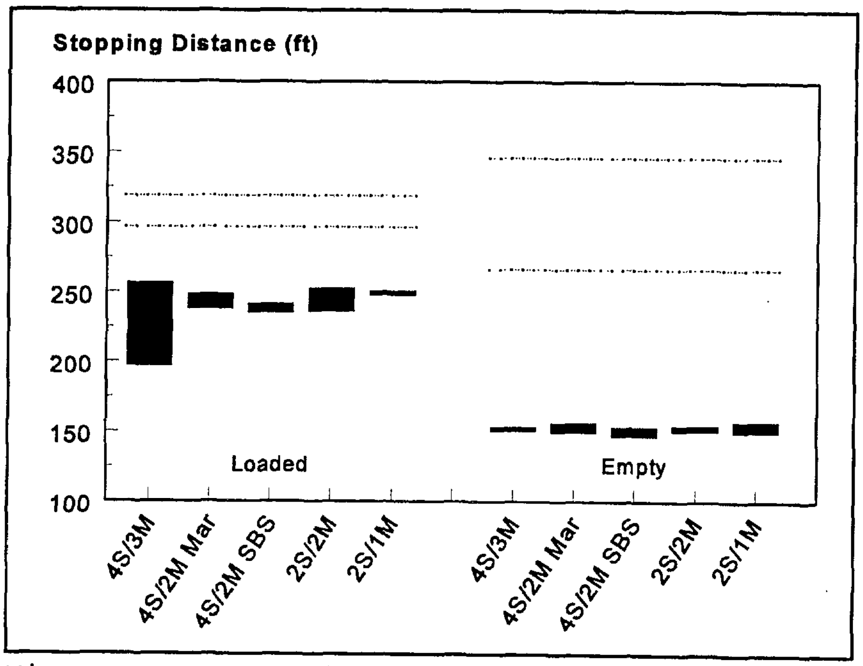

Figure A2 – 30 mph Stops on Wet Jennite Curve

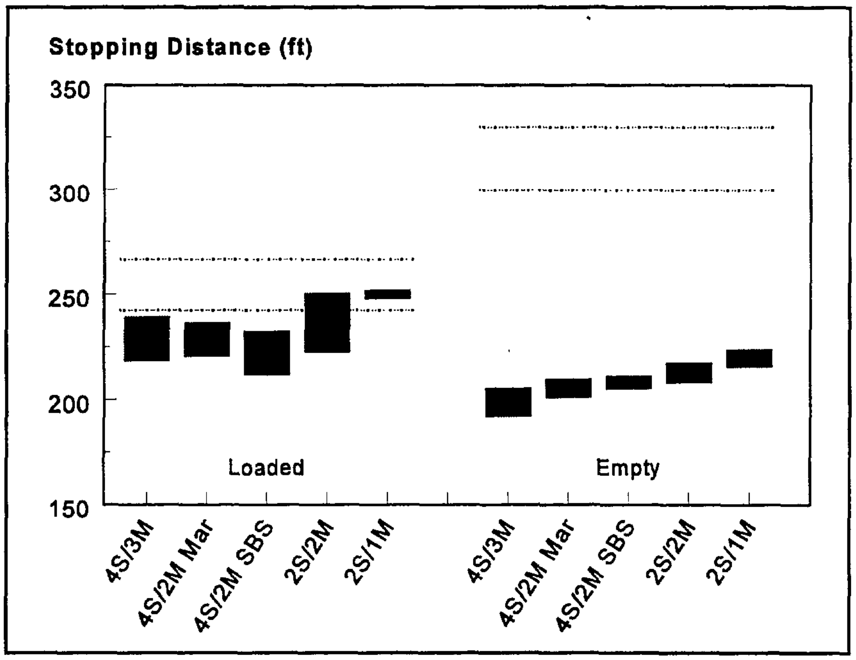

Figure A3 — 28 mph Stops on Wet Jennite Lane Change

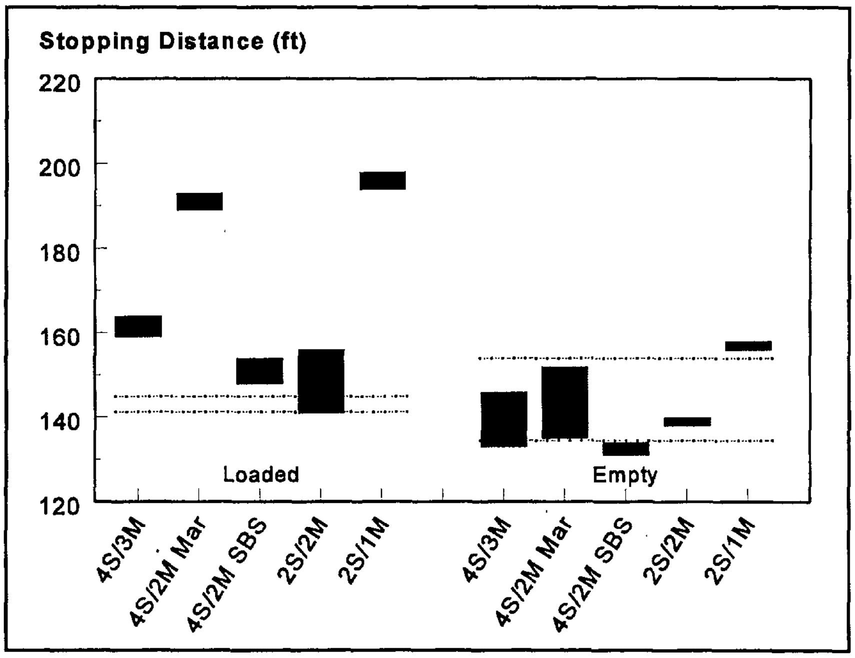

Figure A4 — 35 mph Stops on a Split Coefficient Surface

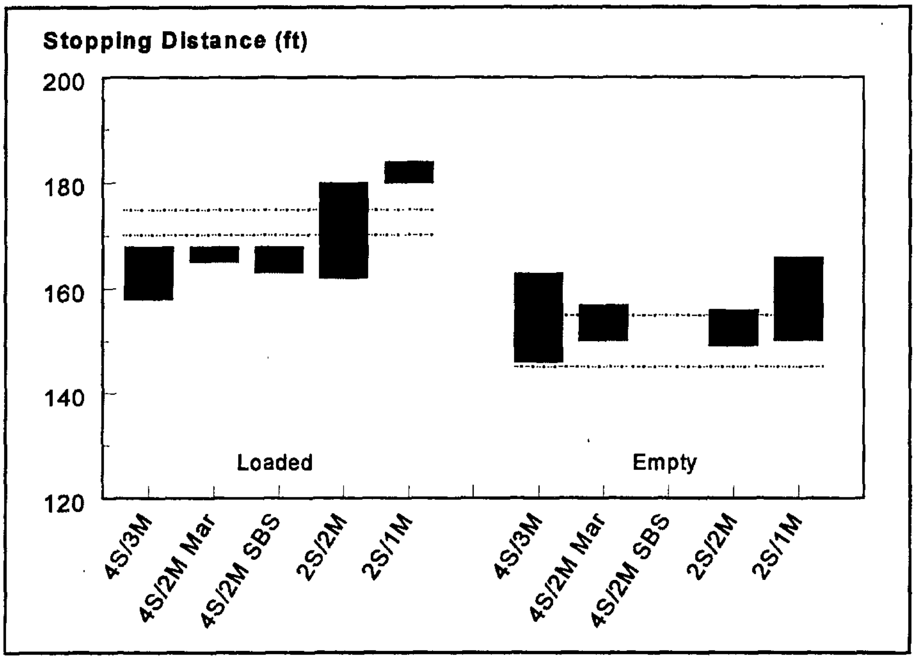

Figure A5 — 35 mph Stops on Polished Concrete

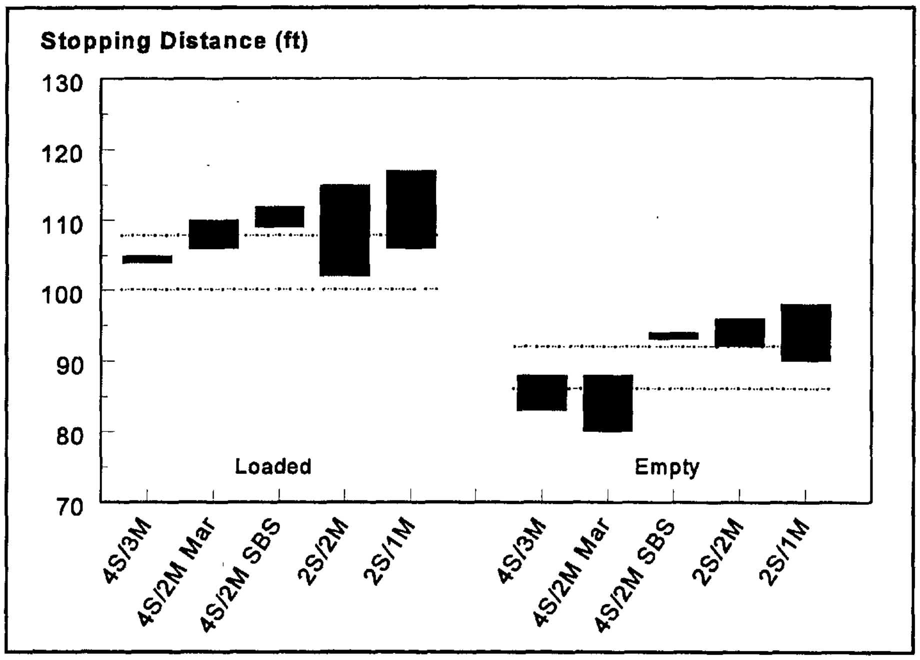

Figure A6 — 35 mph Stops on Smooth Concrete

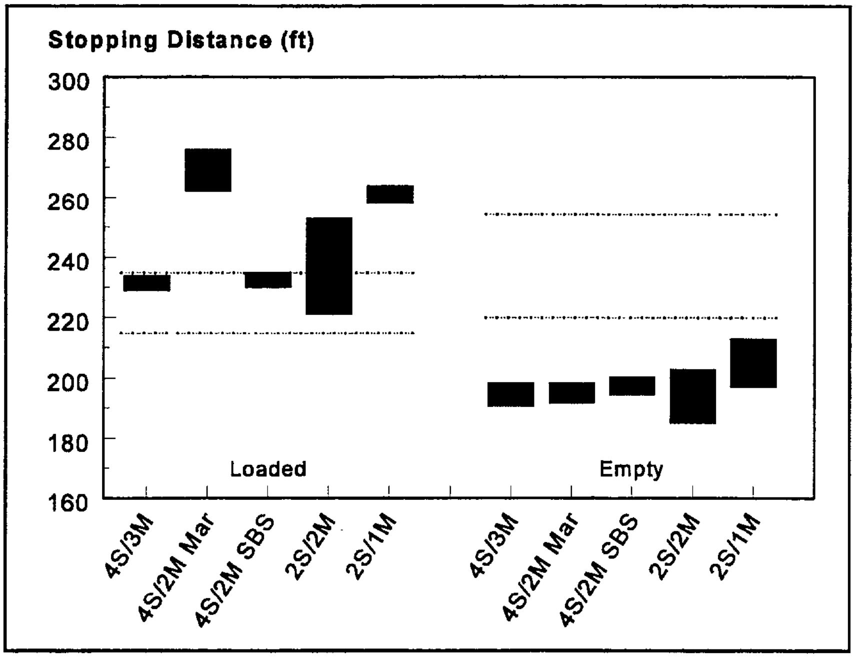

Figure A7 — 50 mph Stops on Wet Asphalt Curve

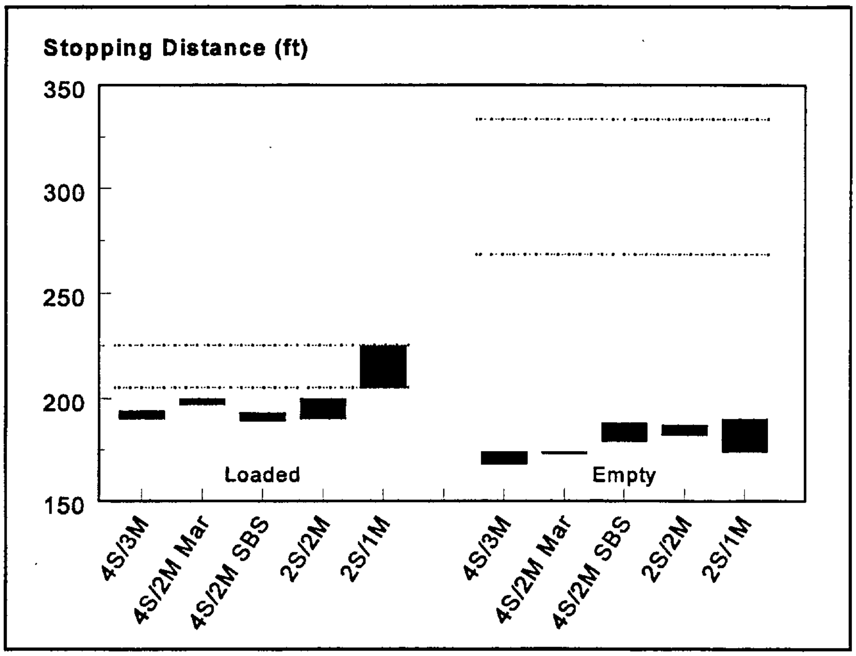

Figure A8 — 50 mph Stops on Asphalt Straight Line

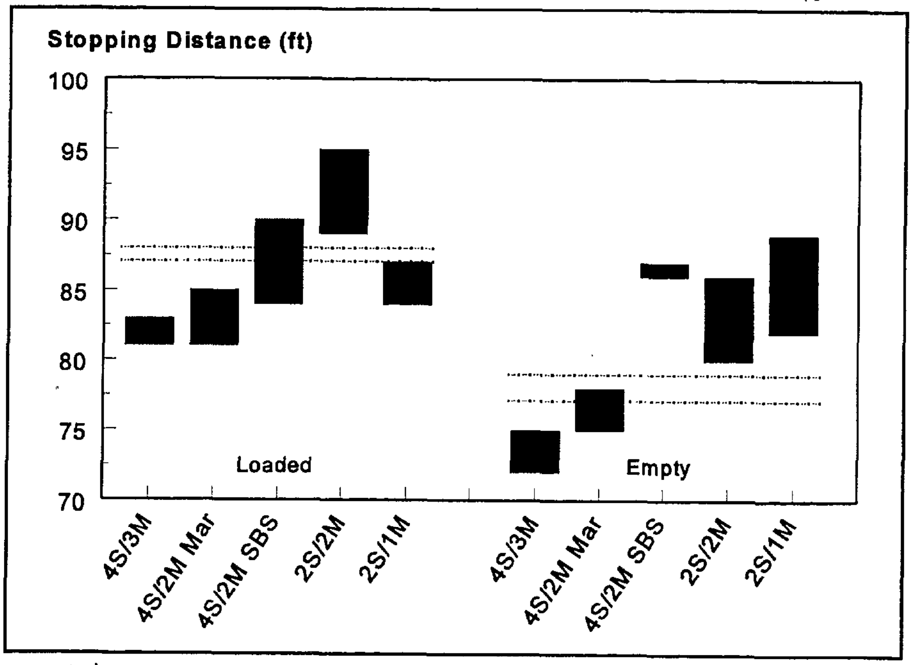

Figure A9 — 35 mph Stops on Dry Concrete

Appendix B

Tests With Four Manufacturers' Systems

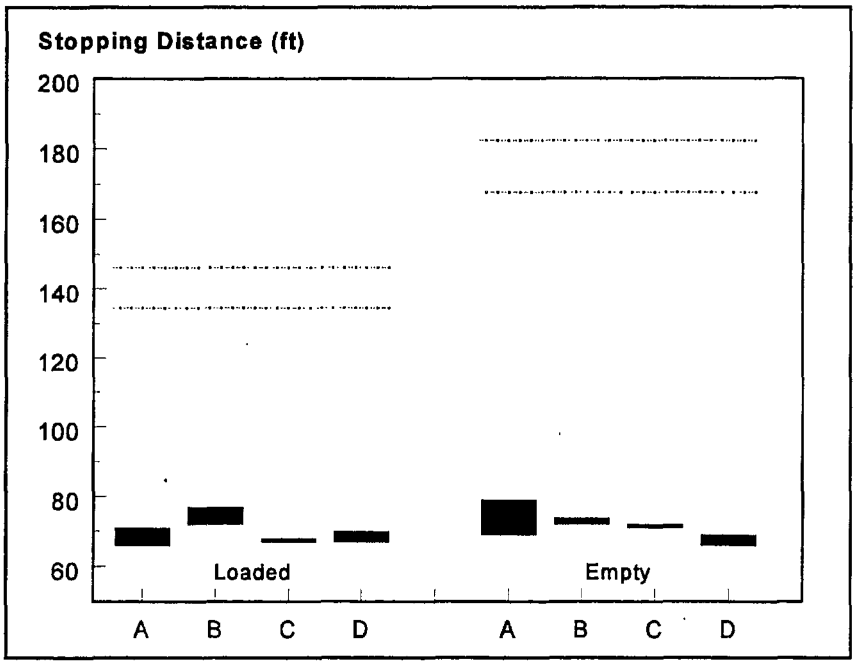

Figure B1 — 15 mph Stops on Epoxy Straight Line

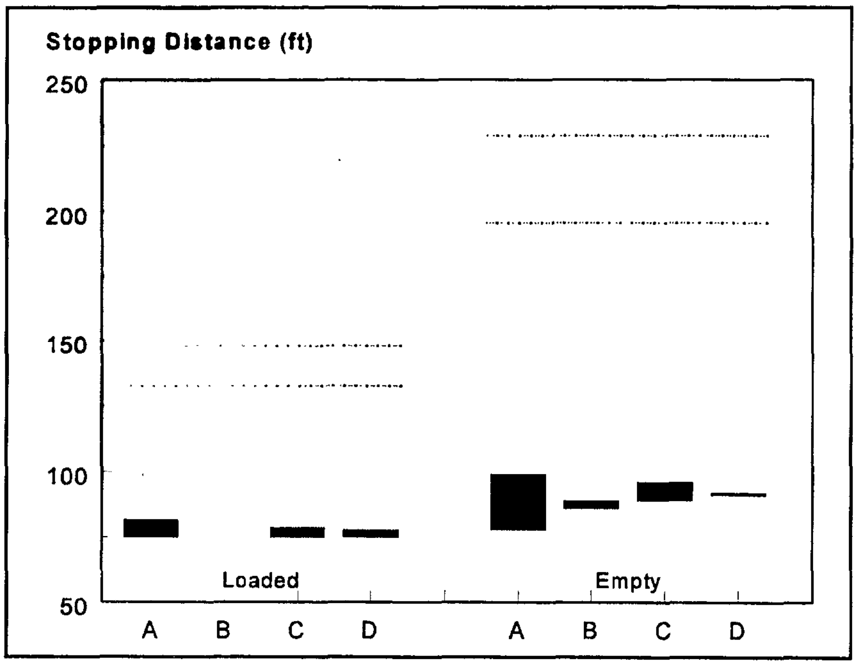

Figure B2 — 15 mph Stops on Epoxy Curve

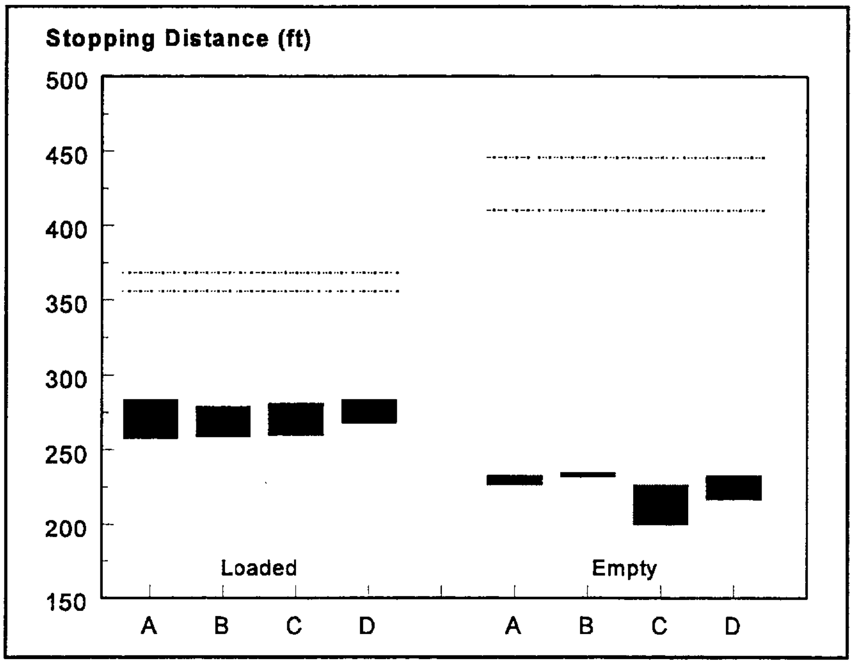

Figure B3 — 30 mph Stops on Jennite Straight Line

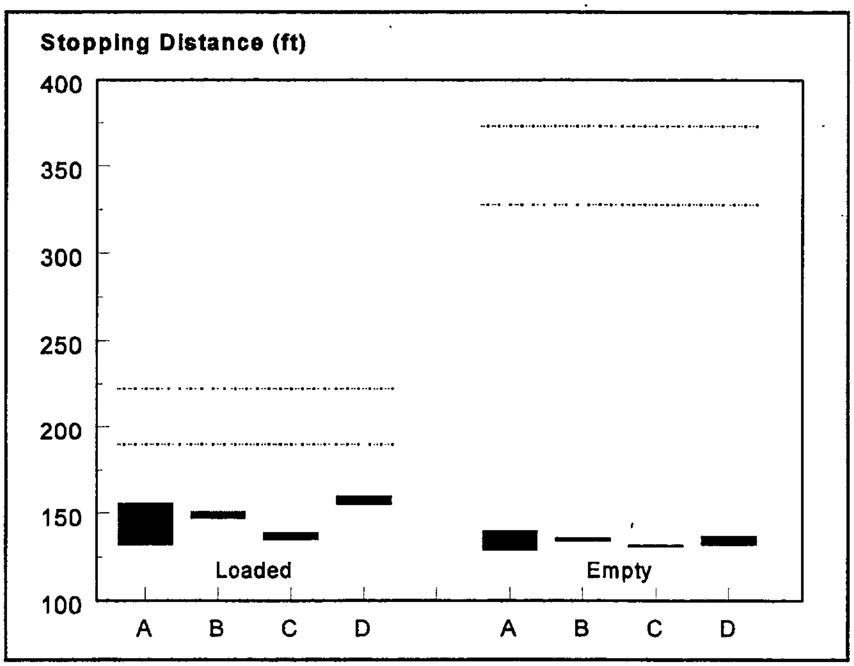

Figure B4 — 25 mph Stops on Jennite Curve

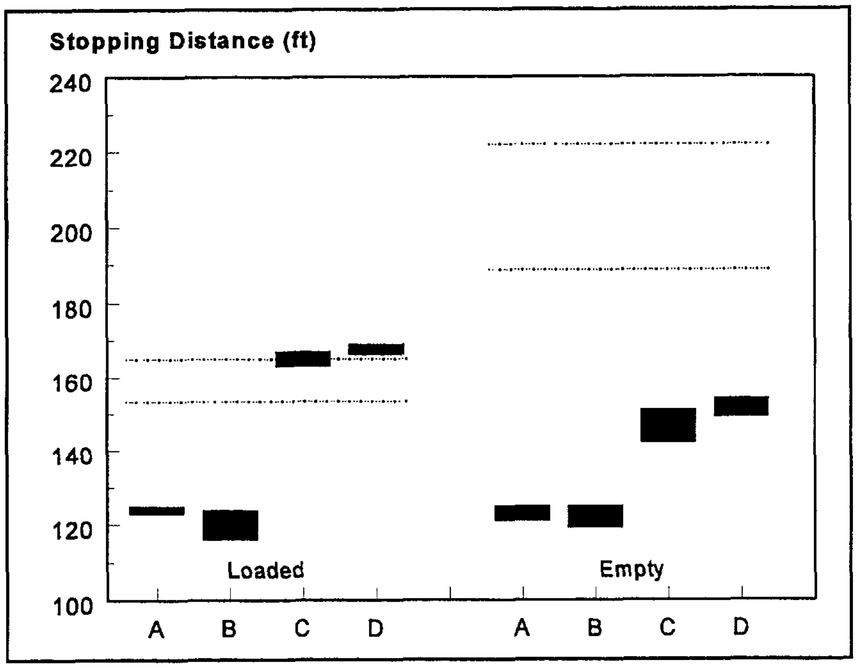

Figure B5 — 30 mph Stops on Epoxy / Asphalt Split coefficient Surface

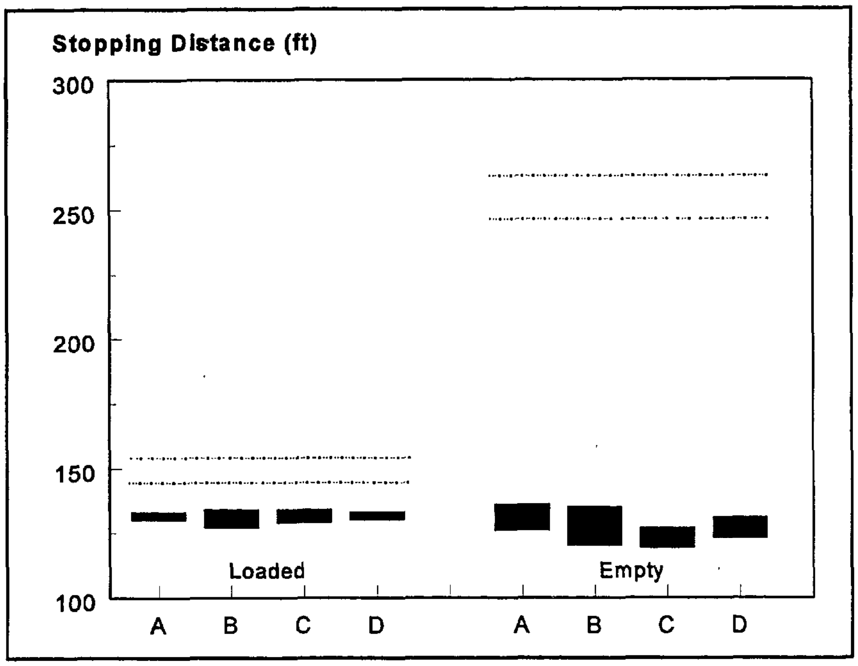

Figure B6 — 30 mph Stops on Polished Concrete

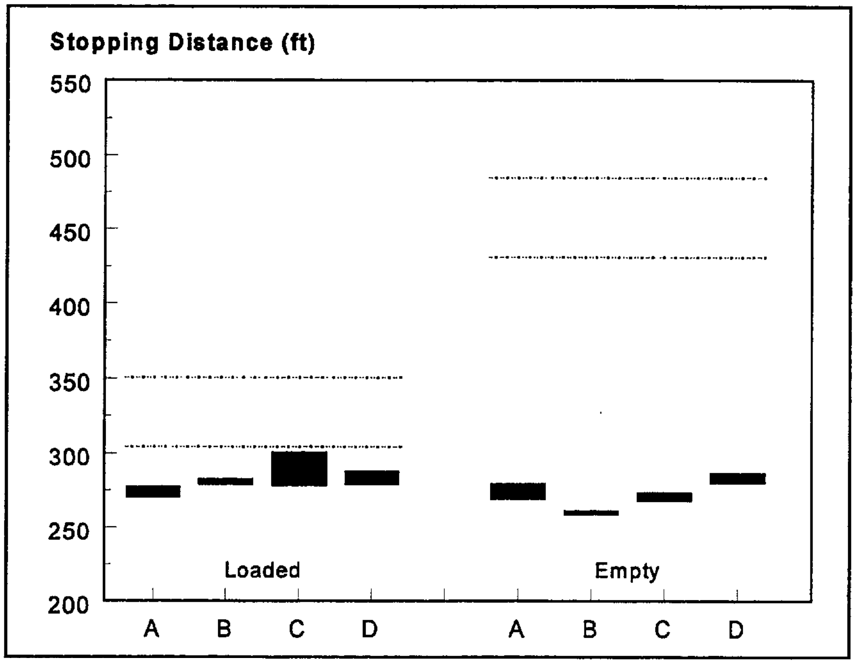

Figure B7 — 60 mph Stops on Dry Concrete

Appendix C

Doubles and Triples Results

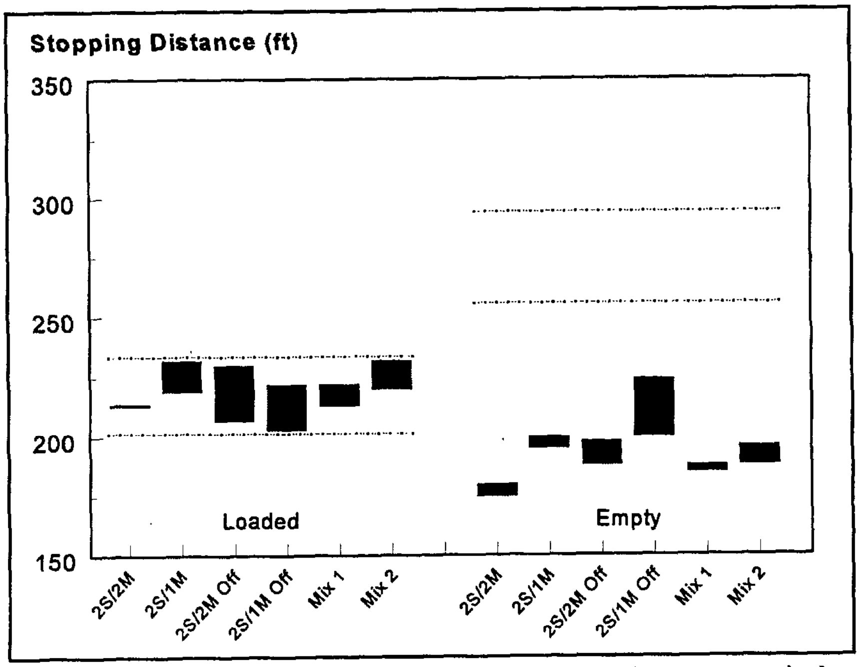

Figure C1 – 30 mph Stops on Jennite Straight Line with Doubles combination

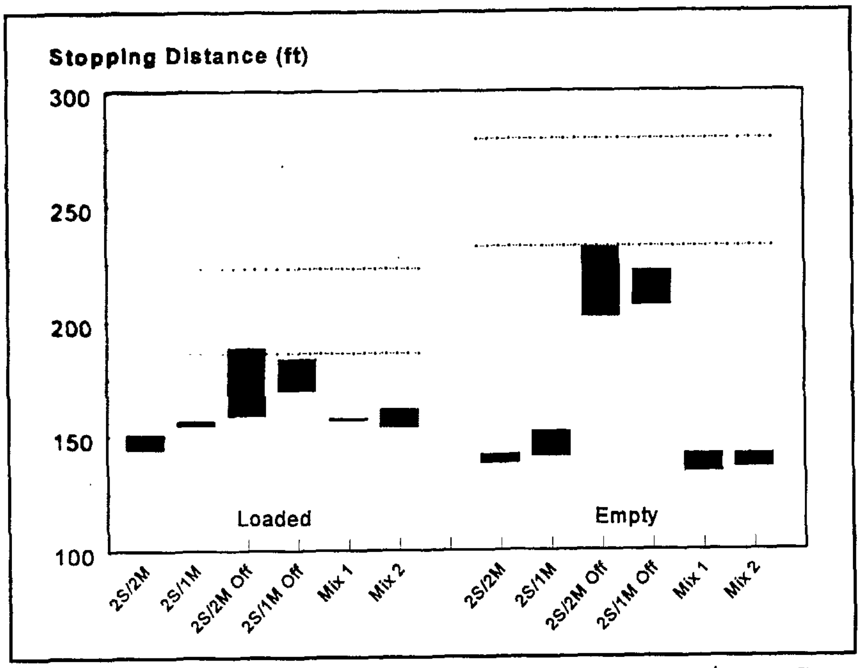

Figure C2 – 30 mph Stops on Jennite Curve with Doubles Combination

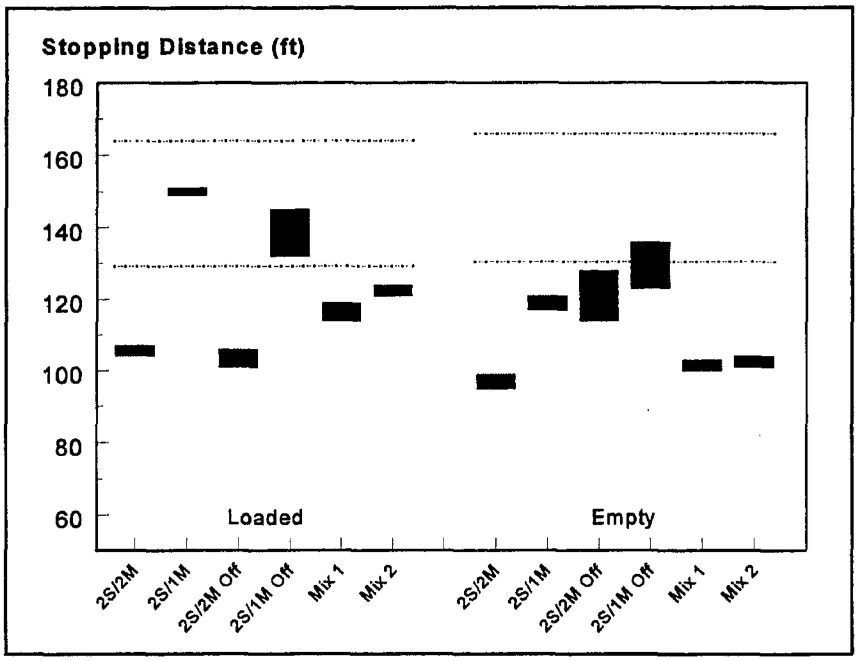

Figure C3 — 30 mph Stops on Split coefficient Surface with Doubles Combination

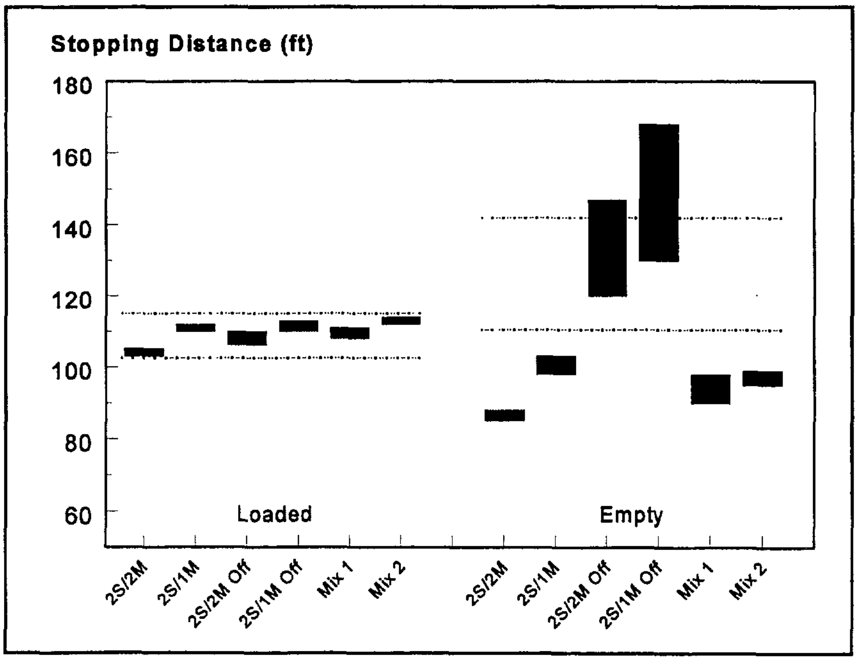

Figure C4 — 30 mph Stops on Polished Concrete with Doubles Combination

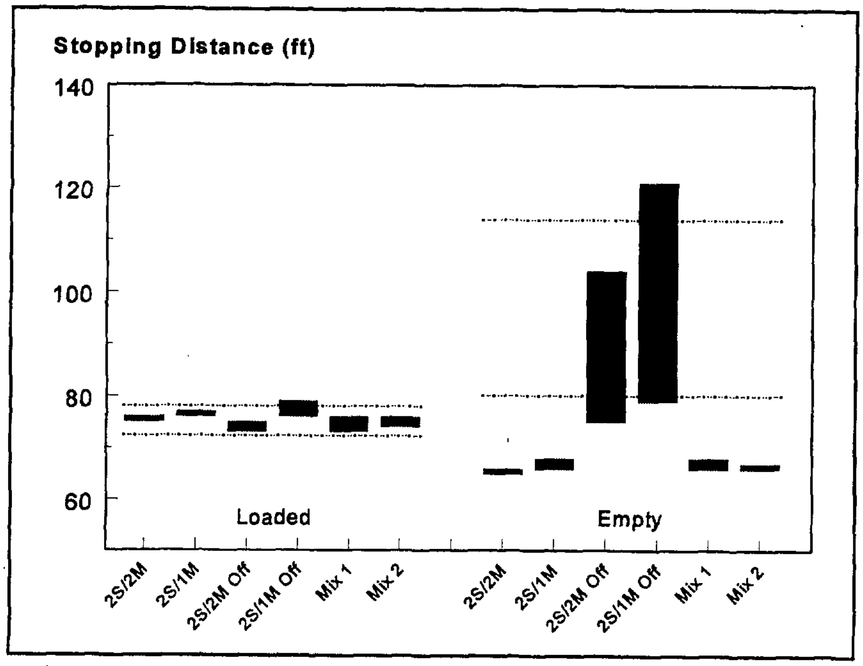

Figure C5 — 30 mph Stops on Smooth Concrete with Doubles Combination

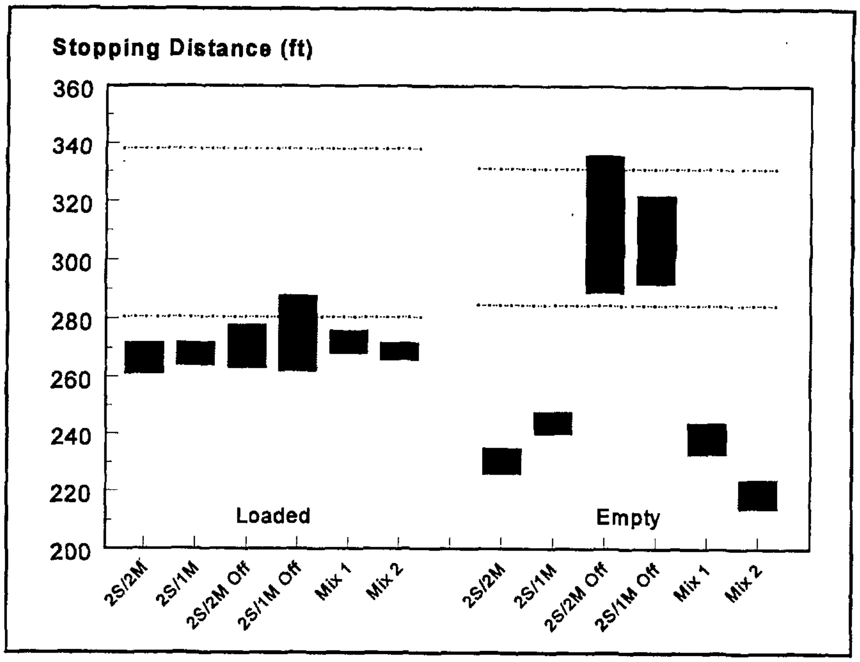

Figure C6 — 60 mph Stops on Dry Concrete with Doubles Combination

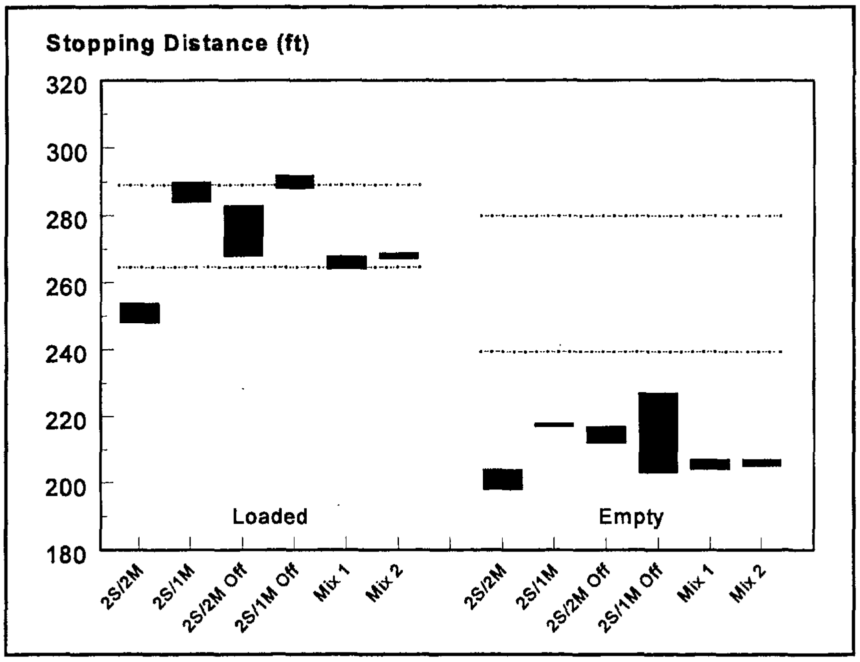

Figure C7 – 30 mph Stops on Wet Jennite Straight Line with Triples Combination

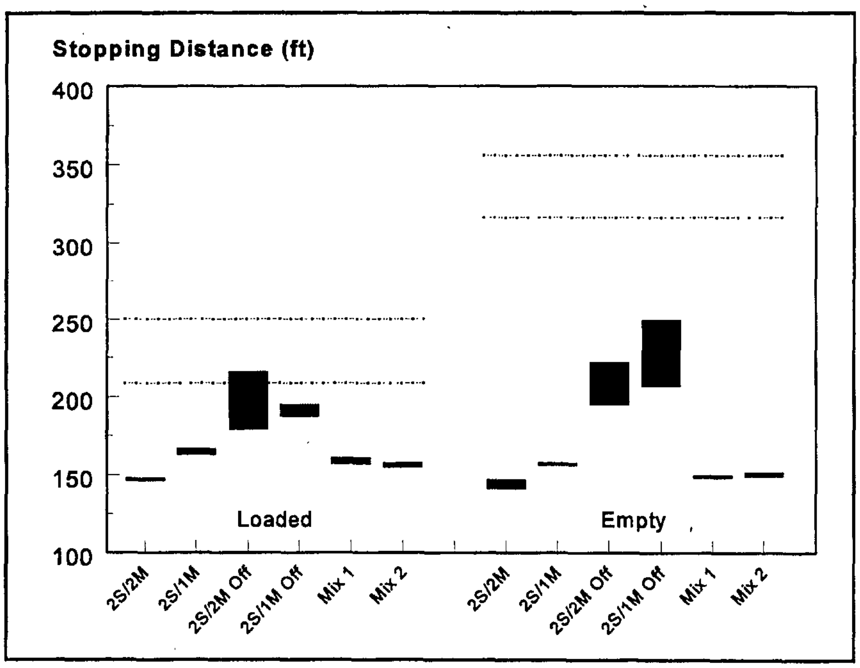

Figure C8 – 30 mph Stops on Wet Jennite Curve with Triples Combination

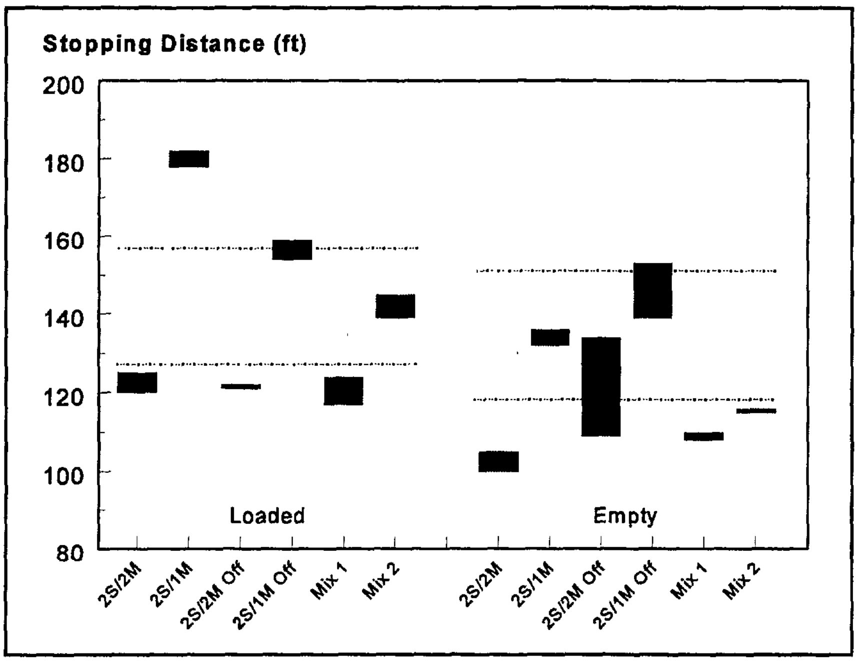

Figure C9 — 30 mph Stops on Split Coefficient Surface with Triples Combination

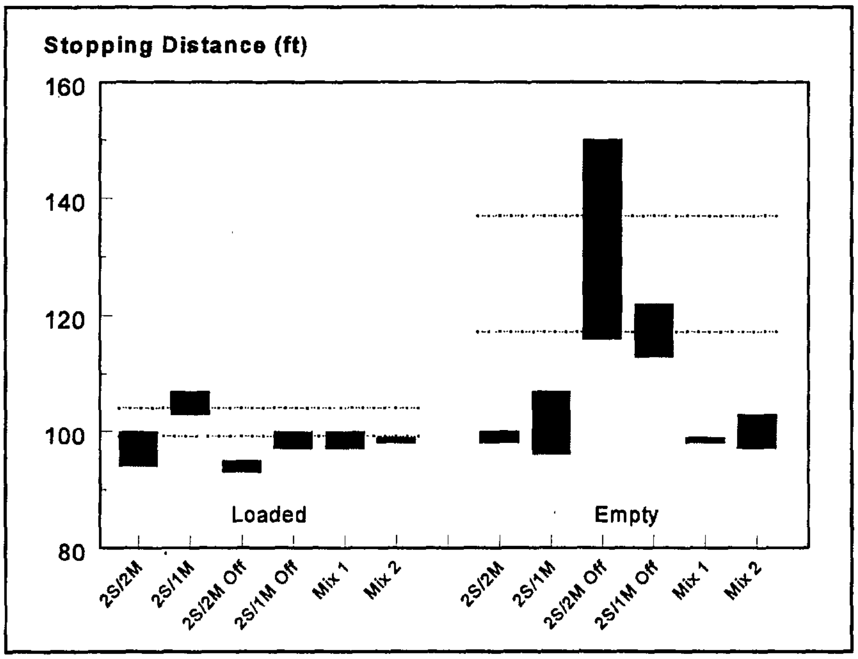

Figure C10 — 30 mph Stops on Polished Concrete with Triples Combination

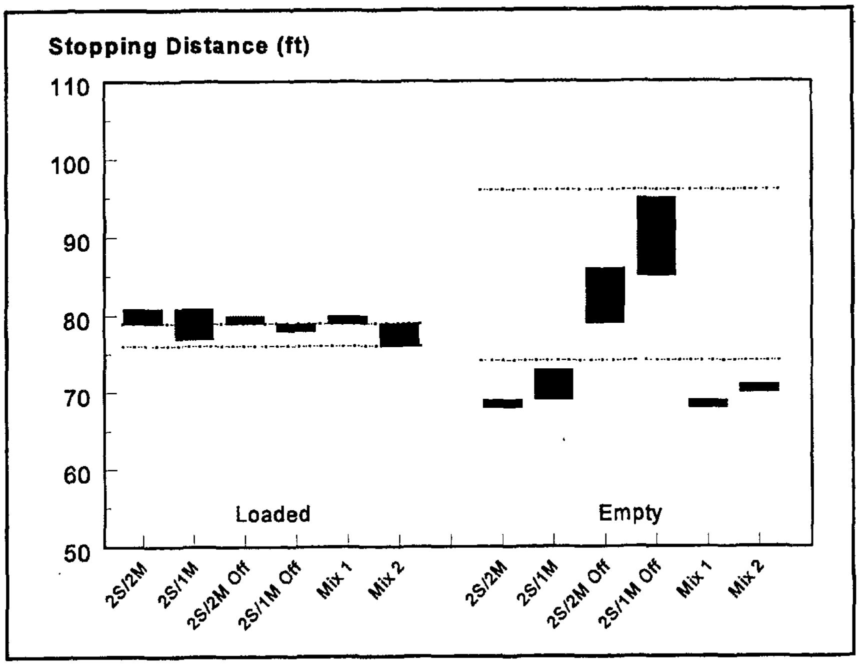

Figure C11 – 30 mph Stops on Smooth Concrete with Triples Combination

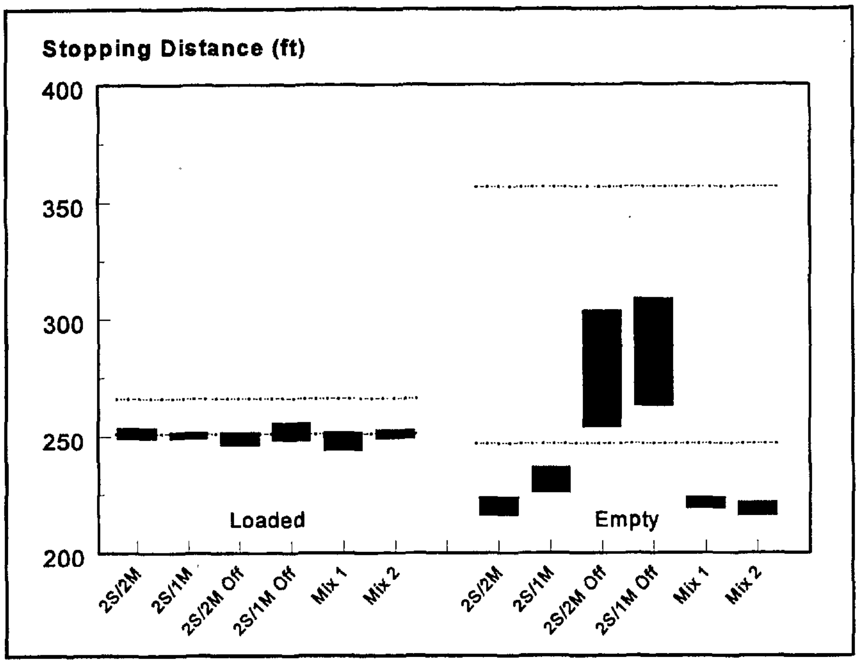

Figure C12 – 60 mph Stops on Dry Concrete with Triples Combination