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Investigation of Driver Reactions to Tread Separation Scenarios in the National Advanced Driving Simulator (NADS)

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16. Abstract

A study was conducted to investigate drivers' reactions to tread separation scenarios using the National Advanced Driving Simulator (NADS). The objectives were to evaluate the effects of vehicle understeer gradient, prior knowledge of an impending tire failure, instructions on how to respond to a tire failure, driver age, and failed tire location on drivers' responses and the likelihood of control loss following simulated tread separation on one of the rear tires of a simulated SUV traveling at high speed.

One hundred and eight (108) subjects experienced two tire failures while driving on a straight divided highway at approximately 75 mph with light surrounding traffic. Subjects were divided equally into three age groups (18-25, 35-45, 55-65) and gender was balanced. Drivers were assigned to one of three understeer conditions. Understeer conditions were referred to as Vehicle 1 (understeer gradient of approximately 4.7 deg/g), Vehicle 2 (3.4 deg/g), and Vehicle 3 (2.4 deg/g). Following left rear tire detread, the understeer gradients resulting from a right turn changed to 1.10, 0.09, and –1.17 deg/g, respectively. The first tire failure was unexpected. The second tire failure was expected, with half of the subjects being given specific instructions on how to respond to a tire failure and the other half were told only that one or more tire failures would likely occur.

Decreasing vehicle understeer was strongly associated with the likelihood of control loss following both the unexpected and expected tire failures. Knowledge of the imminent tread separation reduced the overall probability of control loss from 55% to 20% and had a significant effect on how quickly drivers responded as well as on the nature of their initial responses (i.e., steering or braking). Driver age was marginally associated with increased likelihood of vehicle control loss, but only on unexpected trials. Vehicle speed at the time of first steering input also contributed to the probability of control loss. Neither the location of the tire that failed (left rear vs. right rear) nor the specific instructions about how best to respond to the tread separation influenced the probability of control loss. Differences associated with vehicle understeer conditions observed in the present study were large and consistent, independent of driver expectations and across driver age groups. It is thus fair to conclude that in the event of a complete rear-tire detread, the increased difficulty in vehicle handling and the associated increased likelihood of loss of vehicle control with decreasing vehicle understeer generalize to real-world driving.

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EXECUTIVE SUMMARY

Using the National Advanced Driving Simulator (NADS), research was performed to assess drivers' responses to simulated tread separations. The objectives of this research were to evaluate the effects of the following factors on drivers' responses and the likelihood of control loss following simulated tread separation on one of the rear tires of a simulated SUV traveling at high speed:

1. Vehicle understeer gradient
2. Prior knowledge concerning an imminent tire failure
3. Specific instructions on how to respond following tire failure
4. Driver age
5. Location of tire that failed

One hundred and eight (108) subjects experienced two tire failures while driving on a straight divided highway at approximately 75 mph with light surrounding traffic. Subjects were divided equally into three age groups (18-25, 35-45, 55-65). Half of the subjects in each age group were of each gender. Drivers were assigned to one of three understeer conditions and experienced both tire failures in that understeer condition. Understeer conditions were referred to as Vehicles 1-3. Vehicle 1 had an understeer gradient of approximately 4.7 deg/g with 4 normal tires. Vehicles 2 and 3 were modified from Vehicle 1 so that the resulting understeer gradients were 3.4 and 2.4 deg/g, respectively. Following left rear tire detread, the understeer gradients resulting from a right turn changed to 1.10, 0.09, and –1.17 deg/g, respectively.

The first tire failure was unexpected. Drivers were given no information about the possibility of tire failure; rather, they were told that they were evaluating the realism of the simulator. The second tire failure was expected, although drivers were given different amounts of information. Half of the subjects were given specific instructions on how to respond following the second tire failure, while half were told only that one or more tire failures would likely occur.

Decreasing vehicle understeer was strongly associated with the likelihood of control loss following both the unexpected and expected tire failures. Overall, the proportion of trials resulting in loss of vehicle control increased from 10% (Vehicle 1) to 35% (Vehicle 2) and 68% (Vehicle 3). Knowledge of the imminent tread separation reduced the overall probability of control loss from 55% to 20%, however drivers of Vehicle 3 were still much more likely to sustain loss of vehicle control following the expected tread separation than drivers of Vehicle 1 (39% vs. 3%) and twice as likely to sustain loss of vehicle control following the expected tread separation than drivers of Vehicle 2 (39% vs. 19%).

Knowledge of the imminent tread separation had a significant effect on how quickly drivers responded as well as on the nature of their initial responses. When the tread separation was unexpected, two-thirds of the subjects' first response was a steering input. Sixty-six percent of these steering-first trials resulted in loss of vehicle control. Moreover, the percentages of steering-first trials that resulted in control loss were strongly associated with vehicle understeer condition (13%, 60%, and 97% for Vehicles 1, 2, and 3, respectively). In the unexpected trials, none of the drivers braked as a first response. In contrast, 58% of the drivers braked first when given information about the imminent tread separation. Drivers who responded initially by braking were successful in bringing the vehicle to a controlled stop on 94% of the trials. This trend was consistent across vehicle understeer conditions.

Driver age was marginally associated with increased likelihood of vehicle control loss, but only on unexpected trials. Vehicle speed at the time of first steering input also contributed to the probability of control loss. Neither the location of the tire that failed (left rear vs. right rear) nor the specific instructions about how best to respond to the tread separation influenced the probability of control loss.

Differences associated with vehicle understeer conditions observed in the present study were large and consistent, independent of driver expectations and across driver age groups. It is thus fair to conclude that in the event of a complete rear-tire detread, the increased difficulty in vehicle handling and the associated increased likelihood of loss of vehicle control with decreasing vehicle understeer generalize to real-world driving. Vehicle speed at the time of the subject's first steering input was strongly associated with the likelihood of loss of vehicle control. Thus, any real-world factors (e.g. surrounding traffic, reduced visibility, inclement weather) that might encourage drivers to attempt steering inputs more quickly and at higher speeds than was observed in this study could result in increased likelihood of loss of vehicle control. However, it is also important to note that the model used here for the detreaded tire represents what would be considered to be a worst-case detread event.

In a separate simulation experiment, the offline NADSdyna simulation was used to predict the handwheel angle at which each of the simulated vehicles with a rear detread (i.e., tread separation) would lose control and spin out for different vehicle speeds. This analysis determined the speed-steer stability boundaries for each simulated vehicle. The boundaries increase with understeer gradient. Each vehicle model was run through the right-hand slowly increasing steer maneuver at speed increments of 10 mph, beginning at 25 mph. Loss of control was defined as the point at which the vehicle spins out. At 60 mph with a detreaded rear tire, the handwheel angles sustained by Vehicles 1-3 were 26, 20, and 15 degrees, respectively. The results of the simulation experiment were consistent with those of the simulator experiment involving human subjects.

The magnitude and consistency of differences observed in this study indicate that the effect of vehicle understeer on vehicle handling and resulting loss of control in the event of a rear tire detread is stronger than any other factor considered in this study. The large difference associated with driver knowledge of the upcoming tread separation indicates that findings from test track studies in which test drivers are aware of an imminent tread separation may underestimate the extent to which tread separation occurring the real world leads to instability and loss of vehicle control. At the same time, the large difference associated with prior knowledge suggests that providing information to the driver in real time about the tread separation could significantly reduce the probability of loss of control following tread separation, but only if the drivers also knew that it is important to slow down before attempting to steer.

1.0 INTRODUCTION

Tread separation is a possible failure mode for all radial tires. While one goal of tire design is to minimize the frequency of tread separations, they can occur for all makes and models of radial tires. Tread separation can occur on any wheel of the vehicle. A wheel with a separated tread loses some of its ability to sustain large directional ground forces. At highway speeds, small steering inputs cause the detreaded tire to saturate prematurely, thus losing its ability to handle large lateral forces. From a safety point of view, vehicle dynamics theory predicts that, for straight line driving, rear wheel tread separations will be more dangerous than front wheel ones, due to the decrease in rear axle lateral force capability associated with rear tire tread separation. Following tread separation, if the driver pulls the vehicle off the road to the right, then theory further predicts that separations that occur on the left rear wheel are potentially more dangerous than ones that occur on the right rear wheel. The left rear (detreaded) tire carries more of the load than the right tire during a move to the right and is thus more susceptible to premature loss of lateral force capabilities or increased likelihood of loss of vehicle control.

Based on limited available information, 15 percent of tread separations occur on the left front wheel, 15 percent on the right front wheel, 30 percent on the left rear wheel, and 40 percent on the right rear wheel. There is no definitive reason why rear tires should suffer a higher rate of tread separations. These percentages may merely reflect the relative danger level of a tread separation occurring for each wheel since tread separations that result in a crash or significant driving problem are more likely to be reported to the authorities than are ones that do not.

Recent problems with relatively frequent tread separations for the Firestone Wilderness AT and ATX tires mounted on the Ford Explorer have renewed interest in how drivers react to blowouts and tread separations. Researchers would like to know more about the steering and braking actions of drivers in response to a blowout or tread separation and the resulting motion of the driver/vehicle system. We would also like to know more about how vehicle-to-vehicle changes in lateral stability (characterized by each vehicle’s understeer gradient) may affect driver steering and braking actions following a blowout or tread separation.

2.0 STUDY OBJECTIVES

Using the National Advanced Driving Simulator (NADS), research was performed to assess drivers' responses to simulated tread separations. The objectives of this research were to evaluate the effects of the following factors on drivers' responses and the likelihood of control loss following simulated tread separation on one of the rear tires of a simulated SUV traveling at high speed:

1. Vehicle understeer gradient
2. Prior knowledge concerning an imminent tire failure
3. Specific instructions on how to respond following tire failure
4. Driver age
5. Location of tire that failed

The objectives were accomplished with an experiment in which subjects drove simulated Sports Utility Vehicles (SUVs) on high-speed divided highways with light surrounding traffic. Vehicle understeer gradient was varied by modification of simulated vehicle models. Prior knowledge was manipulated by having subjects experience one tire failure with no advance information and one following an explanation. Half of the subjects received specific instructions about how to best control the vehicle following tread separation, while half were only told that one or more additional tire failures was likely. Half of the tire failures occurred on the left rear tire, half on the right rear tire.

3.0 DEVELOPMENT OF VARIOUS SUV AND TIRE TREAD SEPARATION EVENT MODELS FOR USE ON THE NATIONAL ADVANCED DRIVING SIMULATOR

3.1 Introduction

The object of the vehicle dynamics modeling effort was twofold. First, existing NADSdyna (vehicle dynamics simulation used by the NADS) tire models were extended to model a tire failure (tread separation) event and to model tire force and moment response characteristics after a tread separation occurred. Second, three vehicle models, each with a different level of understeer, were developed.

3.2 Tread Separation Tire Modeling

On the NADS, longitudinal and vertical cues are provided to drivers to alert them to the tread separation event. Movements of the simulator motion base provide longitudinal cues. The NADS has vibration actuators, situated at the four corners of the vehicle, that are used to simulate vertical suspension accelerations/forces (vibrations).

The tire tread separation event is modeled using combinations of harmonic, trigonometric functions as described in Appendix A. Various parameters in the equations can be adjusted to provide longitudinal and vertical tire force oscillations that result in the NADS driver being cued with responses representative of a tread separation event. The parameters used in the equations modeling the tread separation event are given in Appendix A. Appendix A also contains the complete parameter sets for both the detreaded and normal tires used in this study.

For the experiment, the duration and magnitude of the tread separation event forces were subjectively set on the NADS based on actual tread separation event experiments done at the National Highway Traffic Safety Administration's Vehicle Research and Test Center (VRTC). Also, the audio recorded from the VRTC tread separation experiments was used at the onset of the tread separation. The duration of the tread separation event was set to be 4 seconds.

Figures 1 and 2 show the longitudinal and normal (vertical) tire forces during the modeled 4-second-duration tire tread separation event, for vehicle speeds of 30 and 70 mph, respectively. The upper plot of Figure 1 shows Longitudinal Pulsating Force (in pounds) versus Time (in seconds). The force is a half sinusoid whose value is zero before 0.8 seconds, decreases to –100 pounds at 2.6 seconds, and returns to zero at 4.1 seconds. The lower plot shows Normal (Vertical) Tire Force (in pounds) versus Time (in seconds). The force is a sinusoid whose value is 790 pounds before 0.7 seconds, has a maximum oscillation between 860 and 730 pounds at 2.5 seconds, and returns to 790 pounds at 4.3 seconds. The frequency of both the longitudinal and normal forces is 5.6 hertz. The upper plot of Figure 2 shows Longitudinal Pulsating Force (in pounds) versus Time (in seconds). The force is a half sinusoid whose value is zero before 0.8 seconds, decreases to –100 pounds at 2.5 seconds, and returns to zero at 4.2 seconds. The lower plot shows Normal (Vertical) Tire Force (in pounds) versus Time (in seconds). The force is a sinusoid whose value is 790 pounds before 0.7 seconds, has a maximum oscillation between 560 and 1030 pounds at 2.5 seconds, and returns to 790 pounds at 4.3 seconds. The frequency of both the longitudinal and normal forces is 13 hertz. The frequencies of the harmonic forces and the magnitude of the vertical force are functions of the wheel rotational speed.

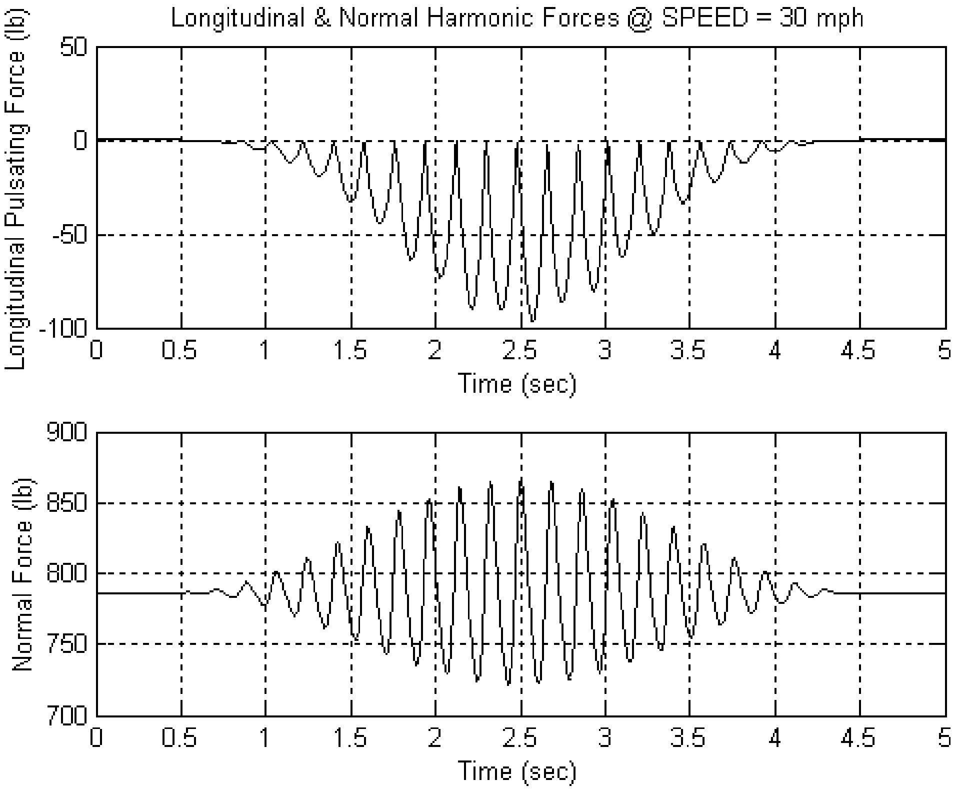


Figure 1. Longitudinal and Normal (Vertical) Tire Forces During Detread Event – 30 mph

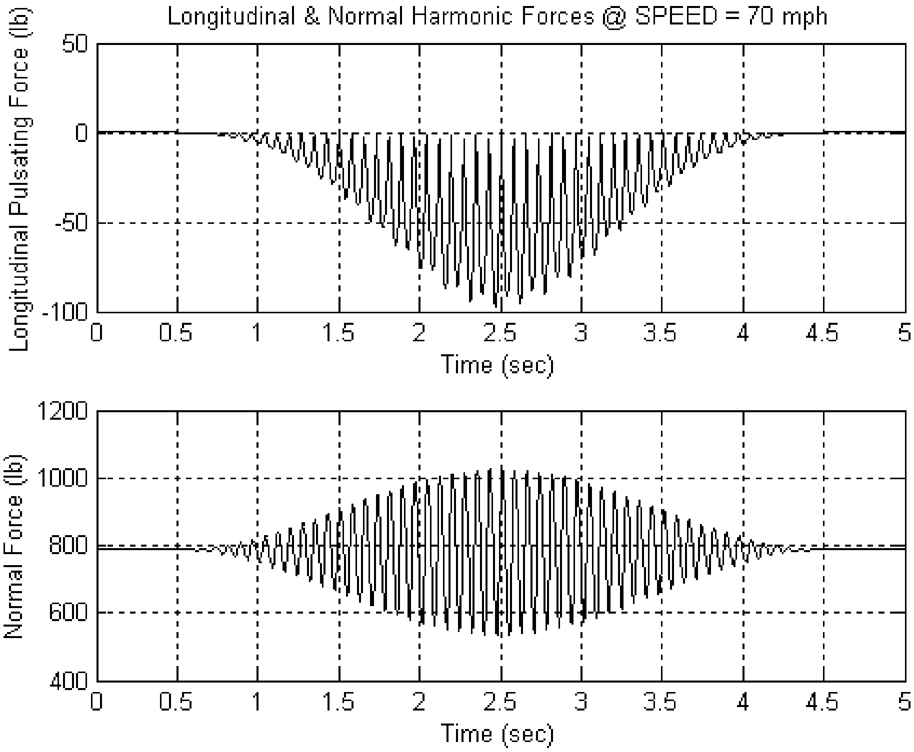


Figure 2. Longitudinal and Normal (Vertical) Tire Forces During Detread Event – 70 mph

For this study, the tire tread separation events being simulated were those that do not result in a loss of air pressure in the tire. In general, after a tire tread separation of this type, the tire force and moment response characteristics are degraded by the loss of the tread. The separation occurs between the layers of steel belts within the tire. The rubber covering the remaining belts is nearly completely removed as a result of the separation or soon after separation as a result of wear. When this happens, the tire is running (at least partially) on the steel cords. The frictional properties of the steel cords on the road surface are much degraded compared to rubber tire tread on the road.

Immediately after the tread separation event is completed (4 seconds after it starts), the properties of the detreaded tire are used in the tire model. The tire parameter file provided in Appendix A also contains the parameters for the post-detread tire model. Figures 3 through 5 show predictions from the NADSdyna tire model for a normal and detreaded tire. Figure 3 shows the lateral force (in pounds) plotted against slip angle (in degrees) for 3 loading conditions. The 3 curves for the normal tire all have the same shape: at –90 degrees, they start at a certain force level, the force peaks near zero slip, it falls to zero at zero slip and continues to go negative as the slip angle goes positive. The curves are point symmetric about zero. The starting values (in pounds) for the normal tire are 500 for a 750-pound load, 1050 for a 1875-pound load, and 1300 for a 3000-pound load. The peak values for the same loading conditions are 750 at –10 degrees, 1600 at –18 degrees, and 1800 at –30 degrees. The 3 curves for the detreaded tire do not have a peak; otherwise, they are the same shape as for the normal tire. The starting values (in pounds) for the detreaded tire are 200 for a 750-pound load, 400 for a 1875-pound load, and 450 for a 3000-pound load. Figure 4 shows the longitudinal force (in pounds) versus slip ratio (dimensionless). The shape of the 6 curves are about the same as the 6 in Figure 3, but the peaks in the normal tire curves are not as pronounced. The starting values (in pounds) for the normal tire are 300, 900, and 1600. The 3 peak values are 350, 1100, and 1800, all occurring around a slip ratio of 0.1. The starting values (in pounds) for the detreaded tire are 100, 250, and 500. Figure 5 plots the friction ellipses for the normal and detreaded tire and shows both longitudinal and lateral forces for the same loading conditions as in the previous two figures. The friction ellipses are not perfect; but they are symmetric about the x-axis. At vertical loads of 1875 and 3000 lbs., both the normal and detreaded tires generate more longitudinal than lateral force. Some representative points for a normal tire at a 3000-lb. load are (-1700, 600), (0, 1050), (1100, 1100), and (1600, 500) lbs. For a detreaded tire at the same load, the forces are (-500, 200), (0, 250), and (500, 200) lbs. Some representative points for a normal tire at a 1875-lb. load are (-980, 400), (0, 900), (550, 950), and (950, 300) lbs. For a detreaded tire at the same load, the forces are (-300, 200), (0, 230), and (300, 200) lbs. At a vertical load of 750 lbs., both the normal and detreaded tires generate less longitudinal than lateral force. Some representative points for a normal tire at this load are (-300, 200), (0, 350), (100, 400), and (300, 150) lbs. For a detreaded tire at the same load, the forces are (-100, 0), (0, 120), and (100, 0) lbs. The force capabilities of the simulated detreaded tire are greatly reduced compared to the normal tire.

The parameters used to model the detreaded tire were not based on force and moment machine measurements typically performed to generate tire model parameters. The parameters for the detreaded tire were in part generated based on detreaded tire responses presented in the literature (1,2). The model developed is representative of a worst case detread event with steel cord exposure for the entire circumference of the tire.

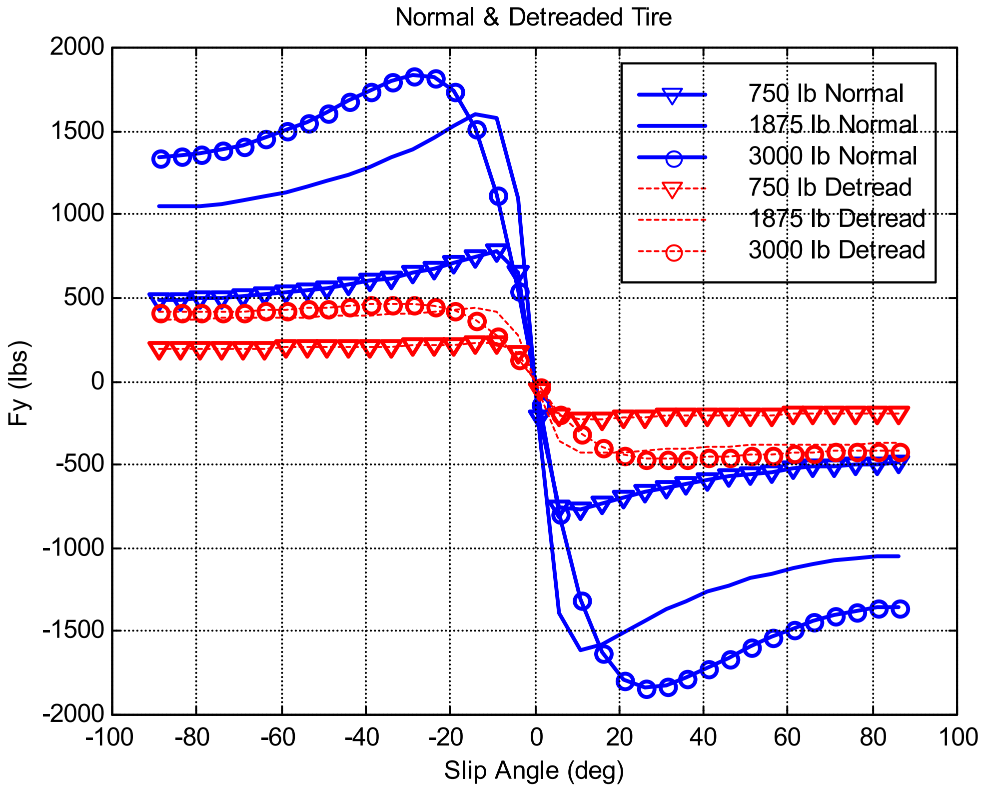


Figure 3. Tire Lateral Force Versus Slip Angle – Normal and Detreaded Tire

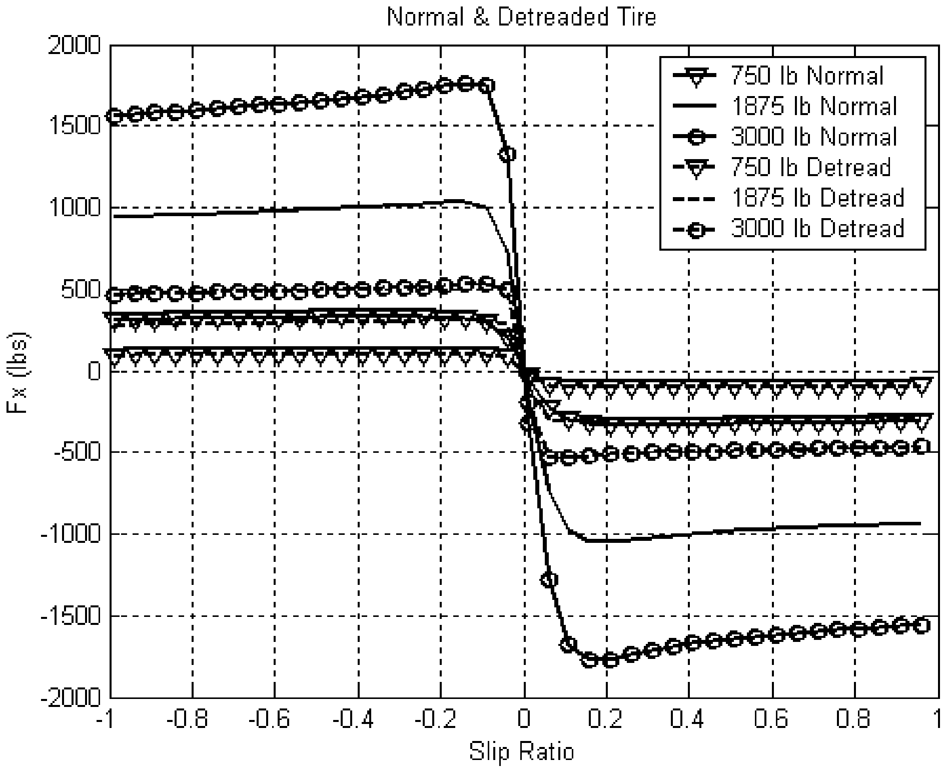


Figure 4. Tire Longitudinal Force Versus Slip Ratio – Normal and Detreaded Tire

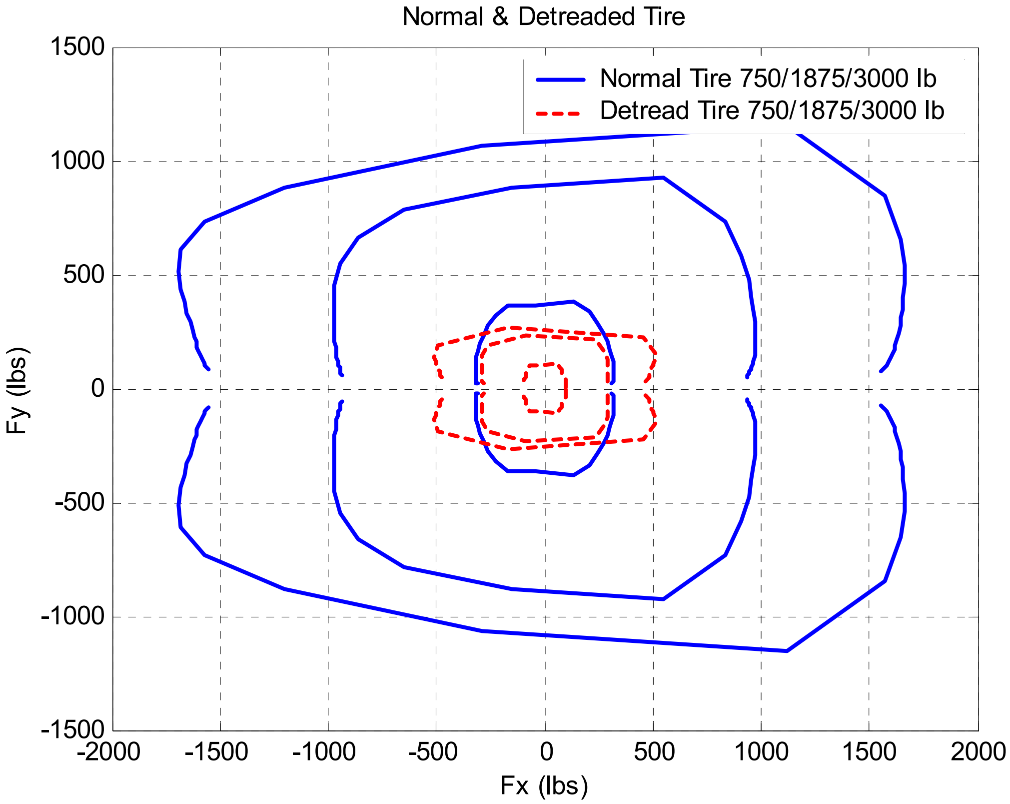


Figure 5. Tire Lateral Force Versus Longitudinal Force – Normal and Detreaded Tire

3.2.1 Discussion on Vehicle Understeer Gradient

The Society of Automotive Engineers (SAE) defines understeer/oversteer gradient as (3):

> *"The quantity obtained by subtracting the Ackerman Steer angle gradient from the ratio of the steering wheel angle gradient to the overall steering ratio."*

This is a general, fairly complex definition of understeer/oversteer gradient (understeer). However, a simpler definition can be presented if one considers a particular test method, a constant radius test, used to measure understeer. During a constant radius circle test, the vehicle is driven from zero speed to some maximum speed under the condition of slowly increasing speed while remaining on the circle. Understeer gradient is a steady-state vehicle response characteristic. During this test, and all other understeer gradient tests, driver inputs are applied in a slow, steady manner so as to maintain a "steady-state" vehicle response. For this test condition, the understeer gradient, in units of deg/g, is defined as the gradient or slope of the road wheel steer angle (deg) versus lateral acceleration (g) graph. The road wheel steer angle used is simply the handwheel steer angle divided by the steering ratio.

Figure 6 contains example measurements of understeer determined by the constant radius circle test method. In this figure the understeer gradient, K, is the slope of the curves. Steering angle divided by steering ratio is the variable on the vertical axis. The horizontal axis contains lateral acceleration (in g's). The upper curve is the limit understeer curve. It starts in the lower left corner, is linear for small values of lateral acceleration, and then curves upward until it reaches a maximum lateral acceleration. The lower curve is the understeer/oversteer curve. It starts in the same place with approximately the same shape but then flattens out. This is the neutral steer point. The curve then begins to descend. This region of negative slope is the oversteer region. The end point of this curve is limit oversteer. During the constant radius test: if the vehicle plows out (or requires an increase in steering input to stay on the circular path) as the speed is increased, the vehicle exhibits understeer and the understeer gradient is positive; if it requires no change in steering input to stay on the path of the circle as speed increases, it exhibits neutral steer and the understeer gradient is zero; and if it turns in toward the center of the circle (or requires a reduction in steering input to stay on the circular path) it is in an oversteer condition and the understeer gradient is negative.

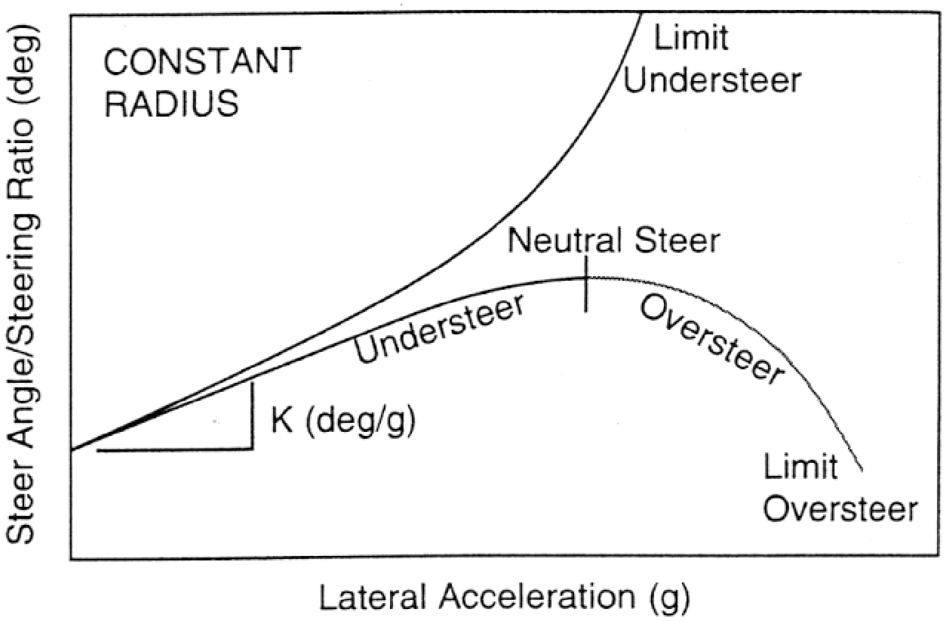


Figure 6. Example Measurements of Understeer Gradient by Constant Radius Method (from Ref. 4)

Another method used to measure understeer gradient, and the method used in the analyses and testing presented here, is the constant speed test. During the constant speed test, the vehicle is driven at a constant speed and the handwheel angle is slowly increased until the vehicle reaches some performance limit or the test is stopped. This is a simple ‘test’ to run using a computer simulation because it does not require the vehicle to be controlled to follow a circular path. It is also a relatively simple test to run on a test surface, but it does require a large amount of test surface area. For the NADS, the vehicle cruise control was used to maintain a constant speed, and a semi-infinite flat surface was modeled in the terrain database.

Figure 7 contains example measurements of understeer determined by the constant speed test method. The axes are the same as in Figure 6. The graph shows a line labeled “Ackerman Steer Angle Gradient”. This straight line is at the slope of a neutral steer vehicle. Steeper slopes represent understeer (positive K) conditions, while less steep slopes indicate oversteer (negative K) conditions. The same two curves (understeer and oversteer) are plotted on Figure 7 as on Figure 6. Both curves have a steeper slope than the Ackerman Steer line. The understeer curve always stays above the Ackerman Steer line while the oversteer curve descends and crosses the Ackerman Steer line at a high lateral acceleration level.

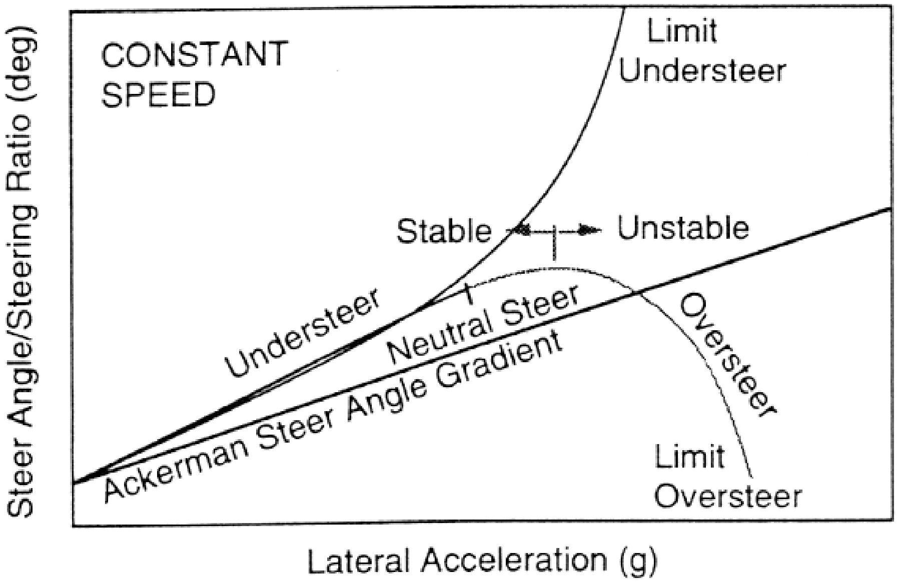


Figure 7. Example Measurements of Understeer Gradient by Constant Speed Method (from Ref. 4)

Understeer concepts are often explained mathematically using formulations based on a bicycle model (4). These mathematical developments assume that the cornering stiffnesses of the front and rear tires (left and right sides combined) remain constant. This is not the case for a vehicle with a detreaded tire. Figure 3 shows that the tire cornering stiffness (slopes of the graphs near slip angles, α, equal zero: F_y/α) of a detreaded tire is considerably less than a normal tire. Consider the case of a vehicle turning right with a left rear tire detreaded. As load is transferred to the left, the detreaded rear tire becomes more heavily loaded and the normal rear tire more lightly loaded. The net effect is a reduction of total rear axle cornering stiffness. Because of this, the bicycle model concept is less appropriate and the vehicle response becomes nonlinear at lower lateral acceleration levels.

As indicated in Figures 6 and 7, vehicles reach either limit understeer or limit oversteer conditions. With a detreaded tire on the rear of a vehicle, it is more likely to spin out because of the reduction in rear axle cornering capacity. If a detreaded tire having characteristics such as those in Figures 3 through 5 were on the rear of any vehicle, it would eventually go to limit oversteer (spinout) given that it had high enough speed and steering input (i.e., high enough lateral acceleration).

For this study, the focus has been primarily on the low lateral acceleration level of understeer, or the so-called linear range of understeer. The linearity and range of linearity of the road wheel steer angle versus lateral acceleration curve is vehicle and maneuver dependent. For a vehicle with four normal tires, the linear range may extend up to a range of 0.3-0.4 g. For a vehicle with a detreaded tire, the linear range does not extend up to as high a lateral acceleration level, as mentioned above. According to SAE Recommended Practice J266 (5), some organizations have adopted a convention in which the understeer gradient obtained at a lateral acceleration of 0.15 g is taken to characterize the vehicle. For offline NADSdyna simulation runs the range between 0.1 and 0.35 g was used to determine the linear range understeer gradient. For the NADS runs, which were driven by a human driver and included runs with detreaded tires, the range used was 0.1 to 0.3 g.

Because of the reduction in cornering stiffness of a detreaded tire, the linear range understeer gradient of a vehicle with a detreaded tire on the rear is significantly less than the same vehicle with four normal tires.

NHTSA has presented a fairly thorough review, analyses, and discussion of several understeer gradient measurement techniques (6). Discussions contained in the referenced report suggest that test variability can contribute up to ±0.25 g/deg of variability in an understeer gradient measurement for a particular vehicle and test condition. Further, the NHTSA report states, "*Based on the above discussion, ODI (Office of Defects Investigation) believes that unless differences of at least 1°/g are found when comparing the measured understeer gradients of different vehicle models, one cannot confidently state that the vehicles truly have different understeer gradients.*"

3.2.2 SUV Models with Different Levels of Linear Range Understeer

The objective of the vehicle modeling effort was to develop three generic SUV models, each with a different level of linear range understeer gradient. Based on understeer gradient values for SUVs measured by NHTSA and others, the goal was to roughly span the SUV understeer gradient range by developing models with understeer gradient values of nominally 4.8, 3.5 and 2.4 deg/g; and the vehicle models developed are referred to as Vehicle 1, Vehicle 2, and Vehicle 3, respectively. These represent an upper limit, lower limit, and a middle value of linear range understeer gradient values seen in a limited sample of real world vehicles. Prior to the onset of this project, VRTC had developed one SUV model for the NADS with an understeer gradient value in the range of approximately 4.7 deg/g. This model, which will be referred to as Vehicle 1, is the baseline model from which modifications were made to develop the Vehicle 2 and Vehicle 3 models. The Vehicle 2 and Vehicle 3 models are not models of real vehicles and should not be referenced to any actual manufactured SUVs. The Vehicle 2 and Vehicle 3 model parameter changed from the Vehicle 1 model parameters were not based on any manufactured vehicles.

An additional aspect of the modeling effort was to develop vehicle and tire model combinations such that with a rear detreaded tire, Vehicle 1 would remain an understeer vehicle, Vehicle 2 would be near a neutral steer vehicle, and Vehicle 3 would be an oversteer vehicle. Previous work done at VRTC and the NADS helped guide the final selection of the appropriate tire parameters for the detreaded tire model. When the modeled detreaded tire was used on the rear, the resulting understeer gradients for each SUV model were reduced by roughly 3.5 deg/g. This is consistent with actual test data made available to NHTSA (6).

Table 1 contains lists of vehicle attributes that can affect vehicle understeer. According to the references cited (4,7,8), the lists include the most significant factors that affect vehicle understeer.

For the purposes of this project, the desire was to change the vehicle's understeer gradient without changing the tire properties. That is, the three vehicle models with different understeer characteristics all used the same normal and detreaded tires. Therefore, factors related to tire properties were not changed to affect the vehicle understeer gradients.

Table 1. Vehicle Attributes Affecting Understeer

Gillespie Reference (Ref. 4)	Bundorf Reference (Ref. 7)	Leffert Reference (Ref. 8)
• Tire Cornering Stiffness • Camber Thrust • Roll Steer • Lateral Force Compliance Steer • Aligning Torque • Lateral Load Transfer • Steering System	• Sprung Weight & Distribution • Unsprung Weight & Distribution • Center of Gravity Heights • Wheelbase • Roll Centers • Roll Rates • Roll Steer Coefficients • Roll Camber Coefficients • Lateral Force Deflection Steer • Aligning Torque Deflection Steer • Tire Cornering Stiffnesses • Tire Camber Stiffnesses • Tire Aligning Torque Properties	• Weight • Tire Cornering Stiffness • Aligning Torque • Roll Camber • Roll Steer • Lateral Force Deflection Steer • Lateral Force Deflection Camber • Aligning Torque Deflection Steer

Also, factors associated with the kinematics of the suspension system, such as roll camber and roll steer, were not changed to affect understeer. For the NADSdyna vehicle model, which is based on a multi-body dynamics formulation, changing these properties would require a change to the geometry of the suspension components. This requires significant reformulation of the NADSdyna model and represents a level of effort beyond the scope or requirements of this project. Accordingly, all three of the SUV models used the same suspension geometry.

For the purposes of developing the three SUV models, remaining vehicle attributes from Table 1 were evaluated to study their individual effects on the baseline SUV understeer gradient values. Factors that would reduce understeer are:

Weight Distribution
- Move Sprung Mass Rearward

Center of Gravity Height
- Increase Sprung Mass CG Height

Aligning Torque Compliance Steer
- Reduce Front Aligning Torque Compliance Steer
- Increase Rear Aligning Torque Compliance Steer

Lateral Force Compliance Steer
- Reduce Front Lateral Force Compliance Steer
- Increase Rear Lateral Force Compliance Steer

Lateral Load Transfer
- Reduce Front Auxiliary Roll Stiffness
- Increase Rear Auxiliary Roll Stiffness

The eight items listed above were all changed separately by the amounts listed in Table 2. The appropriate vehicle model parameters were changed, and NADSdyna simulation runs for both clockwise and counterclockwise constant speed slowly increasing steer maneuvers were run. Figure 8 contains graphs indicating the understeer gradients for the baseline and modified vehicle runs. These runs were used to evaluate the degree of understeer change resulting from each attribute change and to gain understanding of which portions of the understeer range are affected by the various changes. Table 2 summarizes the results.

Table 2. Effects of Changing Individual Vehicle Attributes on Understeer Gradient

	Understeer Gradient (deg/g)		
	CCW	**CW**	**Average**
Baseline	5.06	4.81	**4.94**
Move Sprung Mass CG Rearward by 12 inches	2.14	3.00	**2.57**
Increase Sprung Mass CG Height by 2 inches	4.87	4.85	**4.86**
Reduce Front Lateral Force Compliance to Zero	2.46	2.02	**2.24**
Increase Rear Lateral Force Compliance to 0.006 rad/kN	2.32	3.41	**2.87**
Set Front Aligning Moment Compliance to +0.008 rad/(100Nm)	2.77	3.57	**3.17**
Set Rear Aligning Moment Compliance to -0.008 rad/(100Nm)	3.58	4.17	**3.88**
Increase Front Antiroll Bar Stiffness to 60,000 Nm/rad	4.98	4.90	**4.94**
Reduce Rear Antiroll Bar Stiffness to Zero	5.03	4.95	**4.99**

The graphs in Figure 8 show results from offline simulation runs of constant speed, 50 mph, slowly increasing steer maneuvers. Similar runs were made at 75 mph, and the understeer gradient results computed were found to be fairly insensitive to vehicle speed. The graphs contain straight-line segments for both clockwise (positive steering and lateral acceleration) and counterclockwise (negative steering and lateral acceleration) steering directions. The dark line segments are the linear curve fits to the data. The light line segments are the lines representing the slope of neutral steer (or Ackerman Steer Angle Gradient), indicating the slope where the understeer gradient is zero (Figure 7 indicates a point of neutral steer where the slope of the sample data curve is equal to the slope of the Ackerman Steer Angle Gradient). The graphs in Figure 8 show that all of the conditions simulated resulted in understeer vehicles. The slopes are always greater than the slope of neutral steer, and the vehicles tend to limit understeer.

This evaluation reveals those attributes that have the greatest relative effect on understeer gradient for the baseline vehicle model. These results are not general. Some of the attributes may have a relatively larger influence on understeer in the nonlinear range. Also, for an actual vehicle, many factors contribute to the attributes listed. For example, Bergman (9) lists at least eight vehicle steering components that contribute to steering compliance. Further analyses of these topics are beyond the scope of this current effort.

The reason for studying eight different factors was so that a combination of attribute changes could be used to develop the three different SUV models. The thinking behind this was that it would result in more “real vehicle-like” models for the three SUVs. Simply adjusting only, for example, the front lateral compliance to get different understeer levels would work to get the understeer levels, but such gross changes to a single attribute could result in a vehicle model that was more ‘difficult’ to drive/control than a model comprised of several less dramatic changes.

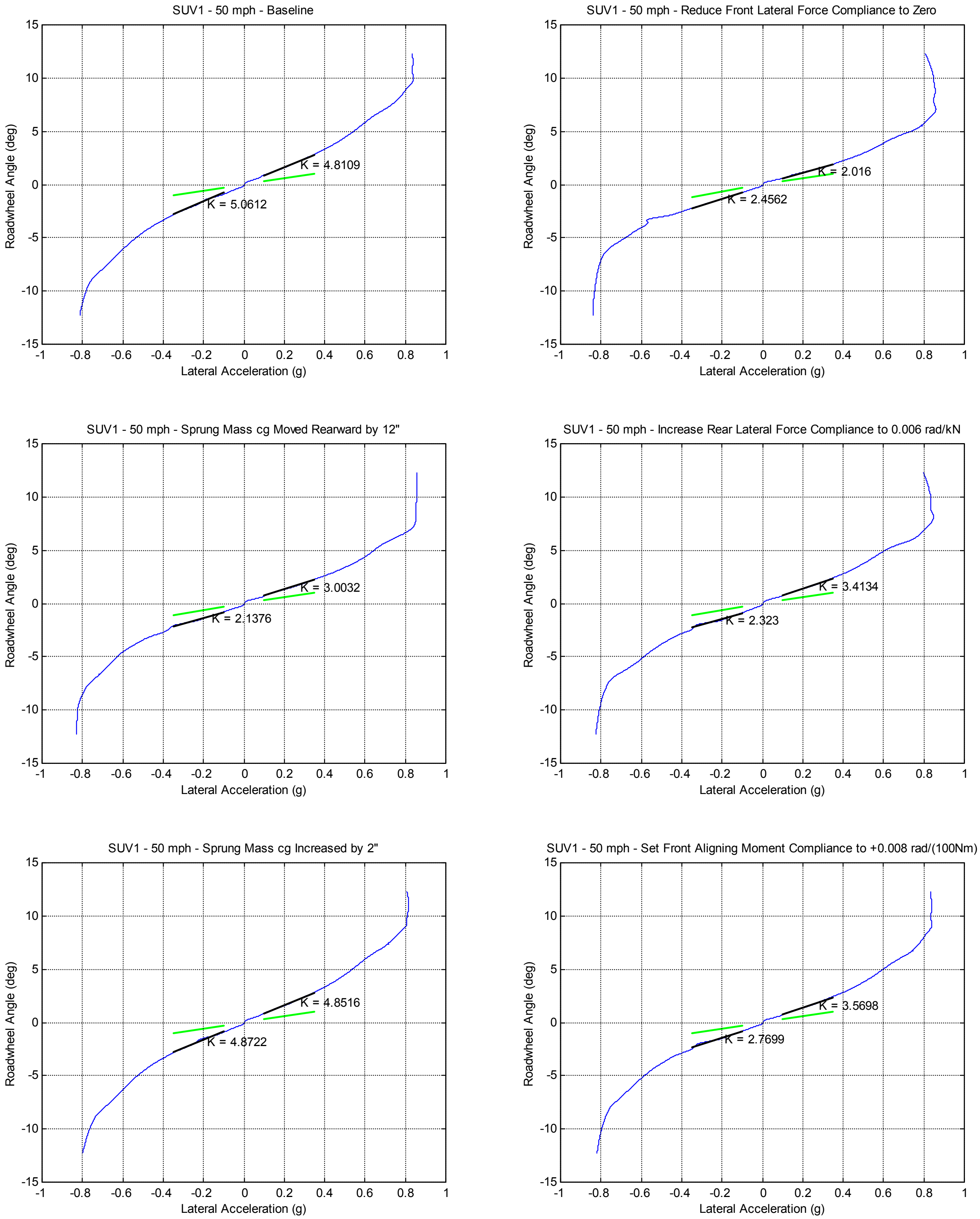
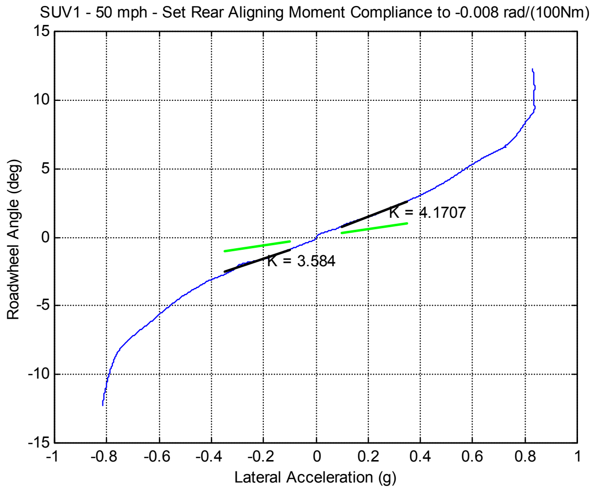
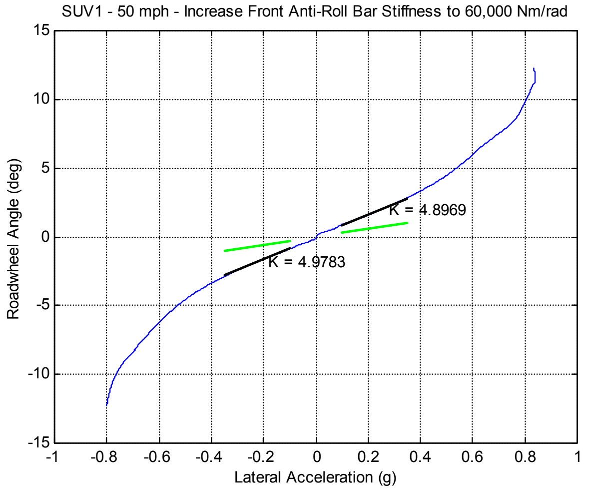


Figure 8. Individual Vehicle Modifications and Their Effects on Vehicle Understeer





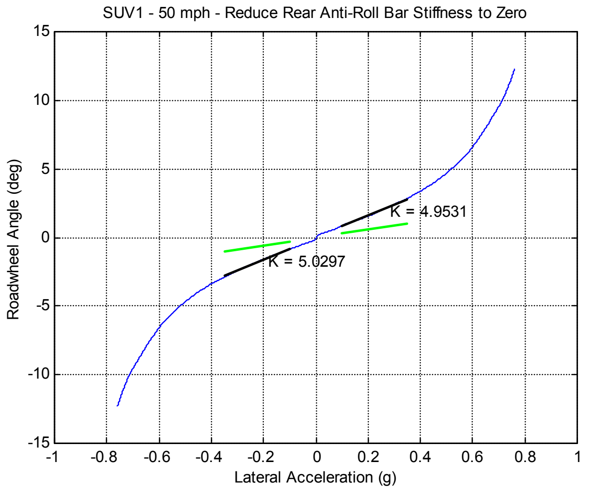


Figure 8. Individual Vehicle Modifications and Their Effects on Vehicle Understeer (Continued)

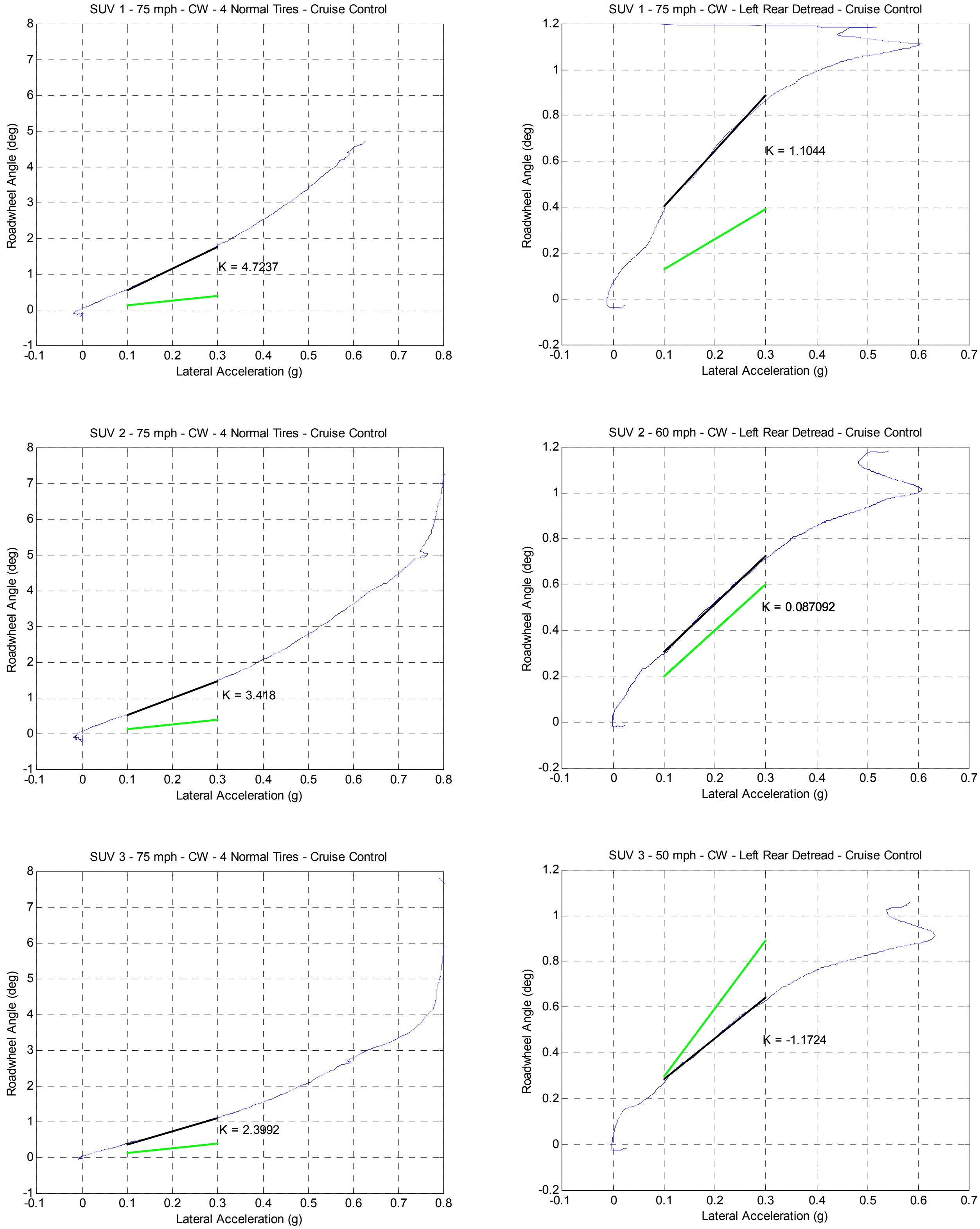
Table 2 shows that increasing the sprung mass CG height by two inches had little effect on the linear range understeer—likewise for the changes made to the front and rear antiroll bar stiffnesses. The CG height has first-order effects on vehicle roll stability, and the antiroll bars direct lateral load distribution and their influences on vehicle handling are particularly important as a vehicle reaches its handling limits. Therefore, neither the CG height nor the antiroll bar stiffnesses were changed from the baseline (Vehicle 1) model to develop the Vehicle 2 and Vehicle 3 models.

The remaining items listed in Table 2, the CG longitudinal position, the front and rear lateral force compliance, and the front and rear aligning moment compliance, were all adjusted to develop models Vehicle 2 and Vehicle 3. Table 3 shows the changes that were made to the various properties for the Vehicle 2 and Vehicle 3 models. The effects of the combinations of these individual changes were studied. However, their overall effects in the linear range of vehicle response are fairly linear. The changes made for the Vehicle 3 model are twice those for the Vehicle 2 model, as indicated in Table 3.

Table 3. List of Changes for Vehicles 2 and 3

Changes in Properties	**Vehicle 2**	**Vehicle 3**
Rearward Movement CG Longitudinal Position	-3 inches	-6 inches
Reduction in Front Lateral Force Compliance	-0.0008 rad/KN	-0.0016 rad/KN
Increase in Rear Lateral Force Compliance	+0.0008 rad/KN	+0.0016 rad/KN
Increase in Front Aligning Moment Compliance	+0.00112 rad/100N-m	+0.00224 rad/100N-m
Reduction in Rear Aligning Moment Compliance	-0.00112 rad/100N-m	-0.00224 rad/100N-m

Figure 9 contains graphs indicating the understeer gradients for the three vehicle models. The left column of Figure 9 contains results for the vehicles with four normal tires and the right column for the vehicles with a left rear detread. The vehicles with normal tires all exhibit understeer, with Vehicle 1 showing the most and Vehicle 3 the least. Vehicle 1 with a detreaded tire still exhibits some understeer; Vehicle 2 exhibits neutral steer; and Vehicle 3 exhibits oversteer. The actual values are listed in Table 4. These results are from constant speed runs made on the NADS. At 75 mph with detreaded tires, Vehicles 2 and 3 may diverge in the yaw direction when cruise control is applied with no steering corrections. This is due to their low understeer gradients and the asymmetry in the driving tires. The defective tire on the left side is modeled to provide lower tire/road forces than the normal tire on the right side. To reduce the effect of driving force differences between left and right wheels, Vehicles 2 and 3 understeer gradients were computed using lower speeds. This reduced the aerodynamics loads and subsequently the needed driving torque to keep the vehicle at constant speed, and provided smooth vehicle responses over the lateral acceleration range from 0.1 to 0.3 g. Understeer gradients are relatively insensitive to vehicle speed in the speed ranges used. Runs for Vehicles 1, 2, and 3 were used to evaluate the understeer gradients measured from NADS runs and to confirm the understeer gradient values for the three SUV models with four normal tires and with a rear tire detread.



SUV 1 - 75 mph - CW - 4 Normal Tires - Cruise Control

SUV 1 - 75 mph - CW - Left Rear Detread - Cruise Control

SUV 2 - 75 mph - CW - 4 Normal Tires - Cruise Control

SUV 2 - 60 mph - CW - Left Rear Detread - Cruise Control

SUV 3 - 75 mph - CW - 4 Normal Tires - Cruise Control

SUV 3 - 50 mph - CW - Left Rear Detread - Cruise Control

Figure 9. Understeer Gradient Curves from NADS Runs - Three SUV Models with Four Normal Tires and with Left Rear Detread

Table 4 and Figure 10 summarize the final understeer results. (Figure 10 displays the understeer values in bar chart format.) The understeer gradient values for the three vehicle models with four normal tires are close to the goal values that were established (4.8, 3.5, and 2.2 deg/g). Likewise, the understeer gradient values for the three vehicle models with a rear detread are close to the desired design values. Vehicle 1 remains an understeer vehicle after a rear detread, Vehicle 2 is close to neutral steer, and Vehicle 3 goes to oversteer with a rear detread. Additionally, the understeer gradient values for the three vehicle models with rear detreads are all roughly 3.5 deg/g less than the normal tire cases, which is consistent with available test data from actual vehicles.

Table 4. Linear Range Understeer Gradients

Clockwise Slowly Increasing Steer Maneuver Values from NADS Runs		
	4 Normal Tires	**Left Rear Detread**
Vehicle 1	4.72 deg/g	1.10 deg/g
Vehicle 2	3.42 deg/g	0.09 deg/g
Vehicle 3	2.40 deg/g	-1.17 deg/g

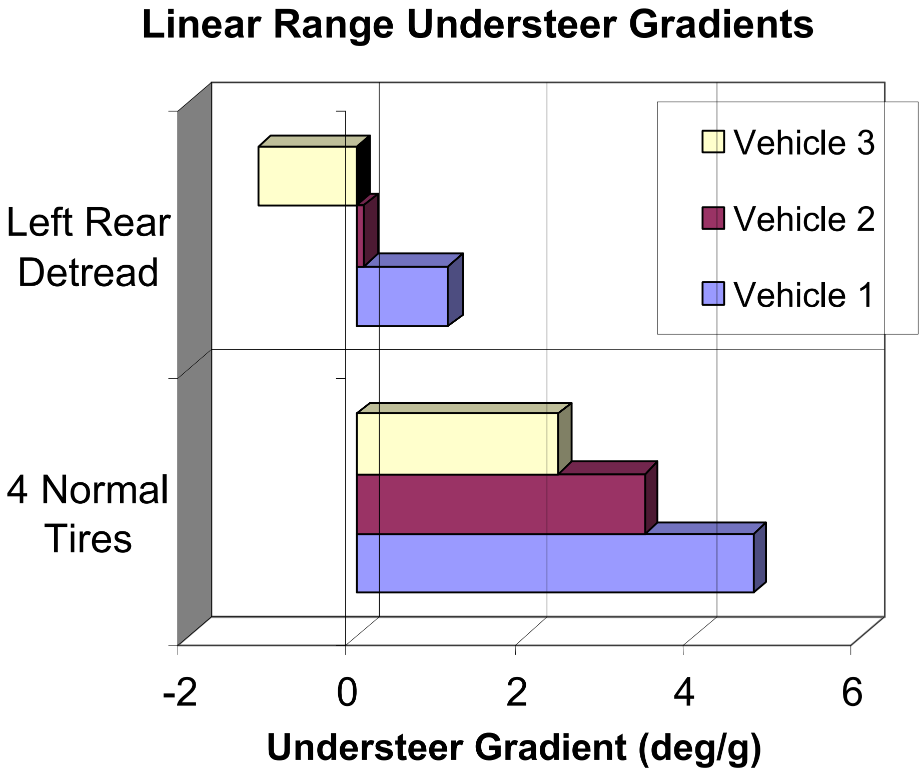


Figure 10. Clockwise Understeer Gradients for Three SUV Models with Four Normal Tires and with Left Rear Detread – Values Measured on NADS

4.0 MODEL OF EXPECTED DRIVER/VEHICLE RESPONSE TO TIRE TREAD SEPARATION

Engineering data have been used to develop a preliminary model of the effects of tread separation. Driver/vehicle response to tire tread separation is divided into two epochs. The first epoch includes the time during which the actual tread separation event is occurring and the properties of the tire are changing. This epoch begins with a flap of the tread breaking loose, continues with the entire tread coming loose, and concludes when the soft rubber between the two steel belts is worn away. The second epoch includes the time during which the driver is driving the vehicle with changed, but constant tire characteristics. This epoch begins at the completion of the wearing away of the soft, inter-belt rubber and concludes when the driver brings the vehicle to a stop. Driver/vehicle reactions during both epochs are of interest.

For the worst type of tread separation (a “leading edge” separation), the first epoch lasts approximately 3 seconds, 1 to 2 seconds for the actual tread separation to occur and 1 to 2 seconds for the wearing away of the soft, inter-belt rubber. To simulate this process, tire properties were linearly degraded for approximately 4 seconds. Vehicle handling during this epoch is transitioning from normal to degraded. Typically, the tread separation event causes the vehicle to pull to the left (for a left rear tread separation), towards the adjacent lane. The expected driver reaction is to attempt to recover by steering to the right. Experienced test drivers who are expecting tread separation can easily maintain control during this epoch. One question this study is trying to answer is whether or not ordinary drivers who do not know that the tread separation is going to occur can maintain vehicle control during this epoch.

Once the soft, inter-belt rubber is worn away, the vehicle’s handling characteristics change. Specifically, the understeer is reduced by approximately 3.5 degrees per g. Therefore, when the driver attempts to pull over to the side of the road and bring the vehicle to a stop (a natural driver reaction to the banging that accompanies tread separation), if the driver enters what would previously have been an appropriate input to steer the vehicle off the road onto the right shoulder, that same input can result in loss of stability, spinout of the vehicle, and uncontrolled road departure due to the degraded handling of the vehicle. Again, test drivers who are expecting tread separation can easily maintain control during this epoch. A second question this study is trying to answer is whether or not ordinary drivers who do not know that the tread separation is going to occur can maintain vehicle control during this epoch.

4.1 Characterizing the Differences Between the Three SUV Models

One method of characterizing the differences between the three SUV models is to determine the speed-steering combination that causes the vehicle to lose stability. The offline NADSdyna simulation is used to predict the handwheel angle at which a vehicle with a detreaded tire on the left wheel will lose control and spin out for different vehicle speeds.

Each vehicle model was run through the right-hand slowly increasing steer maneuver, the same maneuver used to determine the understeer gradient values. For each successive run, the vehicle speed was increased approximately 10 mph (starting at 25 mph). The speed was held constant via the cruise control. To be consistent, the point of loss of control was defined to be the point at which the lateral acceleration reached 0.5 g, which corresponds to the onset of vehicle spin out with a detreaded tire. At this point, the handwheel angle was recorded and the speed-angle pair was added to the graph in Figure 11. In this figure, the area under the curve represents the combinations of speed and steering for which vehicle stability is retained. Points above the curve represent the region in which vehicle control is lost. Examining the results at 60 mph shows that with a detreaded tire on the rear, Vehicle 1 can sustain a handwheel angle of 26 degrees in the constant speed slowly increasing steer maneuver, while Vehicle 2 can only manage 20 degrees, and Vehicle 3 can only manage 15 degrees. This result indicates that drivers may be able to control some vehicles better than others when a tire tread separation occurs.

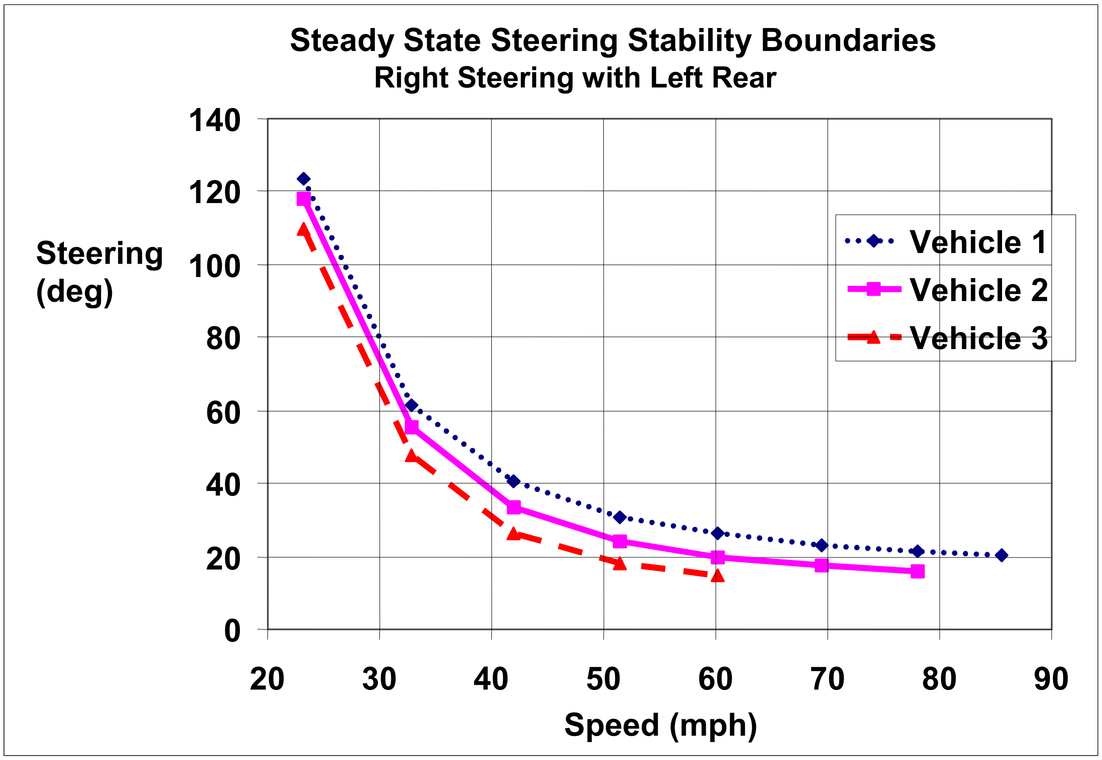


Figure 11. Steady State Steering Stability Boundaries

5.0 METHOD

5.1 Experimental Design

The experiment used a mixed-factor design, with expectation concerning the tread separation as a within-subjects factor, and the following between-subjects factors: instructions (yes, no), tire that failed (left rear, right rear), age (18-25; 35-45; 55-65), and vehicle understeer gradient (three levels, as detailed in Section 3). There were 2 x 2 x 3 x 3 = 36 combinations of these conditions. Three subjects were run in each condition for a total of 108 subjects.

Each subject experienced two tread separations. The first instance of tread separation was unexpected, and the second was expected. After the unexpected tread separation, all subjects were given information about the possibility of a subsequent tread separation. Half were given specific instructions about how best to recover from the tread separation, and the other half received no instruction. The instructions provided to subjects are detailed in the procedure section. Half of the subjects experienced tread separations on the left rear wheel, half on the right rear wheel. For all subjects, the expected tread separation occurred on the same wheel as the unexpected tread separation. All tread separations occurred at high speeds (75 mph) on straight road segments with some surrounding traffic present.

As detailed in Section 3, the levels of understeer implemented in this study were 4.7, 3.4 and 2.4 deg/g. Vehicle models were intended to simulate the handling characteristics of typical SUVs. The tread separation model was modified such that upon activation, the understeer would be reduced by approximately 3.5 deg/g for each vehicle model.

A summary of the matrix of conditions is presented in Table 5.

5.2 Participants

A total of 108 participants, with no prior knowledge of the study objectives, completed the study. Gender was balanced to the extent possible, with primary emphasis placed on balancing the within-vehicle understeer condition. Participants were pre-screened to ensure that they represented one of the three age groups, held a valid driver's license, had been licensed for at least 5 years, had driven at least 5000 miles during the past year, were able to drive an automatic transmission vehicle without assistive devices, and were able to give informed consent. Criteria for participants in the younger group were slightly different in that fewer years of licensure were required. Requirements were for those who were 18, 19, 20, and 21-25 years of age to have been licensed at least 2, 3, 4, and 5 years, respectively. All participants were also required to pass a battery of health screening criteria required by the National Advanced Driving Simulator (NADS) facility. Potential participants were excluded if they had participated in a simulator study within the past 12 months.

Table 5. Subject Numbers per Treatment for Unexpected and Expected Tread Separation Scenarios

Number of Subjects	**Age** (Between Treatment)	**Understeer Condition** (Between Treatment)	**Tire** (Between Treatment)	**Instructions** (Between Treatment)	**Trial** (Within Subject)
3	18-25	1	Left	Yes	1 = Unexpected; 2=Expected
3	18-25	1	Left	No	1 = Unexpected; 2=Expected
3	18-25	1	Right	Yes	1 = Unexpected; 2=Expected
3	18-25	1	Right	No	1 = Unexpected; 2=Expected
3	35-45	1	Left	Yes	1 = Unexpected; 2=Expected
3	35-45	1	Left	No	1 = Unexpected; 2=Expected
3	35-45	1	Right	Yes	1 = Unexpected; 2=Expected
3	35-45	1	Right	No	1 = Unexpected; 2=Expected
3	55-65	1	Left	Yes	1 = Unexpected; 2=Expected
3	55-65	1	Left	No	1 = Unexpected; 2=Expected
3	55-65	1	Right	Yes	1 = Unexpected; 2=Expected
3	55-65	1	Right	No	1 = Unexpected; 2=Expected
3	18-25	2	Left	Yes	1 = Unexpected; 2=Expected
3	18-25	2	Left	No	1 = Unexpected; 2=Expected
3	18-25	2	Right	Yes	1 = Unexpected; 2=Expected
3	18-25	2	Right	No	1 = Unexpected; 2=Expected
3	35-45	2	Left	Yes	1 = Unexpected; 2=Expected
3	35-45	2	Left	No	1 = Unexpected; 2=Expected
3	35-45	2	Right	Yes	1 = Unexpected; 2=Expected
3	35-45	2	Right	No	1 = Unexpected; 2=Expected
3	55-65	2	Left	Yes	1 = Unexpected; 2=Expected
3	55-65	2	Left	No	1 = Unexpected; 2=Expected
3	55-65	2	Right	Yes	1 = Unexpected; 2=Expected
3	55-65	2	Right	No	1 = Unexpected; 2=Expected
3	18-25	3	Left	Yes	1 = Unexpected; 2=Expected
3	18-25	3	Left	No	1 = Unexpected; 2=Expected
3	18-25	3	Right	Yes	1 = Unexpected; 2=Expected
3	18-25	3	Right	No	1 = Unexpected; 2=Expected
3	35-45	3	Left	Yes	1 = Unexpected; 2=Expected
3	35-45	3	Left	No	1 = Unexpected; 2=Expected
3	35-45	3	Right	Yes	1 = Unexpected; 2=Expected
3	35-45	3	Right	No	1 = Unexpected; 2=Expected
3	55-65	3	Left	Yes	1 = Unexpected; 2=Expected
3	55-65	3	Left	No	1 = Unexpected; 2=Expected
3	55-65	3	Right	Yes	1 = Unexpected; 2=Expected
3	55-65	3	Right	No	1 = Unexpected; 2=Expected

Potential participants were recruited through local newspaper advertisements and were contacted by telephone for initial screening. Because one of the study objectives was to compare unexpected and expected tread separation, it was necessary to withhold complete information about the purpose of the study during this initial contact with potential participants to ensure no prior knowledge of the unexpected tread separation. Therefore, potential participants were told that the study was one of the first to be conducted on the new simulator and was intended to evaluate the realism of the simulator device focusing on the simulator’s look, feel, and response with respect to steering, accelerating, and braking. Participants were later debriefed on the complete purpose of the study during their study session.

Participants who met the basic criteria for participation were scheduled for a single, two-hour simulator session at the NADS facility. All participants were asked to refrain from the use of alcohol or other non-prescription drugs for the 24 hours prior to the study session. The study protocol involved asking participants if they had consumed alcohol or other drugs for the 24 hours prior to testing.

A total of 119 participants were scheduled. Eleven of these participants were consented but were dropped from the study due to failure to meet all enrollment criteria, incomplete or invalid data collection, or idiosyncrasies in driving performance that limited comparisons to others in the study sample. A detailed summary of incomplete participants is provided in Table 6.

Table 6. Enrollment and Completion of Participants Per Age Group.

	Age/Gender Category						
	18-25 Yrs.		35-45 Yrs.		55-65 Yrs.		
	Male	Female	Male	Female	Male	Female	Comments
Total Incomplete or Replaced (N=11)	-	1	-	1	-	-	Need for Special Devices While Driving - Violation of Enrollment Criteria
	-	-	1	-	1	-	Simulator Problem - Incomplete Data Collection
	-	-	-	1	-	-	Withdrew Participation Due to Simulator Sickness - Incomplete Data Collection
	-	-	-	-	3	-	Use of Cruise Control - limited comparison of performance metrics
	-	-	2	-	-	-	Two-Footed Drivers - limited comparison of performance metrics
	-	-	-	-	-	1	Extremely Low Velocity - limited comparison of performance metrics
Total Complete (N=108)	18	18	18	18	18	18	

5.3 Apparatus

The National Advanced Driving Simulator (NADS), located at the University of Iowa's Oakdale Research Park in Coralville, was used for this study. A comprehensive description of the features of NADS (10) can be found in Appendix B. The NADS consists of a large dome in which entire cars and the cabs of trucks and buses can be mounted. The dome is mounted on a 6 degree of freedom hexapod which is mounted on a motion system, providing 20 meters of both lateral and longitudinal travel and 330 degrees of yaw rotation. The resulting effect is that the driver feels acceleration, braking and steering cues as if he or she were actually in a real car, truck or bus. The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their make and model. A Jeep Cherokee cab was used for this experiment.

The Visual System provides the driver with realistic field-of-view, including the rearview mirror images. The driving scene is three-dimensional, photo-realistic, and correlated with other sensory stimuli. The Visual System database includes highway traffic control devices (signs, signals and delineation), three-dimensional objects that vehicles encounter (animals, potholes, concrete joints, pillars, etc.), high density, multiple lane traffic interacting with driver's vehicle, common intersection types (including railroad crossings, overpasses, bridge structures, tunnels, etc.), and roadway weather environment.

The Control Feel System (CFS) for steering, brakes, clutch, transmissions, and throttle realistically controls reactions in response to driver inputs, vehicle motions and road/tire interactions over the vehicle maneuvering and operating ranges. The CFS is capable of representing automatic and manual control characteristics such as power steering, existing and experimental drive trains, Antilock Brake Systems (ABS), and cruise control. The control feel cuing feedback has high bandwidth and no discernible delay or distortion associated with driver control actions or vehicle dynamics. An automatic transmission and conventional (non-ABS) brake system were used for this study.

The Motion System provides a combination of translational and angular motion that duplicates scaled vehicle motion kinematics and dynamics with nine degrees of freedom. The Motion System is coordinated with the CFS to provide the driver with realistic motion and haptic cuing during normal driving and pre-crash scenarios. The motion system is configured and sized to correctly represent the specific forces and angular rates associated with vehicle motions for the full range of driving maneuvers. An additional four actuators, one at each wheel of the vehicle, provide vertical vibrations. This simulates the feel of a real road.

The Auditory System provides motion-correlated, three dimensional, realistic sound sources, coordinated with the full ranges of the other sensory systems databases. The Auditory System also generates vibrations to simulate vehicle/roadway interaction. The auditory database includes sounds emanating from current and new design highway surfaces, from contact with three-dimensional objects that vehicles encounter (potholes, concrete/tar joints, pillars, etc.), from other traffic, from the vehicle during operation, and sounds which reflect roadway changes due to changes in the weather conditions.

The Vehicle Dynamics (NADSdyna) System determines vehicle motions and control feel conditions in response to driver control actions, road surface conditions and aerodynamic disturbances. Vehicle responses are computed for commanding the Visual, Motion, Control Feel, and Auditory Systems. Available vehicle dynamics models include passenger cars, light trucks, and heavy trucks. The models encompass normal driving conditions and limit performance maneuvering that might be encountered during crash avoidance situations, including spinout and incipient rollover.

5.3.1 Implementation of Tread Separations

The tread separation event chosen for presentation in this study was intended to be a severe event in terms of safety. Severe tread separations are ones in which the tread separates rapidly leaving little time for the driver to respond. This type of tread separation is associated with high rates of fatalities for SUVs. A tread separation event simulation was developed based on the actual vehicle used to develop Vehicle Model 1. The authors acknowledge that tread separation events can vary based on the vehicle and environmental conditions.

The tread separation event was simulated by a sequence of audio and vehicle vibration cues corresponding to tread separation and by changes in vehicle handling consistent with tread separation. Tread separations were simulated by activating the tread separation model within the NADS combined with the various special effects produced by the NADS subsystems. A model of tire separation was developed and integrated with the tread separation input for this purpose. Once a tread separation was triggered in the dynamics, the various cueing subsystems provided cues to the driver consistent with the output of the dynamics. As discussed in Section 3, appropriate high-frequency vibrations were fed to the vibration actuators while the tread separation was taking place. Limited testing conducted during audio recording of tread separations found that there is little tactile feel associated with road feel following completion of a tread separation. As a result, the change in road feel due to a tread separation after the tread has separated was considered negligible and thus was not simulated.

A high-fidelity audio recording of an actual detread event was recorded for presentation during the scenario-induced tread separation. Three detread events were staged and recorded involving the actual vehicle on which the Vehicle 1 model was based. The detread events were initiated by cutting the tire tread to expedite the detread process. Figure 12 illustrates the location of these cuts. Using a box knife, cuts were made around the circumference of the tire to expose the outside edges of the steel belts. Horizontal cuts where then made laterally between the two belts approximately one inch into the tire on each side. The third and final cuts were vertical ones made from the outside edge of the tread, through the first belt and tread, and extended approximately 1 inch into the tire along the angle of the wires of the outermost belt. The angle of the wire was determined from the first cut. The vehicle was then driven at 70-75 mph until the complete detread occurred. The detread events were observed to occur after 2 to 10 miles of driving. Each of the detread events recorded sounded basically the same, so one was selected arbitrarily for use in the study. While the duration of the actual detread recordings varied, a playback duration of 4 seconds was used in this study. To ensure faithful audio cue reproduction, the detread recording was directionally replayed on a pair of high-fidelity speakers inside the rear of the vehicle cab. The volume level was subjectively tuned by the audio-engineer to ensure consistent and accurate replay.

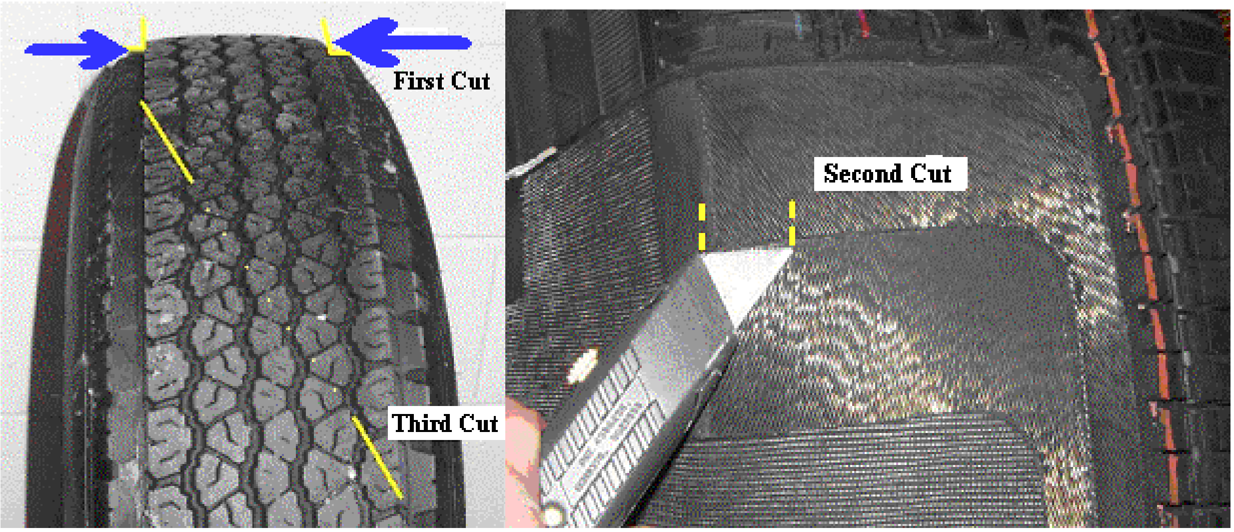


Figure 12. Labeled Photographs Showing Location of Cuts Made on the Tire to Expedite the Detread Process.

5.3.2 Simulator Scenarios

Two scenarios were programmed for this experiment, an unexpected tread separation and an expected tread separation. The failures simulated complete tread separation from the left or right rear tire.

The ***Practice Drive*** consisted of approximately 5 minutes of highway driving on straight and curved segments of roadway designed to help the participant become familiar with driving the simulator vehicle and how it handled. The practice drive began with the simulator vehicle parked on a multilane highway. The in-vehicle experimenter asked the participant to begin driving and to accelerate to the posted speed limit of 75 mph. After driving straight for approximately 1-1/2 minutes and while on a straight road segment, the in-vehicle experimenter asked the participant to change lanes to the far left lane. Then after a few seconds and while still on a straight stretch of roadway, the participant was asked to change lanes back to the far right lane. The participant was then asked to practice braking by slowing down to about 30 mph and accelerating back to 75 mph. At the end of the practice drive, the participant was asked to stop and shift the car into park. Participants were encouraged to asked questions but were told that neither questions nor conversation would be allowed in the experimental scenarios that would follow.

The ***Unexpected Tread Separation Scenario*** consisted of approximately 12 miles of multilane freeway driving on straight and curved segments with light traffic traveling in the same direction as the simulator vehicle. During this segment, the participant was instructed to increase the speed of the simulated vehicle with changes in the posted speed to become familiar to driving at speeds of 55, 65, and 75 mph. The tread separation occurred at a pre-defined point on a straight road segment, while driving at a speed of 75 mph.

The ***Expected Tread Separation Scenario*** consisted of a single tread separation that occurred on a straight multilane freeway road segment approximately two minutes into the scenario drive while driving at a speed of 75 mph. As with the unexpected tread separation, there was light traffic traveling in the same direction as the simulator vehicle. Subjects were instructed before the drive that a tire would fail while driving on the divided highway. Half of the participants were given instructions for handling the tread separation while the other half were not.

5.4 Experimental Procedure

Each research participant was greeted by the experimental staff and asked a few brief questions to ensure compliance with all the inclusion/exclusion criteria. Specific emphasis was placed on verifying that no consumption of alcohol and other drugs had occurred for within the past 24 hours. Participants were reminded that the purpose of the study was to evaluate the realism of the simulator device focusing on the simulator's look, feel, and response with respect to steering, accelerating, and braking. They were given a verbal overview of the material covered in the Informed Consent Document (see Appendix C) and were then asked to read and sign the document before continuing participation in the study. Participants then completed a modified version of the NADS Driving Survey (see Appendix C) to provide basic demographic information and general information about their driving history and past participation in other driving studies.

Participants were then escorted to the simulator where they were introduced to the in-vehicle experimenter, who provided a brief overview of adjustments for the vehicle cab. Participants were told that they would complete a practice drive and two experimental drives. They were told that the experimenter in the cab was available to help them with the route and all other instructions but that no conversation would be allowed during the simulator drives. No mention was made of the tread separations. The in-vehicle experimenter rode in the rear passenger-side seat for all sessions. The In-Vehicle Protocol (see Appendix C) provides complete details of the interactions between the participant and the in-vehicle experimenter.

Participants then completed the 5-minute practice drive during which they drove at up to 75 mph on a multilane freeway with light traffic. During the practice drive, each participant drove on straight and curved roadway segments, made a lane change left and right across all lanes, slowed to 30 mph, accelerated back to 75 mph, and came to a complete stop at the end of the drive.

After the completion of the practice drive, participants were asked if they had any questions about the simulator. After questions were answered, they began the unexpected tread separation scenario. This scenario lasted for approximately 10 minutes and consisted of driving at 55, 65, and 75 mph on straight and curved segments of multilane freeway. The unexpected tread separation occurred at the end of the drive on a straight section of road while driving at a speed of 75 mph. If the participant did not respond to the tread separation within 15 seconds, the control room assistant prompted the in-vehicle experimenter that the tread separation had occurred, and the in-vehicle experimenter told the participant, “You’ve just experienced a tread separation. Drive as you normally would with a tread separation.”

After the simulator came to a controlled or uncontrolled stop, the in-vehicle experimenter verbally briefed the participant on the main purpose of the study. Participants were specifically told that in addition to evaluating how the simulator replicates actual driving, the study was also interested in the performance of drivers who experience simulated tread separation. It was clarified that a primary goal of the project was to compare the performance of drivers who encounter tread separation unexpectedly to conditions where tread separation is expected. Participants were then told of the expected tread separation in the next, and last, driving trial. Half of the participants were given no further instruction while half were given specific instructions for handling the tread separation. The instructions were to: (1) Keep going straight; (2) Gradually brake to slow down; and (3) Pull off the road.

Participants then completed the expected tread separation scenario that lasted approximately two minutes and consisted of a straight roadway segment driven at 75 mph. If the participant did not respond to the tread separation within 10 seconds, the control room assistant prompted the in-vehicle experimenter that the tread separation had occurred, and the in-vehicle experimenter informed the participant, “You’ve just experienced a tread separation. Drive as you normally would with a tread separation.”

After completing this scenario, participants completed the Simulator Sickness Questionnaire (see Appendix C) and returned to the briefing room area. Participants were offered a beverage prior to completion of the Reaction and NADS Tread Separation Surveys (see Appendix C). Participants then completed a structured interview session that was videotaped and transcribed for analysis (see Appendix C). Finally, participants were verbally debriefed on the complete purpose of the study, as well as via a written debriefing statement (see Appendix C). Participants were asked not to discuss the purpose of the study with anyone until a pre-specified time after the anticipated completion of the data collection (approximately 1 month).

5.5 Data Collected

Binary data were collected for all simulator runs. The following driving performance data were collected throughout the simulator runs:

- Vehicle offset from the center line of the lane
- Steering wheel position
- Brake pedal position
- Accelerator pedal position
- Longitudinal velocity of the vehicle
- Accelerations in x, y, and z directions
- Heading angle
- Yaw rate
- Distance to other vehicles
- Driver response time to the tread separation

In addition to the binary data, video data were recorded of all runs. Video frames captured included the following: 1) driver's face, 2) NADS dome, 3) forward road, and 4) a wide-angle side view of the driver from behind. To facilitate coding of the video data the following data items were programmed into the overlay and were recorded on each frame of the video data: vehicle velocity, brake force, accelerator position, steering wheel angle, and time of day.

6.0 RESULTS

6.1 Overview of Data Analyses

Analyses were conducted to address two basic questions. First, we wanted to determine what factors contributed to loss of vehicle control following a tread separation event. Second, we wanted to understand how drivers responded to the tread separation events and to identify factors that affected their ability to maintain vehicle control following the tread separation event. Among the possible factors contributing to loss of vehicle control, we examined the effects of vehicle understeer condition, prior knowledge of the imminent tread separation, driver age, failed tire location, and the effectiveness of the specific instructions given to half the subjects before the expected tread separation. Frequency analyses were conducted to test these effects. The second set of analyses considered how drivers responded following the tread separation events. An example of one driver's inputs and the resulting vehicle response can be seen in the set of plots found in Appendix D. Several different approaches were taken, including an examination of drivers' initial responses and the characteristics associated with all driver responses. We also examined the effects of speed at various points during the sequence of events surrounding the tread separation. These analyses include a combination of frequency analyses and simple parametric tests of driving performance measures. The decision to emphasize univariate analyses rather than multivariate analyses involving the entire experimental design was necessitated in part by our interest in identifying factors associated with trial outcome (loss of vehicle control). In addition, our review of the video records revealed significant variability in the mode and timing of drivers' responses, which motivated our attempts to create subsets to characterize the different ways drivers responded to the tread separations.

6.2 Loss of Vehicle Control

Loss of vehicle control following the tread separation event was determined both by subjective evaluation of video data and by analysis of engineering data. The criterion used with engineering data was a momentary yaw rate of greater than +/-15 degrees/second. This criterion accurately matched complete loss of vehicle control as determined from the video data on 214 (.99) of the 216 trials. The remaining two trials resulted in momentary loss of control from which the driver was able to successfully recover.

6.2.1 Effect of Vehicle Understeer Condition

The proportions of trials that ended in complete loss of vehicle control are shown for each understeer condition in Table 7. The "N" in the column heading stands for the number of occurrences and the "P" stands for the corresponding proportion for the respective understeer condition (table row).

Table 7. Loss of Vehicle Control by Understeer Condition

	Loss of Vehicle Control					
	No		**Yes**		**Total**	
Understeer Condition	**N**	**P**	**N**	**P**	**N**	**P**
Vehicle 1	65	.90	7	.10	72	1.00
Vehicle 2	47	.65	25	.35	72	1.00
Vehicle 3	23	.32	49	.68	72	1.00
Total	135	.63	81	.38	216	1.00

Overall, 81 trials (.38) ended in loss of vehicle control. Loss of vehicle control was strongly affected by vehicle understeer condition. Sixty-eight percent of the trials with Vehicle 3 resulted in loss of vehicle control, versus 35% for Vehicle 2 and 10% for Vehicle 1. The difference between vehicle understeer conditions was statistically significant, $\chi^2(2) = 52.6$, $p < .0001$.

6.2.2 Effect of Prior Knowledge of Imminent Tread Separation

Each driver experienced two tread separations. One tread separation occurred with no prior information; the second tread separation occurred following an explanation given by the in-vehicle experimenter. The difference between these groups is referred to as driver expectation or prior knowledge. Table 8 shows the likelihood of control loss by understeer condition and driver expectation.

Table 8. Loss of Vehicle Control by Understeer Condition and Prior Knowledge

(a) Unexpected tread separations

Understeer Condition	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
Vehicle 1	30	.83	6	.17	36	1.00
Vehicle 2	18	.50	18	.50	36	1.00
Vehicle 3	1	.03	35	.97	36	1.00
Total	49	.45	59	.55	108	1.00

(b) Expected tread separations

Understeer Condition	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
Vehicle 1	35	.97	1	.03	36	1.00
Vehicle 2	29	.81	7	.19	36	1.00
Vehicle 3	22	.61	14	.39	36	1.00
Total	86	.80	22	.20	108	1.00

Overall, 59 (.73) of the 81 observed control failures occurred in the unexpected condition versus 22 (.27) in the expected condition, which indicates that when drivers had prior knowledge of the imminent tread separation, they were significantly less likely to sustain loss of vehicle control following the tread separation, $\chi^2(1) = 27.0$, $p < .0001$. Differences in the proportion of trials resulting in loss of vehicle control between vehicle understeer conditions were tested separately for unexpected and expected trials. Results indicated significant associations between understeer condition and loss of vehicle control for both unexpected ($\chi^2(1) = 47.6$, $p < .0001$) and expected ($\chi^2(1) = 14.5$, $p < .0001$) trials.

The proportions of trials resulting in loss of vehicle control are presented in Figure 13 to emphasize the effects of prior knowledge on control loss for the three vehicle understeer conditions. Clearly, the absolute effect of prior knowledge was greatest among drivers of Vehicle 3. For this group, drivers' knowledge of the imminent tread separation reduced the control loss proportion from .97 to .39. The potential effect of prior knowledge for drivers of Vehicle 1 was constrained by the relatively low proportion of unexpected tread separation trials resulting in control loss (.17). When the reduction in proportion of trials resulting in control loss due to prior knowledge is considered as a percentage of the proportion of unexpected trials resulting in control loss, the reductions are 82%, 62%, and 60% for Vehicles 1,2, and 3, respectively. Thus, the relative reduction in control loss associated with prior knowledge was greatest for Vehicle 1, however this effect must be interpreted with caution due to the small frequencies resulting from the low incidence of control loss for Vehicle 1.

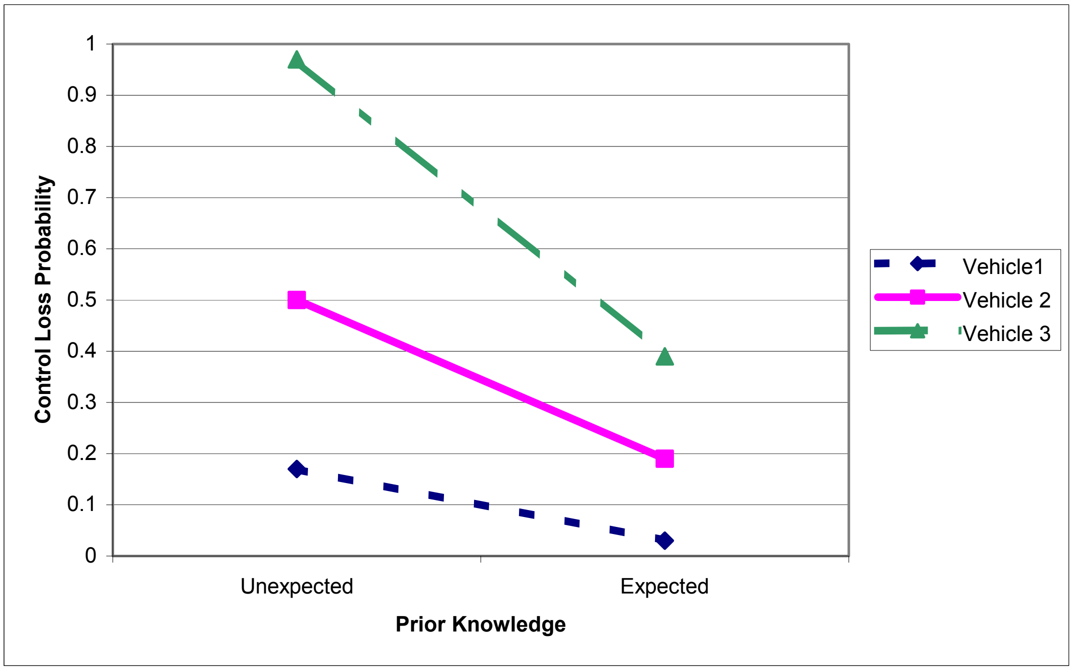


Figure 13. Effect of Prior Knowledge on Likelihood of Control Loss

6.2.3 Effect of Driver Age

Table 9 presents the control loss frequencies by driver age group and prior knowledge of the imminent tread separation. Differences among age groups in the unexpected condition indicate that loss of vehicle control following tread separation increased with driver age at a nearly statistically significant level, $\chi^2(2) = 5.68$, $p = .058$. Differences in the expected condition among age groups were not statistically significant, $\chi^2(2) = 0.80$, $p = .67$.

Table 9. Loss of Vehicle Control by Driver Age Group and Prior Knowledge

(a) Unexpected tread separations

Age Group	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
18 - 25	21	.58	15	.42	36	1.00
35 – 45	17	.47	19	.53	36	1.00
55 – 65	11	.31	25	.69	36	1.00
Total	49	.45	59	.55	108	1.00

(b) Expected tread separations

Age Group	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
18 - 25	29	.81	7	.19	36	1.00
35 – 45	27	.75	9	.25	36	1.00
55 – 65	30	.83	6	.17	36	1.00
Total	86	.80	22	.20	108	1.00

The effects of prior knowledge on the proportion of trials resulting in loss of vehicle control are presented separately for each driver age group in Figure 14. The pattern of results indicates that prior knowledge of an imminent tread separation was most beneficial to the oldest drivers (55-65), among whom the proportion of control loss trials was reduced from .69 to .17.

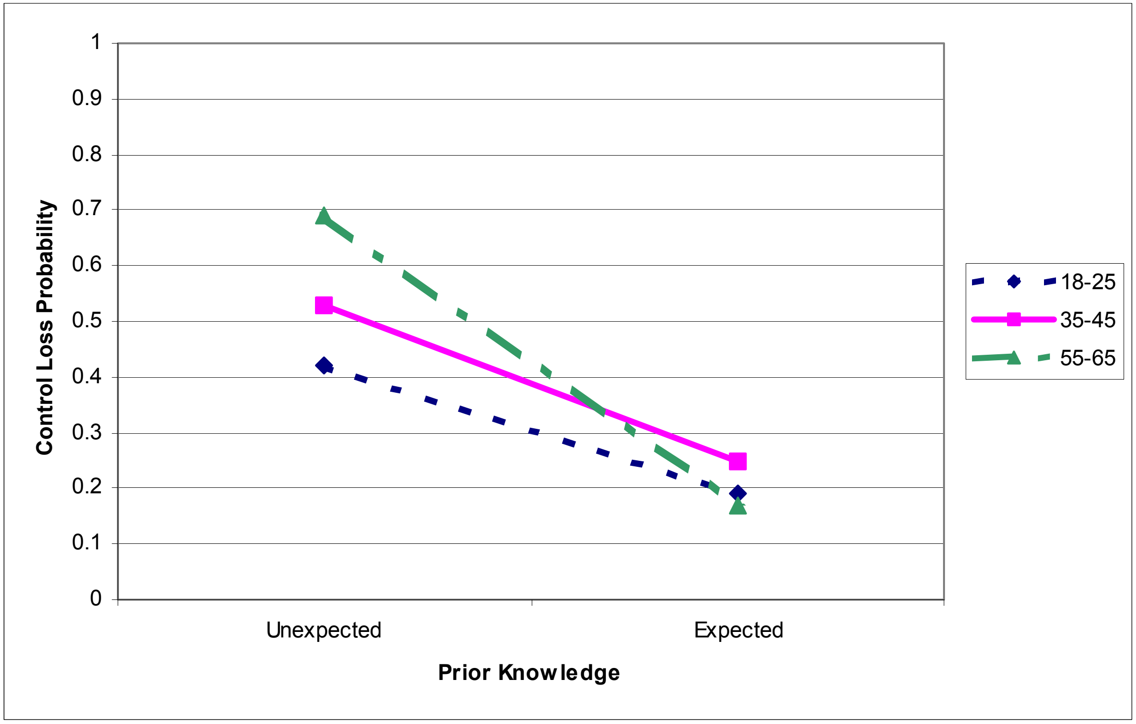


Figure 14. Effect of Prior Knowledge on Probability of Control Loss for Different Age Groups

6.2.4 Effect of Left versus Right Tread Separation

Tread separations occurred on either the left rear or right rear tires. As shown in Table 10, failures of the left rear tire were slightly more likely to lead to control loss (.39 vs. .36 for right rear tread separations). This difference was not statistically significant, $\chi^2(1) = 0.18$, p = .67.

Table 10. Loss of Vehicle Control by Location of Tire That Failed

Tire Location	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
Left Rear	66	.61	42	.39	108	1.00
Right Rear	69	.64	39	.36	108	1.00
Total	135	.63	81	.38	216	1.00

6.2.5 Effect of Instructions

After the first, unexpected, tread separation, all drivers were told that they would experience another tread separation. Half of the subjects were given specific instructions about how best to respond to the tread separation (see Appendix C), and half were told that one would occur, but were not given instructions for responding. The frequencies of trials resulting in loss of vehicle control separated by whether or not the driver received instructions are shown in Table 11.

Table 11. Loss of Control by Instructions for Expected Tread Separations

Instructions	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
Yes	43	.80	11	.20	54	1.00
No	44	.81	10	.19	54	1.00
Total	87	.81	21	.19	108	1.00

Overall, there was no difference between the two instruction conditions in the proportion of trials resulting in control loss.

We also examined the effect of the specific instructions on the outcome for the subset (N = 59) of drivers who experienced loss of vehicle control on the unexpected trial. There was no effect of instruction on probability of loss of control for this group.

6.2.6 Effect of Gender

We examined the effect of gender on the probability of control loss following tire failure. These data are presented in Table 12.

Table 12. Loss of Control by Gender for Expected Tread Separations

Gender	Loss of Vehicle Control					
	No		Yes		Total	
	N	P	N	P	N	P
Female	62	.57	46	.43	108	1.00
Male	74	.69	34	.31	108	1.00
Total	136	.63	80	.37	216	1.00

Although female test subjects were somewhat more likely to sustain loss of vehicle control following tire failure, the difference between genders was not statistically significant, $\chi^2(1) = 2.86$, p = .09. We separated the trials according to driver expectation and found a similar pattern of small but statistically non-significant differences between gender groups. Because gender was not part of the experimental design, we conducted no further analyses on this topic.

6.3 Drivers' Vehicle Control Responses to Tread Separation

Drivers either braked or steered at some point following the tread separation event. Review of video data revealed that on many trials, drivers failed initially to respond to the tread separation. As expected, this was more likely for the unexpected failures. In these instances, after 15 seconds the in-vehicle experimenter notified subjects that a tread separation had occurred and instructed them to respond as they normally would if this situation occurred in real-world driving. Because drivers' responses were based on different amounts of information, this latter group of trials was analyzed separately and is referred to as "Experimenter Notify" ("Exp Notify") in the following analyses.

Two sets of analyses are presented. The first set considers the drivers' initial responses to the tread separation event, while the second set considers all responses.

6.3.1 Analyses of Drivers' Initial Responses Following Tread Separation

Frequencies and associated proportions of drivers' initial responses and trial outcomes are shown in Figure 15 for unexpected tread separations and in Figure 16 for expected tread separations. (Additional descriptive text for Figures 15 and 16 can be found in Appendix E.) The frequencies and proportions for the initial response categories are also presented in Table 13. Braking is defined as the first brake pedal application. Steering is defined as the first input of at least 4 degrees that lasted 0.5 seconds.

Table 13. Drivers' Responses Following Tread Separation by Prior Knowledge

Driver Response	Prior Knowledge					
	Unexpected		Expected		Total	
	N	P	N	P	N	P
Steering	71	.66	28	.26	99	.46
Braking	0	.0	63	.58	63	.29
Steer after Exp Notify	24	.22	10	.09	34	.16
Brake after Exp Notify	13	.12	7	.06	20	.09
Total	108	1.00	108	1.00	216	1.00

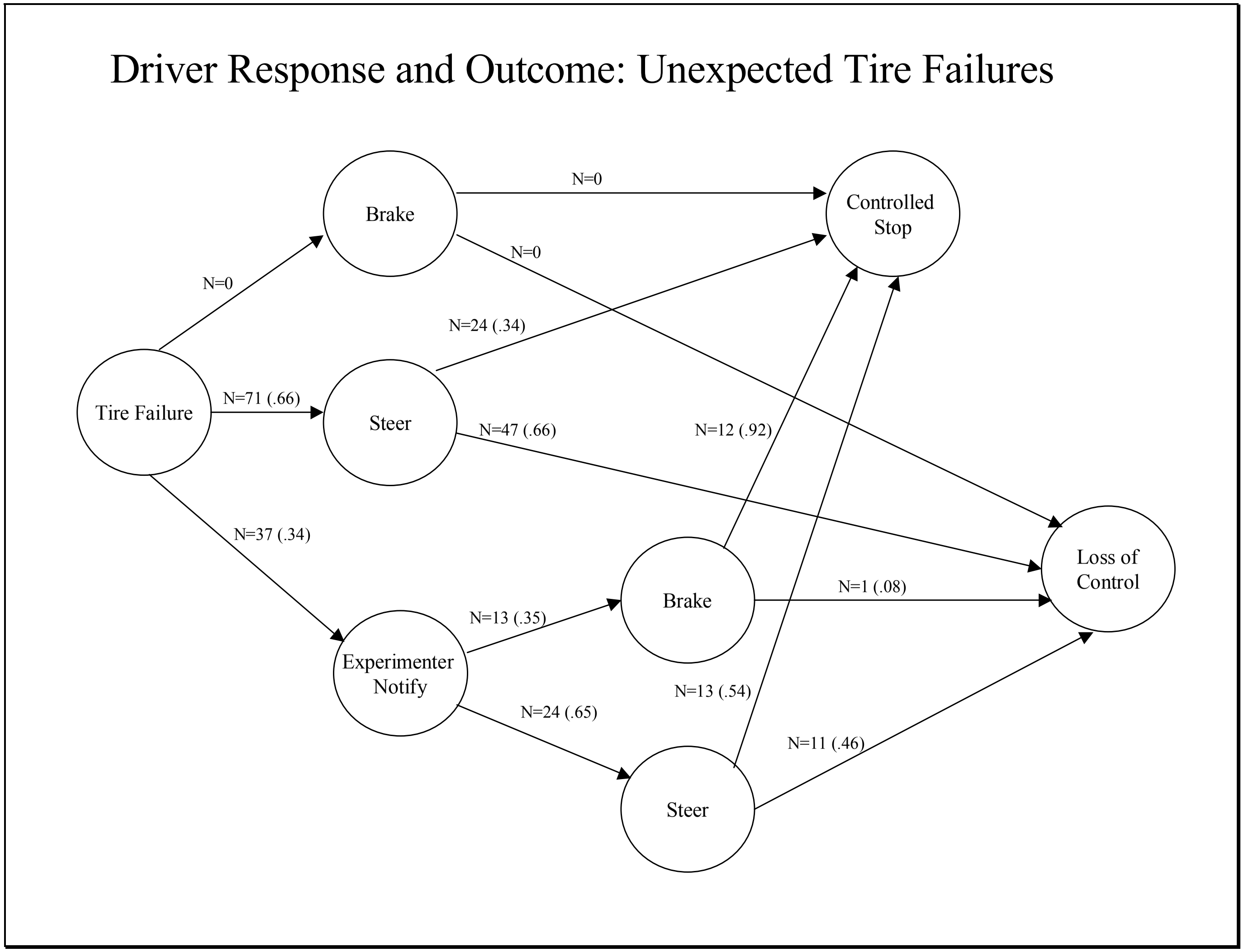
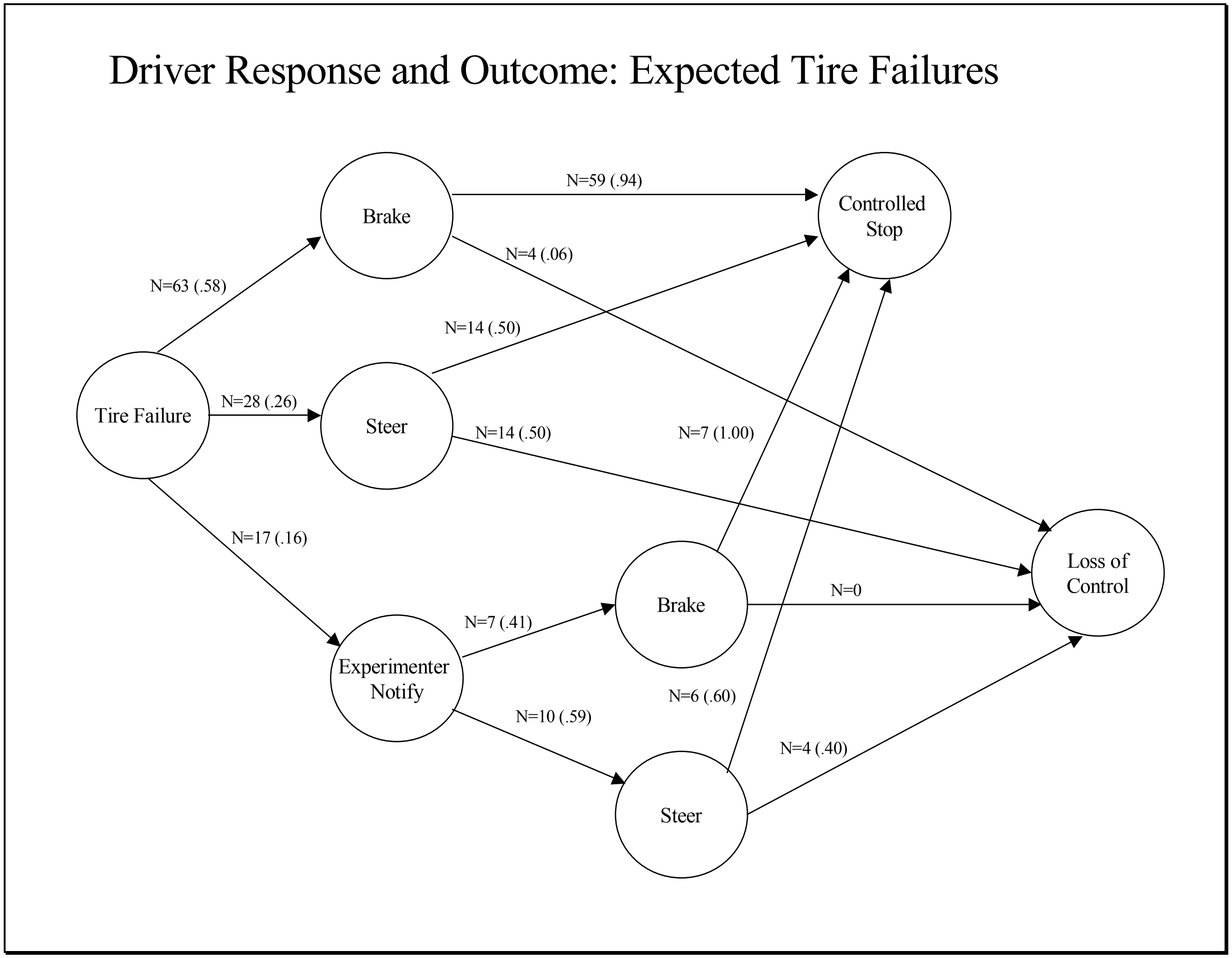


Figure 15. Drivers' Responses to Unexpected Tread Separations and Their Outcomes



Driver Response and Outcome: Expected Tire Failures

Figure 16. Drivers’ Responses to Expected Tread Separations and Their Outcomes

Drivers' initial responses were strongly influenced by their knowledge of the imminent tread separation. When the tread separation was unexpected, none of the subjects responded by braking. In this condition, drivers either steered (N = 71, p = .66) or made no response prior to experimenter notification (N = 37, p = .34). When drivers were aware of the upcoming tread separation, they responded by braking first on 63 (.58) trials, more than twice as often as they responded by steering. Even with knowledge of the event, 17 (.15) drivers did not respond until after being notified by the experimenter.

Table 14 presents frequencies and proportions of trials resulting in loss of vehicle control according to the driver's initial response and prior knowledge about the tread separation. Numerators are frequencies of trials resulting in loss of vehicle control; denominators are the frequencies of trials categorized by initial response and are the same as those presented in Table 13. Proportions were computed from the two frequencies.

Table 14. Proportion of Trials Resulting in Loss of Vehicle Control by Drivers' Initial Response and Prior Knowledge

Driver Response	**Prior Knowledge**					
	Unexpected		**Expected**		**Total**	
	N	**P**	**N**	**P**	**N**	**P**
Steering	47/71	.66	14/28	.50	61/99	.62
Braking	0/0	0	4/63	.06	4/63	.06
Steer after Exp Notify	11/24	.46	4/10	.40	15/34	.44
Brake after Exp Notify	1/13	.08	0/7	.0	1/20	.05
Total	59/108	.55	22/108	.20	81/216	.38

Overall, drivers who responded to tread separations initially by steering were much more likely to sustain loss of vehicle control than those who responded by braking first (.62 vs. .06, $z = 6.84$, $p < .001$). This was also evident for trials in which the experimenter notified the subject before a response was made (.44 vs. .05, $z = 3.02$, $p < .01$). Although knowledge of the imminent tread separation was associated with slightly lower rates of control loss for all response categories, the large overall difference in the proportion of trials resulting in control loss between expected and unexpected trials appears to be due to the shift in initial response mode from steering in the unexpected trials (.66) to braking in the expected trials (.58) together with greater success associated with braking first.

Figures 17 and 18 present the frequencies of drivers' initial responses for unexpected and expected tread separations separately for the three vehicle understeer conditions. (Additional descriptive text for Figures 17 and 18 can be found in Appendix E.) On the unexpected trials (Figure 17) when drivers' initial responses were steering inputs, the proportion of trials resulting in control loss increased with decreasing vehicle understeer [Vehicle 1: .13; Vehicle 2: .60; Vehicle 3: .97], $\chi^2(2) = 32.1$, $p < .0001$. As shown in Figure 18, this effect was also evident for the expected tread separation trials [Vehicle 1: 0; Vehicle 2: .45; Vehicle 3: .69], $\chi^2(2) = 6.0$, $p < .05$, despite the smaller frequencies. This trend did not occur for the expected tread separation trials for which the initial response was braking [Vehicle 1: .04; Vehicle 2: .11; Vehicle 3: .06], $\chi^2(2) = .85$, $p < .50$. (For the unexpected trials, the initial driver response was never braking.)

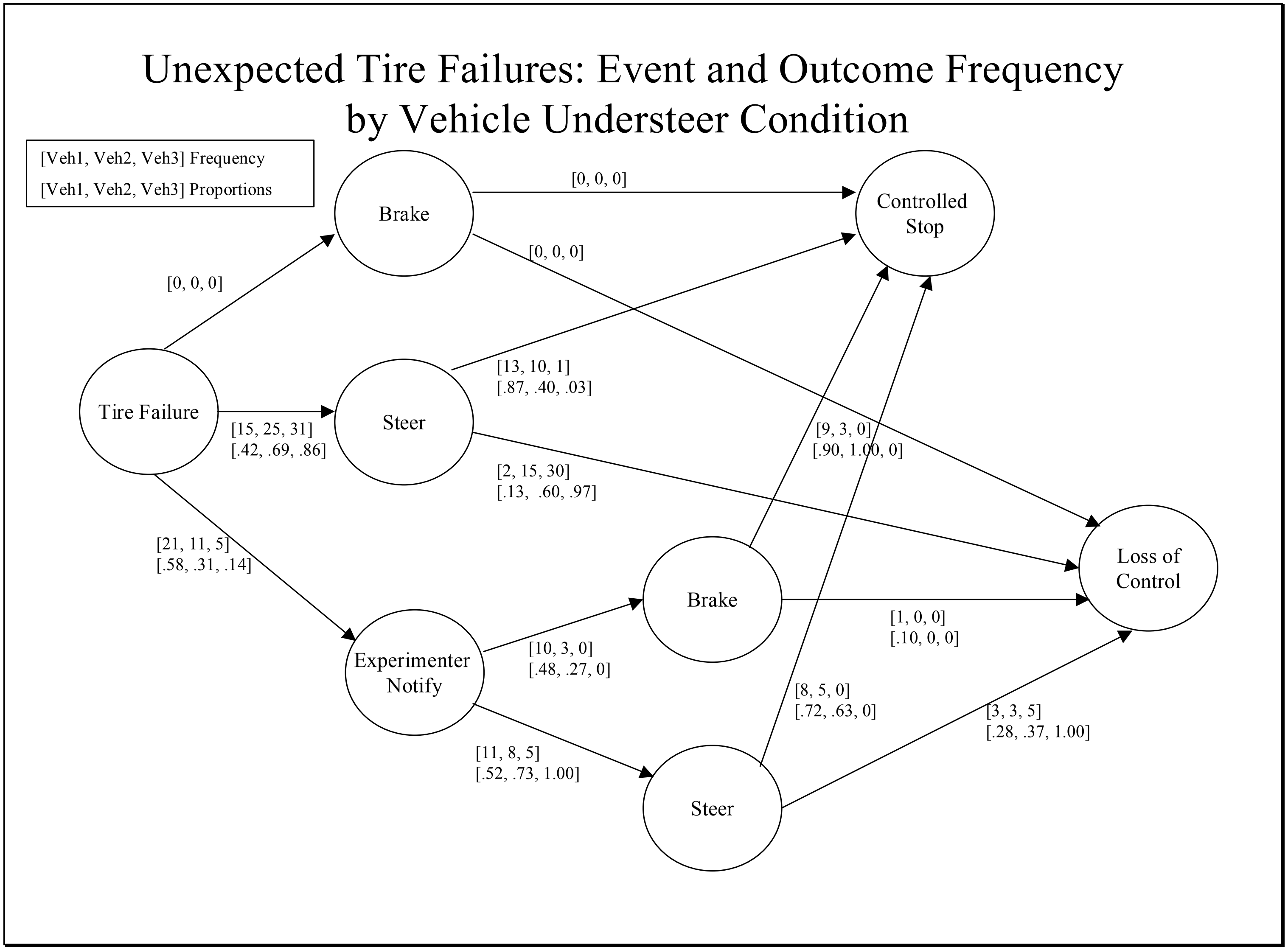


Figure 17. Drivers' Responses to Unexpected Tread Separations and Their Outcomes by Vehicle Understeer Condition

Expected Tire Failures: Event and Outcome Frequency by Vehicle Understeer Condition

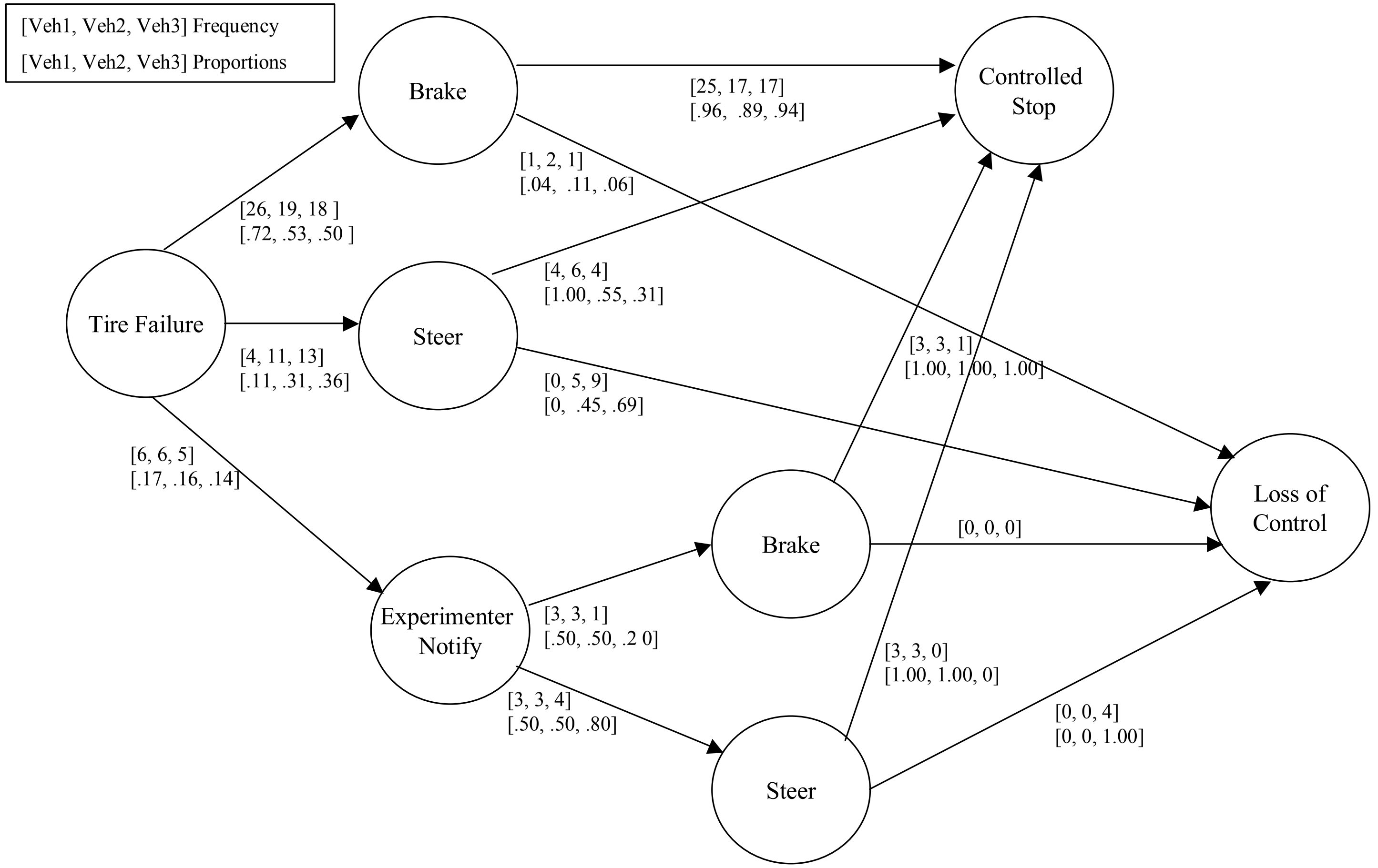


Figure 18. Drivers' Responses to Expected Tread Separations and Their Outcomes by Vehicle Understeer Condition

6.3.2 Timing of Drivers' Initial Responses and Outcomes

Figures 19 and 20 present means and standard deviations for the time intervals between the tread separation events, the drivers' first responses, and the outcomes for unexpected and expected trials, respectively. (Additional descriptive text for Figures 19 and 20 can be found in Appendix E.) Figure 20 shows that for expected tread separations, drivers who braked first did so in 2.3 seconds on average, while those who steered first did so in 5.4 seconds on average. Loss of control was defined as the time at which the momentary yaw rate exceeded 15 degrees/second. On expected trials, loss of control occurred, on average, 4.5 seconds following the steer input for drivers who steered first and 3.9 seconds after the steering response for drivers who responded by steering following experimenter notification.

We examined these same time intervals for the three vehicle understeer conditions to determine if any time intervals were sensitive to differences in vehicle understeer. Three of the time intervals revealed trends reflecting differences between vehicle understeer conditions:

(1) In the expected tread separation condition among those drivers who responded first by steering, the mean steering response time decreased from 7.9 s in Vehicle 1, to 5.2 s and 4.8 s, for Vehicles 2 and 3, respectively.

(2) In the expected tread separation condition among drivers who braked first, subjects braked slightly faster in Vehicle 3, (M = 1.7 s), relative to the other two conditions, which both had mean brake response times of 2.5 seconds.

(3) In the unexpected condition among drivers who responded by steering first, the mean time between the initial steering input and loss of vehicle control was 17.2 s for Vehicle 1, 14.7 s for Vehicle 2, and 7.9 s for Vehicle 3. While this result suggests that the vehicle became more difficult to control following tread separation as vehicle understeer decreased, the absence of a similar trend for the expected trials suggests the need for caution in this interpretation, without considering other factors

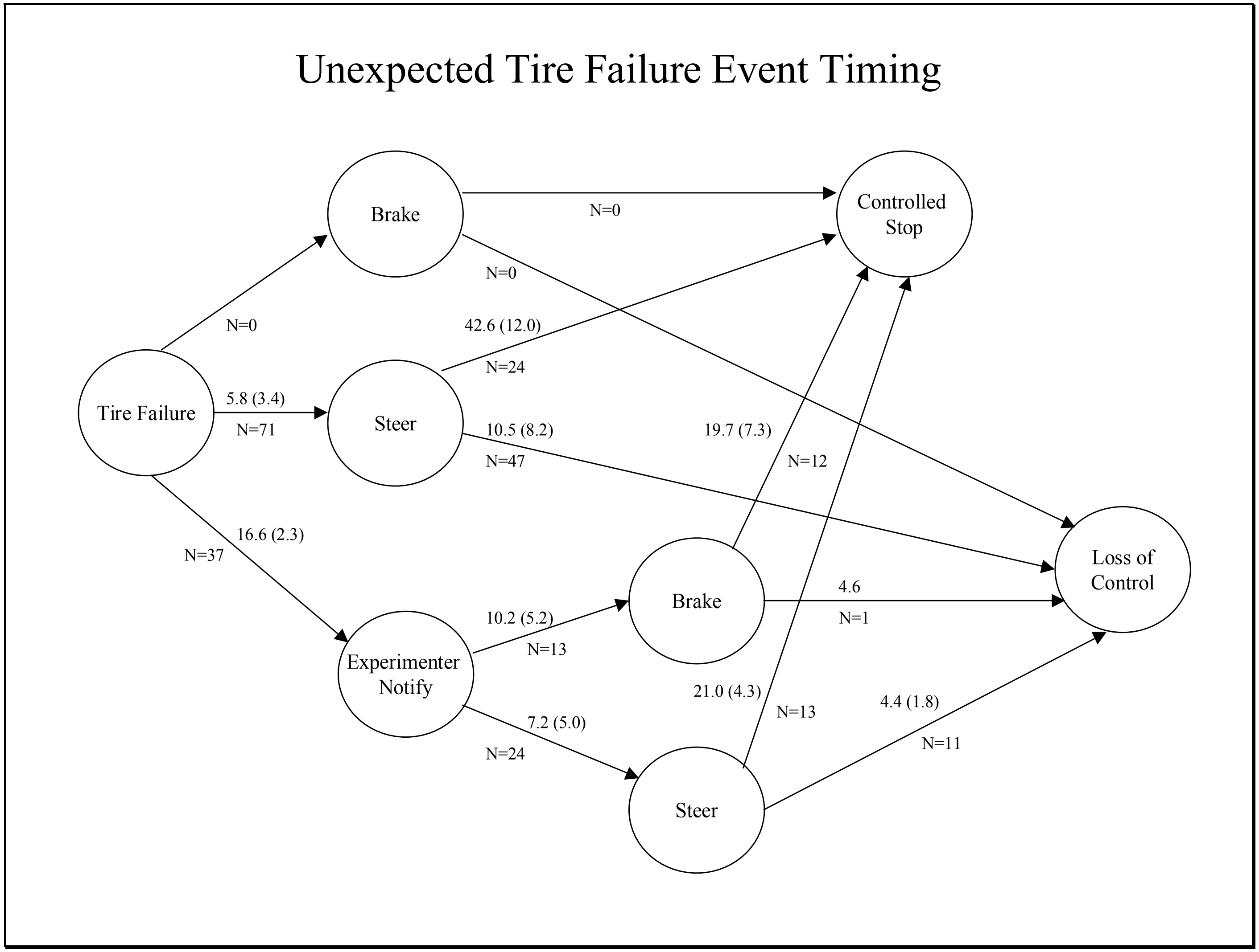


Figure 19. Means (and Standard Deviations) of Times Between Events in Unexpected Tread Separation Trials (Seconds)

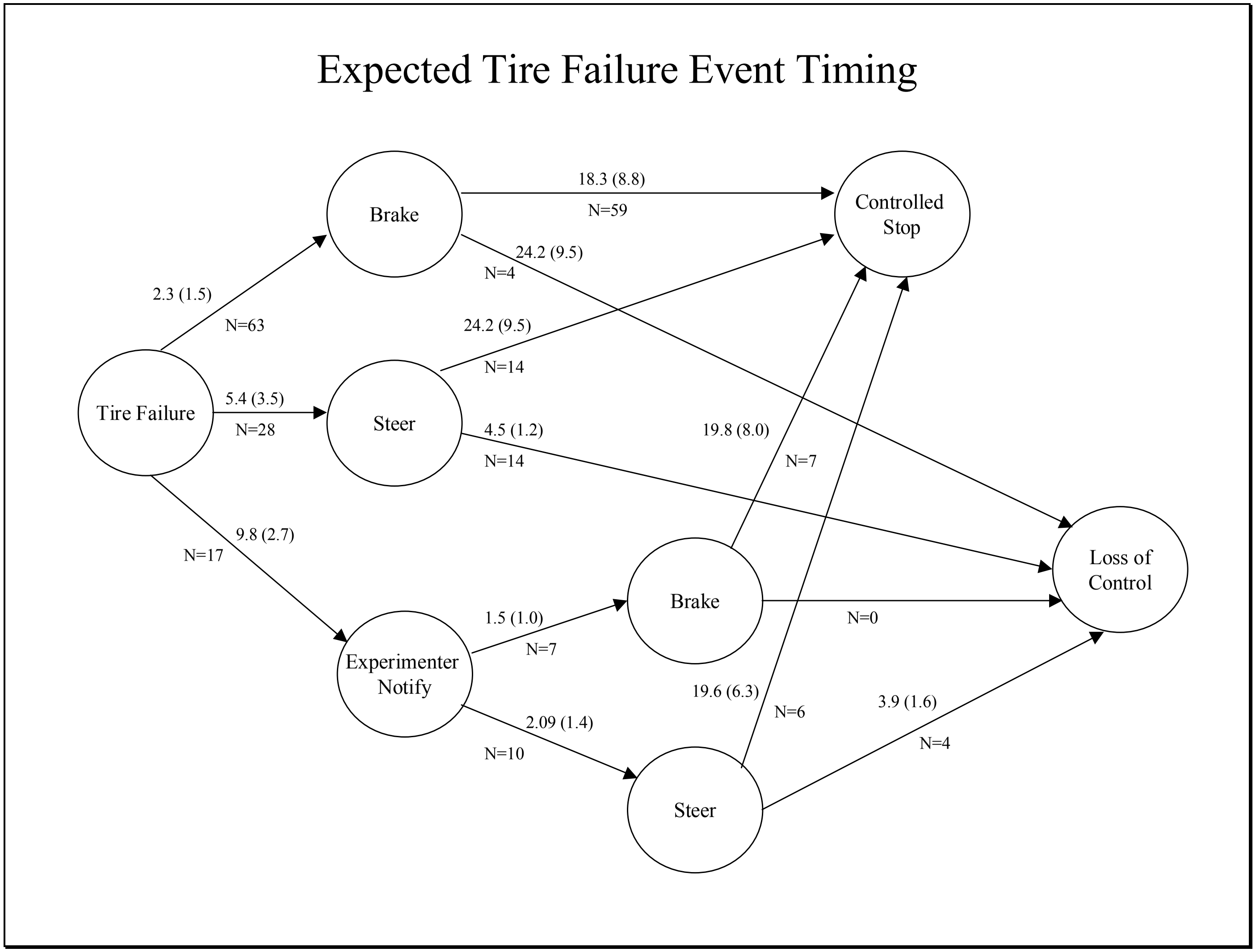


Figure 20. Means (and Standard Deviations) of Times Between Events in Expected Tread Separation Trials (Seconds)

6.3.3 Effect of Instructions on Drivers' Initial Responses

Frequencies and proportions of drivers' initial responses separated by whether or not they received instructions are presented in Table 15.

Table 15. Effect of Instructions on Drivers' Initial Responses to Expected Tread Separation Event (Expected Trials Only)

	Instructions			
	Yes		**No**	
First event after tread separation	**N**	**P**	**N**	**P**
Steer input	12	.22	16	.30
Brake input	31	.57	32	.59
Experimenter notify	11	.20	6	.11
Total	54	1.00	54	1.00

The apparent effect of the instructions was that proportionately fewer drivers steered as a first response to the tread separation; however, this difference was not statistically significant, χ^2 (2) = 2.19 p > .10.

6.3.4 Time to Initial Vehicle Instability

Table 16 presents the mean time between the tread separation event and the time at which the vehicle first sustained a momentary yaw rate of +/-5 degrees per second, without consideration of driver response. This yaw rate criterion is less than the 'loss of control' criterion of 15 degrees per second and is intended to represent the time at which the vehicle first exhibited instability. Only trials on which the driver responded before experimenter notification and the yaw rate exceeded +/-5 degrees per second were included in this analysis.

Table 16. Time (Sec.) from Tread Separation to First Yaw Rate of +/-5 Degrees/Second by Vehicle Understeer Condition and Subjects' Prior Knowledge (Experimenter Notify Trials Removed)

	Prior Knowledge					
	Unexpected			**Expected**		
Vehicle Understeer Condition	**N**	**M**	**SD**	**N**	**M**	**SD**
Vehicle 1	7	27.9	9.0	10	11.7	5.5
Vehicle 2	21	21.2	9.3	16	10.7	4.5
Vehicle 3	31	12.5	8.0	23	8.0	2.5
All Vehicles	59	17.4	10.1	49	9.6	4.2

As is evident, vehicle understeer condition contributed significantly to the time following the tread separation event at which the vehicle first began to become unstable, $F(2,72) = 12.43$, $p < .0001$. This was true for both unexpected and expected tread separations.

Table 17 presents the mean time differences between the driver's first steering input following the tread separation and the time at which the vehicle first started to lose stability. The yaw rate criterion of +/-5 degrees per second was used. All values shown in Table 17 are positive, which indicates that the onset of vehicle instability occurred following rather than before the steering inputs. (We examined the entire distribution and found all but one value to be positive.) Steering inputs led more quickly to instability in Vehicles 2 and 3, relative to Vehicle 1, $F(2,72) = 11.27$, $p < .0001$.

Table 17. Time (Sec.) from Steering Input to First Yaw Rate of +/-5 Degrees/Second by Vehicle Understeer Condition and Subjects' Prior Knowledge (Experimenter Notify Trials Removed)

	Prior Knowledge					
	Unexpected			Expected		
Vehicle Understeer Condition	N	M	SD	N	M	SD
Vehicle 1	7	22.3	8.2	10	5.9	5.4
Vehicle 2	21	14.9	9.5	16	4.0	3.1
Vehicle 3	31	6.9	7.8	23	3.1	2.4

6.3.5 Response Times for All Driver Responses

Figure 21 presents mean response times for accelerator release, brake activation and steering following the tread separation event for all combinations of vehicle understeer condition and prior knowledge. Trials in which the experimenter notification came before the driver's response were eliminated. Otherwise, data are presented for all driver responses (i.e., braking and steering for each driver).

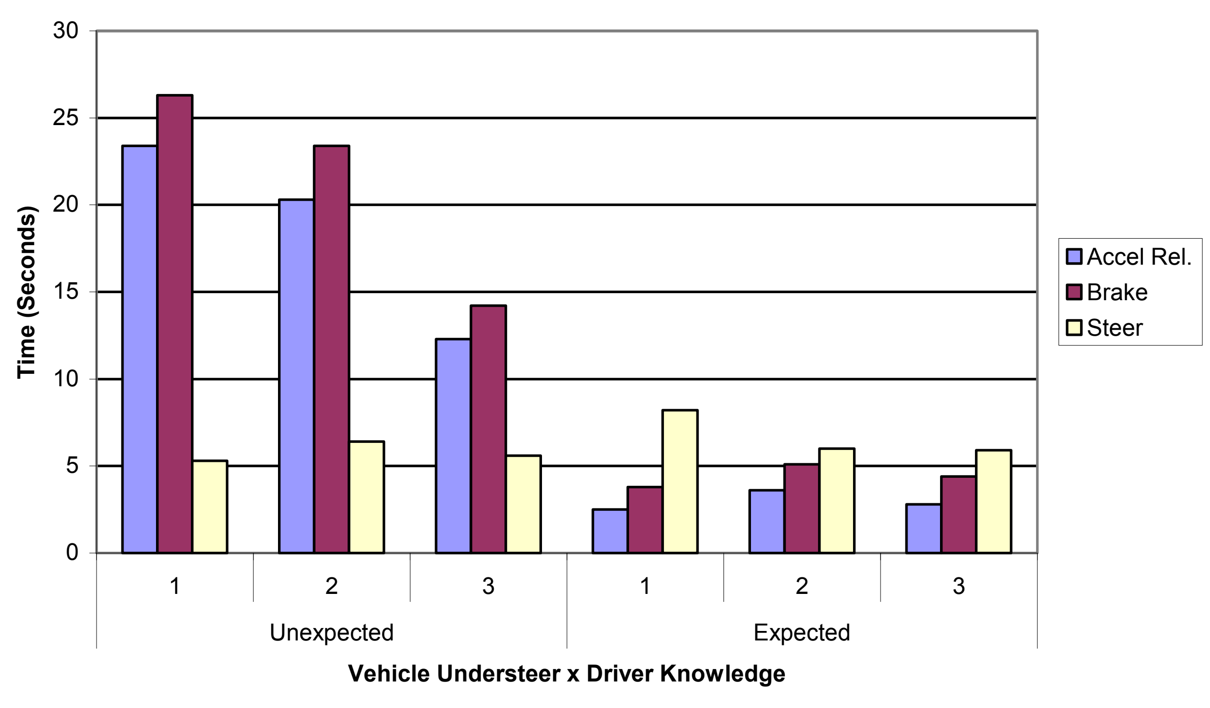


Figure 21. Drivers' Responses to Tread Separation by Understeer Condition and Prior Knowledge (Experimenter Notify Trials Removed)

Knowledge of the impending tread separation affected both the timing and the strategy of drivers' responses. Response times for accelerator release and braking were faster when drivers expected the tread separation. Statistical tests for these effects are summarized in the row labeled Prior Knowledge in Table 18. The marginally significant effect of prior knowledge on steering response time (shown in the same table row) reflects generally slower steering response times in the expected condition. This increase was associated primarily with Vehicle 1, as shown in Figure 21.

As also shown in Figure 21, the average driver steered first then braked in the unexpected condition. However, in the expected trials, the average driver braked before steering. Differences between vehicle understeer conditions were more evident in the unexpected trials, except for steering, as reflected by the significant Vehicle Understeer x Prior Knowledge interactions for accelerator release and braking shown in Table 18. Drivers released the accelerator and braked more quickly with decreasing understeer, as shown by the significant main effects of Vehicle Understeer in Table 18.

Table 18. Results of Statistical Tests for Response Times Associated with Accelerator Release, Braking, and Steering

Independent Variable	**ANOVA d.f.**	**Dependent measure**					
		Accelerator Release		**Brake**		**Steering**	
		F	**Prob.**	**F**	**Prob.**	**F**	**Prob.**
Prior Knowledge	1, 61	319.4	.0001*	268.5	.0001*	4.13	.05*
Vehicle Understeer	2, 94	13.1	.0001*	13.5	.0001*	0.8	.45 (NS)
Driver Age	2,94	5.91	.004*	8.64	.0004*	2.23	.11 (NS)
Vehicle Understeer x Prior Knowledge	2, 61	17.05	.0001*	15.71	.0001*	0.61	.55 (NS)
Prior Knowledge x Driver Age	2, 61	3.00	.06	4.4	.02*	3.19	.05*

* denotes statistically significant effect
NS denotes effect that is not statistically significant

6.3.6 Effects of Driver Age on Vehicle Control Responses

Figure 22 presents vehicle control response times by prior knowledge and driver age group. Trials in which the experimenter notification occurred first were eliminated. Response times for accelerator release and brake activation decreased with increasing age, more so for unexpected trials. One exception is the slightly faster accelerator release and braking times among younger drivers on expected trials, relative to the middle age group. These differences are reflected in the significant Prior Knowledge x Driver Age interaction for brake response time and the marginally non-significant interaction for accelerator release time, shown in Table 18.

For the unexpected trials, drivers generally steered long (10-15 s) before releasing the accelerator and braking. The steering response times are relatively consistent across age groups for the unexpected trials; however, they differ among driver age groups for the expected trials. This reflects the significant interaction effect of Prior Knowledge x Age shown in Table 18.

6.3.7 Vehicle Speed

Drivers were instructed to maintain 75 mph so that all tread separations occurred at the same speed. Nevertheless, speeds at time of tread separation ranged between 71 and 81 mph (M=74.7, SD = 1.9). An ANOVA was computed with speed at tread separation as the dependent measure. Significant main effects were found for driver age group, $F(2, 101) = 5.41$, p = .006 and for prior knowledge, $F(1,101) = 24.7$, $p < .0001$. Examination of the means revealed that increasing driver age was associated with slightly slower speed at the time of tread separation (see Figure 23). Similarly, drivers adopted slightly slower speed in the expected trials. Specifically, the mean speed associated with the unexpected trials was 75.2 (SD = 2.0), while the corresponding mean for the expected trials was 74.1 (SD = 1.6).

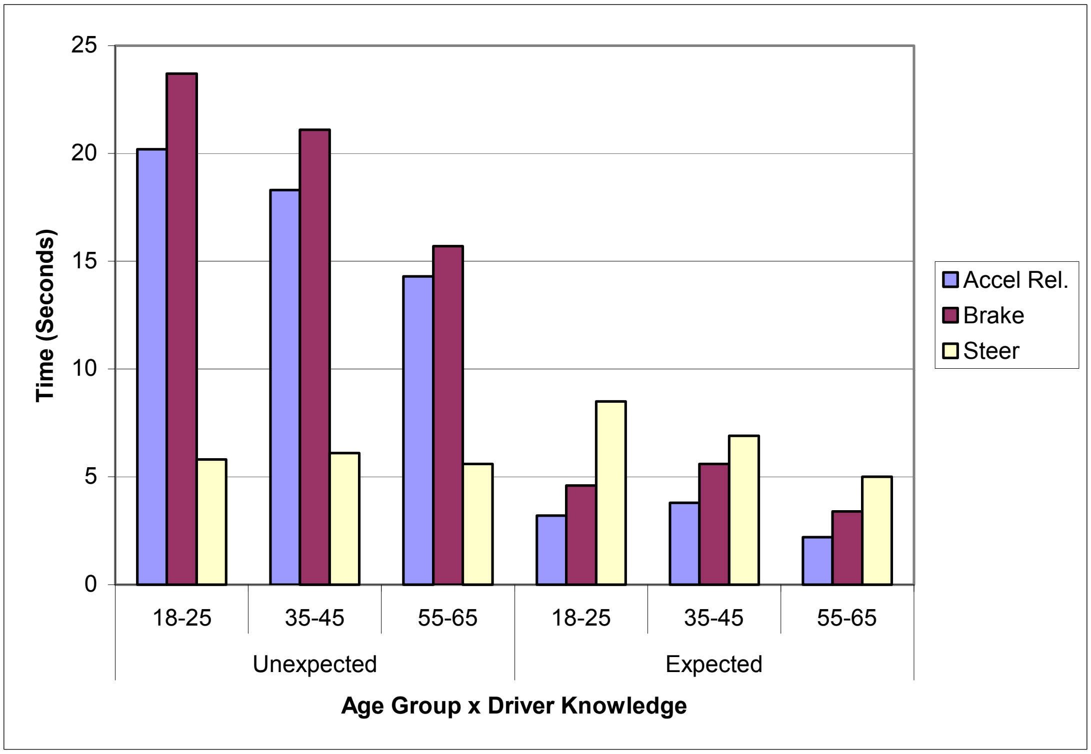


Figure 22. Drivers' Responses to Tread Separation by Driver Age Group and Prior Knowledge (Experimenter Notify Trials Removed)

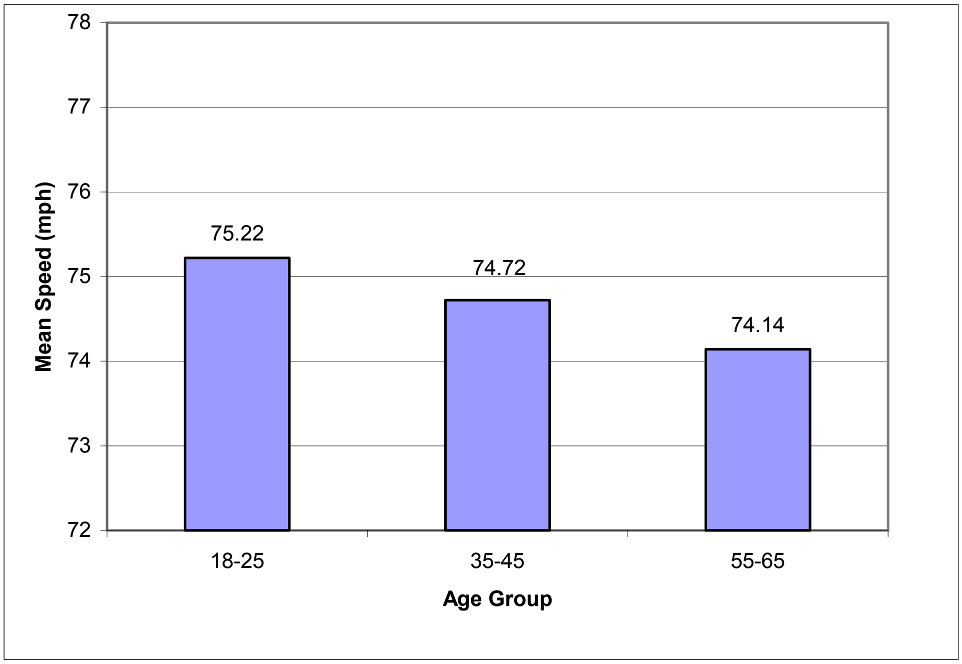


Figure 23. Vehicle Speed at Time of Tread Separation by Age Group (All Trials)

We compared the mean speeds for trials resulting in loss of vehicle control and those in which the vehicle was safely brought to a stop. We found that trials resulting in loss of vehicle control had slightly higher speeds at time of tread separation (M = 75.1, SD = 2.1) as compared to trials not resulting in loss of vehicle control (M = 74.44, SD =1.7) and that this difference was statistically significant, *t* (136) = -2.37, p = .019. We also compared the mean vehicle speed at the time the driver first made a steering input based on the outcome of the trial. The average speed at steering input for trials resulting in loss of vehicle control was 73.4 (SD = 3.2), versus 60.1 (SD = 17.1) for trials not resulting in control loss. The difference between these two groups was statistically significant, *t* (149) = -8.79, p < .0001. The statistical test results indicate that both speed at time of tread separation and speed at time of first steering input contributed to the likelihood of loss of vehicle control, however the magnitude of the respective differences suggests that the speed at the time of first steering input had a considerably stronger effect on the outcome.

6.3.8 Time to Stop Following Control Input

We looked at the time between the driver's first steering and braking response and the time at which the vehicle stopped on trials not involving loss of control. Figure 24 presents these data for unexpected and expected tread separations by vehicle understeer condition.

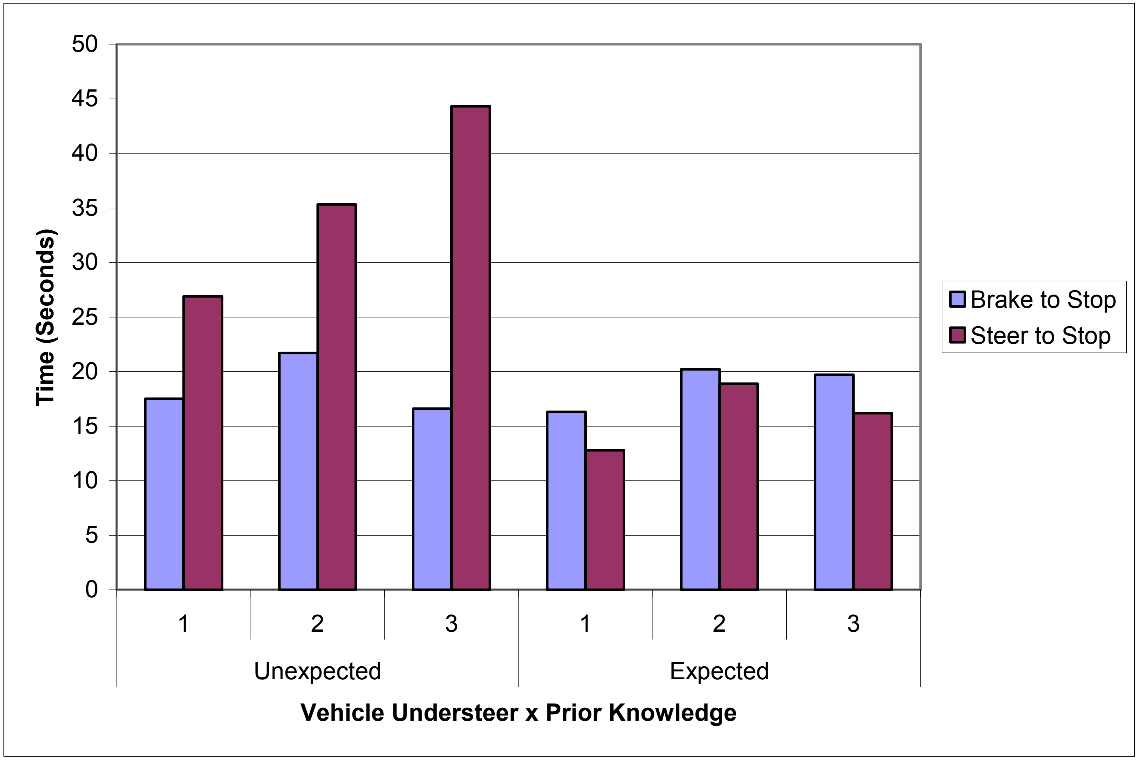


Figure 24. Time from Brake and Steer Inputs to Controlled Stop by Vehicle Understeer Condition and Prior Knowledge (Trials Not Resulting in Loss of Vehicle Control)

Brake-to-stop times and steer-to-stop times for both sets of trials are shorter for Vehicle 1 than for Vehicles 2 or 3, which suggests that decreasing vehicle understeer can make handling more difficult following a tread separation. Care must be taken in interpreting the extremely long stopping time for Vehicle 3 in the unexpected condition as this summarizes the results of only one trial. (The remaining 35 trials in that condition resulted in loss of vehicle control and are thus not shown here.)

6.3.9 Effect of Instructions on Drivers' Responses

As shown earlier, specific instructions following the first tread separation did not help drivers avoid loss of control outcome on the subsequent tread separation event. In this section, we consider whether the instructions affected the timing of drivers' responses following the second tread separation. These data presented in Table 19.

Table 19. Effect of Instructions on Time of Drivers' Responses to Expected Tread Separation Event (Expected Trials Only; Time in Seconds)

	Instructions			
	Yes		**No**	
Performance Measure	**M**	**SD**	**M**	**SD**
Steer response time	8.6	5.2	6.7	4.0
Brake response time	5.9	4.2	5.9	5.4

The average brake response time was 5.9 seconds following the tread separation, whether or not they received instructions. However, instructed drivers delayed their steering response by 1.9 seconds on average, t (106) = -2.11, p < .04, which suggests that they complied to some degree with the instruction to slow down before steering.

7.0 DISCUSSION

The data strongly support the hypothesis that vehicle understeer condition influences the likelihood of vehicle control loss following a complete tread separation on one of the rear tires. The proportion of trials resulting in loss of vehicle control increased from 10% in the highest understeer condition (Vehicle 1) to 68% in the lowest understeer condition (Vehicle 3). This trend was apparent both for unexpected trials, for which the drivers had no prior knowledge of the tread separation, and for trials for which drivers were aware that a tread separation was about to occur. Knowledge of the imminent tread separation reduced the overall probability of control loss from 55% to 20%; however, drivers of Vehicle 3 were still much more likely to sustain loss of vehicle control following the expected tread separation than drivers of Vehicle 1 (39% vs. 3%) and twice as likely to sustain loss of vehicle control following the expected tread separation as drivers of Vehicle 2 (39% vs. 19%).

Whether or not drivers had knowledge of the imminent tread separation had a significant effect on the timing and nature of their initial response. When the tread separation was unexpected, a steering input was the subjects' first response two-thirds of the time. Sixty-six percent of these initial steering response trials resulted in loss of vehicle control. Moreover, the percentages of initial steering response trials that resulted in control loss were strongly associated with decreasing vehicle understeer (13%, 60%, and 97% for Vehicles 1, 2, and 3, respectively). In the unexpected condition, none of the drivers applied brakes as an initial response. In contrast, 58% of the drivers braked first when given information about the imminent tread separation. Drivers who responded initially by braking were successful in bringing the vehicle to a controlled stop on 94% of the trials. This trend was consistent across vehicle understeer conditions.

Furthermore, where steering was the initial driver response, vehicle speed contributed increasingly to the probability of vehicle loss of control. Specifically, for trials resulting in control loss, the mean speed associated with steering input was 73.4 mph, versus 60.1 mph for trials that resulted in a controlled stop.

Several analyses examined the timing of drivers' responses and their outcome. These analyses were complicated by the fact that on many trials, drivers did not respond until notified by the experimenter that a tread separation had occurred. As a result, trials for which the driver's first response was preceded by the experimenter notification were removed. One objective of these analyses was to determine whether the vehicle became uncontrollable as a result of the tread separation alone or as a result of the steering input initiated in an attempt to move the vehicle off the roadway. The most direct evidence supports the latter conclusion. Specifically, for all but one of the trials, for which yaw rate was greater than 5 degrees per second, the first instance of instability occurred following the first steering input. However, the decreasing steering response times associated with decreasing vehicle understeer allows for the possibility that drivers perceived the instability before it reached our threshold.

Increasing driver age was marginally associated with increased likelihood of vehicle control loss, but only on unexpected trials. Older drivers responded more quickly following the tread separation events. Prior knowledge of the event was most helpful to the oldest (55-65 year old) drivers. Older drivers experienced tread separation events at slightly slower speeds, despite instructions to maintain the target speed of 75 mph.

Many subjects were unaware that a tread separation had occurred. Even on the expected trials, some subjects did not immediately interpret the cues appropriately. Many subjects clearly noticed the noise, looked around briefly, and then returned to driving when nothing else occurred. The fact that subjects were much more likely to slow down before steering when they knew a tread separation had occurred, and the finding that this response mode was more likely to lead to a controlled stop, suggests that providing information to the driver in real time about the occurrence of a tread separation could have a safety benefit. However, the same cannot be said about providing specific instructions about how best to maintain vehicle control following the tread separation. Specific instructions did have a small effect on the time drivers waited before attempting to steer following the tread separation, but this delay did not help drivers to maintain control of the vehicle following the tread separation.

Anecdotal evidence suggests that in real world driving, tire tread separation events can go undetected by the driver for a significant period of time, depending on how quickly degradation in vehicle handling becomes noticeable. Thus, it is not unreasonable to expect that some subjects would not respond quickly to the tread separation event in the simulator. However, it should be noted that it may be impossible to replicate drivers' real-world expectations concerning the possible occurrence of an unexpected tire failure in any experimental situation. It is thus possible that, in the real world, a higher percentage of drivers would have been more active in response to the tread separation. Additionally, it is possible that surrounding traffic conditions would influence the immediacy of driver response, although it is not clear whether the response would be delayed or accelerated. Furthermore, it may be that the auditory and tactile cues presented at the time of tread separation, which were derived from an experimentally staged tread separation involving the actual vehicle modeled for simulator vehicle dynamics, were not representative of all such events, some of which may involve loud noises and significant tactile cues resulting from the tread striking the sheet metal of the vehicle. More pronounced cues could be more likely to elicit a response from the driver. Finally, tread separation is a rare event and most drivers would likely have had no experience with such a failure. Thus, drivers would have no expectation that a failure like this could occur and its recognition would therefore be unlikely, particularly with minimal cues. While it may have been possible to tailor subject instructions to suggest the possibility of such a failure (e.g., mechanical), this may have compromised the "unexpected" nature of the event. Nevertheless, while there may be some uncertainty about the realism of the timing of drivers' responses to the simulated tire failures, the range of motion cues available in the simulator and the extensive effort involved in developing the vehicle dynamics model provide strong support for the basic finding that increasing vehicle speed, especially at the time of first steering input, and decreasing understeer gradient increase the likelihood of loss-of-control under tread separation scenarios.

8.0 CONCLUSIONS

This study examined the factors that influence vehicle control when a rear tire loses its tread. It is recognized that a sudden, complete detreading of a tire is a very rare event with potentially catastrophic consequences.

Conclusions of this research are summarized as follows:

- The magnitude and consistency of differences observed in this study indicate that decreasing vehicle understeer strongly influenced drivers' ability to sustain vehicle control following a tread separation at high speed on straight roads. The effect of vehicle understeer on vehicle handling and resulting loss of control is stronger than any other factor considered in this study.
    - Vehicle speed at time of steering input was associated with the likelihood of control loss. Thus, any real-world factors (e.g. surrounding traffic, reduced visibility, inclement weather) that might encourage drivers to attempt steering inputs more quickly and at higher speeds than was observed in this study could result in increased likelihood of loss of vehicle control.
- When drivers had prior knowledge of the imminent tread separation, they were significantly less likely to sustain loss of vehicle control following the tread separation. This implies that:
    - Findings from test track studies in which test drivers were aware of an imminent tread separation may underestimate the extent to which tread separation occurring in the real world leads to instability and loss of vehicle control.
    - Providing information to the driver in real time about the tread separation could significantly reduce the probability of loss of control following tread separation, but only if the drivers also knew that it was important to slow down before attempting to steer.
- Driver age, the tendency to react with steering input, and higher vehicle speeds both at tread separation and more importantly at the time of initial control response, affected drivers' abilities to control the vehicle following tread separation.

Although the Vehicle 1 dynamics model (with normal tire characteristics) was based on a validated vehicle model, Vehicles 2 and 3 were hypothetical vehicles and were not intended to represent any particular vehicle make or model. Vehicles 2 and 3 were used to explore the influence of changes in the understeer gradient on driver response in maintaining vehicle control. Thus, the ability to generalize the above conclusions to specific vehicles is limited. Generalization is also constrained by the assumption that the tire detread event is accurately simulated and that driver responses in the simulator correspond to what they would do in the real world. Nevertheless, it is fair to conclude that, for vehicles traveling at high speeds that experience a complete rear tire detread, the increased difficulty in vehicle handling and the associated increased likelihood of loss of vehicle control with decreasing vehicle understeer generalize to real-world driving.

9.0 REFERENCES

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10.0 APPENDICES

10.1 APPENDIX A: Tire Detread Model

Tire tread separation has an effect on the vehicle's fundamental handling characteristics; the effect depends on the position of the compromised tire on the vehicle. Testing has shown a dramatic difference in vehicle behavior between front and rear tire detreads. The tests indicate that the vehicle pulls toward the damaged tire and that a rear failure causes the vehicle to exhibit oversteer tendencies. Different front-to-rear tire saturation effects are the main cause of the directional stability problems, which explains the effect of the defective tire location. The oversteer tendencies are more pronounced when the more heavily-loaded rear tire is the detreaded tire.

During tread detachment the longitudinal and normal vibrational effects are modeled as follows:

$$F_{xv} = \overline{F}_n \left| \sum_{i=1}^{3} a_i \, sin\left(0.5 i\omega t + \gamma_i\right) \right| \left(0.42 - 0.5 cos\left(2\pi n / M\right) + 0.08 cos\left(4\pi n / M\right)\right) \tag{1}$$

$$F_{zv} = \left(e_t \omega^2 \sum_{i=1}^{3} m_{ti} \cos\left(i\omega t + \varphi_{ti}\right) + \overline{F}_n \sum_{i=1}^{3} \partial K_{ti} \sin\left(i\omega t + \psi_{ti}\right) \right) \left(1 - \cos\left(\frac{2\pi n}{M+1} \right) \right) 0.5$$

(2)

where:

ω : Wheel speed

a_i : Harmonic coefficient for longitudinal vibrational force

γ_i : Harmonic phase for longitudinal vibrational force

e_t : Wheel eccentricity for tread detachment

m_{ti} : Mass imbalance coefficient for tread detachment

φ_{ti} : Mass imbalance phase for tread detachment

$\overline{F}_n$: Averaged normal force for tread detachment

∂K_{ti} : Stiffness imbalance coefficient for a detreaded tire

ψ_{ti} : Stiffness imbalance phase for detreaded tire

M : Total number of frames for tread detachment

n : Current frame number

The longitudinal force acts as a pulsating vibrational effect that mimics the removal and entrapment of the tread material around the tire. The normal force is based on the geometric and mechanical asymmetric properties of the detreaded tire. The forces in Equations (1) and (2) are added to the forces produced from the tire model.

Besides these vibrational effects, tire characteristics such as cornering stiffness, longitudinal stiffness, and peak coefficient of friction also change. Once the failure is triggered, the tire data set is switched to the detreaded tire data until the end of the simulation. The vibrational effect is active only during the detachment event.

The tire dertread event is triggered by the NADS Real Time Executive (RTEX) variable, VVS_Tire_Condition. The lower four bits (bits 3 - 0) of this variable are set to “3” to indicate a tread separation event. The next twelve bits (bits 15 - 4) are set to the number of frames it takes for the tread to separate from the tire (a typical value is 960, 4 seconds times 240 frames per second).

10.1.1 Tire Input Files

Table 20. Tire INP File Data Format

Line #	Variable	Type	Comments
…			
11			Comments
12	Detread_frames	integer	Minimum number of frames in which a detread event can occur
12	Detread_min_vx	integer	Speed below which vibrations will be ignored
13	ntread_detach	integer	Array containing the detreaded tire file index
…			
21	local_name	character	Detreaded tire file name
22	Friction_file	character	Name of the road friction values file

Table 21. Tire Parameter File Format

Line #	Variable	Type	Comments
…			
12 or 19	whl_detread_event	integer	Set to 1 to indicate detread data (line # depends on the
13 or 20	tdx1	double	If whl_detread_event = 1, 1st longitudinal force coef.
13 or 20	tdxg1	double	If whl_detread_event = 1, 1st longitudinal force phase coef.
14 or 21	tdx2	double	If whl_detread_event = 1, 2nd longitudinal force coef.
14 or 21	tdxg2	double	If whl_detread_event = 1, 2nd longitudinal force phase coef.
15 or 22	tdx3	double	If whl_detread_event = 1, 3rd longitudinal force coef.
15 or 22	tdxg3	double	If whl_detread_event = 1, 3rd longitudinal force phase coef.
16 or 23	Tdecc	double	If whl detread event = 1, wheel eccentricity for detread
17 or 24	tdm1	double	If whl_detread_event = 1, 1st mass imbalance coef.
17 or 24	tdph1	double	If whl_detread_event = 1, 1st mass imbalance phase coef.
18 or 25	tdm2	double	If whl_detread_event = 1, 2nd mass imbalance coef.
18 or 25	tdph2	double	If whl_detread_event = 1, 2nd mass imbalance phase coef.
19 or 26	tdm3	double	If whl_detread_event = 1, 3rd mass imbalance coef.
19 or 26	tdph3	double	If whl_detread_event = 1, 3rd mass imbalance phase coef.
…			Units flag and STI data

10.1.2 Tire Parameter File for Detreaded Tire

```
V1.09
1              ................... TIRE TYPE (STI)
0.384          ................... R ~based on rr ~= 0.365
228312.5       ................... tk
2000.0          ...................td
0.72           ................... LATB
0.10           ................... LONGB
5000.0         ................... Long_dampCS
5000.0         ................... Lat_dampCS
0.05           ................... slip_eta
0              ................... whl_vib_hmode (0:no)
1              ................... whl_detread_event (1: yes)
0.120, 0.0     ................... tdx1,tdxg1
0.005, 0.7854  ................... tdx2,tdxg2
0.001, 1.5708  ................... tdx3,tdxg3
0.005          ................... tdecc
30, -0.5236    ................... tdm1,tdph1
5, 0.7854      ................... tdm2,tdph2
2, 1.5708      ................... tdm3,tdph3
0.05, 0.0      ................... tdk1,tdpsi1
0.02, 0.0      ................... tdk2,tdpsi2
0.005,0.0      ................... tdk3,tdpsi3
0              ................... British Units 0 [1 for SI units]
6.5            ................... TWIDTH
-1.6738e+2     ................... A0
5.42           ................... A1
3.4338e+3      ................... A2
-8.8474e-2     ................... A3
4.9327e+2      ................... A4
-0.1986        ................... KA
4463.3589      ................... KX
0.1            ................... KMUY
36.00          ................... TP
-6.126e-5      ................... B1Y
0.3370         ................... B3Y
0.0            ................... B4Y
0.9            ................... KG
10.0           ................... CSFZ ---
0.85           ................... MUNOMY
1874           ................... FZT
-1.2174e-4     ................... KK1
0.4299         ................... C1
0.5983         ................... C2
0.6317         ................... C3
0.4436         ................... C4
1.2732         ................... C5
1.0309         ................... G1
-0.6117        ................... G2
0.85           ................... MUNOMX
0.00000000     ................... B1X  *** VDA
0.276          ................... B3X  *** VDA
0.00000000     ................... B4X  *** VDA
0.1000         ................... KMUX *** VDA
0.0            ................... PLYSTEER : -0.0035
1.0            ................... MURATIO
0.0000333      ................... KLT
0.0200         ................... RL
2500.0         ................... FZMAX
```

10.1.3 Tire Parameter File for Normal Tire

```
V1.09
1               ................... TIRE TYPE (NADSdyna STI Tire Model)
0.384           ................... R ~based on rr ~= 0.365
228312.5        ................... tk
2000.0          ................... td
0.72            ................... LATB
0.10            ................... LONGB
5000.0          ................... Long_dampCS
5000.0          ................... Lat_dampCS
0.05            ................... slip_eta
0               ................... whl_vib_hmode (0:no)
0               ................... whl_detread_event (0:no)
0               ................... British Units 0 [1 for SI units]
6.5             ................... TWIDTH
-1.6738e+2      ................... A0
2.1688e+1       ................... A1
3.4338e+3       ................... A2
-8.8474e-2      ................... A3
4.9327e+2       ................... A4
-0.1986         ................... KA
4463.3589       ................... KX
0.1             ................... KMUY
36.00           ................... TP
-1.2236e-4      ................... B1Y
1.1235          ................... B3Y
-5.6531e-9      ................... B4Y
0.9             ................... KG
18.9542         ................... CSFZ
0.85            ................... MUNOMY
1874            ................... FZT
-1.2174e-4      ................... KK1
0.4299          ................... C1
0.5983          ................... C2
0.6317          ................... C3
0.4436          ................... C4
1.2732          ................... C5
1.0309          ................... G1
-0.6117         ................... G2
0.85            ................... MUNOMX
0.00000000      ................... B1X  *** VDA
0.9200          ................... B3X  *** VDA
0.00000000      ................... B4X  *** VDA
0.1000          ................... KMUX *** VDA
0.0             ................... PLYSTEER : -0.0035
1.0             ................... MURATIO
0.0000333       ................... KLT
0.0200          ................... RL
2500.0      ................... FZMAX
```

10.2 APPENDIX B: NADS DESCRIPTION

U.S. Department of Transportation
National Highway Traffic Safety Administration

THE UNIVERSITY OF IOWA
Iowa City, Iowa 52242

Introduction

The National Advanced Driving Simulator (NADS) is the most sophisticated research driving simulator in the world. Developed by the National Highway Traffic Safety Administration (NHTSA), the NADS at The University of Iowa offers the highest fidelity real-time driving simulation experience.

The NADS' primary mission is to conduct research that will lead to a better understanding of the complex driver-vehicle-roadway interaction in critical driving situations. The results of this research will ultimately lead to reductions in the number of traffic-related deaths and injuries on the nation's highways. The NADS can also be used to conduct vehicle system engineering research that will enhance the productivity of the U.S. automotive manufacturing sector.

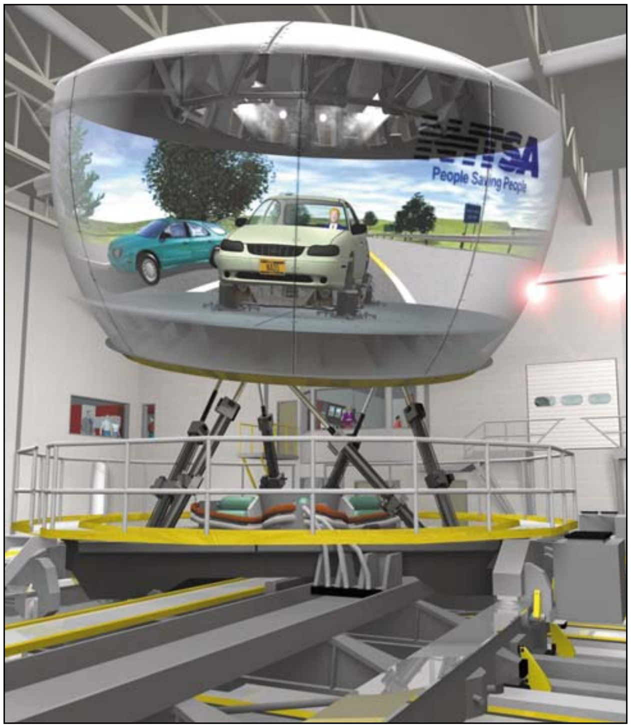
The NADS consists of a large, 24-foot-diameter dome in which entire cars and the cabs of trucks and buses can be mounted. Each vehicle cab is equipped electronically and mechanically using instrumentation specific to its make and model. At the same time, the motion subsystem, on which the dome is mounted, provides 64 feet of horizontal and longitudinal travel and 330 degrees of rotation. The effect is that the driver feels acceleration, braking and steering cues as if he or she were actually driving a real car, SUV, truck, or bus.

The latest in visual display technology, coupled with a high-fidelity audio subsystem, completes the driving experience. The driver is immersed in sight, sound and movement so real that impending crash scenarios can be convincingly presented with no danger to the driver. Vehicle and driver data are collected and stored, and tests can be reproduced. A simulator operator and a researcher control the entire system and provide for the full safety and protection of the driver and equipment during operation.

A world-class team of leaders in simulation technology developed and built the NADS, which is now operated and maintained by a University of Iowa team of highly qualified researchers with a combined total of more than 100 years of simulation and research experience.

NADS Facility at The University of Iowa

The NADS is located at The University of Iowa Oakdale Research Park in Iowa City, Iowa. The University of Iowa was selected in a national competition, among major transportation research universities, conducted for NHTSA by the National Science Foundation. The University of Iowa provided $11.58 million in cost sharing to the NADS project, which included the development of software and the design and construction of a $5.7 million building to house the simulator.



A Look Inside the NADS Dome

The NADS Facility

The NADS facility is comprised of a controlled-access, high-bay area that houses the device, the Simulation Development Module (SDM), an operator control room, and a large cab storage and preparation area. These technical resources are within yards of three participant preparation and briefing rooms and a fully equipped medical room used for studies that require examinations, drug administrations or participant monitoring. The entire area is secure to ensure confidentiality and privacy.


Medical-Equipped Participant Room

Operator and Research Workstations

Two main operator and research workstations, for the simulator operator and the guest researcher, are in the NADS control room and overlook the simulator bay through large glass panels. These workstations include multiple large-screen display monitors that can simultaneously present video and digital data. Workstation operators can select, monitor and record numerous experimental parameters. Additional video monitors are used to view a sequence from the driver's perspective. Headphones and speakers allow direct communication between simulator operators and the driver. All data are recorded and up to five data elements may be selected during run-time for display on a workstation. Simulator monitor and control software provide the operator with the control and status information needed for efficient and safe conduct of the simulation.


Operator Control Room

Program Planning and General Operations

As a national resource for carrying out critical highway safety research, The University of Iowa is responsible for operating and maintaining the NADS facility, as well as scheduling government and private sector usage.

Prior to scheduled experiments, NADS researchers team with experienced software, visual display, and hardware engineers to:

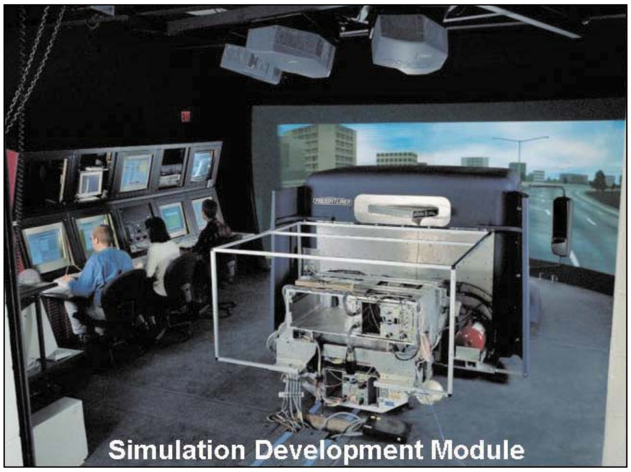
- Prepare a detailed experimental plan;
- Define the scenario;
- Plan software model changes, if necessary, or include models supplied by researcher;
- Plan for data collection and reduction; and
- Plan for the recruiting and preparation of study participants.

All software and databases developed specifically for an experiment are protected and kept isolated from other researchers. Data security is provided to ensure that proprietary rights are protected to the extent permitted by law.

Before actually conducting an experiment on the NADS, the staff and researchers develop and test scenarios, verify the accuracy of the expected data flow, test any necessary special equipment and obtain approval for use of "human subjects" in a particular study. Next, participants for the study are contacted and scheduled. Finally, a cab is configured in the NADS, and all software files and databases are loaded and prepared for the experiment. A library of generic scenarios and city/rural databases is maintained for research in areas that do not require unique properties and characteristics. Daily operational readiness tests are conducted to ensure that systems are safe and ready for use prior to conducting experiments.


Vehicle Loading Position

Following an experiment, the NADS staff assists with data reduction and analysis, depending on the researcher's needs.

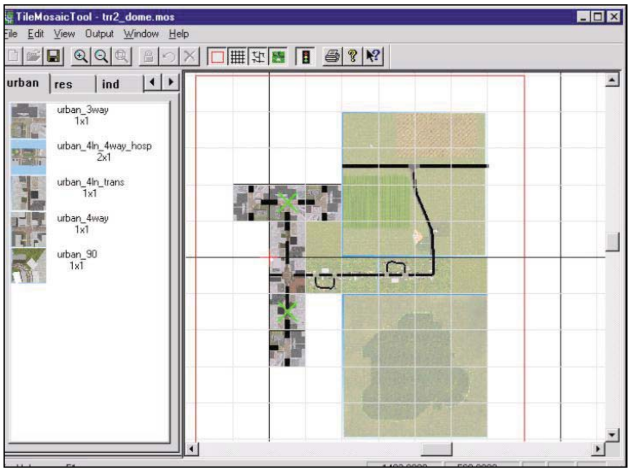

Simulation Development Module

Simulation Development Module

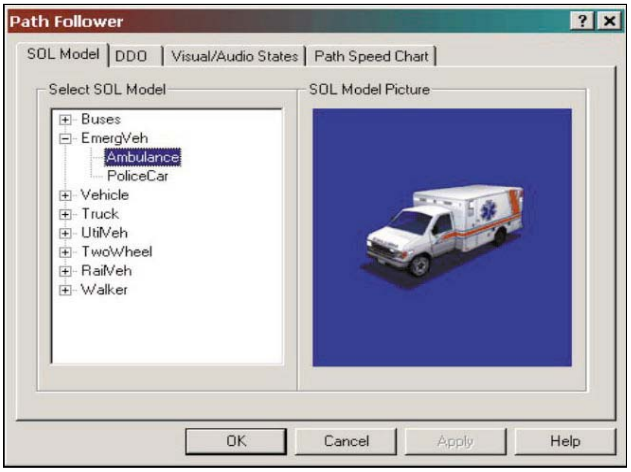
In addition to the NADS, the facility incorporates a Simulation Development Module. The SDM is a fixed-base simulator with a 120-degree field-of-view screen. Each of the available cabs can be installed in the SDM, and the system can replicate the NADS visual environment. The SDM is used to support development and testing of experimental procedures and protocols, including pilot testing of scenarios and training of study participants. This allows for refinement of the scenarios and procedures, and provides a low-cost means of setting up and tuning experiments prior to running experiments on the NADS, thereby greatly reducing development and other experimental costs.

Scenario Definition & Control

The NADS facility includes an extensive, software-based simulation development environment (including tools such as the Tile Mosaic Tool, the Interactive Scenario Authoring Tool, and data reduction workstations) for developing new, or modifying



Tile Mosaic Tool for driving scene databases

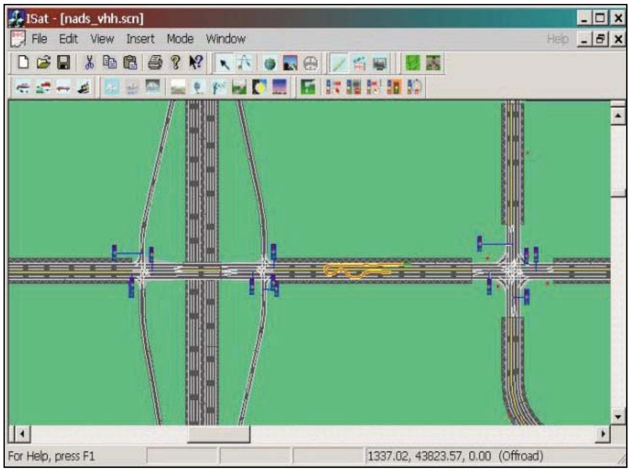


Vehicle Selection Interface

existing, experimental scenarios, special databases (visual, audio, roadways), and data reduction procedures. This software allows a researcher to precisely plan the interactions of the subject vehicle with an elaborate set of scenes and objects. The researcher can also define and control a large set of driving environments - including condition and type of roadway, companion and opposing traffic, traffic control devices and traffic incidents. In addition, the researcher can modify vehicle models populating traffic (e.g., heavy trucks, emergency vehicles) for specific research and develop applications for experimental data collection, reduction and analyses.

System Safety

Ensuring the safety of the study participant is paramount, and the NADS design provides multiple levels of safety controls to protect the driver. During operation, the participant, operator or researcher can halt the simulation at any time. In addition, each motion subsystem contains its own safety monitoring functions to prevent injury to the driver in case of malfunction. The NADS also includes an independent, fully redundant safety monitoring system. This system prevents activation of the simulator, or aborts operation of the simulator, if any potentially hazardous situation exists, or any anomalous system behavior is detected.



Interactive Scenario Authoring Tool

NADS Subsystems

The NADS contains a number of subsystems that provide the driver with a realistic representation of the driving environment. These subsystems work in real time to provide repeatable, natural and realistic representations of the visual, motion, auditory and control feel sensory cues associated with the complete driving experience.

Visual Subsystem

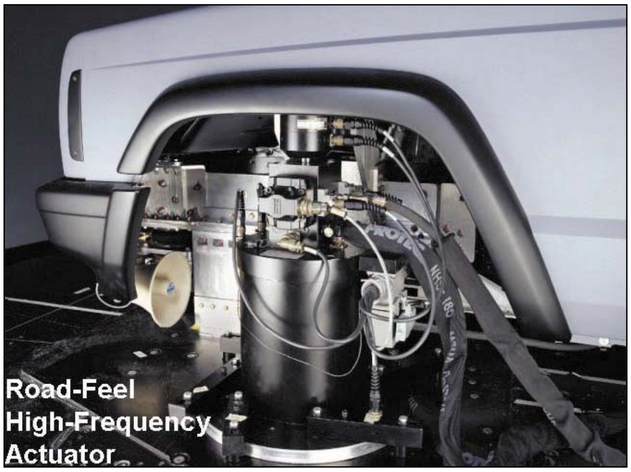
The NADS visual subsystem brings together multiple detailed terrain and driving databases with the latest advances in high-resolution imagery. This subsystem incorporates a 24-foot-diameter dome with a high gain screen and utilizes 15 LCD (Liquid Crystal Display) projectors with high resolution that generate the highly realistic images. Other features of the visual subsystem include:

- Multiple-channel projection system that provides complete front and rear field of view, including use of actual vehicle mirrors
- Rapid database generation for scenario development
- Multiple eye points, view points and display channels
- Complex 3-D imagery with full-color, textured buildings, pedestrians, vegetation and other environmental objects
- Complex 3-D imagery fully correlated with other sensory stimuli
- Animation involving numerous objects that create busy traffic situations with:
  - Independent control rules and logic for animation of other vehicles, pedestrians, scene features and roadways, and
  - Collision detection for all objects
- Visual subsystem database that includes the full range of:
  - Current and new highway traffic control devices (signs and signals);
  - Three-dimensional objects that vehicles encounter (animals, potholes, concrete joints, pillars, etc.);
  - High-density, multiple-lane traffic interacting with the driver's vehicle;
  - Common intersection types (including railroad crossings, overpasses, bridge structures, tunnels, etc.); and
  - Roadway time of day and complete complement of environmental and atmospheric effects

Graphical depiction of typical scene from the forward view.

Design Specifications of the NADS Visual Subsystem

Element	Performance
Polygons (at 60 Hz)	> 15,000
Total Pixels	> 5 M
Transport Delay	≤ 50 ms (at 60 Hz)
Contrast Ratio	25:1
Luminance	5 fL
Field of View	360 deg H x 40 deg V
With High Resolution Inset	28 deg H x 7 deg V
Forward Inset - High Resolution	2.2 ArcMin/Line Pair
Forward and Side Area Resolution	7.0 ArcMin/Line Pair
Rear Area and Rear-View Mirror Resolution	15.0 ArcMin/Line Pair



Motion Subsystem

The motion subsystem provides a combination of translational and angular motion that duplicates vehicle motion kinematics and dynamics within six degrees of freedom. The motion subsystem is coordinated with the vehicle cab subsystem and its high-frequency road feel and control feel subsystem to provide the driver with realistic motion and tactile cues while driving. This subsystem is designed to provide drivers with highly accurate motion cues in all

Design Specifications of the NADS Motion Subsystem

Element	Performance
X-Y Platform	
Displacement	± 32 ft
Velocity	± 20 ft/s
Acceleration	± 20 ft/s^2
Motion Base	
Z (heave)	± 2.0 ft
Z (velocity)	± 5.0 ft/s
Z (acceleration)	± 25 ft/s^2
Pitch	± 25 deg
Pitch rate	± 45 deg/s
Roll	± 25 deg
Roll rate	± 45 deg/s
Yaw (turntable)	± 330 deg
Yaw rate	± 60 deg/s
Pitch, Roll, Yaw accelerations	± 120 deg/s^2
High Frequency Vibration Displacement	± 0.2 in
High Frequency Envelope	3 Hz - 20 Hz
High Frequency Vibration Acceleration	± 1000 lbf
Noise (Multi-axis)	< 0.02 g rms

axes associated with actual vehicle motions for the full range of driving maneuvers.

Key features of the NADS motion subsystem include:

- Isolated, high-frequency, self-reacting cab vibration actuators that faithfully reproduce road feel
- A turntable allowing ±330 degrees of rotation
- A design that allows for low maintenance costs and minimal staffing requirements

Vehicle Cab Subsystem

The vehicle cab subsystem currently consists of four vehicle cabs, configured to fit within the physical environment of the visual dome on the motion subsystem and provides the driver with realistic vehicle controls. Each cab retains the interior of the actual vehicles with few changes to the internal ergonomics and layout. The four vehicle cabs include a standard sedan (Chevrolet Malibu), a sports/utility vehicle (Jeep Cherokee), a midsize sedan (Ford Taurus), and a commercial truck cab (Freightliner).

Featured in the vehicle cab subsystem are interfaces that allow rapid cab changes to meet desired efficiency standards during NADS operations. The dome can be reconfigured to accommodate and operate a different cab in less than eight hours. The vehicle cab subsystem incorporates a full range of vehicle instrumentation interfaces, including fully functioning controls, dashboard, seating and even an operable radio/entertainment system.

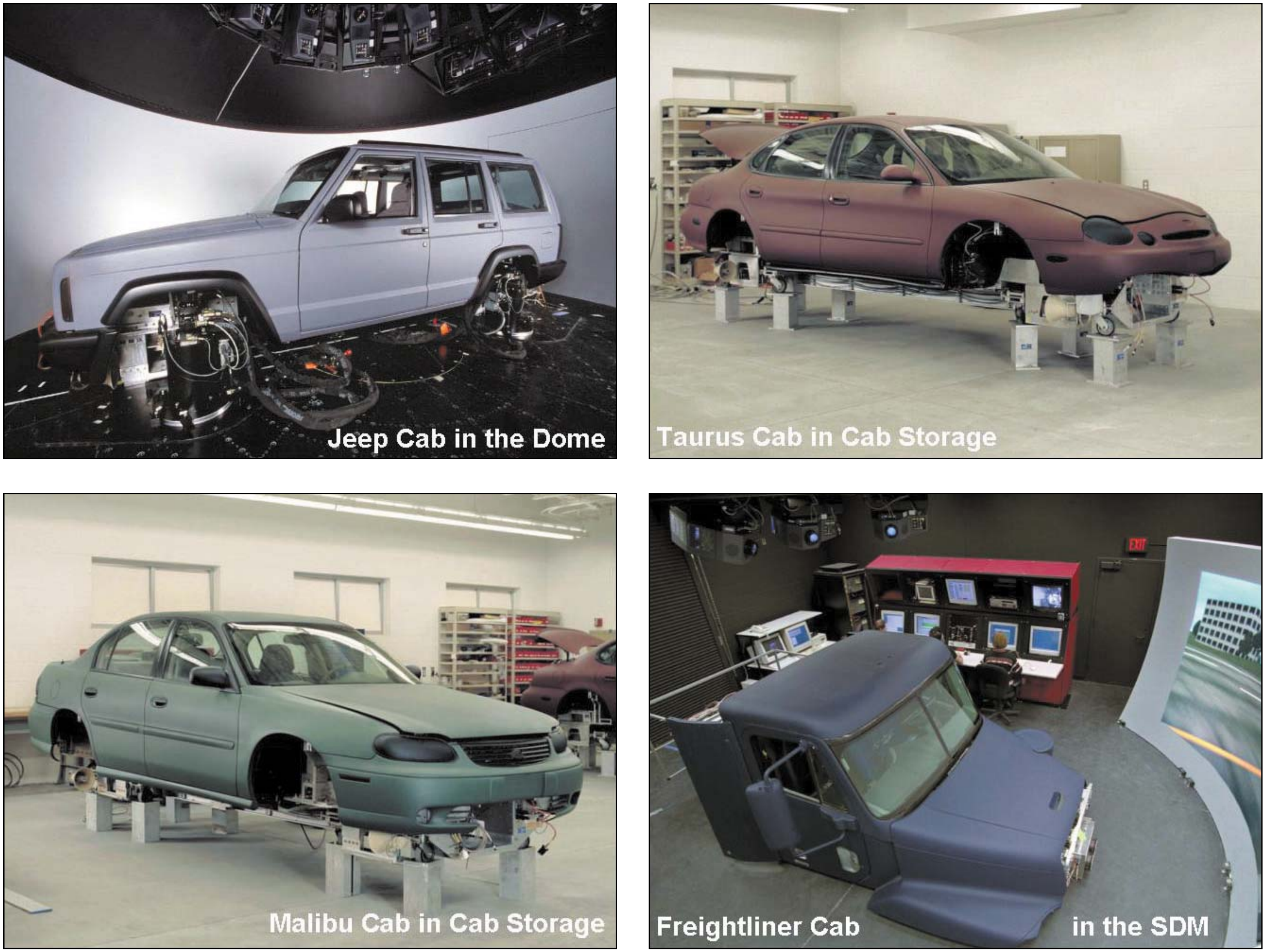
Of particular note is the Eaton truck transmission simulator, incorporated into the Freightliner cab, which can be used to create heavy vehicle scenarios from:

- 140 transmissions,
- 280 engines,
- 33 drive axle ratios, and
- 300 tire sizes.

Additional technology, such as wireless communications, can be incorporated into the vehicle cabs to address specific experimental requirements. In addition, the cab design provides remarkably realistic action and feel for the primary controls (steering, brakes, accelerator) and transmission, and the associated control logic is tunable to allow the simulation of actual or proposed vehicle responses.

Design Specifications of the NADS Cab Subsystem

Element	Performance
Control Feel Bandwidth	> 50 Hz
Weight	< 3,300 lbs
Cab Changeout Time	< 8 hrs



Jeep Cab in the Dome

Taurus Cab in Cab Storage

Malibu Cab in Cab Storage

Freightliner Cab in the SDM

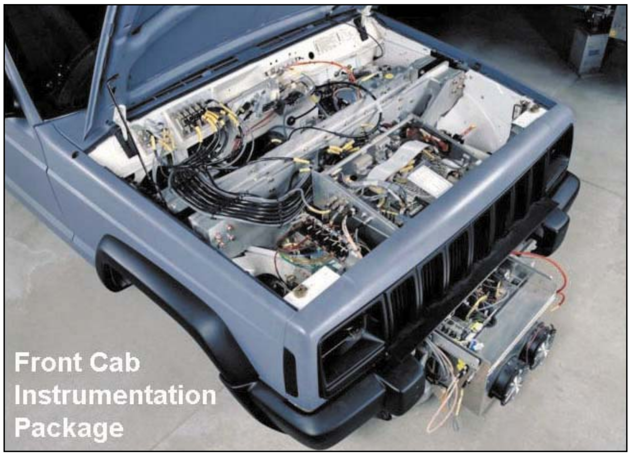
Available Vehicle Cabs


Jeep Cab Interior
Taurus Cab Interior
Malibu Cab Interior
Freightliner Cab Interior

Vehicle Cab Interiors

Control Feel Subsystem

The control feel subsystem for steering, brakes, clutch, transmission shift and throttle provide realistic feedback in response to driver inputs, vehicle motions and road/tire interactions. The control feel subsystem is capable of representing automatic and manual control characteristics such as power steering, existing and experimental drive trains, anti-lock braking systems and cruise control. The control feel cuing feedback has high bandwidth and no discernible delay or distortion associated with driver control actions or vehicle dynamics.


Front Cab Instrumentation Package


Rear Cab Instrumentation Package

Auditory Subsystem

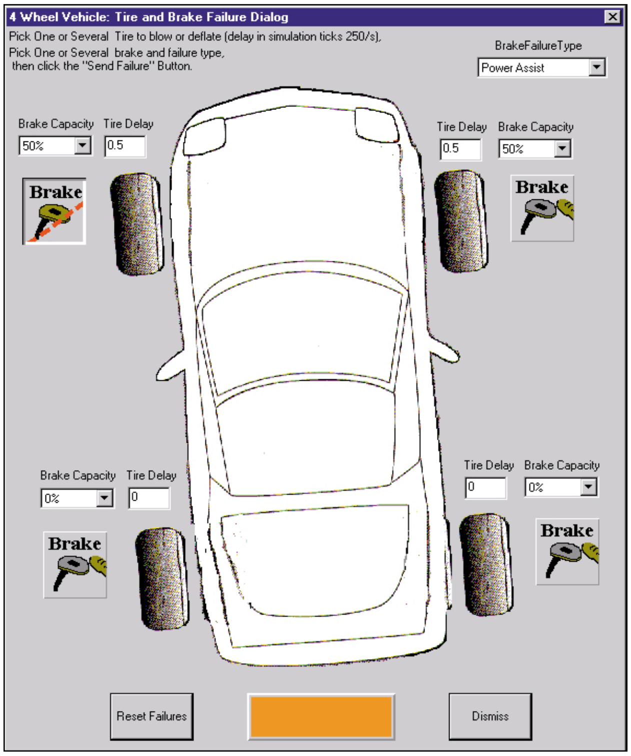
The auditory subsystem provides motion-correlated, directional sound sources via multiple in-cab electrostatic speakers. These sound sources are coordinated with the full range of the visual sensory systems database. The auditory database includes sounds emanating from current and new design highway surfaces, from contact with three-dimensional objects that vehicles encounter (potholes, concrete/tar joints, pillars, etc.), from high-density multiple-lane traffic (including city effects, sirens, tunnel passage), from the vehicle during operation, and sounds that reflect roadway changes due to changes in the weather environments (including wind).

Design Specifications of the NADS Audio Subsystem

Element	Performance
Dynamic Range	100 db
Bandwidth	15 Hz - 20 KHz
S/N Ratio	96 db
Distortion	≤ 1.0 %
Dynamic Synch	< 28 ms

Vehicle Dynamics

The vehicle dynamics software properly represents vehicle motions and control feel conditions in


4 Wheel Vehicle: Tire and Brake Failure Dialog

Pick One or Several Tire to blow or deflate (delay in simulation ticks 250/s),
Pick One or Several brake and failure type,
then click the "Send Failure" Button.

BrakeFailureType: Power Assist

Brake Capacity: 50% Tire Delay: 0.5
Tire Delay: 0.5 Brake Capacity: 50%
Brake Capacity: 0% Tire Delay: 0
Tire Delay: 0 Brake Capacity: 0%

NADS Vehicle dynamics software - Tire and Brake Failure Dialog Screen.

response to driver control actions, road surface friction conditions and aerodynamic disturbances. The vehicle dynamics software incorporates a multi-body vehicle dynamics model that accurately simulates the motion and feel of vehicle linkages and joints.

All required vehicle responses are computed in real time for driving the visual, motion, cab, control feel and auditory subsystems. The vehicle dynamics models cover light passenger cars and trucks, and heavy trucks and buses. The models encompass normal driving conditions and limit performance and maneuvering that might be encountered during pre-crash avoidance situations, including spinout and incipient rollover.

NADS Research Uses

The unique capabilities of the NADS lend themselves to studies that could not otherwise be safely carried out on the open road. In particular, the ability of the NADS to create highly complex but realistic scenarios, typical of actual driving situations, in a highly controlled and repeatable experimental setting allows researchers to address a wide range of issues. The ability to impose realistic demands on drivers, including those associated with in-vehicle tasks, traffic conditions, sudden events and environmental conditions (e.g., roadway, visibility), provide research opportunities not possible on test tracks or the open road.

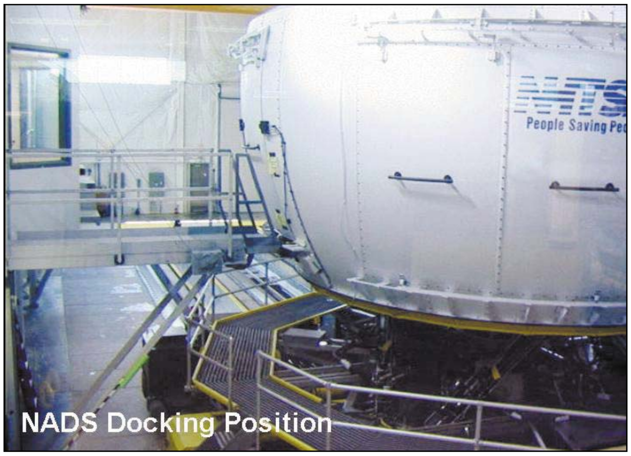
The NADS offers a safe, accurate and repeatable environment for researchers to study human factors issues associated with driver error, which are estimated to be a contributing cause in 90 percent of motor vehicle crashes.

The NADS is a unique research tool that offers the capability to study driver crash avoidance behavior and carry out related crash reconstructions. The complete control of highway environment and traffic scenarios provided by the NADS allows researchers to: 1) set up hazardous driving situations and measure driver response; 2) examine conditions associated with real crash cases; and 3) study driver and vehicle response options and limitations. A clear understanding of driver behavior under these circumstances can lead to the development of effective strategies and countermeasures for improved crash avoidance and to reduce injuries and fatalities.


Dome-Projected Image

The NADS also provides the capability for safely evaluating advanced in-vehicle systems and control technologies. Important questions regarding the effects of these systems on driver workload, attention, behavior and overall safety are best addressed during the development phase. It is imperative to determine before the production phase if any of these advanced systems will have an unintended or adverse impact on driver performance and highway safety.

The NADS can also be used for conducting highway engineering and design research related to traffic safety. In the NADS' synthetic environments, the driving scene and highway geometry are under the complete control of the simulation programmer. Highway researchers can therefore evaluate



NADS Docking Position

alternative designs for intersections, entrances and exits, tunnel and bridge alignments, traffic control devices and highway signing without incurring the prohibitive expense of actual construction.

The benefits of NADS research extends further to the automotive industry, where the results, in combination with those from simulators developed within the industry, are used in the development and testing of new safety devices.

The NADS is also an ideal tool to study the effects of alcohol, drugs, visual impairments and aging on driving. Medical and pharmaceutical researchers, among others, use the NADS to investigate the safety and efficacy of new medicines and medical devices in the driving environment.

Summary

As the world's most sophisticated research driving simulator, the National Advanced Driving Simulator offers easy experiment setup, product integration and data collection. The NADS is the first to employ a large motion base, capable of physically moving 64 feet in two directions, and providing users with true, realistic motion experience, whether accelerating, turning or braking. Its computer image generation system features 15 LCD projectors that provide a 360-degree horizontal field of view and incorporates a database of driving scenes spanning more than 2,500 square miles of terrain. Four vehicle cab types are available for use, as well as multiple secure participant briefing rooms and a medically equipped facility for medical studies. In addition, The University of Iowa offers a highly trained and experienced technical and research team to work with researchers on all aspects of research planning, development, execution and analysis efforts.

This highly realistic driving simulator provides a powerful tool for evaluating driver behavior in a wide range of complex situations that would otherwise be difficult, costly and often unsafe to obtain under actual roadway driving conditions. Representative traffic scenarios can be examined safely with experimental repeatability, easy configurability and comprehensive data collection capability. The level of fidelity allows researchers to implement virtually any experiment that they would consider in a real vehicle on any roadway.

The NADS is dedicated primarily to advancing the cause of improved highway safety. As a national research facility, operated and maintained by The University of Iowa, the simulator is accessible to the widest possible spectrum of researchers from both the public and private sectors. NHTSA, as well as researchers from academic and medical institutions and the automotive/transportation industries, uses the NADS to study the total driver-vehicle-traffic environment system with an eye to improving products, highway designs, and reducing the causes of crashes - in addition to reducing fatalities.

For more information, please contact:

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NADS WEB INFORMATION
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www-nrd.nhtsa.dot.gov

January 2003

10.3 APPENDIX C: Procedural Documents

10.3.1 Telephone Screening Procedures

For a participant to be eligible for this study, they must be able to participate when the study is scheduled, meet all inclusion criteria, and pass the health screening.

Inform the person contacted about the nature of the study and when it will run. Determine if they can and are willing to participate.

Introduction

"Hello, ________. My name is _____________ with the National Advanced Driving Simulator. I am contacting you because you had contacted us with an interest in participating in a study. The purpose of this research study is to investigate simulator realism. This would involve evaluating the simulator's feel, looks and actions, with a focus on steering, accelerating, and braking.

"This research involves a time commitment of approximately two-hours that requires he/she to come to the National Advanced Driving Simulator located on the Oakdale Campus. The appointment will require completion of a questionnaire regarding driving experience and general health questions and signing a consent form. He/she will receive instructions on the simulator cab and the study drive. After driving the simulator for at least three trials of approximately 13 minutes each, he/she will be asked to fill out questionnaires regarding their driving experience. Compensation for participating in this study will be $25.

"Is this a study in which you would be willing to participate?"

- If NO, "Would you like us to keep you on our list of participants?"

  Make a notation concerning wish to remain on list of participants.

  "Thank you for your time."

- If YES, proceed to Inclusion Criteria.

Inclusion Criteria

If a participant fails to meet one of the criteria, stop, skip the Heath Screening and proceed to the Closing.

If all inclusion criteria are meet proceed to Health Screening.

"There are several criteria that must be met for participation in this study. I will need to ask you several questions to determine your eligibility."

1) **Do you possess a valid driver's license within the United States?**

   [Exclude if no current valid driver's license.]

2) **How long have you been a licensed driver?**

   [Exclude if less than five years.]

3) **How many miles per year do you drive?**

   [Exclude if less than 5,000 miles per year.]

4) **Can you operate an automatic vehicle without special equipment?**

   [Exclude if no.]

5) **Have you participated in a simulator study within the past 12 months? If so, what was the nature of the study?**

   [Exclude if yes, make notation of type of study]

6) **What type of vehicle do you drive?**

   Make ________________________

   Model ________________________

   Year ________________________

7) **Do you have another vehicle in your household that you drive?**
   If yes, what percentage of time per year do you drive it?

General Health Exclusion Criteria

If a participant fails to meet one of the criteria, stop and proceed to the Closing.

Before this list of questions is administered, please communicate the following:

"Because of pre-existing health conditions, some people are not eligible for participation in this study. I need to ask you several health-related questions before you can be scheduled for a study session. Your response is voluntary and all responses are confidential. This means that you can refuse to answer any questions that you choose and that only a record of your motion sickness susceptibility will be kept as part of this study. No other responses will be kept. Please answer yes or no to the following questions:"

1) **If the subject is female:**
Are you, or is there a possibility that you are pregnant?

[Exclude if there is any possibility of pregnancy.]

2) **Have you been diagnosed with a serious or terminal illness?** If yes, is the condition still active? Are there any lingering effects? If yes, do you care to describe?

[Exclude if there is any current serious condition.]

3) **Do you have Diabetes?** Have you been diagnosed with hypoglycemia? If yes, do you take insulin or any other medication for blood sugar?

[Exclude if insulin is taken for this condition.]

4) **Do you suffer from a heart condition such as disturbance of the heart rhythm or the experience of a heart attack?** If yes, please describe.

[Exclude if there has been a heart attack within the past 6 months, or if there is a history of ventricular flutter or fibrillation, or systole requiring cardioversion. Potential participants with atrial fibrillation may be acceptable, given that their heart rhythm is now stable following medical treatment or pacemaker implants.]

5) **Have you ever suffered brain damage from a stroke, tumor, head injury, or infection?** If yes, what are the resulting effects? Do you have visual loss, blurring, or double vision; weakness, numbness, or funny feelings in the arms, legs, or face; trouble swallowing; slurred speech; uncoordination or loss of control; trouble walking; trouble thinking, remembering, talking, or understanding?

[Exclude if there has been a stroke within the past 3 months, there is an active tumor, or if there are lingering effects.]

6) **Have you ever been diagnosed with seizures or epilepsy?** If yes, how frequently and what type?

[Exclude if there has been a seizure within the past 12 months.]

7) **Do you suffer from inner ear, dizziness, vertigo, or balance problems?** If yes, please describe. Do you have Meniere's disease?

[Exclude if there is any recent history of inner ear, dizziness, vertigo, or balance problem.]

8) **Do you ever suffer from motion sickness?** If yes, on what mode of transportation and what were the conditions (e.g., rough sea, back seat, etc.)? What symptoms did you experience? How old were you when this occurred?

[Record responses then say, "When we complete this list of questions, I will need to ask you specific questions about your motion sickness history. Until then, let me continue with this list." DO INCLUDE OR EXCLUDE AT THIS TIME.]

9) **Do you suffer from a respiratory disorder such as asthma or chronic bronchitis?** If yes, please describe.

[Exclude if disorder results in obvious or continuous shortness of breath or if the subject requires chronic medical therapy such as theophylline, inhalers, steroid medications, and especially oxygen therapy.]

10) **Have you ever been diagnosed with a mood problem or a psychiatric disorder? If yes, are you taking medication? Please describe.**

[Exclude if there is any diagnosed psychiatric disorder. This includes schizophrenia, depression, mania, personality disorder, dependency or abuse of psychoactive of illicit drugs or alcohol, chronic fatigue syndrome, agoraphobia, hyperventilation, or anxiety attacks.]

11) **Do you have a migraine or tension headaches?** If yes, what is the nature of this pain? How often and when was the last headache? Are you currently taking medication for these headaches? If so, what are you taking?

[Exclude if headaches occur greater than 2 times a month, if there has been a headache in the past 48 hours, or if the subject takes chronic daily or narcotic medications.]

12) **Are you currently taking any medications?** If yes, what is the medication and what is it for?

[Exclude if medication if for motion sickness, psychiatric disorder, or any of the conditions mentioned above that indicates a problem mentioned above that may have been incorrectly denied previously.]

Closing

If participant **MEETS ALL** criteria **(Driving Inclusion and General Health Exclusion Criteria):**

- **Inform the participant to refrain from alcohol and drug intake for the 24 hours preceding the session.**
- **Schedule the appointment.**
- **Give directions** to the National Advanced Driving Simulator, explain where to park and ask them to check in at the front desk inside the main entrance.

- **Stress the importance of attending the session.**
  Tell the participant to contact Sue Ellen Salisbury at 335-4666 or Samantha Hench at 335-4300 at least 24 hours in advance if they cannot attend the session.

If the person **<u>does NOT</u>** meet one or more of these criteria, explain that this study requires meeting all of these conditions, thank the person for their time, and, if reasonable (i.e., they may qualify for a study at another time), ask if they wish to remain on the list of participants for other National Advanced Driving Simulator studies.

10.3.2 Informed Consent Form

INFORMED CONSENT DOCUMENT

Project Title: Realism Assessment of the National Advanced Driving Simulator (NADS)

Investigator(s): Ginger Watson, Ph.D.
Yiannis Papelis, Ph.D.
Samantha Hench, M.S.
Judith Wightman, M.A.
Julie Qidwai, B.S.
Sue Ellen Salisbury, B.S.

PURPOSE:

You have been invited to participate in a study to evaluate the realism of the National Advanced Driving Simulator. We are particularly interested in evaluating how the simulator replicates actual driving, with a focus on how the simulator performs at different highway speeds, as well as overall steering, accelerating, and braking. The information gathered today will help us understand how high-fidelity simulators are perceived by drivers and the usefulness of these simulators as research tools.

We are inviting you to participate in this research study because you are a licensed driver with 5 years of driving experience.

If you agree to participate, you will be asked to sign this Informed Consent Document indicating that you have read the following document and have been told about the goals of this study.

PROCEDURES:

If you agree to participate, your involvement will last for approximately one hour.

The following procedures are involved in this study.

Upon arrival at the simulator facility, you will be briefed on the experimental procedure and participant rights. You will then be asked to sign an Informed Consent Document. Upon completion of the form, you will be asked to complete a questionnaire that focuses on your driving experience. The experimenter will then escort you to the simulator bay, brief you on the simulator cab, and explain the study paths. An experimenter will be present in the back seat of the simulator cab with you to ensure your safety while driving the simulator. You will then be told to begin driving following the roadway of a pre-programmed scenario. All driving trials will be recorded on video. You will practice driving the simulator, complete one driving trial, complete one or more brief questionnaires, receive some additional instruction, and then complete another driving trial. After completion of the second driving trial you will be escorted back to the briefing area where you will complete another one or more questionnaires and a structured interview that will last approximately ten minutes.

The simulator contains sensors that measure certain aspects of vehicle operation, vehicle motion, and driver actions. The system also contains video cameras that capture images of driver actions (e.g., driver's hand position on the steering wheel, forward road scene). These sensors and video cameras are located in such a manner that they will not affect your driving, the vehicle's performance, or obstruct your view while driving. The information collected using these sensors and video cameras is recorded onto data storage media for subsequent analysis by research staff.

RISKS:

The possible risks associated with participating in this research project are as follows. The risk to you, if you actually drive the simulator, is discomfort associated with simulator disorientation. Previous studies with similar driving intensities and simulator setups have produced mild to moderate disorientation effects such as slight uneasiness, warmth, or eyestrain for a small number of subjects. These effects are believed to last for only a short time, usually 10-15 minutes, after leaving the simulator. If you ask to quit driving as a result of discomfort, you will be allowed to quit at once. You will be asked to sit and rest before leaving, while consuming a beverage and a snack. This time may coincide with completion of the questionnaires. There is no evidence that driving ability is hampered in any way, therefore, if you show little or no signs of discomfort, you should be able to drive home. If you experience anything other than slight effects, transportation will be arranged through other means. This seems unlikely since studies in similar devices have shown only mild effects in recent investigations and evidence contends that symptoms decrease rapidly after simulator exposure is complete. If you are driven home, a follow-up call will be made 24 hours later to ensure that you are not feeling ill effects.

BENEFITS:

There may be no personal benefit to you for participating in this study. However, many participants do find driving in a simulator of this type to be an exciting and unique experience. However, it is hoped that this study will provide the University of Iowa and the National Highway Traffic Safety Administration (NHTSA) with information on how members of the public perform while driving the National Advanced Driving Simulator. .

COSTS AND COMPENSATION:

You will not have any costs for participating in this research project.

Should you agree to participate in this study, your compensation will be $10 per hour and your participation is expected to take approximately 1 hour. Payment will be paid by check. Please note that in the event that the test lasts less than 1 hour, your minimum payment for participation will be $10.

CONFIDENTIALITY:

Records of participation in this research project will be kept confidential to the extent permitted by law. However, federal government regulatory agencies and the University of Iowa Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. It is possible that these records could contain information that personally identifies you, especially where video data are concerned. Participants in the study will be given a subject number to which they will be referred to, thereby reducing personal identification of participants. In the event of any report or publication from this study, your name and responses to questionnaire items will not be disclosed. Results will be reported in a summarized manner in such a way that you cannot be identified. Please note that general health information obtained for you during the screening process is not retained in study records.

> The **engineering data** collected and recorded in this demonstration (including any performance scores based on these data) will be analyzed along with data gathered from other participants. NHTSA may publicly release these data in final reports or other publications or media for scientific (e.g., professional society meetings), educational (e.g., educational campaigns for members of the general public), outreach (e.g., nationally televised programs highlighting traffic safety issues), legislative (e.g., data provided to the U.S. Congress to assist with law-making activities), or research purposes (e.g., comparison analyses with data from other studies). Engineering data may also be released individually or in summary with that of other participants, but will not be presented in a way that permits personal identification, except when presented in conjunction with video data.

The **video data** (video image data recorded during your drive) recorded in this demonstration includes your video-recorded likeness and all in-vehicle audio including your voice (and may include, in some views, superimposed performance score information). Video and in-vehicle sounds will be used to examine your driving performance and other task performance while driving. NHTSA may publicly release video image data (in continuous video or still formats) and associated audio data, either separately or in association with the appropriate engineering data for scientific, educational, outreach, legislative, or research purposes (as noted above).

VOLUNTARY PARTICIPATION:

Taking part in this research study is voluntary. You may choose not to take part at all. If you agree to participate in this study, you may stop participating at any time. If you decide not to take part, or if you stop participating at any time, your decision will not result in any penalty or loss of benefits to which you may otherwise be entitled.

Under certain circumstances, your participation in this research study may be ended without your consent. This might happen if you fail to operate the research vehicle in accordance with the instructions provided by NHTSA and NADS staff.

RESEARCH RELATED INJURY:

In the event of research related injury, medical treatment is available at the University of Iowa Hospitals and Clinics. No compensation for treatment of research related injury is available from the University of Iowa unless the injury is proven to be the direct result of negligence by a University employee. Should a research related injury occur, the cost of treatment must be paid for by you and/or your medical or hospital insurance carrier.

QUESTIONS:

Questions are encouraged. If you have any questions about this research project, please contact: Ginger Watson, (319) 335-4679. If you have questions about the rights of research subjects or research related injury, please contact the Human Subjects Office, 300 College of Medicine Administration Building, The University of Iowa, Iowa City, Iowa, 52242, (319) 335-6564, or e-mail irb@uiowa.edu.

DISPOSITION OF INFORMED CONSENT:

Investigators at the University of Iowa will retain a signed copy of this Informed Consent form. A copy of this form will also be offered to you at the time you begin your participation in this study.

INFORMED CONSENT STATEMENT:

Your signature indicates that you have read this document and that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

I, ________________________________, VOLUNTARILY CONSENT TO PARTICIPATE.

Signature	Date

VIDEO DATA RELEASE STATEMENT:

I, ________________________, grant permission, to the National Highway Traffic Safety Administration (NHTSA) and its contractors to use, publish, or otherwise disseminate video image data (including continuous video and still photo formats derived from the video recording) and associated in-vehicle audio data collected about me in this study, either separately or in association with the appropriate engineering data for scientific, educational, outreach, legislative, and research purposes or to demonstrate the fidelity of the National Advanced Driving Simulator. I understand that such use may involve widespread distribution to the public and may involve dissemination of my likeness in video or still photo formats, but will not result in release of my name or other identifying personal information by NHTSA or its authorized contractors or agents.

I may withdraw the permissions granted in this video data release by contacting Ginger Watson at (319) 335-4679 or g-watson@uiowa.edu. Withdraw of this video data release may only be done **within seven days (1 calendar week)** of the date recorded on this consent. The ability to withdraw video data does not extend to the ability to withdraw engineering data.

I understand that, in the event of court action, NHTSA may not be able to prevent release of your name or other personal identifying information.

Signature	Date

INVESTIGATOR STATEMENT

I have discussed the above points with the subject or, where appropriate, with the subject's legally authorized representative, using a translator when necessary. It is my opinion that the subject understands the risks, benefits, and procedures involved with participation in this research study.

Signature of Investigator	Date

Initials of witness	Date

10.3.3 Driving History Questionnaire

Study # _____
Study Date ________
Participant # __ __-__ __ __

NADS Driving Survey

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

Background Information:

1) What is your birth date? __________/__________/__________
Month/ Date / Year

2) What is your gender?

☐ Male
☐ Female

3) How old were you when you started to drive? ___________________ years of age

4) For which of the following vehicles do you currently hold a valid driver's license? (Check all that apply)

Vehicle Type	Year When FIRST Licensed (May be Approximate)	Country & State of License (e.g. USA-Iowa)
☐ Car	___________	___________
☐ Motorcycle	___________	___________
☐ Truck	___________	___________
☐ Other: ____________	___________	___________
☐ Other: ____________	___________	___________

5) 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

6) Approximately how many miles do you drive per year? __________

7) 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)

8) What speed do you typically drive on the highway when the speed limit is
   55? ______
   65? ______

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

<u>Primary</u>
Make (e.g., Ford, Toyota): ____________________________________
Model (e.g., Escort, Celica): ____________________________________
Year: ____________________________________

<u>Secondary</u>
Make (e.g., Ford, Toyota): ____________________________________
Model (e.g., Escort, Celica): ____________________________________
Year: ____________________________________

10) Within the past five years, how many moving violations have you received?______

11) How often do you experience motion sickness? (Check only one)

- ☐ Frequently
- ☐ Occasionally
- ☐ Rarely
- ☐ Never

12) Have you taken any medication(s) in the past 48 hours? (Please list all)

____
____
____

13) Have you consumed any alcohol or other drugs within the last 12 hours? (Check only one)

- ☐ Yes
- ☐ No

14) 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

15) If you have participated in other driving studies, briefly describe what you did in each study.

Study 1

What vehicle was used for this study? (Check only one)

☐ Actual car – only
☐ Another simulator – only
☐ The Iowa Driving Simulator only
☐ Both - actual car and another simulator
☐ Both - actual car and the Iowa Driving Simulator

Brief Description: ______________________________

____

____

____

10.3.4 Experimental Protocol

CAB ORIENTATION (IN DOME, OUTSIDE CAB)

(open car door)

You will be driving a Jeep today. Before you get in, let me explain how to adjust the seat.

The seat adjusts forward and backward with this lever *(point)*. **To adjust the back of the seat, use this lever** *(point)*.

Please be seated.

Note the location of the speedometer, turn signal and gear levers (point to each).

The steering wheel adjusts up and down using this lever (point). You may adjust it now.

The outside mirrors on the left and right adjust using this panel of buttons (point).

You will need to manually adjust the in-cab rearview mirror.

(when participant is comfortable, take seatbelt in hand, pulling out all lax belt)

The doors and seatbelts are equipped with safety sensors that cause the simulator to stop if a door is opened or a seatbelt is loosened. So, it is very important that we leave our doors closed and our seatbelts fastened until our escort opens the simulator dome door *(point)* **to get us out.**

(hand seatbelt to participant)

Please fasten your seatbelt and close the door while I get in the back seat.

Cab Orientation (from back seat of cab)

I will be wearing an earpiece so I can hear the Control Operator. We also have speakers in the car so the Control Operator can hear us at all times. If, for any reason, you want to stop driving, please tell me. The Operator will also hear you and will bring us to a stop in just a few seconds.

(point to gear lever) **When we begin a drive, you will shift into "D" for DRIVE. When we end a drive, you will get off the road, come to a complete stop, and shift into "P" for PARK. When we are not driving, please keep your hands off the steering wheel and your feet back from the pedals.**

The engine is already on.

Practice Drive

You will complete three drives today. The first is a <u>practice drive</u> designed for you to become familiar with driving this vehicle and to get a feel for how it handles. You will practice changing lanes, braking, and accelerating. I will be talking with you during the practice drive, but will remain quiet during the other drives so I won't disturb your driving. Please ask any questions you have about the drive.

When the scenery is turned on, this car will be parked on a multilane highway. When I tell you to begin driving, please accelerate to the posted speed limit, which is 75 miles per hour.

(cue from Control Operator)
Whenever you're ready, shift into drive and begin driving in the far right lane.

(after driving normally for a time and on a straight stretch of road)
Please change lanes to the far left lane.

(after a few seconds and on a straight stretch of road)
Now change lanes back to the far right lane.

(after a few seconds and on a straight stretch of road)
Practice braking by slowing down to about 30 miles per hour, then accelerate to 75 miles per hour.

(cue from control room: "have the participant stop") **This is the end of the practice drive.**

(once the car is stopped) **Shift into park.**

Simulator Driving Trial I (un)

In this study, we are interested in the realism of the simulator at various speeds. During this drive, the posted speed limit will start at 55 and will increase to 65, then to 75 miles per hour. You should maintain a speed at or slightly above the posted speed limit. I will remind you of the posted speed each time it changes. This car will be (is) sitting on the entrance ramp to a multilane highway. Do you have any questions?

(cue from Control Operator). **Whenever you're ready, please shift into drive and begin.** *(after participant has begun to accelerate)* **Please drive in the right lane and accelerate to the posted speed limit, which is 55 miles per hour.**

(cue: 65 mph speed limit sign) **The speed limit is now 65 miles per hour. Please drive at or slightly above 65 miles per hour.**

(cue: 75 mph speed limit sign) **The speed limit is now 75 miles per hour. Please drive at or slightly above 75 miles per hour.**

(15 sec. after TF occurs-cue from control room: "the tread separation just occurred") **You've just experienced a tread separation. Drive as you normally would with a tread separation.**

(15 sec. later-cue from control room: "have the participant stop") **We have reached the end of this drive.**

(debrief)
Initially, you were told that the purpose of this research study was to evaluate the realism of the National Advanced Driving Simulator (NADS). We stated that our interests were in evaluating how the simulator replicates actual driving, with a focus on steering, accelerating, and braking. While we are interested in these issues, the primary purpose of this research is to investigate the performance of drivers who experience simulated tread separation.

One goal of the project is to compare the performance of drivers who encounter tread separation <u>un</u>expectedly to conditions where tread separation is expected. In order to assure performance under <u>un</u>expected tread separation conditions, we could not inform you of the primary purpose of the study prior to completing the drive. We hope that you understand our need to keep this information from you.

Because it is critical that one of the tread separation scenarios be unexpected, it is important that future participants not learn the purpose of this study. Therefore, we ask that you please refrain from discussing the purpose of this study until March 1 when we expect our data collection to be complete.

(BLUE SHEET)
You will complete one more drive, during which you will experience another tread separation. *(go to Trial II)*

(PINK SHEET)
You will complete one more drive, during which you will experience another tread separation. I will give you instructions on how to handle the tread separation. We ask for your continued participation and concentration on the suggested steps for vehicle control during the tread separation. Your instructions are:

1. **Keep going straight.**
2. **Gradually brake to slow down.**
3. **Pull off the road.**

Do you have any questions?

Remember, the instructions for handling the car during tread separation are to:

1. **Keep going straight.**
2. **Gradually brake to slow down.**
3. **Pull off the road.**

(go to Trial II)

Simulator Driving Trial II (exp)

This car will be (is) sitting on the entrance ramp to a multilane highway. During this drive, the speed limit will be 75 miles per hour. You should accelerate quickly to this speed. Do you have any questions?

(cue from Control Operator) **Whenever you're ready, please shift into drive and begin.** *(after participant has begun to accelerate)* **Please drive in the right lane and accelerate to 75 miles per hour.**

(10 sec. after TF occurs-cue from control room: "the tread separation just occurred") **You've just experienced a tread separation.**

(10 sec. later-cue from control room: "have the participant stop") **This is the end of your drive. Keep your seatbelt on and door closed until our escort opens the door to let us out.**

(administer SSQ)

Thank you for driving today. We have a questionnaire and interview for you to complete in another room.

(escort to room C)

10.3.5 Instructions for Handling Tire Separation

1. Keep going straight.

2. Gradually brake to slow down.

3. Pull off the road.

10.3.6 Simulator Sickness Questionnaire

Simulator Sickness Questionnaire

Study # ____
Study Date _______
Participant # __ __-__ __ __
Trial #__ __

Directions: Circle below if any symptoms apply to you right now.

1.	General discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Boredom	None	Slight	Moderate	Severe
4.	Drowsiness	None	Slight	Moderate	Severe
5.	Headache	None	Slight	Moderate	Severe
6.	Eye Strain	None	Slight	Moderate	Severe
7.	Difficulty Focusing	None	Slight	Moderate	Severe
8.	a. Salivation increased	None	Slight	Moderate	Severe
	b. Salivation decreased	None	Slight	Moderate	Severe
9.	Sweating	None	Slight	Moderate	Severe
10.	Nausea	None	Slight	Moderate	Severe
11.	Difficulty concentrating	None	Slight	Moderate	Severe
12.	Mental depression	None	Slight	Moderate	Severe
13.	"Fullness of the Head"	None	Slight	Moderate	Severe
14.	Blurred vision	None	Slight	Moderate	Severe
15.	a. Dizziness with eyes open	None	Slight	Moderate	Severe
	b. Dizziness with eyes closed	None	Slight	Moderate	Severe
16.	* Vertigo	None	Slight	Moderate	Severe
17.	**Visual flashbacks	None	Slight	Moderate	Severe
18.	Faintness	None	Slight	Moderate	Severe
19.	Awareness of breathing	None	Slight	Moderate	Severe
20.	***Stomach awareness	None	Slight	Moderate	Severe
21.	Loss of appetite	None	Slight	Moderate	Severe
22.	Increased appetite	None	Slight	Moderate	Severe
23.	Desire to move bowels	None	Slight	Moderate	Severe
24.	Confusion	None	Slight	Moderate	Severe
25.	Burping	No	Yes:	No. of times	____________
26.	Vomiting	No	Yes:	No. of times	____________
27.	Other	____			

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Visual illusion of movement or false sensations similar to automobile dynamics, when not in the simulator or the automobile.

***Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

10.3.7 Reaction/Realism Survey

Study # ____________
Trial # ____________
Study Date ____________
Participant # ____________

REACTION SURVEY

For each of the following items, circle the number that best indicates how closely the simulator responds, appears, and sounds like an actual car. If an item is not applicable, mark NA.

		Not at all like a real car						Completely like a real car	
1)	Response of the seat adjustment levers	0	1	2	3	4	5	6	NA
2)	Response of the mirror adjustment levers	0	1	2	3	4	5	6	NA
3)	Response of the door locks and handles	0	1	2	3	4	5	6	NA
4)	Response of the gear shift	0	1	2	3	4	5	6	NA
5)	Response of the fans	0	1	2	3	4	5	6	NA
6)	Response of the brake pedal	0	1	2	3	4	5	6	NA
7)	Response of the speedometer	0	1	2	3	4	5	6	NA
8)	Response of the steering wheel while driving straight	0	1	2	3	4	5	6	NA
9)	Response of the steering wheel while driving on curves	0	1	2	3	4	5	6	NA
10)	Response of the steering wheel while making turns at intersections	0	1	2	3	4	5	6	NA
11)	Feel when accelerating	0	1	2	3	4	5	6	NA
12)	Feel when braking	0	1	2	3	4	5	6	NA
13)	Feel when passing other cars or swaying	0	1	2	3	4	5	6	NA
14)	Feel when driving straight	0	1	2	3	4	5	6	NA
15)	Feel when driving on curves	0	1	2	3	4	5	6	NA
16)	Feel when turning at intersections	0	1	2	3	4	5	6	NA
17)	Feel of approximate speed when driving in town	0	1	2	3	4	5	6	NA
18)	Feel of approximate speed when driving 55 mph	0	1	2	3	4	5	6	NA
19)	Feel of approximate speed when driving 65 mph	0	1	2	3	4	5	6	NA
20)	Feel of approximate speed when driving 75 mph	0	1	2	3	4	5	6	NA
21)	Appearance of car interior	0	1	2	3	4	5	6	NA
22)	Appearance of roadside scenery	0	1	2	3	4	5	6	NA
23)	Appearance of roads and road markings	0	1	2	3	4	5	6	NA
24)	Appearance of signs	0	1	2	3	4	5	6	NA
25)	Appearance of other vehicles	0	1	2	3	4	5	6	NA
26)	Appearance of rear-view mirror image	0	1	2	3	4	5	6	NA
27)	Sound of your car	0	1	2	3	4	5	6	NA
28)	Sound of other vehicles	0	1	2	3	4	5	6	NA

For each of the following items, circle the number that best indicates how closely your driving ability in the simulator compares to that of your driving ability in an actual car. If an item is not applicable, mark NA.

		Not at all like real driving						Completely like real driving	
29)	Ability to read road and warning signs	0	1	2	3	4	5	6	NA
30)	Ability to respond to other vehicles	0	1	2	3	4	5	6	NA
31)	Ability to keep straight in your lane	0	1	2	3	4	5	6	NA
32)	Ability to respond at intersections	0	1	2	3	4	5	6	NA
33)	Ability to make turns	0	1	2	3	4	5	6	NA
34)	Ability to stop the vehicle	0	1	2	3	4	5	6	NA

<u>Overall Impressions</u>

For each of the following items, circle the number that best indicates your overall impression of the simulator.

		Not at all like a real car						Completely like a real car	
35)	Overall feel of the car when driving	0	1	2	3	4	5	6	NA
36)	Overall appearance of driving scenes	0	1	2	3	4	5	6	NA

		Not at all like real driving						Completely like real driving	
37)	Overall similarity to real driving	0	1	2	3	4	5	6	NA

10.3.8 Tread Separation Questionnaire

Study # ____
Study Date _______
Participant # __ __ - __ __ __

NADS Tread Separation

As part of this study, it is useful to collect information describing each participant. The following questions ask about your experience with situations involving tread separation in a vehicle. Please read each question carefully, marking only one response unless otherwise indicated. If something is unclear, ask the research assistant for help. Your participation is voluntary and you have the right to omit questions you find offensive.

1) Immediately following the tread separation cues in the simulator what did you initially conclude had occurred?

☐ Tread separation
☐ Other (please specify______________________________)
☐ Unsure of what had occurred.

2) Did you recognize that a tread separation had occurred by the time the vehicle had come to a complete stop?

☐ Yes
☐ No

3) Have you ever experienced a tread separation while you were driving a vehicle? (check only one)

☐ Yes	Continue with question #4.
☐ No	Stop. You are done with this questionnaire.

4) How many tread separations have you experienced while driving?_______

Tread separation #1

5) What type of vehicle were you driving?
- ☐ Automobile
- ☐ SUV
- ☐ Truck
- ☐ Motorcycle
- ☐ Other (please specify _______________)

6) At approximately what speed did the tread separation occur?
_____ mph

7) What type of roadway surface were you traveling on when the failure occurred?
- ☐ Paved
- ☐ Blacktop
- ☐ Gravel

8) Was there any damage to your vehicle or any other vehicles as a result of the tread separation? Please describe.

9) What was the condition of the roadway when the failure occurred?
- ☐ Dry
- ☐ Wet
- ☐ Ice

10) When did this tread separation occur? (Check the most appropriate.)
- ☐ Within 1-6 months.
- ☐ 6 months to one year.
- ☐ 1-2 years.
- ☐ 3 or more years.

Tread separation #2 (if necessary)

5) What type of vehicle were you driving?

- ☐ Automobile
- ☐ SUV
- ☐ Truck
- ☐ Motorcycle
- ☐ Other (please specify _______________)

6) At approximately what speed did the tread separation occur?

_____ mph

7) What type of roadway surface were you traveling on when the failure occurred?

- ☐ Paved
- ☐ Blacktop
- ☐ Gravel

8) Was there any damage to your vehicle or any other vehicles as a result of the tread separation? Please describe.

9) What was the condition of the roadway when the failure occurred?

- ☐ Dry
- ☐ Wet
- ☐ Ice

10) When did this tread separation occur? (Check the most appropriate.)

- ☐ Within 1-6 months.
- ☐ 6 months to one year.
- ☐ 1-2 years.
- ☐ 3 or more years.

Tread separation #3 (if necessary)

5) What type of vehicle were you driving?

- ☐ Automobile
- ☐ SUV
- ☐ Truck
- ☐ Motorcycle
- ☐ Other (please specify _______________)

6) At approximately what speed did the tread separation occur?

_____ mph

7) What type of roadway surface were you traveling on when the failure occurred?

- ☐ Paved
- ☐ Blacktop
- ☐ Gravel

8) Was there any damage to your vehicle or any other vehicles as a result of the tread separation? Please describe.

9) What was the condition of the roadway when the failure occurred?

- ☐ Dry
- ☐ Wet
- ☐ Ice

10) When did this tread separation occur? (Check the most appropriate.)

- ☐ Within 1-6 months.
- ☐ 6 months to one year.
- ☐ 1-2 years.
- ☐ 3 or more years.

10.3.9 Structured Interview Questions

Participant # ______
Date: ____________
Structured Interview Questions

Simulator Handling and Tread separation Performance
Describe your overall experience in the simulator?
What are the most realistic features and why?
What are the least realistic features and why?

How did the realism or lack of realism affect your driving performance in the simulator?

Did you understand what happened during the first simulator trial/drive?
If no, what do you think happened?

Did you expect the first tread separation to happen?
Do you know which tire failed?
Could you tell if it was a tire separation or a tire blowout?

What are your definitions of a tread separation and a tire blow out?
I am going to give you a definition of a tire blow out and a tire separation and I want you to tell me which one you think occurred in the simulator.
Tire Separation - the air stays in the tire and the tread dissipates.
Tire Blowout – the tire deflates causing a decrease in elevation where the blowout occurs.

How realistic was each tread separation?
What about the simulated tread separation was/was not realistic?
Did the sounds associated with the each tread separation seem realistic?

Do you think your ability to handle the tread separation changed from your first failure to the last one you completed today?
How do you think your performance differed?

If you were to tell someone (a friend) how to handle a tread separation, what would you tell them?

When you had a tread separation what was you most concerned about?
steering control (driving straight)
slowing down
pulling off the road

Were the instructions on how to deal with a tread separation understandable?
What was missing that made it difficult to understand?

Have you ever experienced a tread separation outside of the simulator?
If yes, please describe this tread separation.

Physiological Effects
Did you experience any symptoms in the simulator that related to simulator sickness?

Did you experience any symptoms that were not on the questionnaire?
If yes, what were they and how intense were they?

Do you feel as though the questionnaires reflected all symptoms, the magnitude of these symptoms, and lasting effects of these symptoms?
If no, what was missing or how could the questionnaire be improved?

Is there anything else you would like to add about your experience in the simulator, your well-being, or your driving performance.

Don't TALK about study until after the middle of March. Debriefing statement.

10.3.10 Debriefing

Initially, you were told that the purpose of this research study was to evaluate the realism of the National Advanced Driving Simulator (NADS). We stated that our interests were in evaluating how the simulator replicates actual driving, with a focus on steering, accelerating, and braking. While we are interested in these issues, the primary purpose of this research was to investigate the performance of drivers who experience simulated tread separation.

One goal of the project was to compare the performance of drivers who encounter tread separation unexpectedly to conditions where tread separation is expected. In order to assure performance under unexpected tread separation conditions, we could not inform you of the tread separation prior to completing the simulator trials. We hope that you understand our need to keep this information from you.

Because it is critical that one of the tread separation scenarios be unexpected, it is important that future participants not learn the purpose of this study. Therefore, we ask that you please refrain from discussing the purpose of this study until March 1 when we expect our data collection to be complete.

If you have any further questions regarding the purpose of this research that we were unable to answer at this time, you may contact Elizabeth Mazzae, with the National Highway Traffic and Safety Administration (NHTSA) at (937) 666-4511.

10.4 APPENDIX D: Representative Results From NADS Subject Run

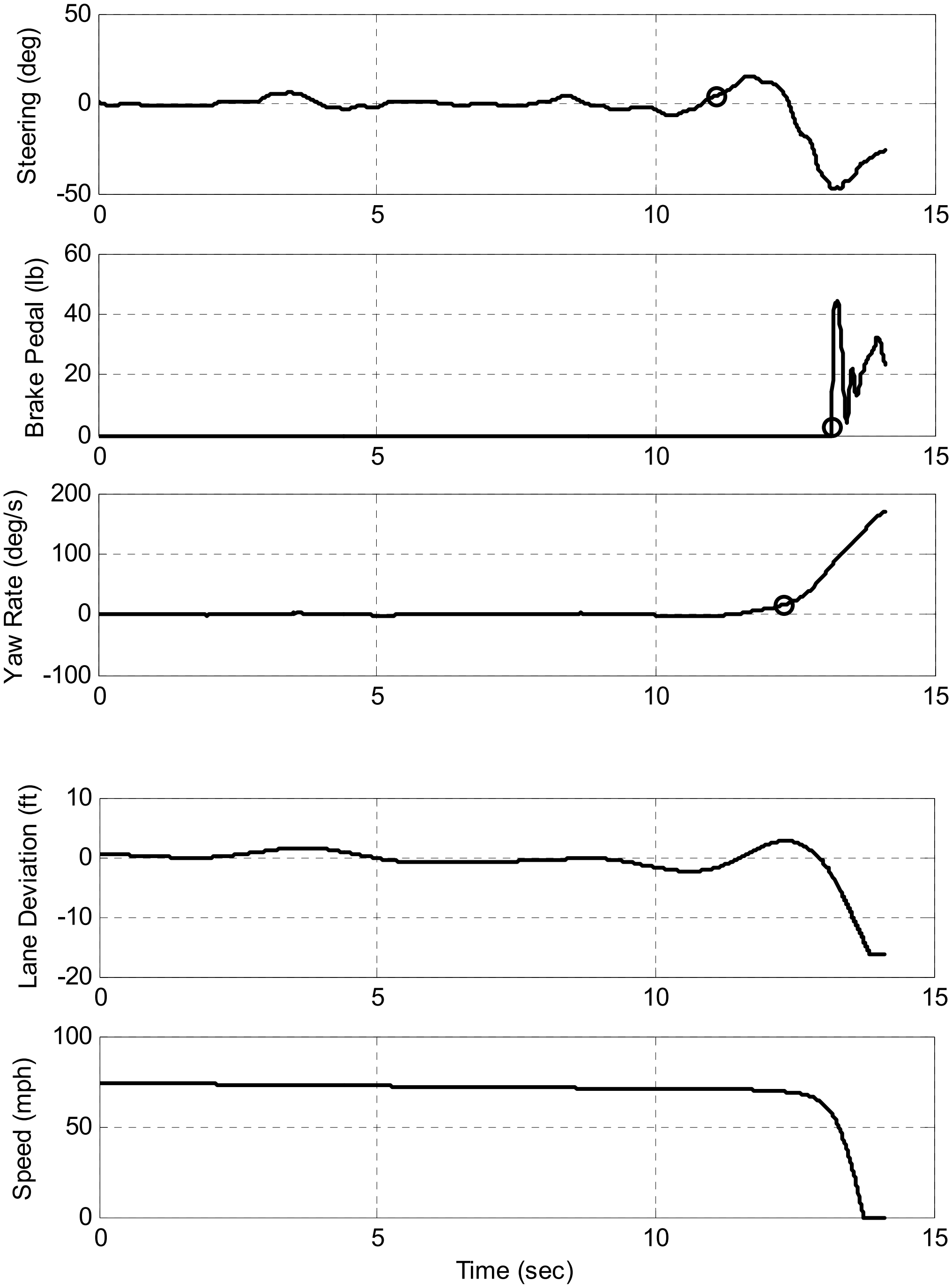

Figure 25. Representative Results From NADS Subject Run – Time Domain Plots

Figure 25 contains time domain results from one of the NADS subject runs. For these plots, the initiation of the tire failure occurs at time zero. The results shown are from an unexpected tire failure run with a left rear detread while driving Vehicle 3. The circles on the steering, brake pedal, and yaw rate plots indicate the threshold onset values used to determine response times. The steering threshold value used was ± 4 degrees of steering. The brake pedal force threshold was any positive braking force. The threshold value shown on the yaw rate plots is the value used to determine vehicle loss of control, 15 degrees per second. Lane deviation and vehicle forward speed are shown on the bottom two plots of Figure 25.

Figure 26 shows the vehicle path and orientation for the final three seconds of the representative run of Figure 25. The vehicle position is shown at 0.25-second intervals. The vehicle veered a few feet left after the tire failure. The driver then steered to the right and lost control of the vehicle.

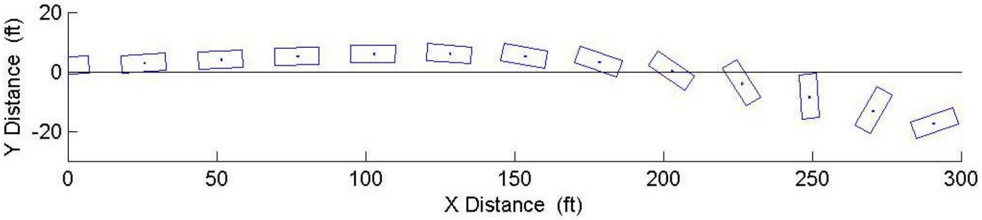

Figure 26. Representative Results From NADS Subject Run – Vehicle Position

10.5 APPENDIX E: Additional Descriptive Text for Figures 15-20.

Figure 15 illustrates drivers' responses to unexpected tire failures and their outcomes. Following the unexpected tire failure, a driver had three first response options: (1) brake, (2) steer, or (3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. Of the 108 subjects, none responded initially by braking, 71 (66%) subjects responded by steering, and 37 (34%) made no response initially to the tire failure. An initial response of braking or steering was followed by one of two outcomes, a controlled stop, or loss of vehicle control. Since zero subjects responded initially by braking, there were zero outcomes for this response. Of the 77 subjects who responded by steering, 24 (34%) brought the simulated vehicle to a controlled stop and 47 (66%) experienced loss of control. Subjects who made no initial response had two response options after experimenter notification: brake or steer. Of the 37 subjects the experimenter had to notify: 13 (35%) responded by braking and 24 (65%) responded by steering. Controlled stop and loss of control were also the outcomes for brake and steer after experimenter notification. Of the 13 subjects who braked, 12 (92%) experienced a controlled stop and 1 (8%) experienced loss of control. Of the 24 subjects who steered, 13(54%) experienced a controlled stop and 11(46%) experienced loss of control.

Figure 16 illustrates drivers' responses to expected tire failures and their outcomes. Following a tire failure a driver had three first response options: (1) brake (2) steer or (3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. Of the 108 subjects, 63 (58%) subjects responded by braking, 28 (26%) subjects responded by steering, and 17 (16%) made no response initially to the tire failure. An initial response of braking or steering was followed by one of two outcomes: controlled stop or loss of control. Of the 63 subjects who responded by braking: 59 (94%) brought the simulated vehicle to a controlled stop and 4 (8%) experienced loss of control. Of the 28 subjects who responded by steering: 14 (50%) brought the simulate vehicle to a controlled stop and 14(50%) experienced loss of control. Subjects who made no initial response had two response options after experimenter notification: brake or steer. Of the 17 subjects the experimenter had to notify: 7 (41%) responded by braking and 10 (59%) responded by steering. Controlled stop and loss of control were also the outcomes for brake and steer after experimenter notification. Of the 7 subjects that braked 7 (100%) experienced a controlled stop and 0 (0%) experienced loss of control. Of the 10 subjects that steered 6 (60%) experienced a controlled stop and 4 (40%) experienced loss of control.

Figure 17 illustrates drivers' responses to unexpected tire failures and their outcomes by vehicle understeer condition. Following the unexpected tire failure, a driver had three first response options: (1) brake, (2) steer, or (3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. None of the drivers responded to the unexpected tire failure by braking, regardless of vehicle understeer condition. The frequencies and respective proportions of drivers who responded first by steering were 15 (.42) for Vehicle 1, 25 (.69) for Vehicle 2, and 31 (.86) for Vehicle 3. The frequencies and respective proportions of drivers who made no initial response were 21 (.58) for Vehicle 1, 11 (.31) for Vehicle 2, and 5 (.14) for Vehicle 3. An initial response of braking or steering was followed by one of two outcomes, controlled stop, or loss of control.

Due to no brake responses there were no outcomes for this response. The frequencies and respective proportions of those who experienced a controlled stop after an initial steering response were 13 (.87) for Vehicle 1, 10 (.40) for Vehicle 2, 1 (.03) for Vehicle 3. The frequencies and respective proportions of those who experienced loss of control after an initial steering response were 2 (.13) for Vehicle 1, 15 (.60) for Vehicle 2, 30 (.97) for Vehicle 3. Among those drivers who responded only after experimenter notification, the frequencies and respective proportions of drivers who responded by braking were 10 (.48) for Vehicle 1, 3 (.27) for Vehicle 2, and 0 for Vehicle 3. The frequencies and respective proportions of drivers who responded by steering after experimenter notification were 11 (.52) for Vehicle 1, 8 (.73) for Vehicle 2, and 5 (1.00) for Vehicle 3. Controlled stop and loss of control were also the outcomes for brake and steer after experimenter notification. The frequencies and proportions of those who experienced a controlled stop after a braking response were 9(.90) for Vehicle 1, 3 (1.00) for Vehicle 2, and 0 for Vehicle 3. The frequencies and proportions of those who experienced loss of control after a braking response were 1(.10) for Vehicle 1 and 0 for Vehicle 2 and Vehicle 3. The frequencies and proportions of those who experienced a controlled stop after a steering response were 8 (.72) for Vehicle 1, 5 (.63) for Vehicle 2, and 0 for Vehicle 3. The frequencies and proportions of those who experienced loss of control after a steering response were 3 (.72) for Vehicle 1, 3 (.37) for Vehicle 2, and 5 (1.00) for Vehicle 3.

Figure 18 illustrates drivers' responses to expected tire failures and their outcomes by vehicle understeer condition. Following a tire failure a driver had three first response options: (1) brake (2) steer or (3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. The frequencies and respective proportions of drivers who responded first by braking were 26 (.72) for Vehicle 1, 19 (.53) for Vehicle 2, and 18 (.50) for Vehicle 3. The frequencies and respective proportions of drivers who responded first by steering were 4 (.11) for Vehicle 1, 11 (.31) for Vehicle 2, and 13 (.36) for Vehicle 3. The frequencies and respective proportions of drivers who made no initial response were 6 (.17) for Vehicle 1, 6 (.16) for Vehicle 2, and 5 (.14) for Vehicle 3. An initial response of braking or steering was followed by one of two outcomes: controlled stop or loss of control. The frequencies and respective proportions of those who experienced a controlled stop after an initial braking response were 25(.96) for Vehicle 1, 17 (.89) for Vehicle 2, 17 (.94) for Vehicle 3. The frequencies and respective proportions of those who experienced loss of control after an initial braking response were 1 (.04) for Vehicle 1, 2 (.11) for Vehicle 2, 1 (.06) for Vehicle 3. The frequencies and respective proportions of those who experienced a controlled stop after an initial steering response were 4 (1.00) for Vehicle 1, 6 (.55) for Vehicle 2, 4 (.31) for Vehicle 3. The frequencies and respective proportions of those who experienced loss of control after an initial steering response were 0 for Vehicle 1, 5(.45) for Vehicle 2, 9 (.69) for Vehicle 3. Among those drivers who responded only after experimenter notification, the frequencies and respective proportions of drivers who responded by braking were 3 (.50) for Vehicle 1, 3 (.50) for Vehicle 2, and 1 (.20) for Vehicle 3. The frequencies and respective proportions of drivers who responded by steering after experimenter notification were 3 (.50) for Vehicle 1, 3 (.50) for Vehicle 2, and 4 (.80) for Vehicle 3. Controlled stop and loss of control were also the outcomes for brake and steer after experimenter notification. The frequencies and proportions of those who experienced a controlled stop after a braking response were 3 (1.00) for Vehicle 1, 3(1.00) for Vehicle 2, and 1 (1.00) for Vehicle 3. The frequencies and proportions of those who experienced loss of control after a braking response were 0 for Vehicle 1,Vehicle 2 and Vehicle 3. The frequencies and proportions of those who experienced a controlled stop after a steering response were 3 (1.00) for Vehicle 1, 3 (1.00) for Vehicle 2, and 0 for Vehicle 3. The frequencies and proportions of those who experienced loss of control after a steering response were 0 for Vehicle 1 and Vehicle 2, and 4 (1.00) for Vehicle 3.

Figure 19 illustrates means (standard deviations) for the time intervals between the unexpected tread separation event, the drivers' first responses and the outcomes for the responses. Following a tire failure a driver had three first response options: (1) brake (2) steer or (3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. Zero subjects responded by braking. 71 subjects responded by steering and the average time between the separation and the steering response was 5.8 seconds with a standard deviation of 3.4 seconds. 37 subjects were notified by the experimenter that the separation had occurred at an average response time of 16.6 seconds with a standard deviation of 2.3 seconds. Zero outcomes were reported for the braking response as there were zero subjects that responded. Of the 71 subjects that responded by steering: 24 experienced a controlled stop in an average time of 42.6 seconds with a standard deviation of 12.0 seconds and 47 experienced loss of control in an average time of 10.5 seconds with a standard deviation of 8.2 seconds. After the experimenter notified 37 subjects of the separation: 13 responded by braking in an average time of 10.2 seconds with a standard deviation of 5.2 seconds and 24 responded by steering in an average of 7.2 seconds with a standard deviation of 5.0 seconds. Of the 13 subjects that responded by braking following experimenter notification: 12 experienced a controlled stop in an average time of 19.7 seconds with a standard deviation of 7.3 seconds and 1 experienced loss of control in an average time of 4.6 seconds. Of the 24 subjects that responded by steering following experimenter notification: 13 experienced a controlled stop in an average time of 21.0 seconds with a standard deviation of 4.3 seconds and 11 experienced loss of control in an average time of 4.4 seconds with a standard deviation of 1.8 seconds.

Figure 20 illustrates means (standard deviations) for the time intervals between the expected tread separation event, the drivers' first responses and the outcomes for the responses. Following a tire failure a driver had three first response options: 1) brake 2) steer or 3) no response. This latter group is called "experimenter notify" because the experimenter notified the subject of the tire failure before the driver made any response. 63 subjects responded by braking and the average time between the separation and the braking response was 2.3 seconds with a standard deviation of 1.5 seconds. 28 subjects responded by steering and the average time between the separation and the steering response was 5.4 seconds with a standard deviation of 3.5 seconds. 17 subjects were notified by the experimenter that the separation had occurred at an average response time of 9.8 seconds with a standard deviation of 2.7 seconds. Of the 63 subjects that responded by braking: 59 experienced a controlled stop in an average time of 18.3 seconds with a standard deviation of 8.8 seconds and 4 experienced loss of control in an average time of 24.2 seconds with a standard deviation of 9.5 seconds. Of the 28 subjects that responded by steering: 14 experienced a controlled stop in an average time of 24.2 seconds with a standard deviation of 9.5 seconds and 14 experienced loss of control in an average time of 4.5 seconds with a standard deviation of 1.2 seconds. After the experimenter notified 17 subjects of the separation: 7 responded by braking in an average time of 1.5 seconds with a standard deviation of 1.0 seconds and 10 responded by steering in an average of 2.09 seconds with a standard deviation of 1.4 seconds. Of the 7 subjects that responded by braking following experimenter notification: 7 experienced a controlled stop in an average time of 19.8 seconds with a standard deviation of 8.0 seconds and 0 experienced loss of control. Of the 10 subjects that responded by steering following experimenter notification: 6 experienced a controlled stop in an average time of 19.6

seconds with a standard deviation of 6.3 seconds and 4 experienced loss of control in an average time of 3.9 seconds with a standard deviation of 1.6 seconds.

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