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Driver Crash Avoidance Behavior with ABS in an Intersection Incursion Scenario on Dry Versus Wet Pavement

Elizabeth N. Mazzae and Frank Barickman
National Highway Traffic Safety Administration

G. H. Scott Baldwin and Garrick Forkenbrock
Transportation Research Center Inc.

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 a test track under dry and wet pavement conditions to examine the effects of ABS versus conventional brakes, ABS brake pedal feedback level, and ABS instruction on driver behavior and crash avoidance performance. This study found that drivers do tend to brake and steer in realistic crash avoidance situations and that excessive steering can occur. However, a significant number of road departures did not result from this behavior for either pavement condition. ABS was found to reduce crashes significantly on wet pavement as compared to conventional brakes.

INTRODUCTION

Since 1985, antilock brake systems (ABS) have been increasingly available on many passenger car and light truck make/models. ABS have been sold as an added safety feature which enhances drivers' ability to control a vehicle and, in some cases, improves vehicle stopping performance. In the interest of reaping the benefits of ABS in terms of a reduction in crashes, the Highway Safety Act of 1991, Section 2507 charged the National Highway Traffic Safety Administration (NHTSA) with the task of determining whether ABS should be required on all passenger vehicles.

As a result, NHTSA undertook a series of investigations to determine the potential benefits of ABS and the effect of ABS on crash rates. Test programs have shown that ABS appear to be very promising safety devices 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 been found to be associated with a reduction in crashes to the expected extent.

CRASH DATA

Kahane [1] found that, with the introduction of ABS, involvements in multi-vehicle crashes involving fatalities 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. Run-off-road crashes, as considered in this report, included rollovers, side impacts with fixed objects , and frontal impacts with fixed objects. Fatal run-off-road crashes were up by 28 percent and nonfatal crashes by 19 percent. On wet roads, fatal run-off-road crashes increased 17 percent and non-fatal run-off-road crashes increased by 24 percent. On dry roads, fatal run-off-road crashed increased by 29 percent while non-fatal crashes increased by 17 percent.

Hertz, Hilton, and Johnson [2] presented results for passenger car run-off-road crashes according to the following crash types: rollovers, side impacts with parked vehicles or fixed objects, and frontal impacts with parked vehicles or fixed objects. For dry roads, ABS was found to be associated with a 17 percent decrease in rollover crashes, a 13 percent decrease in frontal impacts with parked vehicles or fixed objects, and a 7 percent increase in side impacts with parked cars or fixed objects. For pedestrian crashes, ABS was associated with a 30 percent reduction on dry roads and a 10 percent reduction in unfavorable road conditions (i.e., wet, snowy, icy, gravel). In regards to only those crashes involving fatalities, ABS was found to be associated with a 51 percent increase in fatal rollover crashes on dry roads. For fatal side impact crashes, ABS produced a 69 percent increase for unfavorable road conditions, and a 61 percent increase for favorable road conditions.

NHTSA'S LIGHT VEHICLE ABS RESEARCH PROGRAM

In an effort to investigate possible causes contributing to the observed increase in fatal single-vehicle crashes associated with ABS implementation, NHTSA developed its Light Vehicle ABS Research Program. This program contains nine separate tasks addressing issues relating to passenger cars and light trucks such as ABS hardware performance, examination of ABS crash reports, and assessment of driver behavior with ABS (as outlined in [3]). The cumulative results of these varied tasks will provide insight regarding ABS effectiveness. To date, NHTSA research has found no systematic hardware deficiencies in its examination of ABS hardware performance (as documented in [4]) except for the previously identified increase in stopping distance on gravel. 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 of this program, which this paper focuses on, addresses these driver-related issues.

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 fatal 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 and drivers' steering inputs are then 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 address issues such as 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 on dry pavement; and
- Drivers avoid more crashes in ABS-equipped vehicles than in conventionally braked vehicles on wet pavement.

Task 5 of NHTSA's Light Vehicle ABS Research Program includes three studies. Two studies were conducted on a test track (one on dry pavement, one on wet pavement) and one on the 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 behavior and had the potential for subjects driving the vehicle off of the road. This obstacle avoidance scenario is 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 or injury. This paper discusses the method used and a portion of the results from both the dry and wet pavement test track studies.

METHOD

SUBJECTS

Subjects for both the dry and the wet pavement studies were recruited from the central Ohio area using newspaper advertisements and flyers posted in local commercial establishments. Interested persons responded to the ads by telephone and were asked a series of questions regarding health and driving habits to ensure that they were fit to participate.

All subjects were between 25 and 55 years of age. Eligible subjects had no reported health problems which could adversely affect driving ability. Subjects were required to hold a valid driver's license, have driven at least 3,000 miles in the past year, and be able to drive an automatic transmission vehicle without special equipment.

Subjects who were accepted for participation in these studies did not use a vehicle equipped with ABS as their primary mode of transportation. In addition, subjects may have driven an ABS-equipped vehicle before, but had never personally activated ABS.

In order to complete these studies in an economical manner and within the required time frame of the research program, fewer subjects were involved in the wet pavement study than in the dry pavement study. The dry pavement study used 192 subjects while the wet pavement study used 53 subjects.

Subjects were recruited without regard for their occupation and were assumed to be representative of the population of average drivers. A subsequent examination of subject demographics shows that 7 percent were professional truck drivers and as many as 4 percent of subjects in the dry pavement study held an occupation that involved driving in some way. Likewise, approximately 2 percent of subjects (1 subject) in the wet pavement study were reported to be truck drivers and another approximately 2 percent (1 subject) held an occupation that involved driving in some way.

EXPERIMENTAL DESIGN

Independent variables in these studies included type of brake system, ABS brake pedal feedback level, and ABS instruction, braking practice, speed limit, pavement condition, test vehicle, time-to-intersection, and gender. The subset of independent variables common to both the wet and dry test track studies included brake system (ABS, conventional brakes), ABS brake pedal feedback level (light, heavy), and gender. This paper focuses on comparing the results from each of the two studies for these three factors in order to draw conclusions regarding differences between dry and wet pavement findings.

Both studies involved at least 8 subjects per condition for a total of 192 for the dry pavement study and 53 for the wet pavement study. The order of presentation of conditions was randomized. Gender was approximately balanced per experimental condition.

Brake System, ABS Brake Pedal Feedback, and Test Vehicles

Brake system conditions included: a) conventional brake system, b) ABS with minimal pedal feedback; and c) ABS with a large degree of pedal feedback. The use of two test vehicles was required in order to obtain the two ABS brake pedal feedback levels. A 1995 Chevrolet Lumina equipped with Delco VI ABS represented the light feedback condition. A 1996 Ford Taurus equipped with Bosch ABS represented the heavy ABS brake pedal feedback condition. In order to account for any potential vehicle effects, both vehicles were also tested in the conventional case. To create the conventional brake system condition, the ABS were electronically disabled. A secondary independent variable, vehicle, was then examined to identify any potential confounding effects of vehicle make/model.

ABS Instruction

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 these studies. Of the subjects receiving the ABS condition, half received ABS instruction and the other half received no ABS instruction. ABS instruction consisted of a short video containing an initial segment describing the use of seat belts, air bag operation, and safety precautions, as well as a latter segment (taken from an OEM video [5] designed to be given to a buyer with the purchase of a new vehicle) which illustrated ABS operation and use. Subjects in the conventional brake system condition were given no instruction other than the recorded audio instructions which all subjects received instructing them how to drive on the test route and test procedures.

Time-To-Intersection

Time-To-Intersection (TTI) was defined as the time it would take a subject to reach the intersection at their current velocity as measured at a defined "trigger" point in the roadway. 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. Pilot testing was conducted prior to the main test to determine and confirm the TTI values to be used. These values were selected to promote driver steering and to represent two conditions: one in which most but not all drivers would be able to avoid a collision in a vehicle equipped with conventional brakes, and one in which only very few drivers could avoid a crash in a conventional brake system equipped vehicle. Due to difficulties with altering test equipment for accommodation of two TTI

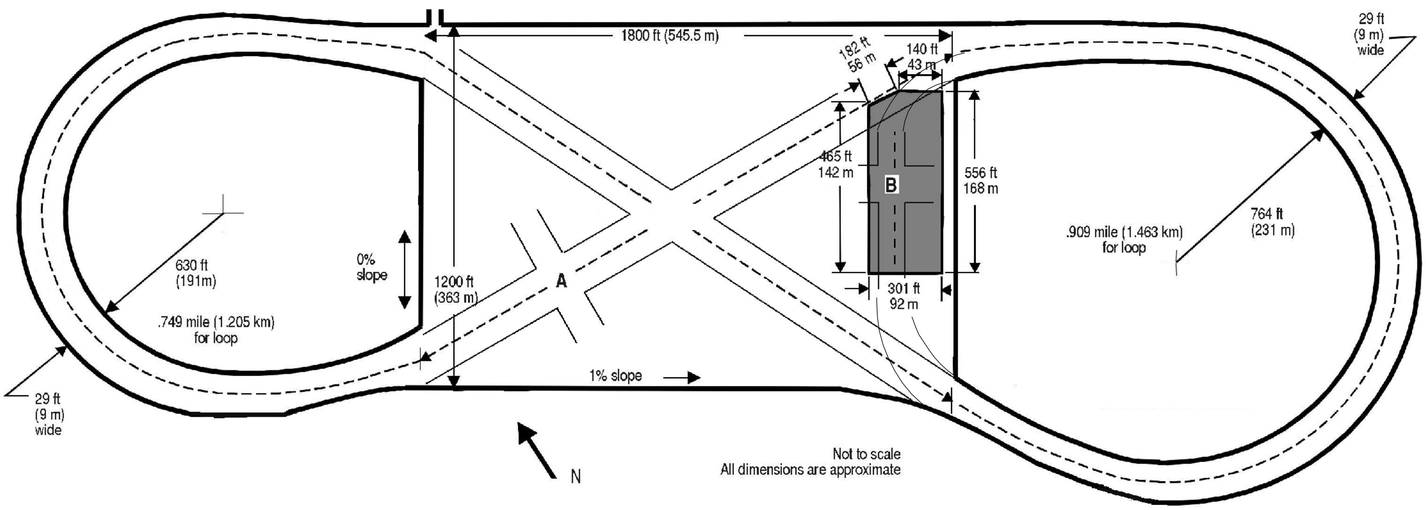

Figure 1. Illustration of location and layout of course used in the dry and wet pavement intersection incursion studies.

values, only one value (2.5 seconds) was used in the wet pavement study. Results presented in this paper for the dry test track study represent both TTI values combined.

Speed Limit

For safety reasons, speed limits in the test track studies were kept to 45 mph (72 kph) on dry pavement and 35 mph (56 kph) on wet pavement. Results for the 45 mph condition could be compared to results for the Iowa Driving Simulator study for the same speed.

Pavement Condition: Dry Versus Wet

The dry test track study was conducted on asphalt pavement having an approximate coefficient of friction of 0.9. For this test a simulated intersection (A) was integrated into a figure eight shaped course, as shown in Figure 1 [6].

For the wet test track study, a simulated intersection was constructed on a Jennite pad which was wetted for testing. In order to accommodate the different location of the intersection (B) for this pavement condition, an oval course was created by using only half of the figure eight course, also illustrated in Figure 1. The approximate coefficient of friction of the wet Jennite surface was 0.4.

INSTRUMENTATION

The test vehicles were instrumented with the Data Acquisition System for Crash Avoidance Research (DASCAR). DASCAR is an unobtrusive data acquisition platform developed by NHTSA and Oak Ridge National Laboratory. This system monitors driver behavior and performance, vehicle performance, and their associations with the external environment [7]. The system was configured to record a variety of parameters to describe the dynamics of the vehicle as well as the subjects' vehicle control inputs. These measures included displacement and rate of the steering inputs, force applied to the brake pedal, displacement of the throttle, vehicle ground speed, individual wheel speeds, traveled distance, and individual brake line pressures. These parameters were sampled at 200 Hz.

Video cameras were used to collect data both inside and outside of the vehicle. Within the DASCAR, views were recorded to collect data on the subjects eye glance behavior, steering inputs, driver hand position, and throttle and brake applications. A fourth view was used to record the forward road scene. These four views were multiplexed into one video signal using a quad picture processor and simultaneously recorded in synchronization with the other measures collected. Additional full-frame video data was collected by two external sources. These views were in front of and behind the intersection scenario to capture the test vehicle during the obstacle avoidance maneuver.

The parameters determined from the data collected using DASCAR included subject vehicle travel speed at intersection approach and at collision (if a collision occurred). Since TTI was based upon an assumed subject vehicle speed of 45 mph, actual TTI was calculated based on the test vehicle's actual speed in case it varied from the desired value. The time from initiation of incursion vehicle motion to each of several driver actions was noted, e.g., throttle release, initial brake application, and initial steering input. The magnitude of each of these measures was also determined. Maximum applied brake pedal force, individual wheel speeds, handwheel input, handwheel rate, pitch, and yaw rate were noted. Longitudinal and lateral accelerations were also recorded. Incidences of wheel lockup and ABS activation were also noted for each subject. These measures provided a comprehensive quantitative description of drivers' actions during the crash avoidance maneuver.

PROCEDURE

Intersection Incursion Scenario Implementation

A course composed of a two-lane road was created on the Vehicle Dynamics Area (VDA) at the Transportation Research Center Inc. (TRC) in East Liberty, Ohio. The VDA is an 1800 foot x 1200 foot, 50 acre flat asphalt surface. This surface allowed sufficient space to lay out the simulated intersections without concern that the test vehicle could unintentionally maneuver onto a surface with a different coefficient of friction or leave the paved test surface entirely. The "figure eight" course on TRC's VDA was taken to simulate a rural two-lane highway with lanes 12 feet in width. The full figure eight course was used in the dry pavement testing. For the wet pavement testing, only half of this course was utilized resulting in a small oval course.

An intersection was created on each course by applying reflective pavement marking tape to define the details of the crossing perpendicular roadway and the remaining intersection layout details according to Ohio Department of Transportation Office of Traffic Engineering specifications appropriate for the type of roadway being simulated. To enhance the realism of the intersection, stop lines and collapsible stop signs were used. Vinyl pylons were placed 6 feet from the outer lane lines to indicate where an unpaved off-road surface might begin.

Two vehicles were positioned at the intersection at the stop lines of the crossing lane, a blue 1995 Dodge Neon coupe on the right and a silver 1992 Saturn SC1 on the left. To examine subjects' behavior in response to an unexpected intersection incursion, the car at the right-side crossing lane was to be projected 6 feet into the subject's lane of travel. The decision to use only a right-side partial incursion scenario, rather than both full and partial incursions from the left and right sides, was made based on the results of a previous IDS study [6] and to minimize test cost.

For safety reasons, the actual vehicles were replaced with realistic artificial vehicles constructed of polystyrene foam prior to the presentation of the incursion scenario. Images of the actual vehicles were silk-screened to the foam and cut out to match the profile of the car. To enable these simulated vehicles to stand upright, small trusses also constructed of foam were used.

No provision for longitudinal motion was required for the vehicle on the left side of the intersection since it was not involved in the incursion. To secure this stationary simulated vehicle, two hinges were attached to its wheels and the VDA. This design allowed it to rest on its printed face and be swung up to its vertical position with ease.

The vehicle on the right side of the intersection was required to allow longitudinal motion in order for it to be moved into the intersection. To reduce friction between this movable simulated vehicle and the road surface, Delrin skid plates were used between the foam and the pavement to allow smooth movement of the simulated vehicle.

Projection of the simulated incursion vehicle (vehicle B) into the intersection was accomplished by attaching a thin cable from the front of the simulated incursion vehicle to the rear of a tow vehicle. The tow vehicle was located far enough from the intersection to prevent it from attracting subjects' attention. The simulated vehicle was equipped with eye screws on the bottom of the trusses which could be hooked to two cables anchored to the surface of the VDA. When the subject vehicle drove over a pressure-sensitive tape switch positioned at an appropriate distance from the intersection to create the 2.5 or 3.0 second TTI, a display near the tow vehicle was illuminated, alerting its driver to pull the foam car into the intersection. When the tow vehicle was driven forward, the simulated vehicle was towed into the intersection to the specified degree by sliding along the cables until it reached stops attached to the cables. The foam car was towed 6 feet into the subject vehicle's lane of travel to yield a partial incursion as shown in Figure 2.

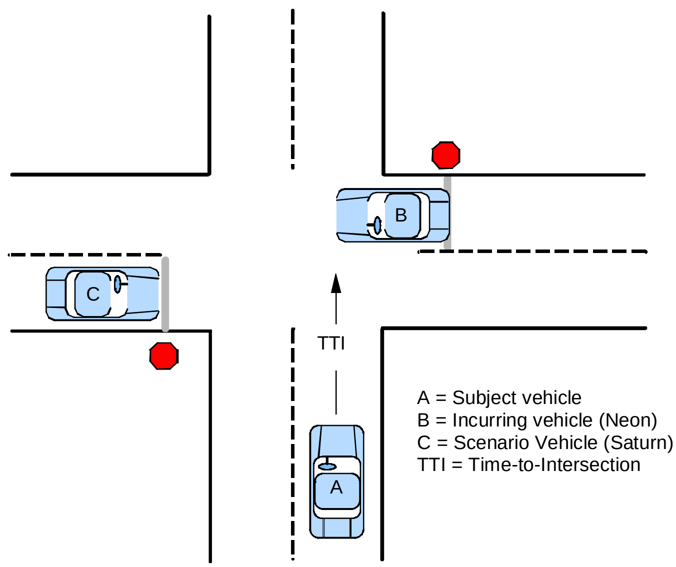

Figure 2. Illustration of final resting position of incursion vehicle.

Ruse

In order to obtain realistic, unbiased driver responses to the crash imminent scenario presented it was imperative to ensure that subjects would not perceive that the true purpose of the study was related to driver behavior in a crash avoidance situation or brake system issues. Experimenters created a ruse to prevent subjects from anticipating that they would be involved in this crash avoidance exercise. Subjects were told that they were participating in a study of driver behavior in which data would be collected to assess how average drivers steer and maintain speed while driving in typical driving conditions. A high technology device, described below, was also introduced for their use part-way into the test to occupy their attention. Subjects were told that their task was to drive normally and that they would be given a questionnaire to collect information regarding their impressions of the drive and use of the high technology device.

To help ensure that subjects would not anticipate the intersection incursion event, subjects were informed they would be driving for approximately 30 minutes. In actuality, the drive was approximately 15 minutes in length.

Test Procedure

When subjects arrived for testing, they were provided with information regarding test procedures and were required to sign an informed consent form. Before beginning the test, some subjects received ABS instruction consisting of a video tape highlighting the function, behavior, and use of an antilock brake system. This video also contained segments addressing seat belt usage and air bag function in an effort to disguise the focus of the study. Providing comparable video instruction for the conventional brake condition was desired to prevent confounding of the data, however, no instruction was found to be readily available for this purpose.

Upon entering the test vehicle, subjects were required to listen to audio instructions which were recorded on a compact disc (CD) which was played by the experimenter. An initial track was played to describe the overall test. Later, other separate CD tracks were played throughout the test to describe braking practice procedures (if applicable) and the use of a high technology device which was used as a distractor task.

Before starting on the test route, some subjects participating in the dry test track study received braking practice consisting of 3 brake stops on a wet Jennite-paved surface. Although the effect of practice with ABS on success in avoiding a crash was of primary interest, braking practice was provided to a portion of subjects in each brake condition in order to prevent confounding of data by giving those driving ABS-equipped test vehicles more familiarity with the vehicle before experiencing the incursion scenario. This practice gave subjects driving an ABS-equipped vehicle the opportunity to experience the brake pedal feedback present in current ABS.

At all times when a subject was in the test vehicle, an experimenter was present in the back seat to direct them through the test route. Subjects were instructed by the experimenter to drive on the specified course. A "lead" vehicle operated by a professional driver was scripted to drive by on the course in front of the subject vehicle at the precise moment that the subject was ready to start onto the course. As the lead vehicle passed, the subject was told, "There's another subject in the study just like you; please turn onto the course behind them and begin your drive." The purpose of this vehicle was to help encourage subjects to believe that if the lead vehicle made it through the intersection without incident that the subject vehicle would do the same. In addition, this lead vehicle encouraged subjects to maintain the specified speed limit.

Each subject completed 3.5 laps of the course. After the first lap, subjects were instructed to begin using a high technology "Laser Rangefinder" device which was installed on the test vehicle. This device consisted of a laser mounted in the grill of the test vehicle which detected the distance to a forward vehicle. A display was mounted at the center of the dashboard which related the distance information. Subjects were told to use the information provided by the display in order to maintain a distance of 200 feet from the forward vehicle which was traveling at the specified speed limit for that study. Use of the system provided a distraction for subjects, helped to prevent them from realizing the true aim of the test, and also helped them maintain the desired travel speed.

As the lead and subject vehicles passed through the intersection the first two times, the actual scenario vehicles were positioned at the intersection. Between the second and third laps, drivers entered the two vehicles when the subject vehicle was out of sight so that on the third lap, the subject could see drivers in the scenario vehicles. Between the third and fourth laps, the artificial vehicles were set in place. The driver of the silver Saturn exited the car, lifted the Saturn likeness into place, and latched it to the VDA. At the same time the driver and back seat occupant of the Neon quickly exited their car and attached the simulated incursion vehicle to its cables. The real scenario vehicles were then removed to a remote location out of view of the subject. When the subject passed over the tape switch on the fourth lap, the simulated vehicle was towed into the lane and stopped with the front of the vehicle 6 feet into the subject's lane of travel. Following this event the experiment ended.

RESULTS

Crash Avoidance Strategy - Overall

In the wet pavement study, 98 percent of the 53 subjects attempted both steering and braking inputs during the avoidance attempt. Of the 98 percent that braked and steered, 46 percent applied the brakes before steering, as their initial response, while 52 percent steered before braking. A summary of these results are presented in Table 1.

In the dry pavement study, 94 percent of the192 subjects attempted both steering and braking inputs in an effort to avoid colliding with the incursion vehicle. Of this 94%, 47 percent applied the brakes before steering, as their initial response, while 46 percent steered before braking.

Driver Input	Dry	Wet
Braked and steered	94	98
- Braked then steered	47	46
- Steered then braked	46	52
Braked only	6	2
Steered only	0	0

Table 1. Percent of subjects who braked and/or steered during the intersection incursion scenario.

For the initial steering maneuver (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), 63 percent of the 192 subjects chose to steer left and 31 percent chose to steer right (12 subjects did not steer) in the dry pavement study. In the wet pavement study, 68 percent of the 53 subjects chose to steer left and 30 percent chose to steer right (one subject did not steer).

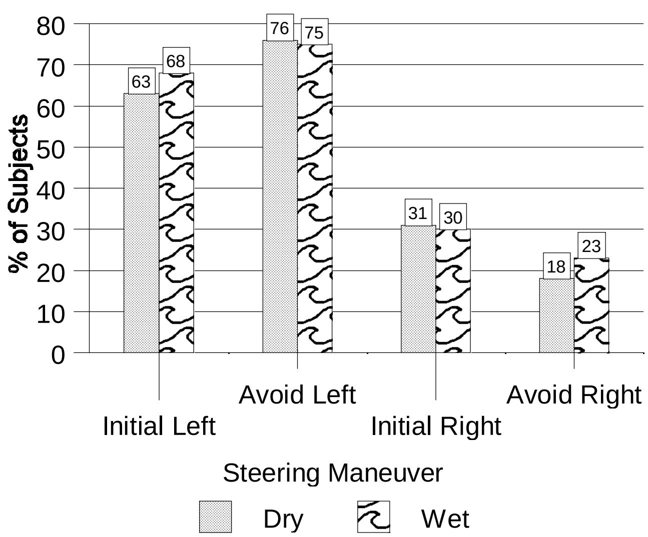

Figure 3. Steering response directions during incursion scenario.

An "avoidance steering input" was defined as the steering input which the subject intended to cause the subject vehicle to travel around the foam vehicle without colliding with it; i.e., the steering input which was in progress as the subject vehicle passed through the plane of motion of the incursion vehicle. Differentiating between initial steering input and avoidance steering input provides some information regarding how many subjects changed the direction of their steering input while trying to avoid a crash with the incursion vehicle (see Figure 3). Seventy-six percent of the 192 subjects chose to try to steer left of the encroaching vehicle and 18 percent made the decision to steer right as an avoidance steering input on dry pavement. For the wet pavement study, 75 percent of the 53 subjects chose to try to steer left of the encroaching vehicle and 23 percent made the decision to steer right to avoid a collision. In the dry pavement study, 36 percent of those whose avoidance steering input was toward the left crashed, while 47 percent who steered right crashed (8 of 12 subjects crashed who did not steer at all). In the wet pavement study, 70 percent of the subjects who steered left in their avoidance steering input crashed, while 75 percent who steered right crashed. The wet pavement study subject who did not steer also crashed.

Steering Behavior - Overall

The average magnitude of avoidance steering input observed was 53 degrees for the dry pavement study and 74 degrees for the wet pavement study. The highest observed steering input from an individual subject during the avoidance maneuver in the dry pavement study was 271 degrees, while for the wet pavement study, this value was 289 degrees.

The average maximum steering rate obtained during the avoidance maneuver was 262 degrees per second for the dry pavement study and 294 degrees per second for the wet pavement study. The highest observed steering rate achieved by a subject in the dry pavement study was 1159 degrees per second, and was 1335 degrees per second in the wet pavement study. Ninety-five percent of steering rates observed were less than 600 degrees per second in the dry pavement study and less than 643 degrees per second in the wet pavement study.

Braking Behavior - Overall

The overall average maximum brake pedal forces obtained were 64 pounds and 68 pounds for the dry and wet pavement studies, respectively. The highest observed brake pedal force input generated by a subject in the dry pavement study was 188 pounds. In the wet pavement study, the highest observed brake pedal force input generated by a subject was 240 pounds.

On dry pavement, 31 percent of the 192 subjects either activated ABS or locked the vehicle's wheels with conventional brakes during the avoidance maneuver. In the wet pavement study, 96 percent of the 53 subjects either activated ABS or locked the vehicle's wheels with conventional brakes during the avoidance maneuver.

Road Departures - Overall

In the dry pavement study, two people out of 192 fully departed the roadway during the collision avoidance maneuver. One subject steered left around the front of the encroaching vehicle and ran off the road to the left. The other subject departed the road to the right after hitting the rear of the incursion vehicle. No four-wheel road departures were seen in the wet pavement study.

Crashes - Overall

During the intersection incursion event, 40 percent of the 192 subjects collided with the incursion vehicle on dry pavement and 72 percent of the 53 subjects crashed on wet pavement.

BRAKE SYSTEM: ABS VS. CONVENTIONAL

Crash Avoidance Strategy by Brake System

For those subjects who braked then steered during the crash avoidance maneuver, the delay time from when they initiated braking to when they began to steer did not differ significantly by brake system. Subjects in the conventional brake system condition waited 0.5 seconds after braking before they initiated steering, while those with ABS waited 0.55 seconds.

Steering Behavior by Brake System

On dry pavement, the average magnitudes of the avoidance steering input was 49 degrees for those with ABS and 61 degrees for those driving a vehicle equipped with a conventional brake system, as shown in Table 2 and Figure 4. However, this difference was not significant [p = 0.4535]. On wet pavement, the average magnitude of the avoidance steering input was significantly different [p = 0.0095] with ABS subjects having inputs averaging 61 degrees and conventional brake system subjects at 103 degrees.

As shown in Table 2 and Figure 5, on dry pavement, the average maximum steering rate of the avoidance maneuver was 246 degrees per second for ABS subjects and 296 degrees per second for the conventional brake system case [p = 0.5701]. In the wet pavement study, the average maximum steering rate of the avoidance maneuver for ABS subjects was 313 degrees per second, while for the conventional group this value was 255 degrees per second [p = 0.8649].

Table 2 also lists results for the time from initiation of incursion motion until subjects applied their largest steering input. In the wet pavement study, for subjects in the ABS condition, the time to maximum steering input was significantly less [p = 0.0003], 2.39 seconds, than that observed for conventional brakes (3.37 seconds). On dry pavement, the time to maximum steering input for the ABS subjects was quite similar to the conventional brake subjects, at 2.73 seconds and 2.70 seconds, respectively.

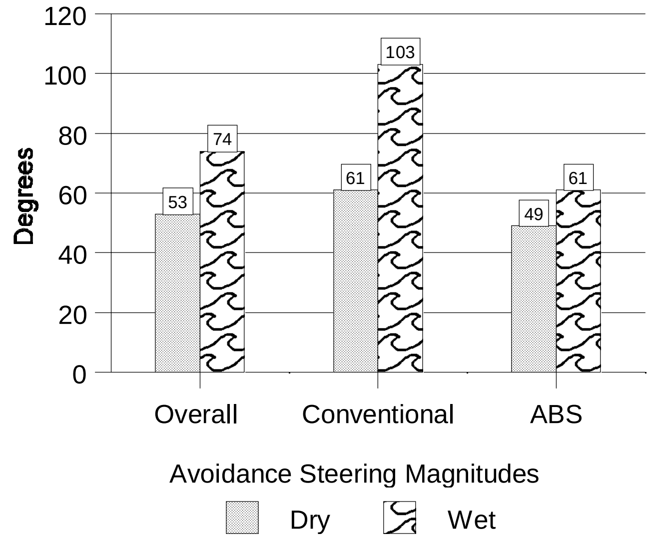

Figure 4. Magnitude of avoidance steering inputs.

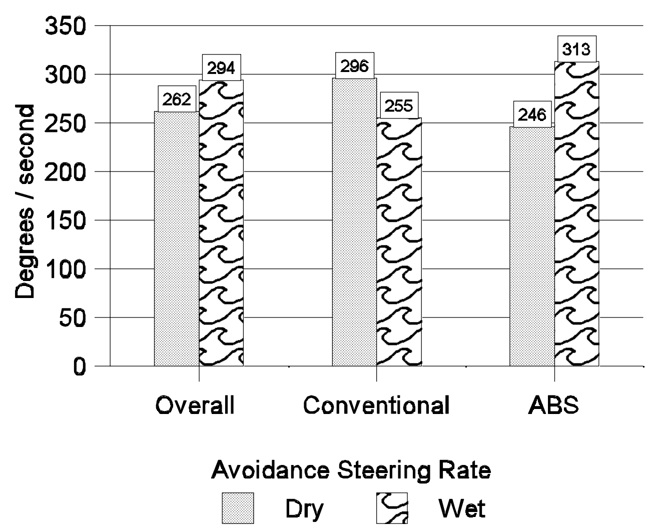

Figure 5. Avoidance steering rates.

Steering Input Characteristics	Brake System	Dry	Wet
Average magnitude of steering input (degrees)	Conventional	61	103*
	ABS	49	61*
Average maximum steering input rate (degrees per second)	Conventional	296	255
	ABS	246	313
Time to maximum steering input (seconds)	Conventional	2.70	3.37*
	ABS	2.73	2.39*

Table 2. Characteristics of observed steering behavior by brake system and pavement condition. (* These values are statistically significantly different.)

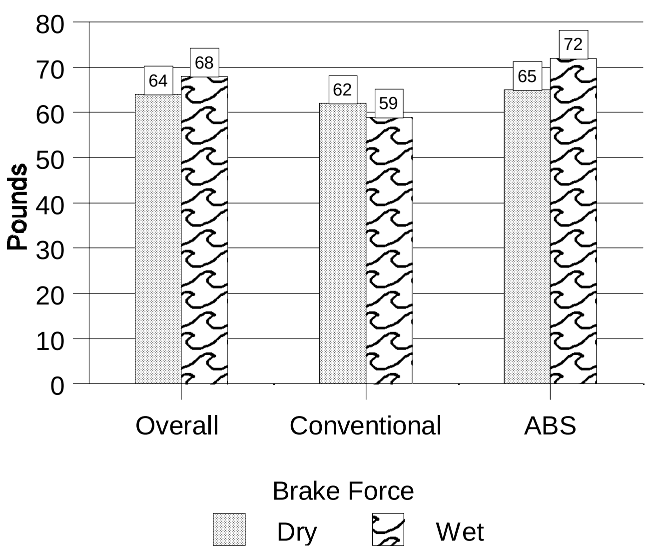

Figure 6. Brake pedal forces.

Braking Behavior by Brake System

As shown in Figure 6, the average maximum brake pedal force observed for subjects in the dry pavement study ABS condition during the avoidance maneuver was 65 pounds. For dry pavement subjects in the conventional brake system case, the average was similar at 62 pounds. This difference was not statistically significant [p = 0.8852]. The wet pavement study did not have significant differences either [p = 0.4730], with ABS at 72 pounds and conventional at 59 pounds.

One might expect that observed brake pedal application durations should be longer for ABS if drivers were using the ABS properly, i.e., maintaining pressure on the brake pedal and not "pumping" the pedal. The average brake pedal application duration observed during the crash avoidance maneuver in the dry pavement study was in fact longer for ABS (2.20 seconds) than for conventional (1.99 seconds); however, this difference was not statistically significant. In the wet pavement study, the opposite result was found. The brake pedal application duration for ABS (2.08 seconds) was shorter than for conventional (3.23 seconds) [p = 0.0864](see Table 3).

Based on a cursory examination of the video recordings of each subject's experience of the intersection incursion scenario from both the dry and wet pavement experiments, no evidence was observed of subjects either pulling their foot off of the brake pedal due to being startled by ABS pedal feedback or attempting to "pump" the brake pedal with ABS.

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. This was true in the dry pavement study. Subjects receiving ABS instruction had an average brake pedal application duration (2.56 seconds) which was significantly longer than for those with ABS who received no instruction (1.91 seconds) [p = 0.0220]. However, in the wet pavement study, subjects receiving ABS instruction had an average brake pedal application duration (2.09 seconds) which was similar to those with ABS who received no instruction (2.06 seconds).

Braking Input Characteristics	Brake System	Dry	Wet
Average maximum brake pedal force (pounds)	Conventional	62	59
	ABS	65	72
Brake pedal application duration (seconds)	Conventional	1.99	3.23
	ABS	2.20	2.08
	ABS (no instruction)	1.91*	2.06
	ABS (instruction)	2.56*	2.09

Table 3. Characteristics of observed braking behavior by brake system and pavement condition. (* These values are statistically significantly different.)

Road Departures by Brake System

In the dry pavement study, 2 subjects out of 192 drove completely off the road (all four wheels) during the avoidance maneuver. Both of these subjects who experienced road departures were in the ABS condition (of 128 subjects) and both activated ABS during their crash avoidance maneuver. None of the 64 subjects who had conventional brakes drove completely off the road during the avoidance maneuver. In the wet pavement study, no one drove completely off the road.

In addition, two partial (two-wheel) road departures were also observed in the dry pavement study. One of the cases involved a subject driving with ABS while the other involved conventional brakes. In the wet pavement study, only one subject had one wheel which crossed over the edge line. That subject was driving with conventional brakes.

Crashes by Brake System

Table 4 summarizes results for subjects ability to avoid a crash according to brake system and pavement condition, as measured by number of crashes. In the dry pavement study, fewer subjects crashed into the encroaching vehicle in the ABS condition (38 percent of 128), than in the conventional brake system condition (45 percent of 64). However, this difference was not statistically significant. In the wet pavement study, 100 percent of the 17 subjects in the conventional brake system condition crashed into the encroaching vehicle and only 58 percent of the 36 subjects in the ABS condition crashed. This difference was statistically significant [p = 0.0020].

Brake System	Dry	Wet
Conventional	45	100*
ABS	38	58*
ABS (light brake pedal feedback)	33	72
ABS (heavy brake pedal feedback)	42	44

Table 4. Percent of subjects who crashed in to the incursion vehicle as a function of brake system and pavement condition. (* These values are statistically significantly different.)

ABS BRAKE PEDAL FEEDBACK

Steering Behavior by ABS Brake Pedal Feedback

In the dry pavement study, the average avoidance steering input magnitude observed was 49 degrees for ABS subjects in both the light and heavy ABS brake pedal feedback conditions. On wet pavement, the average magnitude of the avoidance steering input was 58 degrees for ABS subjects in the light feedback condition and 64 degrees for the heavy ABS brake pedal feedback condition (see Figure 7).

On dry pavement, the average maximum steering rate observed during the avoidance maneuver for both light and heavy ABS brake pedal feedback conditions was 246 degrees per second, as shown in Figure 8. In the wet pavement study, the average maximum steering rate was 362 degrees per second for the light feedback condition and only 264 degrees per second for the heavy feedback condition.

Braking Behavior by ABS Brake Pedal Feedback

In the dry pavement study, subjects in the light feedback condition had an average maximum brake pedal force, during the avoidance maneuver, of 64 pounds. The average was similar at 65 pounds for the heavy feedback subjects. In the wet pavement study however, the light feedback subjects had an average maximum pedal force of 81 pounds and the heavy feedback subjects averaged lower maximums at 63 pounds of brake pedal force (see Figure 9).

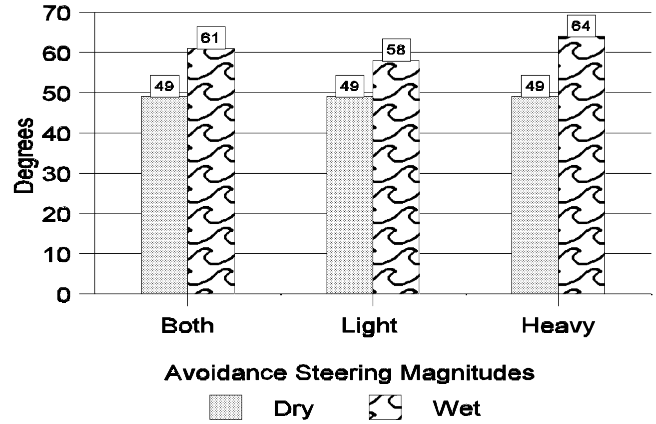

Figure 7. Magnitude of avoidance steering inputs by brake pedal feedback.

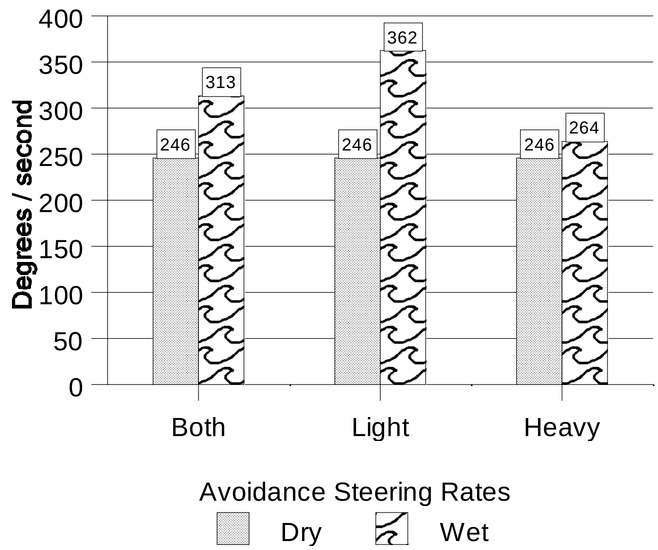

Figure 8. Avoidance steering rates by brake pedal feedback.

Road Departures by ABS Brake Pedal Feedback

As stated earlier, two vehicles departed the roadway fully in the dry pavement study. Both of these road departures involved the heavy brake pedal feedback ABS condition of 64 subjects. In addition, two partial (two-wheel) road departures were observed, one with ABS and one conventional. Each of these cases occurred in the same vehicle (the heavy brake pedal feedback vehicle). In the wet pavement study, no road departures occurred.

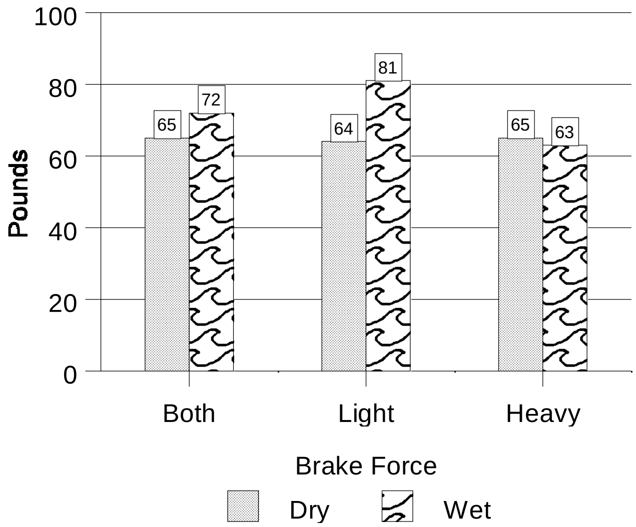

Figure 9. Brake forces by brake pedal feedback.

Crashes by ABS Brake Pedal Feedback

As shown in Table 4, 33 percent of the 64 subjects collided with the incursion vehicle on dry pavement while driving the light feedback vehicle with ABS. In the heavy feedback ABS vehicle, 42 percent of those 64 subjects crashed on dry pavement.

On wet pavement, 72 percent of the 18 subjects driving the light feedback ABS vehicle crashed, whereas 44 percent of the 18 subjects in the heavy feedback ABS condition crashed on wet pavement. However, this 28 percent difference in the crash rates was not statistically significant.

GENDER

Gender was balanced throughout all conditions in this study. Overall, crash avoidance behavior observed for male subjects was characterized by inputs of higher magnitudes than females. However, most of the differences observed between genders were not statistically significant.

Steering Behavior by Gender

Table 5 and Figure 10 show the average magnitudes of the avoidance steering input for females in the dry pavement study was 45 degrees and for males was 59 degrees. The average magnitude of the avoidance steering input for females in the wet pavement study was 72 degrees and for males was 77 degrees (see Figure 11). These differences between genders were not statistically significant.

The average maximum steering rate in any direction for females in the dry pavement study was 213 degrees per second, as listed in Table 5. For males, the average maximum steering rate observed on dry pavement was 306 degrees per second. The average maximum steering rate in any direction for females in the wet pavement study was 269 degrees per second. For males, the average maximum steering rate observed on wet pavement was 321 degrees per second.

Steering Input Characteristics	Gender	Dry	Wet
Average magnitude of avoidance steering input (degrees)	Female	45	72
	Male	59	77
Average maximum steering input rate (degrees per second)	Female	213	269
	Male	306	321

Table 5. Characteristics of observed steering behavior by gender.

Braking Behavior by Gender

Table 6 summarizes braking behavior observed during the incursion scenario as a function of gender. The average maximum brake pedal force was 61 pounds for females and 66 pounds for males in the dry pavement study. The average maximum brake pedal force was 62 pounds for females and 74 pounds for males in the wet pavement study. On dry pavement, females first applied the brake as a reaction to the incursion vehicle at 1.51 seconds and males at 1.48 seconds on average. In the wet pavement study, females first applied the brake as a reaction to the incursion vehicle at 1.37 seconds and males at 1.47 seconds on average. These differences were not statistically significant.

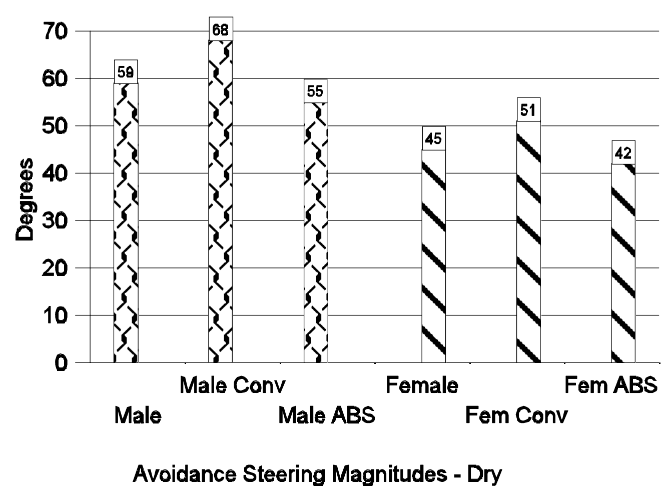

Figure 10. Magnitude of the avoidance steering input by gender and brake system - dry study.

Braking Input Characteristics	Gender	Dry	Wet
Average maximum brake pedal force (pounds)	Female	61	62
	Male	66	74
Brake reaction time (seconds)	Female	1.51	1.37
	Male	1.48	1.47

Table 6. Characteristics of observed braking behavior by gender and pavement condition.

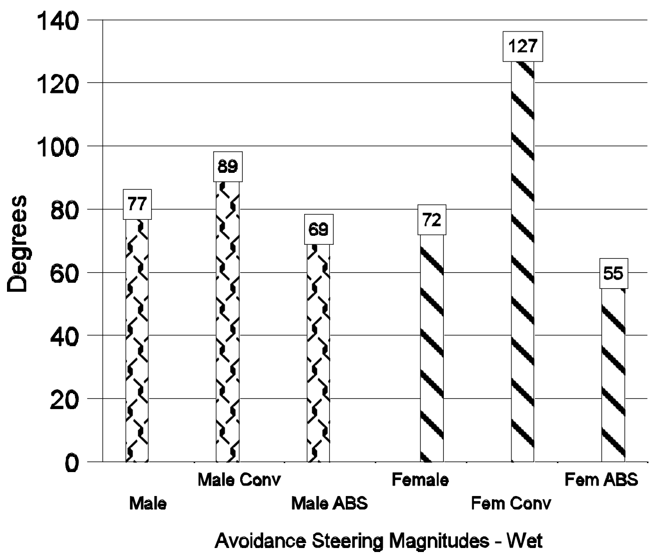

Figure 11. Magnitude of the avoidance steering input by gender and brake system - wet study.

Road Departures by Gender

Of the two subjects in the dry pavement study who drove completely off the road to avoid a crash, the subject who departed the road to the right was a male, while the subject who departed the road to the left was a female. Of the two partial, two-wheel road departures observed in these studies, both occurred in the dry pavement study as well. The right side partial road departure was made by a male subject and the left side departure was made by a female.

Crashes by Gender

On dry pavement, 40 percent of 88 females (40% ABS, 39% conventional) collided with the incursion vehicle. Forty percent of 104 males (35% ABS, 50% conventional) also crashed in this study (see Figure 12).

In the wet pavement study, 67 percent of 27 females (55% ABS, 100% conventional) collided with the incursion vehicle while 77 percent of 26 males (63% ABS, 100% conventional) also crashed (see Figure 13).

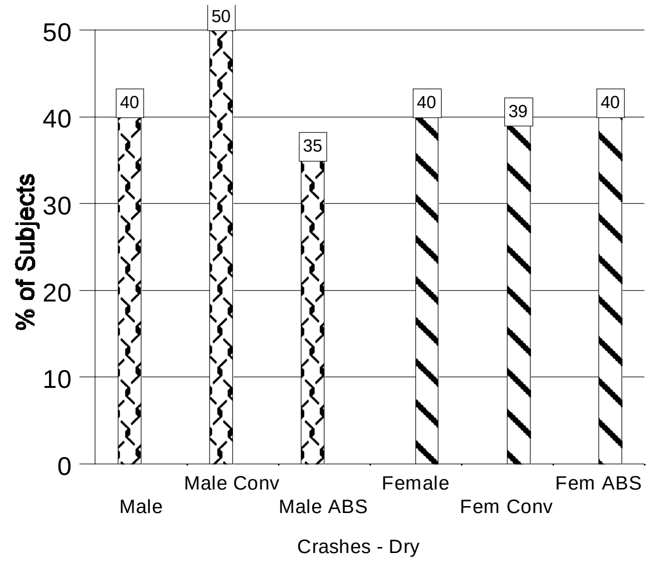

Figure 12. Crashes by gender and brake system - dry pavement study.

DISCUSSION

Do drivers tend to both brake and steer in crash-imminent situations

Nearly all subjects in these studies both braked and steered in an attempt to avoid colliding with the incursion vehicle. For subjects that both braked and steered in an attempt to avoid a collision, the likelihood of whether they braked or steered first was approximately equal for both pavement conditions.

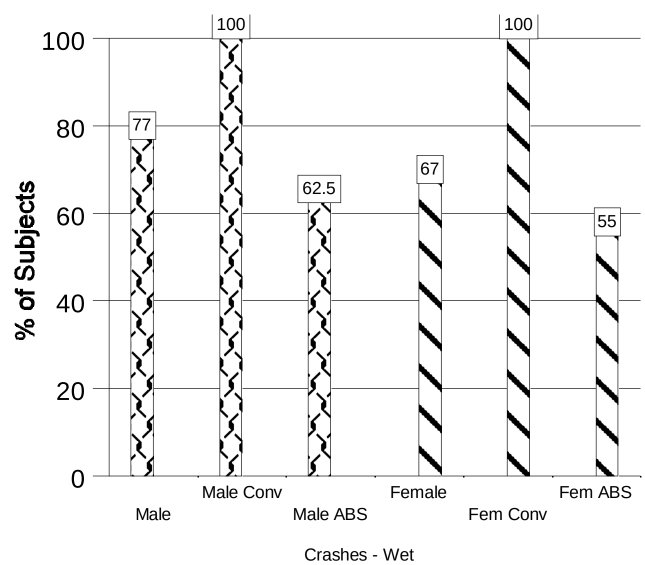

Figure 13. Crashes by gender and brake system - wet study.

Do people exhibit excessive steering behavior during crash avoidance maneuvers?

In general, steering inputs exhibited by subjects in these test track studies were smaller and slower than those observed in the related IDS study [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. However, the observed magnitudes and rates of steering inputs for these test track studies were still relatively large. As noted in the related IDS study [8], 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 steering input 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 have more road departures in ABS-equipped vehicles than in conventionally brakes vehicles?

Overall, results from this research indicate that, although subjects were observed making steering inputs characterized by large magnitudes and high rates, these aggressive steering inputs did not result in a significant number of road departures. In addition, ABS was not associated with significantly higher frequencies of road departures in these studies than were observed in the conventional brake system conditions.

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

On wet pavement, ABS was associated with significantly fewer crashes than conventional brakes. Although fewer subjects crashed with ABS than with conventional brakes on dry pavement, this difference was not significant.

Also on wet pavement, 28 percent fewer crashes were observed with ABS with heavy brake pedal feedback than with light feedback ABS, however, this result was not statistically significant. On dry pavement, more subjects crashed in the heavy ABS feedback condition than in the light feedback ABS condition but not at a significant level. Thus, based on these findings as well as the fact that no subject was observed pulling their foot off of the brake pedal due to being startled by haptic feedback, it is not immediately clear what level of ABS-related brake pedal feedback is most beneficial, appropriate, or lends to fewer crashes.

Overall, ABS was not associated with a significantly greater number of crashes than conventional brakes for any factor discussed in this paper.

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 (conventional, ABS) and pavement condition (dry, wet). Subjects in these studies demonstrated 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 nor driver interaction with ABS. ABS was associated with significantly fewer crashes on wet pavement as compared to conventional brakes.

In conclusion, the results of this study do not appear to indicate that a problem exists due to driver crash avoidance behavior or driver interaction with ABS which would contribute to the apparent increase in fatal single-vehicle crashes as 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 of the increase in fatal single-vehicle crashes observed in conjunction with the implementation of ABS.

ACKNOWLEDGMENTS

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CONTACT

Additional information regarding this research can be obtained by contacting Elizabeth Mazzae, NHTSA Vehicle Research and Test Center, 10820 SR 347, East Liberty, Ohio, 43319 or by e-mail at emazzae@nhtsa.dot.gov.

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ADDITIONAL SOURCES

Additional information regarding this work performed under NHTSA's Light Vehicle ABS Research Program can be found in an upcoming NHTSA report. Status updates on the progress of the research program are provided on the internet at the following web site address: www-nrd.nhtsa.dot.gov/vrtc/ca/lvabs.htm.