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A Comprehensive Light Vehicle Antilock Brake System Test Track Performance Evaluation

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ABSTRACT

To determine if situations and/or conditions exist in which ABS-equipped vehicles do not perform as well as those without ABS, the braking performance of nine passenger vehicles was observed over a comprehensive array of driving conditions.

For most maneuvers, on most surfaces, ABS-assisted stops yielded distances shorter than those made with the ABS disabled. The one exception was on loose gravel where stopping distances increased by an average of 27.2 percent overall. Additionally, the vehicular stability observed during testing was almost always superior with ABS. For the cases in which instability was observed, ABS was not deemed responsible for its occurrence.

INTRODUCTION

The principal reason for equipping passenger cars and light trucks with ABS is to increase safety. However, the many statistical analyses of crash databases performed over the past several years suggest that, for automobiles, the introduction of four-wheel ABS has produced net safety benefits much lower than originally expected [1,2,3,4]. For example, Kahane found that while the involvement of ABS-equipped automobiles in fatal multi-vehicle crashes on wet roads was reduced by 24 percent, fatal single-vehicle crashes increased by 28 percent [4]. Overall, the increase in single-vehicle crashes essentially offsets the safety advantages an ABS-equipped automobile offers over its conventionally-braked counterpart.

In an attempt to examine all plausible reasons as to why the crash data studies do not show that four-wheel ABS has improved automobile safety, the National Highway Traffic Safety Administration (NHTSA) developed its comprehensive Light Vehicle ABS Research Program [5]. NHTSA's Motor Vehicle Safety Research Advisory Committee's (MVSRAC) ABS Working Group, comprised of government and industry participants, assisted with development of the research program's multi-task test plan. The group's contribution is much appreciated.

The evaluation of ABS braking performance, the subject of this paper, is just one of the program's nine tasks. The knowledge gained from this study will be integrated with data from the other tasks to infer why the crash data studies did not demonstrate an overall increase in safety for ABS-equipped automobiles.

BACKGROUND AND STUDY OBJECTIVES

A Test Track Performance Evaluation of Current Production Light Vehicle Antilock Brake Systems was conducted to compare the braking performance of vehicles equipped with present-day antilock brake systems to the performance of the same vehicle without ABS over a broad range of driving conditions. The braking performance of nine vehicles was evaluated in eighteen stopping situations that included a variety of road surfaces, driver steering actions, and vehicle speeds. Testing was performed with lightly and heavily laden vehicles and with the ABS active and disabled.

It is important to understand that it was not the intention of this work to compare vehicles or antilock brake systems to one another. Rather, the motivation was to attempt to find situations and/or conditions in which a vehicle equipped with ABS did not perform as well as the same vehicle's conventionally-braked counterpart. While ABS braking has been measured by many groups over many years (including NHTSA's Vehicle Research and Test Center

(VRTC) in East Liberty, Ohio [6,7]), there is a possibility that poor performance on some unusual surface or during some maneuver may have been overlooked. If such conditions could be found, they may explain the apparent increase in single-vehicle run-off-road crashes involving ABS-equipped automobiles.

The ABS performance evaluation discussed in this paper differs from previously performed by NHTSA researchers in several significant ways. First, the vehicles tested have newer antilock brake systems than those tested in the earlier studies. Second, the vehicles were tested on more surfaces than in the past. Third, the vehicles were tested on a number of surfaces having sudden coefficient of friction transitions. Fourth, the vehicles were tested with additional maneuvers.

TEST PROCEDURE

TEST VEHICLES

The test vehicle fleet included a diverse range of high-production passenger vehicles, ranging from compact cars to sport utility vehicles, from model years 1993 to 1997. Vehicle selection insured that at least one ABS from eight current ABS manufacturers was represented.

The antilock brake systems in seven of the nine test vehicles used four wheel speed sensors (WSS), one at each wheel. The two rear-wheel drive vehicles utilized three WSS, one positioned at each front wheel and one in the rear differential. Four vehicles were equipped with four-channel antilock brake systems that modulated the front and rear brake line pressures at each wheel independently. Five vehicles were equipped with three-channel antilock brake systems that controlled the front line pressures independently, but modulated the right rear and left rear line pressures together. The ABS configurations of each test vehicle are listed in Table 1.

Table 1. Test Vehicle ABS Description.

	Test Vehicle								
	A	B	C	D	E	F	G	H	I
Vehicle Model Year	1995	1994	1993	1996	1997	1996	1995	1995	1997
Number of Wheel Speed Sensors	4	4	4	4	4	4	4	3	3
Number of Hydraulic Channels	4	4	4	3	4	3	3	3	3

INSTRUMENTATION

A fifth wheel assembly mounted to the rear bumper attachment points transmitted vehicle speed and distance signals to a digital performance monitor positioned on the dashboard. The monitor's trigger input was activated by the brake light switch to freeze the initial vehicle speed and zero vehicle position when the brake pedal was depressed.

Brake line pressure transducers were installed between the hard and flexible brake lines to transmit the line pressure seen at each wheel downstream of the ABS hydraulic control unit (HCU). Direct current tachometers attached to each wheel monitored wheel lockup by measuring individual wheel speeds. A load cell was attached to the brake pedal to transmit applied force. Two accelerometers and a rate sensor, positioned at the vehicle's center of gravity to minimize vehicle pitch and roll effects, measured lateral/longitudinal acceleration and yaw rate, respectively. To signal a desired point within a braking maneuver, an optical pickup sensor was installed on the vehicle's front license plate bracket. All data measured by the instrumentation was recorded, as a function of time, by the on-board data acquisition and each channel was sampled at a rate of 100 Hz.

LOADING

Each vehicle was tested at two loading conditions: lightly laden and at the Gross Vehicle Weight Rating (GVWR). Lightly laden was defined as the vehicle weight with a full tank of fuel plus the test driver and instrumentation. The GVWR condition involved loading the vehicle to the maximum vehicle weight recommended by the manufacturer, and was achieved by ballasting the test vehicle with sand bags distributed so that the axle weights were in proportion with the Gross Axle Weight Ratings (GAWR).

TEST MATRIX

Table A1 (presented in the appendix) summarizes this study's test matrix. Braking was performed with the assistance of ABS and with the ABS disabled using two pedal application techniques. The matrix included nine test surfaces and four stopping maneuvers, each performed with the vehicles lightly laden and at GVWR. To disable the ABS, an electrical fuse in the test vehicle's fuse box was replaced with a fused toggle switch to interrupt power to the ABS electronic control unit, solenoid valves, or pump motor.

TEST SURFACES

Nine surface types were used for this study: dry asphalt, wet asphalt, dry concrete, wet polished concrete, wet epoxy, wet Jennite, grass, loose gravel, and an epoxy/sand surface. The polished concrete was designed to simulate a heavily worn road and was created by troweling and polishing with a floor polisher. The epoxy pad (asphalt covered with a coating typically used on factory floors) and wet Jennite (a coal tar emulsion asphalt sealer trade name) surfaces simulated badly worn wet roadways. Due to surface deterioration, the epoxy pad was reconditioned before the final two vehicles could be evaluated, reducing the peak coefficient of friction and slide skid numbers by over one third. The grass surface was approximately 7.6 cm (3 in.) in height, and consisted of fescue grown on clay-based soil. The loose gravel was comprised of #617 crushed limestone with dust. The gravel base was approximately 5.1 cm (2 in.) deep.

This study also utilized a specially designed ABS test course. Created in mid-1996, the course was designed to evaluate ABS performance over a series of simulated "real world" test pads. An antilock brake system's ability to recover vehicle deceleration after returning to asphalt from a given pad was observed. Each of the four ABS test course pads was wet during testing. Test Pad #0 was used to determine vehicle stopping distance for the wet, unperturbed asphalt surface of the course as a baseline condition.

Test Pad #1 included one Jennite strip 61 cm (24 in) wide applied to the asphalt to simulate a stop bar found at an intersection with a stop sign or traffic light. Test Pad #2 (Figure 1) simulated a stop bar followed by two bars to mark crosswalk area, and was oriented as follows: a 61 cm (24 in) wide Jennite stop bar, four feet of asphalt, a 25 cm (10 in) Jennite strip, six feet of asphalt, and a second 25 cm (10 in) Jennite strip.

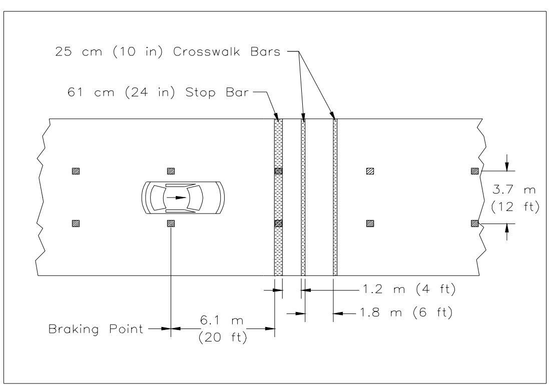

Figure 1. ABS Test Pad #2.

Test Pad #3 (Figure 2) consisted of two adjacent artificial potholes, one in each wheel track, constructed from steel frames set into concrete and treated with an epoxy/sand surface. The wet epoxy/sand surface provided a coefficient of friction similar to dry pavement.

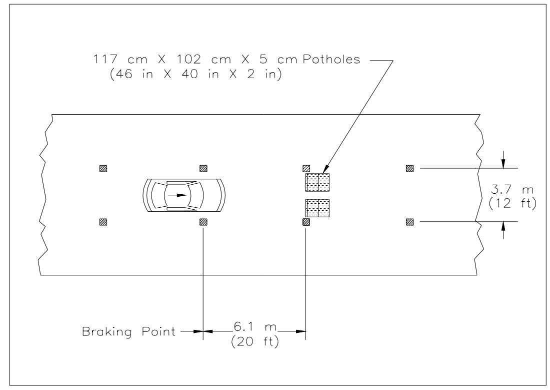

Figure 2. ABS Test Pad #3.

MANEUVERS

This study involved four stopping maneuvers: 1) straight line, 2) curve, 3) J-turn, and 4) single lane change. Straight line stopping maneuvers were performed on several surface types. Those performed on uniform coefficient surfaces will be referred to as straight line maneuvers. Straight line stops made in a lane with different left and right side frictional coefficients will be referred to as split-mu maneuvers. Straight line stops made while the driver applied a panic brake application as the vehicle traveled over surfaces with changing frictional coefficients will be referred to as transition maneuvers (an example is provided in Figure 3). The initial speed and brake application points for transition maneuvers were chosen such that the initial surface transition would be accomplished at approximately 40 km/h (25 mph).

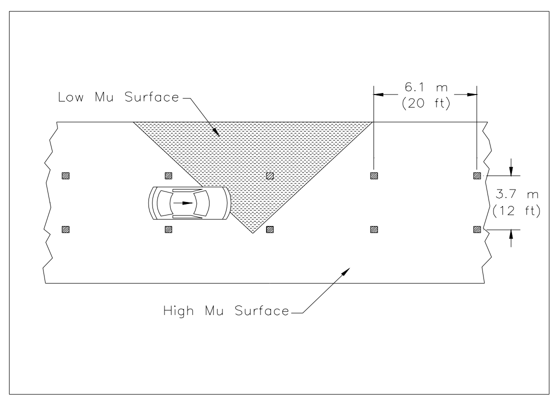

Figure 3. Offset transition.

Braking in a curve of known radius and the J-turn, a maneuver designed to observe how a vehicle responded to a sudden and severe steering input quickly followed by a brake application (Figure 4), each occurred on surfaces with uniform frictional coefficients. All stopping lanes were 3.7 m (12 ft) wide, marked with cones spaced 6.1 m (20 ft) apart. For each maneuver, the test driver was allowed to make steering inputs as necessary to maintain lane position.

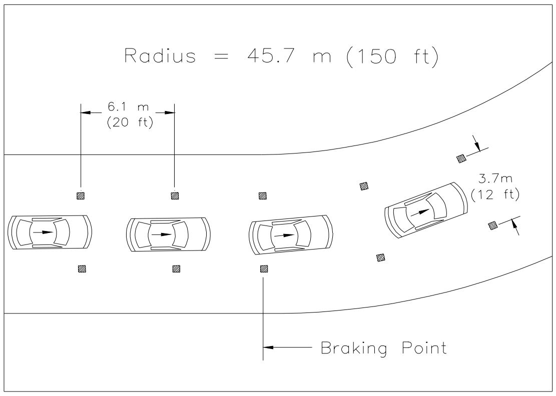

Figure 4. J-turn maneuver.

The lane change maneuver involved a high-speed single lane change to approximate a collision avoidance maneuver in which a vehicle transitions from a high-coefficient of friction roadway lane to a split high coefficient/low coefficient shoulder lane (Figure 5).

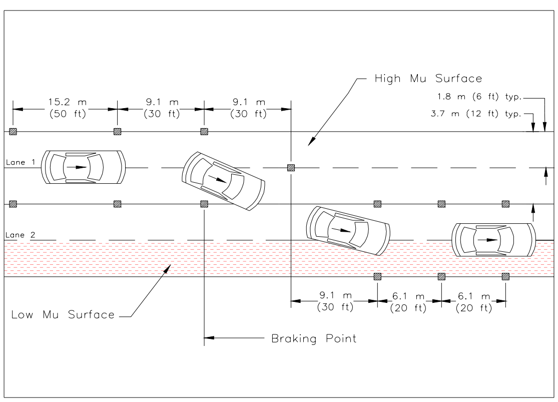

Figure 5. Single lane change maneuver.

STOPPING DISTANCE CORRECTION

The target speeds specified for each maneuver were chosen to reflect available space, real-world utility, and safety considerations. Although these speeds are listed in Table A1, the actual speeds observed while testing varied slightly. As a result, the actual stopping distances were adjusted to represent the distances of those maneuvers as if they had been run at the target speed using the following expression [8]:

$$s' = \frac{v_{target}^2}{v_{actual}^2} \times s_{actual}$$

where

$$s' = corrected\ stopping\ distance$$
$$v_{target} = target\ initial\ vehicle\ velocity$$
$$v_{actual} = actual\ initial\ vehicle\ velocity$$
$$s_{actual} = actual\ stopping\ distance$$

BRAKE APPLICATIONS

Two brake application techniques were used in this study: 1) "panic" and 2) "best effort." The panic technique involved a rapid force application of over 667 N (150 lbs) to the brake pedal. As they were expected to be very repeatable, only three panic stops for each ABS and disabled-ABS condition were conducted. For this study, the only brake application technique used for ABS-assisted braking was that of the panic stop.

Best effort stops required the driver to modulate pedal force as necessary to achieve the shortest possible stopping distance while maintaining vehicle control and lane position. To ensure vehicular stability was maintained, no more than one wheel per axle was permitted to lock. To allow time for driver familiarization with a given vehicle and its braking ability, six best effort stops were used for the maneuvers that required them. To eliminate driver variability effects, only one professional test driver with 17 years experience served as driver for all testing conducted for this study.

With the exception of the stops on the ABS test course, each transition maneuver only included three ABS-assisted stops. Transition maneuvers were designed to evaluate ABS reaction times and responses to sudden changes in roadway frictional coefficients, therefore it was unnecessary for disabled-ABS stops to be conducted.

Best effort stops with the ABS disabled were not performed over the ABS test course transitions. Three disabled-ABS panic stops, however, were included to facilitate an ABS stopping performance comparison.

Three ABS and disabled-ABS panic stops were performed on the grass and loose gravel surfaces. Data collected from straight line best effort stops made on these surfaces, at the low test speeds specified in the test plan, were not expected to possess real-world significance. Best effort stops, therefore, were not conducted on grass and gravel.

The braking in a curve, J-turn, and single lane change maneuvers did not require panic stops with the ABS disabled as it was expected that the vehicles would quickly lock their front wheels and skid out of the intended lane. Disabled-ABS panic stops were likewise omitted from wet asphalt, dry asphalt, wet polished concrete, and dry concrete maneuvers due to the excessive tire wear executing such stops was expected to incur. For these seven maneuvers only three ABS-assisted and six best effort disabled ABS stops were conducted.

TEST TRACK RESULTS

COMMENTS ON THE REPORTING OF ABS PERFORMANCE RESULTS

The results in this section used stopping distance and vehicle stability as measures of braking performance. A vehicle yawing out of control with its wheels locked may stop in a very short distance, while a stable vehicle (directional control maintained throughout the entire stop) may require a very long distance to complete its stop. Each condition presents different safety concerns and demonstrates why stopping distance and directional stability must be evaluated together when discussing ABS performance.

This results section includes many charts providing stopping distances observed with fully laden test vehicles. If a legend is not included with a given chart, the stopping distances were collected using ABS-assisted brake applications only. If a legend is provided, "ABS" refers to an ABS-assisted panic stop, "Full Pedal" refers to a panic stop with the ABS disabled, and "Best Effort" refers to test driver modulated stops made with the ABS disabled.

Thirteen of the eighteen stopping maneuvers required ABS-assisted stopping distances to be compared to those measured with the ABS disabled. To facilitate this comparison, the following equation was used:

$$\text{ABS Stopping Distance Improvement} = \frac{SD_{ABS\ disabled} - SD_{ABS}}{SD_{ABS\ disabled}} \times 100\% \qquad \text{where}$$

$SD_{ABS\ disabled}$ = *disabled-ABS stopping distance (panic or best effort)*
SD_{ABS} = *ABS-assisted stopping distance*

All stopping distances reported in this paper reflect the shortest distance observed for a given test condition (maneuver, brake pedal application technique, and loading condition).

STRAIGHT LINE STOPS ON UNIFORM COEFFICIENT SURFACES

The use of ABS resulted in the shortest straight line stopping distances on the dry concrete and wet polished concrete surfaces for all nine test vehicles at both loading conditions. Figure 6 summarizes the GVWR stopping distances made on dry concrete.

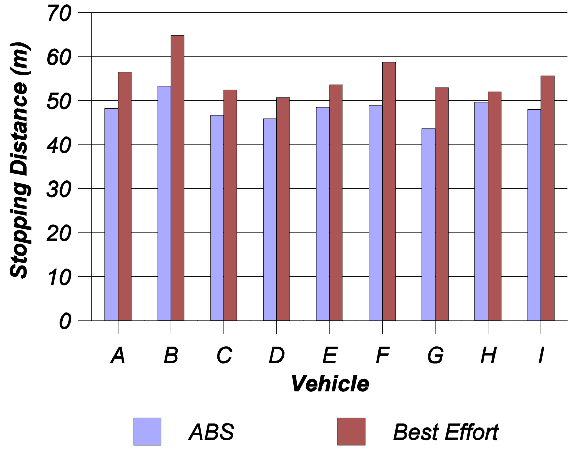

Figure 6. Straight line stopping distances observed on dry concrete. Test vehicles were fully laden to their respective GVWRs.

Antilock brakes facilitated the shortest stopping distances on wet Jennite for each vehicle when at GVWR (Figure 7). When lightly laden, seven of the eight vehicles stopped in the shortest distance with ABS. A best effort brake application was used to stop vehicle "A" 9.2 percent shorter than with ABS on wet Jennite. Lightly laden straight line stops on wet Jennite were not performed with test vehicle "I".

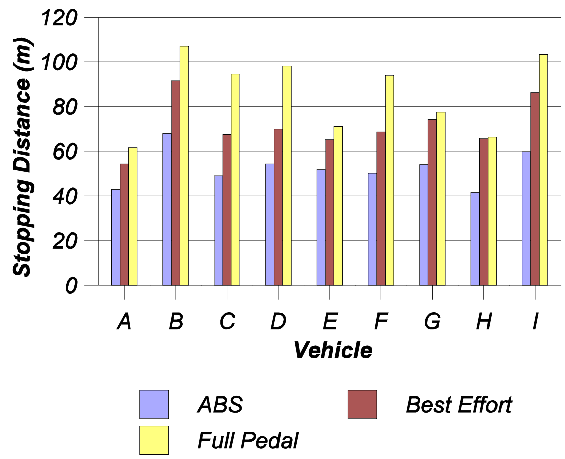

Figure 7. Straight line stopping distances observed on wet Jennite. Test vehicles were fully laden to their respective GVWRs.

On wet asphalt, ABS facilitated the shortest stopping distances for each test vehicle at GVWR. When lightly laden, eight of the nine vehicles stopped in the shortest distance with ABS. For vehicle "H", the test driver's minimum best effort stopping distance was 4.9 percent less than the ABS-assisted stops.

STRAIGHT LINE STOPS ON OFF ROAD SURFACES

Grass

Seven of the nine test vehicles laden to GVWR stopped in the shortest distance using ABS on the grass surface (Figure 8). The ABS-assisted stops were an average of 6.9 percent shorter than those made with the ABS disabled at GVWR. Note that this percentage drops to 4.0 percent if the stopping distances of vehicle "I" are not included in this comparison.

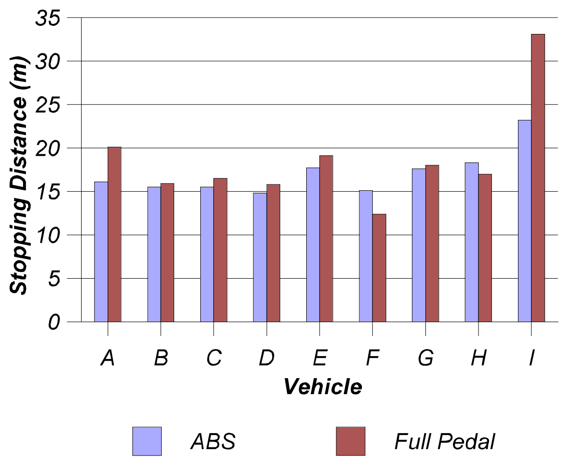

Figure 8. Straight line stopping distances observed on grass. Test vehicles were fully laden to their respective GVWRs. Note: the grass was very wet when the braking performance of vehicle "I" was evaluated.

Unlike the other vehicles, the grass surface was very wet when test vehicle "I" was evaluated at GVWR, and in some areas standing water was present. These test conditions explain why the disabled-ABS stopping distance was 30.1 percent longer than that obtained with ABS for this vehicle. Although skid numbers were not available, it is reasonable to assume the wet grass possessed a much higher peak-to-sliding coefficient of friction ratio than when dry (generally speaking, grass-covered dirt is not homogeneous and attempting to obtain skid numbers would yield highly variable results). A large peak-to-slide ratio predicts wheel lockup will significantly reduce available braking force from what it would be if the wheels were not locked, as in an ABS-assisted stop. Vehicle "I" locked all four wheels on the wet grass, therefore it is not surprising the disabled-ABS stopping distance was significantly longer than that of the ABS-assisted stop.

Contrasting the results obtained at GVWR, six of the eight test vehicles stopped in the shortest distance with the ABS disabled when lightly laden. At this loading condition the ABS-assisted stopping distances were an average of 7.1 percent longer than the disabled-ABS panic stops across the eight vehicle test group. Test vehicle "I" was not evaluated on the grass when lightly laden.

Loose Gravel

On loose gravel, all nine vehicles stopped in the shortest distance with a disabled-ABS panic brake application, regardless of loading condition. Stops made on the gravel were lengthened considerably when ABS was utilized: 24.6 percent when the test vehicles were fully laden (Figure 9) and 30.0 percent when lightly laden.

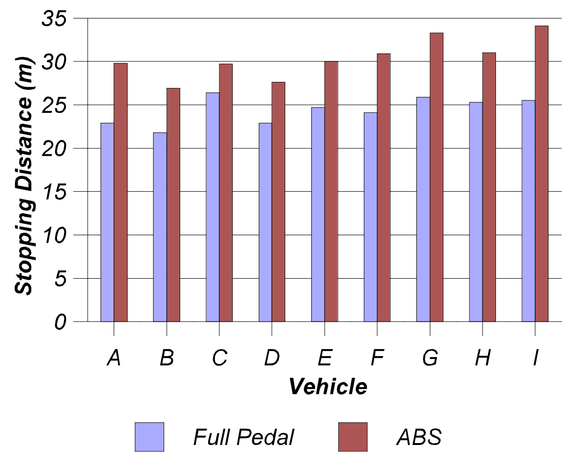

Figure 9. Straight line stopping distances observed on loose gravel. Test vehicles were fully laden to their respective GVWRs. Note: the gravel was wet when the braking performance of vehicle "I" was evaluated.

The fully laden percentage drops to 23.4 percent if the stopping distances of vehicle "I" are not included in this comparison. As with the grass surface, the gravel was very wet when test vehicle "I" was evaluated, unlike for the other vehicles. This may explain the 33.7 percent stopping distance increase with ABS when compared to the distance observed with the ABS disabled.

The ABS-induced stopping distance increase is best explained by examining the tire-to-gravel surface interaction during the braking maneuver. It is generally accepted that the plowing of a vehicle's tires into a deformable surface such as loose gravel generates greater stopping forces than if the wheels were allowed to continue to roll over the surface (as in an ABS-assisted stop). Stopping distances made over the gravel surface therefore represent an ABS design compromise. To preserve the driver's ability to maintain directional control of the vehicle while braking, the wheels must not be allowed to lock. By preserving this control, however, stopping distances made over the loose gravel test surface are extended.

TRANSITION SURFACE BRAKING

The transition braking stopping maneuvers were designed to detect ABS performance deficiencies through the observation of unusually long stopping distances and/or vehicle instability. For each of the nine vehicles, evaluated over three transitions, no apparent shortcomings were revealed. Figure 10 presents typical results. The figure shows the stopping distances recorded on the wet asphalt/wet Jennite transition surface for the test vehicles at their respective GVWRs.

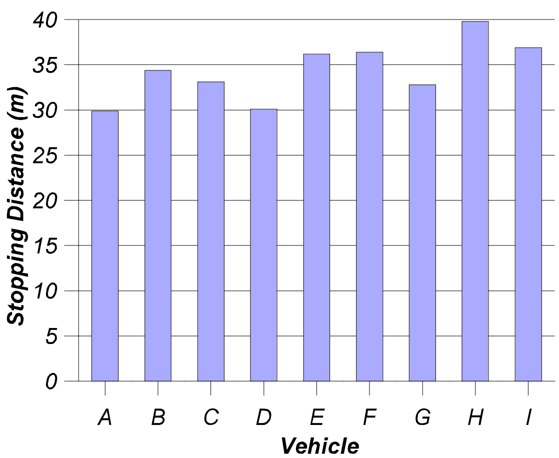

Figure 10. Straight line stopping distances observed on the wet asphalt/wet Jennite transition surface. Test vehicles were fully laden to their GVWRs.

ABS TEST COURSE BRAKING

All nine test vehicles, under both loading conditions, stopped in the shortest distance when the test driver utilized ABS on Test Pad #0, #1, and #2. On Test Pad #3, eight vehicles stopped in the shortest distance using ABS-assisted brake applications, as shown in Figure 11 for the GVWR case. The braking performance of test vehicle "I" was not evaluated on this surface.

When lightly laden, the shortest stopping distance observed on ABS Test Pad #3 for vehicle "H" occurred when the driver utilized a panic brake application with the ABS disabled. In this case ABS stop increased the vehicle's stopping distance slightly (2.0 percent) over the disabled-ABS panic stop conditions.

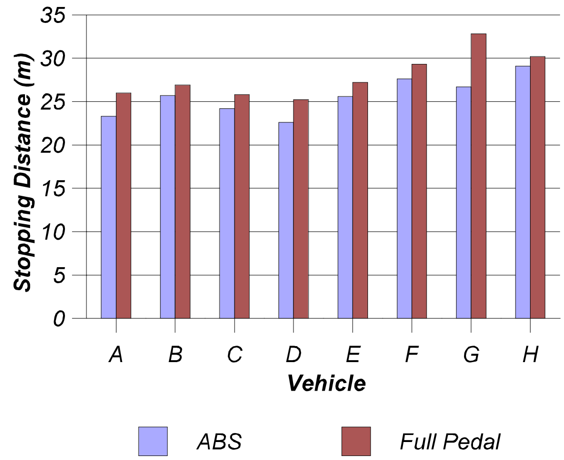

Figure 11. Straight line stopping distances observed on ABS Test Pad #3 (wet). Test vehicles were fully laden to their respective GVWRs. Vehicle "I" braking performance was not evaluated.

SPLIT-MU SURFACE BRAKING

Under both loading conditions, seven of the nine test vehicles achieved the shortest wet asphalt/wet epoxy split-mu stopping distances when the driver used an ABS-assisted brake application (see Figure 12 for the fully laden results). When the ABS was disabled and a panic brake input applied, each test vehicle deviated from its stopping lane by yawing out of control. With ABS, however, the driver had no problem maintaining control of each vehicle while braking during the maneuver.

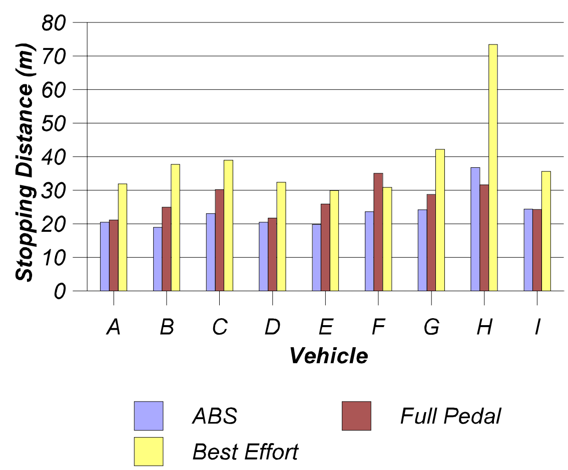

Figure 12. Straight line stopping distances observed on the wet asphalt/wet epoxy split-mu surface. Test vehicles were fully laden to their respective GVWRs. Note: the epoxy surface was reconditioned prior to the brake performance evaluation of vehicles "H" and "I".

The shortest stopping distances for vehicles "H" and "I" were achieved with panic brake applications and the ABS disabled. For vehicle "H", the disabled-ABS panic stops provided lightly laden and fully laden stopping distances 29.3 percent and 16.5 percent shorter than the ABS-assisted stops, respectively. The same brake application and disabled-ABS also resulted in the shortest stopping distances for vehicle "I", although to a lesser extent when lightly laden. The disabled-ABS panic stops provided lightly laden and fully laden stopping distances 13.3 percent and 0.8 percent shorter than the ABS-assisted stops, respectively, for test vehicle "I".

Although the disabled-ABS stopping distances for vehicles "H" and "I" were shorter than those obtained with ABS, it is important to recognize that both of these vehicles deviated nearly 3 m (10 ft) from their 3.7 m (12 ft) wide stopping lane, under each loading condition, due to yaw induced by the lane's two friction coefficients. This phenomenon was prevented when the ABS remained active.

The large stopping distance difference between the ABS-assisted and best effort stopping distances for vehicle "H", apparent at both loading conditions, was most likely due to the extremely low frictional coefficient of the resurfaced epoxy pad and the test driver's unfamiliarity with its characteristics. The surface made it much more difficult for the test driver to prevent wheel lock up through brake force modulation with this vehicle than with those driven prior to it. As the driver became more familiar with the surface, after vehicle "H" testing was complete, the driver was able to better modulate pedal applications to optimize braking. This is indicated by the significant decrease in the ABS-assisted/non-ABS best effort stopping distance differential for vehicle "I" when compared with the results obtained from vehicle "H".

BRAKING IN A CURVE

Two tests involved braking in a curve of known radius: stops made on the wet Jennite 152.4 m (500 ft) radius curve and dry asphalt 91.4 meter (300 ft) radius curve. None of the test vehicles yawed out of control and, with one exception, stopping distances on the wet Jennite curve were found to be shortest with ABS at both loading conditions (see Figure 13 for GVWR condition results). When lightly laden, the stopping distance achieved with test vehicle "A" and a best effort pedal application was 3.7 percent shorter than the comparable ABS-assisted distance on the wet Jennite curve. Test vehicle "I" was not evaluated on this curve when lightly laden.

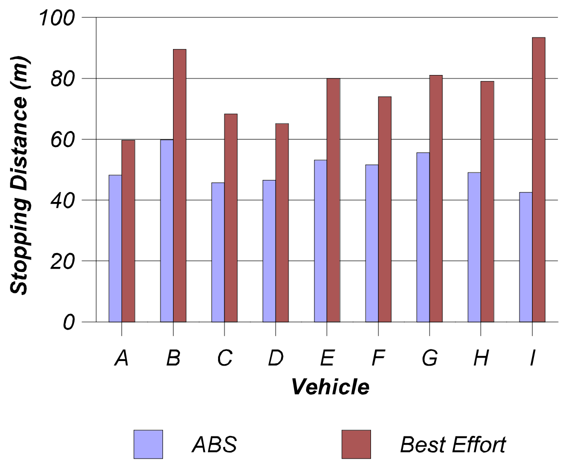

Figure 13. Stopping distances observed on the 152.4 m (500 ft) wet Jennite curve. Test vehicles were fully laden to their respective GVWRs.

Eight of the nine test vehicles were stopped in the shortest distances with ABS on the dry asphalt curve (Figure 14). This trend was not observed for test vehicle "I", as its ABS-assisted stops were longer than the driver's best efforts when lightly laden and at GVWR, 22.5 percent and 11.4 percent, respectively.

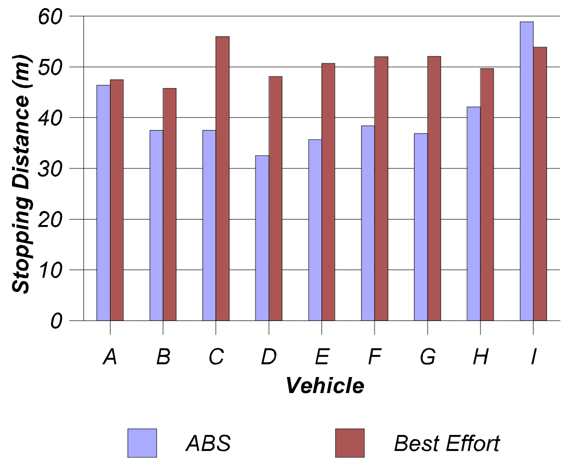

Figure 14. Stopping distances observed on the 91.4 m (300 ft) radius dry asphalt curve. Test vehicles were fully laden to their respective GVWRs.

Analysis of vehicle "I's" braking performance indicated that when a panic brake input was applied while the vehicle was experiencing a high lateral acceleration, the ABS would release brake line pressure in all three channels and hold it very low during the first few seconds of the maneuver. As the vehicle scrubbed off speed (primarily due to the severity of the curve), line pressures were gradually allowed to build. It was not until late in the braking maneuver that brake line pressures were allowed to increase to a level great enough to significantly affect the vehicle's longitudinal deceleration. It should be noted that test vehicle "I" was the only vehicle whose ABS included the capability to monitor the vehicle's lateral acceleration. Further investigation is necessary to determine whether this feature contributed to the apparently extended stopping distances.

J-TURN STOPPING MANEUVER

The J-turn maneuver was designed to observe ABS braking performance while a test vehicle was undergoing hard cornering. Each ABS prevented the test vehicles from yawing out of control, and allowed seven of the nine test vehicles to perform as expected. Vehicles "C" and "I" did exhibit noteworthy braking behavior (see Figure 15 for the fully laden vehicle stopping distances).

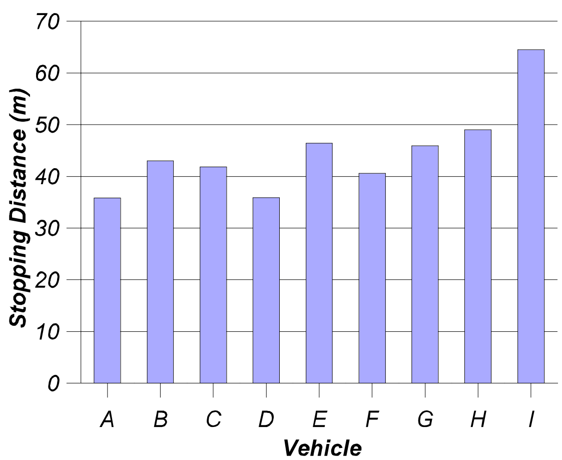

Figure 15. J-turn stopping distances observed on dry asphalt. Test vehicles were fully laden to their respective GVWRs.

Test vehicle "C" deviated an average of 2.5 m (8.3 ft) from its intended stopping lane in each of the three ABS-assisted stops when lightly laden. This vehicle's stopping distances were not noticeably extended, however, and the ABS was not considered to be responsible for this occurrence. It is believed that the lateral road holding capacity of test vehicle "C" was exceeded as it entered the J-turn, inducing understeer. The understeer condition subsided as the vehicle was slowed, and there was no excessive yaw present throughout the stop.

When fully laden, the J-turn stopping distance of vehicle "I" increased 49.1 percent over the lightly laden distance. This increase was far greater than the average increase of the other vehicles (3.4 percent) and its cause is unknown. The test driver's steering and brake inputs were nearly identical for both loading conditions, yet the vehicle's braking performance differed significantly.

SINGLE LANE CHANGE STOPPING MANEUVER

One of the major benefits of ABS is that, unlike conventionally-braked vehicles, it allows the driver to control the path of the vehicle while performing hard and/or panic braking. Drivers will generally use this additional path control to avoid crashes and/or roadway hazards. Occasionally, however, a driver will steer their ABS-equipped vehicle onto a more "difficult-to-drive-on" surface than they would have otherwise driven over by going straight ahead without ABS. The single lane change maneuver was designed to study what might happen when this situation occurs by using an aggressive, transient, brake and steer maneuver.

Unlike most maneuvers used in this program, ABS-assisted braking performance in the single lane change was not compared with disabled-ABS performance. If the ABS was disabled, and a panic brake input applied, the vehicle's front wheels would have locked, causing the vehicle to skid out of the test course without making a lane change. By not making the lane change, no portion of the vehicle would have been driven onto the low-coefficient section of the test course. As a result, the disabled-ABS vehicles would have achieved shorter stopping distances. This, however, is not the situation the maneuver was attempting to simulate. For this reason, the single lane change cannot be used to draw conclusions about ABS versus disabled-ABS braking performance.

Figure 16 presents the fully laden stopping distances recorded for the single lane change. The stopping distances of vehicle "H" and "I" were most likely extended due to the very low coefficient of friction of the newly reconditioned epoxy surface. Test vehicle "I" was not evaluated at the lightly laden loading condition.

Five vehicles, under various loading conditions, experienced excessive yaw and loss of control while attempting the lane change during one or more test runs. It is not believed that the antilock brake systems were responsible for the lost control, rather that the maneuver-imposed handling demands exceeded the capabilities of the test vehicles (e.g., the tires that transitioned onto the epoxy surface were unable to achieve the lateral forces necessary to prevent sliding due to inertial effects). ABS cannot create lateral force. Although ABS is designed to reduce the incidence of spinouts, it cannot completely prevent them. For this reason, the excessive yaw and/or loss of control observed during testing does not necessarily indicate an ABS problem.

With the exception of vehicles "H" and "I" when lightly laden and vehicle "C" at GVWR, each vehicle was able to successfully complete at least one run in which loss of control was not experienced at the desired test speed.

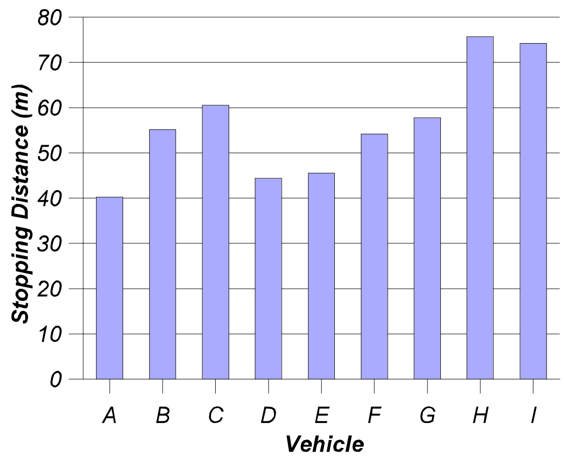

Figure 16. Wet asphalt to wet asphalt/wet epoxy split-mu single lane change stopping distances. Test vehicles were fully laden to their respective GVWRs. Note: the epoxy surface was reconditioned prior to the brake performance evaluation of vehicles "H" and "I".

CONCLUSIONS

For most stopping maneuvers, made on most test surfaces, ABS-assisted panic stops were found to be shorter than those made with best effort or full pedal applications with the ABS disabled (see Table 2).

Table 2. Summary of ABS Stopping Distance Benefits (or Disadvantages).

Test Surface	Benefit (or Disadvantage) Percentage	
	Lightly Laden	Fully Laden
Dry Concrete Straight Line	9.8	12.7
Wet Polished Concrete Straight Line	16.7	23.1
Wet Asphalt Straight Line	11.4	17.2
Wet Jennite Straight Line	17.6*	26.6
Grass Straight Line	(7.1)*	6.9
Loose Gravel Straight Line	(30.0)*	(24.6)
ABS Test Pad #0	7.6	11.6
ABS Test Pad #1	6.2	10.3
ABS Test Pad #2	6.1	10.9
ABS Test Pad #3	4.6*	7.9*
Wet Asphalt/Wet Epoxy Split-mu	11.3	11.4
Dry Asphalt Curve	11.9	19.5
Wet Jennite Curve	18.9*	32.4

*Percentage calculated using eight test vehicles.

The one exception to this trend occurred on the loose gravel, where stopping distances with ABS were extended by an overall average of 27.2 percent over the disabled-ABS panic stops. The ABS-induced stopping distance increases were recorded for each vehicle at both loading conditions. Braking performance on this surface therefore comprises an area in which future efforts to improve ABS might be focused.

The vehicular stability observed during the stops made for this study was almost always found to be superior with ABS. Although it was not specifically quantified in this study, the absence of excessive yaw while braking enhanced the ease with which the driver could maintain lane position, especially on split-mu and low coefficient surfaces. For the cases in which instability was observed, it was generally the result of a vehicle exceeding its lateral roadholding capacity, and not the result of poor ABS performance.

The fact that there exists a condition in which ABS continues to contribute to increased stopping distances (on loose gravel) demonstrates compromises in ABS design continue to exist. That said, most passenger vehicles spend far more time on smooth, paved roads than they do traveling over "soft" road surfaces like gravel and lightly packed snow. One way to optimize ABS operation for such surfaces would be to increase the longitudinal wheel slip threshold. This would, however, reduce a vehicle's ability to turn during an ABS-assisted stop, thereby reducing one of the fundamental attributes of ABS--enabling the driver to effectively brake and steer simultaneously. The evolution of ABS technology that will enable an antilock system to adapt its control algorithm when operating on certain deformable road surfaces may lead to improved vehicle performance on these surfaces.

This study also establishes that antilock brake systems include stopping distance versus vehicular stability compromises. Most antilock brake systems maintain vehicular stability while braking by minimizing excessive yaw. In a curve, this stability may be created by sacrificing the shortest attainable stopping distance. With this said, most test vehicles (only one exception was observed) were stopped in shorter distances with ABS than with disabled-ABS best effort attempts for maneuvers that involved braking and steering (or steering and braking). Under these conditions, ABS prevented wheel lockup and minimized yaw for all nine vehicles.

It was not the intent of this study to compare individual vehicles or antilock brake systems to one another. The test matrix was designed to examine the influence ABS has on a given vehicle's braking performance. Individual system comparison would have necessitated multiple samples of test vehicles identical in every way but ABS. Environmental conditions and test surface temperatures would also have been required to be tightly controlled, monitored, and documented throughout the testing time line. Due to the time required for complete instrumentation and the number of vehicles in the test fleet, such an evaluation would not have been possible.

The results of this study indicate it is unlikely the increase in single-vehicle run-off-road crashes is due to ABS performance deficiencies. Preliminary results of NHTSA's Light Vehicle ABS Research Program Task 3 show that such crashes occur most often on dry, paved roads. Test track results, however, revealed that ABS performance was generally superior to disabled-ABS performance over these surfaces.

It should be recognized that the speeds utilized in this study during off-road testing were quite low. Antilock brake system performance on these surfaces at elevated speeds may reveal different results than those previously observed. "NHTSA's Light Vehicle ABS Research Program Task 6: Testing the Effects of ABS When Performing Road Recovery Maneuvers" will explore this hypothesis and introduce two new brake-and-steer maneuvers.

The evaluation of ABS braking performance is just one of nine NHTSA Light Vehicle ABS Research Program tasks. The knowledge gained from this study will be integrated with data from the other tasks to infer why the crash data studies did not demonstrate an overall increase in safety for ABS-equipped automobiles, and the results will be forthcoming.

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APPENDIX (see next page for Table A1)

Table A1. Light Vehicle ABS Test Matrix.

Surface	Nominal ASTM Skid No. (Peak/Slide)	Maneuver	Speed
Dry Concrete	90/75	Straight Line (Uniform)	97 km/h (60 mph)
Wet Polished Concrete	unknown/60	Straight Line (Uniform)	64 km/h (40 mph)
Wet Asphalt	85/65	Straight Line (Uniform)	80 km/h (50 mph)
Wet Jennite	30/10	Straight Line (Uniform)	64 km/h (40 mph)
Grass	unknown	Straight Line (Uniform)	40 km/h (25 mph)
Loose gravel	unknown	Straight Line (Uniform)	56 km/h (35 mph)
Wet Asphalt to Wet Jennite	(85/65) to (30/10)	Straight Line (Transition)	64 km/h (40 mph) Transition at 40 km/h (25 mph)
Wet Jennite to Wet Asphalt	(30/10) to (85/65)	Straight Line (Transition)	56 km/h (35 mph) Transition at 40 km/h (25 mph)
Wet Asphalt across corner of Wet Epoxy to Wet Asphalt	(85/65) across corner of (20/3)* to (85/65)	Straight Line (Transition)	64 km/h (40 mph) Transition at 40 km/h (25 mph)
ABS Test Pad #0	85/65	Straight Line (Transition)	64 km/h (40 mph)
ABS Test Pad #1	(85/65) to (30/10) to (85/65)	Straight Line (Transition)	64 km/h (40 mph)
ABS Test Pad #2	(85/65) to (30/10) to (85/65)to (30/10) to (85/65)to (30/10) to (85/65)	Straight Line (Transition)	64 km/h (40 mph)
ABS Test Pad #3	(85/65) to unknown to (85/65)	Straight Line (Transition)	64 km/h (40 mph)
Wet Asphalt/Wet Epoxy	(85/65) / (20/3)*	Straight Line (Split-Mu)	48 km/h (30 mph)
Dry Asphalt	90/80	Curve (91.4 m radius)	80 km/h (50 mph)
Wet Jennite	30/10	Curve (152.4 m radius)	64 km/h (40 mph)
Dry Asphalt	90/80	J-turn	80 km/h (50 mph)
Wet Asphalt to Wet Asphalt/ Wet Epoxy Split	(85/65) to (85/65) / (20/3)*	Single Lane Change to Split-mu	80 km/h (50 mph)

* The actual skid numbers of the epoxy surface were much greater than those of the nominal specification during the evaluation of vehicles "A" through "G". The epoxy's average peak and slide coefficients were 52 and 14, respectively, when these vehicles were tested. Vehicles "H" and "I" were evaluated after the epoxy had been reconditioned and its nominal specification criteria satisfied.