1999-01-1290

Driver Crash Avoidance Behavior with ABS in an Intersection Incursion Scenario on the Iowa Driving Simulator

Elizabeth N. Mazzae
National Highway Traffic Safety Administration

G. H. Scott Baldwin
Transportation Research Center Inc.

Daniel V. McGehee
University of Iowa

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) has developed its Light Vehicle Antilock Brake Systems (ABS) Research Program in an effort to determine the cause(s) of the apparent increase in fatal single-vehicle run-off-road crashes as vehicles undergo a transition from conventional brakes to ABS. As part of this program, NHTSA conducted research examining driver crash avoidance behavior and the effects of ABS on drivers' ability to avoid a collision in a crash-imminent situation. The study described here was conducted on the Iowa Driving Simulator and examined the effects of ABS versus conventional brakes, speed limit, ABS instruction, and time-to-intersection (TTI) on driver behavior and crash avoidance performance. This study found that average, alert drivers do tend to brake and steer in realistic crash avoidance situations and that excessive steering can occur. However, this behavior did not result in a significant number of road departures.

INTRODUCTION

Antilock brake systems (ABS) have been introduced on many passenger car and light truck make/models in recent years. In general, ABS appears to be a promising safety device when evaluated on a test track. Under many pavement conditions antilock brake systems allow the driver to stop a vehicle more rapidly while maintaining steering control even during situations of extreme, panic braking. Brake experts anticipated that the introduction of ABS on passenger vehicles would reduce both the number and severity of crashes. However, a number of crash data analyses have been performed in recent years by NHTSA, automotive manufacturers, and others which indicate that the introduction of ABS has not resulted in a reduction in the number of crashes to the anticipated extent.

CRASH DATA

Kahane [1] found that, with the introduction of ABS, involvements in fatal multi-vehicle crashes on wet roads were significantly reduced by 24 percent, and nonfatal crashes by 14 percent. However, these reductions were offset by a statistically significant increase in the frequency of single-vehicle, run-off-road crashes, as compared to cars without ABS. Fatal run-off-road crashes were up by 28 percent and nonfatal crashes by 19 percent.

A later, 1998 study by Hertz, Hilton, and Johnson [2, 3] found that although several types of crashes showed ABS-related reductions including rollovers, frontal impacts, and run-off-road crashes in favorable pavement conditions, some crash types showed increases as well. This study is similar to an earlier study by the same authors [4] except that it is based on more recent (1995 - 96) crash data. The effects found by the 1998 study were generally similar to the findings of the earlier study except that ABS now appears to be decreasing one particular subtype of single-vehicle road departure crashes, frontal impacts with fixed objects, rather than increasing their numbers.

NHTSA'S LIGHT VEHICLE ABS RESEARCH PROGRAM

In an effort to investigate possible causes of the crash rate phenomena, NHTSA developed its Light Vehicle ABS Research Program. This program contains nine separate tasks addressing such issues as ABS hardware performance, examination of ABS crash reports, and assessment of driver behavior with ABS (as outlined in [5]). To date, NHTSA research has found no systematic hardware deficiencies in its examination of ABS hardware performance, except for known degradations in stopping distances on gravel (as documented in [6]). It is unknown, however, to what extent the increase in run-off-road crashes may be due to drivers' incorrect usage of ABS, incorrect response to ABS activation, incorrect instinctive driver response (e.g., oversteering), changes in driver behavior (e.g., behavioral adaptation) as a result of ABS use, or some other factor.

TASK 5: HUMAN FACTORS STUDIES OF DRIVER CRASH AVOIDANCE BEHAVIOR

To determine whether some aspect of driver behavior in a crash-imminent situation may be counteracting the potential benefits of ABS, NHTSA embarked on a series of human factors studies. These studies, which compose Task 5 of the research program, focus on the examination of driver crash avoidance behavior as a function of brake system and various other factors.

One of the theories Task 5 sought to address was whether the apparent increase in single-vehicle crashes involving ABS-equipped vehicles may be due to characteristics of driver steering and braking behavior in crash-imminent situations. According to this theory, in situations of extreme, panic braking, drivers may have a tendency to brake hard and make large steering inputs to avoid a crash. Without four-wheel ABS, aggressive braking may lock the front wheels of the vehicle, eliminating directional control capability, rendering the driver's steering behavior irrelevant. With four-wheel ABS, the vehicle's wheels do not lock; therefore, the vehicle does not lose directional control capability during hard braking, allowing drivers' steering inputs to be effective in directing the vehicle's motion. This directional control could result in drivers avoiding multi-vehicle crashes by driving off the road and experiencing single-vehicle crashes.

To investigate this theory, Task 5 sought to determine whether:

- Drivers tend to both brake and steer (as opposed to only braking or only steering) during crash avoidance maneuvers;
- Drivers tend to make large, potentially excessive, steering inputs during crash avoidance maneuvers;
- Drivers' crash avoidance maneuvers in ABS-equipped vehicles result in road departures more often than in conventionally braked vehicles;
- Drivers avoid more crashes in ABS-equipped vehicles than in conventionally braked vehicles; and
- Speed limit has an effect on whether drivers avoid more crashes in ABS-equipped vehicles than in conventionally braked vehicles.

Task 5 of NHTSA's Light Vehicle ABS Research Program included three studies. Two studies were conducted on a test track (one on dry pavement, one on wet pavement) and one on the University of Iowa's Iowa Driving Simulator (IDS).

These studies used a right-side intersection incursion scenario to elicit a crash avoidance response from human subjects. This scenario was chosen because it was likely to induce steering and obstacle avoidance behavior and had the potential for subjects to drive the vehicle off of the road. This intersection-related obstacle avoidance scenario is obviously not responsible for all run-off-road crashes and results may not be representative of driver behavior in all situations leading to vehicle road departure. Many run-off-road crashes occur when drivers are unable to maneuver through a curve in the roadway or when they are drowsy or under the influence of alcohol. However, it is believed that the results of this study will be useful in determining not only the extent to which drivers are able to maneuver a vehicle, but also drivers' physical capacity to supply control inputs to the vehicle. Insight into drivers' ability to maintain vehicle control during a panic maneuver and ability to avoid a collision can also be gained from this research.

Although the same scenario was involved in each of these experimental venues, advantages to both test track and simulator means of observing driver behavior were present. The test track experiments allowed driver behavior to be examined in a realistic environment at moderate speeds in real vehicles with simulated obstacles on both dry and wet pavement. The IDS study allowed for driver behavior to be examined using a highly repeatable test method in a simulated environment at higher travel speeds and with no chance of actual physical collision. This paper discusses the method and results of the study conducted on the Iowa Driving Simulator.

METHOD

APPARATUS

<u>Iowa Driving Simulator (IDS)</u>

The Iowa Driving Simulator incorporates recent technological advances to create a highly realistic automobile simulator. IDS uses four multi-synch projectors to create a 190 degree forward field-of-view and a 60 degree rear view. Motion cues are produced by a six-degree of freedom motion base. Inside the simulator dome is a fully instrumented vehicle cab. The vehicle cab used in this study was a 1993 Saturn SL2. However, both the vehicle dynamics simulation and the antilock brake system modeled were of a Ford Taurus, a typical mid-sized American car. The Ford Taurus vehicle dynamics model used in this study was developed by NHTSA for use with the National Advanced Driving Simulator (NADS).

<u>Hardware-in-the-Loop Antilock Brake System (ABS)</u>

To facilitate testing of driver behavior with ABS in this study, a hardware-in-the-loop antilock brake system was developed by NHTSA's Vehicle Research and Test Center for implementation on the IDS. Details of this hardware-in-the-loop ABS will be provided in the final NHTSA report for this project. The ABS operates as it would on an actual vehicle by providing both haptic brake pedal feedback and auditory feedback. This hardware-in-the-loop system has the capability of being enabled/disabled by an operator switch so both ABS and non-ABS conditions could be run efficiently without any hardware changes.

Instrumentation

In addition to the objective data quantifying the subjects' vehicle control inputs, four video cameras were also used to record the events on video tape for analysis of driver behavior, response timing, and reaction to the incursion event. One camera focused on the throttle and brake pedals. Another focused on the driver's face. A third focused on the driver's hands on the steering wheel. The fourth camera recorded the forward view of the road scene. Both sensor data and video data were collected at a rate of 30 Hz.

SUBJECTS

Sixty males and 60 females between the ages of 25 and 55 years were selected for participation in this study. Each participant was required to hold a valid driver's license and be able to pass a general health screening. In general, subjects placed in the conventional brake system condition had conventional brakes on their primary personal vehicle, while those in the ABS condition had ABS on their primary vehicle.

EXPERIMENTAL DESIGN

The experimental design used in this study was a 2 (brake system; ABS, conventional brakes) x 2 (ABS instruction; video, no video) x 2 (speed limit; 45, 55 miles per hour) x 2 (time-to-intersection, TTI; 2.5, 3.0 seconds) x 2 (gender) within subjects partial factorial design. This design produced twelve experimental conditions. This paper focuses on the results for brake system, ABS instruction, speed limit, and gender.

To address whether drivers may be more likely to crash in an ABS-equipped vehicle due to lack of knowledge about ABS, ABS instruction was included as an independent variable in this study. Of the subjects in the ABS condition, half received ABS instruction and the other half received no ABS instruction. ABS instruction consisted of an initial segment describing the Iowa Driving Simulator and procedures for entering and exiting the simulator and what to do in the event that the subjects experienced signs of motion sickness, and a latter segment which illustrated ABS operation and was taken from an OEM video [7] designed to be given to a buyer with the purchase of a new vehicle. Subjects in the conventional brake system condition received a shortened version of the same video containing only the segment describing the nature of the IDS and related safety precautions.

TTI was defined as the time it would take the subject vehicle to reach the intersection at its current velocity, as measured at a specific "trigger" point in the road. The purpose of this independent variable was to examine whether subjects altered their collision avoidance strategy based on the time available to respond to the event.

To assess whether drivers are more likely to have unsuccessful crash avoidance maneuvers in ABS-equipped vehicles while traveling at higher speeds, a speed limit independent variable was included in this study. The speeds chosen were 45 and 55 miles per hour (mph). Results for the 45 mph condition could be compared to results for the dry test track study for the same speed. For safety reasons, speed limits in the test track studies were kept to 45 mph on dry pavement and 35 mph on wet pavement.

A counterbalance scheme was used to ensure that each condition accommodated for differences in days, the time of day, and gender differences. An equal number of males and females participated both in the morning and in the afternoon on each day of testing.

PROCEDURE

To help ensure that subjects would not anticipate the intersection incursion event, subjects were informed that they would be driving for approximately 30 minutes. In actuality, the drive was approximately 15 minutes in length. In addition, subjects were told that their task was to assess the looks and feel of the simulator and that they would be given a questionnaire to collect their impressions on this topic after their drive.

Upon entering the simulator, an in-vehicle experimenter instructed the subject to adjust the seat and mirrors. The subject was then told to begin driving and was given time to get comfortable with the feel of the vehicle. The in-vehicle experimenter instructed the subject to get a feel for the steering, braking, and acceleration, during an initial portion of the drive in which no data were collected. No mention was made by the in-vehicle experimenter of the presence of ABS, where applicable, and no encouragement was given for the subjects to practice activating the ABS. Approximately five minutes into the drive, subjects were asked to begin driving normally and assess the simulator.

During their drive, subjects experienced a slow-moving semi tractor-trailer on a hill. This truck required them to reduce speed to approximately 25 mph. Oncoming traffic was spaced such that passing the truck was not an option. Once the subject had crested the hill, the truck pulled over and stopped on the shoulder of the roadway and the subject was able to return to driving at the posted speed limit.

Shortly thereafter, another vehicle, called the "lead vehicle," appeared in the distance ahead of the subject vehicle. This vehicle maintained a six second headway with respect to the subject vehicle. As the subject vehicle approached the intersection where the incursion would take place, the lead vehicle could be seen by the subject driving through the intersection without stopping or braking. The purpose of the lead vehicle was to encourage the subject to feel that there was no need to slow down or stop at the intersection and that it was safe to continue on their path through the intersection.

The intersection at which the incursion event took place was the only intersection present in the route. As depicted in Figure 1, two vehicles were positioned on the perpendicular roadway at the intersection. One vehicle was stopped at a stop sign on the left side of the intersection (a light truck) and another vehicle stopped at a stop sign on the right side of the intersection (a Buick Regal). At the time of the incursion event, no oncoming traffic was present. At the specified TTI, the vehicle on the right side of the intersection drove into the intersection and stopped with its front bumper at the center of the subject's lane of travel, causing subjects to perform evasive maneuvers to avoid collision. Subjects reactions were captured by sensor and video data. Upon the completion of the intersection incursion event, the subject's drive was over. Each subject experienced the incursion event only once.

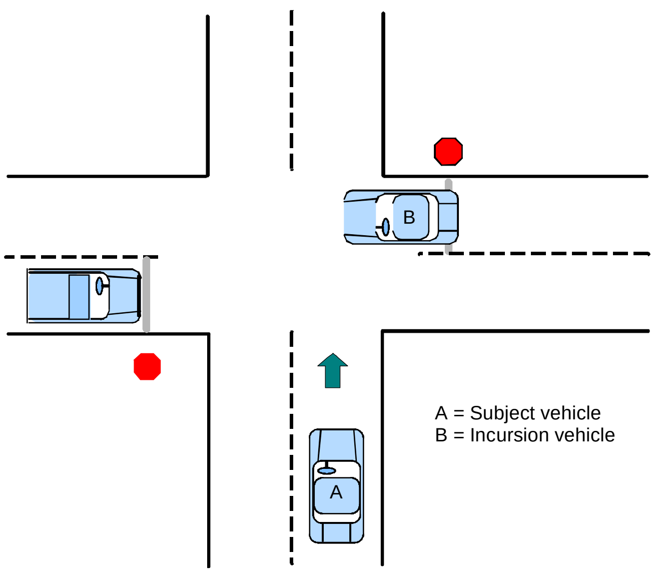

Figure 1. Illustration of intersection and position of vehicles during the incursion event.

RESULTS

Crash Avoidance Strategy -- Overall

All 120 subjects attempted both steering and braking inputs in an attempt to avoid colliding with the scenario vehicle as it encroached into their lane. Seventy-nine percent of the subjects applied the brakes before steering as their initial response. Four percent of the subjects initiated braking and steering inputs simultaneously as an initial response. Seventeen percent of the subjects steered before applying the brakes.

As the incursion vehicle began its motion into the intersection, 60 percent of the subjects chose to steer left as an initial steering input (defined as the first steering input of magnitude greater than six degrees which the subject made after the initiation of the incursion vehicle's motion), and 40 percent chose to steer right.

An "avoidance steering input" was defined as the steering input which a subject made that was intended to maneuver the subject vehicle around the crossing vehicle. This input was not necessarily the subject's first steering input in response to the incursion. During the collision avoidance maneuver, 86 percent of the subjects chose to try to steer left of the encroaching vehicle and 14 percent made the decision to steer right to avoid a collision (see Figure 2). Thirty-six percent of the subjects who steered left crashed, while 29 percent who steered right crashed.

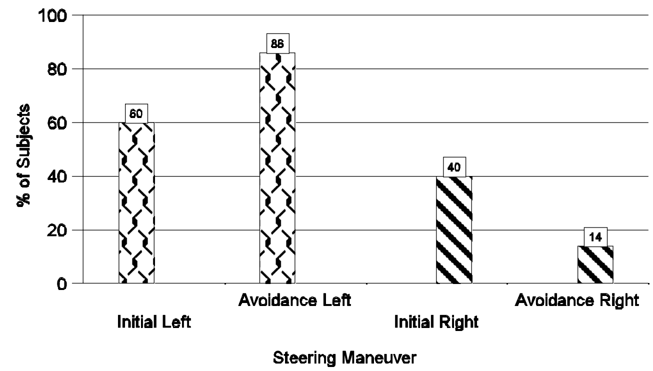

Figure 2. Steering response directions during incursion scenario.

Steering Behavior -- Overall

The average magnitude of avoidance steering input observed was 148 degrees. The highest observed steering input from an individual subject in this study was 540 degrees during the avoidance maneuver.

The average maximum steering rate obtained during the avoidance maneuver was 514 degrees per second. The highest observed steering rate achieved by a subject in this study was 1416 degrees per second. Ninety-five percent of steering rates observed were less than 981 degrees per second.

Braking Behavior -- Overall

The overall average maximum brake pedal force obtained was 90 pounds. The highest observed brake pedal force input generated by a subject in this study was 278 pounds. Ninety-six percent of the subjects either activated ABS or locked the vehicle's wheels with conventional brakes during the avoidance maneuver.

Road Departures -- Overall

Eight people fully departed the roadway during the collision avoidance maneuver. Six subjects made steering inputs severe enough to cause yaw rates resulting in some degree of vehicle spin. In 4 of these 6 cases, the vehicle spun off the road.

Crashes -- Overall

During the intersection incursion event, 35 percent of the subjects collided with the scenario vehicle as it encroached into their lane.

ABS vs. CONVENTIONAL

Overall, 80 subjects were assigned the ABS condition and 40 were assigned the conventional brake system case.

Crash Avoidance Strategy by Brake System

For those who braked then steered during the avoidance maneuver, the delay time from when they initiated braking to when they began to steer did not differ significantly by brake system. Those with ABS waited 0.70 seconds after braking to initiate steering while those with conventional brakes waited 0.62 seconds.

Steering Behavior by Brake System

Table 1 summarizes characteristics of observed steering behavior according to brake system.

Results for the magnitude of avoidance steering inputs by brake system are given in Figure 3. The average magnitude of the avoidance steering input for subjects in the ABS condition was 125 degrees. The average magnitude of the avoidance steering input for subjects in the conventional brake system condition was significantly larger at 192 degrees [p = 0.0064].

As stated previously, a majority of subjects chose to steer left for the avoidance maneuver. On average, those with ABS steered 121 degrees to the left; whereas, the conventional group steered 176 degrees to the left. For those who steered left during the avoidance maneuver, those with ABS steered with a significantly smaller magnitude than those with conventional brakes [p = 0.0334].

The average maximum steering rate of the avoidance maneuver for subjects in the ABS condition was 473 degrees per second. The average maximum steering rate of the avoidance maneuver for subjects in the conventional brake system case was significantly higher at 595 degrees per second [p = 0.0524](Figure 4).

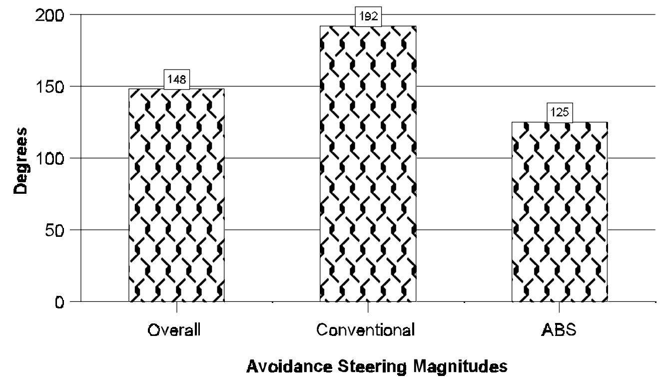

Figure 3. Magnitude of avoidance steering inputs by brake system.

Steering Input Characteristics	Brake System	Value
Average magnitude of avoidance steering input (degrees)	Overall	148
	Conventional	192*
	ABS	125*
Average maximum steering input rate (degrees per second)	Overall	514
	Conventional	595*
	ABS	473*
Time to maximum steering input (seconds)	Conventional	3.69*
	ABS	3.24*

Table 1. Characteristics of observed steering behavior by brake system (* These values are significantly different).

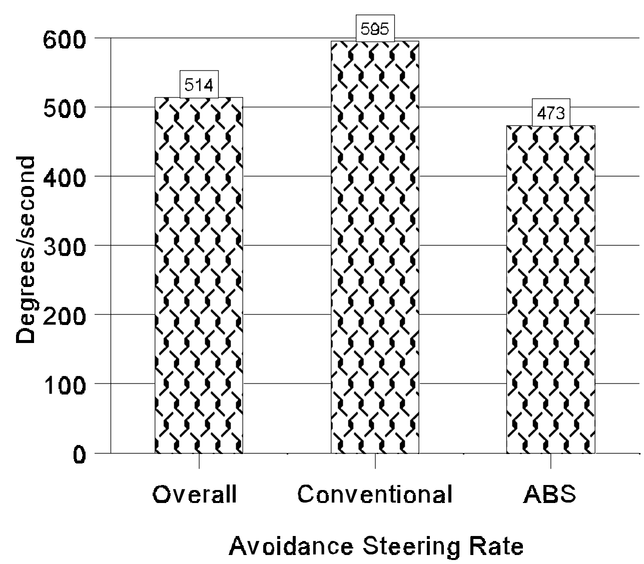

Figure 4. Rates of avoidance steering inputs by brake system.

For subjects in the ABS condition, the time to maximum steering input was significantly less [p = 0.0052] (3.24 seconds) than that observed for those with conventional brakes (3.69 seconds).

Braking Behavior by Brake System

The average maximum brake pedal force observed for subjects in the ABS condition during the avoidance maneuver was 86 pounds. For subjects in the conventional brake system case, the average was 98 pounds (see Figure 5). This difference was not statistically significant [p = 0.0944] at the p = 0.05 level.

One might expect that observed brake pedal application durations should be longer for ABS if drivers were using the ABS properly. However, the average brake pedal application duration observed during the crash avoidance maneuver in this study was significantly longer [p = 0.0435] for conventional brakes (3.12 seconds) than for ABS (2.69 seconds). One also might expect that subjects receiving ABS instruction might have longer brake pedal application durations as a result of being told not to "pump" the brake pedal with ABS. However, subjects receiving ABS instruction had an average brake pedal application duration (2.84 seconds) which was not significantly longer than for those with ABS who received no instruction (2.54 seconds).

Road Departures by Brake System

Four subjects out of the 80, or 5 percent, who were assigned the ABS condition drove completely off the road (all four wheels) during the avoidance maneuver as shown in Figure 6. In each of these four cases the ABS was activated during the crash avoidance maneuver. Four of the 40 subjects, or 10 percent, who had conventional brakes also drove completely off the road during the avoidance maneuver.

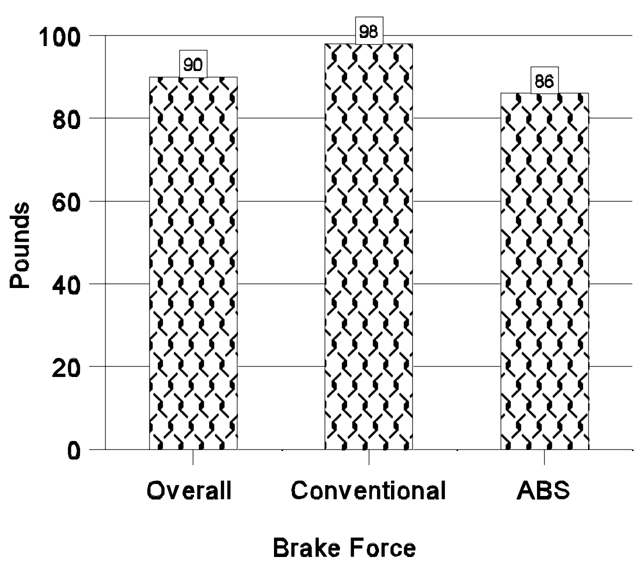

Figure 5. Brake pedal forces by brake system.

All of the instances of four-wheel road departure with ABS were at the 45 mph speed limit. Each of the road departures for conventional brakes was in the 55 mph speed limit condition. Unfortunately, due to the small number of road departures observed in this test, it is difficult to determine whether there is a significant brake system by speed limit interaction.

Six partial (two-wheel) road departures were also observed in this study. One of the cases involved a subject driving with ABS, while the other five involved conventional brakes.

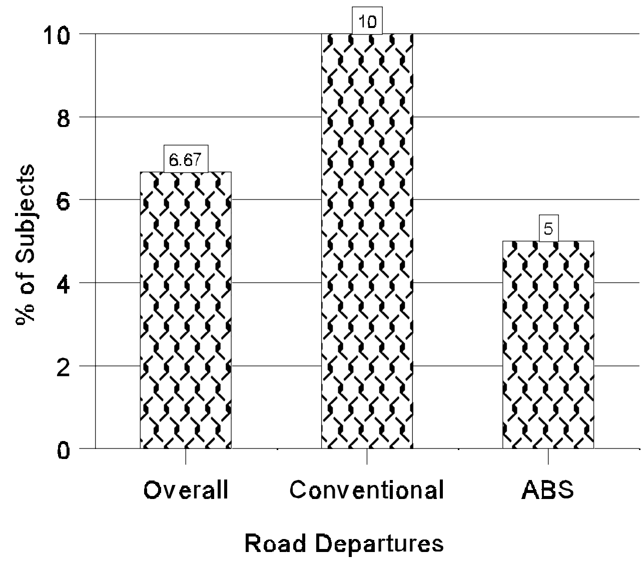

Figure 6. Percent road departures by brake system.

Crashes by Brake System

Figure 7 illustrates results for the number of crashes by brake system. Subjects with ABS crashed less, 31 percent of 80 subjects, than those in the conventional brake system condition, 43 percent of 40 subjects. However, this difference was not statistically significant.

When considering only the sub-sample of subjects who were assigned the ABS condition but were not provided with ABS instruction, these subjects did experience fewer crashes (30 percent crashed) than the conventional group (43 percent crashed). Additional details regarding the effects of ABS instruction on driver behavior and crashes will be provided in the NHTSA final report on this project.

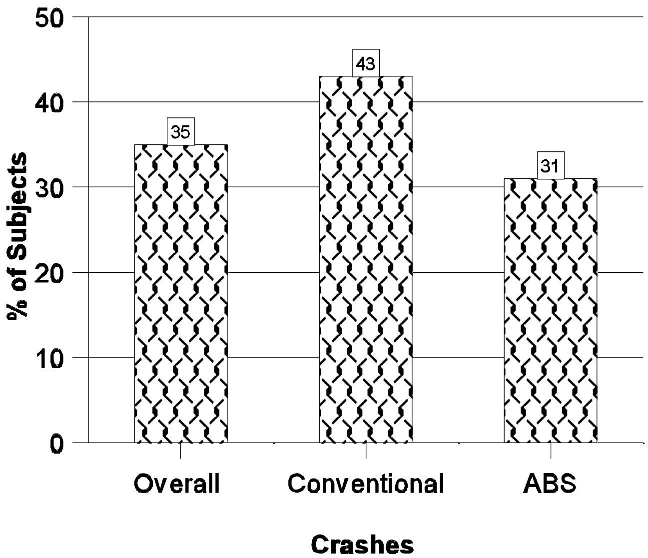

Figure 7. Percent crashes by brake system.

Steering Input Characteristics	Speed Limit	Brake System	Value
Average magnitude of avoidance steering input (degrees)	45	Overall	163
		Conventional	215
		ABS	139
	55	Overall	132
		Conventional	172
		ABS	112
Average maximum steering input rate (degrees per second)	45	Overall	520
		Conventional	569
		ABS	496
	55	Overall	507
		Conventional	621
		ABS	450

Table 2. Characteristics of observed steering behavior by speed limit and brake system.

SPEED LIMIT

Crash Avoidance Strategy by Speed Limit

Regardless of speed limit, subjects tended to brake first and then steer in an attempt to avoid colliding with the crossing vehicle. Of the 20 subjects who steered before applying the brakes, 50 percent were in the 45 mph speed limit condition and 50 percent were in the 55 mph speed limit condition.

Steering Behavior by Speed Limit

Table 2 summarizes subjects' steering behavior as a function of speed limit and brake system.

The average magnitude of the avoidance steering input for subjects in the 55 mph condition was 132 degrees. The average magnitude of the avoidance steering input for those in the 45 mph condition was higher at 163 degrees [$p = 0.1055$](see Figure 8).

The average maximum steering input rate during the crash avoidance maneuver for subjects in the 55 mph condition was 507 degrees per second. The average maximum steering rate of the avoidance maneuver for subjects in the 45 mph speed limit condition was similar at 520 degrees per second as shown in Figure 9.

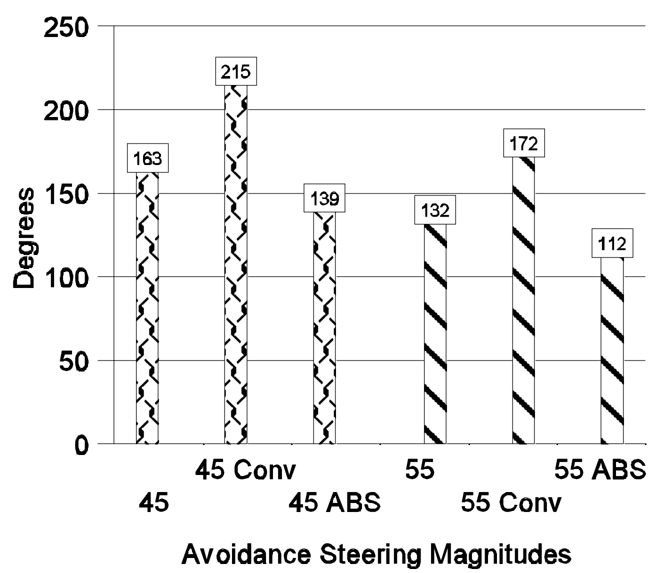

Figure 8. Magnitude of avoidance steering inputs by speed limit and brake system.

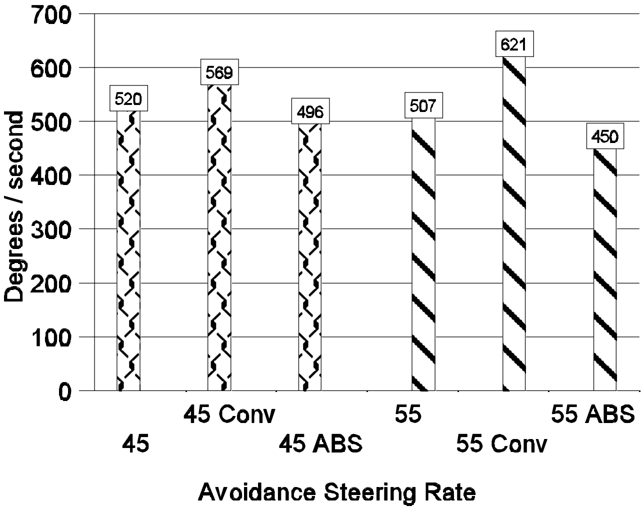

Figure 9. Avoidance steering rates by speed limit and brake system.

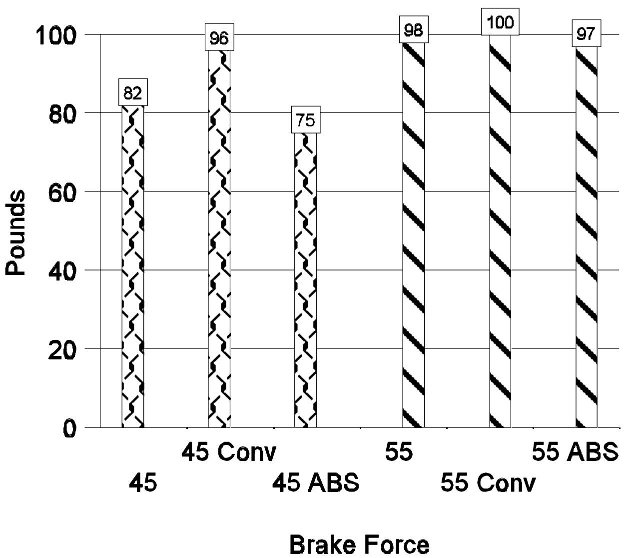

Figure 10. Brake forces by speed limit and brake system.

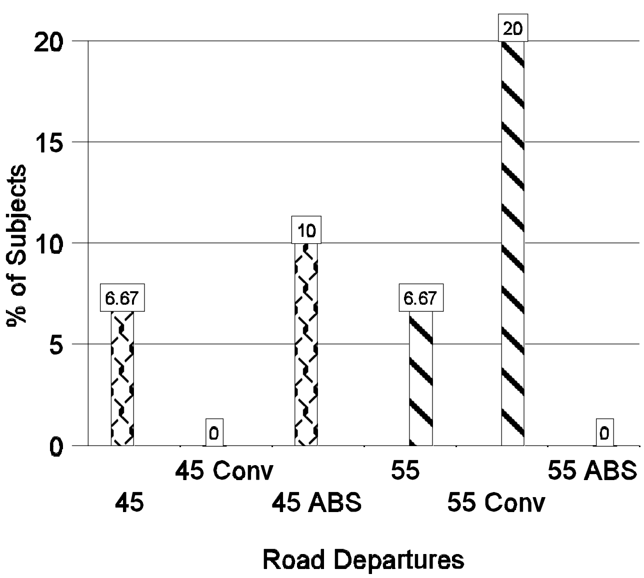

Figure 11. Road Departures by speed limit and brake system.

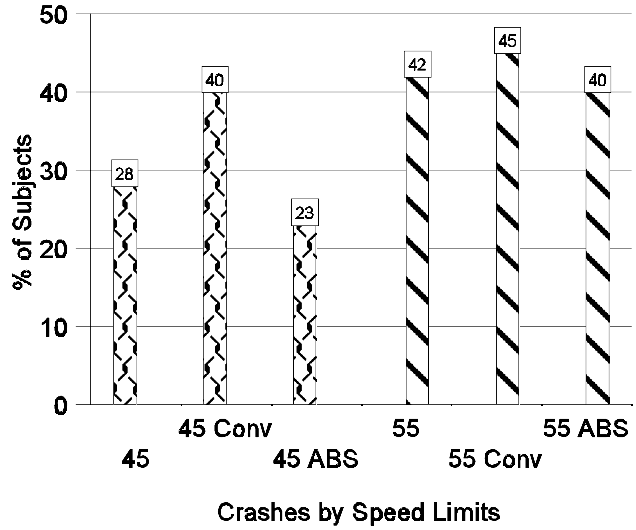

Figure 12. Crashes by speed limit and brake system.

Braking Behavior by Speed Limit

For subjects in the 55 mph speed limit condition, the average maximum brake pedal force obtained during the avoidance maneuver was 98 pounds. The average maximum brake pedal force observed was 82 pounds for the subjects in the 45 mph speed limit condition [p = 0.0981] (Figure 10).

Road Departures by Speed Limit

As stated earlier, four of the instances of road departure were observed for the 45 mph speed limit and all of these involved the ABS-equipped condition. Each of the four road departures for the 55 mph case involved subjects in the conventional brake condition (Figure 11).

Crashes by Speed Limit

For half of the 120 subjects, the posted speed limit on the roadway was 55 mph and for the other half the posted speed limit was 45 mph. Forty-two percent (40 percent ABS, 45 percent non-ABS) of those at the 55 mph speed limit collided with the encroaching vehicle. Only 28 percent (23 percent ABS, 40 percent conventional) crashed in the 45 mph speed limit condition [p = 0.126] as shown in Figure 12.

GENDER

Steering Behavior by Gender

The average magnitude of the avoidance steering input for females was 142 degrees and for males was 154 degrees as shown in Figure 13. The average maximum steering rate in any direction for females was 454 degrees per second and for males was 573 degrees per second as illustrated in Figure 14. Neither the incursion vehicle motion to the time of initial steering input nor the time from

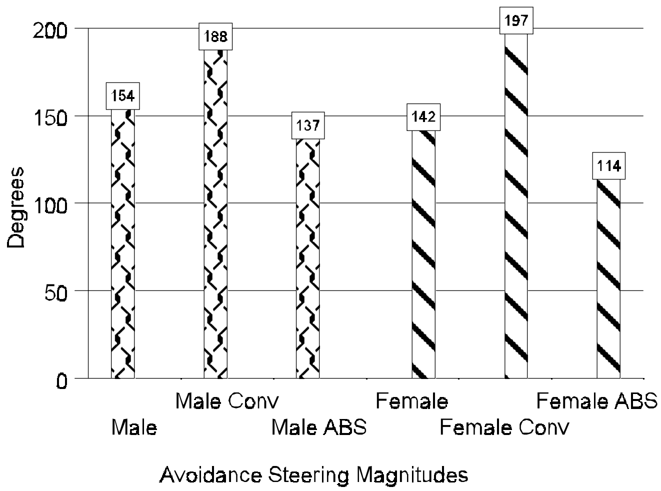

Figure 13. Magnitude of avoidance steering inputs by gender and brake system.

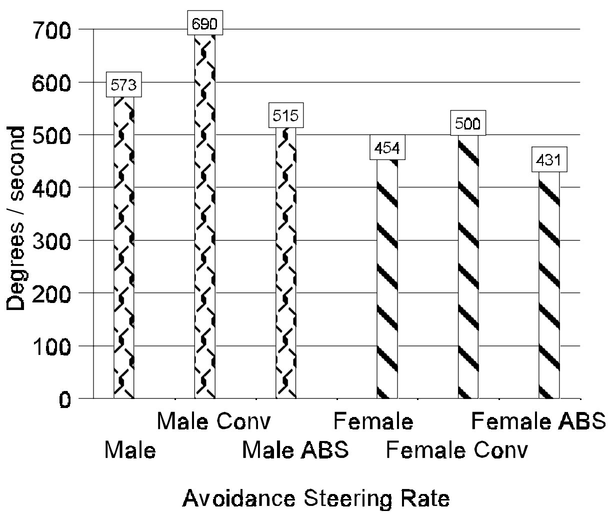

Figure 14. Avoidance steering rates by gender and brake system.

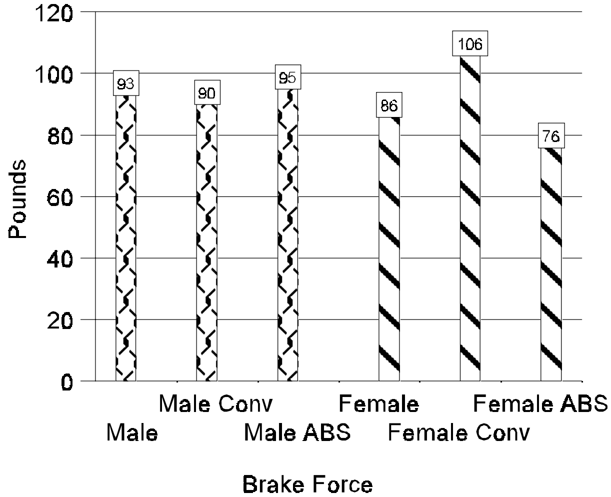

Figure 15. Brake forces by gender and brake system.

initiation of incursion vehicle motion to the time of maximum steering input varied significantly by gender.

Braking Behavior by Gender

The average maximum brake pedal force was 86 pounds for females and 93 pounds for males as shown in Figure 15. This difference was not statistically significant.

In general, braking behavior did not differ according to gender. Males and females produced similar results in terms of the time from the initiation of the incursion vehicle motion to throttle release and maximum braking input. However, reaction time to initial brake application did differ by a nearly significant level [p = 0.06] with males applying the brakes within an average of 1.10 seconds and females doing so within 1.17 seconds.

Road Departures by Gender

Of the eight subjects who drove completely off the road (all four wheels) to avoid a crash, five were males and three were females (see Figure 16).

Crashes by Gender

Figure 17 illustrates crash rates observed in this study by gender and brake system. Thirty-two percent of female subjects crashed into the conflict vehicle during the intersection incursion scenario. Twenty-three percent of the female subjects in the ABS condition crashed, while 50 percent in the conventional case crashed. These data correspond to a statistically significant effect of brake system on crash rates for females, wherein, females in the ABS condition crashed significantly less [p = 0.031] than those with conventional brakes.

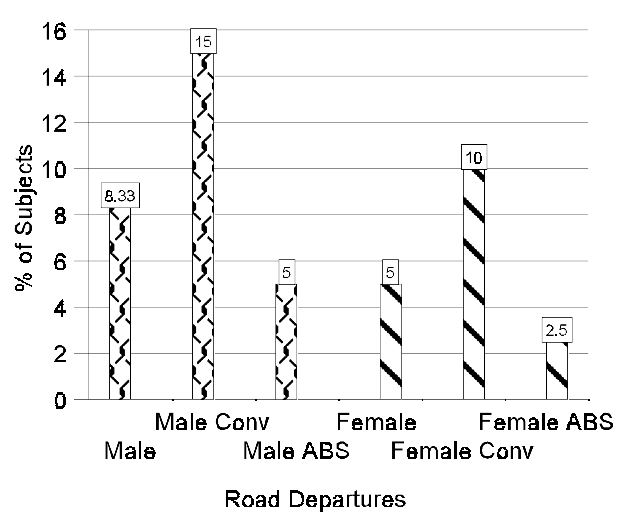

Figure 16. Road departures by gender and brake system.

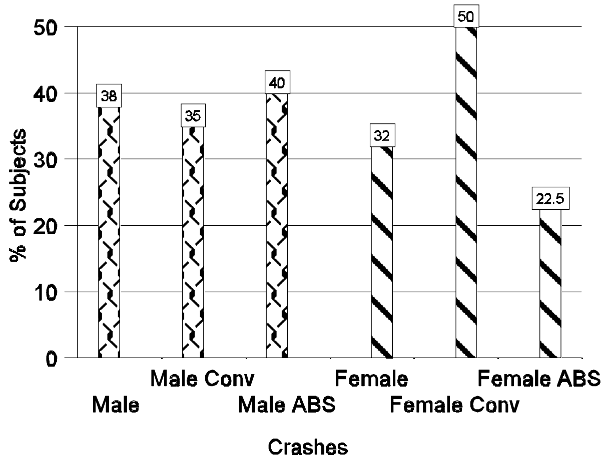

Figure 17. Crashes by gender and brake system.

Thirty-eight percent of males crashed during the intersection incursion scenario. Forty percent of the males in the ABS condition crashed and 35 percent of the males with conventional brakes crashed.

DISCUSSION

Do drivers tend to both brake and steer during crash avoidance maneuvers?

All subjects in this study both braked and steered in an attempt to avoid colliding with the incursion vehicle. Seventy-nine percent of subjects braked before steering during their collision avoidance maneuver. The delay time between when subjects initiated braking to when they made their first steering input did not vary significantly as a function of brake system.

Do drivers tend to make large, potentially excessive steering inputs during crash avoidance maneuvers?

In general, steering inputs exhibited by subjects in this IDS study were larger and quicker than those observed in the related test track studies [8]. This difference is believed to be attributable to the lack of "road feel" present on the IDS as well as the limited range of travel of the simulator motion base. Both of these qualities of the IDS are believed to have contributed to subjects' perception that they were driving on a wet road, although the roadway coefficient of friction in this study was stipulated at 0.8. Despite the larger magnitudes and rates of steering inputs observed in this study, the significance of effects corresponds very well to findings obtained in the wet test track study.

Steering inputs characterized by large magnitudes and high rates of application were observed in this study. However, drivers appeared to alter their steering behavior based on the degree to which they felt the steering inputs were affecting the motion of the vehicle in the desired direction. Subjects with ABS made smaller steering inputs and used lower application rates than subjects with conventional brakes. The reason for this is believed to be that subjects made increasingly large steering inputs with conventional brakes since, with locked wheels, their steering inputs were not effective in directing the vehicle's motion.

Do people experience more road departures in ABS-equipped vehicles than in vehicles with conventional brakes?

Overall, results from this study indicate that although subjects were observed making large steering inputs at high rates, these aggressive steering inputs did not result in a significant number of road departures. This conclusion is true for both conventional brakes and ABS for this study. An equal number of subjects, four per condition, experienced full road departures in both the conventional brakes system and ABS conditions. Six partial road departures were observed in this study, only one of which involved ABS.

Do people crash less frequently in ABS-equipped vehicles than in vehicles equipped with conventional brakes?

Overall in this study, subjects driving with ABS did not crash significantly less than those with conventional brakes. However, females in the ABS condition did crash significantly less than those in the conventional brake system condition. Males in this study crashed approximately the same amount with ABS as they did with conventional brakes.

At the 55 mph posted speed limit, the number of crashes observed by brake system did not vary greatly. However, for the 45 mph speed limit, only 23 percent of subjects with ABS crashed as opposed to 40 percent of subjects with conventional brakes. This finding appears to contradict the opinion of some experts that if ABS is found to be associated with an increase in crashes, this increase is likely to only be associated with vehicle traveling at high rates of speed.

CONCLUSIONS

An experiment was conducted in which drivers' collision avoidance behavior in a simulated right-side intersection incursion scenario was examined as a function of vehicle brake system (ABS versus conventional brakes), time-to-intersection (TTI), instruction, and travel speed (45 mph or 55 mph). Drivers' reactions in terms of steering and braking and their success in avoiding the incursion vehicle were recorded.

Subjects in this study were alert and sober. These subjects did demonstrate the capability to make aggressive steering and braking inputs. However, despite the high magnitudes and rates of many inputs observed, few road departures were observed. Road departures which were observed could not be judged attributable to ABS performance or driver interaction with ABS.

Overall, ABS was not found to be associated with significantly fewer crashes in this study as compared to conventional brakes. However, females were found to crash significantly less with ABS than with conventional brakes. More crashes were observed in this study in the 55 mph speed limit condition than at 45 mph.

The results of this study do not appear to indicate that a problem exists due to the crash avoidance behavior of alert, sober drivers. However, an examination of the behavior of sleepy drivers or drivers under the influence of alcohol may produce different results. This study revealed no indications that driver interaction with ABS may be contributing to the apparent increase in fatal single-vehicle road departure crashes that has been identified in conjunction with vehicles transitioning from conventional to antilock brake systems.

Results from this study will be examined in conjunction with the results of other tasks included in NHTSA's Light Vehicle ABS Research Program to determine whether the collective results viewed as a whole provide some insight into the cause(s) of the increase in fatal single-vehicle crashes observed in conjunction with the implementation of ABS.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of Peter Grant of Ford Motor Company and Garrick Forkenbrock of Transportation Research Center Inc. toward the development of the hardware-in-the-loop ABS for implementation on the IDS for use in this study.

REFERENCES

1. Kahane, C. (December, 1994). Preliminary Evaluation of the Effectiveness of Antilock Brake Systems for Passenger Cars, National Highway Traffic Safety Administration, Technical Report.
2. Hertz, E., Hilton, J., and Johnson, D. M. (1998). "Analysis of the Crash Experience of Vehicles Equipped with Antilock Brake Systems (ABS) - An Update." ESV Paper No. 98-S2-O-07. Enhanced Safety of Vehicles Conference, February, 1998.
3. Hertz, E., Hilton, J., and Johnson, D. (1998). Analysis of the Crash Experiences of Vehicles Equipped with Antilock Braking Systems -- An Update. NHTSA Technical Report No. 808 758. Washington, DC: National Highway Traffic Safety Administration.
4. Hertz, E., Hilton, J., and Johnson, D. (1995). An Analysis of the Crash Experience of Passenger Cars Equipped with Antilock Braking Systems. NHTSA Technical Report No. 808 279. Washington, DC: National Highway Traffic Safety Administration.
5. Garrott, W. R. and Mazzae, E. N. (1999). An Overview of the National Highway Traffic Safety Administration's Light Vehicle Antilock Brake Systems Research Program. SAE Paper No. 1999-01-1286. Warrendale, PA: Society of Automotive Engineers.
6. Forkenbrock, G., Flick, Mark, and Garrott, W. G. (1999). NHTSA Light Vehicle Antilock Brake Systems Research Program Task 4: A Test Track Study of Light Vehicle ABS Performance Over a Broad Range of Surfaces and Maneuvers. Washington, DC: USDOT.
7. General Motors Corporation (1994). Your New Vehicle's Antilock Brake System; How It Works For You. Part No. 15709859.
8. Mazzae, E. N., Barickman, F. S., Baldwin, G. H. S., and Forkenbrock, G. (1999). Driver Crash Avoidance Behavior with ABS in an Intersection Incursion Scenario on Wet Versus Dry Pavement. SAE Paper No. 1999-01-1288. Warrendale, PA: Society of Automotive Engineers.

ADDITIONAL SOURCES

Additional information regarding Task 5 of NHTSA's Light Vehicle ABS Research Program can be found in an upcoming NHTSA report titled, "Examination of Drivers' Collision Avoidance Behavior Using Conventional and Antilock Brake Systems."