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NHTSA Light Vehicle Antilock Brake Systems Research Program Task 5, Part 1:

Examination of Drivers' Collision Avoidance Behavior
Using Conventional and Antilock Brake Systems
on the Iowa Driving Simulator

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16. 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 single-vehicle run-off-road crashes and decrease in multi-vehicle on-road crashes as vehicles 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 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. Drivers in the ABS group showed significantly increased stability and control relative to conventional brakes.

17. Key Words

Antilock Brake Systems, ABS, Crash Avoidance, Driver Behavior, Passenger Vehicles

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TECHNICAL SUMMARY

The National Highway Traffic Safety Administration (NHTSA) developed its Light Vehicle Antilock Brake Systems (ABS) Research Program in an effort to determine the cause(s) of the apparent increase in single-vehicle run-off-road crashes and decrease in multi-vehicle on-road crashes as vehicles 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. Investigation of the hypothesized phenomenon of driver "oversteering" in obstacle avoidance scenarios was a major focus of this study.

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. In this study, 120 subjects drove a simulated route for about 10 minutes until they reached an intersection where they experienced an incursion. Subjects' reactions in response to the crash imminent situation were recorded and analyzed.

This study found that drivers do tend to brake and steer in realistic crash avoidance situations. All 120 subjects in this study both braked and steered in an effort to avoid crashing with the encroaching vehicle. Some excessive steering was observed in this study. However, a significant number of road departures did not result from this behavior with either conventional brakes or ABS. Ninety-five subjects (79 percent) applied the brakes as their initial response before steering. Five subjects (4 percent) initiated braking and steering inputs simultaneously as an initial response. Twenty subjects (17 percent) steered before applying the brakes. The results of this study indicate that for simulated intersection incursions, over-steering or other behaviors that cause a loss of control and/or rollover effects did not show a significant effect with vehicles equipped with ABS.

Evidence of inappropriate use of ABS was not seen in this study. Providing video-based instruction regarding the function and proper use of ABS was not found to be effective in reducing crashes in this experiment.

While no significant differences were found for any of the speed-related variables, individual strategies were quantified. For instance, almost all subjects tended to brake first and steer later when attempting to avoid colliding with the crossing vehicle. Speed limit did not have a significant main effect on any of the steering or braking variables. However, as the slower speed of 45 mph did show a 22 percent ABS crash rate relative to a 40 percent conventional brake crash rate, this result would likely be significant if the number of subjects in the conventional brake conditions matched the ABS condition (80 subjects were in ABS and 40 in conventional). The difference, if significant, would likely be due to the increased stability and control of ABS.

The results of this study show overwhelmingly that ABS-equipped vehicles have increased stability and control in simulated intersection incursions. Overall, drivers in the ABS group showed significantly increased stability and control relative to conventional brakes.

1.0 INTRODUCTION

Antilock brake systems (ABS) have been introduced on many passenger car and light truck make/models in recent years. In general, ABS appear to be very promising safety devices when evaluated on a test track. Under many pavement conditions, antilock brake systems allow a driver to stop a vehicle more rapidly and to maintain 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 performed in recent years by NHTSA, automotive manufacturers, and others indicate that the introduction of ABS has not reduced the number of crashes as expected.

1.1 NHTSA'S LIGHT VEHICLE ABS RESEARCH PROGRAM

In an effort to investigate possible causes of the crash-rate phenomenon, NHTSA developed its Light Vehicle ABS Research Program. 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. It is unknown, however, to what extent the increase in run-off-road crashes may be due to drivers' incorrect use of ABS or incorrect responses to ABS activation, to incorrect instinctive driver response (e.g., over-steering), or to changes in driver behavior (e.g., behavioral adaptation) as a result of ABS use or some other factor.

1.2 HUMAN FACTORS STUDIES OF DRIVER CRASH AVOIDANCE BEHAVIOR

To determine whether some aspect of driver behavior may be counteracting the potential benefits of ABS in a crash-imminent situation, NHTSA embarked on a series of human factors studies. Three of these studies, which compose Task 5 of the research program, focus on the examination of driver crash avoidance behavior as a function of a vehicle's 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 was 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 and rendering a driver's steering behavior irrelevant.

With four-wheel ABS the vehicle's wheels do not lock; as a result, the vehicle does not lose directional control capability during hard braking, and the driver's steering inputs continue to be effective in directing the vehicle's motion. Such directional control could mean that drivers can potentially avoid multi-vehicle crashes by driving off the road, thereby experiencing more 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.
- 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 includes three studies. Two 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). This report describes the results of the Iowa Driving Simulator experiments.

These studies used a right-side intersection-incursion scenario to elicit a crash-avoidance response from drivers. This scenario was chosen as one likely to induce emergency steering and braking behavior; however, since such circumstances are obviously not responsible for all run-off-road crashes, the 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 to avoid a collision can also be gained from this research.

The same scenario was involved in each of these experiments. The test track experiments allowed for examination of driver behavior in a realistic environment at moderate speeds in real vehicles with simulated obstacles on both dry and wet pavement. In the IDS study, driver behavior could 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 report discusses the method and results of the study conducted on the Iowa Driving Simulator.

1.3 IOWA DRIVING SIMULATOR STUDY

Driver behavior in emergency avoidance situations must be thoroughly studied to assess the causes of the apparent shortcomings of ABS. Both epidemiological and experimentally controlled studies have examined driver behavior in emergency situations. The literature shows that drivers in emergency situations resist lateral avoidance movements and prefer to brake, often locking the brakes (Lechner and Malaterre, 1991). One study found that when a lateral movement was attempted, the driver "reacted too late, or too violently, or tried to combine braking with a sideways avoidance movement, which often resulted in loss of control" (Ferrandez, Fleury, and Lepesant, 1984). If drivers often lock the brakes and steer too violently, it may be that the increased lateral control of antilock brakes increases lateral skidding, roadway departures, and subsequent rollovers.

To fill in some gaps in the literature and to better understand driver emergency avoidance behavior, time to that behavior, and magnitude of that behavior, a scenario was simulated. The scenario required an emergency maneuver to avoid colliding with another vehicle crossing the intersection on a perpendicular path. It was hoped that this scenario could be used to determine the following:

- Could over-steering or some other driver avoidance behavior account for the increase in ABS-associated rollover crashes?
- How does the stability and control of either ABS or non-ABS contribute to the control of the vehicle during crash avoidance circumstances?
- How does ABS instruction affect driver performance?
- What behaviors are associated with emergency avoidance in an intersection and what are the associated reaction times to these behaviors?
- What effect does speed have on the stability and control of ABS and non-ABS equipped vehicles?

- How is driver behavior and its associated reaction time altered by an incursion from the left or right side of the driver?

2.0 LITERATURE REVIEW

2.1 MOTOR VEHICLE CRASHES

Since motor vehicle crashes have a significant impact on the health and well-being of this nation, it is important to isolate and mediate the causes of these crashes. A major step toward learning how to mediate crashes is to understand where and how they occur. Table 2–1 shows that in 1992, intersections were the second most common location for crashes. If crashes in areas immediately surrounding intersections are included, they become the most common location, accounting for 41.7 percent of all crashes in 1992. Pierowicz et al. (1994) derived these data from the General Estimate System (GES) as part of an effort to determine methods for avoiding collisions. The GES includes only police-reported crashes selected from specific areas in the United States to provide a statistical estimate of the problem's magnitude.

Crash and injury severity are often considered when determining where to invest limited resources to ameliorate a transportation-related problem. The number of associated fatalities is often used to estimate severity in considerations of injury and safety. In this case, intersection crashes are the second most common type of fatal crash, accounting for approximately 18.5 percent of motor vehicle fatalities in 1992 (Pierowicz et al., 1994). An additional 2.9 percent occurred in areas near intersections, or "intersection-related areas" (see Table 2–1).

It is clear from looking at both the magnitude and severity of the motor vehicle crash problem that the majority of fatal crashes can be attributed to non-junction-and-intersection locations. Since non-junctions comprise much more of the roadway system than intersections, it is not surprising that more fatalities occur in these areas. It is somewhat surprising that drivers are three times more likely to die in a non-junction crash than in an intersection crash. This may be due to the higher speeds associated with non-junction crashes, combined with departing the road and/or hitting fixed obstacles (e.g., barriers or trees). Although the fatality rate is higher for non-junction crashes, intersections, which comprise a relatively small portion of the roadway system, are nevertheless the site of a large proportion of crashes and fatalities.

Table 2–1. Location of Crashes

	All Crashes		Fatal Crashes	
Crash Location	Number	Percent	Number	Percent
Non-junction	2,483,183	41.4	23,689	72.0
Intersection	1,798,904	30.0	6,102	18.5
Intersection-related	701,179	11.7	939	2.9
Driveway, Alley, Access, etc.	623,247	10.4	490	1.5
Entrance/Exit Ramp	53,028	< 1	109	< 1
Rail Grade Crossing	12,225	< 1	520	1.6
Other	22,859	< 1	25	< 1
Unknown Non-interchange	150,777	2.52	7	< 1
Interchange Areas	115,642	1.93	1,004	3.1
Unknown	32,073	< 1	21	< 1
Total	5,992,937	100.0	32,906	100.0

2.2 INTERSECTION CRASHES

Because an intersection is, by its very definition, where automobiles must cross each other's path, it is a prime area for crashes to occur. In 1992, there were 2.5 million intersection or intersection-related crashes (see Table 2-1). Ninety-four percent of these crashes occurred with passenger vehicles (Pierowicz et al., 1994).

Over 90 percent of intersection crashes occurred on straight roadways (Pierowicz et al., 1994), which indicates that the added workload of negotiating a curve was not a causative factor. The majority of the crashes occurred on non-divided roadways and over 90 percent of the cases involved no visual obstruction (Pierowicz et al., 1994). It is clear from this analysis that the majority of these crashes were not caused by an obvious roadway configuration decrement, though it should be noted that further analysis might indicate that redesigning roadways could significantly reduce such crashes.

The speed limit at crossroads where crashes occurred had interesting effects on crash results. While almost a quarter of the crashes (24.49 percent) occurred in 35-mph zones, the most severe crashes occurred in 55 mph zones. Crashes occurring at an intersection with a 55 mph speed limit were seven times more likely to involve fatalities than any other speed limit category (Pierowicz et al., 1994). There is no doubt that higher speeds lead to more serious injuries.

However, even at 45 mph, a speed limit only 10 mph slower, more crashes were substantially less severe.

Intersection crashes can be categorized into several types by evaluating the behavior or intended behavior of the driver who crossed the path of the vehicle with the right-of-way. For the remainder of this discussion, the driver with the right-of-way will be referred to as the primary driver and the driver without the right-of-way will be designated the incursion vehicle driver. Table 2–2 further categorizes the 2.5 million crashes that occurred in 1992 using this classification scheme (Pierowicz et al., 1994). Considering only intersection crashes, over 80 percent could be classified as “change traffic way”, “vehicle turning” or “intersecting paths” (see Table 2–2).

Table 2–2. Further Categorization of Intersection Crashes

Secondary Vehicle Characteristic	Classification	Intersection	Intersection Related	Intersection Percent
Single Driver	Right Roadside Departure	385	18,397	< 1
	Left Roadside Departure	585	14,276	< 1
	Forward Impact	37,568	22,940	3.1
Same Traffic Way	Rear End	133,905	242,327	11.2
Same Direction	Forward Impact	279	55	< 1
	Sideswipe/Angle	22,409	24,280	1.9
Change Traffic Way	Head On	5,031	2,097	< 1
Opposite Direction	Forward Impact	376	100	< 1
	Sideswipe/Angle	5,781	4,585	< 1
Vehicle Turning	Turn into Path	256,502	17,525	21.5
Change Traffic Way	Turn Across Path	259,232	8,694	21.7
Intersecting Paths	Straight Path	446,638	1,935	37.6
Miscellaneous	Backing etc.	27,249	38,159	2.3
Total		1,195,941	395,337	100.0

Crashes classified as “intersecting paths” can be further broken down into three classifications:

- *Straight-path-intersection* takes place when the incursion vehicle driver attempts to cross the intersection on a heading perpendicular to the primary driver.
- *Turn-across-path* happens when the incursion vehicle driver attempts to travel on the same road as the primary driver but at an opposite heading by making a left turn from a perpendicular intersecting road in front of the primary driver.
- *Turn-into-path* occurs when the incursion vehicle driver turns from a perpendicular road to begin driving on the same path and heading as the primary driver.

2.3 ANTILOCK BRAKE SYSTEMS

Antilock brake systems (ABS) prevent drivers from locking the brakes by sensing when the wheels are about to lock and releasing the brakes momentarily. The system reapplies the brakes when the wheels begin to turn normally again. The goal is to modulate the brake pressure level so that the vehicle has maximum deceleration. One side effect of this modulation is that the brake pedal pulses or vibrates. Besides maximizing deceleration, ABS allows the driver to steer and move laterally with the brake pedal fully depressed. Because it was designed to help drivers avoid crashes, ABS is considered a primary safety system; because of its ability to increase deceleration and controllability, ABS has been touted as an effective crash-avoidance technology.

Most research has shown that people can avoid collisions more effectively with ABS. For example, Rompe, Schindler, and Wallrich (1987) had subjects drive a Ford Escort on a test track using both conventional brakes and antilock brakes. Subjects had to avoid unexpected projected obstacles, brake while driving in curves, and brake on roads with different adhesion values on the left and right sides. In all cases, “average drivers” performed better with ABS than with conventional brakes. Robinson and Riley (1989) showed that the crash avoidance potential was greater in four vehicles tested with ABS than in the same four models without ABS. However, this increased avoidance potential has not been turned into reduced claims or reduced property damage (Highway Loss Data Institute, 1994). Some authors believe that the lack of knowledge about ABS (e.g., Williams and Wells, 1994), lack of training (e.g., Mollenhauer, Dingus, Carney, Hankey, and Jahns, 1995), or pulsing of the pedal (e.g., Strandberg, 1991) are possible reasons the added avoidance potential has not translated into more benefit.

Other authors believe that drivers with ABS might exchange this added safety for performance. Wilde, the originator of the Risk Homeostasis Theory (1982), states that "...only those accident countermeasures that are effective in decreasing the preferred level of risk can reduce the accident loss per capita" (1988). Therefore, if a primary safety improvement is implemented that does not reduce the preferred level of risk, certain types of crashes may decrease but other crash types may increase in a compensatory fashion. For example, if drivers believe that antilock brakes significantly increase their likelihood of being able to stop and avoid a collision, they may feel more comfortable driving faster, at closer headways even under poorer road conditions. As a result, the benefit derived from the increased performance of the antilock brake system is negated by the drivers' more risky behavior.

A study done in Munich supports this theory. Taxi drivers were randomly assigned to taxis with ABS and taxis with conventional brakes. The taxi drivers were aware of whether their taxi had ABS but were unaware that some passengers were judging their driving behavior. To reduce bias, the raters judging behavior were "experimentally blinded" to which taxis had ABS. The drivers with ABS drove significantly less cautiously (Biehl, Aschenbrenner, and Wurm, 1987). If the Risk Homeostasis Theory has merit, it could be argued that time should not be wasted on technological advances such as ABS. However, it is doubtful that the Risk Homeostasis Theory alone can explain why the presence of ABS did not reduce the number of crashes.

After reviewing the literature for and against this theory, McKenna concluded there was little support for it and that it has both theoretical and methodological inconsistencies (1988). Other researchers have shown that the most effective safety measures impact behavior and not risk estimates (e.g., Howarth, 1988). The fact that ABS did not reduce the number of crashes can probably be explained by risk compensation combined with other factors (e.g., lack of information and drivers' ineffective use of the technology). If so, modifying these other factors would decrease the number of ABS crashes and increase driver safety. For a more in-depth review of the issues on Risk Homeostasis Theory and potential reasons for drivers' risky behavior, see Volume 4 of the 1988 *Ergonomics Journal*.

ABS may have reduced some types of crashes while increasing other, more costly crashes. This could have occurred independently of Risk Homeostasis Theory or risk compensation. Kullgren and Tingvall performed an analysis of collisions in Sweden (1987). They found that people with ABS were more likely to be struck than to strike another vehicle in rear-end collisions. They also found that drivers with ABS had more crashes in which the vehicle crossed the centerline to the wrong side of the road. When the stopping advantage of ABS is considered, the discrepancy in rear-end collisions is logical—it could simply be caused by ABS drivers' ability to stop faster than non-ABS drivers. The reason for the increase in single-vehicle crashes on the wrong side of the road is not as clear.

Kahane (1994) found that, for passenger cars, involvements in multi-vehicle crashes on wet roads were significantly reduced for cars equipped with ABS: fatal crashes were 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.

"An analysis of Canadian insurance data found a 9 percent reduction in claim frequency but a 10 percent increase in claim severity [Barr and Norup, 1994]" (Evans, 1995). This lends credence to the theory that ABS reduces the number of certain types of crashes while increasing other, more costly crashes. For the 1992 and 1993 calendar years, Evans (1995) performed an analysis of ABS and non-ABS crashes on seven GM passenger vehicles in Texas and Missouri. These models had ABS in 1992, but did not have ABS in 1991, so the comparison was made between these two model years. Although there was a reduction in most crash types, there was a 44 percent increase in rollover crashes (Evans, 1995), which are often more severe and costly.

Evans (1995) offered increased ability to steer during emergency braking as one possible reason for the increase in rollover crashes. This could also explain the increase in single vehicle crashes found by Kullgren and Tingvall (1987), where the vehicle crossed the center lane and the crash occurred on the wrong side of the roadway. Increased steering ability could lead to over-steering in emergency situations. In the past, drivers who "locked up" conventional brakes could not significantly increase their rollover likelihood by steering. Steering, regardless of the magnitude, had little impact on the lateral movement of the vehicle when the brakes were locked. However, aggressive steering without locked brakes can cause a rollover crash. Therefore, if drivers have a tendency to over-steer in emergency situations, it is feasible that ABS would increase the likelihood of rollover crashes, both through increased lateral acceleration and roadway departures. To determine if this theory has merit, driver behavior in emergency avoidance situations must be thoroughly understood.

2.4 EMERGENCY AVOIDANCE BEHAVIOR

Drivers are often forced to maneuver their vehicles in certain ways to avoid collisions. Many of these potential crashes require simple avoidance behaviors, such as releasing the accelerator to allow a vehicle enough time to cross an intersection. Other situations require quick reaction time and/or behavior combinations such as braking and steering to avoid a collision.

Rundkvist stated that Swedish drivers in 10.5 percent of all police-reported crashes had their wheels locked (1973). Fifty percent of the drivers attempted to steer. Unfortunately, they did not examine whether drivers who braked also steered, but it is reasonable to assume a large portion of this 10.5 percent did attempt to steer with the brakes locked. In Sweden, the police only report crashes when there is an injury. Therefore, most of these crashes were probably serious. In 168 of these police-reported accidents (analyzed further for this study), collisions at junctions were the most highly represented (Rundkvist, 1973). This further supports the use of an intersection with an encroaching vehicle to represent an emergency avoidance scenario.

Koppa and Hayes (1976) attempted to determine whether drivers use the full capability of a vehicle in emergency or extreme vehicle maneuvers. Sixty-four drivers were matched and assigned to four groups. Each group was assigned to drive a different-sized vehicle, ranging from a sub-compact to a semi-luxury model. Eight subjects in each of the groups drove in “surprise” tests where drivers avoided obstacles and performed severe maneuvers based on traffic controls. The drivers could experience any, none, or all of the following situations in a given run:

- ***Sudden obstacle.*** A pylon suddenly appears in the subject vehicle’s path at different distances from the vehicle.
- ***Late decision at a freeway exit.*** A “pop-up” sign indicates the subject should exit left or right on a constant radius turn; the sign could also “pop up” blank.
- ***Late decision at an intersection.*** A “pop-up” sign indicates an upcoming 90-degree left or right turn (e.g., as if a driver came upon an unexpected T intersection and had to maneuver left or right).
- ***Blind corner.*** Once the subject is on the curve an obstacle appears in the vehicle’s path.
- ***Sudden lane change.*** The driver’s lane branches into one of three adjacent lanes with traffic signals over each lane set to amber. As the subject approaches, any or all of the lights could turn green. Lights that were not turned green were turned red. Subjects were instructed only to choose lanes with green lights.

The following conclusions were drawn by the Koppa and Hayes study (1976):

- Drivers turned the steering wheels of the vehicles approximately the same, even though the steering wheel ratio between vehicles was different.
- The dynamic control limit of the typical driver may be approximately one second. This was defined as the time that lapses between the first and second peak steering inputs during the lane changes and the avoidance maneuvers.
- Transient maneuvers, such as lane changes and avoidance maneuvers, most frequently showed differences in vehicle-driver closed-loop performance.
- When the driver lost control of the vehicle, it always occurred during the lane maneuver or avoidance maneuver recovery phase.
- Drivers may "normalize their inputs to achieve an acceptable level of lateral acceleration which is relatively independent of the vehicle's capability."

The study indicated that drivers adjust their inputs to a comfortable level of vehicle performance, regardless of the performance capability of the vehicle. The driver, as an integral component of the closed-loop system, limits the system's performance to a threshold that is comfortable and usually successful. On the other hand, these scenarios could have been designed so only limited performance capability was required to successfully perform the maneuvers. As a result, drivers may have used the performance capability that was comfortable but they could have increased the system performance if it was required for success. As described previously, Koppa and Hayes (1976) used scenarios that varied the times-to-obstacles/maneuvers, and there were several "losses of control." As a result, it is likely that drivers were modifying their inputs as required to reach a high enough, but comfortable, level of vehicle performance.

Drivers attempting a severe maneuver were also capable of adjusting for different steering ratios to obtain the desired steering magnitude. This indicates that drivers may rapidly adjust to the different steering behavior of a new vehicle. However, it is not clear whether this adaptation was strong enough to support the recovery phase of a severe steering maneuver. All instances where subjects lost control occurred during this recovery phase. Also, differences between the closed-loop vehicle and driver performance were highest in these transient maneuvers. It would be interesting to determine whether this loss of control was due to adapting to a new system or whether drivers in a familiar vehicle would experience the same problems. Finally, a one-second dynamic control limit for typical driver steering has interesting implications. In a crash avoidance situation, this delta between the first and second steering input could be the difference between a successful avoidance and a collision. However, the emergency avoidance literature reviewed did not discuss such differences.

Olson and Sivak (1986) conducted one of the few studies in the field evaluating perception-response time (PRT), defined as the time period that elapses between when an object or stimulus first becomes visible and when the subject responds. Sixty-four subjects from two age groups participated in the study. Subjects were instructed to drive an instrumented vehicle in a practice session to become accustomed with its characteristics before the experiment started. This helped ensure that the road hazard that occurred during the drive was unexpected. Approximately six kilometers into the drive, a piece of yellow foam rubber approximately 15 cm by 91 cm was positioned on the left side of the driver’s lane. A counter was started just before the subject would have been able to see the foam rubber. This counter was shut off once the accelerator was released and a second counter was started and continued until the brake pedal was pressed. Once subjects had stopped, they returned to the same route and told the experimenter when they were first able to see the road hazard. This information was used to calculate perception time (i.e., time-to-accelerator-release), response time (i.e., transition time from accelerator-to-brake), and PRT (i.e., time-to-brake-press). There was no evidence to indicate that older drivers required more PRT to respond to unexpected roadway hazards. When looking at PRT (i.e., time-to-brake-press), the average time appeared to be close to 1.1 seconds for both the young and the old group. It also appeared that over 90 percent of subjects in both age groups braked before 1.5 seconds had transpired (Olson and Sivak, 1986).

Lerner (1993) also evaluated brake PRTs in the field for both young and old drivers. One unique and beneficial experimental difference between this study and the many others of this type was the use of the subject’s own vehicle for the tests. As a guise, drivers were asked to periodically evaluate road quality. At the end of the drive, subjects merged onto a closed roadway and a large yellow barrel, previously hidden from view, came rolling toward their vehicles. Subjects were traveling approximately 40 mph and the barrel came into view approximately 200 feet away, causing a time-to-collision of approximately 3.4 seconds. The barrel was prevented from going any further than the shoulder area of the road. Valid data was obtained for 116 subjects. Eighty-seven percent of these subjects maneuvered their vehicles in an effort to avoid the encroaching barrel. Thirty-six percent steered only, 43 percent braked and steered, and only eight percent braked only. Measurable brake reaction time was obtained for 56 subjects (roughly half). The mean brake PRT was 1.5 seconds with a standard deviation of 0.4 seconds. Since valid braking data could be obtained for only 56 of the original 200-plus subjects, Lerner stated that this reaction time value should not be considered a precise measure. However, he stated that this sample was sufficient to show that there were no important PRT age-related differences between the groups evaluated. Lerner also reported a somewhat slower brake response time for the drivers who combined braking and steering compared to those drivers who braked alone.

Both Lerner (1993) and Olson and Sivak (1986) indicated that differences in response time for different age groups were minimal. Olson and Sivak also found that a time-to-collision of approximately 3.4 seconds elicited a high percentage of steering responses. Seventy-nine percent of the subjects in this study steered to avoid what they assumed was an encroaching barrel. Other research has shown that steering is not a popular response, and that subjects are more likely to choose braking when sufficient time is available.

For example, Lechner and Malaterre (1991) looked at collision avoidance driving behavior with subjects who had no pre-warning. They used the Daimler-Benz driving simulator, which at the time was the most advanced driving simulator in the world. Subjects were told to drive the simulator as they usually drive (around 90–100 km/h) to become familiar with it. They were told that they would be given new instructions after a familiarization drive. In fact, subjects never received a new set of instructions, but were told this so they would not expect the event requiring collision-avoidance behavior. Subjects came to a four-legged intersection approximately 10 minutes into the familiarization drive. At this intersection the subject vehicle had the right of way. A single vehicle driving toward the intersection on a perpendicular road stopped at a stop sign then proceeded in front of the subject vehicle. This vehicle started crossing in front of the subject vehicle at one of three different times-to-collision (i.e., 2.0, 2.4, and 2.8 seconds). The encroaching vehicle accelerated for 1.9 seconds and then braked to stop, blocking the subject's lane 2.6 seconds after starting.

Forty-nine subjects participated in the study with an approximately equal number of men and women in each of the three time-to-collision conditions. The average time for the subjects' first action was 0.8 seconds for releasing the accelerator pedal (33 subjects) and 0.82 seconds for steering (14 subjects). It took an average of one second to press the brake pedal. There was no significant difference in the first reaction between different times-to-collision. Lechner and Malaterre (1991) reported this was due to it being a "reflex" action. Time-to-brake was significantly different, and appeared to vary based on the urgency of the situation. These authors concluded that 0.8 seconds was required to react to a situation and 0.95 seconds was required to brake or steer to avoid a situation. However, they also alluded to some drivers releasing the accelerator prior to the incursion vehicle moving into the intersection (Lechner and Malaterre, 1991). This could have been due to defensive driving habits or subjects may have been more suspicious than usual because of the experimental context. Since some other reaction times found in the literature are slower (e.g., Olson and Sivak, 1986), these subjects may have reacted more quickly to the unexpected vehicle incursion because they were overly alert to the situation.

In this study, improving subject reaction time by even as much as 25 percent would not have increased braking maneuver success. In fact, two-thirds of the subjects who attempted to brake and collided with the encroaching vehicle would have had to start braking prior to the movement of the encroaching vehicle in order to succeed. This same 25 percent reduction in reaction time would have allowed four subjects who collided while attempting to swerve enough time to successfully swerve in front of the encroaching vehicle (Lechner and Malaterre, 1991).

Lechner and Malaterre (1991) also looked at the success of the different maneuvers across all times-to-collision. Overall, only 10 of the 49 subjects successfully avoided the collision. Six subjects avoided it by braking alone, three avoided it by swerving alone, and one subject avoided it by swerving and braking.

If the subjects' vehicle had been equipped with ABS, an additional seven collisions might have been avoided. These were subjects who steered right behind the vehicle during a skid and might have successfully avoided the encroaching vehicle if they had added steering control available to them. ABS would have probably increased the success rate from approximately 20 percent to approximately 35 percent (Lechner and Malaterre, 1991). This large increase could have been achieved without altering the subjects' behavior. Because subjects knew they were driving a vehicle with conventional brakes, it is possible that an even higher success rate might have occurred if subjects had known they had ABS. It would have been interesting to determine whether any subjects who locked the brakes and steered would have had other, less successful outcomes with ABS. For example, did any subjects over-steer to the point that ABS would have caused them to end the scenario in a worse outcome (e.g., departing the roadway and rolling over)?

Sixteen subjects who braked and collided with the encroaching vehicle would have avoided it if it had continued to accelerate across the intersection at the same rate without braking. This would have increased the success rate from approximately 20 percent to approximately 47 percent. However, the three subjects who swerved in front of the encroaching vehicle would have been "lightly" hit (Lechner and Malaterre, 1991). This is important because it is likely that very few subjects understood the ultimate behavior of the encroaching vehicle. It is likely that most drivers assumed the vehicle would continue to cross the intersection at the same velocity it was traveling when they began to decelerate.

The following conclusions were drawn from the Lechner and Malaterre study (1991):

- Accelerator release is probably a reflex behavior.
- When there is enough time, braking is the avoidance response preferred by most drivers (88 percent attempted braking).
- Drivers usually lock the brakes during avoidance maneuvers.
- The shorter the time to collision, the more likely drivers are to swerve in front of the encroaching vehicle.
- Drivers who swerve in front of the encroaching vehicle start by swerving first.
- Drivers who swerve behind the encroaching vehicle brake prior to swerving.
- Driver reaction time is generally good, so that a device that could effectively alert drivers to increase reaction time is not a feasible collision-avoidance deterrent in this case.
- Drivers in this situation could have improved their ability to avoid a collision with antilock brakes.
- Drivers did not use lateral avoidance maneuvers even though such maneuvers would have been more successful. Fifty-seven percent of the subjects who collided could have avoided the encroaching vehicle by swerving.

This study provided a good indication of driver behavior under conditions where time-to-collision is between 2.0 and 2.8 seconds. It is interesting that only the 2.8 second time-to-collision allowed the driver to witness the end behavior of the encroaching vehicle—under this condition, if the subject vehicle did nothing, the encroaching vehicle would begin decelerating 0.9 seconds before the collision and come to rest 0.2 seconds before the collision. Of course, if the subject slowed after the encroaching vehicle started moving, additional time would have been available for the subject to see the ultimate behavior of this vehicle. In the other conditions, subjects had to anticipate the encroaching vehicle's behavior. In the 2.0 second time-to-collision, subjects probably believed the vehicle was going to continue across the intersection at the same rate of acceleration. Since the vehicle continued to accelerate for 1.9 seconds, it is reasonable to assume that the braking of the encroaching vehicle did not figure into the strategy of these subjects. In the 2.4 second time-to-collision, it is possible that subjects were able to see the encroaching vehicle decelerate. It would be interesting to know if drivers in the 2.4 second time-to-collision changed their behavior or strategy after the encroaching vehicle began slowing. It would have been reasonable for the drivers to have developed an initial strategy based on the vehicle’s continuing to travel across the intersection and a secondary strategy once they saw the vehicle begin to stop. For example, the initial strategy might have been to brake; however, when they saw the vehicle stopping, they might have attempted to swerve around the vehicle.

Driver steering behavior observed in this study was quite interesting: drivers steered in front of the encroaching vehicle more often at shorter times-to-collision, steered in front of the vehicle as the first maneuver, and steered in back of the vehicle after braking. The authors stated that this could be explained by the direction of the moving obstacle and by the space available for maneuvering (Lechner and Malaterre, 1991). Drivers could have been adjusting their strategies based on the size or expected size of the gap. When drivers steered in front of the vehicle, they were attempting to cross the intersection in front of the encroaching vehicle. To maximize this gap in front and successfully avoid a collision, drivers would have had to have steered without decelerating and driven through the intersection as quickly as possible. Some subjects in this study maneuvered in this manner. On the other hand, drivers who attempted to steer behind the encroaching vehicle would have wanted the gap behind the vehicle to be as large as possible. By braking prior to steering, they could allow the encroaching vehicle to move through the intersection, making the gap behind the vehicle bigger. Drivers who steered behind the encroaching vehicle often braked first, indicating this may have been their strategy. Finally, in the shorter times-to-collision the biggest gap would have been in front of the encroaching vehicle. This study found that the shorter the time-to-collision, the greater the tendency to swerve in front of the encroaching vehicle, further supporting the idea that subjects attempted to swerve toward the biggest gap.

INRETS did research prior to this study to determine “why, in certain accident situations where an emergency maneuver is possible, did the driver not make the right decision or implement the maneuver properly” (Malaterre, Ferrandez, Fleury, Lechner, 1988). Unfortunately, many of these studies were written in French and could not be reviewed in their original form for this document. However, in an article written for ERGONOMICS, Malaterre et al. discussed some of these studies and how they impacted their work. We will describe the most pertinent of these studies.

Ferrandez, Fleury, and Lepesant (1984) observed 72 crashes in situ. Only 126 road users were involved, however, because some of the crashes involved only a single road user. Thirty-one of the 72 crashes could have been avoided if a feasible maneuver had been chosen by one of the drivers. From this study, the following conclusions were derived:

- Two-thirds of the time, the feasible avoidance maneuver was a lateral movement without braking.
- Braking was the preferred action.
- Lateral movements were rarely attempted at intersections unless the obstacle was approaching from the right side.
- When lateral movements were attempted, the driver reacted “too late, or too violently, or tried to combine braking with a sideways avoidance movement, which often resulted in loss of control” (Ferrandez, Fleury, and Lepesant, 1984).

Lateral movements that are too violent have direct implications for the increase in ABS rollover crashes. If some drivers over-steer in emergency avoidance situations, the added steering ability of ABS may increase the likelihood of road departures and increased lateral acceleration. It is also interesting that subjects resist steering to avoid an object unless it comes from the right side. This could be due to several things including:

- Drivers expect that the left incursion object will stop prior to entering their pathway.
- Although drivers are actually steering, the steering has minimal effect because the brakes are locked.
- Drivers have a larger escape route when the obstacle incurs from the right. When the obstacle comes from the left and enters their lane, drivers only have their own lane and the shoulder to move into laterally to avoid the crash. When the obstacle comes from the right and enters their lane, drivers also have the entire left lane for avoidance.

It is possible that all three of these factors affect a driver’s lateral movement. As part of this research, Ferrandez and Fleury (1986) analyzed 82 crashes that occurred at intersections and involved entry from the left or right side. The intersections were on a main road with an intersecting secondary road. Although the secondary road user was responsible for the traffic conflict, Ferrandez and Fleury stated that they had “very little scope of avoiding action” (1986). Only half as many obstacles could have been successfully avoided from the left (25 percent) as from the right (50 percent). This was due to the avoiding drivers taking longer to realize there was a potential conflict when the obstacle entered from the left. In general, braking was the preferred maneuver, and lateral movements were usually in the same direction as the moving obstacle (Ferrandez and Fleury, 1986).

The perspective of this study differed from the perspectives of many crash-reconstruction studies that aim at determining why the incursion vehicle pulled into the intersection and how to prevent such incursions from happening. This study analyzed how collisions can be avoided once an incursion has happened. From the analysis, it is apparent that a large number of these crashes could have been avoided by the driver who had the right-of-way on the main road. Again, it is likely that in many of these situations, successful avoidance maneuvers would have had to include lateral movement, a maneuver avoided by many drivers. According to Malaterre et al., the driver must have good visibility, know the trajectory of the object in the conflict, and be a short distance away from that object to use lateral movement as a primary response (1988).

Malaterre et al. (1988) showed subjects a video of a van on a collision course and asked subjects how they would respond. The first response given by subjects was taken as their answer. The authors again found that braking was overused as an avoidance maneuver. Although this study used film and slides and required subjects to report rather than perform their reactions, it remains likely that many subjects would use this information to determine the appropriate collision avoidance response. Therefore, it is assumed that this approach is representative of subjects' actions.

Malaterre, Peytavin, Jaumier, and Kleinmann (1987) tried to determine subjects' perceptions of how close they could get to an obstacle and still successfully avoid it by braking or by steering. On a racing circuit, subjects were told to imagine an obstacle in the location of two pylons and to press a button at the last moment they thought they could successfully steer around the obstacle, and at the last moment they thought they could successfully brake to avoid the obstacle. Subjects did not actually perform the maneuver, so they had no feedback on their success. Thirty-two trials were taken for each of the 12 subjects. As expected, subjects believed they could still successfully steer closer to the object than they could successfully brake. Although different speeds were used, the time-to-collision never exceeded four seconds. This study shows that subjects know that steering is a better option in certain situations; however, the crash statistics and other studies show that subjects avoid steering under these circumstances.

Petit, Priez, Brigout, Tarriere, Collet, Vernet Maury, and Dittmar (1993) performed a study on a test track to determine why antilock brakes have not been more effective at reducing crashes and their severity. They recruited 100 male and female subjects between the ages of 21 and 56 and matched subjects by age, length of time with a driver's license, and emotionality. An equal number of drivers were assigned to a group:

- without ABS,
- with ABS in which the drivers were not informed that the vehicle had ABS,
- with ABS in which the drivers were informed that the vehicle had it, and
- with ABS who attended a half-day training program on its use.

A course was laid out with multiple intersections. Two of the intersections had cars with drivers in them on opposite sides of the subject vehicle. The cars were blocked from the subject's view until approximately one minute before the subject reached the intersection. Drivers drove by these intersections multiple times. On the last trial, an inflated dummy vehicle replaced one of the cars. At a braking distance approximately 15 meters too short to avoid the vehicle, the inflated vehicle pulled out in front of the subject's vehicle from the right. The inflated vehicle blocked the subject's entire lane. The left lane was available to swerve around the incursion inflated vehicle. Drivers were told the driving speed was 100 km/h, and arrived at the obstacle's location at between 40–50 km/h. None of the drivers in the group without ABS were able to avoid the collision. Approximately 20 percent of the drivers in each of the other groups that had ABS were able to avoid the encroaching vehicle. Although not more successful than the other groups with ABS, approximately 80 percent of the group trained in ABS performed the correct maneuver. From this and other results, Petit et al. (1993) concluded that the correct use of ABS is not innate; drivers with ABS-equipped vehicles performed better than drivers of non-equipped ABS vehicles, and drivers would be more successful if they knew how to use ABS better.

Although not discussed by Petit et al. (1993), the graph in the article indicated that approximately 50 percent of the subjects attempted to perform the correct maneuver in each of the three untrained groups. Even though subjects were not successful in the group without ABS, about 50 percent appeared to steer to try to avoid the vehicle. Without ABS, these subjects may have steered with the brakes locked, reducing their ability to move laterally and ultimately forcing them to collide even though they performed the correct avoidance maneuver. It would be interesting to know if there were any differences in the reaction time-to-maneuver and the magnitude of the steering angular deviation between the group of drivers who knew they had ABS and the two groups of drivers who did not know they had ABS. It is probable that there was no difference and that subjects without instruction performed the same actions, regardless of the braking system. It is also reasonable to assume that in similar circumstances, approximately 50 percent of the subjects would tend to steer, and that some would over-steer. This over-steering may be due to drivers having had experience attempting to steer with locked conventional brakes and not having any lateral influence over the vehicle. Drivers may also steer with the brakes locked because they perceive that turning the tires sideways with the skid will improve their deceleration. Additional research is required to determine if any or all of these hypotheses are valid.

Other researchers have looked at driver behavior when a pedestrian crosses into a vehicle's path. One of the first studies to do this in a simulator was conducted by Barrett, Kobayashi, and Fox (1968). For 10 trials, 11 subjects drove a simulated vehicle with the speedometer covered by tape. Subjects were instructed when to increase and decrease speed in an effort to maintain 25 mph. On the tenth trial, subjects were coached on speed adjustment until the driver approached a location with a simulated pedestrian. The simulated pedestrian moved out of a shed and into the path of the subject vehicle at a distance of 82.5 feet in front of the driver. At 25 mph this approximates 2.25 seconds time-to-collision. Ten of the 11 subjects attempted to avoid the collision by braking. One attempted to avoid the collision by steering. Six of the 11 subjects avoided the simulated pedestrian or hit it at less than one mph. In this study, the dependent variables were the number of subjects whose dominant response was steering or braking; the reaction time; the magnitude; and the rate of the initial steering or braking behavior. Although this study had a small sample, it is clear that here again, subjects preferred braking over steering as an avoidance response. It appears that in this type of study, at least these four dependent variables should be analyzed.

Araki and Matsuura (1990) used a driving simulator to study driver behavior when a pedestrian suddenly darted across the road from the driver's right side. The 32 subjects were told that their response to overtaking and being overtaken by other cars on a two-lane road was being monitored. They were also told to drive at approximately 80 km/h. After a practice drive of approximately 20 minutes, the simulated pedestrian darted across the intersection at a rate of approximately 10 km/hr. The simulated pedestrian was approximately 40 meters from the subject's vehicle when it began to move into the intersection. Subjects were not told that a pedestrian would enter their path.

The action taken by a subject to avoid the simulated pedestrian was classified as: no steering, steering left, steering right, no braking, light braking, or hard braking. The 32 subjects were classified as experienced (24 subjects) and novice (eight subjects). Nine of the 32 subjects avoided a collision with the simulated pedestrian. All but one of the novice subjects collided with the simulated pedestrian. Eighteen of the 32 subjects braked hard, seven braked lightly, and seven never braked. Of the subjects who never braked, two drove straight ahead without braking and avoided the collision. One steered left, successfully avoiding the collision; three steered right, with one subject successfully avoiding the collision. Of the subjects who braked hard, nine braked alone, with one avoiding the collision; seven steered right, with three avoiding the collision; and two steered left, with both colliding. Finally, seven subjects braked lightly; of these, two braked alone, three steered left, and two steered right. All the subjects who braked lightly collided, except one who steered right.

The following can be derived from this study (Araki and Matsuura, 1990):

- Most subjects attempted to brake to avoid the collision (25 of 32).
- Most subjects who attempted steering combined it with braking (14 of 18).
- Twice as many subjects attempted to steer behind the pedestrian as in front of the pedestrian (12 and 6).
- More novice drivers (3 of 8) than experienced drivers (0 of 24) attempted to steer behind the pedestrian without braking.
- Novice drivers were more likely (88 percent) than experienced drivers (67 percent) to collide in this scenario.

This study places the simulated pedestrian in the vehicle's path at approximately 1.8 seconds time-to-collision. Subjects at this short time-to-collision still preferred braking to avoid the pedestrian and most subjects who steered combined steering with braking maneuvers. This again shows that drivers resist steering around an obstacle even though they would have a better success rate. Of the subjects who attempted to steer right behind the obstacle, over 40 percent were successful. In this case, since the pedestrian came from the right side, braking to allow the pedestrian more time to cross the intersection then steering behind the pedestrian had merit. It is interesting that three of the eight novice subjects attempted to steer right without slowing first. None of the experienced subjects attempted this maneuver without braking first, indicating that experience may have taught drivers to slow down before steering behind an object moving off the road.

A study done by Masuda, Nagata, Kuriyama, and Sato (1992) specifically evaluated how experienced and inexperienced drivers were affected by obstructions on both sides. Subjects were instructed to maneuver between an obstacle on each side of a road. In some cases the obstacles were stationary and in other cases the obstacles were moving in the same direction as the subject's vehicle. One of the objects was a pedestrian and the other was a van. These obstructions could appear on either the left or right side of the subject vehicle but there was always a pedestrian and van present. Several interesting conclusions were drawn from this study. When the driving task became more difficult, subjects sampled the right side obstruction more often than the left side obstruction. This occurred regardless of whether the van or the pedestrian was on the right side. Also, when the driving task became more difficult, the novice drivers were more concerned with their vehicle's path of travel than with the obstructions. Finally, novice drivers attempted to stay in the right lane, regardless of the obstruction in that lane (Masuda, Nagata, Kuriyama, and Sato, 1992). It is clear from this analysis that experienced drivers behave differently than novice drivers. It is expected that in a difficult situation, novice drivers would have to concentrate more on their vehicle's path. However, it is not expected that these drivers would be more likely to stay in the right lane, regardless of the obstruction in that lane. Finally, it would be interesting to determine whether the high sampling of the right side is a usual aspect of driving or an artifact caused by this experimental procedure.

In a study attempting to assess the benefits of ABS, average drivers were placed in an emergency situation that required both braking and steering to avoid a collision. Seventy-seven drivers were instructed to drive 45 mph on a test track. They were told that when they entered an approximately 10-foot wide lane marked with cones, something might happen that would require them to brake or steer. When they were approximately 114 feet away, a "child-like dummy" was projected into the drivers' path. At 45 mph, the driver had to both steer and brake to avoid the child dummy. Twenty-seven of the 77 subjects tried to avoid the child dummy without attempting a steering maneuver. Of these 27, two successfully avoided the child dummy by braking alone due to their slow entrance speed. In general, the drivers collided with or touched the child dummy 1.2 times less frequently in the vehicle equipped with ABS (Martin and Holding, 1987).

It is interesting that 25 of the 77 subjects unsuccessfully attempted to brake to a stop when steering would have been a more successful maneuver. There was no chance of injury from oncoming traffic or of hitting the cones to the left, yet one-third of the drivers attempted to brake only. Malaterre, Peytavin, Jaumier, and Kleinmann (1987) have shown that subjects know a lateral swerve will be more successful than braking at short times-to-collision. In this case, the time-to-collision would have been approximately 1.73 seconds, so these subjects probably did not resort to braking because they thought it would be more successful than steering. Some other mechanism such as overestimating the braking ability of the vehicle or not being sure of the ultimate behavior of the child dummy may have caused this response.

Prynne and Martin (1995) discuss a two-stage braking phenomenon that appears to be a subsequent finding of this study, or of a very similar study. A high proportion of the subjects braked to a usual point of deceleration, then paused before continuing to fully depress the brake pedal. Drivers who performed this two-stage braking were 17 percent more likely to collide with the child dummy. According to Prynne and Martin (1995), this two-stage braking was part of the drivers' decision processes. They also reported that drivers were intolerant of high deceleration at high speeds and were unwilling to swerve even when this was the best maneuver for success. In this case, subjects had been alerted that something could happen when they entered the 10-foot lane. As a result, their reaction time to the event was probably very quick compared to a similar situation with no forewarning. The reader should consider this when reviewing these results.

2.5 LITERATURE REVIEW CONCLUSIONS

Antilock brake systems (ABS) have been shown experimentally to improve the chances of avoiding collisions by increasing drivers' ability to brake, steer, or perform a combination of braking and steering. Accident statistics, however, have not demonstrated the expected improvements in driver collision avoidance, while they do indicate a large increase in rollover crashes. Researchers have blamed this lack of crash reduction on poor ABS knowledge, lack of training, and compensatory risky behavior. The increase in rollovers related to ABS is thought to be caused by an increased ability to steer. Increases in other aspects of crashes involving ABS (e.g., collisions in which the car is in the wrong lane) support this possibility. However, none of the controlled experimental research reviewed specifically discussed any increased chance of ABS crashes. In fact, all the literature reviewed evaluated ABS only as a positive crash-avoidance technology. Research must also evaluate whether drivers perform some action or combination of actions that increase the likelihood of rollover crashes with ABS. Since emergency avoidance situations can require drivers to push their or their vehicle's performance to their maximum capability, this intersection scenario provides a good mechanism to determine what if any driver behavior(s) increases the number of crashes associated with ABS. Specifically, it could help researchers determine whether drivers in emergency avoidance situations have a tendency to over-steer with locked brakes.

2.5.1 Imminent Crash Avoidance Behavior

Crash statistics have shown that subjects involved in crashes resist lateral maneuvers and prefer to brake to avoid an obstacle. At times, the most feasible maneuver may be a lateral movement without braking. Lateral movements at intersections were attempted usually in the direction of the encroaching vehicle, but were rarely attempted unless the encroaching vehicle was approaching from the right side. It appeared that drivers had an increased chance of avoiding the encroaching vehicle if it approached from the right rather than the left. One study found that when a lateral movement was attempted, the driver "reacted too late, or too violently, or tried to combine braking with a sideways avoidance movement, which often resulted in loss of control." (Ferrandez, Fleury, and Lepesant, 1984). Of course, if this effect is commonly true, ABS could exacerbate the problem.

Experimentally controlled studies reflect many of the findings demonstrated by crash statistics. Studies have been designed with times-to-collision ranging from approximately 1.75 seconds to 3.4 seconds. The obstacles have included barrels, foam blocks, simulated vehicles, and simulated pedestrians. The results indicate that drivers usually release the accelerator first, prefer to brake, avoid lateral maneuvers, and lock the brakes during avoidance maneuvers. When steering, they usually steer towards the largest gap, steer first when going in front of an obstacle, and brake first when going behind an obstacle. In many cases, collision avoidance could have been improved if drivers had steered rather than braked. When subjects do steer, it is often combined with braking. Subjects know they could be more successful steering than braking at shorter times-to-collision, and are more likely to steer in shorter times-to-collision. This is true in all cases reviewed except the 3.4 second time-to-collision with a barrel, where a surprising 79 percent attempted to steer. Thirty-six percent attempted to steer alone while only eight percent attempted to brake alone (Lerner, 1993).

The driver research revealed that emergency perception-reaction time is not greatly impacted by the driver's age, and 1.1 seconds is a good estimate of the average time required to perceive and respond. Drivers rarely use the full capability of the vehicle and obtain the same lateral acceleration regardless of the vehicle's capability. They also adapt to different steering wheel control ratios to obtain the same vehicle deviation. In addition, they may have a dynamic steering control limit of approximately 1.0 seconds and the most difficulty with the recovery phase of transient maneuvers, such as lane changes and avoidance maneuvers.

Most of the articles reviewed analyzed driving outcome and behavior at times-to-collision of 2.8 seconds or less. All the studies that dealt with incursions analyzed driver reaction and behavior based on an incursion from the driver's right side. None of the studies analyzed incursions from the left side, even though the accident literature indicates that there are differences between left- and right-side incursions. Also, none of the studies discussed the magnitude or rate of the steering deviation and few discussed the reaction times to individual driving behavior and the transition time between driving behaviors. A detailed analysis of driving behavior in severe avoidance scenarios at times-to-collision of greater than 2.8 seconds including incursions from both the left and right side would enhance the existing literature on emergency avoidance maneuvers. This analysis should include detailed magnitude, rate, and time analyses of each driver behavior variable.

3.0 METHODS AND PROCEDURE

3.1 APPARATUS

3.1.1 Iowa Driving Simulator

The Iowa Driving Simulator (IDS) incorporates recent technological advances to create a highly realistic automobile simulator. The 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. The simulator dome features 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 were modeled after a Ford Taurus, a typical mid-sized American car. The Ford Taurus vehicle dynamics model used in this study was that developed by NHTSA for use with the National Advanced Driving Simulator (NADS).

3.1.2 ABS Implementation

The experiments described in this report required a means of simulating the behavior of a vehicle equipped with an antilock brake system (including the brake feel). The most accurate way of capturing the pulsation of the brake pedal during ABS operation, as well as the proprietary control algorithms used by manufacturers, was to develop a hardware-in-the-loop simulation using actual antilock brake system hardware taken from a high-production passenger vehicle. An accurate vehicle dynamic model (including the tire model) is needed to ensure that the ABS performs correctly.

The procedure to implement ABS hardware on the Iowa Driving Simulator (IDS) was a two-part development. First, to assess the feasibility of the proposed study, the hardware was stripped from a vehicle and submitted to an open loop bench test. Once this task was successfully completed, the ABS hardware was integrated with the IDS hardware, and the IDS vehicle dynamics software was upgraded to generate the correct signals for the ABS system and to read the correct output from the hardware.

3.1.3 Open Loop Bench Test

The open loop bench test involved playing back a set of wheel speeds recorded during an ABS stop conducted in a 1994 Ford Taurus. As the wheel speed time histories were fixed no matter what the ABS system did to the brake-line pressures, the control loop was not closed. This test was undertaken as a first step to assess the feasibility of the proposed hardware-in-the-loop experiment.

The entire ITT-Teves Mk IV antilock brake system was stripped from a 1992 Ford Taurus. The ABS warning lamp, brake and pump relays, data-link connector, electronic control unit (ECU), brake pedal position and stop light switches, engine compartment fuse panel, Hydraulic Control Unit (HCU), front and rear brake calipers and rotors, the entire ABS wiring harness, tandem master cylinder, vacuum brake booster, and brake pedal assembly were all removed from the donor vehicle and mounted on a bench test platform. The rotors did not spin on the test platform, but the calipers did push against them. The load-sensitive rear proportioning valves were not removed from the donor vehicle; instead, two adjustable proportioning valves were installed in each of the rear brake lines and the bias was set to the factory-specified values. Due to problems during testing, the 1992 ECU was replaced with a compatible (but not identical) 1995 ECU.

Preliminary evaluation of the bench-mounted hardware revealed that the ABS pump and valves would draw in excess of 30A while in operation, and that insufficient power would lead to failure of the ABS. To prevent this from happening, the system was powered from a 12-Volt automotive battery connected in parallel with a battery charger. A small electric vacuum pump and a 0.5 ft^3 reservoir were used to supply the necessary vacuum for the boost. The system was able to maintain enough vacuum for two panic brake applications from 50 mph. This was deemed sufficient for the bench testing.

Strain gauge type pressure transducers were installed on each of the four brake lines downstream of the HCU at the flexible brake line connection point. The transducers were connected to wide-band strain gauge amplifiers, and subsequently to a 12-bit A/D card installed in a 33 MHz desktop PC. This system sampled the brake pressures at 100 Hz. Brake pedal force was monitored using a load cell, however, as the bench test was run in an open-loop mode, the brake pedal force was somewhat arbitrary. The PC also had a 12-bit D/A that was used to output four voltages proportional to the wheel speeds.

The wheel speed data used for the bench test were recorded using a 1994 Ford Taurus. Initially, a set of data was recorded during a straight-line stop from 50 mph on a low friction coefficient (low-μ) surface (μ_{max}=0.34, $\mu_{sliding}$=0.11). A second set of data was recorded during a straight-line stop from 50 mph on a split friction coefficient (split-μ) surface (left surface/μ_{max}=0.34, $\mu_{sliding}$=0.11and right surface/μ_{max}=0.81, $\mu_{sliding}$ =0.76). The data were only collected during the deceleration phase of the drive, so a “ramp-up” section was pre-appended to the data. This ramp up section gradually increased the wheel speeds from zero to 50 mph. The wheel speed data was collected at 100 Hz (every 10 ms). Since the ABS ECU main loop time is 7 ms, there was concern that the wheel speed data may have been sampled too slowly for accurate operation of the ABS algorithm.

The ECU expects wheel speed signals in the form of an oscillatory waveform. Each wheel has a toothed ring that passes by a stationary magnetic sensor. Since the ECU only looks at the edges of the wheel speed signal, the exact shape of the waveform is not critical as long as the edges are steep enough to be detected. A voltage-to-frequency converter (V-to-F) was used to simulate the signal produced by the teeth passing by the sensor by generating a square wave whose frequency was proportional to the applied voltage. The front and rear wheels of the 1992 Ford Taurus both have toothed rings with 52 teeth. If the rolling radius of the tire is R_e, the conversion from velocity, V (m/s) to frequency, F (Hz) for the tire in free rolling is,

$$F = 52VR_e / 2\pi \tag{1}$$

The rolling radius was determined by measuring the frequency of the wheel signal as a function of forward speed. This was done on the Transportation Research Center Inc. high-speed test track in East Liberty, Ohio using a 1992 Ford Taurus. The Taurus did not have rear-wheel drive, so the back wheels were essentially free rolling. The V-to-Fs were calibrated with a set of four capacitors to provide the correct scaling from the D/A output voltage to frequency.

Plots of brake-line pressures during an actual split-μ stop and a bench test simulated stop are shown in Figures 3–1 and 3–2. In an attempt to emulate the brake application used by the driver during the actual stop, an experimenter visually monitored their brake pedal force throughout the simulation. Since this method is not extremely accurate, exact comparisons cannot be made between the bench test and recorded data. Examination of the bench test and recorded brake-line pressures and wheel speeds did show very similar trends.

Results for the low-μ stop are shown in Figures 3–3 and 3–4. The comparisons are similar to the split-μ test. Note that in Figure 3-3, the LR and RR traces are not meaningful. The testing which produced these traces was performed for another research program using a 1994 Ford Taurus whose rear load-sensing proportioning valve had been disabled. As a result, this vehicle's brake system was not operating within manufacturer specifications. The increased front-bias state prohibited the rear line pressures from building to the extent they would have otherwise been expected to.

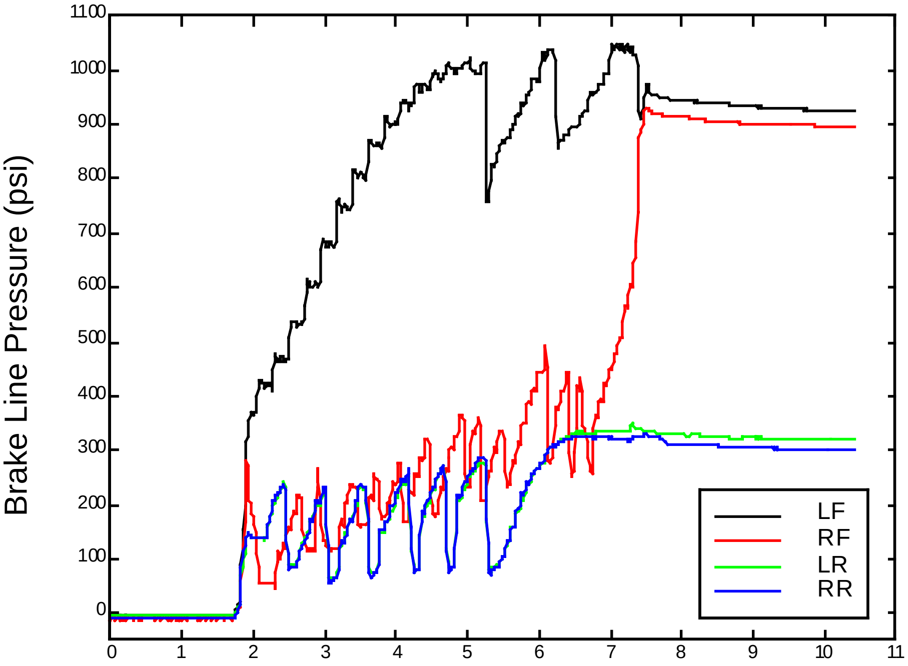

Figure 3–1. 1994 Ford Taurus 0.5 g split-μ stop

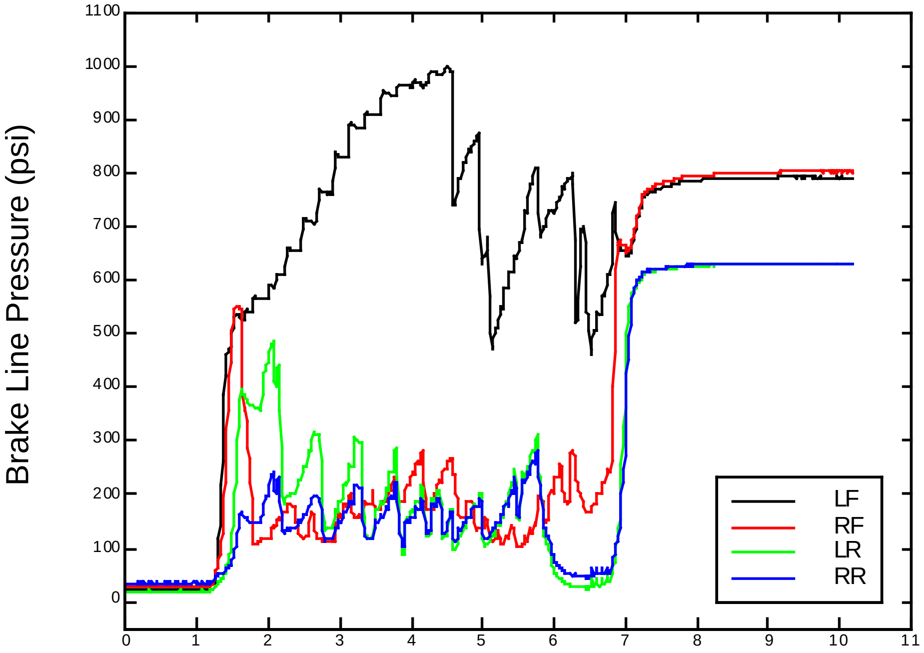

Figure 3–2. Bench test 0.5 g split-μ stop

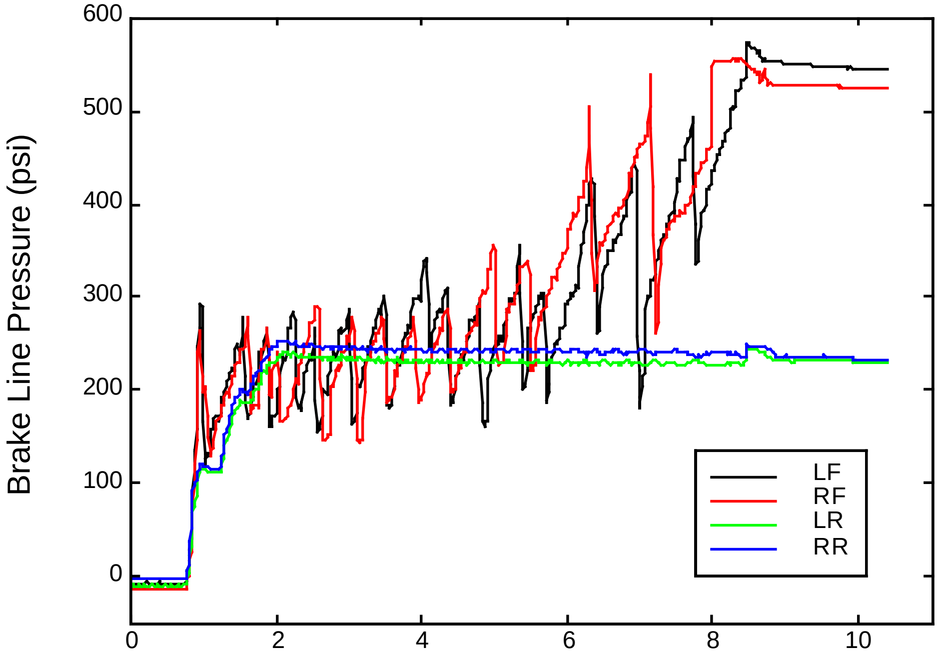

Figure 3–3. 1994 Ford Taurus low-μ stop

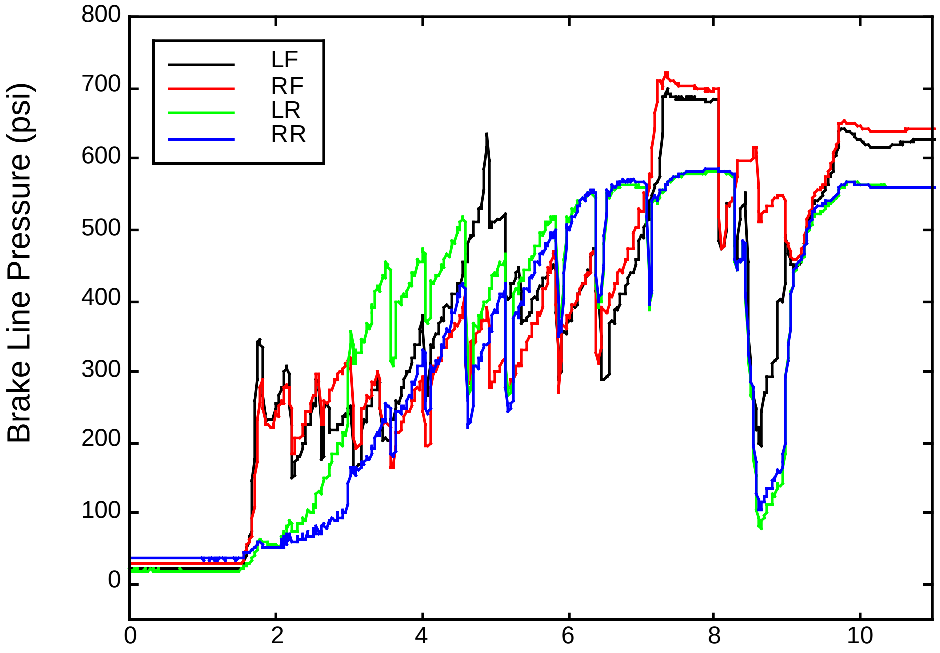

Figure 3–4. Bench test low-μ stop

Based on Figures 3-1 through 3-4, the behavior of the ABS hardware during the bench test and the in-vehicle ABS operation was similar enough to warrant development of the hardware-in-the-loop simulation.

3.1.4 Hardware Installation

The cab used for the current experiment was a 1993 Saturn. The 1992 Taurus ABS hardware, including the 1995 ECU, was integrated into the 1993 Saturn cab. The Taurus master cylinder was mounted to the Saturn firewall using an extremely stiff adapter plate. The brake pedal assembly from the Saturn was modified to match the mechanical advantage between the pedal end and master cylinder push rod pin in the Taurus by moving the master cylinder rod pin location on the pedal assembly. This ensured that the Saturn pedal geometry would be maintained yet provided the appropriate scaling of applied force and displacement to match the Taurus system. An adjustable-length master cylinder push rod was manufactured and adjusted to give proper vacuum booster operation. The Taurus brake pedal travel switch, used by the ABS system to prevent excessive pedal displacement during ABS operation, was fitted to the Saturn pedal. The standard Saturn brake light switch was used in place of the Taurus switch. A separate 40 A power supply with a large external capacitance was used to power the HCU. A large-capacity vacuum pump with a regulator was used to supply 20 inches of mercury to the vacuum boost canister.

The ignition switch was wired into a digital output channel of the Saturn cab I/O system. This digital line was used to turn the ABS system on and off. The ABS status light signal from the ECU was connected to a digital input line on the Saturn cab I/O system. This line was connected to allow the simulation software to detect ABS failures. Twisted pair shielded cables were used to connect four channels of an analog input board mounted in the real-time host (Concurrent Nighthawk 6800) to the brake line pressure transducers. Twisted pair shielded cables were also used to connect four channels from an analog output board mounted in the real-time host to the inputs of the V-to-Fs. Care was taken to ensure maximal noise rejection on all cabling. The Saturn I/O system analog input and analog output boards were not used because the data transfer rates from the Saturn I/O system to the real-time host were too slow to support proper ABS operation.

The entire Taurus ABS hardware was mounted in an enclosure bolted to the floor of the IDS motion system next to the Saturn cab passenger door. A long rubber hose was used to connect the master cylinder reservoir with the HPU reservoir. The hose was routed to ensure there would be no entrapped air bubbles. The entire system was filled with hydraulic fluid and bled to remove all air.

3.1.5 Software Implementation

The NADS Vehicle Dynamics Simulation, Release 4.0, software was integrated into the IDS real-time system for this project. The 1994 Taurus model described by Salaani et al. (1997) was used. The NADSdyna code uses the STI tire model modified by Salaani et al. (1998) and the Iowa State tire dynamics described by Bernard and Clover (1995), and Clover and Bernard (1998). A couple of modifications were made to the NADSdyna software. First, the integration scheme was changed from 3rd order Adams Bashforth to 2nd order Adams Bashforth, and the time step was changed from 2 ms to 4.166 ms. The larger time step was required to meet the real-time constraint on the Concurrent Nighthawk 6800. Because this larger time step is near a stability boundary for the 3rd order integration method, the accuracy of the solution was poor. The 2nd order Adams Bashforth integration method has a larger stability boundary than the 3rd order method, and therefore produced more accurate results for this time step.

NADSdyna has a kinematic model of the steering system hardware from the wheel hub to the steering rack. A rudimentary model of the steering system from the rack to the steering wheel was added to the NADSdyna code to calculate the torque at the steering wheel. This torque was used to drive the Saturn cab control loader. The simple steering model included a saturated viscous damper (to simulate coulomb friction in the system) and a non-linear steady-state boost function. The boost function was given by,

$$K_{boost} = -3.37x10^{-8} F_{rack}^{2} - 8.57x10^{-5} F_{rack} + 0.3 \tag{2}$$

The torque applied to the steering wheel is equal to the force on the rack multiplied by K_{boost}. The coulomb friction force added onto the rack was defined to be,

$$\begin{aligned} F_{fric} &= 300 \qquad if \quad v_{rack} > 0.8 \\ F_{fric} &= \frac{300\left|v_{rack}\right|}{0.8} \qquad otherwise \end{aligned} \tag{3}$$

where F_{fric} is the friction force in Newtons and v_{rack} is the velocity of the rack in m/s.

The ITT-Teves ABS algorithms are proprietary and details regarding the potential time stamping of edges could not be ascertained. It was known however, that the main loop executed every 7 ms. Given the lack of information regarding the controller, an experiment was run to determine if a vehicle dynamics model time step of 4.166 ms would result in accurate ABS behavior. For this experiment a simplified vehicle model was combined with the previously described tire model. This simplified model took less than 1ms to execute on the Nighthawk 6800. To keep the time delays associated with brake-line pressure sampling and wheel speed output to a minimum, a separate program was used to sample the brake line pressures and output the wheel speeds. This program always ran at 1 ms intervals. The pressure data was put into global memory and the wheel speeds were read out of global memory for each iteration. A spring-loaded actuator was used to load the brake pedal in a consistent manner. The actuator load was always on the brake pedal, but the software ignored the brake-line pressures until a specified speed was reached. At this speed, the throttle was disconnected (in the software), and the brake pressures were applied to the vehicle model. It was found that time steps as large as 4.166 ms could be used without a noticeable change in ABS performance (at least for the surface friction coefficients tested). Very low coefficient surfaces may require higher update rates to deal with the larger wheel accelerations that can occur on these surfaces. Figures 3–5 to 3–7 compare the wheel speeds and brake-line pressures for this simplified model running at 1000 Hz and 240 Hz on a high-μ surface.

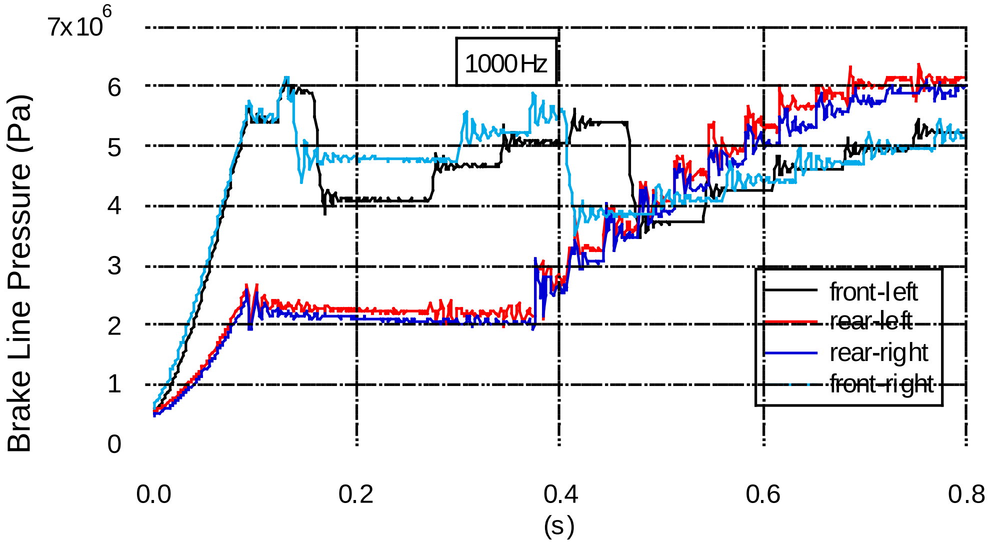

Figure 3–5. Line pressures, simplified model, 1000 Hz

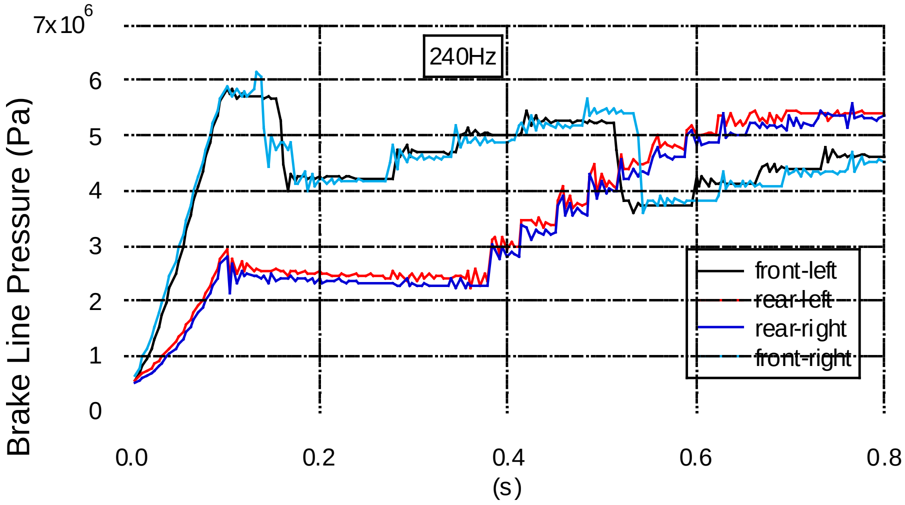

Figure 3–6. Line pressures, simplified model, 240 Hz

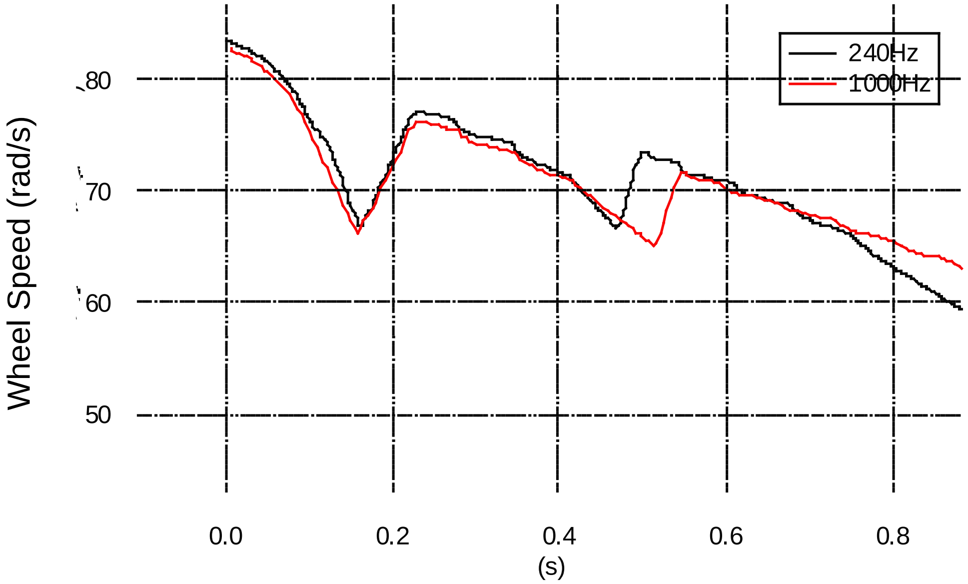

Figure 3–7. Wheel speeds, simplified model, 240 and 1000 Hz

Based on these experiments, and the computational constraints, the vehicle dynamic model was evaluated every 4.166 ms. The program that outputs the wheel speeds and reads the line pressures was run at 1ms intervals and always used the most recent data available. The accelerations and brake line pressures of simulated high-μ ABS stops for the fully integrated NADSdyna Taurus model (running at 240 Hz) and the sampling program (running at 1000 Hz) are shown in Figures 3-8 and 3-9. To confirm the ABS was operating correctly, and that the simulated braking responses were accurate, acceleration and brake line pressures were recorded during an ABS stop on wet asphalt using a 1997 Chrysler Concorde. The results of this test are shown in Figures 3-8 and 3-10. The 1997 Concorde uses the same Teves Mark IV controller as the 1992-95 Taurus. Although the tuning of the controller may not be exactly the same in the two vehicles, it was expected to be similar, an assumption verified by comparison. According to NHTSA data, the wet asphalt skid-pad number was roughly 90% of the dry asphalt skid-pad on the same test surface.

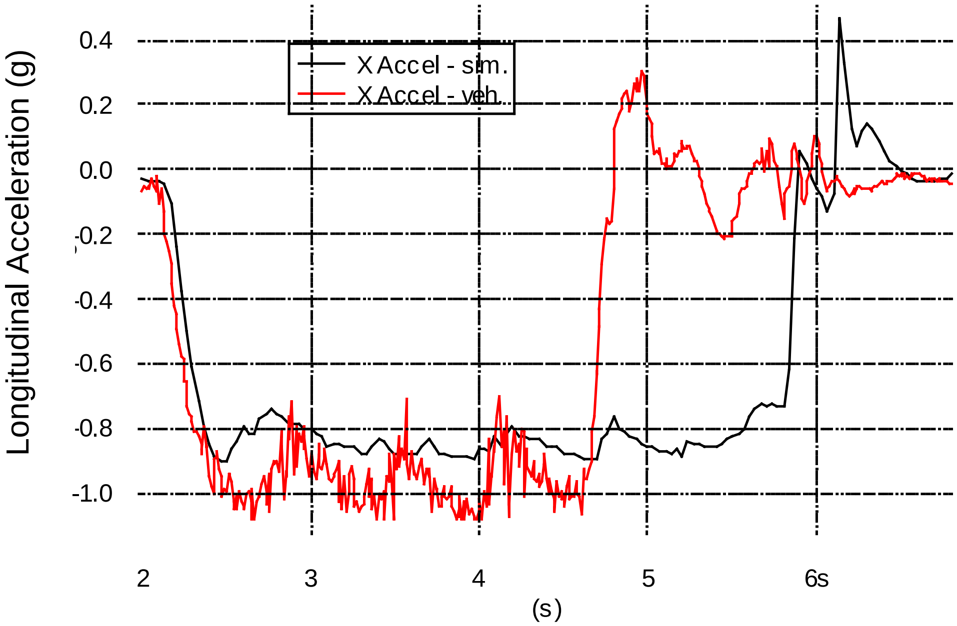

Figure 3–8. Comparison of ABS deceleration of 1997 Concorde and simulated 1994 Taurus

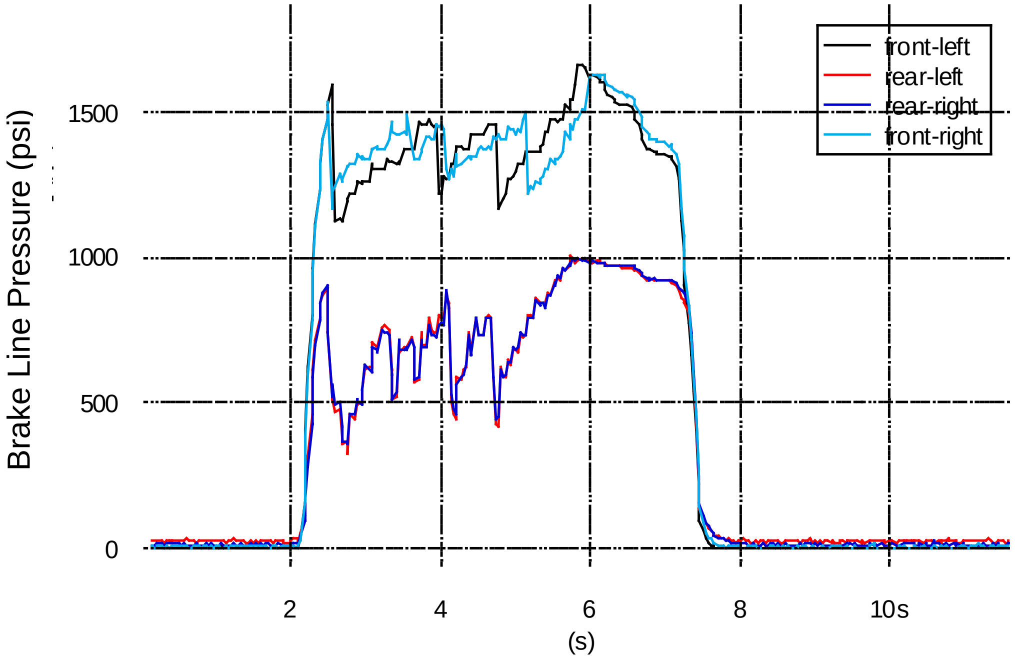

Figure 3–9. Brake line pressures, ABS, high-μ, simulated, 1994 Ford Taurus

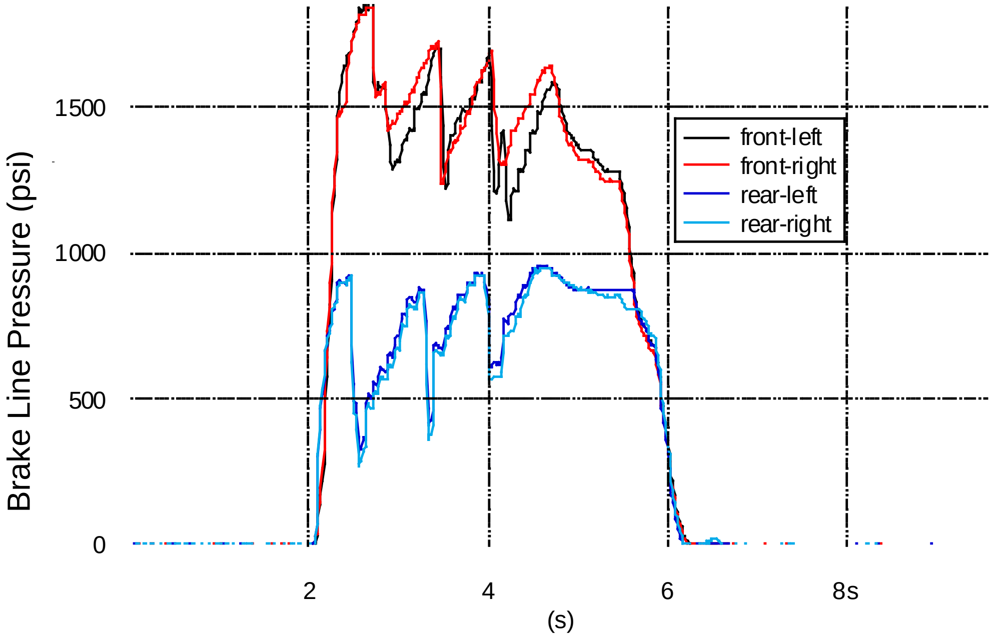

Figure 3–10. Brake line pressures, ABS, wet asphalt, track, 1997 Chrysler Concorde

The simulated Taurus with the ABS hardware and the 1997 Chrysler Concorde show very similar ABS braking performance. The Taurus stop is longer since the deceleration run was started at 65 mph, while the Concorde deceleration run was started at 50 mph. Although the 1997 Concorde braking data was not corrected to remove potential pitch effects, the similarity of the decelerations suggests that either the Taurus tire testing used to fit the NADSdyna tire model was done on a surface with a skid pad number close to the wet asphalt track, or the Taurus tire is a harder compound tire with less traction than the tire used on the 1997 Concorde. Based on these results, we concluded the ABS hardware and Taurus simulation were functioning correctly on high-μ surfaces. All experiments in this study were performed on a simulated high-μ surface.

3.1.6 Video Instrumentation

In addition to data that objectively quantified subjects’ vehicle control inputs, four video cameras recorded the events on videotape for later analysis (see Figure 3–11). The first view was shot from just above the passenger’s seat next to the passenger door. This view over the driver’s right shoulder showed the right side of the driver, all steering wheel movement, and the vehicle’s instrument panel. The second view was shot from the dash near the driver’s door and showed the driver’s face and all eye and head movement. The third view was shot from under the dashboard and directed towards the driver’s feet. This view was designed to obtain any movement of the driver’s foot between the gas and brake pedals. The fourth and final view was the forward view of the driving environment that was being projected onto the screen.

Figure 3–11. Video Tape Configuration

An overlay of linked real-time data from the drive was superimposed on each video view. Both sensor data and video data were collected at a rate of 30 Hz. Figure 3–11 also shows how the following data was located on each of the views:

- the speed the subject was driving in miles per hour
- the steering wheel position in degrees from center, ranging from + 480 degrees (steering input to the left) to -480 degrees (steering input to the right)
- the normalized accelerator pedal position in proportion deviated from 0 (fully released) to 1 (fully depressed)
- the normalized brake pedal position in proportion deviated from 0 (fully released) to 1 (fully depressed)
- the distance to the center of the intersection in feet
- the frame number linking this data with all the data collected and stored on the computer (See section 3.5 on dependent variables for a description of all the data.)

3.2 SUBJECTS

Sixty females and 60 males between the ages of 25 and 55 participated in this study. Subjects were recruited using advertisements placed in local newspapers and flyers distributed throughout eastern Iowa. To be eligible, subjects had to have a valid driver's license, pass the IDS health-screening criteria, and not have previously participated in an IDS driving study.

3.3 EXPERIMENTAL DESIGN

The study used a 2 x 2 x 2 x 2 experimental design. The between-subjects factors were brake type (ABS or conventional), speed limit (45 or 55 mph), TTI (2.5 or 3.0 seconds), and instruction (ABS-specific or safety-only video).

Eighty subjects were assigned the ABS condition and 40 were assigned the conventional brake system condition. To address the question of whether drivers are more likely to crash in an ABS-equipped vehicle due to lack of knowledge about ABS, ABS instruction was included as an independent variable. Of the 80 subjects in the ABS condition, 40 received ABS instruction and 40 received no ABS instruction. ABS instruction consisted of a short video with two parts—a segment describing the nature of the IDS and safety precautions, and a segment illustrating ABS operation and use taken from an original equipment manufacturer video designed for purchasers of new vehicles. For the non-ABS control condition, subjects viewed only the IDS and safety section of the video.

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.

TTI was defined as the time it took subjects to reach the intersection at their current velocity as measured from a 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. TTI values of 2.5 and 3.0 seconds were selected for comparability with the ABS test track study.

A counterbalance scheme was used to ensure that each condition accommodated for differences in days, time of day, and gender differences.

The experiment took four and a half days to conduct. In general, each subject spent less than one hour completing the experiment—about 15 minutes were spent in preparing for the drive (consent forms, briefing and video), 15 minutes were spent in the simulator, and 30 minutes were spent filling out a post-drive questionnaire.

3.4 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, the scenario taking place along a fifteen-mile-long stretch of two-lane rural roadway. 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.

When subjects entered the simulator, an experimenter seated inside the vehicle instructed them to adjust the seat and mirrors. The subject was then told to begin driving. During an initial portion of the drive during which no data were collected, the experimenter allowed the subject to get comfortable with the feel of the simulator. The subject started the five-mile practice portion of the drive on the roadway shoulder. After two vehicles passed from behind, the subject was instructed to merge and practice steering and braking and accelerating. This was to ensure that the subject had experience controlling the vehicle prior to the intersection incursion. Approximately five minutes into the drive, subjects were asked to begin to drive normally and to assess the simulator.

Red and white stripes on the roadway indicated the beginning of the actual drive and the beginning of data collection. The speed limit was either 45 or 55 mph throughout the drive. Seven miles into the actual drive, subjects came upon a slow-moving semi tractor-trailer (i.e., truck) driving 40 mph (see Figure 3–12). The truck approached a hill and slowed to 25 mph, maintaining this speed while climbing the hill. Thus, subjects driving behind the truck were also required to reduce their speed to approximately 25 mph. Oncoming traffic was spaced at six vehicles per mile in order to eliminate the possibility of passing. 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.

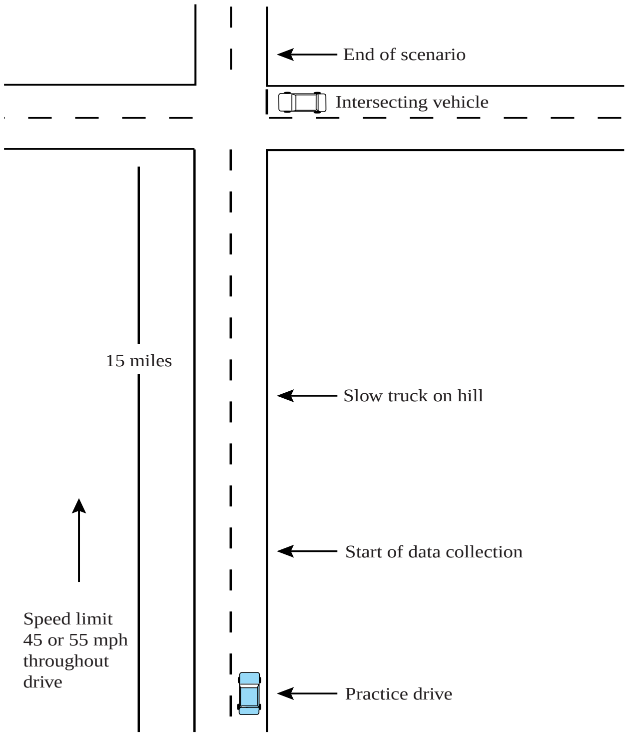

Figure 3–12. Map of the simulated drive

Shortly thereafter, another vehicle called the lead vehicle appeared 400 feet ahead of the subject vehicle traveling 40 mph. As the subject moved closer to the vehicle, it accelerated to maintain a headway of 6 seconds. 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 ahead, and that nothing out of the ordinary would occur. As the subject vehicle approached the intersection where the incursion would take place, the lead vehicle could be seen by the subject as it drove through the intersection without stopping or braking. When the lead vehicle came within two seconds of the intersection, it accelerated away from the subject at a rate of 3 ft/sec^2. The subject was thus at least six seconds or more away from the intersection when the lead vehicle passed through it.

The intersection at which the incursion event took place was the only intersection in the route. As depicted in Figure 3–13, two vehicles were positioned on the perpendicular roadway at the intersection. A light truck was stopped at a stop sign on the left side of the intersection, and a Buick Regal at a stop sign on the right side of the intersection, with its front bumper positioned 48.5 feet away from the yellow centerline. At the time of the incursion event, there was no oncoming traffic. Time-to-intersection (TTI) was defined as the time it would take the subject vehicle to reach the intersection at its current rate of speed. At one of two specified TTIs—either 2.5 or 3.0 seconds—the Buick pulled out into the intersection at a rate of 13.8 ft sec^2 for 1.98 seconds. The Buick then decelerated and stopped (3.0 seconds after beginning the incursion) with its front bumper six feet into the right lane. This left enough room so the subject vehicle could fit between the incursion vehicle and the yellow centerline, but made it necessary for subjects to perform evasive maneuvers to avoid collision. The subject's reactions were captured by sensor and video data. Each subject's drive ended after the completion of the intersection incursion event. Subjects experienced the incursion event only once.

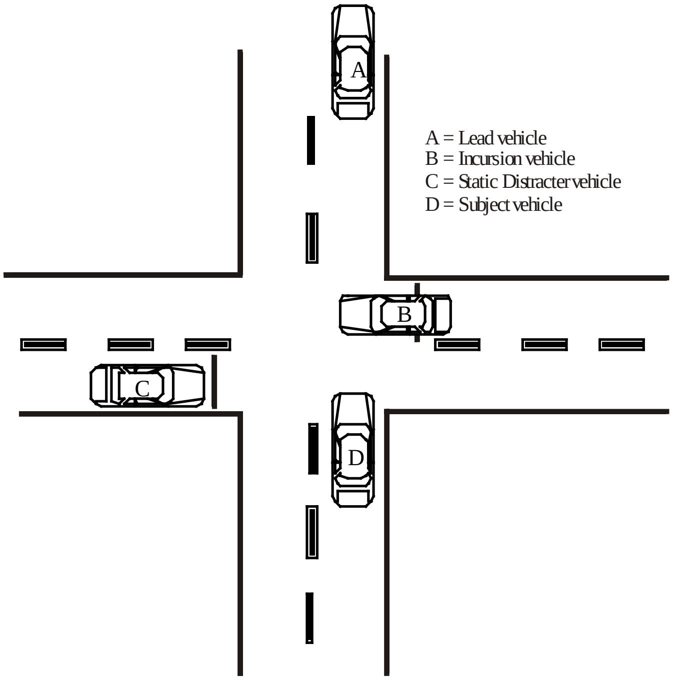

Figure 3–13. Intersection incursion from the right

3.5 DEPENDENT VARIABLES

To isolate driver behavior, a number of variables were captured and recorded to a data file at 30 hertz. These variables were:

- subject number
- gender
- condition subject was assigned
- simulator frame number associated with this data stream
- absolute time from approximately 7500 feet from the intersection
- distance-to-intersection in feet
- time-to-intersection in hundredths of a second
- speed the subject was driving in miles per hour
- steering wheel position in degrees from center ranging from + 480 degrees (steering input to the left) to -480 degrees (steering input to the right)
- accelerator pedal position normalized from 0 (fully released) to 1 (fully deviated)
- brake pedal position normalized from 0 (fully released) to 1 (fully deviated)
- lane position in meters deviated from the center of the lane
- longitudinal acceleration in feet per second squared
- lateral acceleration in feet per second squared
- brake pedal force in pounds
- whether there was a collision with the encroaching vehicle
- when the encroaching vehicle started to move in absolute time
- distance the encroaching vehicle moved in feet
- center of gravity of subject vehicle in lane

In addition to these data, subjects filled out several questionnaires that asked specific questions about their driving experience (see Appendixes F and G for these questionnaires). The in-vehicle experimenter log sheets and the videotape analysis were also used to determine driver behavior when a collision occurred, and the circumstances surrounding the collision.

3.5.1 Videotape Analysis

All the videotapes were analyzed in detail to verify the results found in the in-vehicle log sheets and to determine driver behavior before and after the vehicle incursion. The following in-vehicle log sheet information was verified: subject avoidance behaviors, subject vehicle position in the lane and on the roadway, whether the subject collided with the encroaching vehicle, and the impact location on the encroaching vehicle. During this verification analysis, the final outcome for successful maneuvers was also noted. Subjects could avoid the encroaching vehicle by swerving around it to the right, swerving left around it, or braking to a stop prior to reaching the intersection.

The videotapes were also used to determine time-to-driver behavior and transition time between driver behaviors. All times were defined from the point at which the encroaching vehicle began to move. Driver behaviors of interest included releasing or pressing the accelerator, releasing or pressing the brake pedal, and turning the steering wheel. The videotapes were viewed frame by frame to determine the point at which subjects began to perform each of these behaviors. The four primary time-to-driver behaviors were accelerator release, brake press, full brake, and steering. Accelerator release was defined as the point at which the subject's foot started to release the accelerator; brake press occurred when the subject's foot was over the brake pedal; full brake was defined as the point at which the brake pedal was fully depressed as determined using the on-screen value of brake pedal position normalized from 0 (fully released) to 1 (fully applied); and steering was said to occur when the subject initiated a steering input of at least six degrees at a rate of at least 0.5 degrees every 0.033 seconds. These definitions were also used to determine all transition times between the release of the accelerator and full depression of the brake pedal. For example, transition time from accelerator release to brake press was defined as the time between when the subject began to release the accelerator to the subject's foot being over the brake pedal.

4.0 RESULTS

The wide array of dependent measures recorded for this study (see Methods section) were grouped into three categories: initial responses, emergency steering/braking measures, and final outcome (crash, impact speed, road departure, etc.). A separate analysis of variance (ANOVA) was conducted for each measure (initial response time, steering, and braking), using a 2 (brake system) x 2 (instruction) x 2 (TTI of 2.5 or 3.0 seconds) x 2 (speed limit 45 or 55 mph) between-subjects model to test for significant differences in each of the experimental factors. In addition, crash outcome was analyzed using logistic regression.

The experimental results are presented in the following order:

- overall effects of brake system
- effects of instruction
- effects of TTI
- effects of speed limit

4.1 OVERALL FINDINGS AND EFFECTS OF BRAKE SYSTEM

4.1.1 Initial Responses and Response Times

Driver crash-avoidance behavior was examined relative to the initial movement of the encroaching vehicle. Time-to-accelerator-release, time-to-brake-press, and time-to-first-steering were analyzed along with transition times between these behaviors.

Time-to-accelerator-release. Almost all of the 120 subjects released the accelerator as their initial response to the vehicle incursion (one subject steered > 6 degrees first). The overall mean accelerator release time in response to the incursion event was 0.97 seconds. Seven subjects released the accelerator prior to the incursion event and were not included in this particular analysis. No significant differences were found between brake response times for subjects in the two brake conditions.

Time-to-brake-press. Brake press was defined as the point at which a subject’s foot was located over the brake pedal. The overall mean brake response time was 1.14 seconds. The two brake system types were not found to have a significant effect on brake response times.

Time-to-first-steering. First steering was defined as the point at which the subject had made a steering input of 6 degrees. The overall average steering response time was 1.65 seconds. No significant differences were found between the response times to first steering.

Transition times. Overall average transition times were calculated between these initial responses, as well as between the initial responses themselves and their respective maximum reactions. The mean accelerator-to-brake transition time was 0.17 seconds, while the mean brake-to-full-brake transition time was 1.06 seconds. The mean accelerator-to-steering transition time was 0.68 seconds, and the steering-to-full-steering transition time was 1.74 seconds.

4.1.2 Emergency Braking and Steering Responses

Crash Avoidance Strategy. All 120 subjects used some form of steering and braking input in an attempt to avoid colliding with the scenario vehicle as it encroached into their lane. Ninety-five subjects (79 percent) applied the brakes before steering. Five subjects (4 percent) initiated braking and steering inputs simultaneously. Twenty subjects (17 percent) steered before applying the brakes.

Initial steering input was defined as the first steering input of a magnitude greater than six degrees made after the encroaching vehicle had begun to move. In this study, 72 subjects (60 percent) steered to the left for their initial steering input, and 48 (40 percent) steered to the right.

The measure “avoidance steering input” was defined to identify that steering input which the subject attempted in order to maneuver around the crossing vehicle. This measure was operationally defined as the steering input that was in progress as the subject vehicle passed through the plane of motion of the encroaching vehicle. This input was not necessarily the subject’s first steering input in response to the incursion. During the collision avoidance maneuver, 103 subjects (86 percent) attempted to steer left of the encroaching vehicle and 17 (14 percent) attempted to steer right to avoid a collision. Thirty-seven of the subjects who steered left crashed (35.9 percent), while five of those who steered right crashed (29.4 percent).

Steering Behavior. Maximum steering input was measured in three ways: 1) “maximum steering input” was defined as the greatest magnitude in degrees that the steering wheel deviated from the zero degree midpoint, with a maximum of 480 degrees in either direction; 2) “maximum steering range” summed the angular displacement from the greatest deviation to the left to the greatest deviation to the right, and could produce a result as high as 960 degrees if the subject steered to the “lock” on the left and the “lock” on the right while attempting to avoid the encroaching vehicle; 3) “maximum steering rate” measured the maximum acceleration at which the steering wheel was turned to obtain an estimate of the maneuver severity. To qualify for a single steering wheel input, the rate could not drop below 0.5 degrees every 0.033 seconds and the input had to be at least six degrees in magnitude.

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

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

Table 4–1 presents mean emergency steering measures by brake system. As can be seen, brake system type had a strong effect on steering in this study, with more severe steering generally seen for subjects with conventional brakes than for those with ABS.

Table 4–1. **Mean steering behavior measures by brake system (significant results in bold text)**

Steering Behavior	Conventional Brake System	ABS	F RATIO	P-Value
Magnitude of avoidance steering input (degrees)	**192**	**125**	**7.74**	**0.0064**
Maximum left steering input (degrees)	**176**	**121**	**4.64**	**0.0334**
Maximum right steering input (degrees)	131	105	1.28	0.2615
Maximum steering input, right or left (degrees)	**212**	**131**	**10.87**	**0.0013**
Maximum steering input rate (degrees per second)	595	473	3.85	0.0524
Time to maximum steering input (seconds)	**3.687**	**3.239**	**8.14**	**0.0052**
Maximum steering range (degrees)	284	222	2.66	0.1057

Brake type had a significant effect on the average magnitude of the avoidance steering input, with an average of 125 degrees for ABS subjects compared to 192 degrees for conventional brake subjects.

As described previously, a majority of subjects steered left for the avoidance maneuver. Of those steering left, ABS subjects steered a significantly smaller magnitude (121 degrees) than did subjects with conventional brakes (176 degrees). The maximum right-steering measure was also greater for the conventional brake condition, but the difference was not statistically significant. The “maximum steering input, right or left” measure again reflected these differences, with means of 212 degrees for conventional brakes versus 131 degrees for ABS.

The average maximum steering rate of subjects’ avoidance maneuvers showed an almost significant effect from the brake system, with the ABS subjects steering at a lower rate (473 degrees per second) than subjects in the conventional brake system condition (595 degrees per second).

The time-to-maximum-steering input was likewise significantly affected by brake condition. On average, subjects in the ABS condition reached their maximum steering 448 ms faster than those with conventional brakes.

Maximum steering range was the only steering measure besides the maximum right steering measure that did not show a nearly statistically significant effect due to brake type. Nevertheless, here again, what differences did appear were in the direction of greater steering for conventional brakes than for ABS.

Braking Behavior. 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.

Table 4–2 presents braking measure data for the two brake system types. A t-test found a significant difference in brake pedal duration, with longer duration for conventional brakes (3.12 seconds) than for ABS (2.69 seconds).

Table 4–2. Mean braking measures for conventional and ABS brake conditions

Braking Measure	Mean for conventional brake condition	Mean for ABS condition	F-Ratio	P-Value
Brake pedal duration (seconds)	3.12	2.69	4.18	0.0435
Maximum Pedal Force (pounds)	98.2	85.8	2.85	0.0944
Time to maximum pedal force (seconds)	2.115	2.246	0.38	0.5365

The other braking measures—maximum brake pedal force and time-to-maximum-braking—did not show a main effect for brake system type.

4.1.3 Final Outcome

Road Departures. Eight people completely 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 four of these six cases, the vehicle spun off the road.

The eight subjects who departed the roadway completely during collision avoidance were evenly divided between the two brake conditions. Four of the 80 subjects in the ABS condition (5 percent) drove off the road totally; in each case the ABS was activated during the crash avoidance maneuver. Four of the 40 subjects who had conventional brakes (10 percent) also left the road completely.

All four instances of full road departure with ABS were at the 45 mph speed limit, whereas each of the four road departures with 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.

Crashes. Overall, 42 of the 120 subjects, or 35 percent, collided with the scenario vehicle as it encroached into their lane. Subjects with ABS crashed less frequently (31 percent) than those in the conventional brake system condition (43 percent), but this difference was not found to be statistically significant by the ANOVA using the dichotomous “speed limit” variable. However, since subjects did not always drive exactly 45 or 55 mph as instructed, it was felt that a more predictive variable would be the “scenario entrance speed” (i.e., the speed at which a subject was driving when the Buick began its incursion into the intersection). Therefore, a logistic regression was carried out using dummy variables for TTI, brake type, and instruction, and a continuous variable for scenario entrance speed. This logistic regression analysis did find a significant main effect for brake type ($p = 0.03$).

4.2 EFFECT OF INSTRUCTION

Forty of the ABS subjects viewed videotaped ABS usage instructions; the other 40 subjects in the ABS condition, and the 40 subjects in the conventional-brake condition, viewed a general driver-safety video with no ABS instruction. Instruction was balanced throughout the ABS conditions.

4.2.1 Initial Responses

The ANOVA found no significant differences between the group of 40 ABS subjects who received ABS instruction and the other 40 ABS subjects who received no instruction.

4.2.2 Emergency Steering and Braking Behavior

Steering behavior. When tested with an ANOVA, none of the steering measures were found to show a significant effect of instruction.

Braking measures. Separate ANOVAs were run for the braking variables of maximum brake pedal pressure, maximum brake duration, and time-to-maximum braking. None of these showed a significant effect of instruction.

4.2.3 Final Outcome

Roadway departures. As stated earlier, four of the 80 ABS subjects had all four wheels depart the roadway during the avoidance maneuver. This number was divided equally between the instruction and non-instruction conditions.

Crashes. Also as stated earlier, 31 percent or 25 of the 80 ABS subjects crashed into the encroaching vehicle. Of the 40 subjects who received ABS instruction, 33 percent or 13 of 40 subjects crashed into the encroaching vehicle, while 30 percent or 12 of the 40 subjects who were in the ABS condition but did not receive ABS instruction crashed into the encroaching vehicle. This difference was not statistically significant.

Impact speed. No significant results were found for impact speed by instruction. The ABS instruction group was found to have a significantly higher impact speed when compared ABS subjects who did not receive instruction. The mean impact speed for ABS subjects who received instruction was 32.5 mph versus 27.5 mph for ABS subjects who did not receive instruction.

4.3 EFFECT OF TTI

4.3.1 Initial Responses

Separate ANOVAs were run for the performance measures of time-to-accelerator-release, time-to-brake-application, and time-to-first-steering. Several small but statistically significant main effects for TTI were found for these initial-response time measures. On average, subjects in the shorter (2.5 second) TTI condition were 78 ms slower to release the accelerator and 90 ms slower to apply the brake than subjects in the longer (3.0 second) TTI condition. However, the shorter-TTI subjects were 240 ms faster than the longer-TTI subjects on the time-to-first-steer measure (see Table 4–3).

Table 4–3. Mean initial response time for subjects in the 2.5 second and 3.0 second TTI condition

Response	Mean for shorter TTI condition (2.5 seconds)	Mean for longer TTI condition (3.0 seconds)	F-Ratio	P-Value
Time-to-accelerator release	1.014	0.936	3.7	0.0572
Time-to-brake-application	1.183	1.093	6.45	0.0125
Time-to-first-steering	1.527	1.767	7.42	0.0075

4.3.2 Emergency Braking and Steering Behavior

Steering behavior. The ANOVA found no statistically significant main effects of TTI on steering measures.

Braking behavior. Table 4–4 shows mean brake time by braking force for the two TTI groups. The ANOVA revealed a significant effect of TTI on time-to-maximum-brake-pedal-force. The average time was 321 ms faster for the shorter TTI group than for the longer. (This was despite the slower initial time-to-brake-application seen for the shorter TTI group.)

Table 4–4. Mean brake time for subjects in the 2.5 second and 3.0 second TTI condition

Braking Measure	Mean for shorter TTI condition	Mean for longer TTI condition	F Ratio	P-value
Maximum Pedal Force (pounds)	90.9	89.0	0.04	0.8452
Time to maximum pedal force (seconds)	2.042	2.363	9.65	0.0024

4.3.3 Final Outcome

Road departures. As noted above, there were too few road departures to analyze statistically.

Crashes. TTI was found to exert a strong effect on crash outcome. A logistic regression found a statistically significant main effect for TTI ($p<0.0001$). Only 10 percent (6 of 60 subjects) in the 3.0 second TTI group crashed, as compared with 60 percent (36 of 60) in the 2.5 second TTI group.

4.4 EFFECT OF SPEED LIMIT

4.4.1 Initial Responses

The ANOVA found no main effects of speed limit on the means for any of the following variables: time-of-first-action, time-to-throttle-release, time-to-brake-application, and time-to-first-steering.

4.4.2 Emergency Steering and Braking Behavior

Regardless of speed limit, subjects tended to brake first and steer later when attempting to avoid colliding with the crossing vehicle. Speed limit did not have a significant main effect on any of the steering or braking variables.

4.4.3 Final Outcome

Road departures. Four 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 in the 55 mph condition involved subjects in the conventional brake condition.

Crashes. Forty two percent (40 percent ABS, 45 percent non-ABS) of those driving in the 55 mph speed limit collided with the encroaching vehicle. Only 28 percent (22 percent ABS, 40 percent non-ABS) crashed in the 45 mph condition. No differences were statistically significant.

4.4.4 Scenario Entrance Speeds

While subjects were instructed to drive at either 45 or 55 mph, they were free to vary their actual speed from these values. The speed at which subjects were driving at the point just prior to the intersection incursion was recorded as the “scenario entrance speed.” Figure 4–1 shows the frequency distribution of scenario entrance speeds for subjects in the 45 and 55 mph speed limit conditions. The differences in the two distributions demonstrate that subjects complied with the speed limit to a large extent. The average scenario entrance speed for the 45 mph speed limit condition was 45.6 mph; the average scenario entrance speed for the 55 mph condition was 53.2 mph.

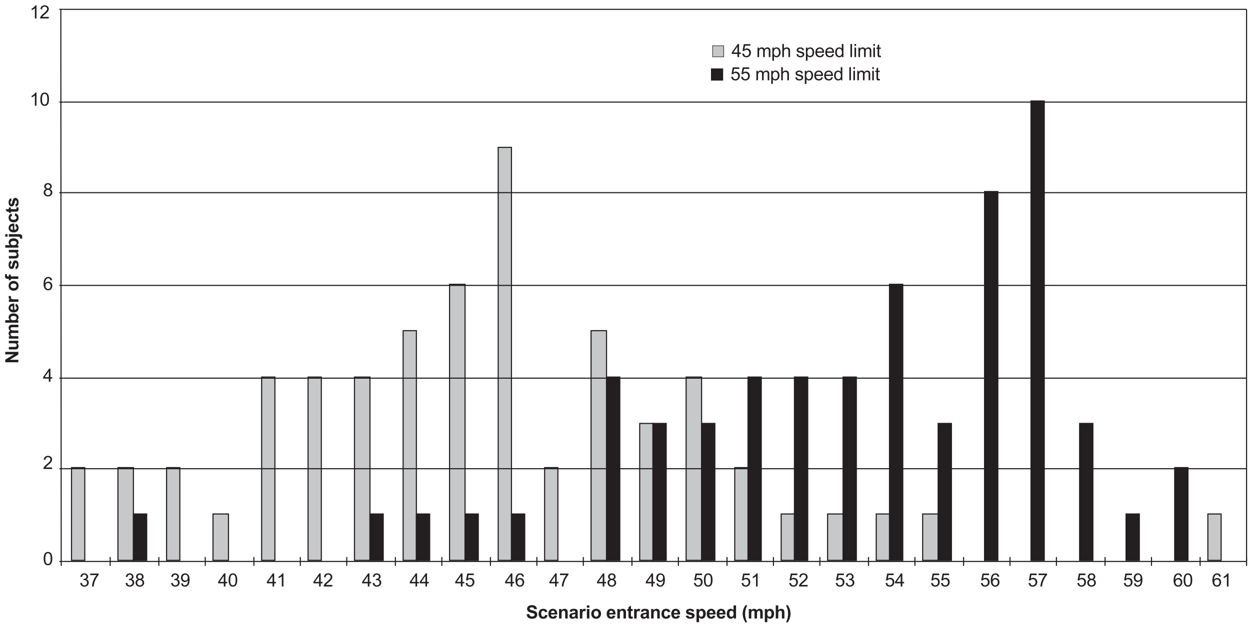

Figure 4–1. Frequency distribution of scenario entrance speeds for subjects in the 45 mph and 55 mph speed limit conditions

4.5 SIMULATOR REALISM

A standard IDS post-drive questionnaire was used to assess subjects' perceptions of the simulator's realism. Four questions were of particular interest for the present study—two concerning the realism of the steering and two concerning the realism of the braking.

Lane maintenance. Figure 4–2 shows the distribution of subjects' ratings when asked how frequently they needed to make steering adjustments to stay in the lane in the simulator, compared to their own vehicle. As can been seen, subjects tended to report needing to steer more frequently in the simulator. Actually, since the simulated roadway was straight and smooth, subjects were rarely required to steer to maintain their lane position. Therefore, reported difficulties in maintaining lane position were self-induced and possibly affected by lack of sufficient road feel.

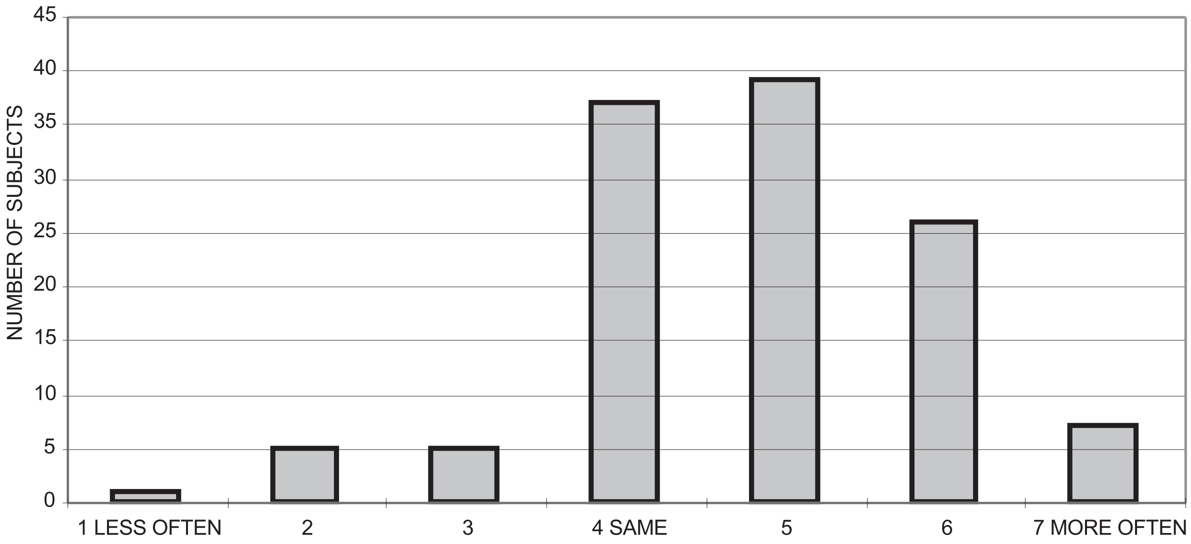

Figure 4–2. Lane maintenance rating

Steering tightness, stopping ability, and brake force ratings. Figures 4–3 through 4–5 depict the distribution of subjects' ratings for steering tightness, stopping ability, and required brake force in the simulator, as compared to driving their own vehicle. As can be seen, most subjects found the simulator was "just right" or nearly so for these three parameters.

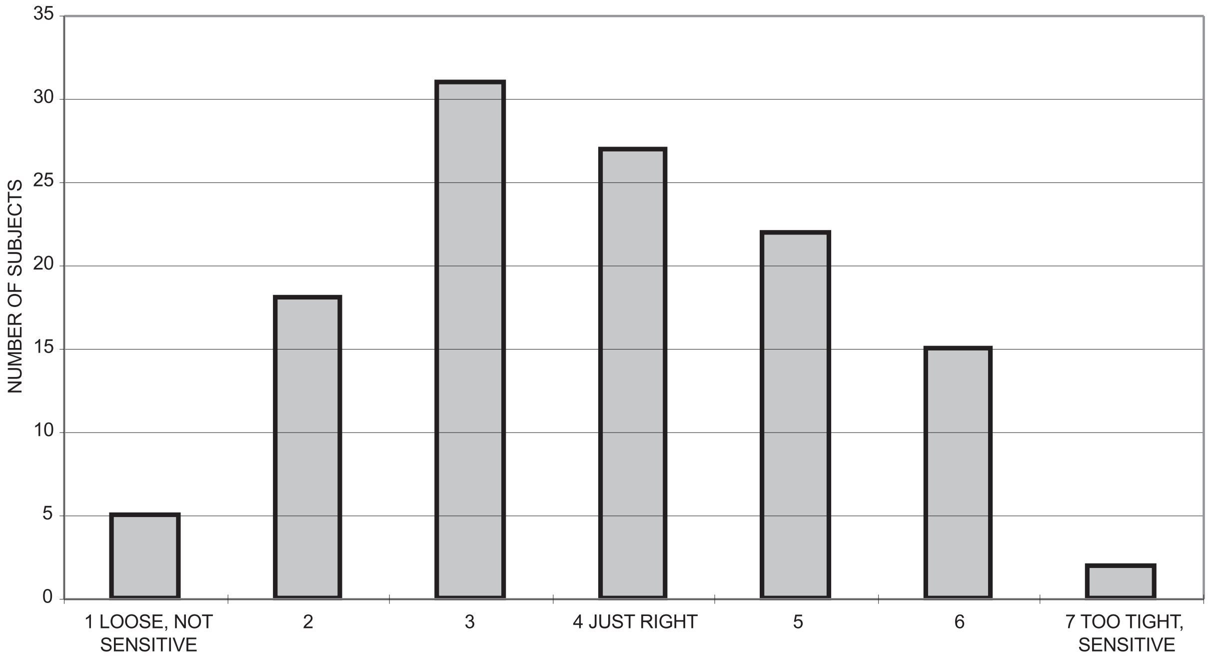

Figure 4–3. Steering tightness rating

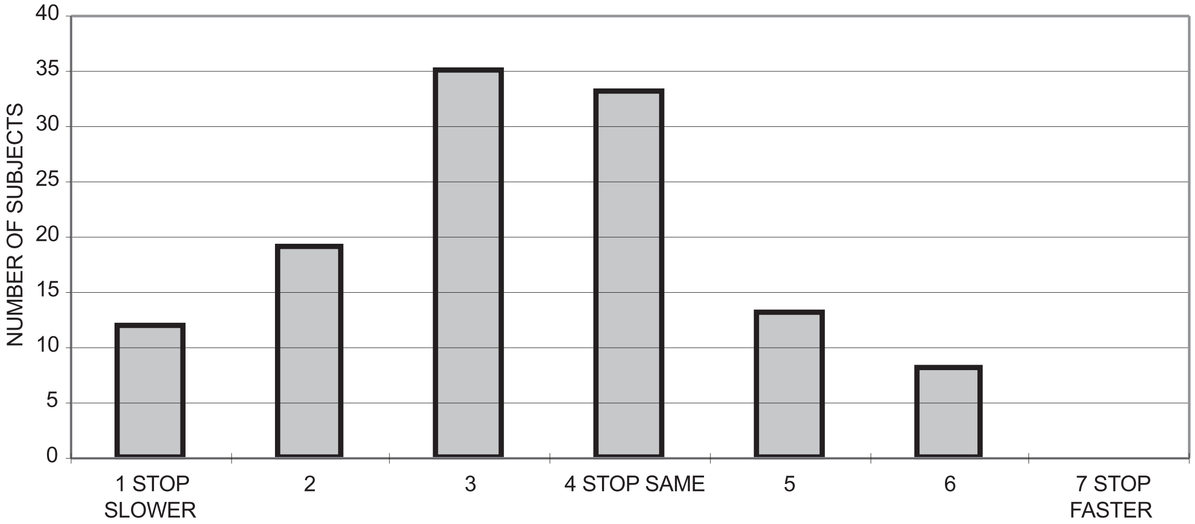

Figure 4–4. Stopping ability rating

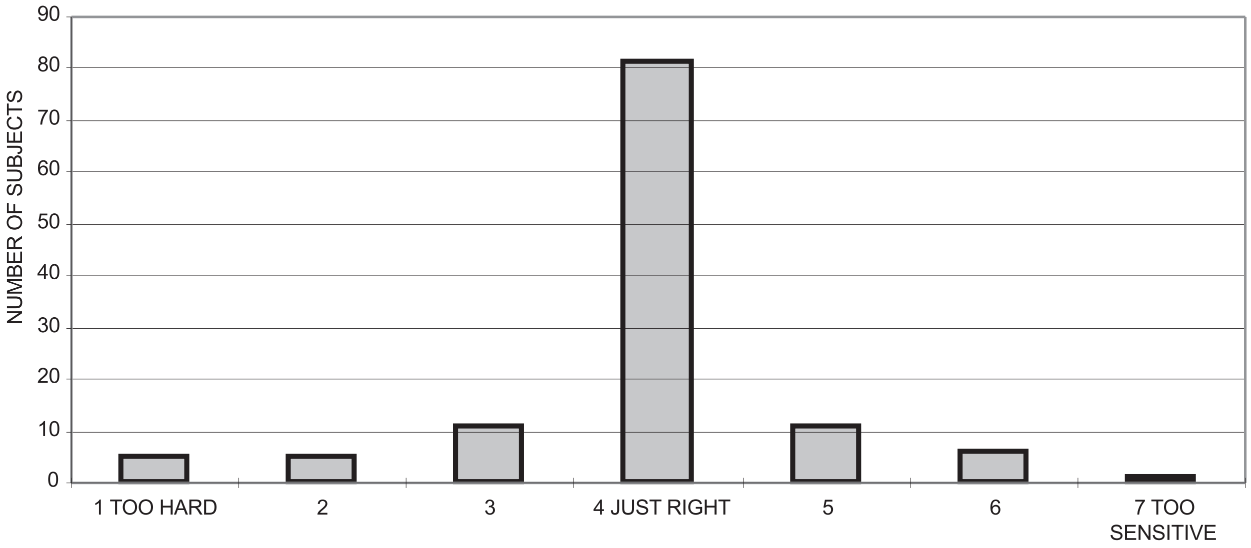

Figure 4–5. Brake force rating

5.0 DISCUSSION

This study was designed to assess driver behavior and associated reaction time using ABS and conventional brakes in a crash avoidance scenario. The braking and steering behaviors of drivers presented with an intersection incursion were of primary interest. Scenarios used an incursion vehicle that started moving into an intersection at either 2.5 or 3.0 seconds time-to-intersection (TTI). The vehicle intersected from the driver's right side and blocked one-half of the driver's lane. These scenarios were designed to be surprise events in an effort to elicit emergency avoidance behaviors. This research was designed to provide information on the following research questions:

- Could over-steering or some other driver avoidance behavior account for the increase in ABS-associated rollover crashes?
- How does the stability and control of either ABS or non-ABS contribute to the control of a vehicle during crash avoidance circumstances?
- How does ABS instruction affect driver performance?
- What behaviors are associated with emergency avoidance in an intersection, and what are the associated reaction times to these behaviors?
- What effect does speed have on the stability and control of ABS and non-ABS equipped vehicles?

5.1 OVERALL EFFECTS OF BRAKE SYSTEM

5.1.1 Initial Responses and Response Times

Subjects' braking, steering, and acceleration were monitored prior to their approach to the intersection. Driver crash-avoidance behavior was examined relative to the initial movement of the incursion vehicle. Time-to-accelerator-release, time-to-brake-press, and time-to-first-steering were analyzed along with transition times between these behaviors. Nearly all of the 120 subjects released the accelerator as their initial response to the vehicle incursion. The overall mean accelerator-release time in response to the incursion event was 0.97 seconds. No significant differences were found between initial brake and steering-response times for subjects in the two brake conditions. This result was consistent with expectations, since brake type should not affect initial response. Steering response times also did not vary by brake system type.

The questionnaires used to assess subjects' opinions on the intersection scenario and the simulator indicated that the incursion was an unanticipated event. Almost all subjects reported that they approached the intersection as they usually would have in the real world. The intersection incursion appeared to be a surprise event and subject interaction with the encroaching vehicle appeared to be realistic and unbiased by suspicion. The videotape analysis of the intersection incursion confirmed that most subjects were surprised by the encroaching vehicle's behavior. This indicates that the ruse protocol was effective. Furthermore, the lead vehicle ahead of the subject was successful in ensuring that the subject would not anticipate that the encroaching vehicle was a threat.

Finally, there was some concern that subjects would be distressed by being placed in an emergency avoidance situation that often ended in collision. Most subjects, however, rated this study as a positive experience. Facial expressions and verbal comments recorded on videotape seem to indicate that the experience, although compelling, was not overly stressful.

5.1.2 Emergency Steering and Braking Behavior

All 120 subjects used some form of steering and braking input in an attempt to avoid colliding with the scenario vehicle as it encroached into their lane. Ninety-five subjects (79 percent) applied the brakes before steering. Five subjects (4 percent) initiated braking and steering inputs simultaneously. Twenty subjects (17 percent) steered before applying the brakes. This unanimous tendency to both brake and steer to avoid a crash was not seen in any studies reviewed as background for this research. For example, Araki and Matsuura (1990) showed that only 44 percent of subjects both braked and steered in response to a simulated pedestrian darting into their path. Olson and Sivak (1986) found that 79 percent of subjects steered at some point during their maneuver to avoid a crash with a piece of yellow foam rubber that appeared in their lane. It is possible that the nature of the obstacle (degree of danger it presents to the driver) as well as the perceived amount of time in which to avoid crashing into it may have an effect on drivers strategy to avoid a collision in this type of scenario.

Initial steering input was defined as the first steering input of a magnitude greater than six degrees made after the incursion vehicle had begun to move. In this study, 72 subjects (60 percent) steered to the left for their initial steering input, and 48 (40 percent) steered to the right.

Braking and steering responses by brake system type are important since the ultimate outcome of a crash avoidance event is to successfully maneuver around the hazard (in this case the encroaching vehicle). Successful avoidance is also affected by the time at which such incursions occur—relative to the distance in time from the event. This study examined two different times to intersection, 2.5 and 3.0 seconds. Subjects in the shorter TTI reacted significantly slower overall relative to those subjects in the longer TTI condition in both the accelerator release (78 ms slower) and initial brake press (90 ms). This same effect was also found in previous braking studies on the IDS (McGehee et al 1996). This suggests that there may be a "point of no return" at which drivers are committed to an action. Subjects may have dismissed the likelihood of the vehicle encroaching and shifted their attention to the forward roadway and thus had a larger delay in reacting.

The measure "avoidance steering input" was defined to identify that steering the subject attempted in order to maneuver around the crossing vehicle. This measure was operationally defined as the steering input that was in progress as the subject vehicle passed through the plane of motion of the incursion vehicle. This input was not necessarily the subject's first steering input in response to the incursion. During the collision avoidance maneuver, 103 subjects (86 percent) attempted to steer left of the encroaching vehicle and 17 (14 percent) attempted to steer right to avoid a collision. Thirty-seven of the subjects who steered left crashed (35.9 percent), while five of those who steered right crashed (29.4 percent). It should be noted that there was no oncoming traffic so subjects were able to clear the encroaching vehicle without risking a head-on crash.

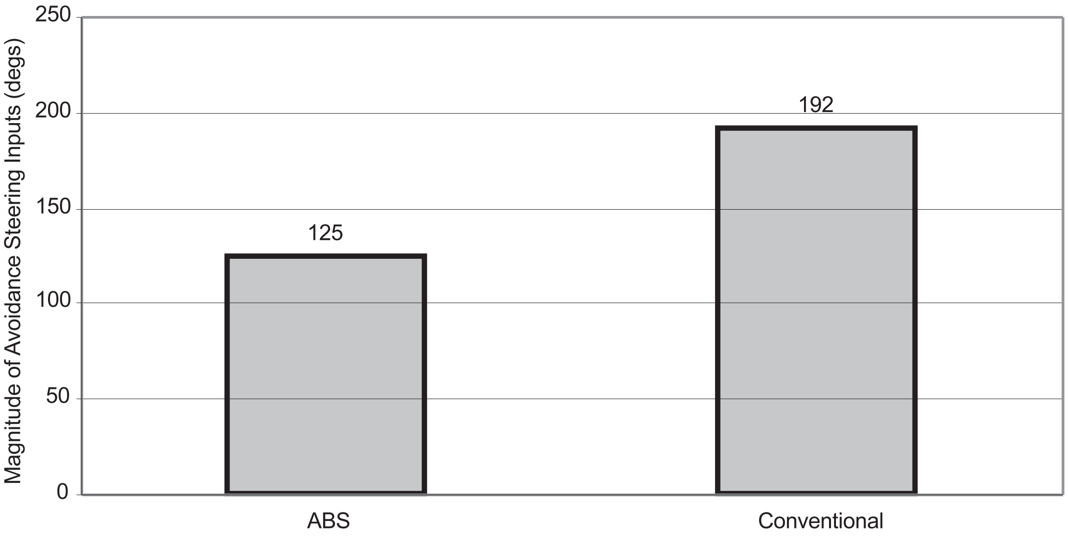

Figure 5–1. Magnitude of steering by brake type

In perhaps the strongest results of this study, subjects with ABS clearly demonstrated significantly greater stability and control in regard to steering relative to those with conventional brakes. Subjects with ABS did not have such large steering inputs as shown in Figure 5-1.

The large steering inputs seen in the conventional brake condition indicate less control relative to the ABS condition. Large differences were also found for steering in the maximum steering to the left, maximum steering rate and time-to-maximum steering rate.

5.2 EFFECTS OF INSTRUCTION

The effect of instruction was a key issue in this study since it is widely believed that drivers lack instruction in 1) how ABS operates mechanically, and 2) how ABS affects the "feel" of braking when activated. With ABS, the brake pedal back pressure paired with the vibration may startle some drivers into releasing the brake pedal. It should be noted that this study did not examine the effect of different brake pedal back pressures. However, the Taurus brake model back pressure used for this study can be compared to the NHTSA VRTC test track study that was conducted in parallel.

The instruction results showed no significant effects. The ABS instruction group was found to have a somewhat (not significant) higher impact speed when compared to the result for ABS subjects who did not receive instruction. The mean impact speed for ABS subjects who had received instruction was 32.5 mph, while subjects who did not receive instruction had a mean impact speed of 27.5 mph. As there was no statistical difference in the number of crashes between instruction and non-instruction groups, this must be viewed as a detrimental result.

One limitation of this study was that subjects were instructed passively on ABS. In other words, they had no direct experience of ABS in their instruction, and were not given the opportunity to practice using the ABS prior to the emergency maneuver. This was done in order to protect the ruse, and points to the challenge of this type of experimental measure. It is difficult to train subjects completely in the proper use of systems such as ABS in crash avoidance without giving away the fact that you are interested in crash avoidance behavior and thus exposing the "evaluation of simulator fidelity" ruse. It may not be possible to truly examine this factor accurately without doing longer, field-based studies. Again, the VRTC test track study should provide more information relating to this effect.

Since lack of training seems to be a factor in terms of early brake release due to pedal feedback, a second analysis was conducted to examine whether subjects released their feet when the brake pedal began to vibrate. None of the subjects released the brake at vibration onset; thus, this did not seem to be an effect. Nor did the questionnaire data flag any anomalies in the ABS feel relative to the conventional brakes.

5.3 EFFECTS OF TTI

To determine at what point in time an encroaching vehicle became a threat to the subject driver, time-to-intersection was included in this study. *When* a driver must react to a threat affects the driver’s strategy in avoiding a crash, as well as the ensuing stability and control of the vehicle. Generally, the farther back a driver begins an avoidance maneuver the more the brakes will be used, and the closer the driver is to a collision threat the more he or she will steer (McGehee et al., 1996). ABS-equipped vehicles are likely to show a benefit in cases where the driver requires both steering and braking, that is, at the midpoint of these extremes.

This study examined two different times-to-intersection—2.5 and 3.0 seconds. These values were based on a VRTC test track study. Subjects in the shorter TTI reacted significantly slower than those who had more time to react in the longer TTI condition in both the accelerator release (78 ms slower) and initial brake press (90 ms). This same effect was found in previous braking studies on the IDS (McGehee et al., 1996). As mentioned previously, this suggests that there may be a “point of no return” at which drivers are committed to going through an intersection. Subjects may have dismissed the likelihood of the vehicle encroaching and shifted their attention to the forward roadway, thus delaying their reaction.

Time-to-steering behavior showed an opposite result in terms of driver reaction. While subjects in the short TTI released the accelerator later, their steering reaction was significantly faster than that of subjects in the longer TTI. This is consistent with previous hypotheses that drivers’ steering is the more important factor in extreme avoidance actions.

5.4 EFFECTS OF SPEED LIMIT

Because speed is also related to driver collision avoidance strategy and the stability and control of the vehicle, multiple speed limits were used as a factor for this study. While no significant differences were found for any of the speed-related variables, individual strategies were quantified. For instance, almost all subjects tended to brake first and steer later when attempting to avoid colliding with the crossing vehicle. Speed limit did not have a significant main effect on any of the steering or braking variables. However, as the slower speed of 45 mph did show a 22 percent ABS crash rate relative to a 40 percent conventional brake crash rate, this result would likely be significant if the number of subjects in the conventional brake conditions matched the ABS condition (80 subjects were in ABS and 40 in conventional). A significant difference in this case would likely be due to the increased stability and control of ABS. Since there was no statistical difference in the two speed groups, a separate analysis was conducted that attempted to pair actual intersection entrance speeds. The analysis determined that the two distributions demonstrate that subjects complied with the speed limit to a large extent.

6.0 CONCLUSIONS

To determine whether some aspect of driver behavior may be counteracting the potential benefits of ABS in a crash-imminent situation, this study examined driver crash avoidance behavior as a function of a vehicle's brake system and various other factors.

One of the theories that this study sought to address was whether the apparent increase in single-vehicle crashes involving ABS-equipped vehicles was 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 and rendering a driver's steering behavior irrelevant. With four-wheel ABS, the vehicle's wheels do not lock; as a result, the vehicle does not lose directional control capability during hard braking, and the driver's steering inputs continue to be effective in directing the vehicle's motion. Such directional control could mean that drivers gain the potential to avoid multi-vehicle crashes by driving off the road and experiencing single-vehicle crashes.

Towards this end, the following questions were asked:

1. Could over-steering or some other driver avoidance behavior account for the increase in ABS-associated rollover crashes?

The results of this study indicate that for simulated intersection incursions, over-steering or other behaviors that cause a loss of control and/or rollover effects did not show a significant effect with vehicles equipped with ABS.

2. How does the stability and control of either ABS or non-ABS contribute to the control of the vehicle during crash avoidance circumstances?

The results of this study show overwhelmingly that ABS-equipped vehicles have increased stability and control in simulated intersection incursions.

3. How does ABS video taped based instruction affect driver performance?

Overall, video taped based instruction was not found to be effective in this experiment.

4. What behaviors are associated with emergency avoidance in an intersection incursion and what are the associated reaction times to these behaviors?

All 120 subjects used some form of steering and braking input in an attempt to avoid colliding with the scenario vehicle as it encroached into their lane. Ninety-five subjects (79 percent) applied the brakes as their initial response before steering. Five subjects (4 percent) initiated braking and steering inputs simultaneously as an initial response. Twenty subjects (17 percent) steered before applying the brakes. Furthermore:

- The overall mean accelerator release time in response to the incursion event was 0.97 seconds.
- The overall mean brake response time was 1.14 seconds.
- The overall average steering response time was 1.65 seconds.
- The mean accelerator-to-brake transition time was 0.17 seconds, while the mean brake-to-full-brake transition time was 1.06 seconds. The mean accelerator-to-steering transition time was 0.68 seconds, and the steering-to-full-steering transition time was 1.74 seconds.

5. What effect does speed have on the stability and control of ABS and non-ABS equipped vehicles?

While no significant differences were found for any of the speed-related variables, individual strategies were quantified. For instance, almost all subjects tended to brake first and steer later when attempting to avoid colliding with the crossing vehicle. Speed limit did not have a significant main effect on any of the steering or braking variables. However, as the slower speed of 45 mph did show a 22 percent ABS crash rate relative to a 40 percent conventional brake crash rate, this result would likely be significant if the number of subjects in the conventional brake conditions matched the ABS condition (80 subjects were in ABS and 40 in conventional). The difference, if significant, would likely be due to the increased stability and control of ABS.

6.1 RECOMMENDATIONS FOR FUTURE STUDY

The intersection incursion scenario for this study proved effective in testing extreme crash avoidance reactions by drivers. The scenario captured true, unalerted driver reaction time because of the sophisticated ruse and secondary scenarios that were set in place. These have been proven effective in a number of crash avoidance studies conducted for NHTSA, and should be continued for the NADS.

The one experimental design tradeoff made for this study due to budget considerations was having an unbalanced design in terms of baseline drivers. While having 40 drivers was adequate for direct experimental comparisons, as soon as variables like brake instruction were collapsed, an imbalance occurred.

A future study for the NADS would be one that examined run-off-road crash scenarios. This would provide additional data towards the goals of the overall NHTSA research program.

7.0 REFERENCES

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APPENDIX A: INFORMATION SUMMARY

INFORMATION SUMMARY

5/20/98

Project Title: CPO #5 - A (IQC1)	Principal Researchers:	Dan McGehee Peter Grant Liz Mazzae

Background: The purpose of the study you are participating in is to evaluate the realism of the Iowa Driving Simulator. From time to time we bring in drivers from the community to assess the simulator's feel, looks, and actions. We are particularly interested in evaluating the visual scenes and the feel of the steering, accelerating, and braking. The information gathered today will help us understand how devices of this kind are perceived by drivers and the usefulness of these simulators as research tools.

If you agree to participate, you will be asked to sign an Informed Consent Form indicating that you have read and understand the goals of this study.

Study Description: Driver responses to the realism of an automotive simulation are influenced by their unique capabilities and background. To help calibrate your responses, prior to driving the simulator, we will ask you to make a series of responses to four calibration tasks on a touch screen. These calibration tasks include a basic reaction-time task, a choice task, a tracking task, and a sequencing task. The calibration tasks should require only 5 to 10 minutes altogether. Following the touch-screen task, you will view a video tape on the driving simulator. You will then be asked to drive for approximately 20 minutes in the driving simulator and complete questionnaires that describe your reactions to the simulator's fidelity. Your total participation time will be about one hour.

Compensation: Should you agree to participate in this study, your compensation will be $30.

Risks: You should know that a small number of people experience something similar to motion sickness when operating simulators. The effects are typically slight and usually consist of an odd feeling or warmth which lasts only 10–15 minutes. If you feel uncomfortable, you can ask to stop at any time. Most people enjoy driving the simulator and do not experience any discomfort.

You should understand that in the event of physical injury resulting directly from the research procedures, no compensation will be available in the absence of negligence by a state employee. Medical treatment is available at the University Hospitals and Clinics, but you will be responsible for making arrangements for payment of the expenses of such treatment. Further information may be obtained from the Human Subjects Office, (319) 335-6564.

Benefits: This study will provide the University of Iowa with information on how members of the public perceive the fidelity of the Iowa Driving Simulator and will also provide the National Highway Traffic Safety Administration (NHTSA) with data on driver performance while driving in the simulator. The data may be used for educational purposes or in research on driver behavior and performance.

Informed Consent: By signing this form, you agree that your participation is voluntary. You may discontinue participation at any time without any penalty or loss of benefits to which you are entitled. You should understand that you have the right to ask questions at any time and that you can contact the principal investigator of this project Dan McGehee at (319) 335-6819 for information about the study and your rights as a participant in this research.

Confidentiality: A record of your driving performance on the simulator will be collected and the data recorded will be analyzed along with data gathered from other participants in this study. All engineering data will be stored and analyzed without reference to your name. Your name will not be associated with any data in the final report, publications, or other media that might arise from this study. By signing the informed consent statement below, you agree that NHTSA shall have unrestricted use of engineering data collected during participation without reference to your personal identity for scientific, educational outreach and research purposes in perpetuity.

Additional use of video images: Your video images (continuous or single framed) may be used for scientific, educational, and outreach purposes. By signing the permission statement below, you agree that the National Highway Traffic Safety Administration shall have unrestricted use of the video recording of your drive, which may contain images of your face.

I have discussed the above points, including the information required by the Iowa Fair Information Practices Act, with the research participant or the legally authorized representative, using a translator when necessary. It is my opinion that the subject understands the risks, benefits, and obligations involved with participation in this project.

____

Investigator Date

APPENDIX B: INFORMED CONSENT

INFORMED CONSENT

I certify that I have been informed about the study in which I am about to participate. I have been told the procedures to be followed and how much time and compensation is involved. I have been given adequate time to read the information summary. I understand that my participation is voluntary and that I may refuse to participate, or withdraw my consent, or stop taking part in the study at any time without penalty or loss of benefits to which I may be entitled. I understand the possible risks to me that may result from my participation in the research. I understand that I have the right to ask questions at any time and that I can contact Dan McGehee at (319) 335-6819 for information about the research and my rights.

I understand that for scientific, educational, and outreach purposes, the engineering data collected during my participation may be used without reference to my personal identity by the National Highway Traffic Safety Administration or the University of Iowa, in perpetuity.

I, _____________________________, UNDERSTAND THE TERMS OF THIS AGREEMENT AND VOLUNTARILY CONSENT TO PARTICIPATE.

____

Signature Date

Permission for NHTSA to use video images

I, ______________________________, grant permission, in perpetuity, to the National Highway Traffic Safety Administration to use, publish, or otherwise disseminate the video images with engineering data (including still photo formats derived from the video images without reference to my name) collected during my participation in this study for educational, outreach, and research purposes. I understand that such use may involve presentation of the video at professional technical society meetings and in NHTSA outreach campaigns and may involve dissemination of my likeness in videotape or still photo formats, but will not result in release of my name or other identifying personal information.

I grant NHTSA permission to use my video images.

____

Signature Date

APPENDIX C: EXPERIMENTAL PROTOCOL

Upon arriving at the IDS facility, subjects reported to the briefing room. The briefing experimenter welcomed subjects as they entered. The subject was then given the information summary and the informed consent (see Appendix A) to read. After answering the subject's questions, the briefing experimenter co-signed the information summary and the subject signed the informed consent. A second experimenter witnessed the information summary.

If the simulator queue was running behind schedule, the subject was then asked to fill out the questionnaire containing demographic and basic driving information. Subjects were informed that the survey was voluntary and that they could leave any portion of it blank. When the simulator queue was on schedule, this survey was filled out after the simulator drive (see Post-Drive Protocol for further discussion). Current magazines and newspapers were available to subjects in the briefing room, although the wait was generally only a few minutes.

In-Simulator Protocol

When it was time to bring the subject downstairs to the simulator, the simulator operator contacted the briefing experimenter by phone or via two-way radio. One of two possible in-vehicle experimenters escorted the subject to the simulation bay. The subject and in-vehicle experimenter waited outside the bay until the previous subject and in-vehicle experimenter exited. The in-vehicle experimenter then proceeded into the bay and gave the IDS operator a videotape with the subject's number and condition written on it. The in-vehicle experimenter gave the subject a brief introduction to the IDS system, then escorted the subject into the dome. The experimenter, with hands on the railing, followed behind the subject to help ensure the subject did not slip and fall on the stairs.

Once in the simulator dome, the experimenter asked the subject to go around the back of the vehicle and sit in the driver's seat. The experimenter helped subjects adjust their seat and provided a safety briefing. In addition, the experimenter made sure the subject knew the location of the speedometer, gearshift, and air conditioning controls. The subject was asked to make sure the rear-view and side-view mirrors were adjusted appropriately. After shutting the door and securing the subject in the vehicle, the experimenter sat down in the passenger-side back seat and inserted the communication earpiece.

Since this study had a reaction-time component that needed to be accurate to a fraction of a second, the in-vehicle experimenters were told to minimize discussion with the participant during the driving portion of the experiment. Also, no comments were made to the simulation operator during the actual drive. To help with this and to maintain consistency between the two in-vehicle experimenters, a written script was used during the simulation.

In-Vehicle Experimenter Log Sheet

The in-vehicle experimenter used an in-vehicle log sheet to obtain critical information about the drive. It was thought that having a perspective from inside the vehicle might provide the in-vehicle experimenter with some unique insights. All the information used in this study was later verified using videotapes of the drives. The in-vehicle experimenter obtained the following types of information:

- The speed of subjects prior to the movement of the encroaching vehicle at the intersection.
- Whether the experimenter felt subjects anticipated that the encroaching vehicle was going to cross. This was a judgment made on the part of the in-vehicle experimenters. They were asked to note any anticipation that seemed to exceed the fact that the subject was coming to an unfamiliar intersection.
- Which of seven possible behaviors subjects attempted to avoid the encroaching vehicle. Subjects could: do nothing, brake, brake hard enough to lock the wheels, accelerate, steer to the left, steer to the right, or perform a combination of these reactions such as braking and steering to left. The in-vehicle experimenter circled all reactions elicited in response to the encroaching vehicle. Once subjects had collided with the vehicle, subsequent reactions were not recorded.
- For subjects in the conventional brake condition, experimenters noted which of four possible skidding behaviors described the subject vehicle during the evasive maneuver. The vehicle could: not skid, skid but rotate less than 30 degrees, skid and rotate more than 30 degrees clockwise, skid and rotate more than 30 degrees counter-clockwise. The in-vehicle experimenter marked which outcome best described the vehicle’s behavior in trying to avoid the encroaching vehicle. Once the subject had collided with the vehicle, subsequent outcomes were not recorded.
- Which of seven possible outcomes best described the subject’s vehicle position in the lane and on the roadway: 1) the vehicle could depart the roadway to the left 2) or depart the roadway to the right, 3) the vehicle could stay in the right lane, 4) have up to one-half of the vehicle in the left lane, 5) have over one-half the vehicle in the left lane, 6) have up to one-

half of the vehicle in the right shoulder, 7) or have over one-half of the vehicle in the right shoulder. The in-vehicle experimenter marked which outcome occurred when subjects attempted to avoid the encroaching vehicle. Once subjects had collided with the vehicle, subsequent outcomes were not recorded.

- Whether subjects collided with the encroaching vehicle at the intersection was also recorded on the log sheet. At times, it was difficult to determine if there was a collision. If in-vehicle experimenters were unsure whether or not a collision had occurred, they recorded a question mark. Subsequent analyses were then used to determine if there had been a collision. These included the videotape analysis and the 30-hertz simulator data stream.
- If there had been a collision, the in-vehicle experimenter shaded the area of the scenario vehicle that was hit. This information was used to help determine the specifics and severity of the collision.
- A space was also provided for the in-vehicle experimenter to write down any additional information that might influence the results of the experiment.

Protocol After Evasive Maneuver

After completing the evasive maneuver to avoid the encroaching vehicle, the subject was told that this was always where the drive ended. This was to help reassure the subject that their behavior had not caused the simulation to end (i.e., they did nothing wrong). Subjects were then asked to place the vehicle in park and to stay in the vehicle with their seat belts on until the operator opened the door to the dome.

After the operator opened the door, the experimenter guided the subject to the debriefing room. If at any point after the drive, subjects commented about their driving ability, they were reassured that they had done fine. They were also told that after they filled out the questionnaires they would be given a debriefing that would provide them with more information about the experiment. If they appeared upset about their performance or the drive in general, the researcher in charge of the study was contacted to discuss the situation with the subject.

Post-Drive Protocol

Upon arriving at the debriefing room, subjects were asked if they would like to use the restroom or have a cool beverage. Once subjects were comfortable, they were asked to fill out four questionnaires. The questionnaires were always presented individually and in the same order, and subjects had to finish each questionnaire before the next questionnaire was given. This was to ensure that the questions most important to the study were answered first and that subject’s answers would not be biased by some of the other questions. The first questionnaire was the most important and was designed to extract specific information about the collision avoidance maneuver at the intersection (see Appendix F). Most of the questions required yes/no responses, along with requests for descriptive narratives about why “yes” or “no” was chosen. The second questionnaire was designed to extract information about the simulator’s validity compared to the real world from the subject’s perspective (see Appendix G). If it had not already been given while the subject waited in the simulator queue, the final questionnaire obtained basic demographic and driving information (see Appendix E). Subjects were told that information on the demographic questionnaire was strictly voluntary and they could leave any portion blank.

After all questionnaires had been filled out, the subject was given a debriefing sheet to read and take home. As shown in Appendix H, the sheet explained the following information:

- The importance of this research to improving traffic safety.
- That collision with the encroaching vehicle was almost impossible to avoid.
- That collision with this vehicle was in no way a reflection on the subject’s ability to drive or avoid a collision.
- That the encroaching vehicle must be a surprise event in this study, and that the subject should not discuss this event with other people who would be participating in the study.

The debriefing experimenter reiterated and pointed out on the sheet for each subject that the crash was almost impossible to avoid and the importance of not discussing the study with others who might participate.

After the debriefing, subjects were paid a minimum of $30.00 for their time. Some subjects were paid an additional amount if they had to wait longer than expected prior to participation. Subjects filled out a payment receipt with their name, address, social security number, and the amount paid. Subjects then signed the document signifying that they had received payment. If subjects were paid an additional amount beyond the typical ten dollars, it was explained by the post-drive experimenter under the comments section on the payment receipt.

Typically, subjects left the debriefing room at this point, unless one of the experimenters felt an additional interview would provide more insight.

APPENDIX D: IN-VEHICLE SCRIPT

The in-vehicle script was designed to be read after specific behaviors or actions occurred. The underlined information is the behavior or action that occurred prior to the in-vehicle experimenter speaking from the script. The script used was as follows:

After inserting the ear-piece:

“The operator is able to hear everything in the vehicle. I have an ear-piece so that I can hear the operator. If at any time you feel uncomfortable, just say so and I will have the operator stop the simulator. If for any reason there is an emergency, **don’t touch it now**, but that red button on the IDS box is an emergency stop button. The best way to stop the simulator though is to tell me and I will have the operator stop it.”

Prior to the simulator being ready:

“The first part of this drive is a practice drive to let you get comfortable with the way the vehicle drives. You should practice accelerating, braking, and steering to get a good feel for the vehicle. I will tell you when the actual drive starts. During the actual drive I cannot talk to you because I want you to concentrate on driving and assessing the simulator. Remember, after the drive you will fill out a questionnaire assessing the looks, controls, and actions of the simulator. It is important to tell me though, at any point, if you want to stop the simulator or when you start feeling uncomfortable. Also, the stairs have been removed from the simulator so you should not try to get out of the vehicle until the operator comes and gets us. Are there any questions before we get started? Just so you know, when the simulator starts you will feel a kind of rumbling. This is just the simulator raising up on its legs. This is normal and you will feel it each time a drive is started or stopped.” [It should be noted that sometimes the simulator moved prior to this statement. In those cases, the statement was inserted into the script at the closest reasonable point after the simulator moved.]

After the simulator is ready:

“Before we start driving we need to let two vehicles pass from behind you.” [It should be noted in some cases the vehicles passed during the pre-drive script. In those cases the prior statement was skipped.]

After the vehicles pass:

“Okay, go ahead and merge onto the road. The speed limit is **45 [or 55] mph**. Go ahead and practice accelerating, braking, and getting a feel for the steering.” [Most subjects attempted braking with this suggestion. However, when subjects did not attempt braking they were told again to:]“go ahead and try the brakes so you can get a feel for them.” [This ensured that all subjects had used the brakes prior to the interaction with the truck].

Prior to the actual drive:

“Are you feeling okay? These red and white stripes coming up on the road signify the start of the actual drive. The speed limit is **45 mph [or 55 mph]** throughout the drive. Remember, let me know at any time if you start feeling uncomfortable. Once again, I cannot talk to you during the drive.”

If participants did try to talk during the actual drive, the in-vehicle experimenter would remain quiet or answer this when applicable.

“Make a mental note of that and I will talk to you about it after the drive.” *Or* “I am sorry, I can’t talk to you during the actual drive.”

APPENDIX E: DEMOGRAPHIC AND DRIVING QUESTIONNAIRE

Subject #_________ Study NADS CPO 5 IQC1

Study Date ____

IDS Driving Survey

As part of this study, it is useful to collect information describing each participant. The following questions ask about you, your personal vehicle and your driving patterns. Please read each question carefully, marking only one response unless otherwise indicated. If something is unclear, ask the research host for help. Your participation is voluntary and you have the right to omit ANY question.

1) What is your birth date? _________/__________/______

Month / Date / Year

2) What is your gender?

☐ Male ☐ Female

3) What is your marital status? (Check only one)

☐ Married
☐ Separated or Divorced
☐ Widowed
☐ Single

4) What was you and your spouse’s (if married) total annual income last year? (Check only one)

☐ 0-$4,999
☐ $5,000 - $9,999
☐ $10,000 - $14,999
☐ $15,000 - $19,999
☐ $20,000 - $29,999
☐ $30,000 - $39,999
☐ $40,000 - $49,999
☐ $50,000 or more

5) Of which ethnic origin do you consider yourself? (Check only one)

☐ Afro-American (not of Hispanic origin)
☐ Caucasian (not of Hispanic origin)
☐ Hispanic (Mexican, Cuban, or other Spanish culture, regardless of race)
☐ Native American Indian, Eskimo, Aleut
☐ Oriental, Asian-American
☐ Other __________________________

6) What is the highest education level you have completed? (Check the most appropriate category)

☐ Primary School
☐ High School Diploma
☐ Technical School
☐ Some College or University
☐ Associates Degree
☐ Bachelors Degree
☐ Some Graduate or Professional School
☐ Graduate or Professional Degree

7) What is your present employment status? (Check only one)

☐ Work part-time
☐ Work full-time
☐ Retired
☐ Unemployed
☐ None of the above

8) What is your occupation (e.g., teacher, law enforcement official, housewife)?

____

9) For which of the following vehicles do you currently hold a valid driver's license <u>within</u> the United States? (Check all that apply)

	Vehicle Type	Year When FIRST Licensed (May be Approximate)
☐	Car ______________	______________
☐	Motorcycle ______________	______________
☐	Truck ______________	______________
☐	Other: ______ ______	______________
☐	Other: ______________________________	

10) For which of the following vehicles do you currently hold a valid driver's license <u>outside</u> the United States? (Check all that apply)

	Year When FIRST Licensed	Country of License	Vehicle Type (May be Approximate)
☐	Car ______________	________	________
☐	Motorcycle ______________	________	________
☐	Truck ______________	________	________
☐	Other: ______________	________	________
☐	Other: ______________	________	________

11) Approximately how many miles do you drive per year in each vehicle type? (Check only one for each vehicle)

Car	Motorcycle	Truck
☐ Under 2,000	☐ Under 2,000	☐ Under 2,000
☐ 2,000 - 7,999	☐ 2,000 - 7,999	☐ 2,000 - 7,999
☐ 8,000 - 12,999	☐ 8,000 - 12,999	☐ 8,000 - 12,999
☐ 13,000 - 19,999	☐ 13,000 - 19,999	☐ 13,000 - 19,999
☐ 20,000 or more	☐ 20,000 or more	☐ 20,000 or more
☐ Do not drive	☐ Do not drive	☐ Do not drive
Other: __________	Other: __________	Other: __________
☐ Under 2,000	☐ Under 2,000	☐ Under 2,000
☐ 2,000 - 7,999	☐ 2,000 - 7,999	☐ 2,000 - 7,999
☐ 8,000 - 12,999	☐ 8,000 - 12,999	☐ 8,000 - 12,999
☐ 13,000 - 19,999	☐ 13,000 - 19,999	☐ 13,000 - 19,999
☐ 20,000 or more	☐ 20,000 or more	☐ 20,000 or more

12) How often do you drive? (Check the most appropriate category)

☐ At least once daily
☐ At least once weekly
☐ Less than once weekly
☐ Do not drive

13) Is any driving you do work related? This does not include traveling to and from work. (Check only one)

☐ Yes
☐ No (skip to question #15)

14) If you answered yes to question #13, how many work related miles do you drive per year? (Check only one)

☐ Under 2,000
☐ 2,000 - 7,999
☐ 8,000 - 12,999
☐ 13,000 - 19,999
☐ 20,000 or more

15) In which environment do you most typically drive? (Check only one)

☐ Rural highway (e.g., Route 1, Route 6, or Route 218)
☐ Small town (e.g., Solon, West Branch)
☐ Suburban (e.g., Iowa City, Cedar Rapids)
☐ City (e.g., Des Moines, Davenport)
☐ High density city (e.g., Chicago, Los Angeles)
☐ Highway/freeway (e.g., Interstate 80)
☐ Do not drive

16) What speed do you typically drive on the freeway when the speed limit is
55? _______
65? _______

17) When the following conditions or situations occur, how frequently do they keep you from driving? (Check the most appropriate answer for each condition)

	Frequently	Occasionally	Rarely	Never	Not Applicable
At night	☐	☐	☐	☐	☐
In fog	☐	☐	☐	☐	☐
In rain	☐	☐	☐	☐	☐
In snow or sleet	☐	☐	☐	☐	☐
During rush hour	☐	☐	☐	☐	☐
On highway/freeway	☐	☐	☐	☐	☐
While smoking	☐	☐	☐	☐	☐
After drinking alcohol	☐	☐	☐	☐	☐
With children	☐	☐	☐	☐	☐

18) How comfortable do you feel when you drive in the following conditions or perform the following maneuvers? (Check the most appropriate answer for each condition)

	Very Comfortable	Slightly Comfortable	Slightly Uncomfortable	Very Uncomfortable	Not Applicable
At night	☐	☐	☐	☐	☐
In fog	☐	☐	☐	☐	☐
In rain	☐	☐	☐	☐	☐
In snow or sleet	☐	☐	☐	☐	☐
During rush hour	☐	☐	☐	☐	☐
On highway/freeway	☐	☐	☐	☐	☐
While smoking	☐	☐	☐	☐	☐
After drinking alcohol	☐	☐	☐	☐	☐
With children	☐	☐	☐	☐	☐
In high density traffic	☐	☐	☐	☐	☐
When passing other cars	☐	☐	☐	☐	☐
When changing lanes	☐	☐	☐	☐	☐
When making left turns at uncontrolled intersections	☐	☐	☐	☐	☐

19) How did you learn to drive? (Check all that apply)

☐ Formal instruction (e.g., driver's education class)
☐ Informal instruction (e.g., from a relative or friend)

20) Have you ever participated in any special driving schools (e.g., AARP or insurance courses, racing school, or as part of law enforcement training)?

☐ Yes (Please describe) ____
☐ No

21) What type of automobile do you drive most often?

Make (e.g., Ford, Toyota): ______________________________
Model (e.g., Escort, Celica): ______________________________
Year: ______________________________

22) Which of the following features does this automobile have? (Check all that apply)

☐ Air Bag
☐ Antilock Brakes
☐ Automatic Transmission
☐ CB Radio
☐ Cellular phone
☐ Manual Transmission
☐ Power Brakes
☐ Power Steering
☐ Radar Detector
☐ Other technologies (e.g., trip computer, moving-map display, vehicle information center)
Please list these: ____
____
☐ None of these

23) How many vehicles have you driven on a regular basis over the last 5 years? (Check only one)

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5 or more

APPENDIX F: VEHICLE INCURSION QUESTIONNAIRE

VEHICLE INCURSION QUESTIONNAIRE IQC 1

Vehicle Incursion Questionnaire
Subject #: ______ Post Drive Questionnaire 1 Date: ______

1) What do you think the purpose of today's drive was?

____
____
____
____
____
____

2) At any point during the simulation did you begin to drive more carefully than you normally would in typical daily driving?

Yes No

If yes, describe what happened to make you start driving more cautiously?

3) While driving the simulator, did you feel that the slow moving truck on the hill behaved the way you would expect it to in the real world?

Yes No

If not, how was it different?

____
____
____
____
____

4) When you came upon the slow moving truck, was your reaction to the truck typical of how you would behave in the real world?

Yes No

If not, why not?

____

____

____

5) Remember when you approached the intersection and the vehicle pulled out in front of you. Did this sequence of events seem realistic?

Yes No

If not, why not?

____

____

____

6) When the vehicle pulled out in front of you, describe your reaction in as much detail as possible. (When did you decide to react? What did you do to try to avoid a collision?)

____

____

____

____

7) When you approached the intersection, did you anticipate or expect that the car may pullout in front of you?

Yes No

Please explain

____

____

____

____

8) Did anything about the vehicle which pulled out in front of you seem strange or unrealistic?

Yes No

If yes, please explain

____

____

____

____

____

____

9) Were you startled by the vehicle pulling out in front of you?

Yes No

Please explain

____

____

____

____

____

10) When you tried to avoid hitting the car, do you feel that you reacted as you would have in the real world?

Yes No

If not, what would you have done differently?

____

____

____

____

11) Why did you react the way you did when the vehicle pulled out in front of you (e.g., steered only, braked only, combination)?

____

____

12) If the situation where the vehicle pulled out from the intersection had occurred in the real world, what do you think would have happened?

1	2	3	4	5	6	7
I Would Have Been Able to Avoid a Collision			Don't Know			I Would Not Have Been Able to Avoid a Collision

13) If the vehicle you drove in the simulator had been equipped with antilock brakes, do you think that it would have made any difference when a vehicle pulled into the intersection like this one did?

Yes No

If yes, what would have been different?

____

____

____

____

____

14) If the situation where the vehicle pulled out from the intersection had occurred in the real world, what would you have done? Please circle the best answer.

I would have just steered to the right
I would have just steered to the left
I would have just braked in a straight line
I would have braked and steered to the right
I would have braked and steered to the left
I would have accelerated and steered to the right
I would have accelerated and steered to the left
I would not have done anything
I wouldn't have steered or braked
I am not sure

15) Have you ever activated antilock brakes before?

Yes No

If yes, please describe the circumstances

APPENDIX G: IDS VALIDITY QUESTIONNAIRE

IDS Validity Questionnaire

Subject #: ______ Post Drive Questionnaire 2 Date: ______

1) How did driving in the simulator compare to driving your vehicle?

|_________|_________|_________|_________|_________|_________|

1	2	3	4	5	6	7
Easier			Same			Harder

2) Rate your ability to see out of the windshield in the simulator as compared to the real world.

|_________|_________|_________|_________|_________|_________|

1	2	3	4	5	6	7
Could not see as far as normal			Could see the same as normal			Could see further than normal

3) Rate the feeling of motion in the simulator as compared to motion in the real world (i.e., responsiveness of the simulator).

|_________|_________|_________|_________|_________|_________|

1	2	3	4	5	6	7
Moved too Slow			Moved Just right			Moved too Fast

4) Rate how often you had to steer to stay in your lane as compared to the real world.

|_________|_________|_________|_________|_________|_________|

1	2	3	4	5	6	7
Steered less often			Steered the same			Steered more often

5) Rate the steering of the simulator as compared to the real world.

|_________|_________|_________|_________|_________|_________|

1	2	3	4	5	6	7
Too loose or Not sensitive			Just right			Too tight or Not sensitive enough

6) Rate your ability to stop the car as compared to the real world.

1	2	3	4	5	6	7
Stopped slower			Stopped the same			Stopped faster

7) Rate moving the brake pedal compared to the real world.

1	2	3	4	5	6	7
Too Hard			Just right			Too sensitive

8) Rate moving the gas pedal compared to the real world.

1	2	3	4	5	6	7
Too Hard			Just right			Too sensitive

9) When comparing the speed viewed on the speedometer to the speed you felt you were driving, did you feel you were traveling slower or faster than the speedometer stated?

1	2	3	4	5	6	7
Felt slower than the speedometer indicated			Felt the same as the speedometer indicated			Felt faster than the speedometer indicated

10) As you approached the intersection, did you expect the vehicle to pull out in front of you?

1	2	3	4	5	6	7
Did not expect the car to pull out			Not sure			Expected the car to pull out

11) Rate your personal feeling about driving the simulator.

|_________|_________|_________|_________|_________|_________|
1 2 3 4 5 6 7
Had a bad time … Had a good time

12) In what ways can the Iowa Driving Simulator be improved?

Thank you very much for participating!

We hope that you enjoyed the experience.

APPENDIX H: IQC 1 POST-DRIVE DEBRIEF

As described in the information summary, the purpose of this study is to assess the simulator. Beyond the standard validity checks, we are interested in using the simulator to assess severe maneuvering scenarios. This is why we included the last event where the car came suddenly into the intersection and stopped in the middle of the road. The simulator offers a controlled and safe environment to study an otherwise unsafe act. This type of research is the first step to understanding severe maneuvering events and developing methods to avoid serious accidents in the future.

This event was designed to require an extremely severe braking and/or steering response. It was expected that very few people, if any, would be able to avoid colliding with this car. This event was designed so it would be almost impossible to avoid the accident. This should in no way be considered a reflection of your ability to drive or avoid an accident.

If you know other people who are participating in this study, please do not discuss any of the details of the drive with them until after they have driven the simulator. It is important that they see and drive the simulator without any advance information about the drive. This is particularly true of the last event which was designed to be a surprise event and requires that participants do not have any advanced knowledge of the drive.

We would like to again thank you for coming in and helping us today. If you have any questions, please discuss them with the research host. Also, remember that you can call Dan McGehee, Principal Investigator, at 335-6402 if you have any further questions.

APPENDIX I: PAYMENT RECEIPT

Payment Form for IQC 1
Principal Investigator: Dan McGehee
Telephone: (319) 335-6819

DOCUMENTATION OF PARTICIPATION AND PAYMENT

Participant Information

Participant's Name: ________________________

Address: ________________________________

City: _________________ State: ____ Zip Code _________

Phone Number: ______– _____________

Social Security Number: ________– _____– ________

Acknowledgment

I have received cash in the amount of $ _______ for participation in the Cooperative Project Order 5 (IQC1) as stated above.

____
Signature of Participant

For Research Staff Only

Payment Information

Date: _______________ Amount Paid $ _________

Payment Certification

I certify that all information has been completed by the participant and the above payment had been received.
Research Host Authorizing: ________________________________

(full name required)
Comments:

APPENDIX J: POST-DRIVE DEBRIEF

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