US Department
of Transportation

**National Highway
Traffic Safety
Administration**

DOT HS 809 357 **August 2001**

An Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover –

Phase I-A of NHTSA's 1997-1998 Vehicle Rollover Research Program

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipients's Catalog No.

4. Title and Subtitle An Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover - Phase I-A of NHTSA's 1997-1998 Vehicle Rollover Research Program	5. Report Date August 2001 6. Performing Organization Code NHTSA/NRD-22
7. Author(s) J. Gavin Howe, W. Riley Garrott, Garrick Forkenbrock, Gary J. Heydinger, and Jeff Lloyd	8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box 37 East Liberty, OH 43319	10. Work Unit No. (TRAIS)n code 11. Contract of Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 400 Seventh Street, S.W. Washington, DC 20590	13. Type of Report and Period Covered Final, May 1997 - July 2000 14. Sponsoring Agency Code NHTSA

15. Supplementary Notes

16. Abstract

Rollovers are the second most dangerous type of crash occurring on our nation's highways. During the five years 1991 through 1998, Fatality Analysis Reporting System (FARS) data showed that an average of 9,237 people were fatally injured each year in light vehicle rollover crashes (all types, including multi-vehicle crashes and ones for which rollover was not the first harmful event). Due to the relatively low percentage of rollover crashes, when measured by either fatalities or incapacitating injuries per occupant involved, rollover crashes are the most dangerous type of collision for all classes of light vehicles.

This report documents the results of Phase I-A testing for NHTSA's 1997-1998 Light Vehicle Rollover Research program. This phase was an initial, exploratory study of using test track maneuvers to quantify on-road, untripped rollover propensity. This study examined a broad range of maneuvers that might induce on-road, untripped rollover including: J-Turn, J-Turn With Pulse Braking, Brake and Steer, Steering Reversal, Toyota Fishhook, Double Lane Change, Split-Mu Two Wheels Off-Road Recovery Simulation, and Toyota Fishhook with Pulse Braking.

Three vehicles were selected for the Phase I-A testing. The vehicles selected were a 1984 Ford Bronco II, a 1997 Jeep Cherokee, and a 1990 Toyota 4Runner. These test vehicles were not in new condition. None of the test vehicles necessarily performed as would new vehicles without outriggers. However, this was not important for the Phase I-A research. The goal of the Phase I-A research was maneuver selection and test procedure development, not vehicle characterization.

After the analysis was complete, it was decided that the following maneuvers should be evaluated further as part of NHTSA's rollover research: J-Turn, J-Turn With Pulse Braking, Toyota Fishhook, and Toyota Fishhook with Pulse Braking. The Brake and Steer maneuver did not produce two-wheel lift for the vehicles. The Steering Reversal procedure has many potential steering profiles and was replaced by the steering reversal profile specified in the Toyota Fishhook procedure. The Double Lane Change and Split-Mu Two Wheels Off-Road Recovery Simulation maneuvers had the potential for greater driver variability, had steering reversal type inputs found in more repeatable maneuvers, and produced two-wheel lifts less frequently than did the Toyota Fishhook maneuver.

17. Key Words On-Road, Untripped Rollover Propensity Static Stability Factor, Tilt Table Ratio, Critical Sliding Velocity, and Lateral Acceleration at Rollover	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	299	

Form DOT F1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

This document has been prepared under the sponsorship of the United States Department of Transportation's National Highway Traffic Safety Administration. The opinion, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its contents or use thereof. When trade or manufacturers' names or products are mentioned, it is only because they are considered essential to the object of the document and should not be construed as an endorsement. The United States Government does not endorse products or manufacturers.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Section **Page**

TABLE OF CONTENTS (continued)

Section **Page**

LIST OF FIGURES

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF TABLES

LIST OF TABLES (continued)

ACKNOWLEDGMENTS

The testing program documented in this report was a coordinated effort by the National Highway Traffic Safety Administration (NHTSA) Vehicle Research and Test Center (VRTC) and the Transportation Research Center Inc. (TRC) to develop potential rollover propensity maneuvers.

The authors wish to recognize the outstanding support of our research colleagues. Larry Jolliff and Don Phipps were instrumental in performing the testing. Larry Armstrong and Dave MacPherson prepared the vehicles for testing by providing instrumentation and outrigger installation. Dave Dashner and Leslie Portwood performed data analysis and provided tabulated and graphical data for the report.

John Hinch from NHTSA Research and Development and Mike Pyne, Gayle Dalrymple, Pat Boyd, and Gary Woodford from NHTSA Safety Performance Standards office contributed to the development of the test procedures used in this study.

J. Gavin Howe
W. Riley Garrott, Ph.D.
Garrick Forkenbrock
Gary J. Heydinger, Ph.D.
Jeff Lloyd

Department of Transportation
National Highway Traffic Safety Administration

TECHNICAL SUMMARY

Report Title: An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover - Phase I-A of NHTSA's 1997-1998 Vehicle Rollover Research Program	Date: August 2001
Report Author(s): J. Gavin Howe, W. Riley Garrott, Garrick Forkenbrock, Gary Heydinger, Jeff Lloyd	

This report documents the results of Phase I-A testing for the National Highway Traffic Safety Administration's (NHTSA) 1997-1998 Light Vehicle Dynamic Rollover Research program. This phase was an initial, exploratory study of using test track maneuvers to quantify on-road, untripped rollover propensity. This study examined a broad range of maneuvers that might induce on-road, untripped rollover. Each maneuver studied was either discarded or retained for further study in subsequent program phases. Maneuvers were evaluated based upon:

1. Their objectivity and repeatability, i.e., whether they could be performed objectively with, for the same vehicle, repeatable results.

2. Their discriminatory capability, i.e., whether they resulted in on-road untripped rollover for some, but not all, vehicles.

3. Their face validity, i.e., whether they might be performed by actual drivers while driving (particularly in emergencies).

4. Their metric measurement capability, i.e., whether one or more metrics that are expected to quantify a vehicle's rollover propensity can be calculated from data collected during the maneuver.

Maneuver objectivity and repeatability were of great concern throughout this research.

Three vehicles were selected for the Phase I-A testing. The vehicles selected were a 1984 Ford Bronco II, a 1997 Jeep Cherokee, and a 1990 Toyota 4Runner. These test vehicles were not in new condition. None of the test vehicles necessarily performed as would have new vehicles without outriggers. However, this was not important for the Phase I-A research. The goal of the Phase I-A research was maneuver selection and test procedure development, not vehicle characterization.

A total of eight test procedures were evaluated in this study: J-Turn (without pulse braking), J-Turn With Pulse Braking, Brake and Steer, Steering Reversal, Toyota Fishhook (without pulse braking), Double Lane Change, Split-Mu Two Wheels Off-Road Recovery Simulation, and Toyota Fishhook with Pulse Braking.

The J-Turn (without pulse braking) maneuver consists of a single steering input. Large steering angles were chosen to saturate the tires of all of the test vehicles. The inputs for this test maneuver were very repeatable due to the simple, single steering motion, the use of a mechanical steering stop, and the minimal requirements that this maneuver imposes on the driver. In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response. The J-Turn tests conducted were found to be fairly repeatable and multiple two-wheel lifts occurred for one of the test vehicles. However, these two-wheel lifts happened when testing with tires for which significant tire shoulder wear was thought to have occurred. (Note that the tire shoulder wear which occurs during rollover testing is not like the tire wear that occurs during normal driving; the effect on maximum tire side force generation capability is thought to be quite different for the two types of tire wear.) There is no way to determine whether these two-wheel lifts would have happened if the testing had been performed with unworn tires. The J-Turn maneuver was a simple test to conduct relative to other vehicle response handling tests and therefore will be considered during future dynamic rollover research.

J-Turn With Pulse Braking uses the same steering input as a function of time as does the J-Turn. The test procedure differs from the test procedure for the J-Turn in that after the driver has turned the steering handwheel to the mechanical steering stop, the throttle was released and a short duration, hard pulse force was applied to the brake pedal. The braking pulse momentarily decreases the lateral force capabilities of the tires, thereby decreasing the vehicle's lateral acceleration. When the braking pulse ends, the lateral force capabilities of the tires increase very rapidly. This sometimes produces vehicle lateral acceleration levels which can produce two-wheel lift for some vehicles that do not have two-wheel lift for the J-Turn (without pulse braking) maneuver. Further testing is required to better define and understand the J-Turn With Pulse Braking test. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. The authors recommend further development of this maneuver during the dynamic rollover research program.

The Brake and Steer maneuver increases maneuver complexity by adding sustained braking to the J-Turn (without pulse braking). Brake and Steer uses the same steering input as a function of time as does the J-Turn. In general, the brakes were applied at the same time as the steering input for the testing in this study. During analysis of the first vehicle's Brake and Steer testing, the well known fact that applying and maintaining hard braking during steering decreases the lateral force capabilities of the tires was recognized. This reduces the lateral acceleration of the vehicle and the potential for two-wheel lift. Since sustained braking tends to decrease the rollover potential for the vehicle, the authors recommend that this maneuver not be further developed for rollover testing.

The Steering Reversal maneuver consists of two steering inputs; the steering handwheel is first turned in one direction and then is rapidly reversed resulting in a turn in the opposite direction. There are many possible combinations of initial and second steering magnitudes that can be used with this test procedure. Test severity can be increased by increasing the magnitudes of the steering inputs, raising the initial vehicle speed, or both. Only a small number of the possible first and second steering input magnitudes were tested in this evaluation. The Toyota Fishhook maneuver is also a steering reversal type maneuver which replaced the Steering Reversal maneuver after testing one vehicle.

The Toyota Fishhook (without pulse braking) maneuver is described in Toyota Engineering Standard TS-A1544. This test procedure is designed to produce two-wheel lift by imparting to the vehicle a rapid steering reversal that causes the vehicle to be at or near maximum lateral acceleration in one direction and then rapidly taken to maximum or near maximum lateral acceleration in the other direction. This rapid change in lateral acceleration direction also imparts a large angular momentum change to the chassis due to the vehicle leaning at a relatively large angle to one side and then being forced to lean in the opposite direction. The combination of the change in direction for lateral acceleration and the large roll angular momentum can produce two-wheel lift. All three Phase I-A test vehicles had two-wheel lift when subjected to the Toyota Fishhook maneuver. Tire wear may have contributed to some of the two-wheel lifts observed. This maneuver has the potential for evaluating the on-road, untripped rollover propensity of vehicles and will be further studied and developed.

For the Double Lane Change maneuver, the test driver steers the vehicle through an entrance lane, turns left to avoid the single cone in the second lane, turns right to return to the original lane, and then straightens the vehicle to leave the course via an exit lane. A large number of cone placements are possible for a Double Lane Change maneuver. Note that picking a single Double Lane Change course for all vehicles may not be advisable since any given course geometry may excite the natural frequency of some, but not all, vehicles. This type of test can produce dramatically different results depending on the test driver's "steering style" for negotiating the course. Two Phase I-A test vehicles had two-wheel lift with this maneuver. Again, tire wear may have contributed to some of the two-wheel lifts observed. Given the complexities associated with the Double Lane Change maneuver relative to the Toyota Fishhook and since the Toyota Fishhook produced two-wheel lift in a greater number of test vehicles, the authors recommend that the Double Lane Change Maneuver not be further developed at this time.

The Split-Mu Two Wheels Off-Road Recovery Simulation was developed to try to simulate a scenario that has been documented as frequently occurring in rollover crash data that has been collected by NHTSA. This maneuver simulates the return of a vehicle that has two wheels off the road to having all four wheels on the road surface. For this maneuver, the vehicle is driven onto a split-coefficient-of-friction (split-mu) surface, i.e., the tires on the right side of the vehicle are on the low coefficient-of-friction, wet-epoxy surface and the tires on the left side are on the higher coefficient-of-friction dry-asphalt surface. The driver then turns the vehicle to the left to bring all four tires on to the dry-asphalt surface. This is followed by a turn to the right to try to keep the vehicle within a two lane width boundary (24 feet). Very few tests produced two-wheel lift with this maneuver and the driver inputs were not controlled enough to produce repeatable results. This test also required two different test surfaces and since test surface friction can change with time, weather, amount of water (on low coefficient surface), etc., the amount of variability in results for this test would be expected to increase over a test run on a single surface. Given the complexities involved with conducting this test procedure, the authors decided that this maneuver should not be further developed at this time.

The Toyota Fishhook With Pulse Braking used the same course and steering input as a function of time as does the Toyota Fishhook (without pulse braking). The test procedure differs from the test procedure for the Toyota Fishhook (without pulse braking) in that after the driver has completed the second steering movement, the throttle was released and a short duration, hard pulse applied to the brake pedal. The effect of the brake pulse in this maneuver is very similar to that in the J-Turn with Pulse Braking maneuver. During the current testing, the Toyota Fishhook with Pulse Braking did not appear to give any greater indication of rollover propensity than did the combination of the Toyota Fishhook (without pulse braking) and the J-Turn with Pulse Braking maneuvers. Although there are many complexities with this maneuver, the authors recommend that it be further evaluated during Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. A focus of this research should be to see if this maneuver provides any more information than that from the Toyota Fishhook (without pulse braking) and the J-Turn with Pulse Braking Maneuver.

1.0 INTRODUCTION

1.1 The Rollover Crash Problem

Rollovers are the second most dangerous type of crash occurring on our nation's highways. During the eight years 1991 through 1998, Fatality Analysis Reporting System (FARS) data showed that an average of 9,237 people were fatally injured each year in light vehicle rollover crashes (all types of rollover crashes including multi-vehicle crashes and ones in which rollover was not the first harmful event). This is second only to the average for people who died due to frontal collisions. Using data collected by the National Automotive Sampling System General Estimates System (NASS-GES) for the years 1995-1999, an estimated annual average of 57,000 vehicle occupants received injuries either rated as K (killed) or A (incapacitating, actual severity depends on local practice) on the KABCO police injury scale in light vehicle rollovers. These large numbers of rollover crash fatalities and incapacitating injuries occurred even though the NASS-GES estimated average number of light vehicle rollover crashes, 241,000, was approximately only 2 percent of the average number of all NASS-GES crashes for these years. Due to this relatively low percentage of rollover crashes, when measured by either fatalities or incapacitating injuries per occupant involved, rollover crashes are the most dangerous type of collision for all classes of light vehicles.

Some types of light vehicles are involved in rollover crashes more frequently than others. The average annual number of rollover fatalities reported in the FARS for the years 1991 through 1998 by class of light vehicle is presented in Figure 1.1. As this figure shows, small cars have the most rollover crash fatalities of any class followed by small pickups and SUVs.

Some classes of light vehicles are more common than others in the vehicle fleet. To assess the relative risk of a rollover fatality by class of vehicle, the data shown in Figure 1.1 were divided by the number of registered vehicles of each class. The resulting average annual number of rollover fatalities per million registered vehicles for the years 1992 through 1996 by class of light vehicle is presented in Figure 1.2.

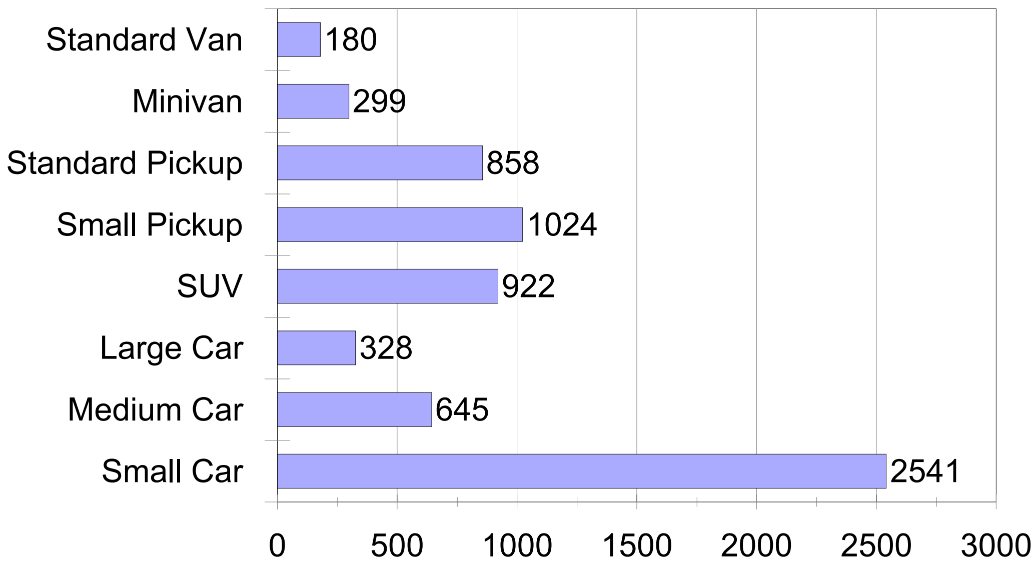

Figure 1.1 – Average Annual Rollover Fatalities by Vehicle Class, Based on 1991-98 FARS Data

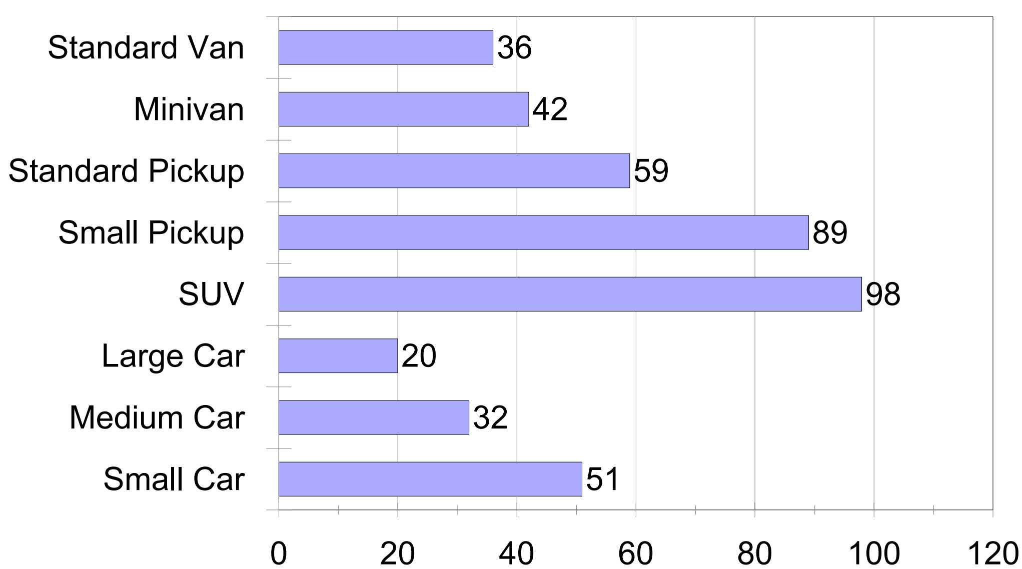

Figure 1.2 – Average Annual Rollover Fatalities per Million Registered Vehicles, Based on 1991-1998 FARS

As Figure 1.2 shows, Sport Utility Vehicles (SUVs) have the highest rollover fatality rate per million registered vehicles (more than three times as many as medium and almost five times as many as large cars). Small pickup and standard pickup trucks have the next highest rates respectively. Small and standard vans have very similar rates that fall between those for small cars and those for medium and large cars. The small car rate is two and a half times higher than that for large cars.

1.2 Types of Rollover Crashes

Rollover crashes can be subdivided into categories depending upon where the rollover occurs and the mechanism that initiated the rollover. The definitions of these categories are not universally agreed upon. The types of rollover crashes and category definitions used in this report are:

> **Off-Road Rollover** – This type of rollover occurs when a vehicle is not on a paved road surface. Due to the large variety of possible tripping mechanisms present in an unpaved (off-road) environment, most off-road rollovers occur due to tripping. Note that off-road rollover can occur while a vehicle is on an unpaved road. Also, it cannot occur while a vehicle is on a paved surface that is not part of the roadway but is designed to be driven on (i.e., rollovers that occur on a paved road shoulder are not off-road rollovers but ones that occur on a paved sidewalk are).
>
> **On-Road, Tripped Rollover** – This type of rollover occurs when a vehicle is on a paved surface that is meant to be driven upon and rolls over due to impact with a tripping mechanism (such as a raised manhole cover or a significant pavement discontinuity). A hard part of the vehicle, such as a wheel rim, digging into the pavement and thereby inducing rollover, would also be considered to be an on-road, tripped rollover.
>
> **On-Road, Untripped Rollover** – This type of rollover occurs when a vehicle is on a paved surface that is meant to be driven upon and rolls over without impacting a tripping mechanism. This type of rollover may result from either intentional, driver controlled, severe vehicle maneuvering or from unintentional, out-of-control, vehicle motions.

Since the above definitions are not universally agreed upon, the percentage of all rollover crashes falling into each of the above categories will not be given in this report. However, perusal of the various rollover crash databases clearly shows that the off-road rollover category contains the vast majority of all light vehicle rollover crashes. The limited data available indicates that the on-road, untripped rollover category is responsible for approximately two-thirds of on-road light vehicle rollovers.

On-road, untripped rollovers due to vehicle maneuvering are responsible for only a small portion of the rollover safety problem. However, there are enough fatalities due to rollover crashes that even a small portion of the problem equates to a substantial number of fatalities per year.

1.3 Focus of This Study

The focus of this study is on-road, untripped rollovers by one class of light vehicles, sport utility vehicles.

Light vehicles are defined as vehicles that have a gross vehicle weight rating (GVWR) of 10,000 pounds or less, excluding motorcycles. While heavy vehicles are recognized as having a significant rollover problem, the causes of heavy vehicle rollover can be very different from those of light vehicles due to articulated vehicles (tractor/trailer combinations), major weight shift due to improper loading, etc.; therefore, heavy vehicles were not included in this study. Similarly, motorcycles are fundamentally different than light vehicles with four wheels and therefore were not included. To focus this study's effort, a decision was made to only test one class of light vehicles. Due to their high rollover rate per registered vehicle, sport utility vehicles were selected for testing.

As discussed above, the vast majority of rollovers result from the vehicle leaving the roadway and tripping. While unfortunate (and all too often tragic), the causes of off-road, tripped rollover are well understood. Any light vehicle will roll over if it impacts a suitable tripping mechanism with sufficient lateral velocity. However, vehicle design parameters such as center of gravity height, track width, roll moment of inertia, etc., will play a major roll in determining the lateral velocity required to trip a particular vehicle. Lower center of gravity heights and larger track widths will typically increase the speed required to produce a rollover.

In comparison with tripped, off-road rollover, the causes of untripped, on-road, rollover are not well understood. Past testing that has been performed by NHTSA has never found a light vehicle for which, when empty, the most severe attainable steady state turn (with the steering handwheel turned slowly to initiate the turn) exceeds the vehicle's rollover threshold. (This is not the case for heavy vehicles, many of which will rollover if they try to perform too severe a steady state turn.) While placing a load in a vehicle generally raises a vehicle's center of gravity height, moves the center of gravity location towards the rear of the vehicle, and allows a vehicle's rollover threshold to be exceeded during a steady-state turn, most rollovers occur for vehicles that contain only one occupant and no significant cargo. Therefore, this report will not further consider the effects of vehicle loading.

As explained in more detail later in this report, the goal of this research was to develop test maneuvers and procedures that could be used to determine the untripped, on-road, rollover propensity of light vehicles. Therefore, the focus of this study is on testing related issues, principally the determination of test maneuvers that are severe enough to induce on-road, untripped rollovers while maximizing test repeatability.

1.4 Overview of This Report

This chapter has presented statistics about the magnitude of the rollover crash problem, defined different categories of rollover crashes, and stated the focus of the report. Chapter 2.0 continues with a brief summary of past NHTSA rollover research. Chapter 3.0 concludes the introductory portion of this report by presenting the objectives of the current, Phase I-A, study.

The middle portion of the report describes the testing that was performed for this study. This portion begins with Chapter 4.0 which lists the vehicles selected for testing, discusses the reasons for selecting these vehicles, and presents selected vehicle parameters. Chapter 5.0 then describes the instrumentation and data acquisition system used during this testing. The chapter lists the sensors used and shows their mounting locations, describes the data acquisition system that was used, and discusses the technique that was developed to accurately calculate roll angles from measured sensor data. Chapter 6.0 concludes the testing portion of the report by presenting the test procedure used for each of the eight maneuvers that were examined during this study.

The next portion of the report contains the results of this study. This portion of the report contains Chapters 7.0 through 14.0 which present maneuver-by-maneuver results and analysis for each of the eight maneuvers. The focus of this chapter is to show which of the eight maneuvers has the best discriminatory capabilities and repeatability. Finally, Chapter 15.0 concludes this portion of the report by briefly summarizing the work performed and results found, presenting the conclusions that can be drawn from this research, and making recommendations for future on-road, untripped rollover research.

The report concludes with a list of references and an appendix that contains additional data tables for the Double Lane Change maneuver.

2.0 BACKGROUND

There currently are no Federal Motor Vehicle Safety Standards (FMVSS) that are intended to reduce the number of rollover crashes. (There is a requirement that short wheelbase sport utility vehicles have a rollover warning label.) This is not for lack of trying. The NHTSA has, over the last 30 years, performed multiple major research efforts aimed at the development of such an FMVSS.

The first major research effort was initiated in 1971. The following excerpt from [1] summarizes the work performed and results obtained by this research effort:

> "In the period 1971 - 1974 NHTSA, through contracts with the University of Michigan, Texas Transportation Institute and Calspan, made a concerted effort to develop a consistent dynamic test procedure for vehicle rollover. The "VHTP" procedures: braking in a turn, trapezoidal steer, sinusoidal steer, and "drastic steer and brake maneuver", all using automatic vehicle controllers to remove the human element, were developed. The conclusion of this effort was that rollover testing is essentially a "can of worms" for two reasons: tire variability, and roll/yaw synergism. For bias-ply tires, max sideforce was found to increase as much as 40 percent with successive J-turn runs due to shoulder wear, and noticeable increases could occur even during a single run. Radial tires exhibited a similar characteristic, but to a significantly lesser degree, especially tires with rounded shoulders. The second problem, of roll/yaw synergism, made the timing of steer reversals the dominant factor in rollover. Test demonstrations performed by several organizations in the period 1974 - 1982 showed that a human driver, after a few practice runs to get a "feel" for the car, could tip up passenger cars that would not roll under the automatic controller's program, and that a controller program that would roll a vehicle at one loading configuration would not roll it with a different load."

Based upon this early-1970s research, the NHTSA issued an Advance Notice of Proposed Rulemaking (ANPRM). The following excerpt from [2] summarizes the purpose of and findings from this ANPRM:

> "In 1973 the Agency issued an ANPRM on Rollover Resistance, Docket 73-10; Notice 1. This ANPRM was primarily directed toward obtaining comments on the development of a test procedure, test conditions, and performance requirements to evaluate "rollover tendencies on smooth, dry pavement." After reviewing the comments to that notice and after conducting several research studies related to vehicle control and stability, the Agency decided to discontinue activity in this area. One study titled "Development of Vehicle Rollover Maneuver," concluded that although a vehicle's rollover resistance is dependent on its stability factor "to the first order," that resistance to rollover "can, however, be degraded by other design and operational features under real-life performance conditions." At that time, the Agency decided that until the influence of those other factors on real world accidents was better understood, Agency action could not be justified."

Another major NHTSA rollover research effort was initiated in September 1986 when a petition was received from Congressman Wirth (the Wirth petition) requesting NHTSA to issue a FMVSS to "limit the rollover propensity of passenger automobiles, utility vehicles, and pickup trucks." The following excerpt from [2] summarizes the actions that this petition requested NHTSA to take:

1. Propose an FMVSS to require that the rollover propensity of light duty vehicles including passenger cars, light trucks, and multipurpose vehicles, be limited by requiring that they have a minimum [static] stability factor, defined as the vehicle's half-track width divided by the vehicle's center of gravity height, of a specified value. The petitioner recommended that the Agency consider a value of 1.2 for that minimum [static] stability factor.

2. Conduct defect investigations of existing light duty vehicles whose [static] stability factors do not meet the minimum required by the proposed FMVSS.

3. Obtain and publish [static] stability factor information for vehicles being manufactured for sale in the U.S. and make it available to the public.

4. Immediately warn the owners of those vehicles with the greatest propensity to rollover of the limits of these vehicles and give them information as to steps that they can take to prevent death and injury."

To respond to this petition, the NHTSA initiated a research program to examine the relationship between a vehicle's rollover propensity and its static stability factor. In the denial notice NHTSA stated [2]:

> "Based on its analysis, the agency has determined that while a vehicle's stability factor can reasonably predict whether a vehicle which is already involved in a single vehicle accident will rollover, it does not accurately determine its likelihood of becoming involved in an accident that includes rollover"

The agency believed that it was necessary to identify vehicle metrics that could predict a vehicle's likelihood of involvement in a single vehicle accident as well as metrics to predict its rollover risk in that circumstance before it could approach a problem it described as multifaceted. The denial also noted concern that the [proposed] rule could result in the outlawing of all or most of an entire vehicle type. The Agency indicated it would pursue additional research in the area of rollover prevention and consider rulemaking at the completion of the research.

Based on the Wirth petition denial, and the subsequent granting by the NHTSA in September 1988 of a petition from the Consumer's Union of the United States to establish a minimum stability standard to protect against "unreasonable risk of rollover," the NHTSA embarked upon a major rollover propensity research program. In this program, which lasted from 1987 to 1991, the NHTSA determined the relationship between a vehicle's rollover propensity and its measured and/or calculated metrics. The principal metrics studied were static stability factor, tilt table ratio, side pull ratio, rollover prevention metric, and critical sliding velocity. The first three are considered static rollover stability metrics while the last two are dynamic metrics. The static metrics are estimates of the lateral acceleration at incipient rollover, while the dynamic are based on the concept of estimating the amount of energy that is needed to cause a vehicle to roll over as a result of being tripped while skidding sideways.

The static and dynamic vehicle rollover metrics were determined for a wide range of vehicles including passenger cars, pick-up trucks, vans, and sport utility vehicles. Regression curves were developed to relate vehicle rollover propensities with each of the static and dynamic vehicle rollover metrics. The best fit regression curve correlation coefficient values ranged from approximately 0.55 to 0.65 when predicting based upon the vehicle rollover metrics alone, and were as high as 0.80 when other factors such as vehicle operating conditions, demographic factors, and single-vehicle rate were included. A complete summary of the findings of this research is contained in [3].

The NHTSA decided not to proceed with rollover propensity rulemaking based upon either static or dynamic vehicle rollover metrics. This decision was made because even though relatively good correlations between predicted and actual rollover rates existed, none of the metrics provided a sudden transition between good and bad performing vehicles in terms of rollover. As a result, requiring reasonably achievable improvements to any of the static or dynamic vehicle rollover metrics resulted in only a small reduction in rollover crash fatalities. A complete summary of the benefits that the NHTSA expected to obtain from requiring, via an FMVSS, that vehicles exceed specified minimum levels of these rollover metrics is contained in [4].

In July 1996, the NHTSA decided to initiate another rollover propensity research program. For the reasons discussed in Section 1.3, the focus of this research program is to be on-road, untripped rollover.

Prior to the initiation of the new rollover propensity research program, the NHTSA received two petitions from Consumer's Union of the United States. One petition, which was granted, requested that NHTSA establish a consumer information program on rollover resistance. The second petition, which was denied, requested that NHTSA open a defect investigation as to whether 1995 and 1996 model year Isuzu Trooper and Acura SLX had an unreasonably high rollover propensity. The testing performed by the NHTSA to formulate a response to the second Consumer's Union petition is documented in [5] and [6]. The principal findings of this research that are relevant to the current study were:

1. There exist maneuvers that induce large (i.e., both wheels off of the ground by substantial amounts) two-wheel lifts for at least some modern sport utility vehicles. This finding is consistent with results from the 1971 - 1974 rollover research program and indicates that the results of the 1971 - 1974 program apply to modern vehicles.

2. A vehicle's rollover (two-wheel lift) behavior in a complex maneuver (such as a double lane change) depends strongly upon the precise steering inputs provided by the driver. At a given speed, a driver can use different sets of steering inputs to follow the same course. These different sets of steering inputs can result in a vehicle having a completely different rollover behavior. For example, one set of steering inputs may allow the driver to proceed completely through a course without any two-wheel lift while a second set of steering inputs, at the same speed, may result in large two-wheel lift and rollover. Again, this finding is consistent with results from the 1971 - 1974 rollover research program.

Starting in 1997, NHTSA began another light vehicle rollover research program designed to develop either an FMVSS or a consumer information program to reduce rollover crashes. When originally planned, NHTSA's 1997 - 1998 Light Vehicle Rollover Research program was to consist of the Phase I research (to be performed during the spring through fall of 1997) which was to develop a set of untripped, on-road, rollover test maneuvers, and the Phase II research (to be performed during the summer of 1998) which was to further develop the Phase I maneuver set by using them on a broad range of vehicles. However, preliminary analysis of the Phase I results revealed a number of issues that had to be resolved before the Phase II testing could begin. Therefore, the spring through fall of 1997 testing was renamed the Phase I-A research and additional testing, called the Phase I-B research, was performed during the winter and spring of 1998.

This report covers the work performed for Phase I-A of NHTSA's 1997 - 1998 Light Vehicle Rollover Research program. This testing was performed from May through November of 1997. Although report writing continued until July 2000, the bulk of the analyses of this data was performed from November 1997 through March 1998.

3.0 STUDY OBJECTIVES

A goal of NHTSA is to reduce the number of fatalities and injuries that are due to rollover crashes. To achieve this goal, the NHTSA is conducting research programs both to reduce the number of rollover crashes that occur and to mitigate the adverse consequences when rollover crashes do occur. The current study is part of the NHTSA's research to reduce the number of rollover crashes.

To reduce the number of rollover crashes, the NHTSA is working to develop either an information program which will make consumer's more aware of vehicle make/models with a high rollover propensity or a Federal Motor Vehicle Safety Standard (FMVSS) which would prevent the sale of new vehicles that have too high a rollover propensity or both. One key step towards developing either a rollover propensity consumer information program or a rollover propensity FMVSS is the development of a methodology for determining a vehicle's rollover propensity. This study focuses on the development of such a methodology.

There are two reasonable ways to proceed with the development of a methodology for determining a vehicle's rollover propensity. One way will be referred to as the Actual Rollover Occurrence approach, the other will be called the Rollover Propensity Metrics approach.

For the Actual Rollover Occurrence approach, a vehicle being tested is driven through a prescribed test procedure that may result in on-road, untripped rollover. This test procedure consists of a series of selected maneuvers. The maneuvers would be selected to: (1) require steering, braking and throttle inputs that are within the envelope of actual driver capabilities, (2) could potentially occur during "real world" driving, and (3) attempt to induce on-road, untripped rollover. Maneuvers may be performed at different severity levels, speeds, etc. A vehicle's rollover propensity for either consumer information or an FMVSS could be determined if any maneuvers actually resulted in vehicle rollover (or would have resulted in rollover if not prevented by outriggers).

To proceed with the Actual Rollover Occurrence approach, the NHTSA needed to develop one or more candidate dynamic test procedures to identify vehicles with a relatively high on-road, untripped rollover propensity. These dynamic test procedures should be composed of maneuvers that: (1) result in on-road untripped rollover for some, but not all, vehicles, (2) might be performed by actual drivers while driving (particularly in emergencies), and (3) can be performed objectively with, for the same vehicle, repeatable results. Once such test procedures had been developed, the next step would be to test them using many classes of vehicles (the Phase II testing).

For the Rollover Propensity Metrics approach, a vehicle is tested according to a prescribed procedure. The prescribed procedure may include dynamic driving tests, laboratory tests (such as measurement of Tilt Table Angle) or both. From analyses of data collected while performing this test procedure, metrics are calculated that are expected to quantify a vehicle's rollover propensity. A vehicle's rollover propensity for either consumer information or an FMVSS would be based upon one or more of these metrics.

A required step for the Rollover Propensity metrics approach is to demonstrate that the metrics chosen do, in fact, quantify the rollover propensity of many vehicle make/models. Metrics are typically initially developed based on the physics of vehicle rollover. A correlation between the metric values and real world rollover propensity then has to be shown. This is usually done by measuring metric values for a significant fraction of the vehicle fleet and then correlating these values with "real-world" rollover crash statistics.

To proceed with the Rollover Propensity Metrics approach, the NHTSA needed to develop one or more candidate dynamic rollover propensity metrics and test procedures to measure them. These metric measurement test procedures do not need to be composed of maneuvers that are performable by drivers while driving. However, methods must be developed to perform these metric measurement test procedures objectively with, for the same vehicle, repeatable results. Once such metric measurement test procedures have been developed, the next step would be to use them to measure rollover propensity metrics for many make/models of vehicles (again, the Phase II testing).

At the initiation of this research, NHTSA had not yet decided whether to use the Actual Rollover Occurrence approach or the Rollover Propensity Metrics approach. Therefore, work was performed in parallel upon both approaches.

The current research, Phase I-A of NHTSA's 1997 - 1998 Light Vehicle Rollover Research Program, was an initial, exploratory study of using test track maneuvers to quantify on-road, untripped rollover propensity. This study examined a broad range of maneuvers that might induce on-road, untripped rollover. Each maneuver studied was either discarded or retained for further study in subsequent program phases. Maneuvers were evaluated based upon:

1. Their objectivity and repeatability, i.e., whether they could be performed objectively with, for the same vehicle, repeatable results.

2. Their discriminatory capability, i.e., whether they resulted in on-road untripped rollover for some, but not all, vehicles.

3. Their face validity, i.e., whether they might be performed by actual drivers while driving (particularly in emergencies).

4. Their metric measurement capability, i.e., whether one or more metrics that are expected to quantify a vehicle's rollover propensity can be calculated from data collected during the maneuver.

Maneuver objectivity and repeatability were of great concern throughout this research. Unfortunately, a programmable steering/braking/throttle controller was not available for use in the Phase I-A work. The authors recognize that having to rely on test driver generated control inputs may have adversely affected maneuver objectivity and repeatability. A programmable steering controller became available for subsequent phases of this research (beginning with some portions of the Phase I-B research).

4.0 TEST VEHICLES

4.1 Vehicles Selected

Three vehicles were selected for the Phase I-A testing. The vehicles selected were a 1984 Ford Bronco II, a 1997 Jeep Cherokee, and a 1990 Toyota 4Runner. Table 4.1 lists selected descriptive parameters for each test vehicle.

The 1990 Toyota 4Runner has two sizes of original equipment tires, the size listed in Table 4.1 and P225/75R15. The larger of the two sizes, which is the size listed in the table, was used for the Phase I-A research.

Table 4.1 -- Descriptive Parameters for each Test Vehicle

Vehicle	Significant Options	Tires	Wheelbase (inches)	Track Width (inches)	Curb Weight (pounds)
1984 Ford Bronco II	Rear Mounted Spare Tire	P205/75R15	94.4	56.8	3366
1997 Jeep Cherokee	None	P225/75R15	101.5	57.8	3502
1990 Toyota 4Runner	Sunroof, Rear Mounted Spare Tire	31x10.50R15LT	103.2	57.9	4245

The test vehicles used for the Phase I-A research were selected following consultation between personnel belonging to the NHTSA's Offices of Safety Assurance, Safety Performance Standards, and Research and Development. The selection criteria used were:

1. That only sport utility vehicles were to be tested. While rollovers occur for all classes of vehicles, sport utility vehicles are one of the classes that is most susceptible to on-road, untripped rollovers.

2. To minimize program costs. This could be achieved by either testing already NHTSA owned and available sport utility vehicles or by purchasing used sport utility vehicles.

3. Not to use vehicle make/models that were then being studied by the NHTSA's Office of Defects Investigation.

4. To test popular (high sales volume) vehicles.

5. To test vehicles from both U.S. and foreign manufacturers. No more than one vehicle make/model was to be selected from any one manufacturer.

Both the 1984 Ford Bronco II and the 1997 Jeep Cherokee were selected because they were already NHTSA owned, available for use by this program, and met all of the other selection criteria. The other, already NHTSA owned, available sport utility vehicle at the beginning of this research, a 1996 Acura SLX (essentially the same as a 1996 Isuzu Trooper) was not selected since this vehicle was, at that time, being studied by the NHTSA's Office of Defects Investigation and because of its low sales volume. Since the first two vehicles selected, the 1984 Ford Bronco II and the 1997 Jeep Cherokee, were both made by U.S. manufacturers, a decision was made that the third vehicle selected would be an import. Based on popularity, the Toyota 4Runner was selected. A 1990 Toyota 4Runner was purchased based on the vehicle's availability and to minimize costs.

The test vehicles used for this research were not in new condition.

Both the 1984 Ford Bronco II and the 1990 Toyota 4Runner had been driven many thousands of miles prior to their participation in this testing. Almost all the Bronco II suspension components were replaced with Ford replacement parts. Replacement torsion bars could not be found so the original equipment was left on the vehicle. The shocks were built by an aftermarket supplier, but were believed to be to Ford specifications. The only suspension components replaced on the 4Runner were the shocks. The other parts were deemed to be in acceptable condition. Despite these component replacements, there is no way to insure that these vehicles performed as they did when new.

The 1997 Jeep Cherokee is a fairly new vehicle with, at the start of this research, relatively low mileage (approximately 1,000 miles). However, this vehicle was originally purchased by the NHTSA so that its dynamics could be modeled for the National Advanced Driving Simulator. As part of the National Advanced Driving Simulator dynamics modeling process, the Jeep Cherokee's suspension was disassembled so that the geometries, masses, and moments of inertia of various suspension components could be measured. This work was performed by S.E.A., Inc. While the Jeep Cherokee's suspension was reassembled by the S.E.A., Inc. staff and inspected by a Jeep dealership mechanic, there is no way to insure that this vehicle performed as it did when new.

Additionally, all three test vehicles were equipped with outriggers during the Phase I-A testing. The effects of outriggers on a vehicle's performance and on-road, untripped rollover propensity are not fully known.

In summary, none of the test vehicles necessarily performed as would have new vehicles without outriggers. However, this was not important for the Phase I-A research. The goal of the Phase I-A research was maneuver selection and test procedure development, not vehicle characterization.

4.2 Static and Dynamic Rollover Metric Values for the Test Vehicles

Each of the three test vehicles was tested by S.E.A., Inc. on their Vehicle Inertial Measurement Facility (VIMF) and on their Tilt Table. The 1984 Ford Bronco II was tested on the VIMF both with and without outriggers, the other two vehicles were tested on the VIMF only without outriggers. All three vehicles were tested on the S.E.A. Tilt Table both with and without outriggers.

All tests on the VIMF and the S.E.A. Tilt Table were conducted with one sandbag occupant in the drivers seat, no other load in the vehicle, and a full fuel tank. The sandbag occupant was designed by S.E.A., Inc. The center of gravity location and inertial properties of the sandbag occupant are similar to those of a fiftieth percentile male.

Based on the results of this testing, two static rollover propensity metrics, Static Stability Factor and Tilt Table Ratio, and one dynamic rollover propensity metric, Critical Sliding Velocity, were calculated for each test vehicle. The precise definitions of each of these static and dynamic rollover propensity metrics are contained in [3]. The values of each of these static and dynamic rollover propensity metrics, both with and without outriggers, are shown in Table 4.2.

Table 4.2 -- Static and Dynamic Rollover Propensity Metric Values for the Test Vehicles

	Static Stability Factor		Tilt Table Ratio		Critical Sliding Velocity (km/hr)	
Vehicle	Without Outriggers	With Outriggers	Without Outriggers	With Outriggers	Without Outriggers	With Outriggers
Bronco II	1.04	1.06	0.91	0.92	15.1	15.6
Cherokee	1.08	NA	1.01	1.03	15.7	NA
4Runner	0.99	NA	0.91	0.92	14.4	NA

The NHTSA has collected either Static Stability Factor or Tilt Table Ratio (or both) data on over 20 sport utility vehicles under similar loading conditions (one occupant and full fuel tank). The Static Stability Factor of these vehicles ranged from 1.04 to 1.16 while their Tilt Table Ratio's ranged from 0.88 to 1.06.

The 1990 Toyota 4Runner has a lower Static Stability Factor than any of the other sport utility vehicles for which NHTSA has data. Based on conversations with Toyota personnel, this vehicle is thought to have a very high center of gravity partially because the larger sized tires for this vehicle were used during this research and partially because it has both a sunroof and a rear mounted spare tire. Toyota personnel have stated that they believe that these two options raise this vehicle's center of gravity height by approximately 30 millimeters (1.2 inches). Reducing the Toyota 4Runner's center of gravity height by 1.2 inches would increase its Static Stability factor to 1.04.

As Table 4.2 shows, adding the outriggers increased all of the Ford Bronco II's static and dynamic rollover propensity metrics. The increase was quite small for both Static Stability Factor and Tilt Table Ratio. This indicates that one of the design goals for the outriggers, not changing a vehicle's center of gravity height, was almost achieved. The larger increase due to outriggers in Critical Sliding Velocity is primarily due to the effects of the outriggers on a vehicle's roll moment of inertia. Even though the designer tried to minimize the mass of the outriggers, the outriggers inevitably add mass well away from the vehicle's longitudinal centerline. As a result, outriggers always substantially increase a vehicle's roll moment of inertia.

The increase in all the Ford Bronco II's static and dynamic rollover propensity metrics due to outriggers indicates that the vehicle configuration used for testing during the Phase I-A research probably offers greater resistance to tripped rollover than does the nominal vehicle. However, as was previously stated, the effects of outriggers on a vehicle's on-road, untripped rollover propensity are not fully known.

5.0 VEHICLE INSTRUMENTATION

Each test vehicle was instrumented for the on-road, untripped rollover testing with sensors, a data acquisition system, and auxiliary equipment (such as a steering stop). All three vehicles were identically instrumented.

5.1 Sensors and Sensor Locations

Table 5.1 contains a list of the sensors used to measure vehicle responses that were recorded by the in-vehicle data acquisition system. Note that there was an additional speed measurement sensor that was not recorded; this sensor is discussed as part of auxiliary equipment in Section 5.2.

The three accelerometers were mounted perpendicularly to each other on a block positioned at each vehicle's center of gravity (with one occupant) to minimize yaw, pitch, and roll effects. These accelerometers were not inertially stabilized; lateral acceleration corrected for the effects of vehicle roll was calculated during data analysis. The roll/yaw rate sensor was located directly behind the accelerometer block.

An ultrasonic vertical displacement sensor was mounted on the left and right side of each vehicle. In an attempt to reduce sensor noise, approximately one-half of the Ford Bronco II testing (Runs 1 through 92) had the ultrasonic transducers located at the left and right front corners of the vehicle. For other testing (all runs with the Toyota 4Runner and Jeep Cherokee plus Runs 93 through 140 with the Bronco II), these sensors were mounted to the left and right side of each vehicle at the longitudinal position of the vehicle center of gravity. This position was preferred because it did not include the effect of torsional deflection of the vehicle body in the calculated roll angle; however, in some instances it did result in increased sensor noise.

The handwheel steer angle transducer was attached to the steering column shaft using a toothed belt in conjunction with a specially fabricated steering wheel. The handwheel steer torque transducer was fitted between the specially fabricated steering wheel and the steering column.

Brake pedal force was measured with a load cell transducer attached to the vehicle brake pedal.

Table 5.1 -- Vehicle Sensor Information

Vehicle Channel	Sensor Type	Sensor Range	Sensor Manufacturer	Sensor Model Number
Lateral Acceleration	Accelerometer	" 2g	Setra	141A
Longitudinal Acceleration	Accelerometer	" 2g	Setra	141A
Vertical Acceleration	Accelerometer	" 2g	Setra	141A
Roll Rate	Gas Beam Rate Sensor	" 50 deg/sec	Humphrey	RT10-0127-1
Yaw Rate	Gas Beam Rate Sensor	" 50 deg/sec	Humphrey	RT10-0127-1
Left Vertical Displacement	Ultrasonic Position	4 - 22 inches	Massa	M4000
Right Vertical Displacement	Ultrasonic Position	4 - 22 inches	Massa	M4000
Handwheel Steer Angle	10 Turn Potentiometer With 2:1 Gear Ratio	Lock-to-lock	Servo Systems	7603-424-0
Handwheel Steer Torque	Hollow Reaction, Strain Gauge	" 600 in-lb	Himmelstein	RTM2030
Brake Pedal Force	Strain Gauge Load Cell	0 - 300 lbs	GSE	3100A
Event Trigger	Optical Position Detector	Not Applicable	SunX	RS-120H-1
Vehicle Speed	Tachometer Generator	0 - 60 mph	Servo-Tek	SN7466F-1

Data acquisition was started by an event trigger which consisted of a SunX RS-120H-1 optical sensor mounted on each vehicle's front bumper. The SunX transducer detected when it passed over a reflective plate. This reflective plate was placed at a pre-selected location at the beginning of each test maneuver's course.

Vehicle speed was measured using a Servo-Tek, seven volts per thousand rpm, Model SN7466F-1 tachometer generator mounted on a Tracktest Model 600004-1 fifth wheel. Also mounted on the fifth wheel was a Labeco Model 615001-1 fifth wheel transmitter that output vehicle speed to a

Labeco performance monitor which was placed on top of the vehicle dashboard to provide driver feedback.

5.2 Data Acquisition and Auxiliary Equipment

During each test run, data was collected by a Cascade, semi-ruggedized, portable computer with a 100 MHz Pentium microprocessor running the DACS data acquisition software developed at the NHTSA's Vehicle Research and Test Center (VRTC). Signals from all of the transducers listed in Table 5.1 were conditioned using Analog Devices 3B signal conditioners and then digitized at a rate of 100 samples per second per channel using an RTI-815, 12 bit, analog-to-digital converter board.

Data acquisition was started by an event trigger, the SunX RS-120H-1 optical sensor. Once data acquisition had been initiated, 12.0 seconds of data were collected for each maneuver.

The signal conditioning performed by the Analog Devices 3B signal conditioners consisted of amplification and filtering. The amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Except for three channels, filtering was performed using a two-pole Butterworth filter with the nominal filter breakpoint frequencies (15 Hz) selected to prevent aliasing. The three exceptional channels were vertical acceleration, handwheel steer torque, and the event trigger. Due to an error in the setup of its Analog Devices 3B signal conditioner, vertical acceleration had much higher filter breakpoint frequencies (approximately 95 Hz). For the handwheel steer torque channel, the filter breakpoint frequencies were set to a much higher nominal value (105 Hz). Having higher breakpoint frequencies minimized phase lag for this channel at the cost of possible data aliasing. Similarly, analog filtering was not used on the event trigger channel so as to minimize phase lag. Table 5.2 lists the actual, measured breakpoint frequencies that were achieved for each filter pole for each channel.

Table 5.2 -- Filter Breakpoint Frequencies for Each Data Channel

Vehicle Channel	Actual Breakpoint Frequency of First Pole	Actual Breakpoint Frequency of Second Pole
Lateral Acceleration	15.0 Hz	19.1 Hz
Longitudinal Acceleration	15.0 Hz	19.1 Hz
Vertical Acceleration	89.4 Hz	102.0 Hz
Roll Rate	15.0 Hz	19.1 Hz
Yaw Rate	15.0 Hz	19.1 Hz
Left Vertical Displacement	15.0 Hz	19.1 Hz
Right Vertical Displacement	15.0 Hz	19.1 Hz
Handwheel Steer Angle	15.0 Hz	19.1 Hz
Handwheel Steer Torque	102.0 Hz	108.0 Hz
Brake Pedal Force	18.9 Hz	19.1 Hz
Event Trigger	None	None
Vehicle Speed	15.0 Hz	19.1 Hz

As was previously mentioned, a Labeco performance monitor was placed on top of each vehicle's dashboard. During the approach to a test course, this performance monitor continuously displayed vehicle speed for the driver. This helped the driver perform each maneuver at a speed very close to the maneuver's desired initial speed.

Also mounted in each test vehicle was a steering stop mechanism. The steering stop allowed the driver to rapidly turn the steering handwheel to a pre-selected angle and then hold it fixed at that angle. The steering stop used allowed the desired angle to be set in 10 degree increments up to "330 degrees. The steering stop could only be used to constrain the steering in one direction at a time. The stop was developed at the NHTSA's VRTC.

All test runs were videotaped by an off-vehicle hand-held video camera which was operated by the test observer. Post-test analysis of these videotapes was performed to determine whether two-wheel lift occurred during a test run.

5.3 Filtering of Ultrasonic Height Sensors – Outlier Rejection Filter

For the last several years, the NHTSA's VRTC has been using a technique originally suggested by General Motors Corporation engineers to determine vehicle roll angle. For this technique, two ultrasonic position transducers, one on each side of the vehicle, are used to measure the time-varying height of each transducer above the road surface. The difference between the heights of the two ultrasonic transducers above the road surface at each instant in time and the measured, fixed, lateral distance between the ultrasonic transducers is used to calculate the vehicle's roll angle as a function of time.

Unfortunately, ultrasonic transducers are sensitive to light conditions, road surface conditions, ambient wind, and mechanical vibrations. Therefore, the signals from the ultrasonic transducers are normally quite noisy.

At large vehicle roll angles, much of the signal emitted by the ultrasonic transducers is reflected away from the vehicle. Only a small portion of the signal is returned to the transducer's receiver head. As a result, the signal-to-noise ratio is substantially decreased. Therefore, many more false transducer-to-road distance values are generated at large roll angles than the already substantial number that are generated for small roll angles.

To reduce noise, after analog filtering (see Table 5.2) and digitization, the measured vertical heights above the road of the two ultrasonic transducers are again filtered using a digital outlier rejection filter. The outlier rejection filter routine performs data outlier rejection on the ultrasonic data to eliminate spurious spikes and data dropouts present with the ultrasonic devices used in this application. Data outliers that deviate from a running average of the data by more than a specified range are eliminated from the data channel, and replaced with the value of the running average. The running average is the average value of a specified number of points immediately prior to the point of interest. In this application, ten points were used in the running average. Data within the outlier range is unaffected by this outlier elimination routine. The outlier range specified was started at 0.5

inches; meaning that ultrasonic data values that vary by more than 0.5 inches from the running average of the ten previous values in one time frame (0.01 sec) are considered to be spurious and are eliminated.

The ultrasonic data sometimes contained a considerable amount of noise and dropouts. In some instances, it was necessary to increase the outlier range in order for the outlier filter to successfully filter the entire channel without losing track of the desired data and rejecting large sections of data. To mitigate potential problems with the outlier rejection filter, the filtering of all ultrasonic data channels was done interactively. If the outlier filtered data appeared reasonable it was accepted, and if not the outlier rejection filter was adjusted by increasing the outlier range by 0.25 inches and the data was then reprocessed. Multiple iterations were sometimes necessary.

Following the outlier filtering, the ultrasonic transducer data was filtered again, this time with a 6 Hertz, 12 pole, "phaseless," digital filter. A "phaseless" filter is one which minimizes phase lag due to filtering. "Phaseless" filtering cannot be performed real-time, only on previously collected data. It consists of first filtering the collected data with a two-pole Butterworth digital filter with an appropriate breakpoint frequency (approximately one- third higher than the desired breakpoint frequency at the completion of the entire "phaseless" filtering process for the 12 pole case) and with time running in the normal direction. The data is then filtered with the Butterworth digital filter with time running in the reversed direction. This completes one pass. The phase shift from the filtering during the pass with time running in the reverse direction approximately cancels the phase shift from the filtering with the time running in the forward direction; hence the name "phaseless." As many passes as necessary are performed to achieve the desired number of poles (three passes for the 12 pole case). Note that the number of poles for "phaseless" filtering must be a multiple of four.

Figures 5.1 and 5.2 contain plots of the raw and processed data for both ultrasonic channels from a Bronco II test. The top plots are the raw data, the middle plots show the data passed through the outlier rejection filter, and the bottom plots show the final processed data, having been passed through both the outlier rejection and 6 hertz digital filters. Figure 5.1 shows that the outlier rejection filter eliminated the spurious spikes in the data and had no affect on the data within the rejection range.

This process proved to be laborious, but the results are believed to be better than those obtained using the more straightforward median average filter that was used in the past at VRTC. Median average filters sometimes do not eliminate large spikes when frequent data dropouts are present.

5.4 Roll Angle Determination – Sensor Fusion

After outlier rejection and digital filtering of data from the ultrasonic position transducers has been performed, the difference between the two ultrasonic transducer's heights above the road surface can be combined with the transducer's known lateral locations to calculate the vehicle's roll angle. For low to moderate roll angles, roll angle determination from ultrasonic transducer data has worked well for past VRTC research [7]. However, the large ultrasonic distances/vehicle roll angles that had to be measured during the Phase I-A research resulted, some of the time, in noisy signals and, at some distances, ultrasonic sensor saturation. Figure 5.1 shows a range between 2.75 and 5.0 seconds where the ultrasonic transducer is saturated.

To provide continuous, smooth, and meaningful measurements of large vehicle roll angles, a technique that relies on using two different types of sensors is used. This technique involves computing roll angles from the ultrasonic height transducers for low to moderate roll angles, and on computing large roll angles from the integration of the measured roll rate.

Integrating roll rate to compute roll angle poses two difficulties, (1) determining a time when a vehicle's roll angle is zero to start integrating, and (2) the time-varying drift typically present in roll rate measurement transducers.

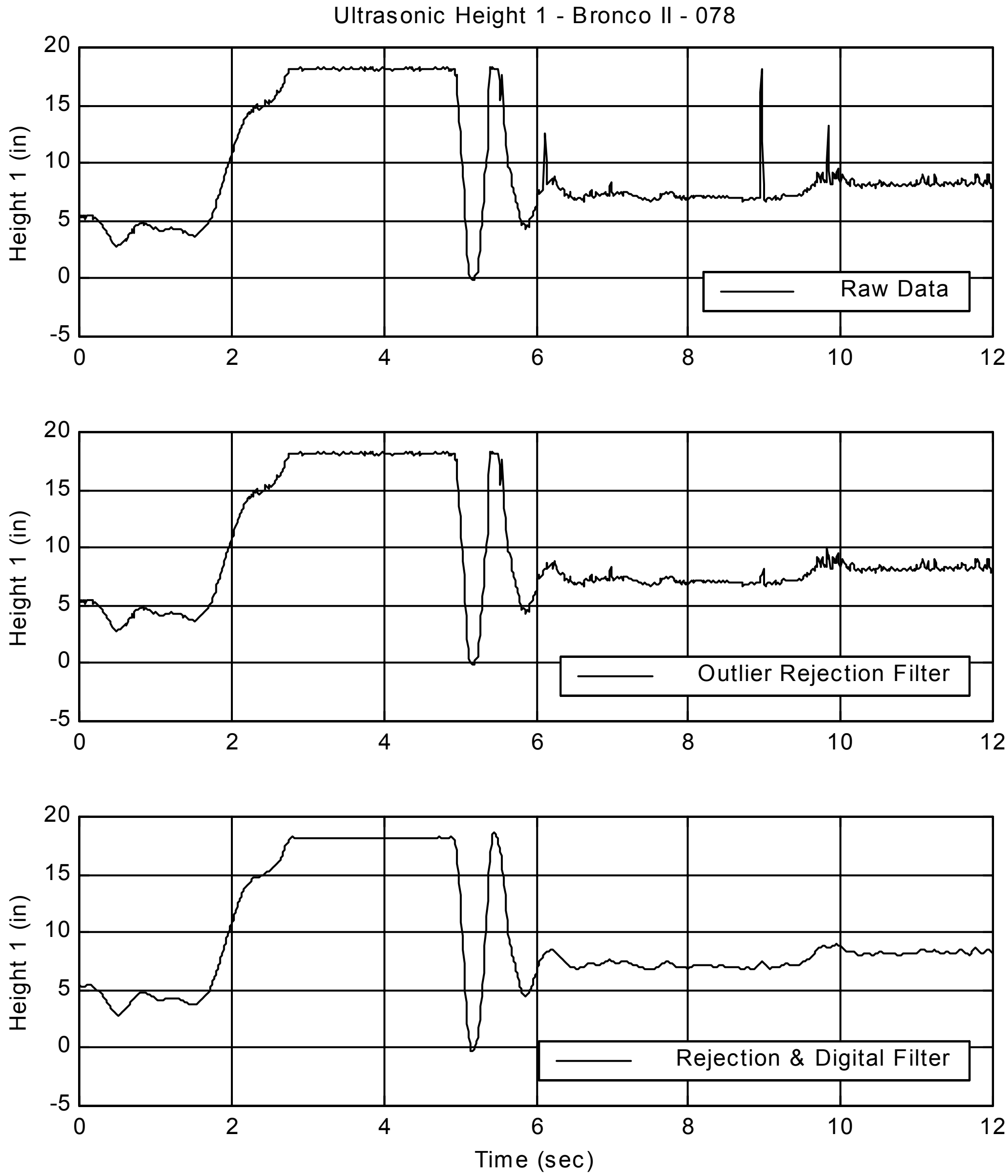

Figure 5.1 -- Ultrasonic Height 1 Data: Raw, Filtered using Outlier Rejection Filter, and Filtered using Outlier Rejection and 6 Hz Digital Filters

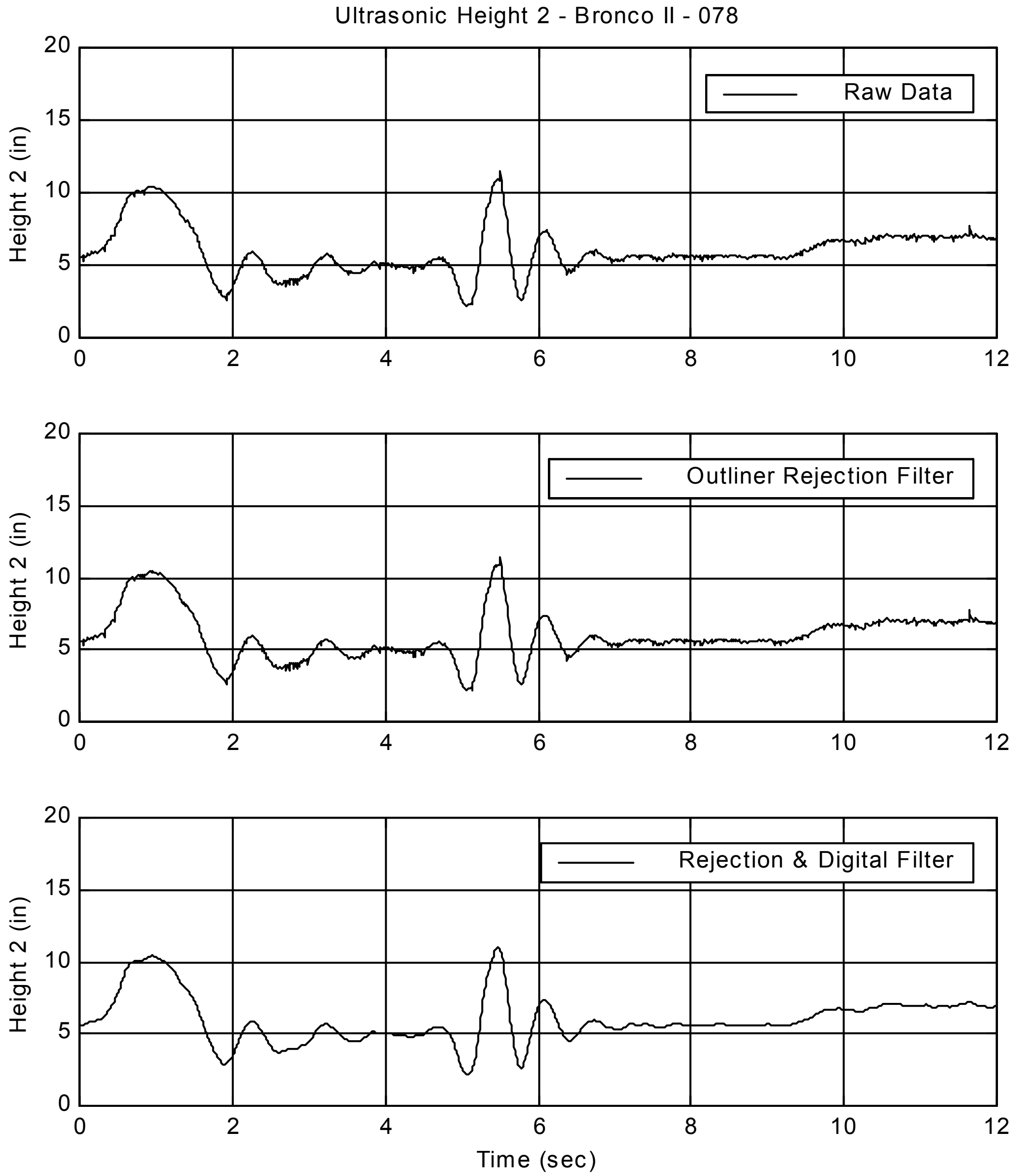

Figure 5.2 -- Ultrasonic Height 2 Data: Raw, Filtered using Outlier Rejection Filter, and Filtered using Outlier Rejection and 6 Hz Digital Filters

A combination of the above techniques, which will be referred to as the "Sensor Fusion" method, resolves all of the above listed vehicle roll angle determination problems, albeit with the disadvantages of requiring additional sensors to be present and additional processing during data reduction.

For the Sensor Fusion method, the roll angle is first calculated from the ultrasonic position transducers via the previously described techniques. This method is used for all roll angle computations as long as the ultrasonic transducer to ground height is within a specified range. For the Jeep Cherokee and most of the Bronco II tests, this range was 0.5 to 17.0 inches. Tests 1 through 38 for the Bronco II had the upper range limit reduced to 12.0 inches. For the Toyota 4Runner the range used was 0.5 to 9.0 inches. The ranges differ for the different vehicles based on the configuration of the sensor hardware. Outside of these ranges, the ultrasonic transducers are assumed to be potentially noisy or saturated, and data from them are not used; rather, the roll angle is computed using the integrated roll rate signal.

Since the measured roll rate is likely to have an offset due to the time-varying drift typically present in roll rate measurement transducers, a constant is added to (or subtracted from) the measured roll rate prior to integration. The value of this constant is determined by requiring that the value of the vehicle roll angle that is determined by integration matches the value determined from the ultrasonic position transducers at the time when the ultrasonic position signal first gets outside the range specified.

A method of compensation is used to assure that the roll angle varies continuously when going from the roll angle computed by integrating the roll rate back to the roll angle computed from the ultrasonic transducer data. The compensation method consists of determining the offset in the roll angle computed using the two different techniques at the transition point, and linearly distributing this offset over the time span when roll angle is being computed by integration of the roll rate. Thus, at the end of the period when roll angle is being computed by integration, the roll angle value matches the roll angle computed from the ultrasonic transducer data.

One curve in Figure 5.3 shows the vehicle roll angle, calculated via VRTC's traditional method using ultrasonic transducers, corresponding to the data shown in Figures 5.1 and 5.2. Also shown are the curves including sensor fusion and sensor fusion plus compensation. The sensor fusion method uses the integrated roll rate based roll angle when Ultrasonic 1 is beyond 17.0 inches (in the range between 2.75 and 5.0 seconds) or below 0.5 inches (near 5.25 seconds). As shown in Figure 5.3, compensating the fused signals provides a continuous signal which is believed to better represent the roll angle response of the actual vehicle.

5.5 Calculation of Corrected Lateral Acceleration

The lateral and longitudinal accelerometers used during this research were not "stabilized," i.e., when the vehicle rolled or pitched, the acceleration measured by the accelerometers was due both to the acceleration of the vehicle (the desired data) and to gravity. The contribution of gravity to the readings of the longitudinal accelerometers is, for vehicles performing the type of maneuver studied during this research (e.g., maneuvers with small pitch angles), negligible. However, the contribution of gravity due to vehicle roll may have a significant effect on the measured lateral acceleration.

Therefore, following computation of the vehicle roll angle using the techniques described above in Sections 5.3 and 5.4, the measured lateral acceleration was corrected at each instant in time, for the effect of gravity by means of the equation:

$$a_{yc} = a_{ym} \cos(\phi) + a_{zm} \sin(\phi) \qquad \textbf{(5.1)}$$

where:

- a_{yc} is the corrected lateral acceleration, i.e., the vehicle's lateral acceleration in a horizontal plane,
- a_{ym} is the measured lateral acceleration, i.e., in the vehicle fixed coordinate system, this is the acceleration in the vehicle's y direction,
- a_{zm} is the measured vertical acceleration (equal, except for hitting bumps or potholes and small angle effects, to the acceleration due to gravity), and
- ϕ is the vehicle's roll angle.

The corrected lateral acceleration is the lateral acceleration that is used for all of the analyses that follow.

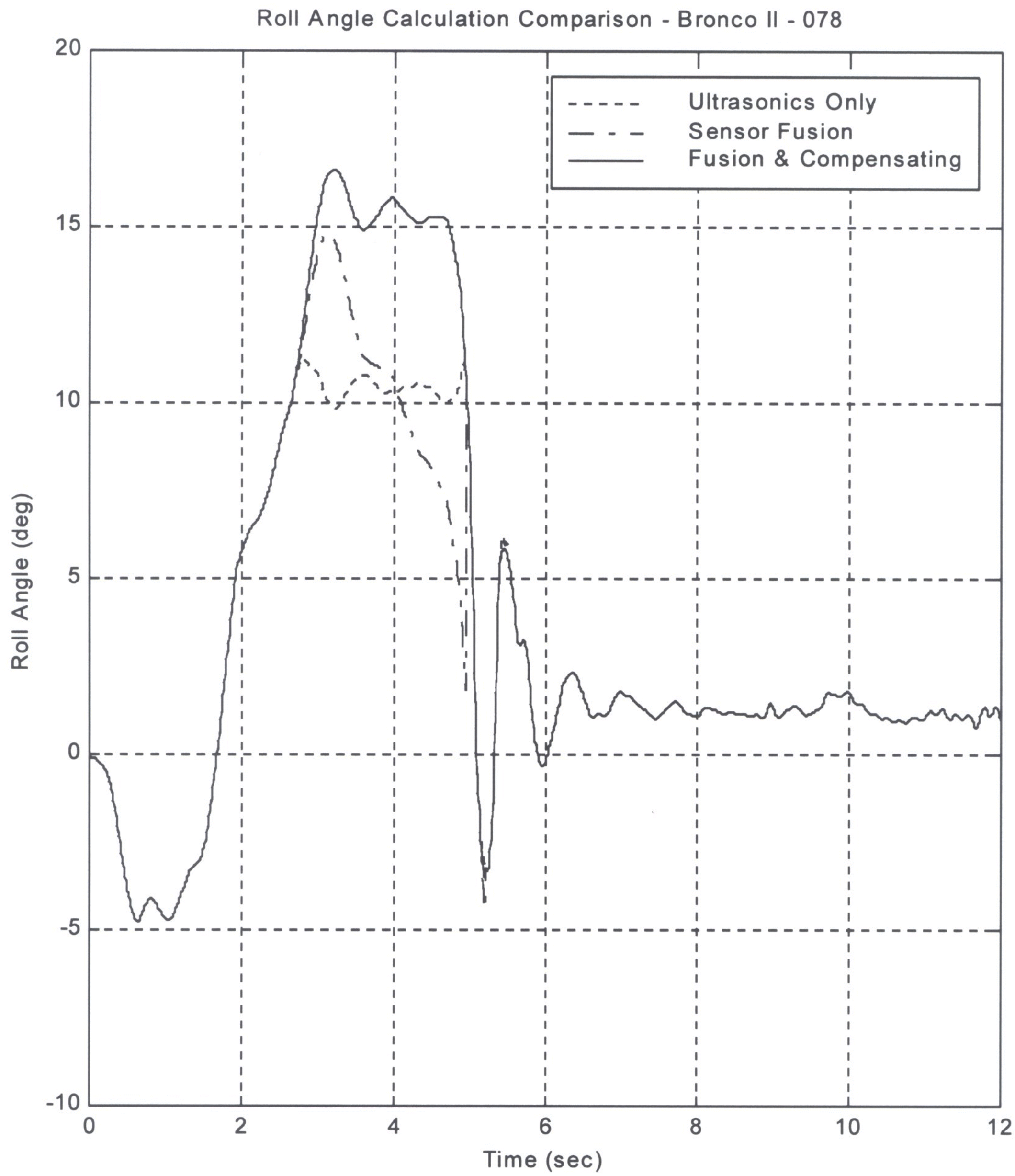

Figure 5.3 -- Roll Angle Computation Comparisons: Ultrasonics Only, Sensor Fusion, and Sensor Fusion with Compensation

6.0 TEST MANEUVERS

A total of eight test maneuvers were evaluated during the Phase I-A testing: J-Turn, J-Turn With Pulse Braking, Brake and Steer, Steering Reversal, Toyota Fishhook Without Pulse Braking, Double Lane Change, Split-Mu Two-Wheels Off-Road Recovery Simulation, and Toyota Fishhook With Pulse Braking. The first three test maneuvers (J-Turn, J-Turn With Pulse Braking, and Brake and Steer) use a single steering input while the others (Steering Reversal, Toyota Fishhook Without Pulse Braking, Double Lane Change, Split-Mu, and Toyota Fishhook With Pulse Braking) use various forms of steering reversals, i.e., steering in one direction and then reversing the steering input towards the opposite direction. All of these test maneuvers will be described in further detail in the following sections. A brief description of the tire changes during the course of testing is also given.

6.1 J-Turn (Without Pulse Braking) Maneuver Test Procedure

The J-Turn (without pulse braking) maneuver consists of a single steering input as is depicted in Figure 6.1. The steering input is made rapidly (as quickly as the test driver can turn the steering handwheel into the steering stop) to maximumly excite the roll dynamics of the vehicle and to reduce the effects of timing on maneuver results. Test severity can be increased by increasing the magnitude of the steering movement, raising the initial vehicle speed, or both. This test maneuver can also be used for determining understeer/oversteer characteristics as described in SAE Surface vehicle Recommended Practice J266 “Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks” [8].

For this research, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the J-Turn tests. These large steering angles were chosen to saturate the tires of all of the test vehicles. This was expected to improve maneuver repeatability. J-Turns maneuvers were performed with turns to both the left and to the right.

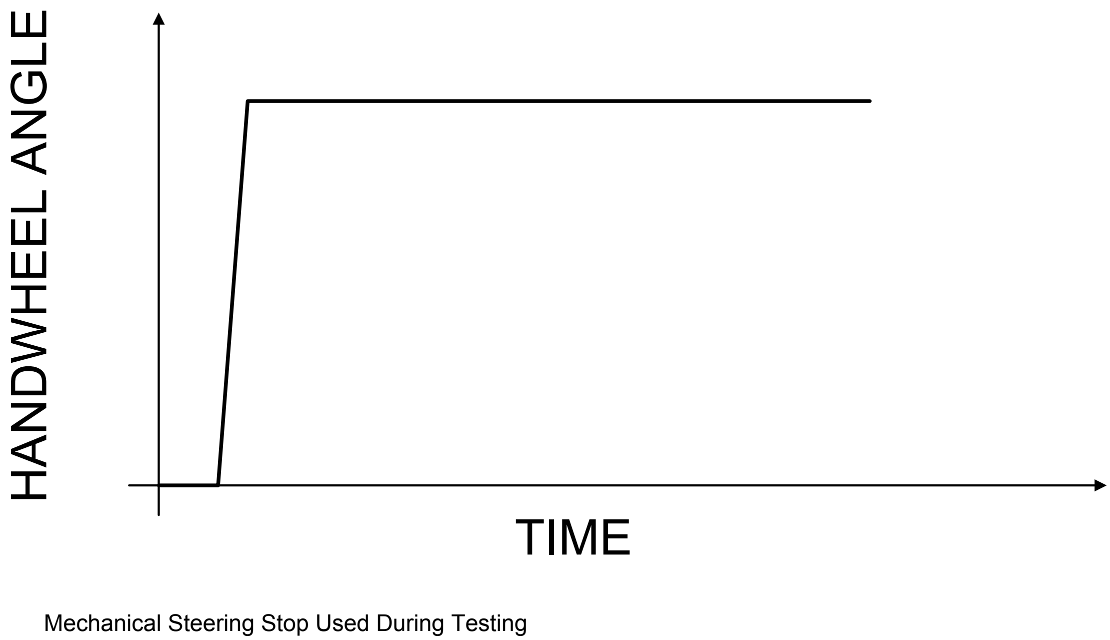

Figure 6.1 -- Steering Handwheel Input for the J-Turn, J-Turn With Pulse Braking, and Brake and Steer Maneuvers

To perform this maneuver, the test driver starts with the steering handwheel in the straight ahead position and tries to attain the desired vehicle speed for the run. Shortly after crossing over the retro-reflective plate that triggers the start of data acquisition the test driver turns the steering handwheel as rapidly as possible until the mechanical steering stop is impacted. Throughout the entire run, the test driver uses the throttle to attempt to maintain a constant vehicle speed. With the high steering input used in this study, maintaining a constant vehicle speed was not always achievable.

The inputs for this test maneuver are very repeatable due to the simple, single steering motion, the mechanical steering stop, and the minimal requirements that this maneuver imposes on the driver.

6.2 J-Turn With Pulse Braking Maneuver Test Procedure

The J-Turn With Pulse Braking maneuver adds pulse braking to the J-Turn (without pulse braking). J-Turn With Pulse Braking uses the same steering input as a function of time as does the J-Turn (see Figure 6.1). The test procedure differs from the test procedure for the J-Turn in that after the driver has turned the steering handwheel to the mechanical steering stop, the throttle was released and a short duration, hard (for many tests, hard enough to result in wheel lockup), pulse force was applied to the brake pedal as is depicted in Figure 6.2.

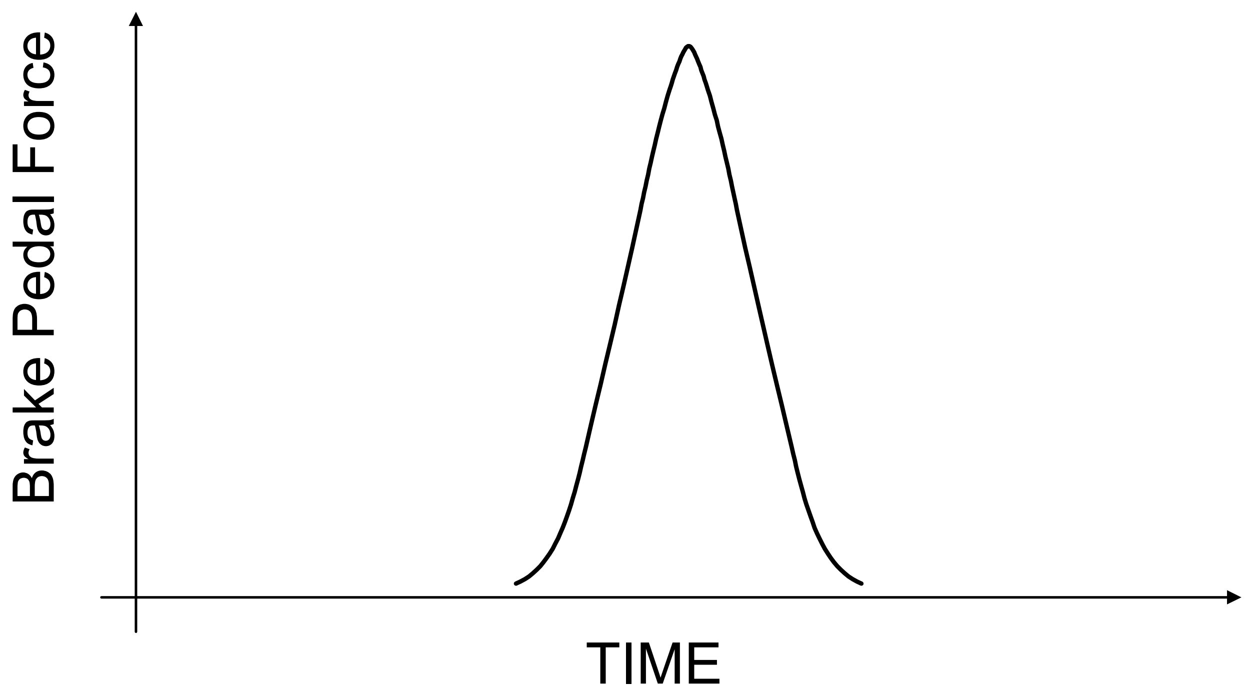

Figure 6.2 -- Brake Pedal Input for the J-Turn With Pulse Braking Maneuver

To allow the brake pulse to achieve the amount of longitudinal tire slip needed to significantly reduce the longitudinal tire forces, the antilock brake system (ABS) was disabled during this test for all test vehicles that were equipped with ABS.

As was the case with the J-Turn (without pulse braking) maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the J-Turn With Pulse Braking tests.

These large steering angles were chosen to saturate the tires of the test vehicles. This was expected to improve maneuver repeatability. J-Turn With Pulse Braking maneuvers were performed with turns to both the left and to the right.

No electronic or mechanical assistance was given to help the driver make the brake pulse repeatable. Since this was exploratory research, between many J-Turn With Pulse Braking runs, test drivers deliberately varied the magnitude and/or duration of the braking pulse. However, even for those runs for which the test drivers were trying to input the same braking pulse magnitude and duration, the brake pulse was not as repeatable as was the steering input.

The braking pulse momentarily decreased the lateral force capabilities of the tires, thereby decreasing the vehicle's lateral acceleration. When the braking pulse ends, the lateral force capabilities of the tires increase very rapidly. This sometimes produces vehicle lateral acceleration levels and/or roll angles which surpass those achieved prior to the onset of braking. These larger lateral accelerations and/or roll angles can result in two-wheel lift for some vehicles that do not have two-wheel lift for the J-Turn (without pulse braking) maneuver. The effects of pulse braking on lateral acceleration and roll angle will be illustrated in the results section of this report.

6.3 Brake and Steer Maneuver Test Procedure

The Brake and Steer maneuver increases maneuver complexity by adding sustained braking to the J-Turn (without pulse braking). Brake and Steer uses the same steering input as a function of time as does the J-Turn (see Figure 6.1). The test procedure differs from the test procedure for the J-Turn (without pulse braking) in that at a specified time relative to the initiation of steering, the brake was applied hard (for many tests, hard enough to result in wheel lockup) and kept on. For all but two of these tests, the brakes were applied at the same time as the steering input. For two of these tests, the brakes were applied well after the steering handwheel had reached the steering stop.

As was the case with the J-Turn maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the Brake and Steer tests. These large steering angles were chosen to saturate the tires of all of the test vehicles. This was expected to improve maneuver repeatability. Due to the limited amount of testing performed using this maneuver (see below), Brake and Steer tests were performed only with turns to the right.

No electronic or mechanical assistance was given to help the driver make the brake application repeatable. Since this was exploratory research between many Brake and Steer runs, test drivers deliberately varied the magnitude of the braking.

During analysis of the first vehicle's Brake and Steer testing, the well known fact that applying and maintaining hard braking during steering decreases the lateral force capabilities of the tires was recognized. This reduces the lateral acceleration of the vehicle and the potential for two-wheel lift. As a result, only one vehicle was tested using this maneuver.

6.4 Steering Reversal Maneuver Test Procedure

A second way to increase maneuver complexity (i.e., other than by adding braking) beyond that of the J-Turn (without pulse braking) is to add a second steering input. By having the second steering movement in the opposite direction to the initial steer, the vertical load on the vehicle's suspension is first concentrated on one side and then on the other. The combination of a sudden change in direction of lateral acceleration and a large roll angular momentum was expected to increase the likelihood of on-road, untripped rollover occurring.

The Steering Reversal maneuver consists of two steering movements as is depicted in Figure 6.3. The steering handwheel is first turned in one direction and then is rapidly reversed resulting in a turn in the opposite direction. The initial steering movement can be either to the left or to the right as long as the second steering movement is always in the opposite direction. There are a large number of combinations of initial and second steering magnitudes that can be used for this maneuver. Test

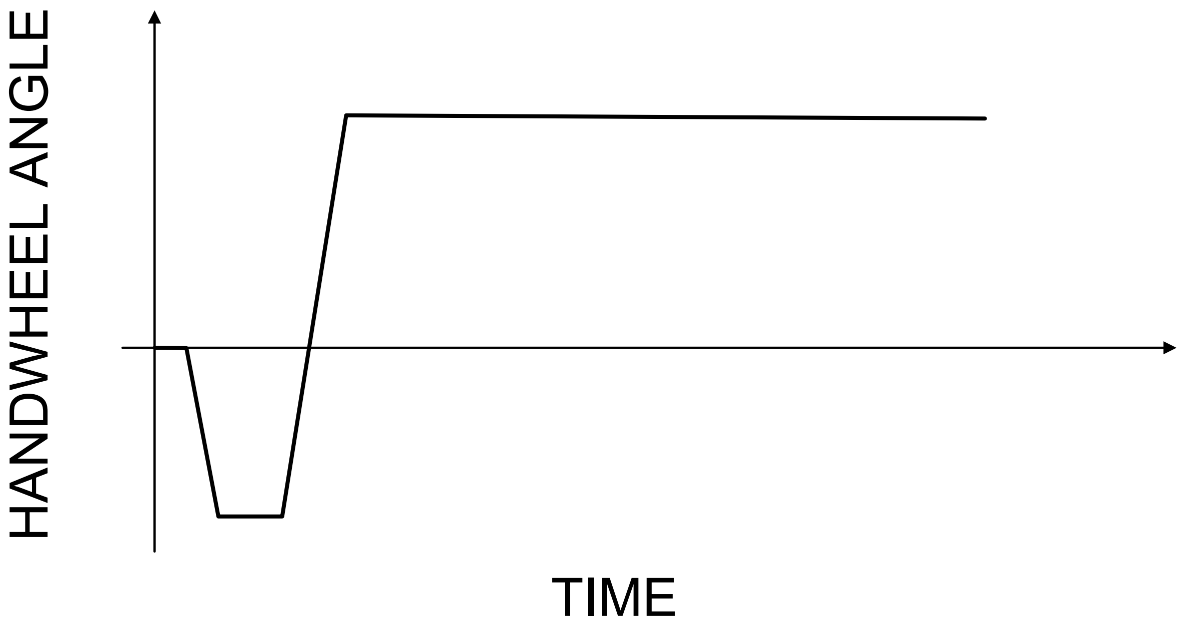

Figure 6.3 -- Steering Handwheel Input for the Steering Reversal maneuver

severity can be increased by increasing the magnitudes of steering inputs, raising initial vehicle speed, or both.

To perform this maneuver, the test driver starts with the steering handwheel in the straight ahead position and tries to attain the desired vehicle speed for the run. Shortly after crossing over the retro-reflective plate that triggers the start of data acquisition the test driver turns the steering handwheel as rapidly as possible through the initial steering movement. As soon as possible after completing the initial steering movement, the test driver turns the steering handwheel back through the second steering movement. Throughout the entire run, the driver uses the throttle to attempt to maintain a constant vehicle speed. With the high steering input used in this study, maintaining a constant speed was not always achievable.

Initial testing for this maneuver was performed using the mechanical steering stop. Unfortunately, the mechanical steering stop was found to hinder the driver's ability to perform the maneuver. While the mechanical steering stop could have been modified to be more user friendly, not enough time was available to make the required modification. Therefore, the mechanical steering stop was used for some, but not all, test runs. In the end, the mechanical steering stop had to be abandoned. No other electronic or mechanical assistance was given to help the driver make the steering inputs repeatable.

Although the test drivers tried not to vary the magnitude and timing of the two steering movements, their inability to use the mechanical steering stop for either one or both of the two steering movements for most test runs degraded maneuver control input repeatability. Furthermore, the addition of the second steering input introduced the possibility of variations in steering timing. As a result, the control inputs for the Steering Reversal maneuver were not as repeatable as were the control inputs for the J-Turn maneuver.

This test maneuver was only performed for one vehicle because, before the other vehicles could be tested, the Toyota Fishhook maneuvers were brought to the Government's attention. The Toyota Fishhook (without pulse braking) is a Steering Reversal maneuver with a particular set of steering magnitudes. The Toyota Fishhook maneuver uses large steering magnitudes for both the initial and second steering movements. The large steering input magnitudes of the Fishhook result in the vehicle's tires being saturated for most of the maneuver. This is expected to improve maneuver repeatability. Therefore, a decision was made to replace the Steering Reversal maneuver with the Toyota Fishhook maneuver for the other test vehicles.

6.5 Toyota Fishhook (Without Pulse Braking) Maneuver Test Procedure

The Toyota Fishhook maneuver is detailed in Toyota Engineering Standard TS-A1544. This test procedure is designed to produce two-wheel lift by imparting to the vehicle a rapid steering reversal while the vehicle is at maximum lateral acceleration in one direction due to the initial steer. This rapid steering reversal quickly changes the vehicle's lateral acceleration to the maximum value in the other direction. This rapid change in lateral acceleration direction imparts a large roll angular momentum change to the chassis due to the vehicle leaning at a relatively large angle to one side and then being forced to lean in the opposite direction. The combination of a sudden change in the direction of lateral acceleration and a large roll angular momentum can produce two-wheel lift at lower lateral acceleration levels than for the J-Turn. The test course and steering inputs for this procedure are given in Figures 6.4 and 6.5, respectively.

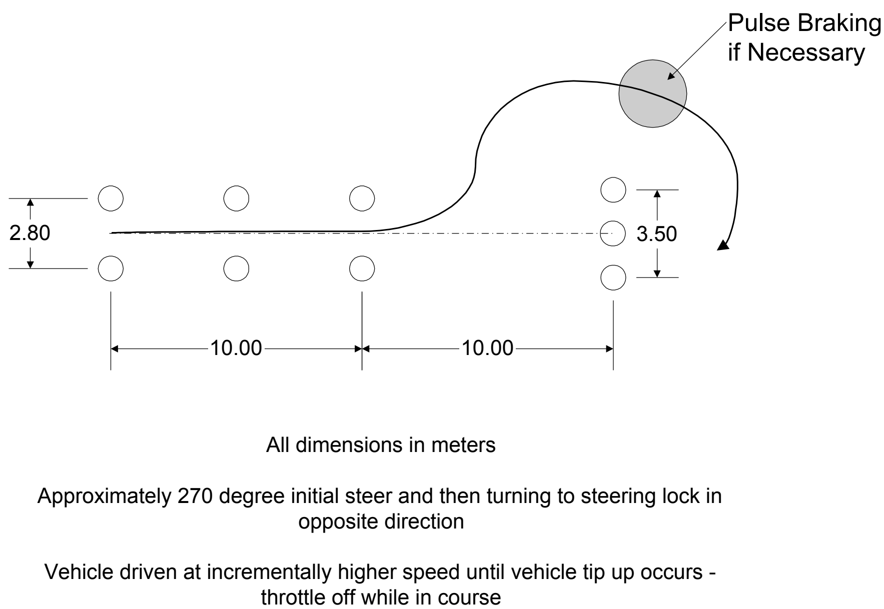

Figure 6.4 -- Test Course Layout for the Toyota Fishhook Maneuver

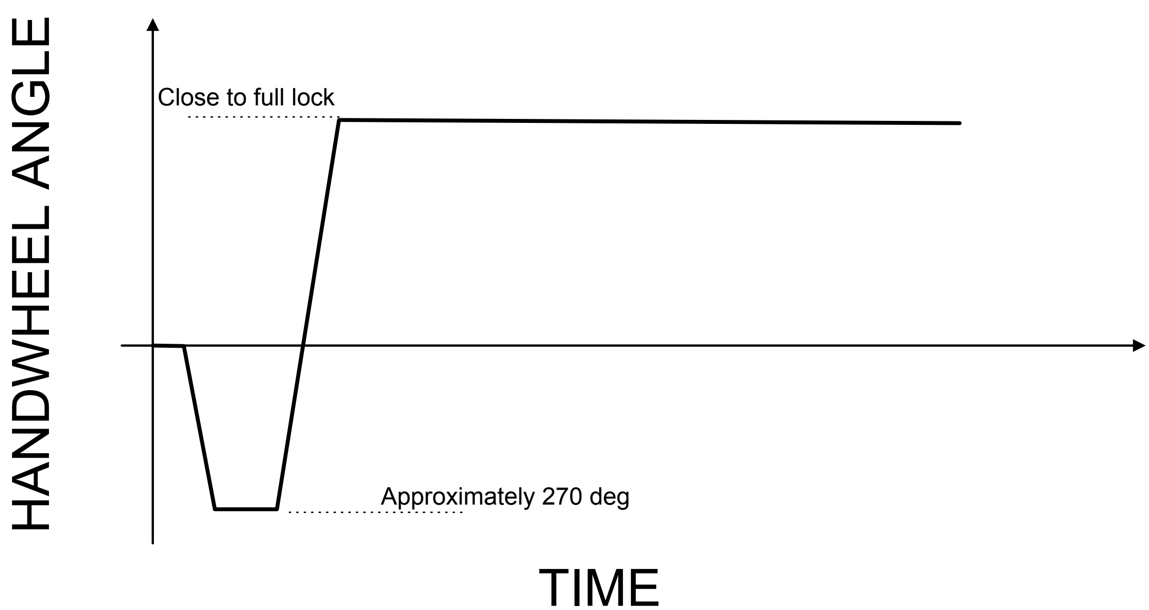

Figure 6.5 -- Steering Handwheel Input for the Toyota Fishhook Maneuver

To perform this maneuver, the test driver starts with the steering handwheel in the straight ahead position and tries to attain the desired vehicle speed for the run. Shortly after crossing over the retro-reflective plate that triggers the start of data acquisition (located between the leftmost cones in Figure 6.4) the test driver turns the steering handwheel as rapidly as possible through the initial steer. Immediately upon completing the initial steer, the test driver turns the steering handwheel back through the second steer (steering reversal). The driver releases the throttle as the vehicle passes between the gate cones (the leftmost cones in Figure 6.4) and allows the vehicle to coast through the remainder of the course.

The initial handwheel steering input used for this research was approximately 270 degrees. The initial steer could be either to the left or to the right. The second steer is to, or close to, the steering lock in the opposite direction from the initial steer. Toyota Engineering Standard TS-A1544 states the initial steer should be approximately 180 degrees, but engineers working for Toyota have stated that they typically use steering inputs of 270 degrees (as was used for this research).

The Toyota Fishhook is run starting with relatively low course entry speeds. The course entry speed is then gradually increased for each successive run until several runs with two-wheel lift are produced. If two-wheel lift cannot be produced at any speed with just steering input, then pulse braking can be added (see Section 6.8). A group of test runs, starting at a low course entry speed and working up until a termination condition occurs is referred to as a “set”.

At the time of the Phase I-A research, VRTC’s mechanical steering stop could not be used to help perform the Toyota Fishhook maneuver. Therefore, no electronic or mechanical assistance was given to help the driver make the initial steer or the timing of the second steer repeatable. As a result, although the test drivers tried not to vary the magnitude and timing of the steering reversal, the steering inputs were not as repeatable as those for the J-Turn.

6.6 Double Lane Change Maneuver Test Procedure

The Double Lane Change course and vehicle path are depicted in Figures 6.6 and 6.7, respectively. The test driver steers the vehicle through the entrance lane, turns left to avoid the single cone in the second lane, turns right to return to the original lane, and then straightens the vehicle to leave the course via the exit lane cones.

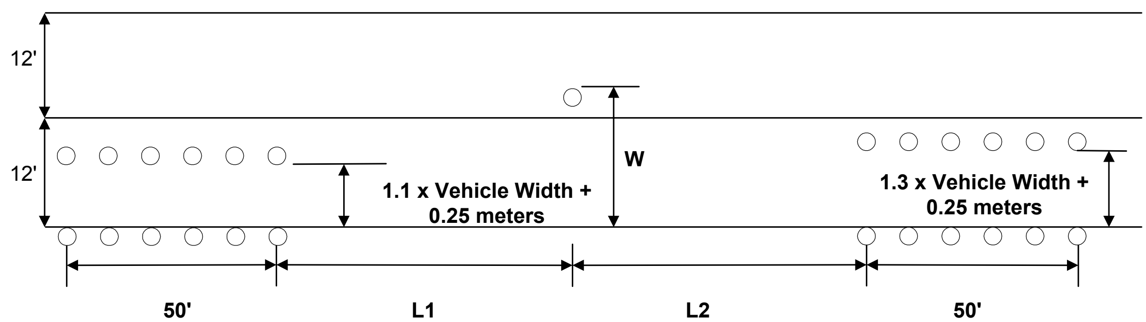

Figure 6.6 -- Course Layout for the Double Lane Change Maneuver

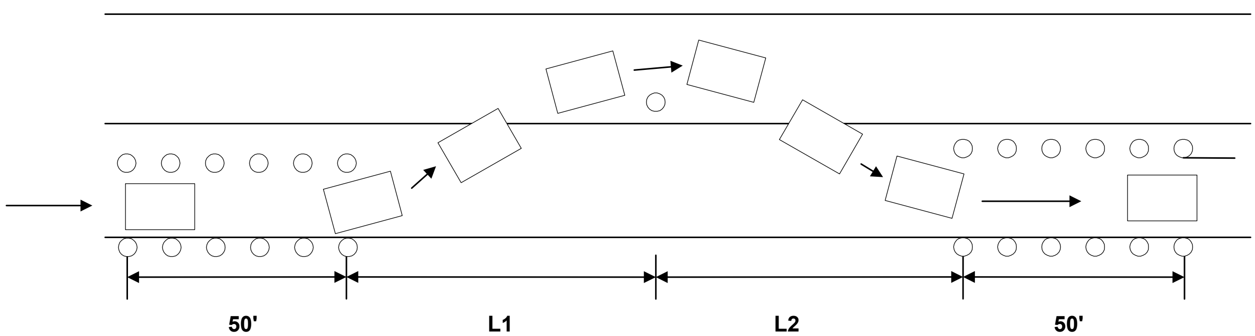

Figure 6.7 -- Vehicle Path for the Double Lane Change Maneuver

A large number of cone placements are possible for a Double Lane Change maneuver. For this research, the entrance and exit lane widths and lengths chosen were similar to those specified in the International Standards Organization (ISO) Technical Report 3888. The ISO Double Lane Change test has a row of cones in the second lane, while only a single cone was used for the Double Lane Change course used in this study. The single cone required a much more rapid steering reversal by the driver which could produce higher levels of lateral acceleration than for those courses with a longer dwell time in the second lane. The course used for a given test run is indicated through the notation L1/L2/W (e.g., the 70/70/14 course). The values for L1, L2, and W in Figure 6.6 were varied and are specified in the results section for each vehicle. Note that picking a single Double Lane Change course for all vehicles may not be advisable since any given course geometry may excite the natural frequency of some, but not all, vehicles.

To perform this maneuver, the test driver starts with the steering handwheel in the straight ahead position and tries to attain the desired vehicle speed for the run. The driver releases the throttle as the vehicle passes between the entrance gate cones (the leftmost cones in Figure 6.6) and allows the vehicle to coast through the remainder of the course. Instead of turning the steering handwheel by a fixed amount as was done for the previously described test maneuvers, the driver attempts to have the vehicle follow the path delineated by the cones. Driver steering was in anticipation of/reaction to the trajectory being followed by the vehicle. As such, this control input was not very repeatable.

6.7 Split-Mu Off-Road Recovery Simulation Maneuver Test Procedure

The Split-Mu Off-Road Recovery Simulation was developed to try and simulate a scenario that has been documented in the rollover crash data collected by NHTSA. This maneuver simulates the return of a vehicle that has two wheels off the road to having all four wheels on the road surface. A more realistic simulation would require the two wheels off the road surface to climb a lip as they re-entered the road surface. This lip was not simulated to reduce test complexity and variability.

The Split-Mu Off-Road Recovery test course and approximate vehicle path are depicted in Figure 6.8. The vehicle is driven onto a split-coefficient-of-friction (split-mu) surface, i.e., the tires on the right side of the vehicle are on a low coefficient-of-friction, wet-epoxy surface and the tires on the left side are on a higher coefficient-of-friction, dry-asphalt surface. The driver then turns the vehicle to the left to bring all four tires on to the dry-asphalt surface. This is followed by a turn to the right to try and keep the vehicle within a two lane width boundary (24 feet).

To perform this maneuver, the test driver starts with the steering handwheel in the straight ahead position and tries to attain the desired vehicle speed for the run. The driver releases the throttle as the vehicle passes between the gate cones (the leftmost cones in Figure 6.8) and allows the vehicle to coast through the remainder of the course. After reaching the end of the entry lane, the driver makes an initial large, rapid steering movement to the left. Following this initial steering movement, the driver attempts to maintain control while keeping the vehicle on the course.

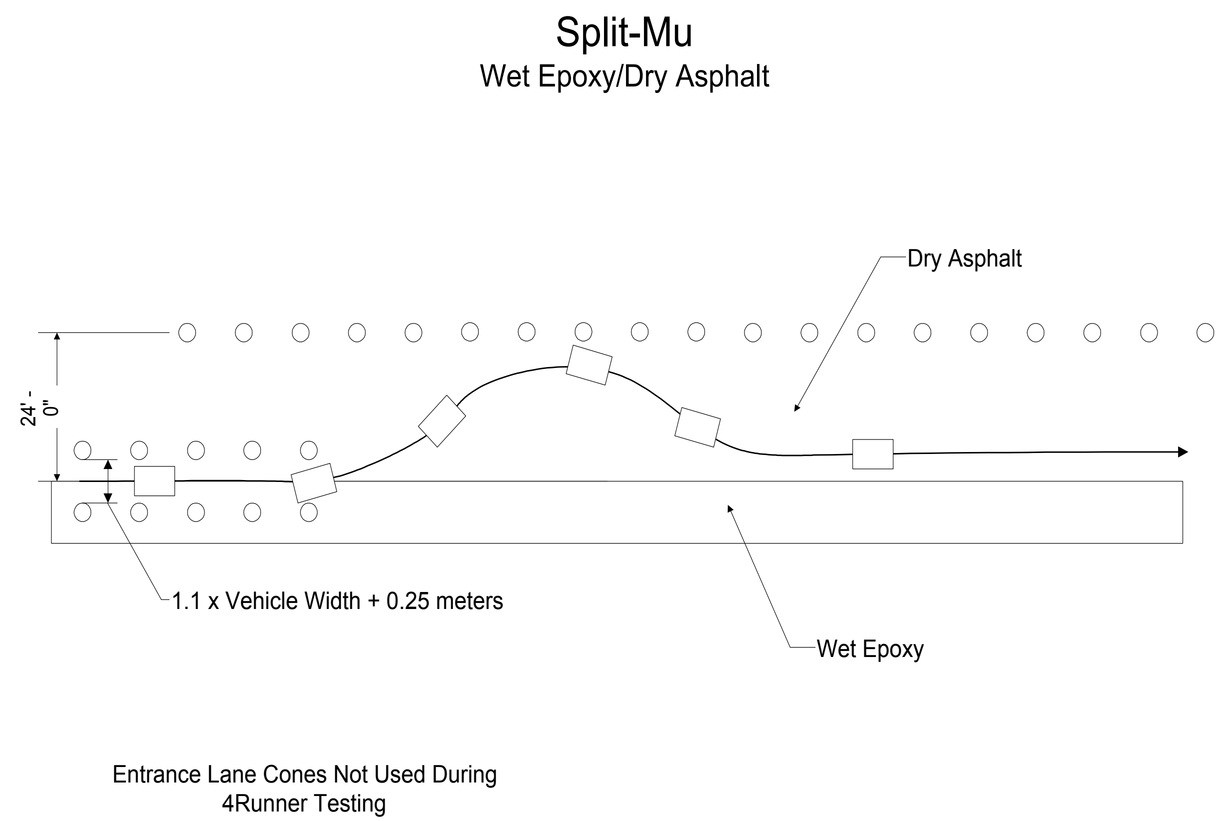

Figure 6.8 -- Course Layout for the Off-Road Recovery (Split-Mu) Maneuver

In an attempt to reduce test variability, a mechanical steering stop was used to control the magnitude of the first steering movement (when the vehicle was turned to drive off of the wet-epoxy surface) for some of the early tests. This version of the steering stop was very cumbersome; therefore, later tests were performed without the use of a steering stop. For these tests, no electronic or mechanical assistance was given to help the driver make the initial steering movement repeatable. As a result, although the test drivers tried not to vary the magnitude and timing of the initial steering movement, the initial steering movement was not as repeatable as was the steering input for the J-Turn.

Driver steering subsequent to the initial steering movement was a reaction to the trajectory being followed by the vehicle. As such, despite the test driver's best efforts, this input was not very repeatable.

6.8 Toyota Fishhook With Pulse Braking Maneuver Test Procedure

The next level of complexity beyond a reverse steer type of maneuver is achieved by adding braking. This research studied the Toyota Fishhook With Pulse Braking maneuver which added pulse braking to the previously described Toyota Fishhook. The Toyota Fishhook With Pulse Braking uses the same course and steering input as a function of time as does the Toyota Fishhook Without Pulse Braking (see Figures 6.4 and 6.5). The test procedure differs from the test procedure for the Toyota Fishhook Without Pulse Braking in that after the driver has completed the second steering movement, a short duration, hard pulse was applied to the brake pedal as is depicted in Figure 6.2. The brake pulse is timed to occur near the point of maximum lateral acceleration and body roll caused by the second steering movement.

For the same reasons as were discussed above for the J-Turn With Pulse Braking maneuver (see Section 6.2), vehicles with ABS had the ABS disabled while performing this maneuver.

The addition of the braking pulse degraded maneuver repeatability relative to the Toyota Fishhook (Without Pulse Braking). No electronic or mechanical assistance was given to help the driver make the brake pulse repeatable. As a result, although the test drivers tried not to vary the magnitude and duration of the braking pulse, the brake pulse was not as repeatable as was the steering input.

The pulse braking causes a sharp decrease in the lateral acceleration capabilities of the tires as the brakes are applied and then a sharp increase as the brakes are released. This rapid increase in the lateral acceleration can produce lateral accelerations that are significantly higher than the lateral acceleration prior to the application of the brakes. Pulse braking also produces large roll angular momentum changes because the chassis roll angle decreases as the brakes are applied and rapidly increases as the brakes are released.

6.9 Tire Changes During the Phase I-A Testing

Past NHTSA rollover research [9] found that tire variability due to shoulder wear greatly increases the non-repeatability of rollover testing. (Note that the tire shoulder wear which occurs during rollover testing is not like the tire wear that occurs during normal driving; the effect on maximum tire side force generation capability is thought to be quite different for the two types of tire wear.) For bias-ply tires, the maximum sideforce could increase by as much as 40 percent from one run to the next due to tire shoulder wear. The maximum side force generated by radial tires can also increase from run-to-run due to tire shoulder wear; however, the increase is smaller than for bias-ply tires.

While the authors were aware of past NHTSA rollover research findings, we did not know how much tire side force generation capability would increase with tire shoulder wear for the modern radial tires used in the current research. Therefore, a vehicle's tires were **not** changed on a systematic basis during this testing. Instead, a vehicle's tires were changed either when, based on a visual inspection, one or more tires were judged to have substantial shoulder wear or when, during testing, unexpected (based on the pattern from previous testing) two-wheel lifts occurred. Based on subsequent analyses of test data, the authors believe that some Phase I-A tests were performed with tires that had substantial increases in their maximum side force generation capability due to shoulder wear.

Data collected during the Phase I-A and Phase I-B testing has been used to develop a systematic tire change procedure which will be used during subsequent phases of NHTSA's Light Vehicle Rollover Research Program.

7.0 J-TURN TEST RESULTS AND ANALYSIS

7.1 Tests Performed for Each Vehicle

Table 7.1 summarizes the J-Turn tests with valid data that were performed with the Toyota 4Runner. Similarly, Table 7.2 summarizes the J-Turn tests with valid data that were performed with the Ford Bronco II while Table 7.3 summarizes the valid J-Turn tests for the Jeep Cherokee.

The tables list, for each of these tests, the Test Number, the Initial Speed, the magnitude of the Steering Input (the steering stop was set at a positive angle for J-turns to the right and a negative angle for left turns), the Maximum Corrected Lateral Acceleration (largest absolute value), the Maximum Roll Angle (largest absolute value), and the Amount of Two-Wheel Lift (if any).

The second column in each of the tables shows Initial Speed. This is determined from the average speed over 0.1 seconds (average of 10 data points) measured at the beginning of each test. The average is taken starting 0.1 seconds before the handwheel angle reaches 50 degrees.

The Steering Input value is taken as the average over a range of "flat" steering input. The individual processing the data selects the range specific to each test run. A mechanical steering stop was used for the J-Turn tests, so the "flat" steering range is easy to identify and the values over the range are quite constant.

Figure 7.1 contains a graph of data from typical J-Turn test (Test Number 144 for the Jeep Cherokee). The top graph of this figure shows the steering handwheel angle as a function of time. This graph shows the steadiness of the steering handwheel angle that was typically achieved during a J-Turn maneuver.

The fourth column in the tables is Maximum Corrected Lateral Acceleration (largest absolute value). The computation of corrected lateral acceleration is discussed earlier in this report (Section 5.5). In some instances, there are two entries listed in this column for a single test. In these instances, the first entry is the maximum lateral acceleration observed during the J-Turn maneuver, and the second is the maximum lateral acceleration observed prior to the peak roll angle. These cases are discussed in Section 7.5, below.

The fifth column in the tables is Maximum Roll Angle (largest absolute value). Figure 7.1 shows the values that would be selected for a typical J-Turn test for Maximum Corrected Lateral Acceleration and Maximum Roll Angle.

In Tables 7.1 through 7.3, the contents of the Amount of Two-Wheel Lift Column are either Major, Moderate, Minor, or None. These values are assigned after examination of each test run's video. The definitions of these values are:

Major – Easily discernable two-wheel lift occurred for a significant period of time and the vehicle's outriggers touched the ground during this portion of this test run. Major two-wheel lift can always be observed by the test driver and observers.

Moderate - Easily discernable two-wheel lift occurred for a significant period of time. However, the vehicle's outriggers did not touch the ground at any time during this test run. Moderate two-wheel lift can always be observed by the test driver and observers.

Minor – Minor two-wheel lift is two-wheel lift that occurs only for a brief moment (a fraction of a second) during the test run. Minor two-wheel lift is difficult to discern, and it is not readily apparent during casual viewing of the test run's video. Careful examination of the video, sometimes frame-by-frame analysis, is required to establish when Minor two-wheel lift occurs.

None – Two-wheel lift did not occur during this test run.

As is implied by the above definitions, distinguishing between these different values of two-wheel lift is a somewhat subjective process. This is particularly true when attempting to distinguish between the Minor and None amounts of two-wheel lift. During the current research, the video of each test run was examined by two observers. Additional, careful, examinations were then made for cases for which the two observers disagreed.

The J-Turn tests were run with increasing severity up to the limits of vehicle performance; either plow out, spin out, or two-wheel lift. A mechanical steering stop was used to provide a steady steering angle throughout the J-Turn maneuvers. This phase of testing was considered exploratory, and the protocol for the testing was not rigid. Rather the test progression followed the concept of increasing test severity by either increasing steering wheel amplitude or test speed. The maximum steering angles achievable using the steering stop hardware were in the range of 330 degrees.

Table 7.1 -- Summary of J-Turn Testing for the Toyota 4Runner

Test Number	Initial Speed (mph)	Steering Input (deg)	Maximum Corrected Lateral Acceleration (g)	Maximum Roll Angle (deg)	Amount of Two-Wheel Lift
522	41.9	-165	-0.72	6.2	None
523	41.3	-165	-0.72	6.3	None
524	41.6	-165	-0.72	6.0	None
525	41.9	-164	-0.73/-0.72[1]	6.1	None
526	42.1	-195	-0.77	6.8	None
527	41.9	-235	-0.80	6.9	None
528	41.9	-265	-0.82	7.5	None
529	42.0	-305	-0.84	7.5	None
530	46.4	-154	-0.73	6.3	None
531	48.4	-184	-0.81	7.5	None
532	46.5	-236	-0.83	7.5	None
533	45.7	-256	-0.83	7.6	None
534	45.7	-276	-0.88	7.6	None
535	45.9	-285	-0.83	7.4	None
536	46.0	-306	-0.83	7.5	None
617	39.3	-318	-0.84	7.4	None
618	43.9	-318	-0.89	7.9	None
619	44.3	-318	-0.85	7.8	None
620	47.2	-318	-0.92/-0.88	9.1	Minor
621	50.2	-318	-0.92/-0.85	8.0	None
622	49.3	-317	-0.88/-0.87	8.2	None
623	53.3	-318	-0.88	9.5	Minor
624	55.9	-318	-0.91	9.7	Moderate
625	59.1	-317	-0.91	10.6	Moderate

[1]The second number listed after the slash is the Maximum Corrected Lateral Acceleration prior to Maximum Roll Angle.

Table 7.2 -- Summary of J-Turn Testing for the Ford Bronco II

Test Number	Initial Speed (mph)	Steering Input (deg)	Maximum Corrected Lateral Acceleration (g)	Maximum Roll Angle (deg)	Amount of Two-Wheel Lift
1	40.9	-268	-0.76	6.0	None
2	44.4	-268	-0.72	5.1	None
3	46.8	-269	-0.72	5.4	None
4	45.1	-268	-0.74	5.5	None
5	46.7	-268	-0.74	5.4	None
6	50.1	-268	-0.74	5.7	None
8	53.2	-268	-0.74	5.8	None
9	55.2	-268	-0.76	6.0	None
10	55.1	-269	-0.75	6.4	None
11	56.6	-268	-0.76	5.9	None
13	50.6	329	0.77	-5.3	None
15	57.9	329	0.82	-6.2	None
16	56.9	329	0.81	-5.9	None
17	58.3	329	0.80	-5.8	None
18	56.8	-336	-0.76	5.6	None

Table 7.3 -- Summary of J-Turn Testing for the Jeep Cherokee

Test Number	Initial Speed (mph)	Steering Input (deg)	Maximum Corrected Lateral Acceleration (g)	Maximum Roll Angle (deg)	Amount of Two-Wheel Lift
141	47.8	-331	-0.80	5.9	None
142	49.1	-331	-0.80	5.8	None
143	52.8	-331	-0.77	5.9	None
144	45.04	-330	-0.80/-0.72[2]	6.1	None
145	53.8	-331	-0.80	6.5	None
146	56.4	-331	-0.79	6.2	None
147	59.4	-331	-0.80/-0.71	6.1	None
149	59.7	-328	-0.83/-0.77	5.7	None
150	60.4	-328	-0.83/-0.76	5.8	None
151	60.6	-328	-0.83	5.7	None
152	60.3	-330	-0.85/-0.71	5.5	None
153	60.6	-329	-0.87	6.0	None
211	60.0	337	0.87/0.81	-6.2	None
212	60.2	336	0.88/0.79	-6.1	None
213	60.6	338	0.85/0.81	-6.1	None
214	60.6	335	0.86/0.79	-6.0	None

[2]The second number listed after the backslash is the Maximum Corrected Lateral Acceleration prior to Maximum Roll Angle.

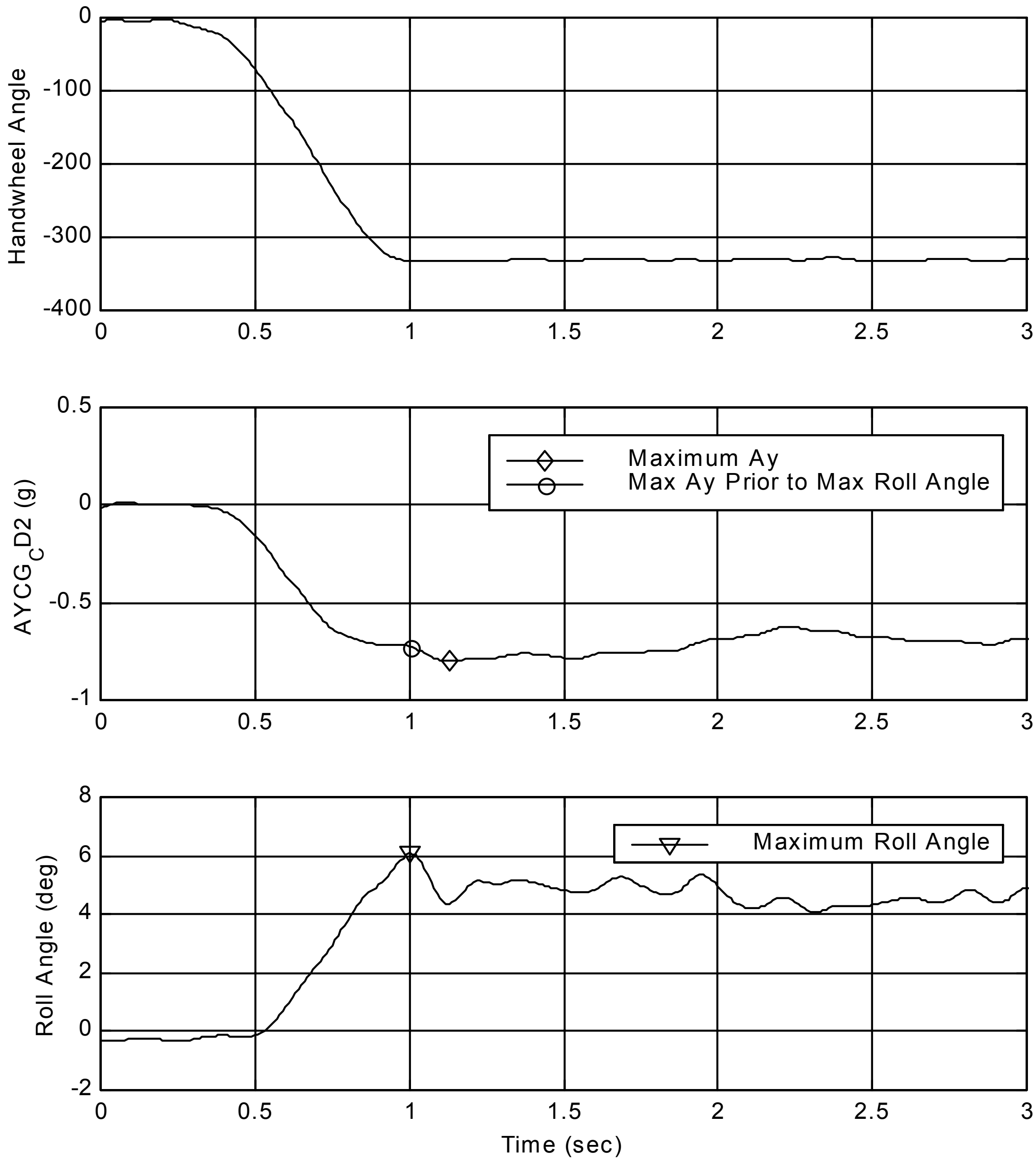

Figure 7.1 -- Typical Test Data From a J-Turn Maneuver - Jeep Cherokee Test Number 144

7.2 The J-Turn and Rollover Propensity

For two of the vehicles tested, the Ford Bronco II and the Jeep Cherokee, no two-wheel lift was observed during the J-Turn testing. For the Toyota 4Runner, both minor and moderate two-wheel lifts were observed during the J-Turn testing.

In general, increasing J-Turn severity, by increasing either the magnitude of the Steering Input or the Initial Speed, resulted in increasing maximum corrected lateral accelerations and roll angles up to the point of limit response. For the Ford Bronco II and Jeep Cherokee the limit responses observed were plow outs. Typically, once a maneuver becomes severe enough to elicit a limit response, further attempts to increase severity result in the same limit response. For a plow out condition the tires on the front axle become saturated and the vehicle plows. The Bronco II reached limit lateral accelerations around 0.75 g. in the left-hand turns and 0.80 g. in the right-hand turns, and the Cherokee reached limit lateral accelerations around 0.85 g. in the left-hand turns and 0.87 g. in the right-hand turns. Once these ranges of limit lateral acceleration were achieved, increasing the J-Turn severity did not significantly increase vehicle lateral acceleration or roll angle response.

The Toyota 4Runner experienced two-wheel lift at the limit response. Note that, as is discussed in Section 7.4 below, the tests with two-wheel lift were performed after significant tire wear is believed to have occurred. There is no way to determine (from the data that was collected during this testing) whether or not two-wheel lift would have occurred for these tests if the significant tire wear had not happened. Also, note that the tire shoulder wear which occurs during rollover testing is not like the tire wear that occurs during normal driving; the effect on maximum tire side force generation capability is thought to be quite different for the two types of tire wear.

For the Toyota 4Runner tests that resulted in minor two-wheel lift, the average lateral acceleration was 0.90 g. and the average roll angle was 9.31 degrees. For the tests that resulted in moderate two-wheel lift, the average lateral acceleration was 0.92 g. and the average roll angle was 10.03 degrees. Test Numbers 621 and 622, which did not result in two-wheel lift, used the same nominal steering input and were run at higher speeds than Test Number 620, which resulted in minor two-wheel lift. As the test speed was increased beyond 55 mph, moderate two-wheel lift was observed.

7.3 Repeatability of the J-Turn

The J-Turn tests were found to be very repeatable. Test Numbers 522 through 525 for the Toyota 4Runner, 2 through 5 for the Ford Bronco II, and 149 through 153 and 211 through 214 for the Jeep Cherokee were all run using the same nominal input conditions, and they are representative of the repeatability of J-Turn tests using a test driver. For all these groups of repeatability tests, the resulting maximum lateral accelerations varied by at most 0.04 g and the maximum roll angles varied by at most 0.5 degrees.

There are two main factors related to the testing that influences the repeatability of the test results. The driver was instructed to turn the steering handwheel as rapidly as possible into the steering stop. However, there is some variability in the steering rates used for the J-Turns. Also, although the initial speed of each test is well defined and measured, there is some variability in the vehicle longitudinal acceleration at the start of each test. Since cruise control was not used for these tests, in some cases the vehicles may have been accelerating or decelerating slightly at the instant of steering initiation. A programmable steering controller and special care to start the tests at constant speed should improve test repeatability.

As is discussed in Section 7.4 below, tire wear can significantly affect test results. For the Toyota 4Runner, nine tests were run with Steering Inputs of either -317 or -318 degrees. Although it is difficult to disentangle the effects of tire wear from those of changes in Initial Speed, the authors believe that significant tire wear effects were present for the last six of these tests. The significant tire wear appears to have resulted in higher Maximum Corrected Lateral Accelerations and Maximum Roll Angles. The only J-Turn tests for which two-wheel lift occurred were run with tires that are thought to have been significantly worn.

In addition to test input variability, there is inherent non-repeatability in the tires (other than that due to tire wear), the vehicle components (e.g. shock absorbers, bushings, etc.), and the test surface. These effects are random in nature and little can be done to eliminate their effects on repeatability.

There are test conditions that have a non-random influence on the measured vehicle responses. For example, testing at a different ambient temperature or on a somewhat different surface could result in different measured vehicle responses. The effect of changes of this sort on the overall outcome of a test regarding the limits of vehicle response, i.e., whether the test would result in two-wheel lift, spin out, or plow out, is not known.

7.4 Effects of Magnitude of Steering Input on J-Turn Results

What should be the magnitude of the steering input for the J-Turn maneuver? The goal is to use a magnitude that is large enough to saturate the lateral forces produced by the vehicle's low-side tires but that is small enough to not substantially reduce vehicle lateral acceleration due to scrubbing off a large amount of vehicle speed.

Although not initially intended for this type of analysis, the data collected during J-Turn testing with the Toyota 4Runner was analyzed to try and answer the above question. As shown in Table 7.1, Toyota 4Runner J-Turn testing was performed using a range of Steering Inputs (handwheel steering input magnitudes) varying from approximately -150 to -300 degrees (only left-turn J-Turns were performed for this vehicle) for two Initial Speeds: 42 and 46 mph. A series of tests with a constant Steering Input (-318 degrees) and Initial Speeds varying from 39 to 59 mph was also run. It should be noted that Test 531 was not included in the analysis that follows because the Initial Speed for this test (48.4 mph) was considered to be too far above the 46 mph range.

Data collected while testing the Toyota 4Runner was used for this analysis because J-Turn tests conducted with the Ford Bronco II and Jeep Cherokee were performed using a very limited number of Steering Inputs (Table 7.2 shows that Steering Inputs of 329, -268, -269, and -336 degrees were used for the Bronco II, while Table 7.3 shows that Steering Inputs of 338 through 335 and -329 through -331 degrees were used for the Cherokee). This data has insufficient independent variable range to be used to study the effects of steering input magnitude on the vehicle's response.

During this testing, the Toyota 4Runner's Initial Speed varied between 39.3 and 59.1 mph. The effects of this variation on Initial Speed will also be examined during this analysis.

Figure 7.2 shows Maximum Corrected Lateral Acceleration (Max Ay) versus Steering Input for J-Turn tests performed with the Toyota 4Runner. The different speed ranges are represented by different symbols. The data clearly show that the Max Ay is a function of both speed and handwheel angle.

The 42 and 46 mph Max Ay data are plotted again in Figures 7.3 and 7.4. A quadratic trend line of the combined 42 and 46 mph data is presented in Figure 7.4. The trend line appears to give a reasonable fit for the data and suggest that the tires become saturated near 250 degrees of steering input.

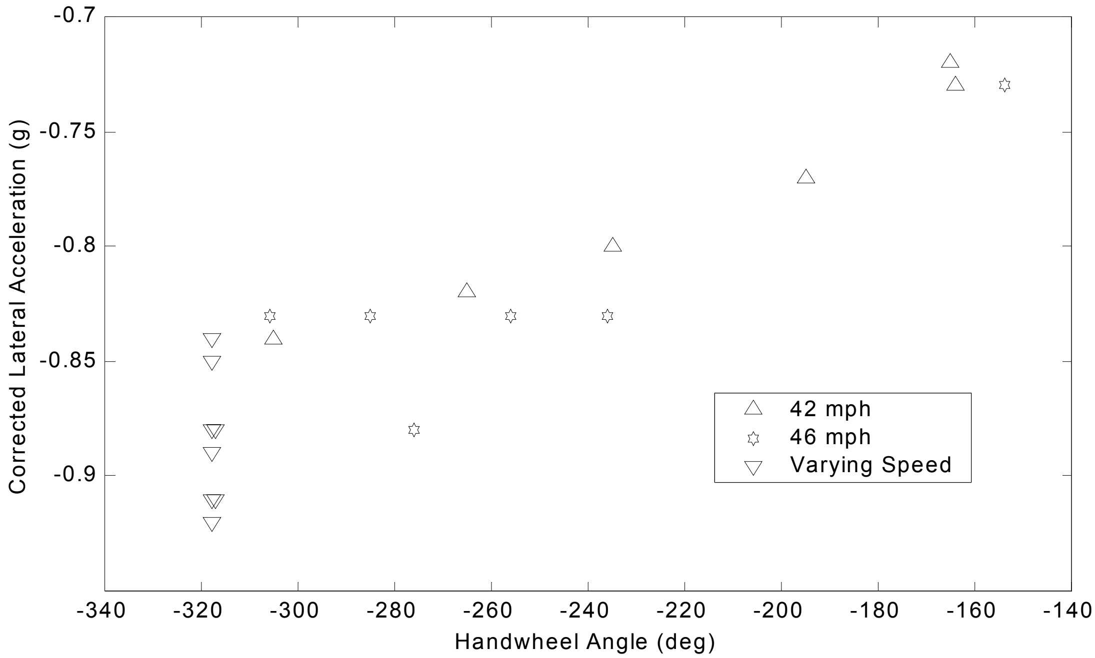

Figure 7.2 – Maximum Corrected Lateral Acceleration versus Steering Input Magnitude for Toyota 4Runner J-Turn Tests

The Max Ay data for 318 degree Steering Input/varying Initial Speed tests are plotted as a function of speed in Figure 7.5. A linear fit of the data is given in Figure 7.5. The R^2 value for this linear fit is 0.42.

The data presented in Figure 7.2 through 7.5 show that no reduction in Max Ay with increasing steering input magnitude (due to the vehicle scrubbing off speed faster for larger Steering Input magnitudes) was seen during this testing.

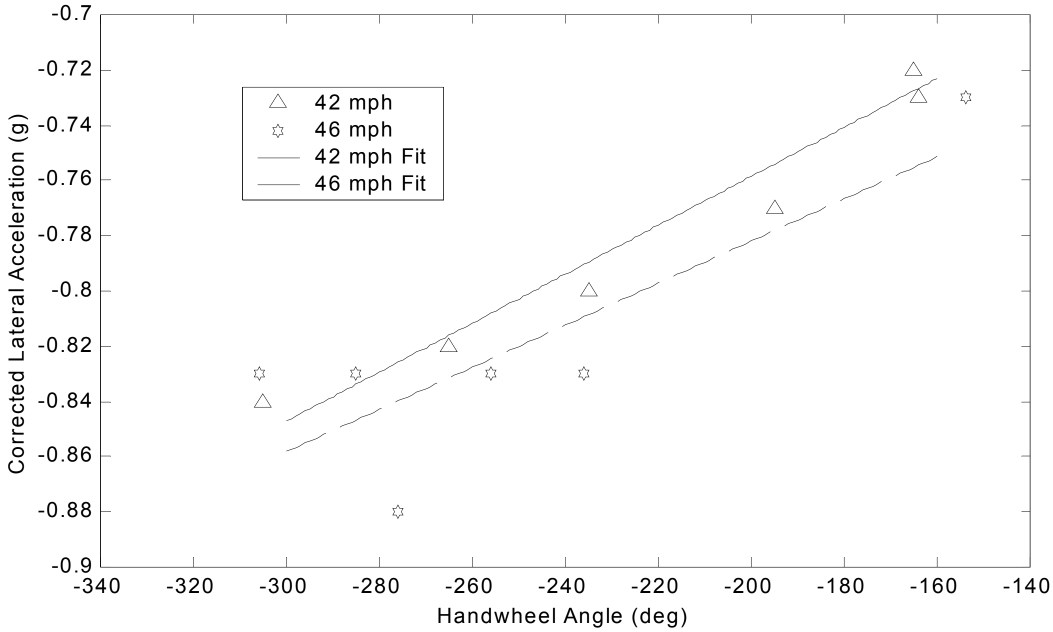

Figure 7.3 – Linear Fits of 42 and 46 mph Maximum Corrected Lateral Acceleration versus Steering Input Magnitude Data

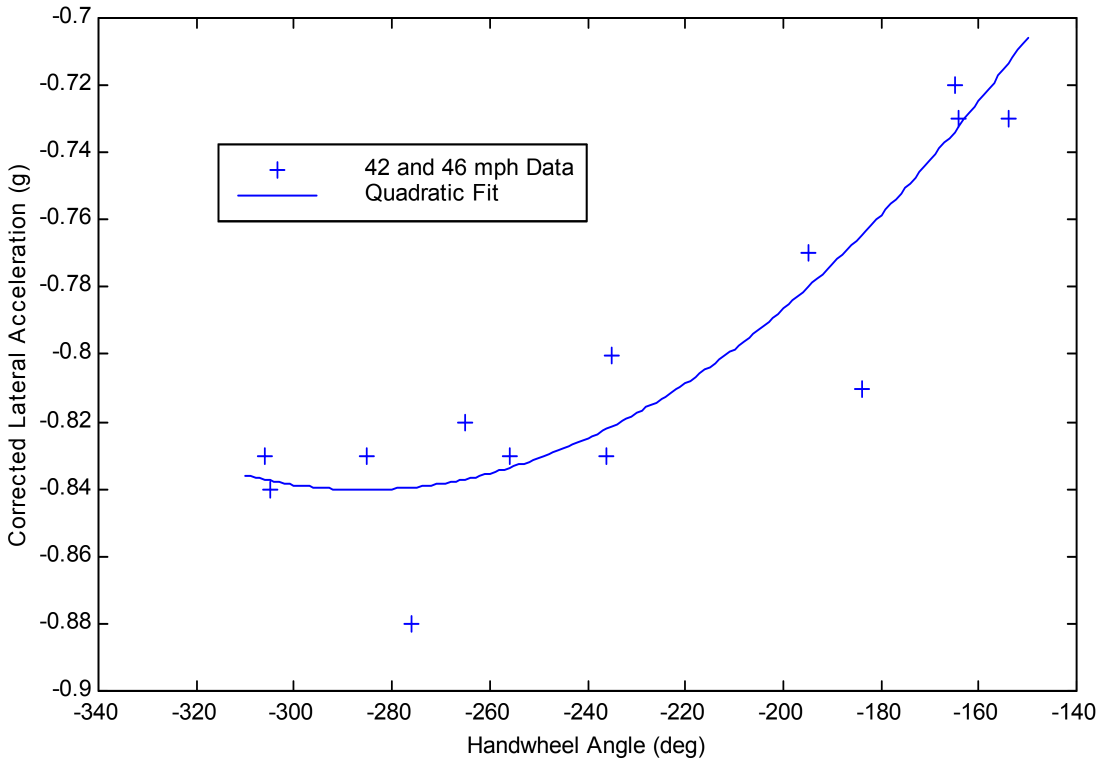

Figure 7.4 – Quadratic Fit of Combined 42 and 46 mph Maximum Corrected Lateral Acceleration versus Steering Input Magnitude Data

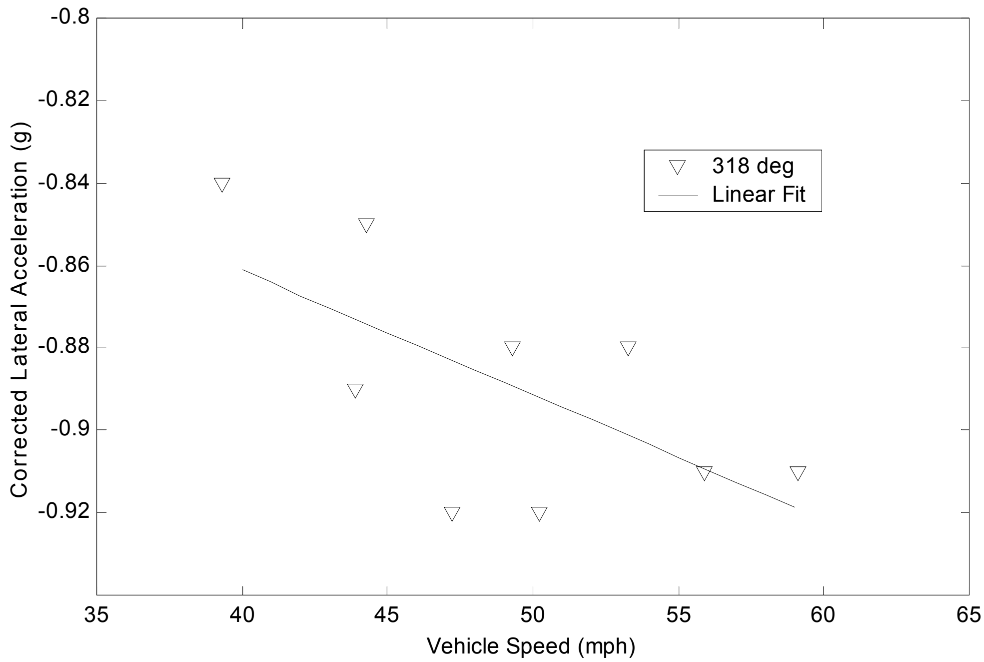

Figure 7.5 – Maximum Corrected Lateral Acceleration versus Vehicle Speed for Toyota 4Runner J-Turn Tests

The 42 and 46 mph Maximum Roll Angle values are plotted as a function of handwheel angle in Figures 7.6 and 7.7, while the 318 degree handwheel angle (varying speed) tests are plotted as a function of speed in Figure 7.8. Linear regressions are included in both Figures 7.6 and 7.8, while a quadratic fit is given in Figure 7.7. The R^2 values for the 42 and 46 mph linear regressions are 0.91 and 0.75 respectively (Figure 7.6). As was the case with Max Ay, the 46 mph slope is less than the 42 mph slope (-0.0081 and 0.0106 deg/deg respectively). As was the case for lateral acceleration, the quadratic trend line (Figure 7.7) appears to give a reasonable fit for the data and suggest that the tires become saturated near 250 degrees of steering input. The 318 degree handwheel angle has an R^2 value of 0.81 and a slope of 0.15 deg/mph (Figure7.8).

Multiple regression analysis for the all of the Maximum Corrected Lateral Acceleration and Roll Angle values showed that both increase with increasing magnitude of handwheel angle and speed. The R^2 values were 0.90 and 0.91 respectively.

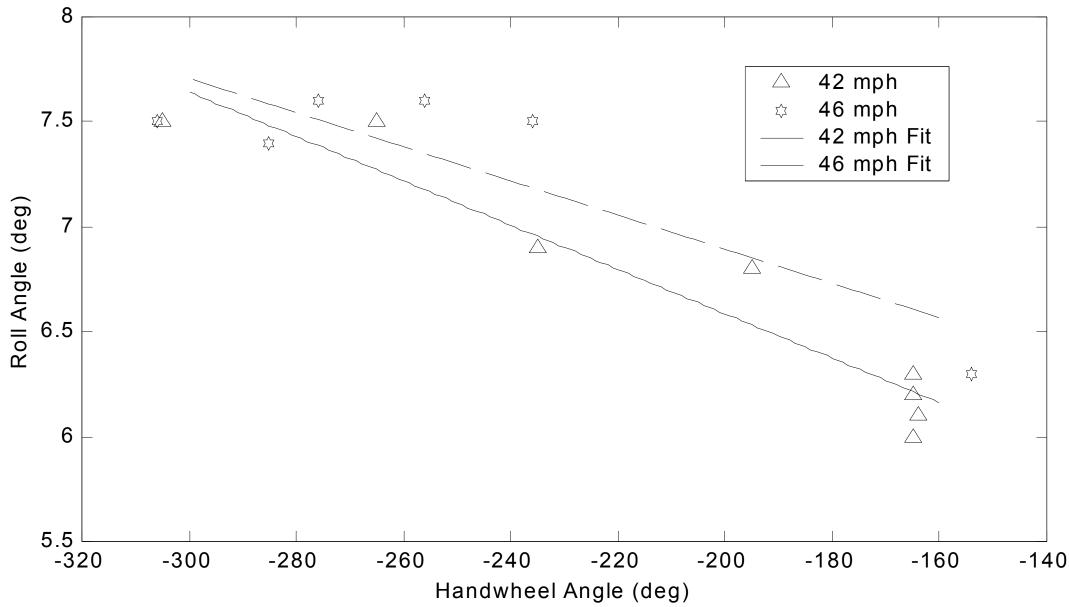

Figure 7.6 – Linear Fits of 42 and 46 mph Maximum Roll Angle versus Steering Input Magnitude Data

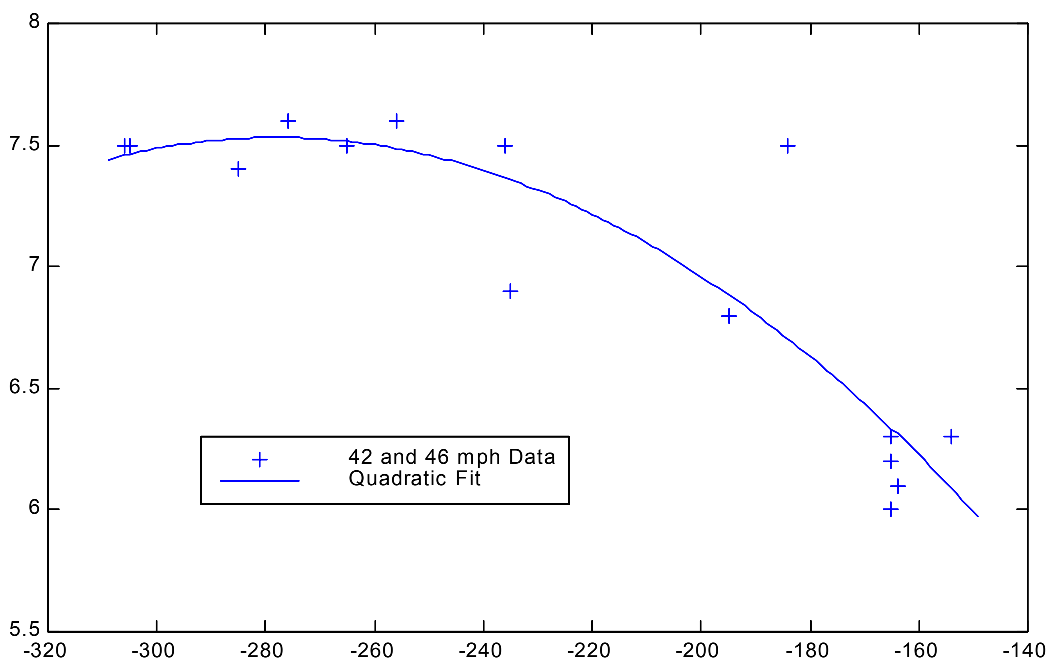

Figure 7.7 – Quadratic Fit of Combined 42 and 46 mph Maximum Roll Angle versus Steering Input Magnitude Data

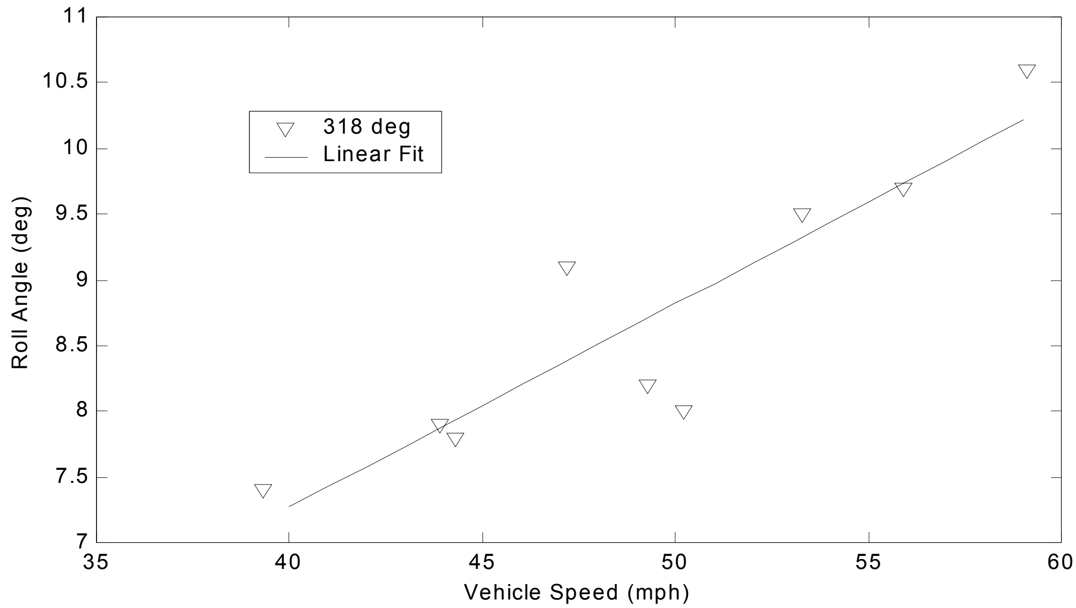

Figure 7.8 - Maximum Roll Angle versus Vehicle Speed for Toyota 4Runner J-Turn Tests

What should be the magnitude of the steering input for the J-Turn maneuver? The results of the above analyses indicate that the magnitude of the J-Turn steering input should be as high as possible. No reduction in Max Ay or Max Roll was seen due to increasing the Steering Input. Therefore, the largest steering input that can easily be generated with a steering stop, ±330 degrees, is recommended for future testing.

7.5 Timing of the Peak Lateral Acceleration and Peak Roll Angle

Figure 7.1 contains results from a test where the peak lateral acceleration occurred after the peak roll angle. The absolute peak lateral acceleration is indicated with the diamond symbol, the peak lateral acceleration prior to the peak roll angle is indicated with the circle, and the peak roll angle is indicated with the triangle.

Preliminary thinking was that the peak lateral acceleration would precede the peak roll angle for all J-Turn tests. This was found to be true for the Ford Bronco II. The Jeep Cherokee and Toyota

4Runner both had tests where the peak lateral acceleration occurred after the peak roll angle. The results shown on Figure 7.1 are typical of these tests.

The occurrence of the peak lateral acceleration in a J-Turn maneuver is closely synchronized with the peak in roll angle. Whether or not the peak lateral acceleration occurs before or after the peak roll angle is dependent on the dynamic response of the vehicle and is dependent on many factors such as shock and spring characteristics and suspension design. The relative timing of the peaks in a J-Turn maneuver does not appear to be a factor in the peak values observed, or whether or not two-wheel lift occurs.

7.6 J-Turn Testing Problems

The J-Turn maneuver is a simple test to conduct relative to other vehicle rollover propensity tests. As mentioned in the previous section, steering rate and constant initial speed should be well controlled to provide the best repeatability.

As described in Chapter 5, the ultrasonic devices used to measure roll angle were problematic, particularly at high roll angles. These problems were especially prevalent in some of the J-Turn testing because the J-Turns were the first series of tests conducted for each vehicle. Some J-Turn test results could not be used due to poor ultrasonic transducer data quality.

7.7 Summary of J-Turn Results

In general, increasing J-Turn severity, by increasing steering magnitude or vehicle initial speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response.

For the Ford Bronco II and Jeep Cherokee the limit responses were plow outs. No two-wheel lift was observed during the J-Turn tests of these two vehicles.

For the Toyota 4Runner the limit response during the J-Turn tests was two-wheel lift. Both minor and moderate two-wheel lifts were observed. However, the two-wheel lifts did not occur until after the 4Runner's tires had significant wear. There is no way to determine (from the data that was collected during this testing) whether or not two-wheel lift would have occurred for the 4Runner if the significant tire wear had not happened.

This testing found that the magnitude of the J-Turn steering input should exceed 250 degrees. No reduction in Maximum Corrected Lateral Acceleration or Maximum Roll Angle was seen due to increasing the Steering Input. Therefore, the largest steering input that can easily be generated with a steering stop, ±330 degrees, is recommended for future testing.

Preliminary thinking was that the peak lateral acceleration would precede the peak roll and for all J-Turn tests. This was found to be true for the Ford Bronco II. The Jeep Cherokee and Toyota 4Runner both had tests where the peak lateral acceleration occurred after the peak roll angle.

The J-Turn maneuver was found to be very repeatable. For any given vehicle, for all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum corrected lateral accelerations varied by, at most, 0.04 g. and the maximum roll angles varied by, at most, 0.5 degrees.

The J-Turn maneuver is a simple test to conduct relative to other vehicle rollover propensity tests. It appears to induce two-wheel lift for some vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. For the above reasons, the J-Turn maneuver is a good candidate for use in a potential dynamic rollover propensity test procedure. As such, further consideration of this maneuver during later phases of NHTSA's Light Vehicle Dynamic Rollover Research program is recommended.

8.0 J-TURN WITH PULSE BRAKING TEST RESULTS AND ANALYSIS

8.1 Tests Performed for Each Vehicle

Table 8.1 summarizes the J-Turn With Pulse Braking tests with valid data that were performed with the Ford Bronco II. Similarly, Table 8.2 summarizes the J-Turn With Pulse Braking tests with valid data that were performed with the Jeep Cherokee. Since the Toyota 4Runner had two-wheel lift during J-Turn (without Pulse Braking) testing, J-Turn With Pulse Braking testing was **not** conducted with this vehicle.

The tables list consists of, the Test Number, Initial Speed, magnitude of the Steering Input (the steering stop was set at a positive angle for J-turns to the right and a negative angle for left turns), Maximum Pedal Force during the brake pulse, Brake Pulse Width, Maximum Corrected Lateral Acceleration prior to (Pre-Pulse) and after (Post-Pulse) the brake pulse, the Maximum Roll Angle prior to and after pulse braking, and the Amount of Two-Wheel Lift (if any). The same nomenclature is used to categorize the amount of two-wheel lift that occurred (if any) as is described in Section 7.1 for the J-Turn (without pulse braking) maneuver.

Brake Pulse Width is defined as the time from when the Brake Pedal Force first rises above 5.0 pounds until the next time when the Brake Pedal Force is below 5.0 pounds. The 5.0 pound limits were used so that transducer noise would not appear to generate false brake pulses.

Initial vehicle speeds of 54.0 mph and higher in Table 8.2 were taken from the test driver's log, as opposed to the data acquisition system. After each test, the test driver recorded the initial speed in the log, rounded to the nearest mile per hour, as shown on the Labeco display. Use of speeds from the log was required because, for safety reasons, a maximum initial speed of 50 mph was originally specified for all testing conditions, and the vehicle's data acquisition system was only configured to record speeds up to 53.0 mph. The maximum allowable initial speed was later increased to 60 mph for some test maneuvers (after safety concerns had been resolved); however, the data acquisition system setup was inadvertently not changed during the Jeep Cherokee testing.

The Jeep Cherokee's four-wheel antilock braking system (ABS) was disabled during this testing. The authors recognize this is not the normal operating condition for this vehicle. The system was disabled because the effects of the brake pulse during a J-Turn were expected to be negligible when the ABS was functional.

During J-Turn With Pulse Braking testing, the abrupt brake pulse was expected to be great enough to lock some (or all) of the vehicle's wheels. This locking of wheels and their subsequent release was expected to make this maneuver more severe than the J-Turn (without Pulse Braking) due to the rapid decrease, then increase in lateral acceleration that the brake pulse imposes on the vehicle. When an ABS detects excessive wheel slip, the line pressure at the affected wheel (or wheels) is released, and a modulation process is initiated. In the J-Turn With Pulse Braking maneuver, this pressure release was expected to greatly reduce the sharp spike in lateral acceleration, and increase in roll angle, that frequently occurs when this maneuver is performed for vehicles without ABS. Therefore, testing the Jeep Cherokee with ABS enabled was expected to result in vehicle responses much like those that were observed in J-Turn (without Pulse Braking) testing. Since the reason for performing the J-Turn With Pulse Braking testing was to determine how the pulse braking affected vehicle responses, the Cherokee's ABS was disabled for the Phase I-A testing.

Table 8.1 -- Summary of J-Turn With Pulse Braking Testing for the Ford Bronco II

Test Number	Initial Speed (mph)	Steering Input (deg)	Max. Pedal Force (lbf)	Brake Pulse Width (sec)	Max. Corrected Lateral Acc., Pre-Pulse (g)	Max. Corrected Lateral Acc., Post-Pulse (g)	Maximum Roll Angle, Pre-Pulse (deg)	Maximum Roll Angle, Post-Pulse (deg)	Amount of Two-Wheel Lift
33	49.0	+330	50	0.65	0.73	0.79	-5.3	-10.6	None
35	49.9	+330	18	0.24	0.80	0.86	-5.9	-6.4	None
37	52.2	+330	66	0.34	0.78	0.83	-5.4	-8.0	None
56	42.1	-330	77	0.56	-0.76	-0.80	4.9	11.7	None
58	45.3	-330	66	0.47	-0.74	-0.85	4.8	13.3	Moderate
59	43.9	-330	60	0.47	-0.80	-0.91	5.2	8.8	Moderate
60	45.1	-330	38	0.45	-0.81	-0.93	5.1	8.1	Moderate
68	43.0	-330	42	0.50	-0.78	-0.80	4.7	8.0	Minor
69	44.0	-330	55	0.50	-0.75	-0.86	4.5	9.7	Moderate
87	40.2	-330	61	0.45	-0.74	-0.72	5.2	6.4	None
88	42.3	-330	95	0.45	-0.73	-0.81	5.5	11.8	None
89	44.3	-330	92	0.40	-0.73	-0.86	5.5	11.8	None

Table 8.2 -- Summary of J-Turn With Pulse Braking Testing for the Jeep Cherokee

Test Number	Initial Speed (mph)	Steering Input (deg)	Max. Pedal Force (lbf)	Brake Pulse Width (sec)	Max. Corrected Lateral Acc., Pre-Pulse (g)	Max. Corrected Lateral Acc., Post-Pulse (g)	Maximum Roll Angle, Pre-Pulse (deg)	Maximum Roll Angle, Post-Pulse (deg)	Amount of Two-Wheel Lift
164	39.8	-330	170	0.57	-0.85	-0.81	6.3	5.4	None
165	42.1	-330	178	0.55	-0.86	-0.79	5.0	5.0	None
166	46.1	-330	192	0.54	-0.84	-0.81*	5.1	6.3	None
167	48.6	-330	207	0.48	-0.82	-0.82*	5.4	6.6	None
168	50.2	-330	171	0.56	-0.87	-0.80	5.6	5.1	None
169	51.3	-330	204	0.51	-0.83	-0.81*	5.4	5.2	None
170	52.4	-330	179	0.58	-0.89	-0.82*	5.3	5.3*	None
171	52.4	-330	182	0.68	-0.82	-0.82*	5.0	4.9*	None
172	52.4	-330	212	0.44	-0.83	-0.81*	5.6	6.4	None
173	45.1	-640	145	0.49	-0.77	-0.71*	5.6	4.5*	None
175	41.2	-180	130	0.75	-0.86	-0.76	5.5	5.8	None
176	45.3	-180	173	0.53	-0.89	-0.96	5.7	8.9	None
177	44.2	-180	206	0.53	-0.86	-0.86	5.1	7.9	None
179	48.9	-180	204	0.64	-0.85	-0.86*	5.3	6.6	None
180	51.3	-180	205	0.52	-0.85	-0.84	5.7	8.1	None
181	50.2	-120	175	0.59	-0.76	-0.74	4.6	5.3	None
182	51.4	-140	209	0.49	-0.82	-0.85	5.2	6.5	None
183	51.5	-160	198	0.51	-0.86	-0.89	5.9	7.3	None

Table 8.2 -- Summary of J-Turn With Pulse Braking Testing for the Jeep Cherokee (continued)

Test Number	Initial Speed (mph)	Steering Input (deg)	Max. Pedal Force (lbf)	Brake Pulse Width (sec)	Max. Corrected Lateral Acc., Pre-Pulse (g)	Max. Corrected Lateral Acc., Post-Pulse (g)	Maximum Roll Angle, Pre-Pulse (deg)	Maximum Roll Angle, Post-Pulse (deg)	Amount of Two-Wheel Lift
184	50.6	-200	198	0.58	-0.90	-0.86*	5.1	7.3	None
185	50.9	-200	206	0.59	-0.81	-0.86*	4.9	7.4	None
186	51.3	-200	208	0.52	-0.87	-0.84*	5.4	7.8	None
188	54.0	-200	210	0.59	-0.82	-0.85	8.7	9.7	None
189	56.0	-200	206	0.57	-0.86	-0.87	8.5	8.0	None
191	56.0	-160	203	0.55	-0.84	-0.86	5.1	8.3	None
192	58.0	-160	207	0.48	-0.86	-0.91	6.0	8.5	None
193	58.0	-140	183	0.55	-0.85	-0.93	5.9	9.1	None
194	60.0	-140	188	0.56	-0.84	-0.82	7.4	7.9	None
215	46.6	+320	176	0.32	0.87	0.85	-5.7	-6.1	None
216	52.2	+340	211	0.42	0.86	0.84*	-5.5	-7.3	None
217	54.0	+340	211	0.41	0.86	0.85*	-5.9	-7.9	Minor
218	54.0	+330	202	0.32	0.84	0.84*	-5.8	-6.8	Minor
219	56.0	+330	206	0.40	0.87	0.88	-5.3	-8.5	Moderate
220	58.0	+320	203	0.58	0.83	0.88	-6.2	-7.8	Moderate

* Value obtained after the start of a second brake application.

An important difference between the driver inputs used for Ford Bronco II and Jeep Cherokee testing was the unexpected presence of secondary brake applications with the Cherokee. Although the test driver received the same brake application instructions for both vehicles, multiple applications were recorded for all valid Jeep Cherokee tests. All secondary brake applications were much less than the preceding pulses, often by a factor of ten. Four tests containing multiple brake applications occurred during Ford Bronco II J-Turn With Pulse Braking testing; however, these tests were considered to be not valid since the second applications were hard brake pulses. Figure 8.1 shows the multiple brake pedal force applications of Ford Bronco II Test Number 36 while Figure 8.2 shows the multiple brake pedal force applications for Jeep Cherokee Test Number 180.

The authors do not know why the test driver applied additional brake applications in such close proximity to the single "intentional" pulse during Jeep Cherokee testing. The most likely explanation is that the driver's foot inadvertently came in contact with the brake pedal due to the physical demands execution of this maneuver placed on the driver.

To be aware of when these secondary brake application might have caused confounding effects to occur, the start times of the secondary brake applications for the Jeep Cherokee were determined and compared to the times of Post-Pulse Maximum Corrected Lateral Accelerations, roll rates, and Roll Angles.

Table 8.3 shows the times from the start of the secondary brake application to the Post-Pulse Maximum Corrected Lateral Acceleration and/or Roll Angle for 14 Jeep Cherokee tests. The Post-Pulse Maximum Corrected Lateral Accelerations and Roll Angles of the remaining 19 Jeep Cherokee tests occurred before the secondary brake application began. While not shown in Table 8.3, the post-pulse maximum roll rate occurred prior to secondary brake application for all tests.

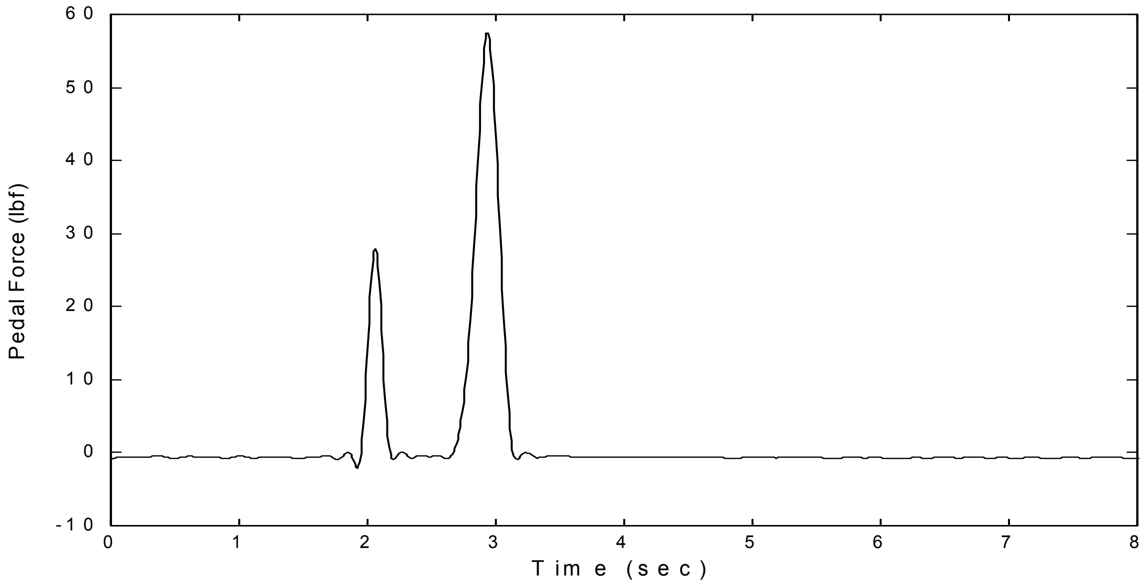

Figure 8.1 -- Brake Pedal Force versus Time for Ford Bronco II J-Turn With Pulse Braking Test Number 36 - Not Valid Test

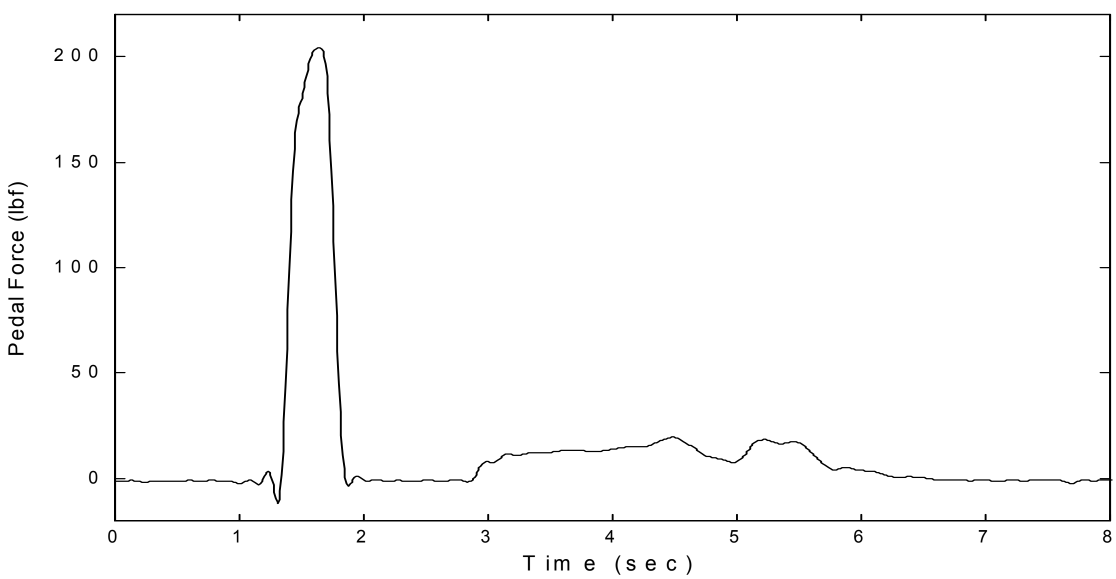

Figure 8.2 -- Brake Pedal Force versus Time for Jeep Cherokee J-Turn With Pulse Braking Test Number 180 - Valid Test

Table 8.3 -- Timing of Maximum, Post-Pulse, Corrected Lateral Acceleration and Roll Angle Peaks Relative to Start of Secondary Brake Applications for Jeep Cherokee J-Turn With Pulse Braking Testing

Test Number	Initial Speed (mph)	Time From Start Of Second Brake Application		Amount of Two-Wheel Lift
		To Post-Pulse Max Cor. Lat. Accel. (sec.)	To Post-Pulse Max Roll Angle (sec.)	
166	46.1	0.04	Not Applicable	None
167	48.6	0.12	Not Applicable	None
169	51.3	0.07	Not Applicable	None
170	52.4	0.20	0.09	None
171	52.4	0.52	0.59	None
172	52.4	0.08	Not Applicable	None
173	45.1	2.09	2.25	None
179	48.9	0.05	Not Applicable	None
184	50.6	0.11	Not Applicable	None
185	50.9	0.14	Not Applicable	None
186	51.3	0.15	Not Applicable	None
216	52.2	0.15	Not Applicable	None
217	54.0	0.24	Not Applicable	Minor
218	54.0	0.55	Not Applicable	Minor

Fourteen Post-Pulse Maximum Corrected Lateral Acceleration peaks occurred after the second brake pulse, and two-wheel lift was observed for two of these runs. These two runs, however, were conducted at higher test speeds than the other 14 tests, and were the only ones to include positive (clockwise) steering inputs. Only three of the 33 Jeep Cherokee Post-Pulse Maximum Roll Angles occurred after the secondary brake application, and two-wheel lift was not observed during any of these tests.

To distinguish tests for which the secondary brake application might have had a confounding effect upon the data, if the beginning of a secondary application was found to be before a particular post-pulse maximum response, it is specified in Table 8.2 with an asterisk. Based on the Phase I-A testing results, the effects of the secondary brake applications on the Jeep Cherokee's rollover propensity appear to be less significant than the effects of the maneuver's Initial Speed.

8.2 The J-Turn With Pulse Braking and Rollover Propensity

For both of the vehicles tested, the Ford Bronco II and the Jeep Cherokee, two-wheel lifts were observed during the J-Turn With Pulse Braking testing. Both vehicles had both minor and moderate two-wheel lifts. Since neither of these vehicles had two-wheel lifts during the J-Turn (without Pulse Braking), this demonstrates that the addition of pulse braking to the J-Turn maneuver can result in two-wheel lift as well as higher, Post-Pulse, Maximum Corrected Lateral Accelerations and Roll Angles.

Figures 8.3 through 8.6 illustrate these higher, post-pulse, maximum corrected lateral accelerations and roll angles for the Ford Bronco II. These figures show selected data channels as a function of time from Test Numbers 59 and 60. Both of these tests resulted in two-wheel lift. Figure 8.3 shows vehicle speed, handwheel angle, and brake force data channels; Figure 8.4 shows lateral acceleration and roll angle data channels; and Figure 8.5 roll rate and yaw rate data channels. Figure 8.6 shows the left and right side ride height sensor data channels for Test Number 60.

The upper graph in Figure 8.4 shows that the corrected lateral acceleration for both tests was about -0.80 g prior to braking. After braking, the corrected lateral acceleration was oscillatory with a peak value of -0.91 g for Test Number 59 and -0.93 g for Test Number 60. The lower graph in Figure 8.4 shows that the roll angle for both tests was about 5 degrees prior to braking and in the range of 8 to 9 degrees (enough to result in moderate two-wheel lift) after the pulse braking.

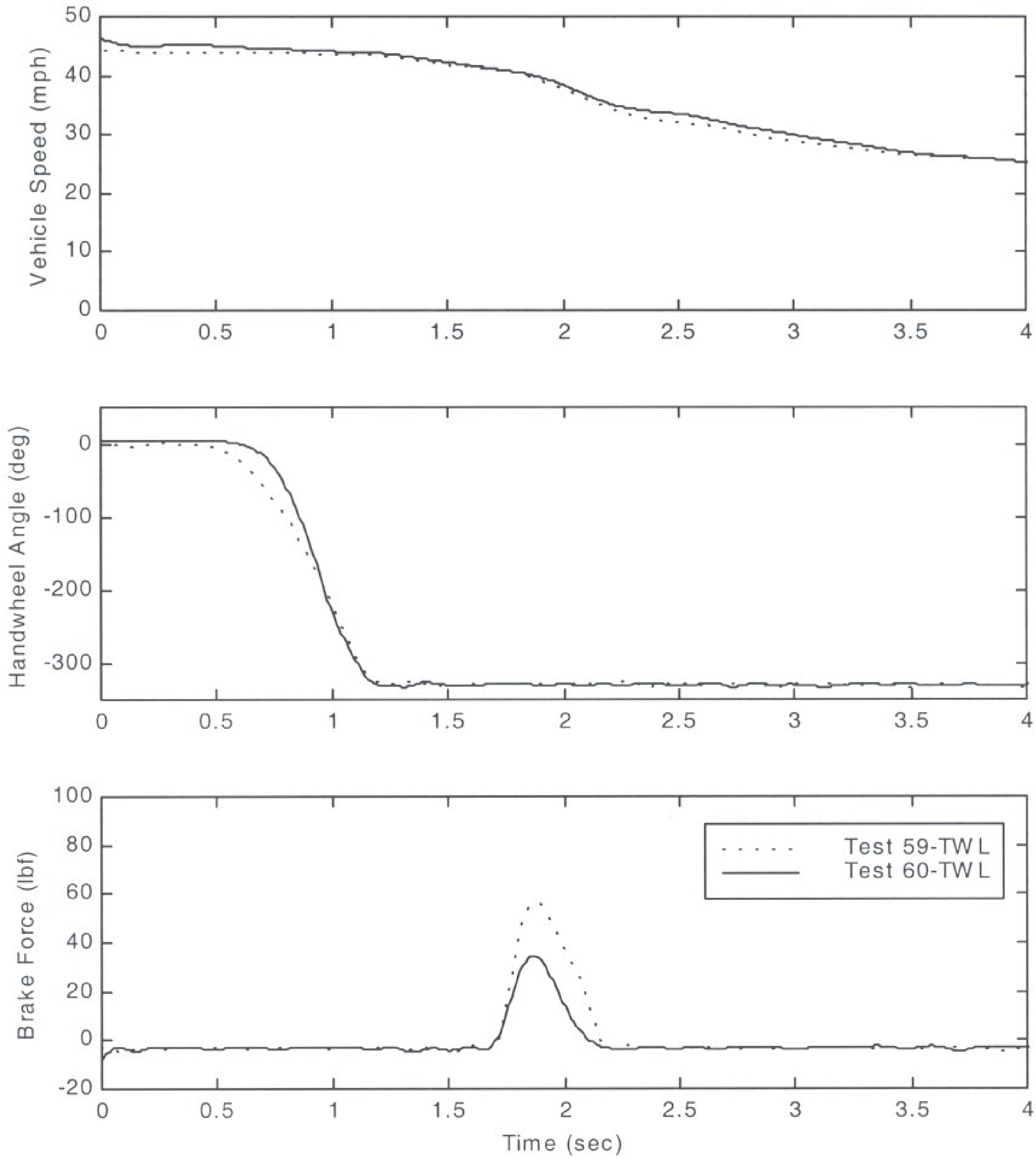

Figure 8.3 -- Vehicle Speed, Handwheel Angle, and Brake Force versus Time for Two Ford Bronco II J-Turn With Pulse Braking Tests

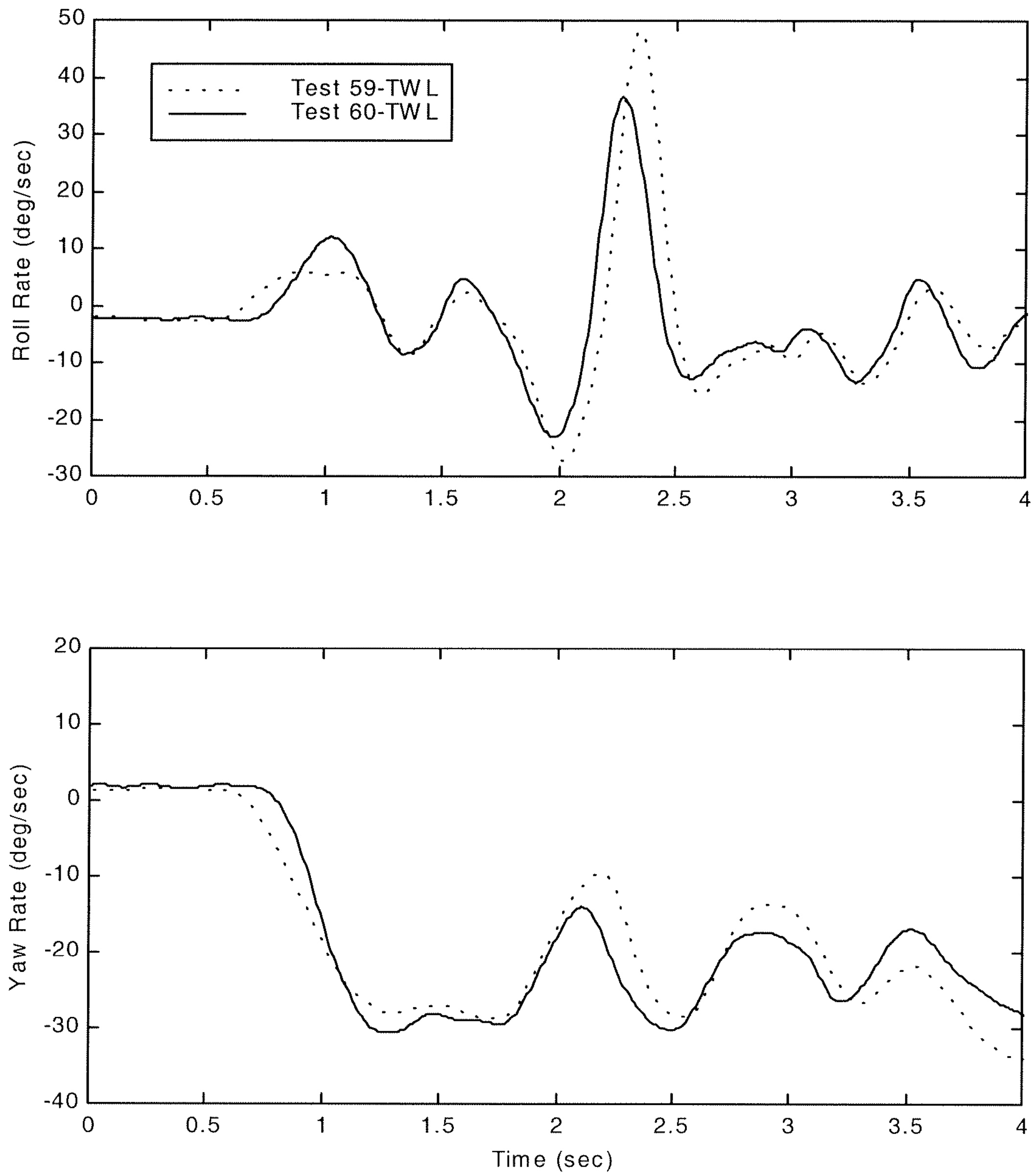

Figure 8.4 -- Corrected Lateral Acceleration and Roll Angle versus Time for Two Ford Bronco II J-Turn with Pulse Braking Tests

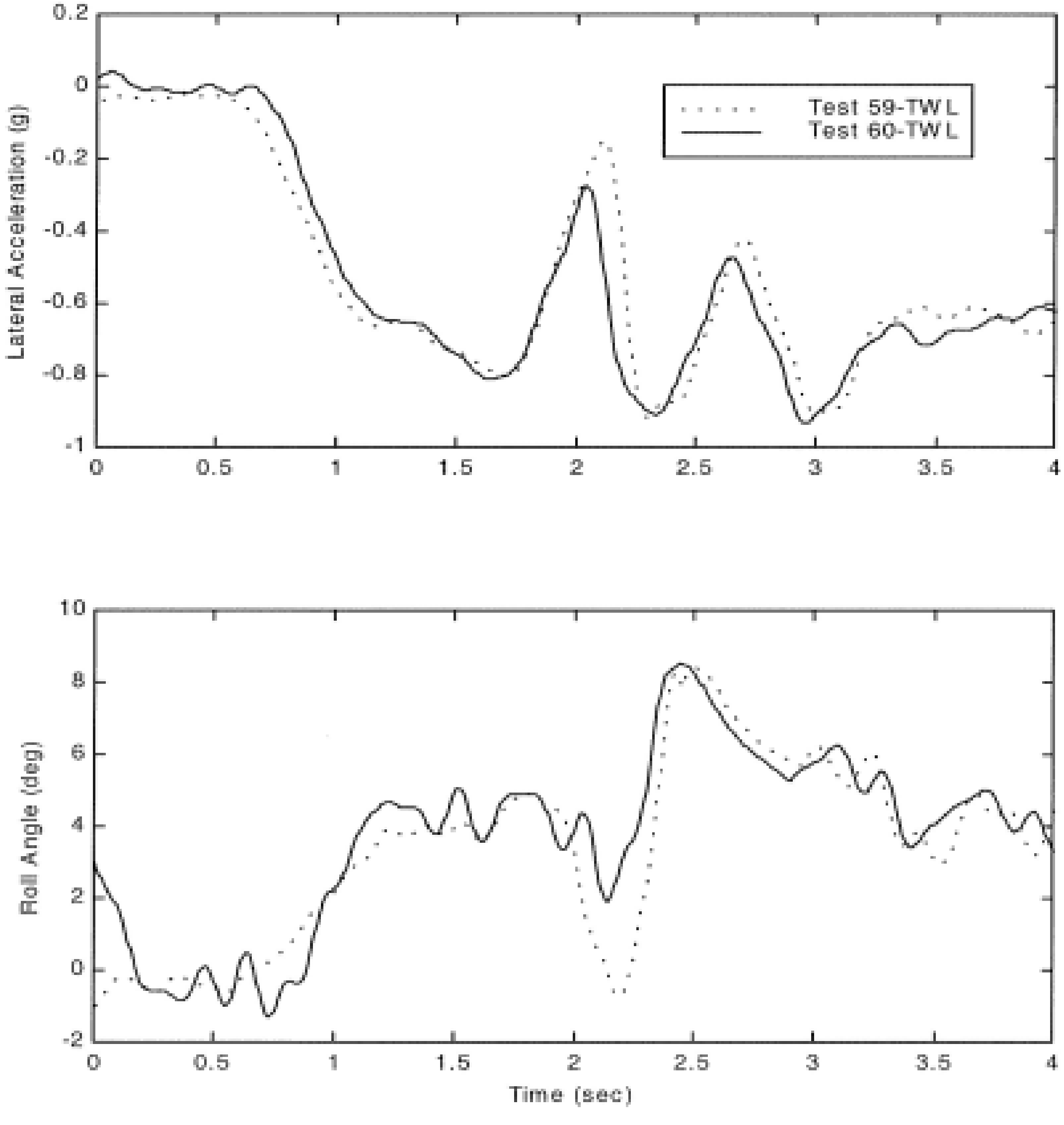

Figure 8.5 -- Roll Rate and Yaw Rate versus Time for Two Ford Bronco II J-Turn with Pulse Braking Tests

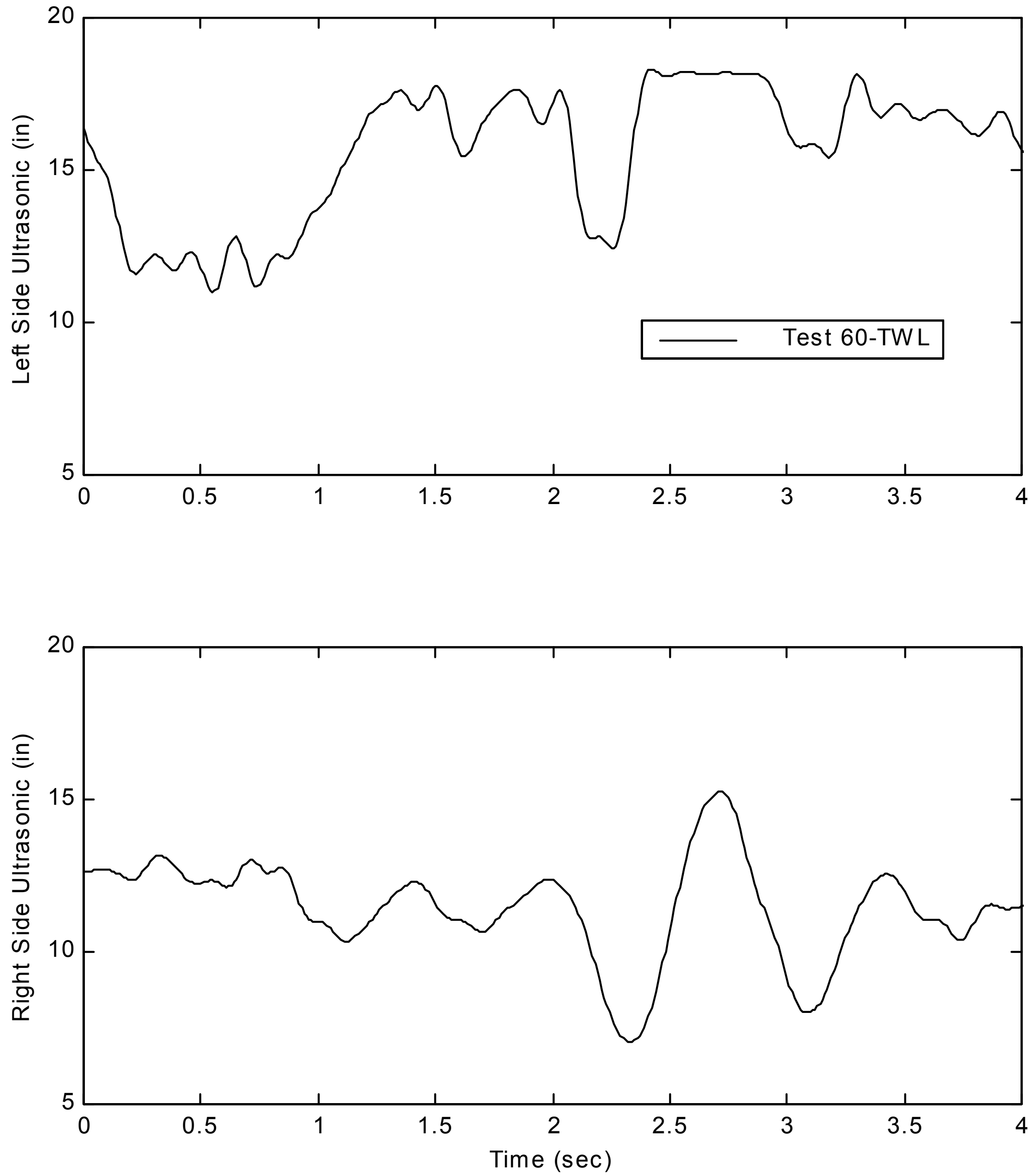

Figure 8.6 -- Left and Right Side Ultrasonic Outputs versus Time for One Ford Bronco II J-Turn With Pulse Braking Test

Why did the Ford Bronco II have higher corrected lateral acceleration and roll angle peaks after pulse braking was performed? During pulse braking the lateral force capabilities of the tires decreased. As a result, roll angle and lateral acceleration decreased significantly as the vehicle decelerated, pitched forward, and partially straightened its path. Once the braking ceased, the lateral force capabilities of the tires quickly increased. This resulted in the lateral acceleration and roll rate increasing rapidly (more rapidly than during the initial J-Turn). These rapid increases coupled with the vehicle's tendency to pitch and heave in the direction of its pre-braking state typically caused significant increases in peak corrected lateral acceleration and roll angle. In some cases, these increases were enough to result in two-wheel lift (even though this vehicle did not have two-wheel lift for the J-Turn (without Pulse Braking) maneuver).

Similar results were seen for the Jeep Cherokee. Figures 8.7 through 8.9 show selected data channels as functions of time from Test Number 218, which resulted in two-wheel lift. Figure 8.7 shows the vehicle speed, handwheel angle, and brake force data channels; Figure 8.8 shows the lateral acceleration and roll angle data channels; and Figure 8.9 the roll rate and yaw rate data channels. For several of the two-wheel lift cases, the corrected lateral acceleration shortly after the pulse brake is at a slightly lower level than that prior to the pulse. This is evident in the lateral acceleration trace for Test Number 218 which is shown in the upper graph of Figure 8.8. Even though the lateral acceleration is slightly lower, the corresponding roll angle is much greater as is seen in the lower trace of Figure 8.8. This increase in roll angle resulted in two-wheel lift for this run.

As was the case for the J-Turn (without Pulse Braking), the severity of the J-Turn With Pulse Braking maneuver appears, in general, to be increased by increasing either the magnitude of the Steering Input or Initial Speed. However, as is discussed in Sections 8.4 and 8.5, below, both the magnitude and width of the brake pulse influence the severity of a particular test run.

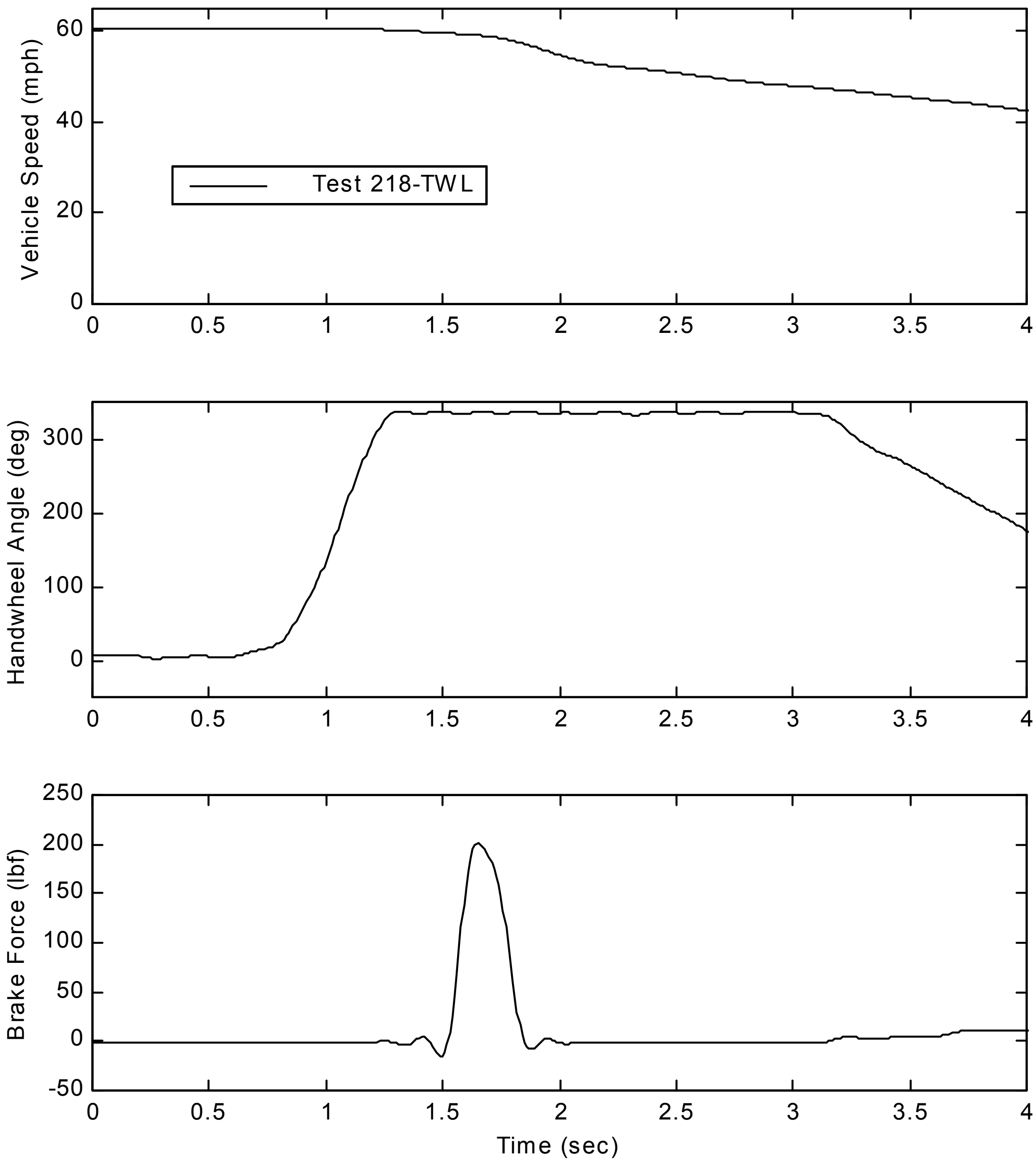

Figure 8.7 -- Vehicle Speed, Handwheel Angle, and Brake Force versus Time for a Jeep Cherokee J-Turn With Pulse Braking Test

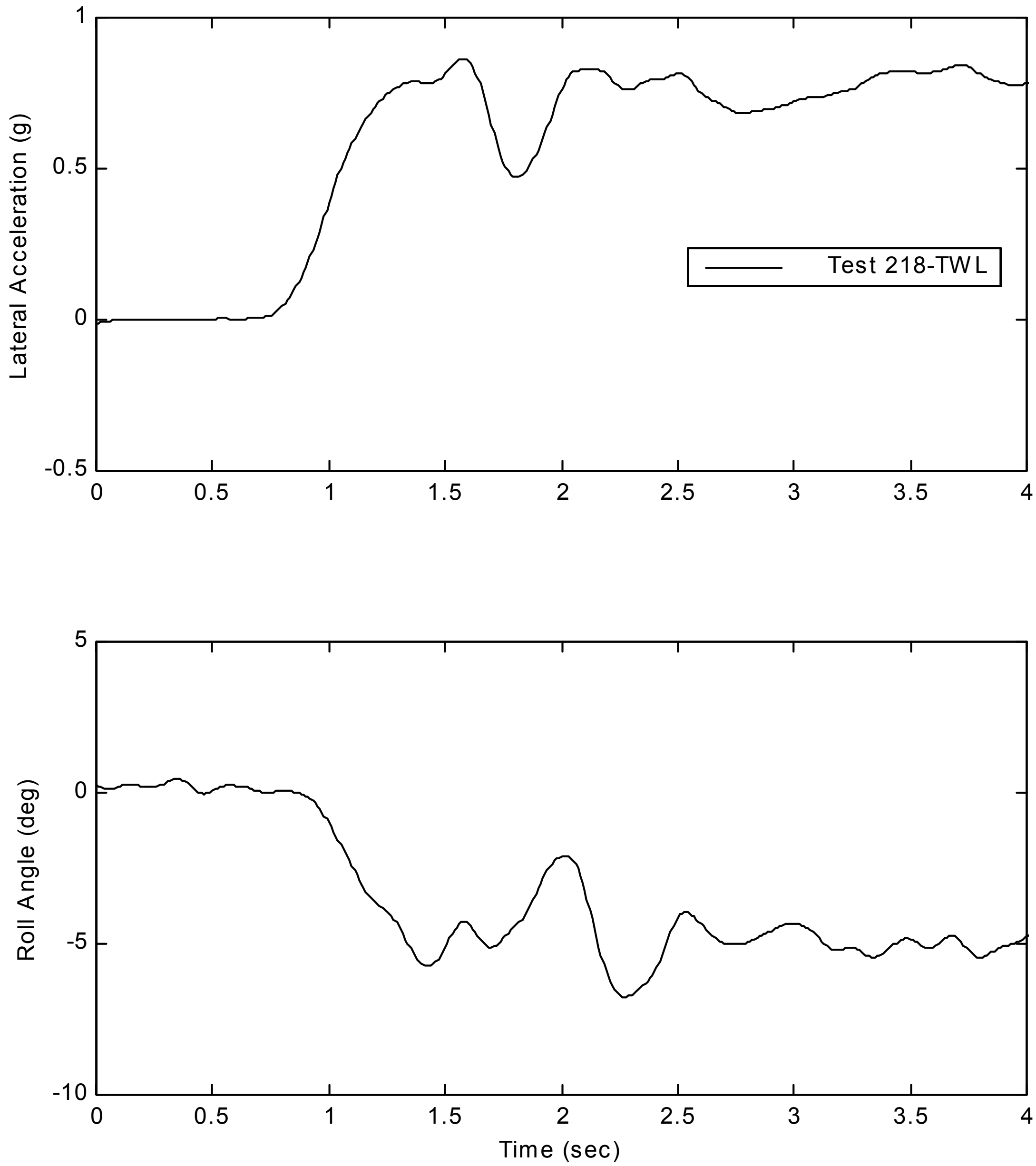

Figure 8.8 -- Corrected Lateral Acceleration and Roll Angle versus Time for a Jeep Cherokee J-Turn With Pulse Braking Test

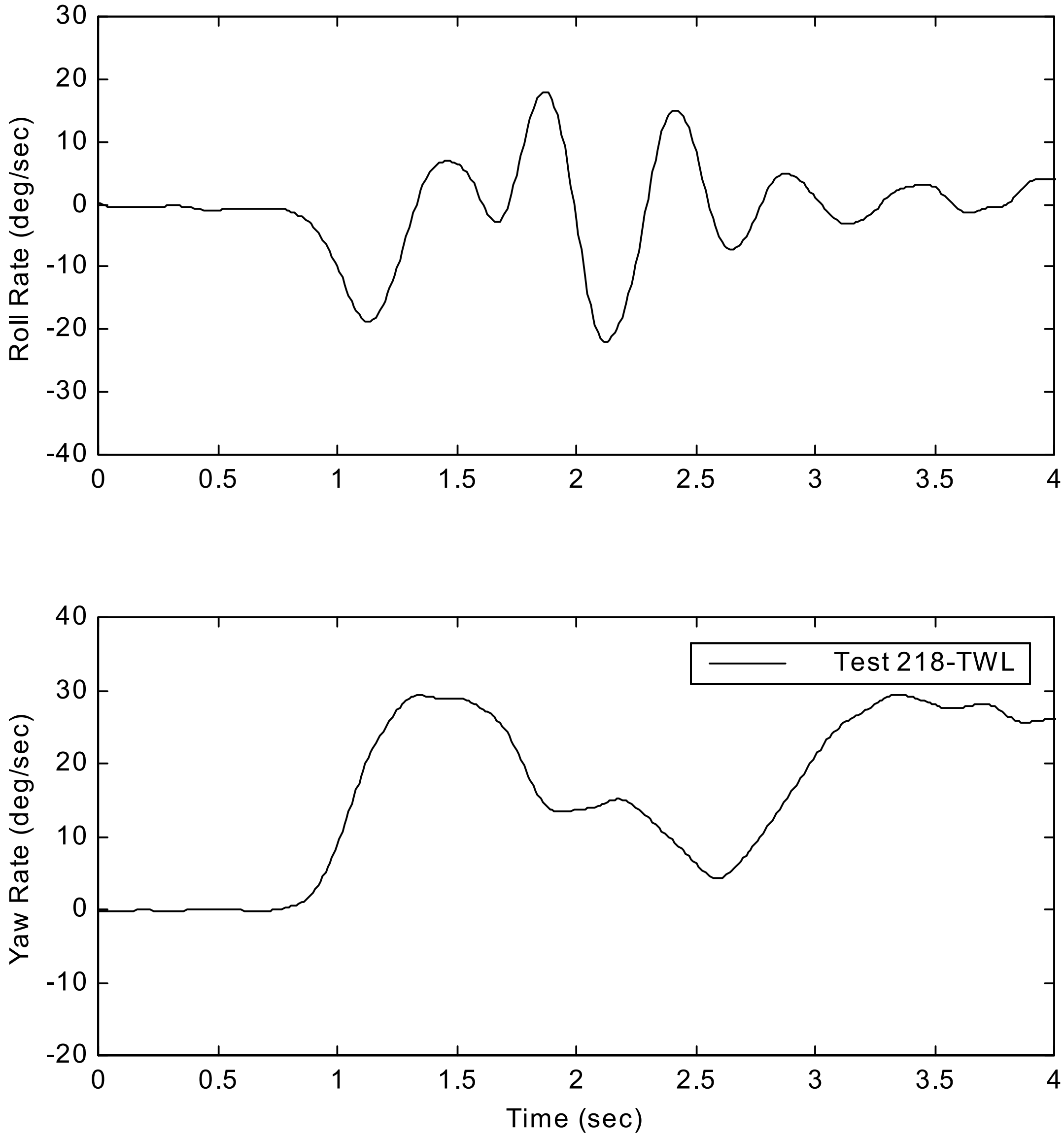

Figure 8.9 -- Roll Rate and Yaw Rate versus Time for a Jeep Cherokee J-Turn With Pulse Braking Test

For both the Ford Bronco II and the Jeep Cherokee, the limit condition for the J-Turn With Pulse Braking appears to depend upon the direction in which the individual test run was made.

Examining Table 8.1, for the Ford Bronco II, left turns (negative handwheel steer angle) were used for all runs that produced two-wheel lift. Two-wheel lift was observed for left-turn tests with Initial Speeds of 43.9, 44.0, 45.1, and 45.3 mph. Even right-turn runs with substantially higher initial test speeds (up to 52.2 mph), nearly equivalent steering/brake inputs, and similar pre/post-pulse brake lateral accelerations did not produce two-wheel lift. Plow outs appear to be the limit condition for this vehicle for right turns with pulse braking, although it should be noted that only a small amount of testing was performed in this direction. It should be noted that the brake pedal forces for the Bronco II tests are much lower than those for the Cherokee. In Phase IB, higher brake forces will be evaluated.

Examining the results in Table 8.2, for the Jeep Cherokee, right turns (positive handwheel steer angle) were used for all runs that produced two-wheel lift. Two-wheel lift was observed for right-turn tests beginning with initial test speeds of 54.0, 56.0, and 58.0 mph. Even left-turn runs with initial test speeds of up to 60.0 mph did not induce two-wheel lift. Note that the highest speed left-turn runs (greater than 54 mph) used much smaller handwheel steer angles (140, 160, and 200 degrees) than the right-turn runs with two-wheel lift (320, 330, and 340 degrees). Interestingly, the maximum post-pulse corrected lateral accelerations of two left turns conducted at 58 mph using handwheel angles of 140 and 160 degrees were found to be 0.93 and 0.91 g, respectively. There was no two-wheel lift for these runs. Using a handwheel angle of 320 degrees, the 58 mph right turn test resulted in a maximum post-pulse corrected lateral acceleration of 0.88 g and moderate two-wheel lift. Plow outs appear to be the limit condition for this vehicle for left turns with pulse braking.

8.3 Repeatability of the J-Turn With Pulse Braking

The J-Turn With Pulse Braking tests were less repeatable than were the J-Turn (without pulse braking) tests. The J-Turn With Pulse Braking maneuver has five primary test parameters: Initial Speed, Steering Input, Maximum Pedal Force, Brake Pulse Width, and Time of Pulse Start (this last parameter is not listed in either Table 8.1 or 8.2) as compared to two for J-Turn (without pulse braking) maneuver: Initial Speed and Steering Input. Both the Maximum Pedal Force and Brake Pulse Width were difficult for the driver to control in a precise and repeatable fashion. Although the test driver was instructed to keep the Time of Pulse Start constant throughout this testing, no electronic or mechanical assistance was provided to the driver, so there were inevitably run-to-run differences.

With five primary test parameters, especially since three of these test parameters were difficult for the driver to control in a precise and repeatable fashion, only a few runs with close to the same nominal test parameters were made. However, for each vehicle, the two runs with the closest Initial Speed and the two runs with the closest brake pulse parameters were found and analyzed for repeatability.

For the Ford Bronco II, the two test runs with the closest Initial Speed (differing by 0.1 mph) were Test Numbers 59 and 69. These two tests had the same Steering Input. Maximum Pedal Forces were 60 and 55 pounds (force), respectively, and the Brake Pulse Widths were 0.47 and 0.50 seconds, respectively. Since the differences between these two runs' brake pulse parameters were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Ford Bronco II Tests 59 and 69 had the same amount of two-wheel lift (Moderate). Test 59 had Maximum Corrected Lateral Accelerations, both Pre-Pulse and Post-Pulse, that were larger, in absolute value, than those of Test 69 by 0.05 g. The Pre-Pulse Maximum Roll Angle for Test 59 exceeded that of Test 69 by 0.7 degrees, but Test 69 had a larger Post-Pulse Maximum Roll Angle by 0.9 degrees.

For the Ford Bronco II, the two test runs with the closest brake pulse parameters (a Maximum Brake Pedal Force difference of 1 pound (force) and a Brake Pulse Width difference of 0.02 seconds) were Test Numbers 59 and 87. These two tests had the same Steering Input. The Initial Speeds were 43.9 and 40.2 mph, respectively. Since the difference between these two runs' Initial Speeds was substantial (the authors consider speed differences greater than 2.0 mph substantial), it is **not** reasonable to expect these two runs to produce the same results.

Since Ford Bronco II Test Number 59 was run with a higher Initial Speed than was Test Number 87, Test 59 is expected to have been a more severe test. This is shown by the data with Test 59 having larger, in absolute value, Pre-Pulse and Post-Pulse Maximum Corrected Lateral Accelerations, a larger Post-Pulse Maximum Roll Angle, and a Moderate (compared to None) amount of two-wheel lift. The Pre-Pulse Maximum Roll Angle was the same for the two tests.

For the Jeep Cherokee, several pairs of tests were run with the same Initial Speeds. Of these pairs, the two test runs with the same Steering Inputs and the closest brake pulse parameters were Test Numbers 170 and 171. These two tests had Maximum Pedal Forces of 179 and 182 pounds (force), respectively, and Brake Pulse Widths of 0.58 and 0.68 seconds, respectively. Since the differences between these two runs' brake pulse parameters were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Jeep Cherokee Tests 170 and 171 had no two-wheel lift. Test 170 had a Pre-Pulse Maximum Corrected Lateral Acceleration that was larger than that of Test 171 by 0.07 g. The two tests had the same Post-Pulse Maximum Corrected Lateral Accelerations. The Pre-Pulse Maximum Roll Angle for Test 170 exceeded, in absolute value, that of Test 171 by 0.3 degrees, while Test 170 had a larger, in absolute value, Post-Pulse Maximum Roll Angle by 0.4 degrees.

For the Jeep Cherokee, the two test runs with the closest brake pulse parameters (no difference in the Maximum Brake Pedal Force and a Brake Pulse Width difference of 0.01 seconds) were Test Numbers 216 and 217. These two tests had the same Steering Input and Initial Speeds of 52.2 and 54.0 mph, respectively. Since the difference between these two runs Initial Speeds is approaching, but not quite, substantial (the authors consider speed differences greater than 2.0 mph substantial), it is reasonable to compare data from these two runs to get a measure of maneuver repeatability. However, Test Number 217 is expected to have been a slightly more severe test than Test 216.

The actual data matches this expectation. Tests 216 and 217 have identical Pre-Pulse Maximum Corrected Lateral Accelerations and almost the same Post-Pulse Maximum Corrected Lateral Accelerations. (Test 217's Post-Pulse Maximum Corrected Lateral Acceleration is 0.01 g larger than Test 216's. This difference is less than the amount of accelerometer noise thought to be present.) Test 217 has larger, in absolute value, Pre-Pulse and Post-Pulse Maximum Roll Angles (by 0.4 and 0.6 degrees, respectively) than does Test 216. Test 217 also had a Minor (compared to None for Test 216) amount of two-wheel lift.

A final measure of repeatability is to look at the pattern of two-wheel lifts that occurred. For the Ford Bronco II, Table 8.1 shows that two-wheel lifts occurred for tests with left-turns and Initial Speeds of 43.9, 44.0, 45.1, and 45.3 mph. Two-wheel lift was not observed for left-turn runs made with Initial Speeds of 40.2, 42.1, 42.3, 43.0, and 44.3 mph. Except for the 44.3 mph run, all left-turn runs with two-wheel lift were at higher Initial Speeds than the left turns without two-wheel lift. As is discussed below in **Section 8.6, Miscellaneous J-Turn With Pulse Braking Testing Problems**, the 44.3 mph run may not have had two-wheel lift solely because the rear outrigger struck the ground during the maneuver.

From Table 8.2, looking at the Jeep Cherokee, two-wheel lift occurred for right-turn runs with Initial Speeds of 54.0, 56.0, and 58.0 mph. Two-wheel lift was not observed for right-turn runs made with Initial Speeds of 46.6 and 52.2 mph. All right-turn runs with two-wheel lift were conducted at higher speeds than those without two-wheel lift, although it is acknowledged that only six such test runs were performed during this research.

In summary, during this research, only a limited number of tests were conducted over a range of initial test speeds, steering inputs, and brake pulse parameters. Completely assessing repeatability, with so few tests is not possible. That said, the data collected shows that although the J-Turn With Pulse Braking maneuver is not as repeatable as is the J-Turn (without Pulse Braking), it is repeatable. Only small differences were seen between data from runs that were expected to be comparable. Run severity increases when expected. The Ford Bronco II only had one run for which two-wheel lift did not occur when it was anticipated to do so, and that may have been entirely due the rear outrigger striking the ground during the maneuver. The difference between the slowest left-turn run for which two-wheel lift occurred and the fastest left-turn run for which two-wheel lift did not occur was only 0.4 mph. For the Jeep Cherokee, no right-turn runs without two-wheel lift were made at higher speeds than the speed of the slowest right-turn run with two-wheel lift.

8.4 Effects of Magnitude of Brake Pedal Force on J-Turn With Pulse Braking Results

As shown in Figure 8.3, the Maximum Pedal Forces of Test Numbers 59 and 60 are quite different; however, both tests resulted in moderate two-wheel lift. The effects of the greater brake pedal force are clearly evident in Figures 8.4 and 8.5. The lateral acceleration and yaw rate for Test Number 59 (more braking) were reduced more than for Test Number 60. The negative roll rate peak (during the pulse brake, while the vehicle was decreasing its roll angle from of the initial J-Turn) and positive roll rate peak (after the brake pulse, while the vehicle was rolling back up after the pulse) are both of greater magnitude as a result of the stronger brake pulse of Test Number 59.

Analysis of Table 8.1 shows that a wide range of pedal forces were used to generate the brake pulses used for Ford Bronco II testing. The largest applied force was 95 lbf, the smallest force 18 lbf, and the average force 60 lbf. Similarly, Table 8.2 shows the large range of pedal forces used to generate the brake pulses for the Jeep Cherokee. The largest applied force was 212 lbf, the smallest force 130 lbf, and the average force 193 lbf.

The large ranges of brake pedal forces are not surprising given the exploratory nature of this research. Reasonably consistent pedal force applications can be obtained by the test driver. This is demonstrated by the last 21 test runs in Table 8.2. By this point in the research, the authors thought that they had established what the desired brake pedal force pulse was (at least for the Jeep Cherokee). The range of pedal forces for these runs was from 175 lbf to 211 lbf with an average of force of 200 lbf. Seventeen out of 21 of these tests had brake pedal forces within ± 10 lbf of the average value.

The effect of pulse braking on lateral acceleration is inconsistent. For each test listed in Tables 8.1 and 8.2, the absolute value of the maximum pre-pulse corrected lateral acceleration was subtracted from the absolute value of the post-pulse maximum corrected lateral acceleration to produce a quantity called Delta Ay. For the Ford Bronco II tests, Delta Ay had a maximum value of 0.13 g, a minimum value of -0.02 g, and an average value of 0.07 g. For the Jeep Cherokee tests, Delta Ay had a maximum value of 0.08 g, a minimum value of -0.10 g, and an average value of -0.01 g.

Figures 8.10 and 8.11 present the Delta Ay values as a function of Maximum Pedal Force for the Ford Bronco II and Jeep Cherokee, respectively, along with linear regression lines based on this data. The data generally tends to increase with Maximum Pedal Force; however, there is a great deal of scatter in the data. The correlation coefficients of the best fit linear regression lines, R^2, were quite low (0.02 for the Ford Bronco II and 0.27 for the Jeep Cherokee) which suggests that there is no linear relationship between Delta Ay and Maximum Pedal Force. Speed effects may be confounding the issue.

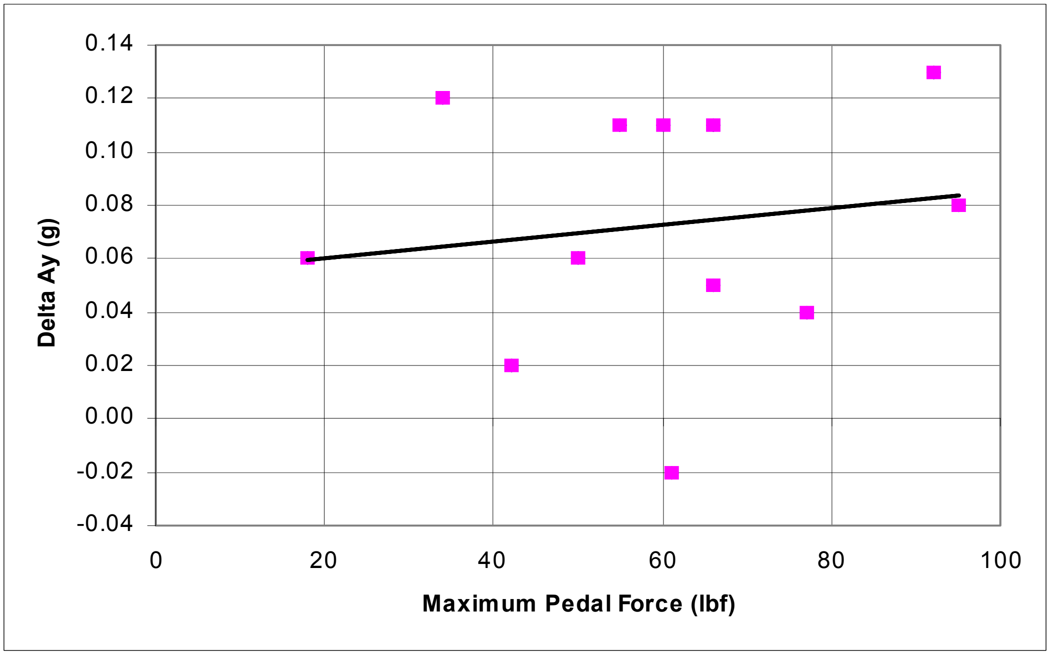

Figure 8.10 -- Ford Bronco II Delta AY vs. Maximum Pedal Force

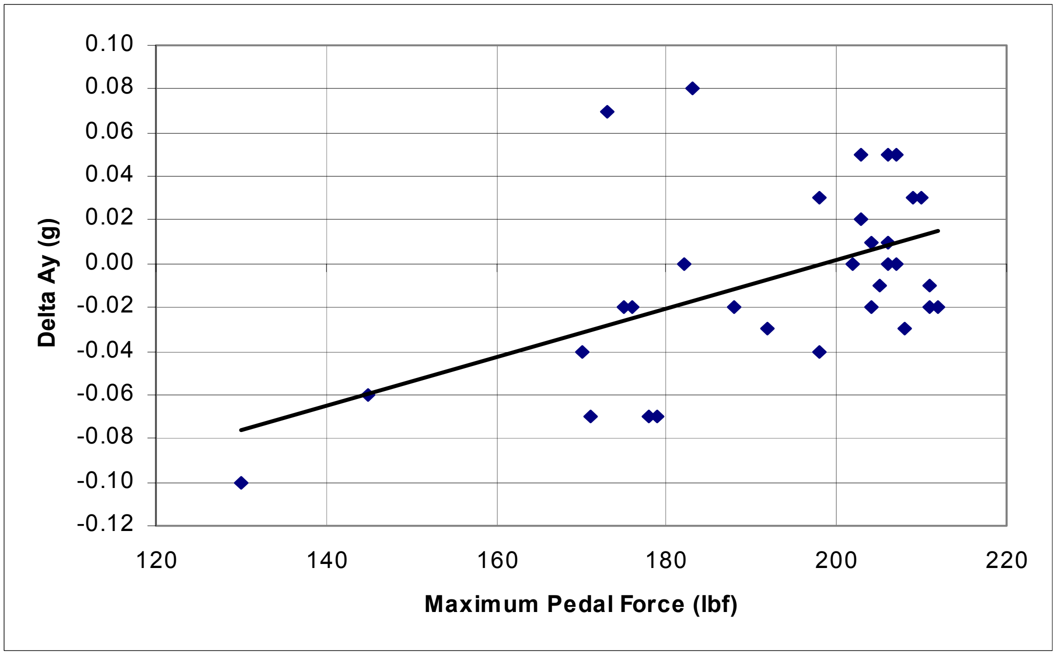

Figure 8.11 -- Jeep Cherokee Delta AY vs. Maximum Pedal Force

It should be noted that in this analysis and all of the analyses that follow, the effects of changes in other test parameters are not taken into consideration. Other test parameters that are varying from test-to-test include Initial Speed, Steering Input, Brake Pulse Width (or Maximum Pedal Force when Brake Pulse Width is studied in Section 8.5), and Time of Pulse Start relative to the initiation of steering input. To fully study the effects of Maximum Pedal Force or Brake Pulse Width, these other test parameters would have to be held constant. In Phase I-B, more testing was performed to more thoroughly study the effects of Pulse Brake Magnitude on test results.

For the test runs listed in Tables 8.1 and 8.2, the absolute value of the maximum Pre-Pulse roll angle was subtracted from the absolute value of the Post-Pulse maximum roll angle to produce a quantity called Delta Roll Angle. For the runs made with the Ford Bronco II, Delta Roll Angle had a maximum value of 8.5 degrees, a minimum value of 0.5 degrees, and an average value of 4.4 degrees. For the runs made with the Jeep Cherokee, Delta Roll Angle had a maximum value of 3.2 degrees, a minimum value of -1.1 degrees, and an average value of 1.2 degrees.

For both vehicles, linear regression showed that Delta Roll Angle increased slightly as the Maximum Pedal Force was increased. The correlation coefficients of the best fit linear regression lines, R^2, were 0.42 for the Ford Bronco II and 0.24 for the Jeep Cherokee. Figures 8.12 and 8.13 present the derived Delta Roll Angle values as a function of brake pedal force for the Ford Bronco II and Jeep Cherokee, respectively, along with linear regression lines based on this data. The data generally tends to increase with increasing Maximum Pedal Force; however, there is a great deal of scatter in the data. The slope of the regression curve for the Bronco II and Jeep Cherokee were 0.07 and 0.03 degree/pound-force respectively.

In general, both the Delta Ay and Delta Roll Angle increase with increasing brake magnitude. To maximize the effects of pulse braking, the authors recommend that a 200 pound-force Maximum Pedal Force be applied in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program. The effects of pulse brake magnitude were studied further in Phase I-B Research.

8.5 Effects of Brake Pedal Pulse Duration on J-Turn With Pulse Braking Results

Analysis of Table 8.1 shows that a reasonably narrow range of Brake Pulse Widths were used to generate pulse braking for the Ford Bronco II. The longest Brake Pulse Width was 0.65 seconds, the shortest was 0.24 seconds, and the average was 0.46 seconds. Table 8.2 also shows that a reasonably narrow range of Brake Pulse Widths were also used to generate pulse braking for the Jeep Cherokee. The longest Brake Pulse Width was 0.75 seconds, the shortest was 0.32 seconds, and the average was 0.53 seconds.

For the final 21 Jeep Cherokee tests (used previously to examine Maximum Pedal Force variability in Section 8.4), 17 Brake Pulse Widths were within ±0.10 seconds of the average Brake Pulse Width of 0.50 seconds. Overall, including data from the Ford Bronco II and Jeep Cherokee, 35 out of 45 Brake Pulse Widths (78 percent) were within ±0.10 seconds of the average Brake Pulse Width of 0.51 seconds. This level of repeatability is probably as good as can be expected from a test driver not using electronic or mechanical assistance.

The correlation coefficients of the best fit linear regression lines, R^2, were both quite low (less than 0.01 for the Ford Bronco II and 0.02 for the Jeep Cherokee) for Delta Ay as a function of Brake Pulse Width. The 90 percent confidence limits for both regression line slopes include zero. Therefore, Delta Ay was essentially independent of Brake Pulse Width over the range of values achieved by the driver during this testing. Figures 8.14 and 8.15 present the derived Delta Ay values as a function of Brake Pulse Width for the Ford Bronco II and Jeep Cherokee, respectively, along with the linear regression lines based on this data.

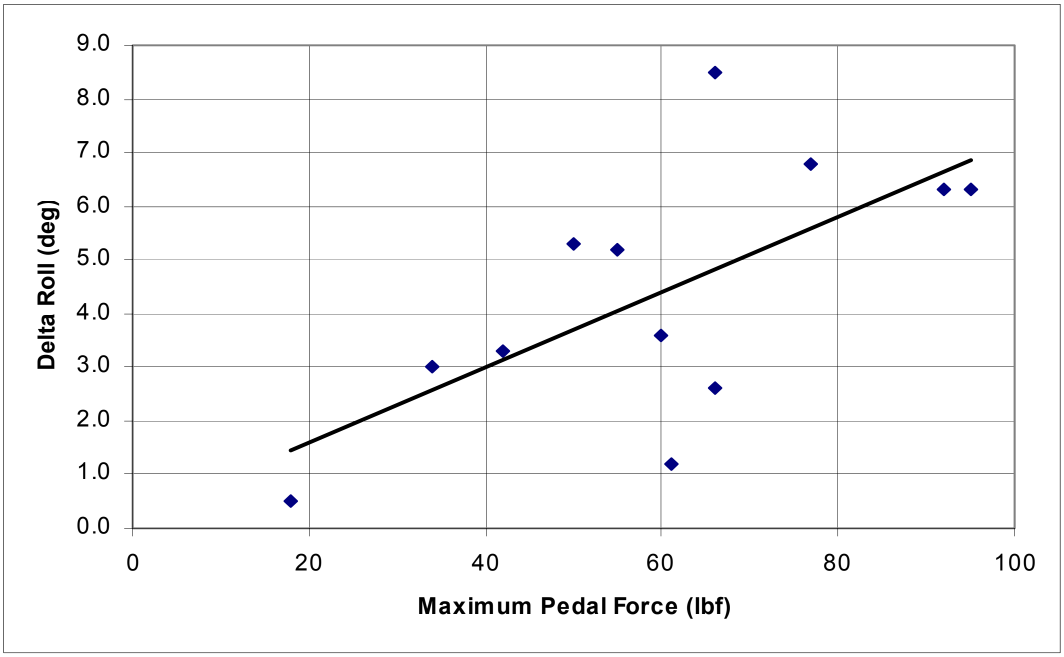

Figure 8.12 -- Ford Bronco II Delta Roll Angle vs. Maximum Pedal Force

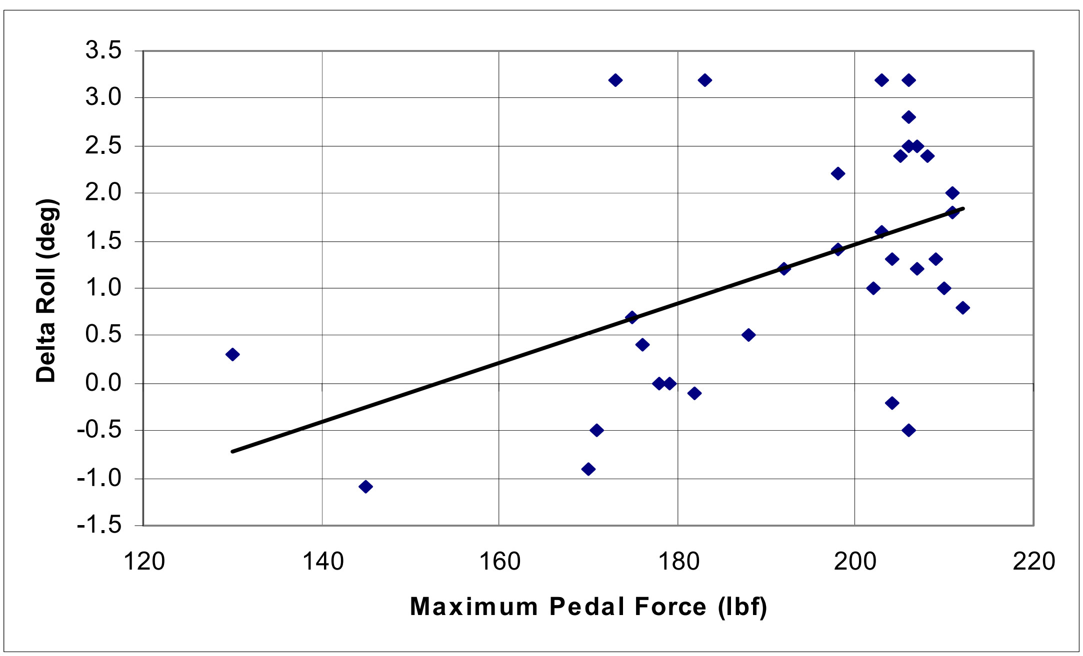

Figure 8.13 -- Jeep Cherokee Delta Roll Angle vs. Maximum Pedal Force

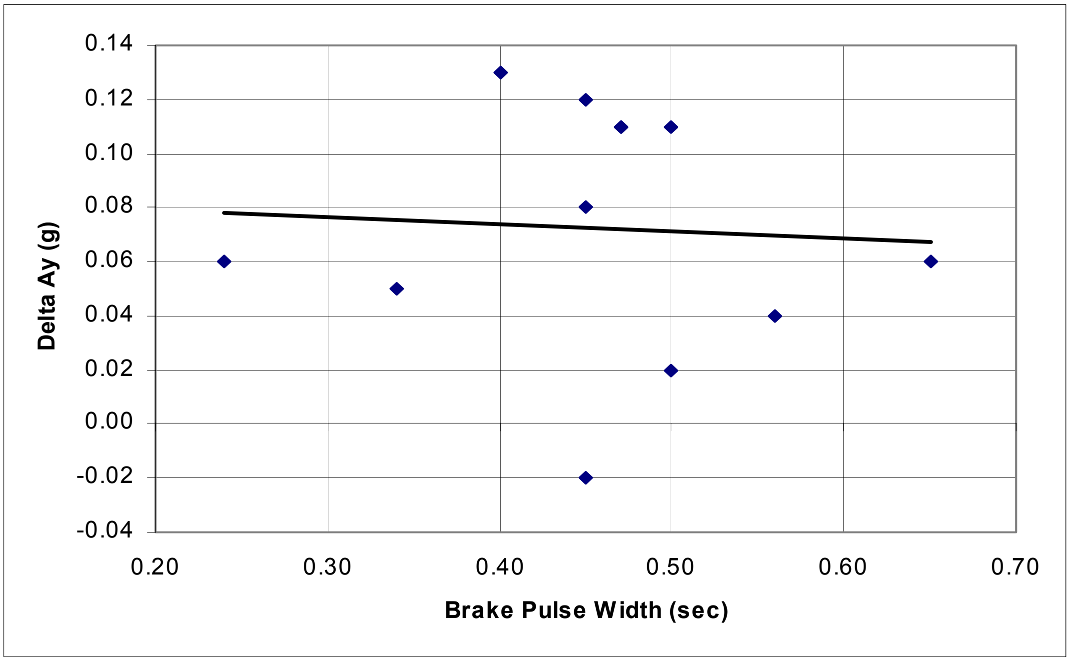

Figure 8.14 -- Ford Bronco II Delta AY vs. Brake Pulse Width

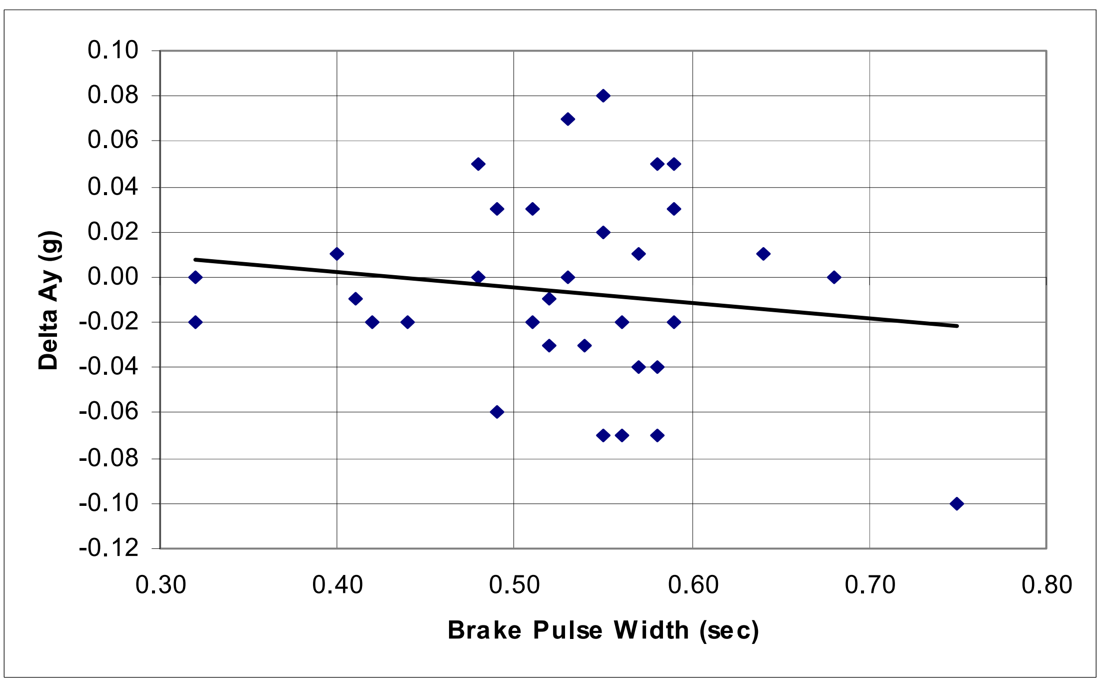

Figure 8.15 -- Jeep Cherokee Delta AY vs. Brake Pulse Width

The correlation coefficients of best fit linear regression lines for Delta Roll Angle versus Brake Pulse Width, R^2, were 0.27 for the Ford Bronco II and 0.03 for the Jeep Cherokee. These low values suggest little or no correlation between these two values. Figures 8.16 and 8.17 present the Delta Roll Angle values as a function of Brake Pulse Width for the Ford Bronco II and Jeep Cherokee, respectively, along with linear regression lines based on this data. The linear regression is positive for the Bronco II and is negative for the Cherokee.

In summary, Delta Ay appeared to be independent of Brake Pulse Width over the range of values achieved by the driver during this testing while Delta Roll Angle showed different trends for the two vehicles (increasing with Brake Pulse Width for the Ford Bronco II, decreasing slightly with Brake Pulse Width for the Jeep Cherokee). The average Brake Pulse Width achieved naturally by the test driver (approximately 0.50 seconds) appeared to be a good value for the brake pulse to cause substantial roll angle effects for both vehicles.

In both the analyses for Maximum Pedal Force and Brake Pulse Width, the effects of changes in other test parameters were not taken into consideration. Other test parameters that are varying from test-to-test include Initial Speed, Steering Input, and Time of Pulse Start relative to the initiation of steering input. Because Initial Speed has been shown to increase two-wheel propensity for some vehicles, its variability has likely introduced confounding effects to this analysis. Brake pulse timing may also have a strong influence. To make more definitive statements about the effects of pulse braking, the Time of Pulse Start relative to the initiation of steering input, Maximum Pedal Force, and Brake Pulse Width would have to be more repeatable than what a driver can produce.

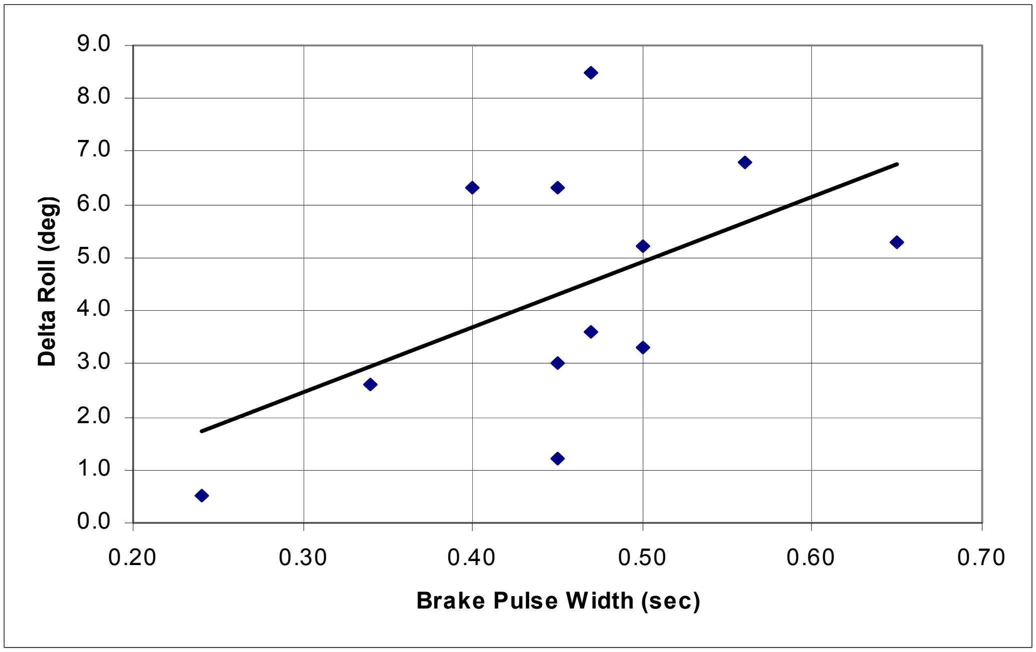

Figure 8.16 -- Ford Bronco II Delta Roll Angle vs. Brake Pulse Width

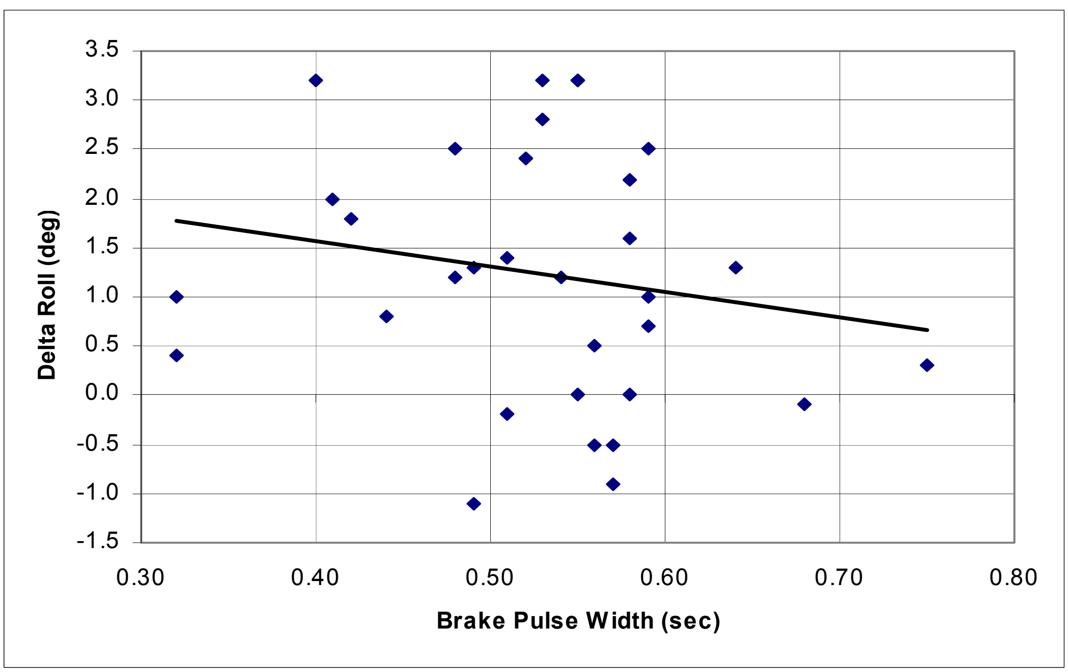

Figure 8.17 -- Jeep Cherokee Delta Roll Angle vs. Brake Pulse Width

8.6 Miscellaneous J-Turn With Pulse Braking Testing Problems

Table 8.1 indicates two-wheel lift did not occur for Tests 88 and 89 with the Ford Bronco II. However, based upon review of test videos, it appears that the rear outrigger may have prevented two-wheel lift from occurring. For these two tests, the Maximum Pedal Forces were higher than for the other Ford Bronco II tests. Upon the cessation of braking, the vehicle exhibited relatively large rearward pitch and heave motions, causing the rear outrigger to contact the ground in a manner that prohibited two-wheel lift. A similar observation was noted for Test 68. Minor two-wheel lift was observed during this run; however, although the rear outrigger appears to have restricted the two-wheel lift severity.

For the Jeep Cherokee, Tests 164 through 194 were all left turns while Tests 215 through 220 were all right turns. Note that none of the left-turn runs resulted in two-wheel lift, while several of the right-turns runs did. Recall that all Initial Speeds associated with the right-turn two-wheel lifts were greater than the Initial Speeds used for any left turn tests using the same Steering Input.

8.7 Summary of J-Turn With Pulse Braking Results

During pulse braking the lateral force capabilities of the tires decrease. As a result the roll angle and lateral acceleration decrease significantly as the vehicle decelerates, pitches forward, and straightens its path somewhat. Once the braking ceases, the lateral force capabilities of the tires increase quickly. This results in the lateral acceleration and roll rate increasing rapidly (more rapidly than during the initial pre-pulse stage of the maneuver). These rapid increases coupled with the vehicle's tendency to pitch and heave in the direction of its pre-braking state may cause significant increases in peak lateral acceleration and/or roll angle.

The Toyota 4Runner had two-wheel lift in the J-Turn (without Pulse Braking) maneuver and therefore was not tested using the J-Turn with Pulse Braking maneuver. Both the Ford Bronco II and the Jeep Cherokee had minor to moderate lift during the course of testing. Major lift for the Bronco II may have been prevented by the rear outriggers being set too low.

The J-Turn With Pulse Braking tests were less repeatable than were the J-Turn (without Pulse Braking) tests. The J-Turn With Pulse Braking maneuver has five primary input variables: Initial Speed, Steering Input, Maximum Pedal Force, Brake Pulse Width, and Time of Pulse Start as compared to two for J-Turn (without Pulse Braking) maneuver: Initial Speed and Steering Input. The Maximum Pedal Force, Brake Pulse Width, and Time of Pulse were difficult for the driver to control in a precise and repeatable fashion. However, maneuver repeatability is still felt to have been acceptable. For any given vehicle, all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum lateral accelerations varied by, at most, 0.07 g. and the maximum roll angles varied by, at most, 0.9 degrees.

This research found that both Delta Ay and Delta Roll Angle increased with increasing values of Maximum Pedal Force. Further research on this issue was conducted in Phase I-B, but based on this research it appears that a 200 pound value for Maximum Pedal Force would be appropriate.

This research found that Delta Ay appeared to be independent of Brake Pulse Width. The effect of Brake Pulse Width on Delta Roll Angle varied between the two vehicles. However, the average Brake Pulse Width achieved naturally by the test driver (approximately 0.50 seconds) appeared to be a good value for the Brake Pulse Width to cause substantial roll angle effects for both vehicles.

Neither Delta Ay nor Delta Roll Angle were very sensitive to either Maximum Pedal Force or Brake Pulse Width. Therefore, having a test driver manually generate the brake pulse appeared to be adequate for future light vehicle dynamic rollover testing.

The above analyses (using less sophisticated post-test processing to calculate roll angles than was subsequently developed) were originally performed while the Phase I-B testing was being performed. Based on these analyses, a decision was made to have the test driver manually pulse the brakes during the Phase II light vehicle dynamic rollover testing. The only actions that were taken to improve brake pulse repeatability were that the test driver practiced attaining a Maximum Pedal Force of 200 pounds and a timer/buzzer was installed in each test vehicle to make the time to the start of the brake pulse more constant.

No attempt was made to use the Phase I-A data to study the effects on vehicle rollover propensity of varying the timing of the brake pedal application relative to the initial steering input. This report is actually being written after the Phase II testing has been completed and all of the Phase II test data analyzed. Based on the Phase II data, the authors believe that a vehicle's behavior during the J-Turn With Pulse Braking maneuver is quite sensitive to the timing of the brake pedal application relative to the initial steering input. Therefore, the authors now recommend that any pulse braking performed during future light vehicle dynamic rollover testing be performed using a brake machine that can precisely time both the start of the pulse relative to the initiation of steering input and the Brake Pulse Width.

In both the analyses for Maximum Pedal Force and Brake Pulse Width, the effects of changes in other test parameters were not taken into consideration. Other test parameters that vary from test-to-test include Initial Speed, Steering Input, and Time of Pulse Start relative to the initiation of steering input. Because Initial Speed has been shown to increase two-wheel propensity for some vehicles, its variability has likely introduced confounding effects to this analysis. Brake pulse timing may also have a strong influence. To make more definitive statements about the effects of pulse braking, the Time of Pulse Start relative to the initiation of steering input, Maximum Pedal Force, and Brake Pulse Width would have to be more repeatable than what a driver can produce.

The J-Turn With Pulse Braking maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. The maneuver may be an indicator of asymmetrical two-wheel lift propensity (dependent on direction of steer). For these reasons, the J-Turn With Pulse Braking maneuver should be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

9.0 BRAKE AND STEER TEST RESULTS AND ANALYSIS

9.1 Tests Performed for Each Vehicle

Tables 9.1 and 9.2 provide test data for all 18 Brake and Steer valid tests performed with the Toyota 4Runner. The Ford Bronco II and Jeep Cherokee were not tested in this maneuver. Table 9.1 provides data for the runs where the brake pedal application was simultaneous with the beginning of the steering movement. The table has columns for Test Number, Initial Speed, Steering Input Magnitude, Maximum Brake Pedal Force, Maximum Corrected Lateral Acceleration, Maximum Roll Angle, and the Amount of Two-Wheel Lift (if any). Table 9.2 provides data for the tests when the brake application was heavier and delayed from the steering input, and includes additional columns for pre- and post-braking Maximum Corrected Lateral Acceleration values, pre- and post-braking Maximum Roll Angle values, as well as the Braking Time Delay. The Maximum Brake Pedal Force value indicated, is generally the first peak value as the pedal is initially depressed. The driver was not able to apply a constant force, so higher brake pedal forces may have occurred later in the trace, but the vehicle speed was reduced when these higher peaks occurred.

As mentioned in the test description section, the prolonged braking used in these tests reduces the lateral force capabilities of the tires, and therefore reduces the lateral acceleration capability of the vehicle and the potential for two-wheel lift. This phenomenon can been seen in Figures 9.1 and 9.2. These figures compare a J-turn test with a Brake and Steer test with similar speed and handwheel inputs and a one second delayed brake application. As can be seen in Figure 9.2, the lateral acceleration and roll angle plots follow one another closely until the onset of braking causes a significant drop from their maximum values. Brake and Steer tests with simultaneous braking never reached comparable maximums of lateral acceleration or roll angle when compared with similar J-turn tests.

Table 9.1 -- Summary of Toyota 4Runner Brake and Steer Tests with Simultaneous Brake and Steer

Test Number	Initial Test Speed (mph)	Steering Input (deg)	Max. Pedal Force (lbf)	Max. Corrected Lateral Acc. (g)	Maximum Roll Angle (deg)	Amount of Two-Wheel Lift
605	42.1	-104	91	-0.49	4.1	None
606	41.7	-203	70	-0.51	5.0	None
607	42.6	-253	35	-0.56	5.1	None
608	45.4	-254	46	-0.58	5.3	None
609	46.0	-254	34	-0.68	6.7	None
610	50.1	-255	41	-0.64	5.7	None
611	48.7	-286	41	-0.64	5.9	None
612	49.5	-316	43	-0.70	6.6	None
613	52.7	-316	47	-0.74	7.9	None
614	54.5	-316	32	-0.82	7.9	None
615	58.0	-316	31	-0.84	7.9	None
616	59.9	-316	32	-0.84	8.7	None

Table 9.2 -- Summary of Toyota 4Runner Brake and Steer Tests with Harder and Delayed Braking

Test Number	Initial Test Speed (mph)	Steering Input (deg)	Max. Pedal Force (lbf)	Brake Time Delay (sec)	Max. Corrected Lateral Acc., pre-Brake (g)	Max. Corrected Lateral Acc., post-Brake (g)	Max. Roll Angle, pre-Brake (deg)	Max. Roll Angle, post-Brake (deg)	Amount of Two-Wheel Liftoff
641	39.0	-318	91	0.84	-0.83	-0.10	8.4	1.4	None
642	39.8	-318	73	0.82	-0.80	-0.63	8.0	7.3	None
643	51.9	-317	87	-0.02	N.A.	-0.60	N.A.	7.6	None
644	53.4	-317	87	0.20	-0.63	-0.53	7.8	6.8	None
645	54.0	-317	85	0.98	-0.86	-0.59	10.3	8.2	Minor
646	54.4	-318	51	1.70	-0.86	-0.63	11.5	8.7	Minor

9.2 Effects of Braking Magnitude and Delayed Braking

The following figures provided in this section compare Brake and Steer tests using different levels of braking and using delayed braking.

Lighter and harder braking effects are compared in Figures 9.3 and 9.4. Figure 9.3 shows the steering input, brake pedal force, and vehicle speed, and Figure 9.4, the roll angle, yaw rate and lateral acceleration for Tests 614 (lighter) and 644 (harder). No sustained two-wheel lift was observed during these tests.

The harder braking applied in Test 644 caused the vehicle to plow to a relatively sudden stop. As shown in Figures 9.3 and 9.4, harder braking reduces the peak roll angle, yaw rate, and lateral acceleration, and eliminates the side-to-side rocking motion. Also, under hard braking the roll angle, yaw rate, and lateral acceleration decrease rapidly. These responses first overshoot the zero value and then return to zero as the vehicle plows to a stop.

The roll angle response for Test 614 in Figure 9.4 reveals an oscillatory response that occurred during the higher speed, less severe braking Tests (613 through 616). The vehicle rocked slightly side-to-side in an oscillatory fashion, and slight bouncing-related wheel lift was observed during Test 616. Tests 605 through 612 also exhibit similar trends, but lesser magnitude oscillatory motion was found for these lower speed, less severe maneuvers. These oscillations were not as noticeable to the test observer. The vehicle simply plowed to a smooth stop.

Figures 9.5 and 9.6 show the same variables as Figures 9.3 and 9.4 for Tests 644 and 645. Test 645 was done with the initiation of braking delayed from that of Test 644, by about 0.8 seconds. Delayed braking allows the roll angle and lateral acceleration to build up to greater levels than the simultaneous steering and braking cases, to the point where slight two-wheel lift was observed in both Tests 645 and 646. Further delayed braking would result in vehicle responses similar to those in a J-turn maneuver. However, upon the initiation of heavy braking, as indicated in Figures 9.5 and 9.6, the roll angle, yaw rate, and lateral acceleration reduce to zero as the vehicle plows to a stop.

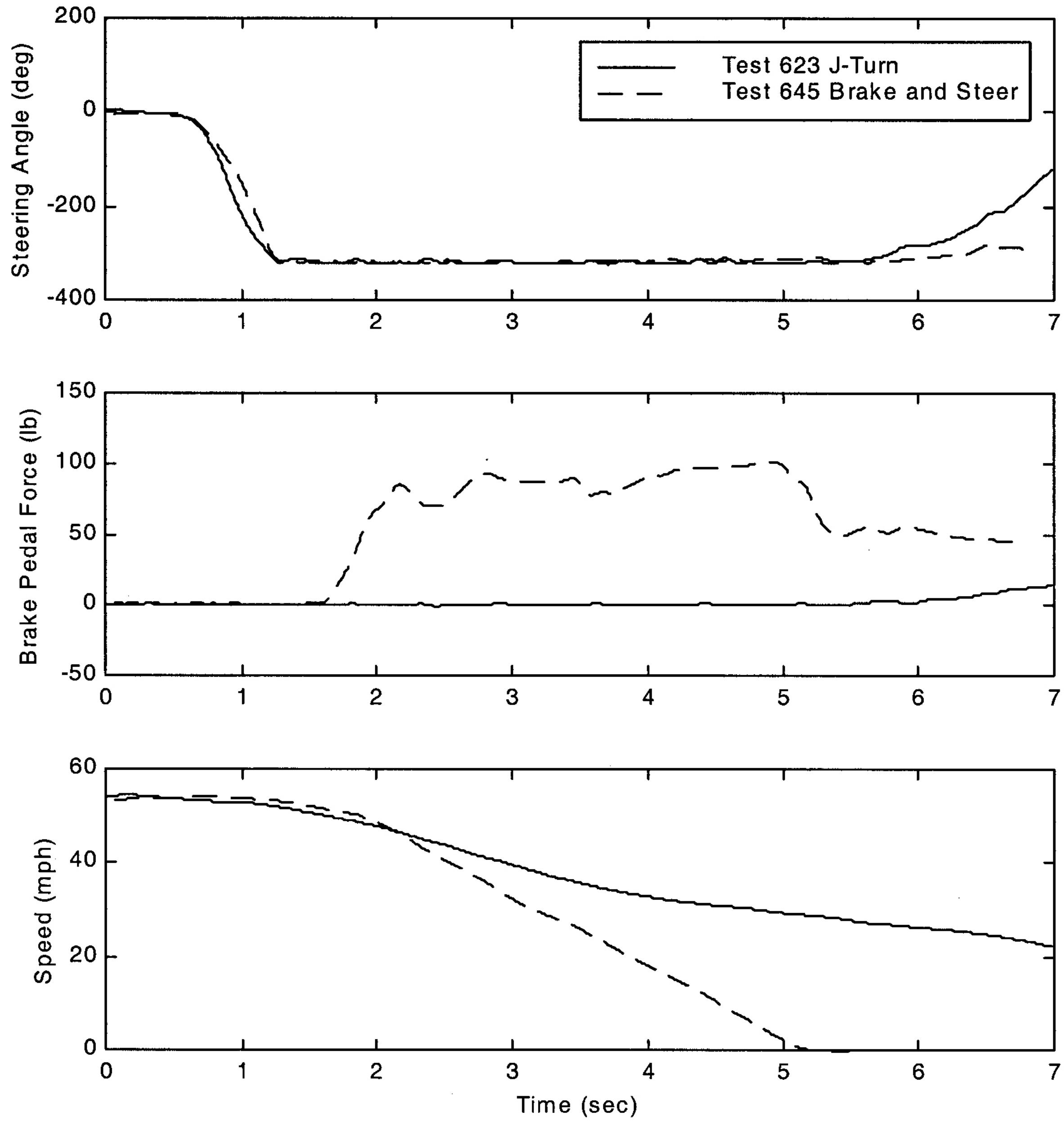

Figure 9.1 -- J-Turn versus Brake & Steer Comparison for the Toyota 4Runner - Steering Angle, Brake Pedal Force, and Speed

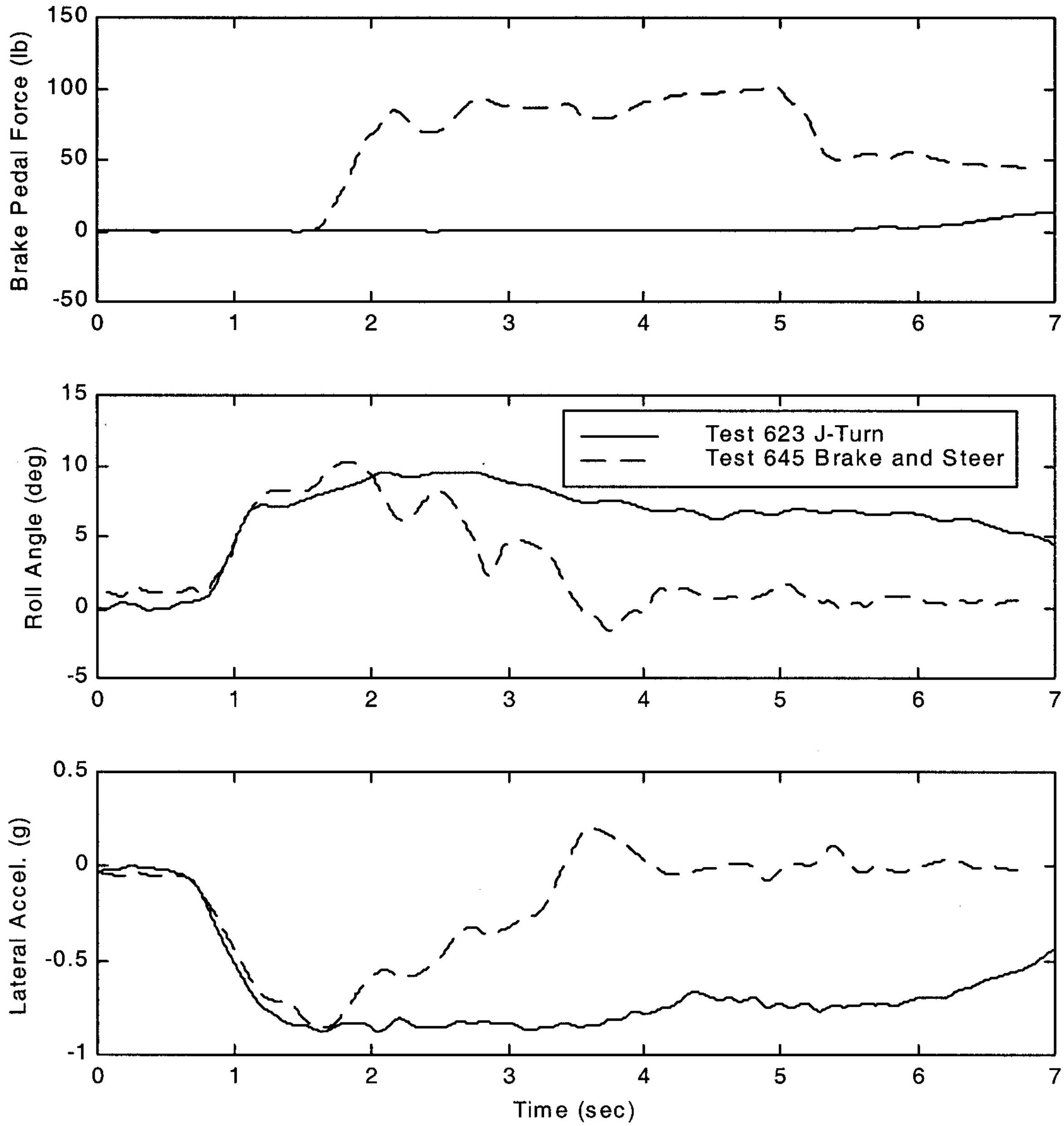

Figure 9.2 -- J-Turn versus Brake & Steer Comparison for the Toyota 4Runner - Brake Pedal Force, Roll Angle, and Lateral Acceleration

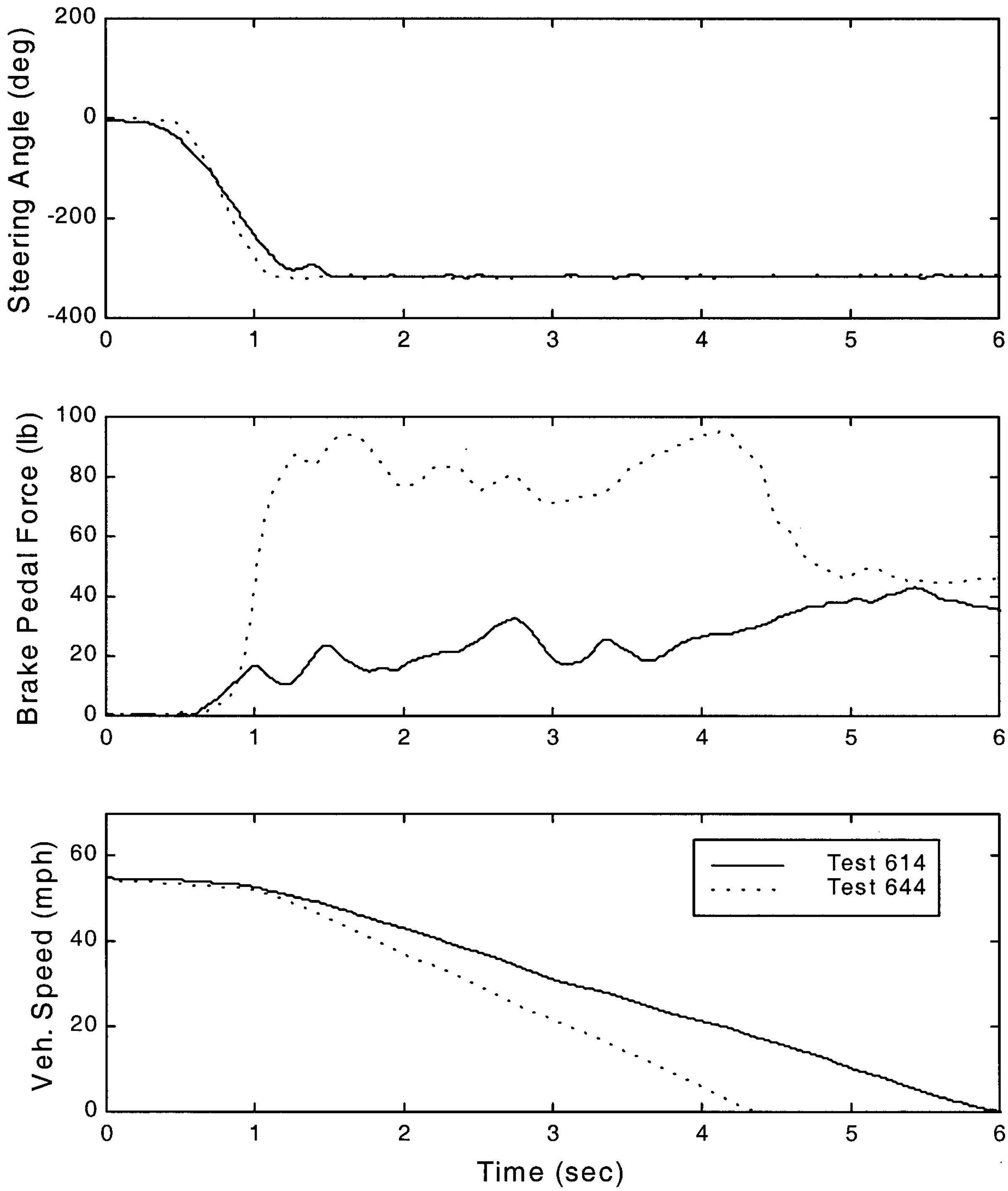

Figure 9.3 -- Steering Wheel Angle, Brake Pedal Force and Vehicle Speed for Toyota 4Runner Brake and Steer Tests 614 and 644

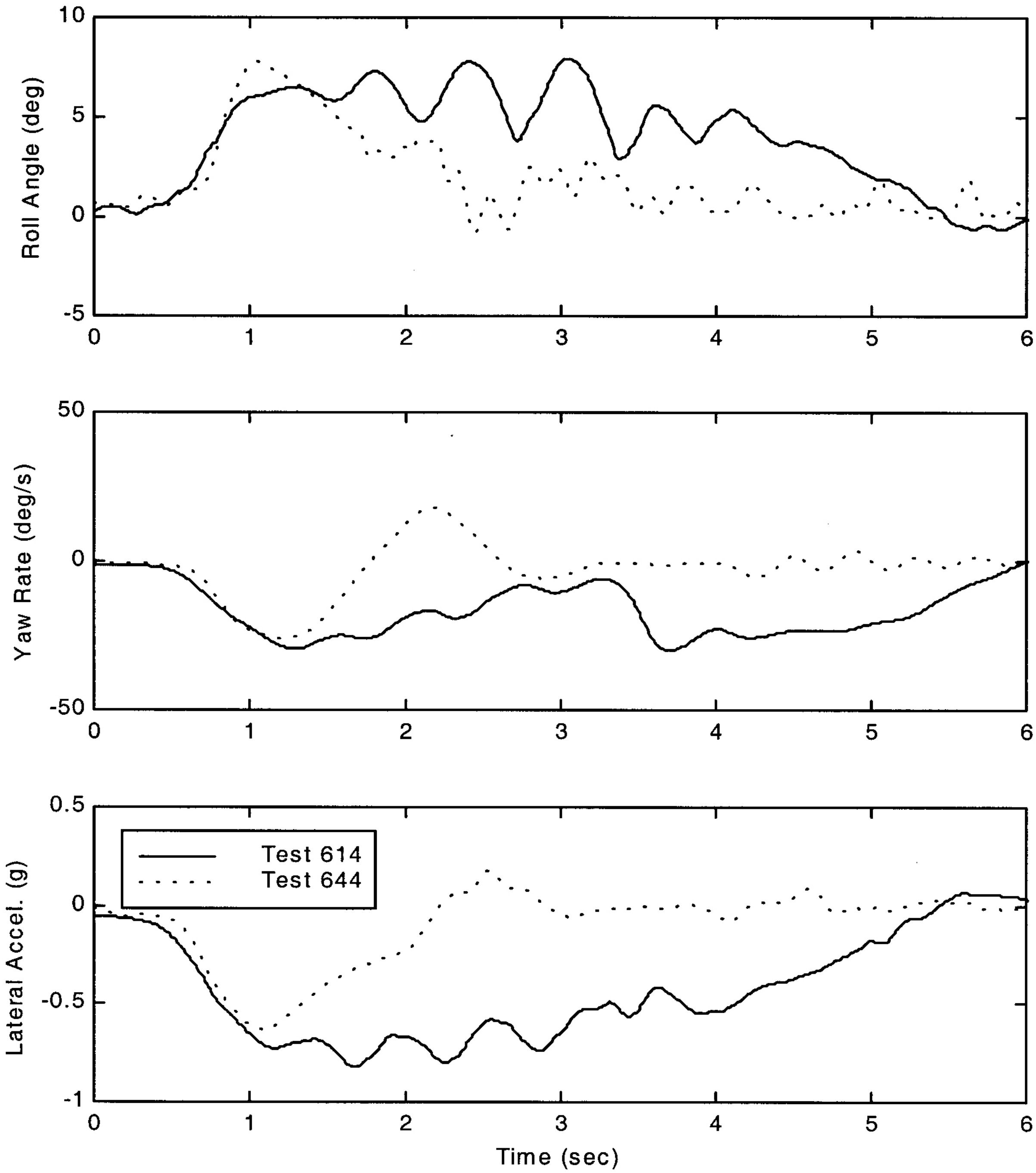

Figure 9.4 -- Roll Angle, Yaw Rate, and Lateral Acceleration for Toyota 4Runner Brake and Steer Tests 614 and 644

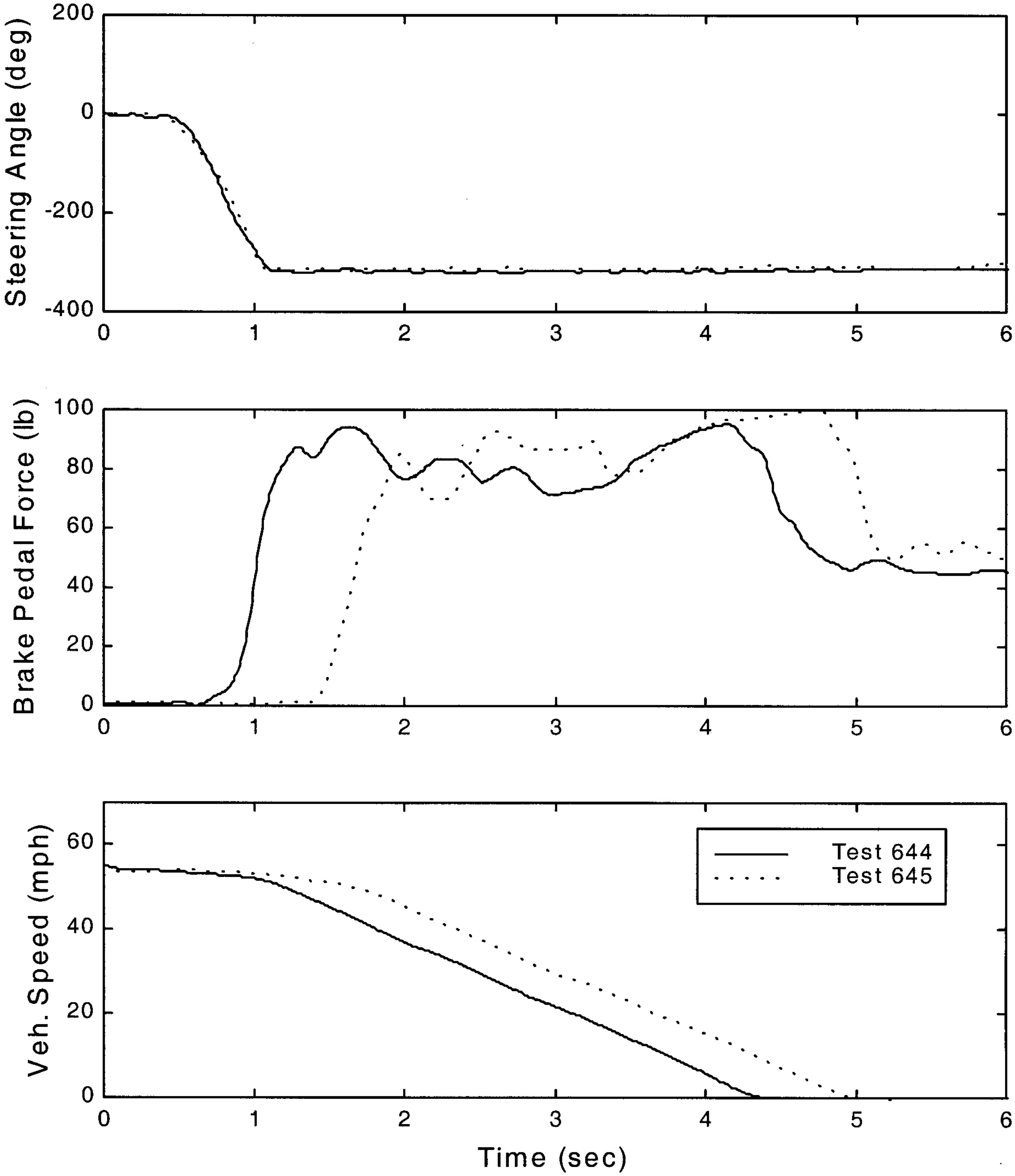

Figure 9.5 -- Steering Wheel Angle, Brake Pedal Force, and Vehicle Speed for the Toyota 4Runner Brake and Steer Tests 644 and 645

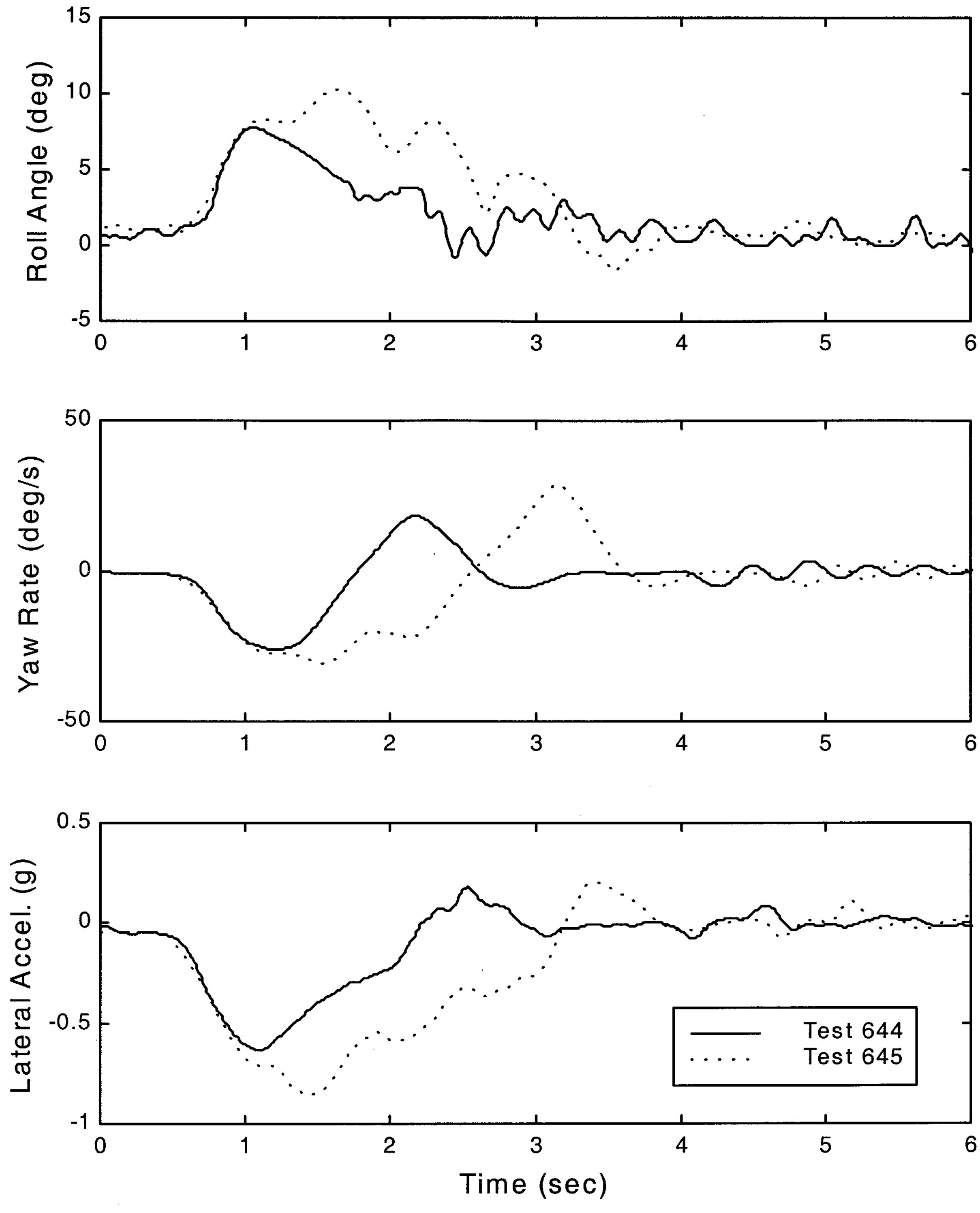

Figure 9.6 -- Roll Angle, Yaw Rate, and Lateral Acceleration for the Toyota 4Runner Brake and Steer Tests 644 and 645

9.3 Summary of Toyota 4Runner Brake and Steer Results

Under hard braking the roll angle, yaw rate, and lateral acceleration decrease rapidly. These responses first overshoot the zero value and then return to zero as the vehicle plows to a stop. Delayed braking allows the roll angle and lateral acceleration to build up to greater levels than the simultaneous steering and braking cases, to the point where two-wheel lift can occur. However, upon the initiation of heavy braking, the roll angle, yaw rate, and lateral acceleration reduce to zero as the vehicle plows to a stop.

The Brake and Steer maneuver did not result in two-wheel lift when the brakes were applied simultaneously with the start of steering even though the vehicle tested had two-wheel lift for the J-Turn maneuver. Since this maneuver reduced the chances of two-wheel lift occurring relative to the J-Turn, it is not expected to discriminate between vehicles with different rollover propensities (i.e., hardly any vehicles will experience two-wheel lift due to this maneuver). This being the case, further consideration of this maneuver during the dynamic rollover research program is not recommended.

10.0 STEERING REVERSAL TEST RESULTS AND ANALYSIS

10.1 Tests Performed for Each Vehicle

The Toyota 4Runner was the only vehicle tested with the Steering Reversal maneuver. All of the 40 valid steering reversal tests performed with the Toyota 4Runner are listed in Table 10.1. The table has columns for Test Number, Initial Speed, the First and Second Steering Input magnitudes (note that during the Second Steering Movement the steering wheel is actually turned through the sum of the First and Second Steering Input magnitudes that are shown in the table), when (if at all) the steering stop was used, the Maximum Corrected Lateral Acceleration associated with each steering input, the Maximum Roll Angle associated with each steering input, and the Amount of Two-Wheel Lift (if any).

The Steer Stop Used? column indicates whether or not a steering stop was used for a particular test run. If a steering stop was not used at all during a run, the column contains “Neither”. For most of the runs, only the second steering input was constrained with the steering stop. For this case, the Steer Stop Used? column contains “Second”. Due to difficulties in using the steering stop, for two runs for which the second steering input was to be constrained with the steering stop, the driver failed to engage the stop correctly and overshot the desired steering input. These two runs have “Overshot” in this column. A few tests were conducted using the steering stop for both the initial and secondary steering inputs; for these tests the Steer Stop Used? column contains “Both”.

The same nomenclature is used to categorize the amount of two-wheel lift that occurred (if any) as is described in Section 7.1 for the J-Turn (without pulse braking). For Tests 559 and 561, the video data clearly shows that the front wheels lifted off the ground, but it was not clear whether or not the rear wheels did. Therefore, for these tests the Amount of Two-Wheel Lift Column contains a “?”.

10.2 Steering Reversal and Rollover Propensity

For the single vehicle tested (the Toyota 4Runner), the Steering Reversal maneuver produced both minor and moderate two-wheel lift. Of the 40 test runs conducted four had confirmed two-wheel lift. As mentioned above, for two runs the video data clearly shows that the front wheels lifted off the ground. However, due to poor video coverage of the rear wheels, it cannot be determined whether or not the rear wheels left the ground. The remaining 34 tests did not have two-wheel lift.

For the 34 tests that did not produce two-wheel lift, the Initial Speeds ranged from 40.1 to 48.1 mph. The four tests that did have two-wheel lift had speeds ranging from 45.9 to 48.5 mph. This suggests that there is some overlap in the speeds that will and will not produce two-wheel lift. However, the higher speed tests that did not produce two-wheel lift generally had a lower First or Second Steering Input magnitude. As an example, Test 554 was a 48.1 mph test that did not produce two-wheel lift, while Test 603 was a 45.9 mph test that did. Test 554 had only 121 degrees First Steering Input compared to 177 degrees for Test 603.

A comparison of tests that did and did not produce two-wheel lift is given in Figures 10.1 through 10.3. As seen in Figure 10.1, the two-wheel lift test run had a higher Initial Speed, but the speed dropped off more dramatically during the course of the test due to the driver releasing the throttle. The driver maintained constant throttle for the non-two-wheel lift test. The two-wheel lift test did have a higher speed up to the point of two-wheel lift which occurred near the 4 second point as seen in the roll angle plot (Figure 10.2). The First Steering Input for the two-wheel lift case is greater than the non-two-wheel lift case, but the Second Steering Input is the same. The speed of the steering reversal for the two-wheel lift case is much faster. The lateral accelerations, roll rate, and yaw rate associated with each steering input are substantially greater for the two-wheel lift case. This is due to the combination of the faster vehicle speed, the larger initial steering magnitude and the speed of the steering reversal.

The First and Second Steering Input magnitudes given in Table 10.1 are only a small sampling of the large number of first and second steering movements that could be performed. A thorough examination of a significant number of these possibilities would require more resources than were available to perform this research. While contemplating how best to perform the Steering Reversal maneuver, the authors were fortunately made aware of the Toyota Fishhook maneuver. The Toyota Fishhook (without pulse braking) is a form of the Steering Reversal maneuver with selected values for the First and Second Steering Input magnitudes. Toyota Motor Corporation has performed a substantial amount of work to determine good values for the Fishhook's steering input magnitudes. We did not wish to repeat this work. Furthermore, the Toyota Fishhook maneuver uses large steering magnitudes for both the initial and second steering movements. The large steering input magnitudes of the Fishhook result in the vehicle's tires being saturated for most of the maneuver. This is expected to improve maneuver repeatability. Therefore a decision was made to try running the Toyota Fishhook maneuver for the Toyota 4Runner. Once the Fishhook maneuver had been run successfully for this vehicle, a decision was made to use the Toyota Fishhook as the only form of Steering Reversal performed for the other two test vehicles.

Table 10.1 -- Summary of Steering Reversal Testing for the Toyota 4Runner

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
537	40.9	69	-168	Both	0.37	-0.75	-3.7	6.6	None
538	43.2	72	-198	Both	0.38	-0.78	-3.9	6.6	None
539	42.6	68	-229	Both	0.39	-0.80	-4.0	7.0	None
541	42.5	79	-239	Both	0.42	-0.78	-4.5	7.2	None
542	43.2	89	-229	Both	0.48	-0.78	-5.2	7.4	None
543	42.7	99	-219	Both	0.50	-0.81	-7.3	6.9	None
544	40.5	105	-250	Second	0.52	-0.75	-5.4	8.8	None
545	40.5	115	-280	Second	0.56	-0.74	-6.0	8.6	None
546	40.4	121	-300	Second	0.55	-0.75	-6.5	8.9	None
547	41.3	112	-320	Second	0.53	-0.77	-6.6	9.0	None
548	40.9	104	-320	Second	0.51	-0.77	-6.2	9.1	None
549	42.1	109	-350	Second	0.50	-0.80	-5.6	9.5	None
550	42.0	120	-350	Second	0.54	-0.77	-6.6	9.1	None
552	40.2	126	-268	Second	0.55	-0.77	-8.4	6.4	None
553	41.7	128	-309	Second	0.55	-0.81	-8.4	6.7	None
554	48.1	121	-427	Overshot	0.63	-0.85	-6.9	7.2	None
555	47.9	134	-198	Second	0.63	-0.76	-9.2	6.4	None
556	47.7	125	-218	Second	0.59	-0.79	-8.8	7.0	None
557	47.5	142	-240	Second	0.69	-0.82	-7.6	7.0	None
558	47.6	143	-258	Second	0.62	-0.83	-8.7	7.4	None

Table 10.1 -- Summary of Steering Reversal Testing for the Toyota 4Runner (continued)

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
559	49.3	151	-287	Overshot	0.66	-0.94	-9.4	8.8	?
560	47.5	140	-269	Second	0.60	-0.84	-9.0	7.2	None
561	48.8	161	-286	Second	0.68	-0.93	-9.9	9.3	?
562	46.3	99	-268	Second	0.51	-0.80	-4.8	7.5	None
563	48.4	168	-269	Neither	0.68	-0.95	-6.3	9.4	Minor
564	44.5	202	-441	Neither	0.75	-0.78	-7.2	7.8	None
565	47.0	164	-228	Neither	0.71	-0.79	-7.3	7.5	None
581	40.1	265	-76	Second	0.73	-0.42	-7.4	5.4	None
582	39.1	207	-107	Second	0.69	-0.54	-7.4	5.6	None
583	40.3	206	-137	Second	0.70	-0.65	-6.5	7.1	None
584	39.5	231	-157	Second	0.71	-0.63	-6.5	7.1	None
585	40.3	183	-177	Second	0.71	-0.62	-6.5	6.2	None
586	40.1	216	-177	Second	0.74	-0.67	-6.9	6.8	None
587	41.1	200	-197	Second	0.74	-0.67	-6.8	6.6	None
588	42.5	196	-218	Second	0.74	-0.72	-6.8	7.5	None
589	40.5	185	-238	Second	0.70	-0.71	-6.3	7.1	None
590	40.5	203	-259	Second	0.73	-0.73	-6.6	7.3	None
602	48.5	169	-329	Neither	0.78	-0.86	-7.0	10.2	Minor
603	45.9	177	-288	Neither	0.77	-0.91	-6.8	10.3	Moderate
604	47.7	192	-337	Neither	0.78	-0.86	-6.8	12.4	Moderate

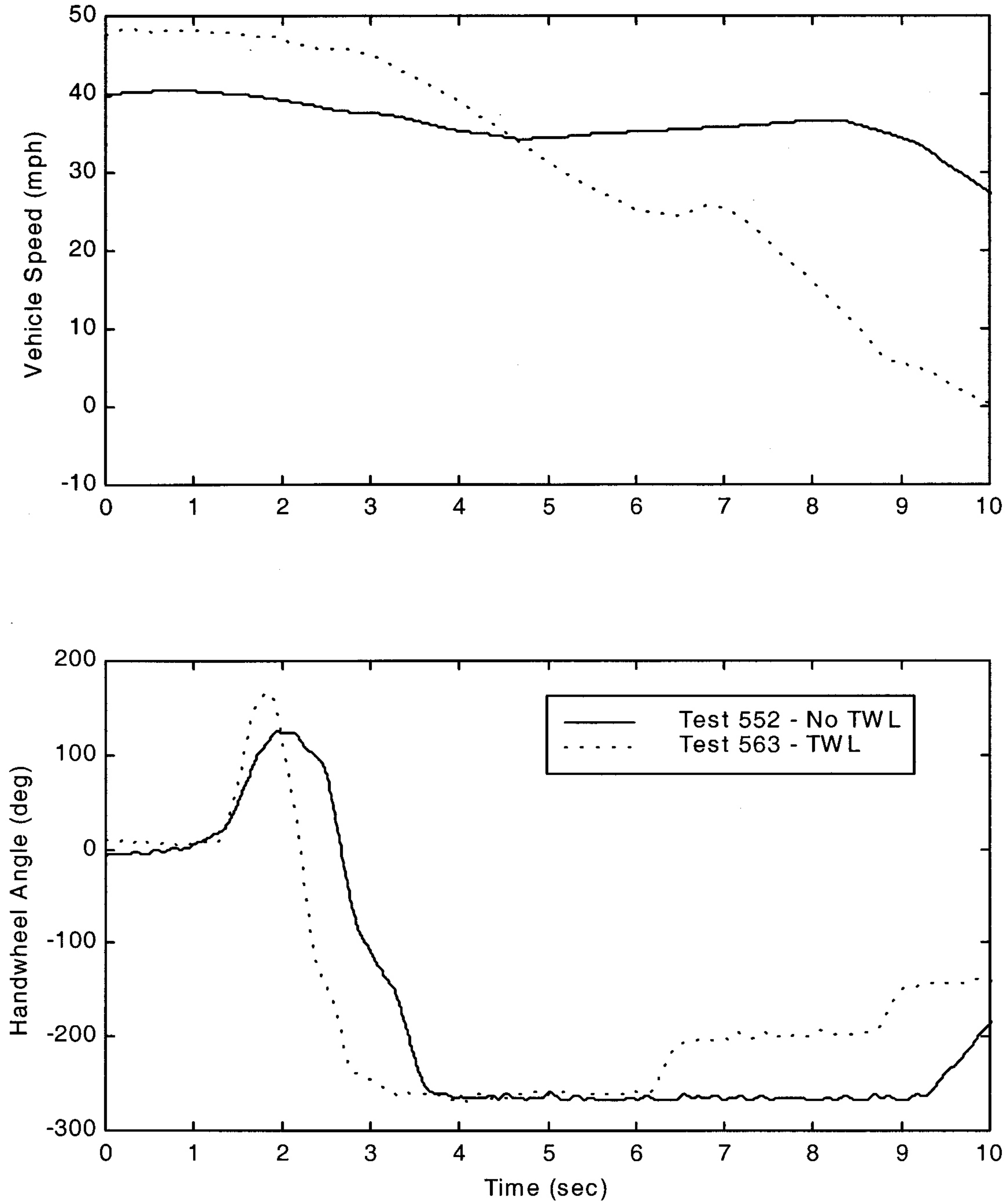

Figure 10.1 -- Two-Wheel Lift and Non-Two-Wheel Lift Comparison - Vehicle Speed and Handwheel Angle

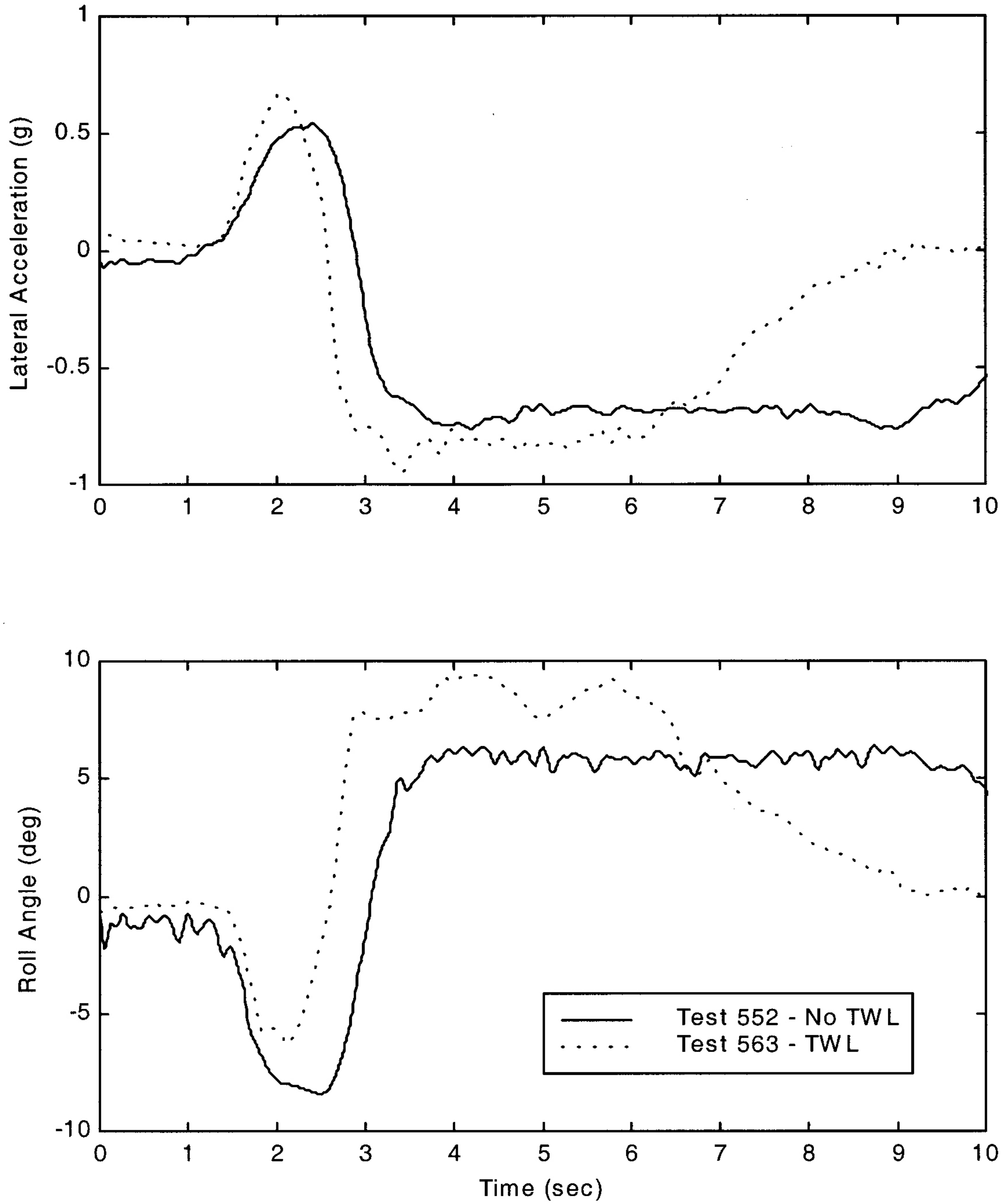

Figure 10.2 -- Two-Wheel Lift and Non-Two-Wheel Lift Comparison - Lateral Acceleration and Roll Angle

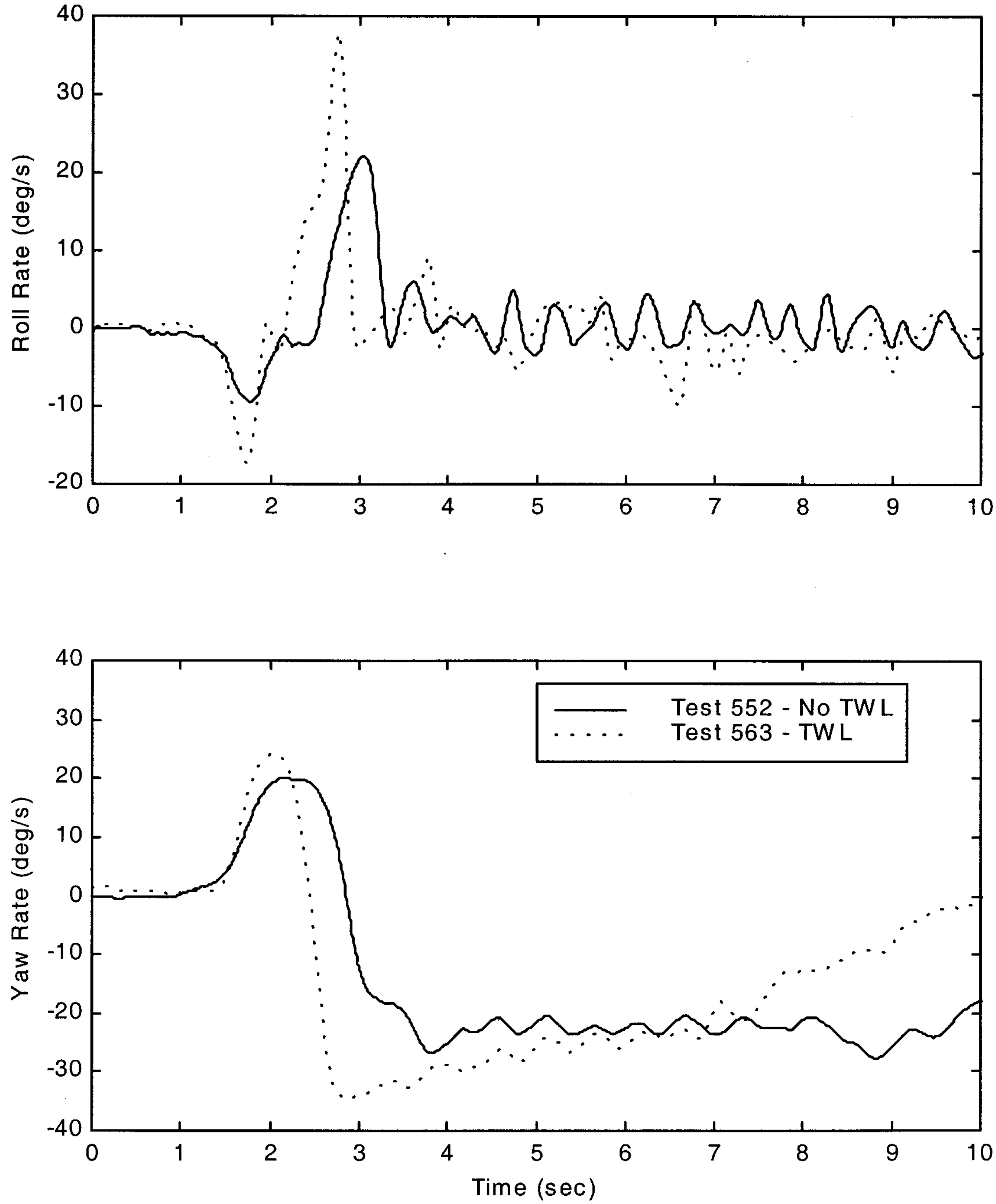

Figure 10.3 -- Two-Wheel Lift and Non-Two-Wheel Lift Comparison - Roll Rate and Yaw Rate

10.3 Repeatability of the Steering Reversal Maneuver

Figure 10.4 presents some examples of steering inputs that used the steering stop for both the first and second steering input, just the second steering input, and with no steering stops. In the case where steering stops were used for both steering inputs, it is clear that the magnitude of the steering input is constant and highly repeatable. For the case where neither input is controlled, it is clear that the driver cannot maintain a constant steering input. The driver also has a tendency to overshoot the desired input when a steering stop is not available. For Tests 552 through 562, the driver was trying to input approximately a 90 degree initial steering input. As seen in Table 10.1, the actual values varied from 99 to 161 degrees.

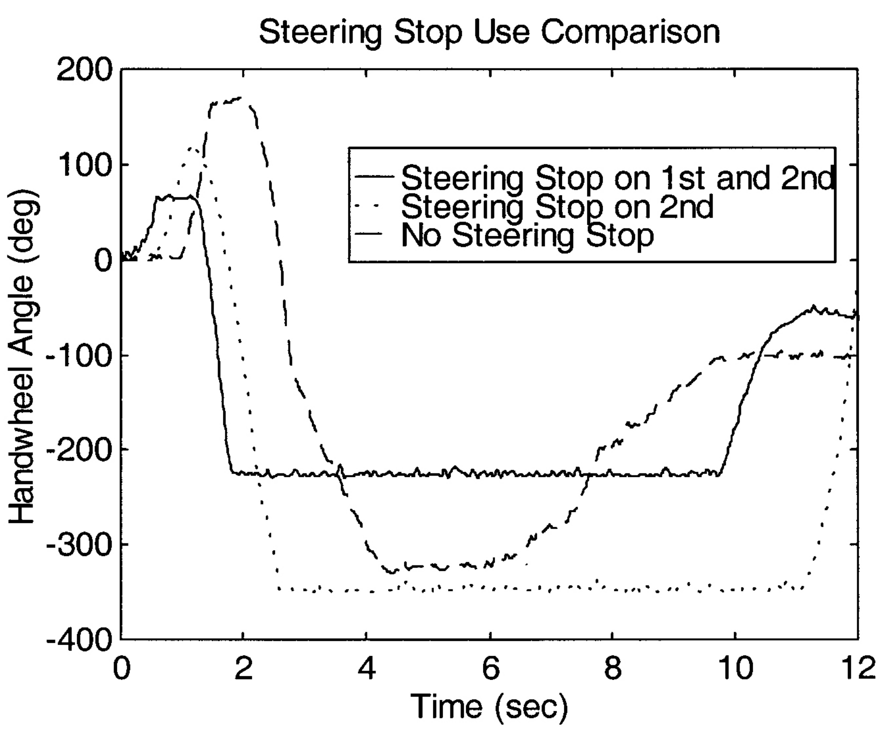

Figure 10.4 -- A Comparison of Various Steering Stop Combinations

With three primary input variables, Initial Speed, First Steering Input, and Second Steering Input, no repeated runs with exactly the same inputs and only a few runs with close to the same input conditions were made. Three pairs of runs which came closest to the same Initial Speed and First and Second Steering Inputs were found and analyzed for repeatability.

The first matching pair of test runs are Test Numbers 547 and 548. These tests had Initial Speeds of 41.3 and 40.9 mph, respectively, First Steering Inputs of 112 and 104 degrees, respectively, and Second Steering Inputs of -320 degrees for both tests. The Second Steering Inputs are identical because the steering stop was used for this steering movement. Since the differences between these two runs' input parameters were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Both tests had the same amount of two-wheel lift, “None”. Looking at the post-first steer data from these runs, Test 547's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 548 by 3.9 percent. The absolute value of the Maximum Roll Angle from the First Steer was 6.5 percent larger for Test 547. Both of these results are in line with the 7.7 percent increase in the First Steering Input and the 1.0 percent increase in Initial Speed from Test 548 to Test 547. Looking at the post-second steer data from these runs, the Maximum Corrected Lateral Accelerations from the Second Steer are the same. The Maximum Roll Angles from the Second Steer differed by 0.1 degrees. This difference is less than the noise level of the Roll Angle measurement process. In summary, the repeatability of the outputs from these two runs is very good.

The second matching pair of test runs are Test Numbers 549 and 550. These tests had Initial Speeds of 42.1 and 42.0 mph, respectively, First Steering Inputs of 109 and 120 degrees, respectively, and Second Steering Inputs of -350 degrees for both tests. The Second Steering Inputs are identical because the steering stop was used for this steering movement. Since the differences between these two runs' input parameters were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Both tests had the same amount of two-wheel lift, “None”. Looking at the post-first steer data from these runs, Test 550's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 549 by 8.0 percent. The absolute value of the Maximum Roll Angle from the First Steer was 17.8 percent larger for Test 550. Both of these results are in line with the 10.1 percent increase in the First Steering Input from Test 549 to Test 550. Looking at the post-second steer data from these runs, the Maximum Corrected Lateral Accelerations from the Second Steer differed by 0.02 g. The Maximum Roll Angles from the Second Steer differed by 0.4 degrees. Therefore, the repeatability of the outputs from these two runs is good (although not quite as good as was seen for the first pair of runs examined).

The third matching pair of test runs are Test Numbers 558 and 560. These tests had Initial Speeds of 47.6 and 47.5 mph, respectively, First Steering Inputs of 143 and 140 degrees, respectively, and Second Steering Inputs of -258 and -269 degrees, respectively. While the steering stop was used for these runs second steering movement, it was set to a different angle for the two tests. Since the differences between these two runs’ input parameters were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Both tests had the same amount of two-wheel lift, “None”. Looking at the post-first steer data from these runs, Test 558's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 560 by 0.02 g or 3.3 percent. The absolute value of the Maximum Roll Angle from the First Steer was 0.3 degrees or 3.4 percent smaller for Test 558. The corrected lateral acceleration result is in line with the 2.1 percent increase in the First Steering Input of Test 558 relative to Test 550. However, the change in the maximum roll angle, although small, is in the opposite direction from what is anticipated. Looking at the post-second steer data from these runs, the Maximum Corrected Lateral Accelerations from the Second Steer differed by 0.01 g. The Maximum Roll Angles from the Second Steer differed by 0.2 degrees. Both of these differences are less than what the authors believe to be the noise levels of the corrected lateral acceleration and roll angle measurement processes. This is reasonable since, while the Second Steering Input values do differ by 4.3 percent between the two runs, the Second Steering Input values are large enough that tire saturation is expected to occur. Therefore, the repeatability of the outputs from these two runs is good (although not quite as good as was seen for the first pair of runs examined).

10.4 Steering Reversal Testing Problems

The data acquisition trigger for Test 540 (not included in Table 10.1) probably occurred prior to entering the course and therefore the data collected was not correct. Video data for this test does exist.

For Tests 554 and 559, the driver overshot the intended steering stop. The steering stop design used during this testing was difficult for the driver to use during a Steering Reversal test.

For Tests 559 and 561, the video data clearly shows that the front wheel lifted off the ground. However, due to poor video coverage of the rear wheels, it was not clear whether or not the rear wheels left the ground.

10.5 Summary of Steering Reversal Results

This testing found that for some, but not all, sets of input parameters the Steering Reversal maneuver resulted in two-wheel lift for the Toyota 4Runner. The difference between non-two-wheel lift and two-wheel lift input parameters were faster Initial Speeds and larger First and Second Steering Inputs.

This testing found good repeatability for the Steering Reversal maneuver. Data changed from run-to-run as expected based upon changes in the input parameters. The largest, unanticipated, differences that were found by looking at three pairs of matched runs were 0.02 g for maximum corrected lateral acceleration and 0.4 degrees for maximum roll angle. There were no unanticipated differences in the amount of two-wheel lift that was seen.

This testing used only a small sampling of the large number of First and Second Steering Input magnitudes that could have been performed with the Steering Reversal maneuver. A thorough examination of a significant number of these possibilities would require more resources than were available to perform this research. While contemplating how best to perform the Steering Reversal maneuver, the authors were fortunately made aware of the Toyota Fishhook maneuver. The Toyota Fishhook (without pulse braking) is a form of the Steering Reversal maneuver with selected values for the First and Second Steering Input magnitudes. Toyota Motor Corporation has performed a substantial amount of work to determine good values for the Fishhook's steering input magnitudes. We did not wish to repeat this work. Furthermore, the Toyota Fishhook maneuver uses large steering magnitudes for both the initial and second steering movements. The large steering input magnitudes of the Fishhook result in the vehicle's tires being saturated for most of the maneuver. This is expected to improve maneuver repeatability. Therefore a decision was made to try running the Toyota Fishhook maneuver for the Toyota 4Runner. Once the Fishhook maneuver had been run successfully for this vehicle, a decision was made to use the Toyota Fishhook as the only form of Steering Reversal performed for the other two test vehicles.

While the Steering Reversal maneuver is a more complex test to perform than the J-Turn maneuver, it is still a good candidate for use in a potential dynamic rollover propensity test procedure. It appears to induce two-wheel lift for some vehicles. The initial test speed and the magnitudes of the steering inputs appear to be measures that can be used to quantify a vehicle's rollover propensity. The maneuver seems to be quite repeatable.

The authors decided to focus on one particular set of First and Second Steering Input magnitudes for the Steering Reversal maneuver, the ones developed by Toyota for the Fishhook, for the remainder of this research. Findings for testing that was performed using the Fishhook maneuver are presented in the next section.

11.0 TOYOTA FISHHOOK TEST RESULTS AND ANALYSIS

11.1 Tests Performed for Each Vehicle

One set of Toyota Fishhook tests was performed with the Toyota 4Runner. (As discussed in Section 6.5, the Toyota Fishhook is run starting with relatively low course entry speeds. The course entry speed is then gradually increased for each successive run until several runs with two-wheel lift are produced. A group of test runs, starting at a low course entry speed and working up until a termination condition occurs is referred to as a "set".) These tests were all run with an initial steering input to the right followed by a steering input to the left. A total of twelve tests runs were made for this vehicle. Of these twelve, eight produced two-wheel lift that ranged from Minor to Major.

A complete listing of Toyota 4Runner test results is given in Table 11.1. The Table lists, for each test run, Test Number, Initial Speed, magnitude of the First and Second Steering Inputs, Maximum Corrected Lateral Acceleration resulting from the First and Second Steering Inputs (note that during the Second Steering Movement the steering wheel is actually turned through the sum of the First and Second Steering Input magnitudes that are shown in the table), Maximum Roll Angle resulting from the First and Second Steering Inputs, and the Amount of Two-Wheel Lift (if any). The two-wheel lift categorization method used in this table is the same as was described in Section 7.1 for the J-turn maneuver.

Typical data plots for one of these tests are given in Figures 11.1 and 11.2. The handwheel angle data was clipped for the test shown in these figures (although full-scale for the transducer almost went to the vehicle's built-in steering stop). During later testing, the handwheel angle sensor was calibrated to be able to measure more turns of the steering wheel. The handwheel rate is calculated from the handwheel angle data and therefore this channel goes to zero when the handwheel angle channel was clipped (of course, it would have gone to zero anyway when the built-in stop was reached).

Five sets of Toyota Fishhook tests were performed using the Ford Bronco II. Data from these tests is summarized in Table 11.2. This table contains the same columns as does Table 11.1 with the addition of a Set Number column. All of the Ford Bronco II Toyota Fishhook tests were conducted with an initial right and then left steering input.

In the testing conducted during Phase I-A, the Ford Bronco II would not produce two-wheel lift without pulse braking unless the tires had shown significant signs of shoulder wear. An initial set of tests were conducted with Initial Speeds ranging from 35 to 46 mph. None of these tests produced two-wheel lift, although significant front wheel lift was noted. The data acquisition system was not working for this initial set of tests (and, as a result, they are not listed in Table 11.2), so a second set was run from 36 to 46 mph and again the vehicle did not have two-wheel lift (Bronco II Tests 20-22), although significant front wheel lift was noted.

Ford Bronco II Tests 78 through 80 were then run and two-wheel lifts occurred at Maximum Corrected Lateral Accelerations from the Second Steer of -0.78 and -0.74 g for Tests 78 and 80 respectively. These two-wheel lifts occurred at Initial Speeds as low as 42.3 mph. The people performing the testing noted that significant shoulder wear had occurred on the right front tire, so that tire was replaced and another series of tests was conducted. Tests 81 through 86 were performed with Initial Speeds of 39.4 through 46.5 mph and produced Maximum Corrected Lateral Accelerations from the Second Steer ranging from -0.70 to -0.79 g. Even though the Initial Speeds were significantly higher, no two-wheel lifts were observed, although significant front wheel lift was observed. Tests 90 through 92 were conducted after significant tire shoulder wear was again noted by the testers. Again, two-wheel lift occurred (for Test 92 with a Maximum Corrected Lateral Acceleration from the Second Steer of 0.76 g and a Test Speed of 42.9 mph).

Five sets of Toyota Fishhook tests were performed using the Jeep Cherokee. A complete listing of Jeep Cherokee Toyota Fishhook test results is given in Table 11.3. This table contains the same columns as does Table 11.2.

The first set of Toyota Fishhook tests conducted with the Jeep Cherokee used an initial right then left steering input (Tests 101 through 106). These tests were performed at Initial Speeds ranging from 40.6 to 52.1 mph. None of these tests produced two-wheel lift. Tests 107 and 108 were also conducted with the initial right then left steering input, but with pulse braking added (see Section 14.0). However, the Cherokee's antilock braking system (ABS) was not disabled for these tests (as was the case for all other Toyota Fishhook With Pulse Braking test runs that were performed using the Cherokee). For these tests, the Maximum Roll Angle from the Second Steer occurred prior to the initiation of the braking pulse. Neither of these tests had two-wheel lift. Since the ABS was enabled and since pulse braking did not influence the major test results, data from these runs is included with the Toyota Fishhook (**without** pulse braking) results.

The second set of Jeep Cherokee Toyota Fishhook tests (Tests 109 and 111 through 112), were conducted with an initial left then right steering input. The Initial Speeds ranged from 47.5 to 52.1 mph and Maximum Corrected Lateral Acceleration from the Second Steer values ranged from 0.81 to 0.82 g. No two-wheel lifts occurred during these test runs.

Table 11.1 -- Summary of Toyota Fishhook Testing for the Toyota 4Runner

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
701	31.3	291	-630	0.69	-0.73	-7.3	9.1	None
702	31.7	330	-629	0.69	-0.74	-7.3	9.9	None
703	34.8	298	-630	0.70	-0.80	-7.6	9.7	None
704	33.8	295	-630	0.67	-0.77	-7.8	9.8	None
705	36.8	333	-630	0.73	-0.82	-8.1	11.1	Minor
706	36.0	265	-630	0.68	-0.86	-7.6	10.5	Minor
707	38.0	320	-630	0.72	-0.80	-8.4	12.2	Moderate
708	38.3	316	-630	0.70	-0.84	-7.8	11.6	Moderate
709	38.4	324	-630	0.72	-0.82	-8.5	14.6	Major
710	36.9	248	-630	0.69	-0.86	-7.2	10.5	Minor
711	38.0	323	-630	0.73	-0.82	-8.4	14.2	Major
712	38.9	284	-630	0.71	-0.88	-8.4	12.6	Moderate

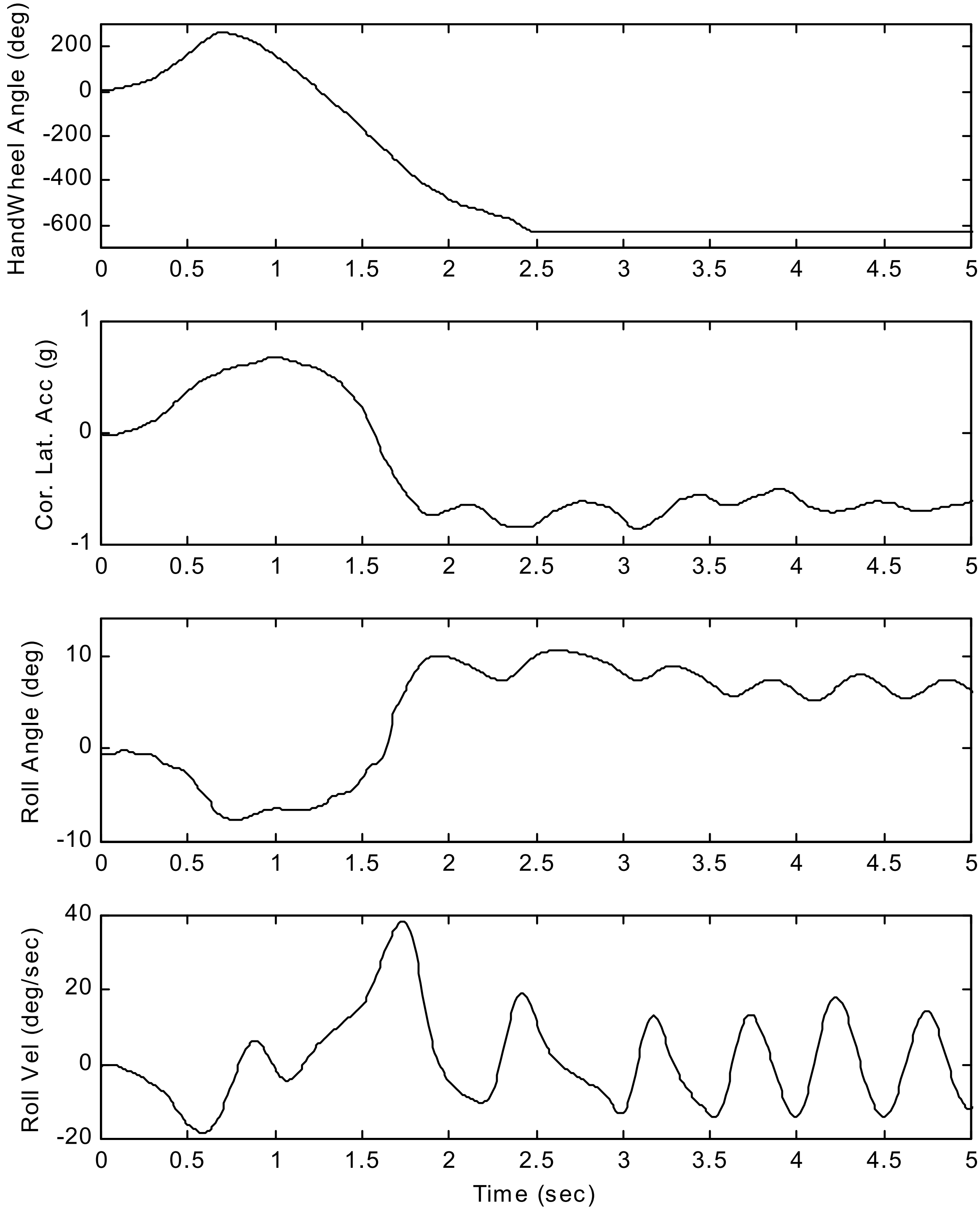

Figure 11.1 -- Typical Toyota Fishhook Test Results for the Toyota 4Runner - Handwheel Angle, Corrected Lateral Acceleration, Roll Angle and Roll Rate

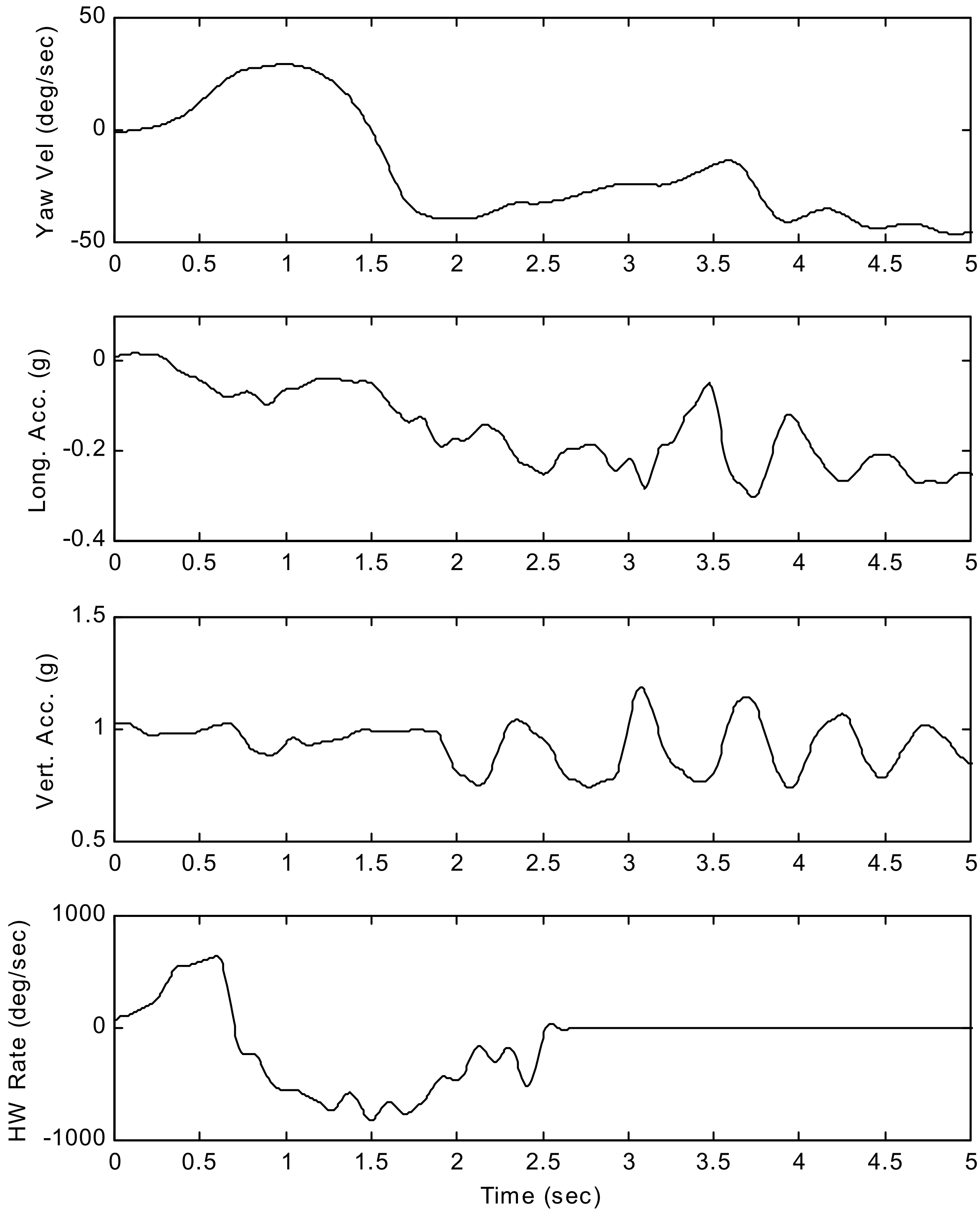

Figure 11.2 -- Typical Toyota Fishhook Test Results for the Toyota 4Runner - Yaw Rate, Longitudinal Acceleration, Vertical Acceleration and Handwheel Rate

Table 11.2 -- Summary of Toyota Fishhook Testing for the Ford Bronco II

Set Number	Test Number	Initial Test Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Max. Roll Angle from First Steer (deg)	Max. Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
2	20	36.7	288	-737	0.69	-0.67	-4.2	5.7	None
2	21	42.1	264	-736	0.71	-0.69	-4.3	7.4	None
2	22	46.9	262	-736	0.71	-0.72	-4.4	7.2	None
3	78	45.0	267	-437	0.76	-0.78	-4.8	16.6	Major
3	79	38.7	286	-629	0.72	-0.67	-4.3	6.1	None
3	80	42.3	262	-471	0.75	-0.74	-5.2	20.0	Major
4	81	39.4	328	-492	0.74	-0.70	-4.6	6.1	None
4	82	40.8	282	-492	0.73	-0.71	-4.7	6.6	None
4	83	44.1	241	-452	0.74	-0.76	-4.9	6.4	None
4	84	42.0	306	-651	0.74	-0.73	-4.5	5.9	None
4	85	45.3	249	-671	0.76	-0.79	-4.7	6.6	None
4	86	46.5	324	-418	0.77	-0.79	-5.0	9.7	None
5	90	38.9	250	-548	0.71	-0.76	-4.8	5.2	None
5	91	40.7	263	-509	0.76	-0.80	-5.1	5.4	None
5	92	42.9	304	-422	0.73	-0.76	-5.2	21.1	Major

Table 11.3 -- Summary of Toyota Fishhook Testing for the Jeep Cherokee

Set Number	Test Number	Initial Test Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Max. Roll Angle from First Steer (deg)	Max. Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
1	101	40.6	342	-529	0.80	-0.77	-4.9	6.4	None
1	102	43.8	284	-555	0.80	-0.73	-5.3	5.7	None
1	103	46.0	289	-476	0.81	-0.75	-5.0	6.3	None
1	104	49.1	277	-437	0.82	-0.83	-5.0	6.7	None
1	105	50.9	274	-472	0.82	-0.77	-5.0	7.2	None
1	106	52.1	335	-417	0.81	-0.85	-5.3	6.8	None
1	107	44.4	210	-371	0.81	-0.81	-5.0	6.6	None
1	108	44.1	275	-370	0.83	-0.81	-4.9	6.9	None
2	109	47.5	-240	381	-0.83	0.82	5.0	-7.3	None
2	111	48.1	-285	455	-0.82	0.82	4.7	-7.2	None
2	112	52.1	-304	463	-0.86	0.81	4.8	-7.7	None
3	201	52.9	-314	283	-0.90	0.95	5.0	-8.9	Moderate
3	202	52.4	-332	334	-0.89	0.93	5.3	-8.6	Minor
3	203	52.2	-318	335	-0.91	0.96	5.0	-9.6	Moderate
4	204	51.2	221	-445	0.84	-0.83	-5.0	6.7	None
5	205	50.4	-284	359	-0.83	0.87	5.1	-8.1	Minor
5	206	53.2	-296	341	-0.82	0.94	5.0	-8.8	Moderate
5	207	53.3	-257	288	-0.83	1.01	4.6	-8.7	Moderate
5	208	54.4	-324	274	-0.80	0.97	4.7	-8.4	Moderate
4	209	51.4	263	-383	0.87	-0.82	-5.5	7.1	None
4	210	55.6	217	-409	0.86	-0.81	-5.4	7.1	None

Jeep Cherokee Tests 195 through 199 (not shown in Table 11.3) were Toyota Fishhook **with** Pulse Braking tests that were conducted with an initial left then right steering input. Two-wheel lift was found for these tests. (Results from these tests are further discussed in Section 14.0.) The testers thought that the two-wheel lift which was seen during these test runs was occurring prior to the start of pulse braking. Tests 201 through 203 were run without pulse braking to confirm this observation. Two-wheel lift occurred during all three of these tests. The Initial Speeds ranged from 52.2 to 52.9 mph and Maximum Corrected Lateral Acceleration from the Second Steer values ranged from 0.93 to 0.96 g. This Initial Speed range was only slightly higher than that used for Tests 109, 111, and 112. However, Tests 109, 111, and 112 did not produce two-wheel lift and had a much lower Maximum Corrected Lateral Acceleration from the Second Steer range. Therefore, the testers thought that significant tire wear might have occurred and may be affecting results. Therefore, all four of the Cherokee's tires were replaced.

After replacing the tires, Jeep Cherokee Tests 204, 209, and 210 were conducted with an initial right then left steering input. Consistent with the first set of Toyota Fishhook test runs for the Cherokee (which were also performed with an initial right then left steering input), no two-wheel lifts occurred. The Initial Speeds ranged from 51.2 to 55.6 mph and Maximum Corrected Lateral Acceleration from the Second Steer ranged from -0.81 to -0.83 g.

Jeep Cherokee Tests 205 through 208 were conducted with an initial left then right steering input. All four of these tests produced two-wheel lift for Initial Speeds ranging from 50.4 to 54.4 mph with Maximum Corrected Lateral Acceleration from the Second Steer levels ranging from 0.87 to 1.01 g. These results are consistent with the two-wheel left and Maximum Corrected Lateral Acceleration from the Second Steer levels seen for Tests 201 through 203. Since this set of tests was run with new tires, this suggests that tire wear did not influence Tests 201 through 203.

11.2 Determining Maximum Lateral Acceleration and Lateral Acceleration for Rollover (LAR)

Toyota Engineering Standard TS-A1544 describes the procedure for determining the Used Maximum Corrected Lateral Acceleration for each test in a test series and for using these values in the calculation of Lateral Acceleration for Rollover (LAR) in this standard. The Used Maximum Corrected Lateral Acceleration is determined by finding the peak in the corrected lateral acceleration trace that occurs closest in time to the maximum roll angle (generally this is the first peak). If two-wheel lift is sustained, or if two-wheel lift occurs more than once, the peak corrected lateral acceleration that occurs closest in time to the moment when two-wheel lift first occurred is used.

The LAR value is determined by taking the largest Used Maximum Corrected Lateral Acceleration for the tests that did not produce two-wheel lift and the smallest Used Maximum Corrected Lateral Acceleration for the tests that did produce two-wheel lift (Toyota specifies that there should be a minimum of three tests that produced two-wheel lift in the series).

The procedure for selecting the maximum LAR is straightforward if the maximum roll angle or two-wheel lift occurs at the first peak for the roll angle. It is also straightforward if the maximum roll angle or two-wheel lift occurs at a secondary peak. It is the opinion of the authors that a problem occurs when examining a sequence of tests that have a maximum roll angle or two-wheel lift occurring at the first peak for some tests and at secondary peaks for other tests. This results in "comparing apples to oranges" when calculating the LAR value. This can best be demonstrated by examining a few sample plots.

The corrected lateral acceleration, roll angle, and roll rate traces for a test (Toyota 4Runner Test 712) that produced two-wheel lift are given in Figure 11.3. In the roll angle trace, two-wheel lift starts at Point A. Even though the magnitude of the corrected lateral acceleration is larger at Points B and C, Point A is the magnitude of corrected lateral acceleration that produced the onset of two-wheel lift. Note that the larger corrected lateral acceleration at Point C does not produce a correspondingly larger roll angle. The roll angle at Point A is larger due to the significant roll momentum that occurs as the vehicle leans from one side to the other. This is indicated by the large roll rate (third trace) that occurs prior to two-wheel lift at Point A. Even though the corrected lateral acceleration is larger at Point C, there is not as large a roll momentum and therefore not a corresponding increase in the roll angle.

The corrected lateral acceleration, roll angle, and roll rate traces for a test (Toyota 4Runner Test 706) that produced two distinct instances of two-wheel lift are given in Figure 11.4. In the roll angle trace, two-wheel lift occurs at Points A and B. Even though the magnitude of the corrected lateral acceleration is larger at Point B than at Point A, Point A is the corrected lateral acceleration that produced the first two-wheel lift and therefore, in accordance with Toyota's procedure, it would be selected over Point B. The larger corrected lateral acceleration at Point B does produce a slightly larger roll angle, but it is not by as much as one might expect. Again, an examination of the roll rate channel explains why this is the case. The roll rate prior to the roll angle peak at Point B is much less than it is at Point A and therefore the roll momentum effect is not as great for this second peak.

The same three traces for a test (Toyota 4Runner Test 710) that did not produce two-wheel lift on the first peak in roll angle (Point A), but did on the second peak (Point B) are shown in Figure 11.5. As in Figure 11.4, the larger corrected lateral acceleration at Point B in Figure 11.5 does produce a slightly larger roll angle, but it is not by as much as one might expect. Again the roll rate prior to the roll angle peak at Point B is much less than it is at Point A and therefore the roll momentum effect is not as great for this second peak. This again emphasizes the fact that lateral acceleration is not the only thing that contributes to peak roll angle and two-wheel lift in the Toyota Fishhook maneuver. There are also the roll momentum effects because the vehicle first leans in one direction due to the initial steering input and then leans in the opposite direction due to the very rapid steering reversal.

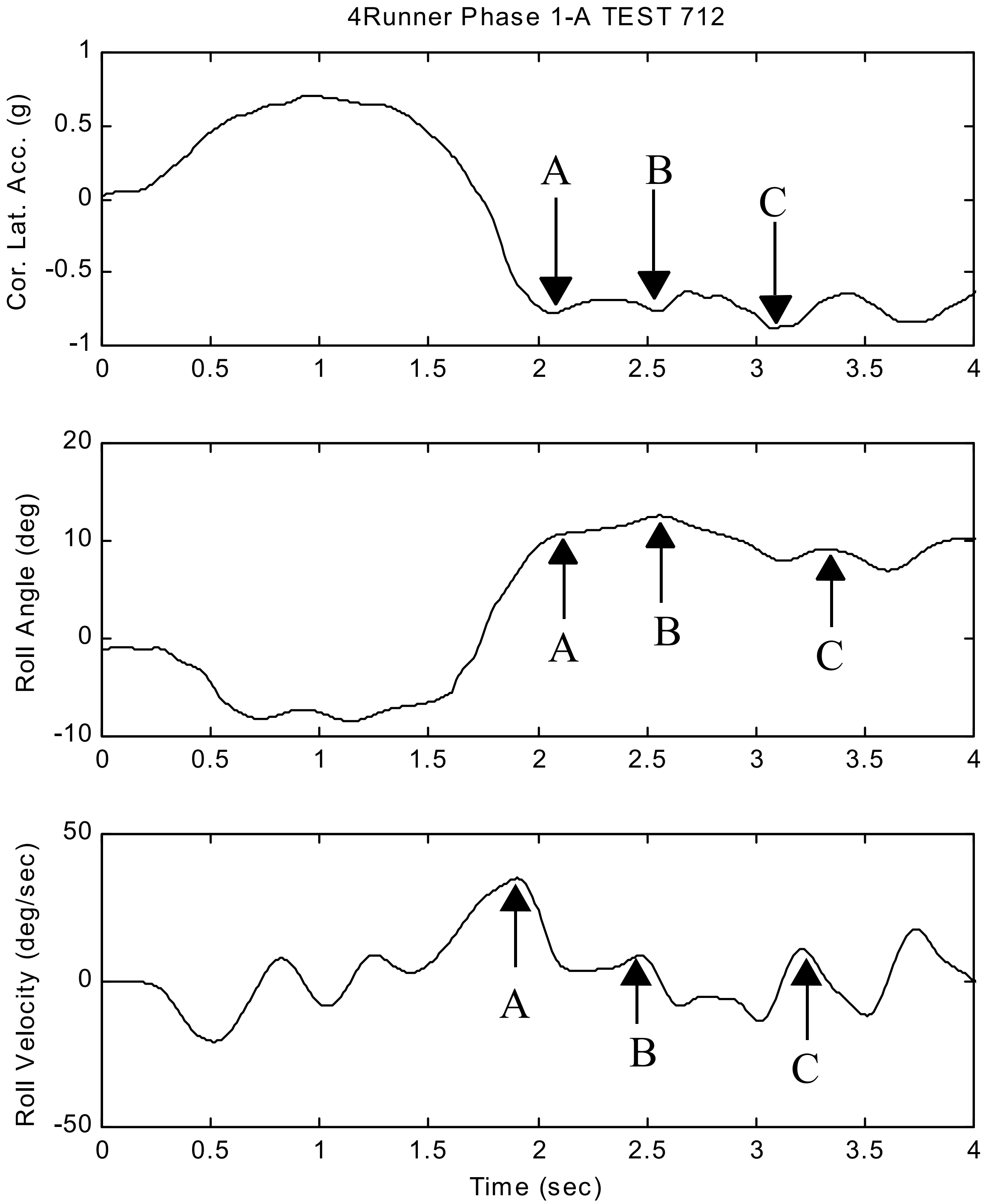

Figure 11.3 -- Lateral Acceleration Used to Determine LAR - Onset of Initial Two-Wheel Lift

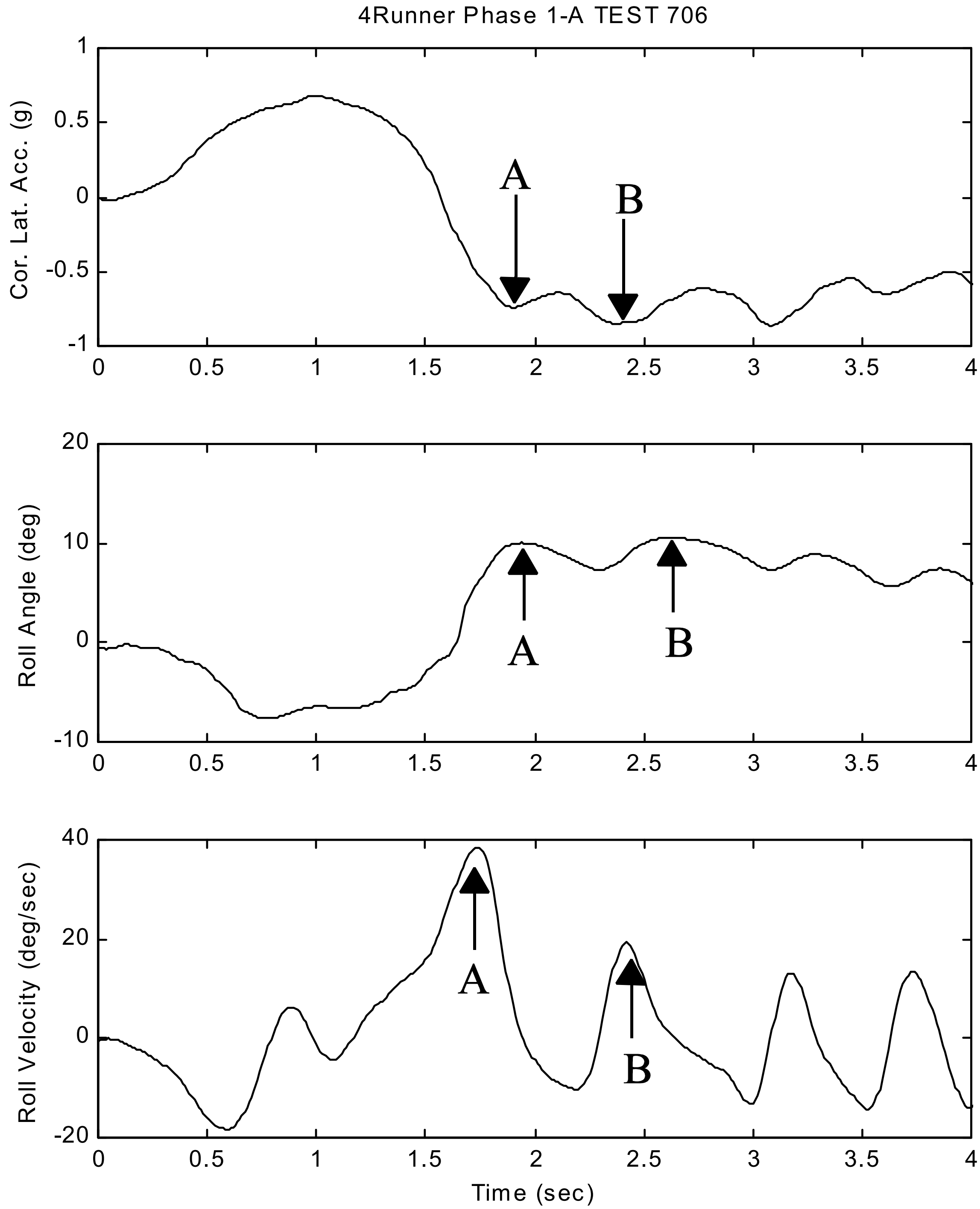

Figure 11.4 -- Lateral Acceleration Used to Determine LAR - Two Instances of Two-Wheel Lift

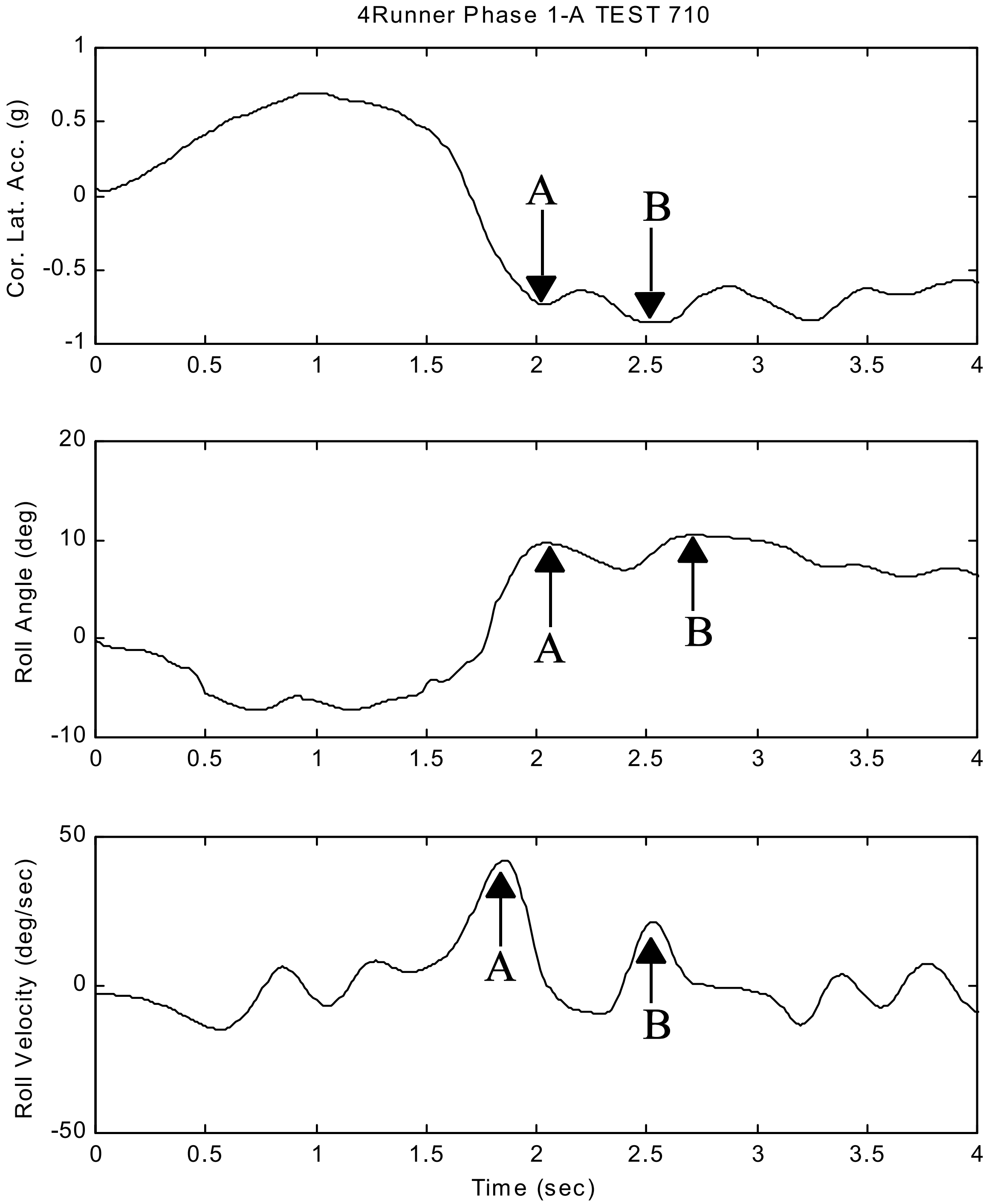

Figure 11.5 -- Lateral Acceleration Used to Determine LAR - Two Wheel Lift on Second Peak but Not the Initial Peak

Since Point B has a slightly higher roll angle than does Point A, the larger corrected lateral acceleration at Point B should, according to Toyota's procedure, be chosen as the Used maximum Corrected Lateral Acceleration because this is where two-wheel lift first occurred. However, this is where we start "comparing apples to oranges." The acceleration at Point B for this test is larger than the corrected lateral acceleration that produced the initial two-wheel lifts for Tests 706 and 712 (whose data is shown in Figures 11.3 and 11.4). If we choose to use Point B in this case, or in any case where the second roll angle peak is greater than the first, then the corrected lateral accelerations for non-two-wheel lift cases with second roll peaks greater than the first will be greater, sometimes significantly greater, than those that have two-wheel lift on the first peak.

The results of using Point A for the two-wheel lift cases and Point B for non-two-wheel lift cases for a series of Toyota 4Runner tests are shown in Figure 11.6. These are clearly backwards from what would be expected with most of the non-two-wheel lift test runs having Used Maximum Corrected Lateral Accelerations that are greater than those of the test runs with two-wheel lift. The results of using Point A for both the two-wheel lift and non-two-wheel lift cases are shown in Figure 11.7. These are more what would be expected; the non-two-wheel lift cases generally have lower Used Maximum Corrected Lateral Accelerations than do the test runs for which two-wheel lift occurred.

During analyses of the Phase I-B Toyota 4Runner Toyota Fishhook data, the first peak and second peak cases will be examined separately. For all other sets of Toyota Fishhook tests (all vehicles in Phase I-A and the Ford Bronco II in the Phase I-B testing), only the first peak or the first peak after pulse braking cases were/will be examined.

11.3 Lateral Acceleration for Rollover Determination for Each Vehicle

The Toyota 4Runner Used Maximum Corrected Lateral Acceleration values for Tests 701 through 712 are plotted in Figure 11.8. The smallest (in absolute value) Used Maximum Corrected Lateral Acceleration that produced two-wheel lift was -0.80 g and the largest (in absolute value) Used

Maximum Corrected Lateral Acceleration that did not produce two-wheel lift was -0.80 g. The average of the absolute value of these two numbers is the LAR, giving a value of 0.80 g. To produce a complete LAR value, testing would also have to be conducted in the other direction (an initial left then right steering input) and a second LAR value calculated. According to the Toyota test procedure, the lower of these two LAR values is the LAR value for the vehicle.

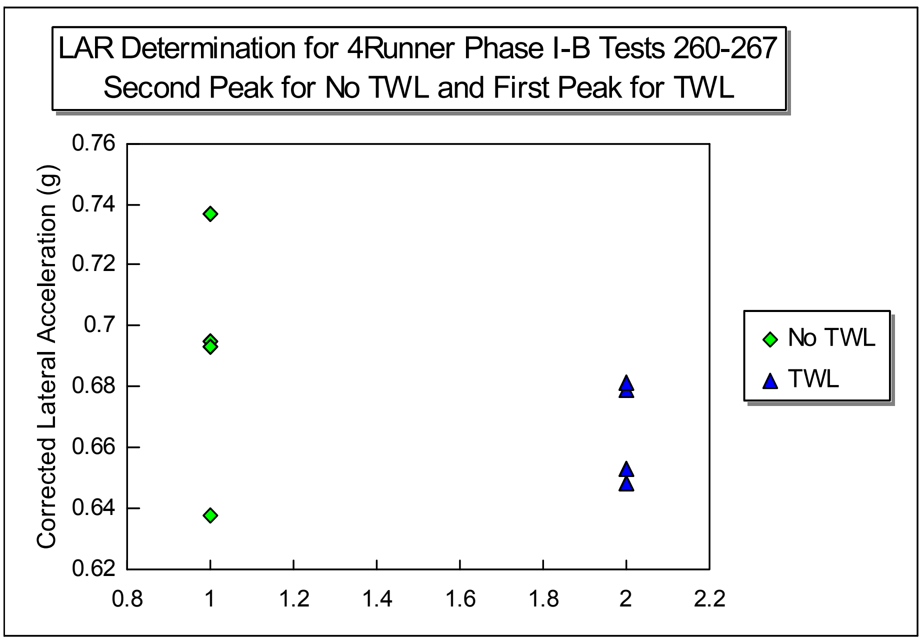

Figure 11.6 -- LAR Determination - Secondary Peaks for No Two-Wheel Lift Cases

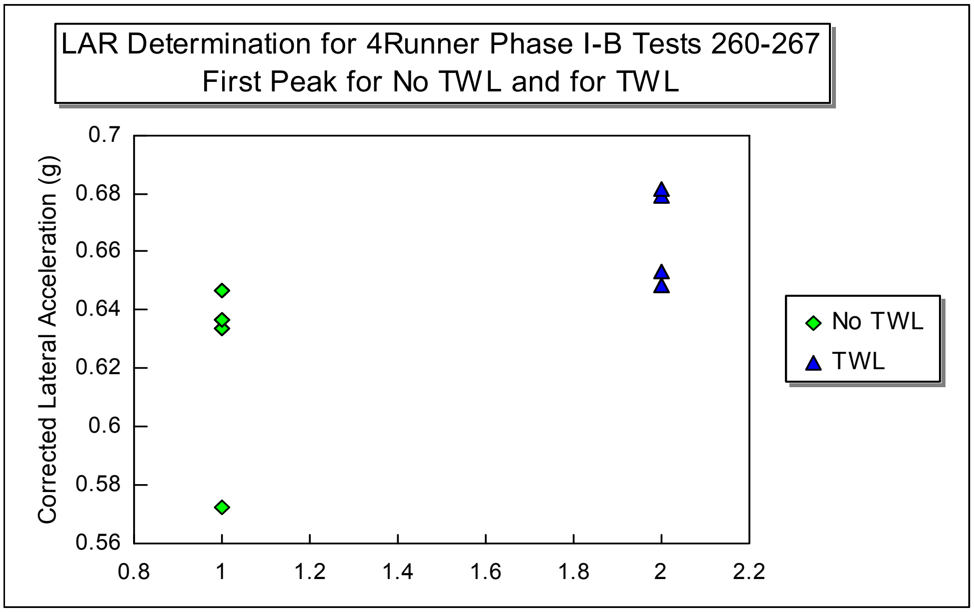

Figure 11.7 -- LAR Determination - First Peaks for No Two-Wheel Lift Cases

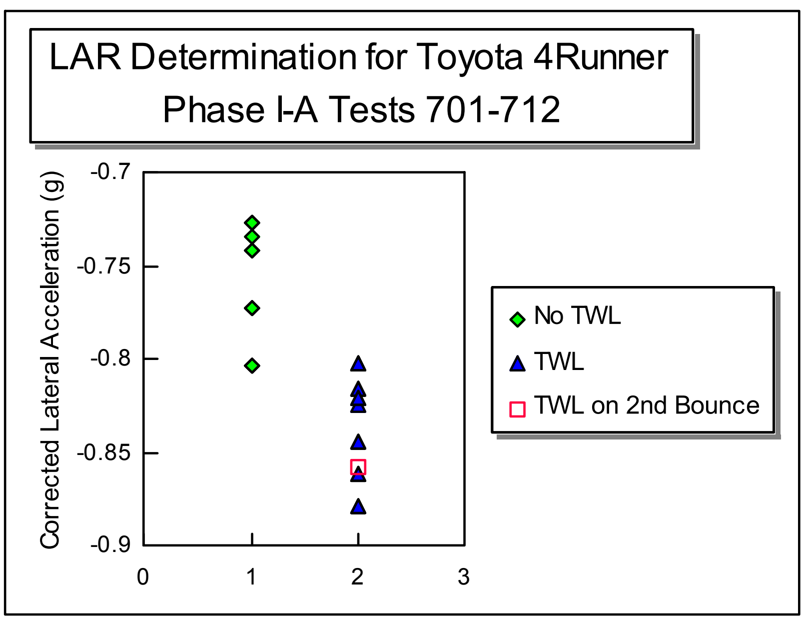

Figure 11.8 -- Toyota 4Runner LAR Determination

Note that one Toyota 4Runner test produced two-wheel lift on the second roll angle peak after the secondary steering input (Test 710 - see Figure 11.5 and the discussion in Section 11.2). This test is labeled individually because all of the other Toyota 4Runner tests had maximum roll angles or two-wheel lift occurring at the first peak in the roll angle. The maximum corrected lateral acceleration peak prior to the first roll angle peak was used for all other tests and are the values shown in Figure 11.8.

For the Ford Bronco II, there were very few tests conducted with the same tire set that produced two-wheel lift. Therefore, an LAR value cannot be determined from the Phase I-A test data for this vehicle. The tire wear issue also makes calculating an LAR value for this vehicle inappropriate.

A total of five sets of Toyota Fishhook tests were performed for the Jeep Cherokee. The first set consisted of Tests 101 through 108. These tests were performed with an initial right then left steering input. The Used Maximum Corrected Lateral Accelerations, which ranged from -0.73 to -0.85 g, are plotted in Figure 11.9. None of these tests produced two-wheel lift. Therefore, an LAR value cannot be determined from this set of tests.

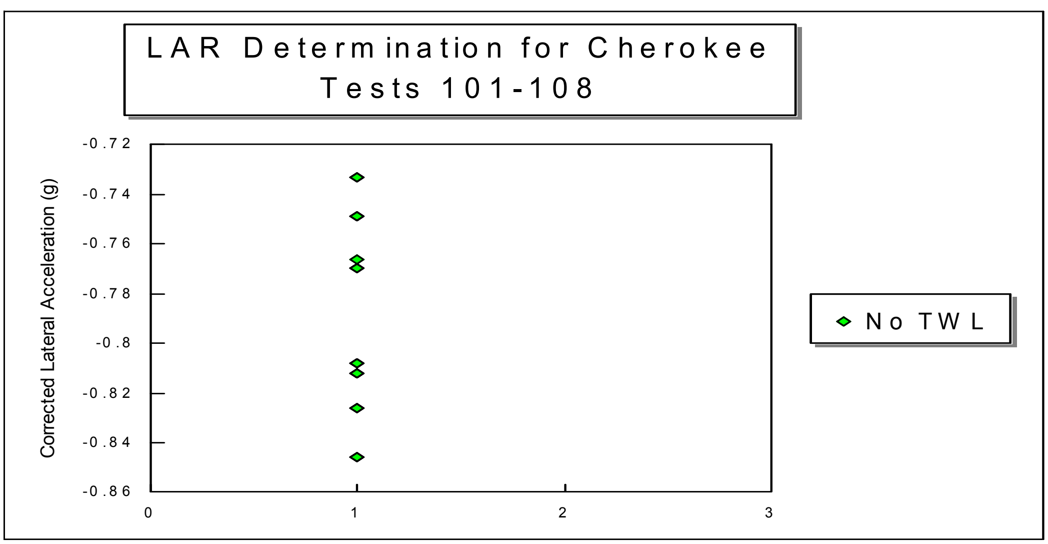

Figure 11.9 -- LAR Determination for Cherokee Tests 101-108

The second set of Toyota Fishhook runs consisted of Tests 109, 111, and 112. These tests were performed with an initial left then right steering input. The Used Maximum Corrected Lateral Accelerations, which ranged from 0.81 to 0.82 g, are plotted in Figure 11.10. None of these tests produced two-wheel lift. Therefore, an LAR value cannot be determined from this set of tests.

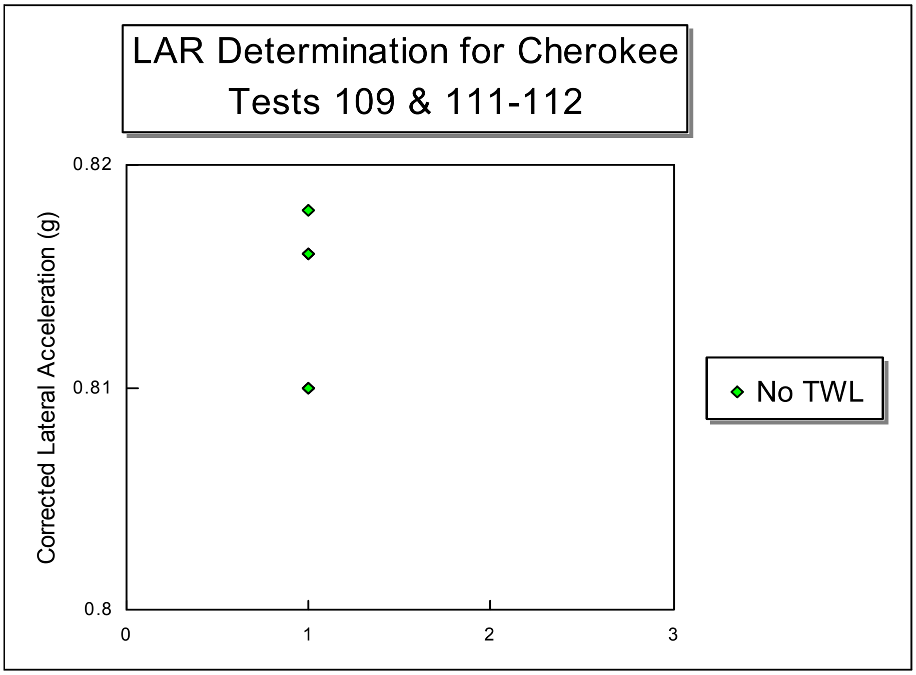

Figure 11.10 -- LAR Determination for Cherokee Tests 109, 111, and 112

The third set of Toyota Fishhook runs consisted of Tests 201 through 203. These tests were performed with an initial left then right steering input. The Used Maximum Corrected Lateral Accelerations, which ranged from 0.93 to 0.96 g, are plotted in Figure 11.11. All of these tests produced two-wheel lift. Therefore, an LAR value cannot be determined from this set of tests.

The fourth set of Toyota Fishhook runs consisted of Tests 204, 209, and 210. These tests were performed with an initial right then left steering input. The Used Maximum Corrected Lateral Accelerations, which ranged from -0.81 to -0.83 g, are plotted in Figure 11.12. None of these tests produced two-wheel lift. Therefore, an LAR value cannot be determined from this set of tests.

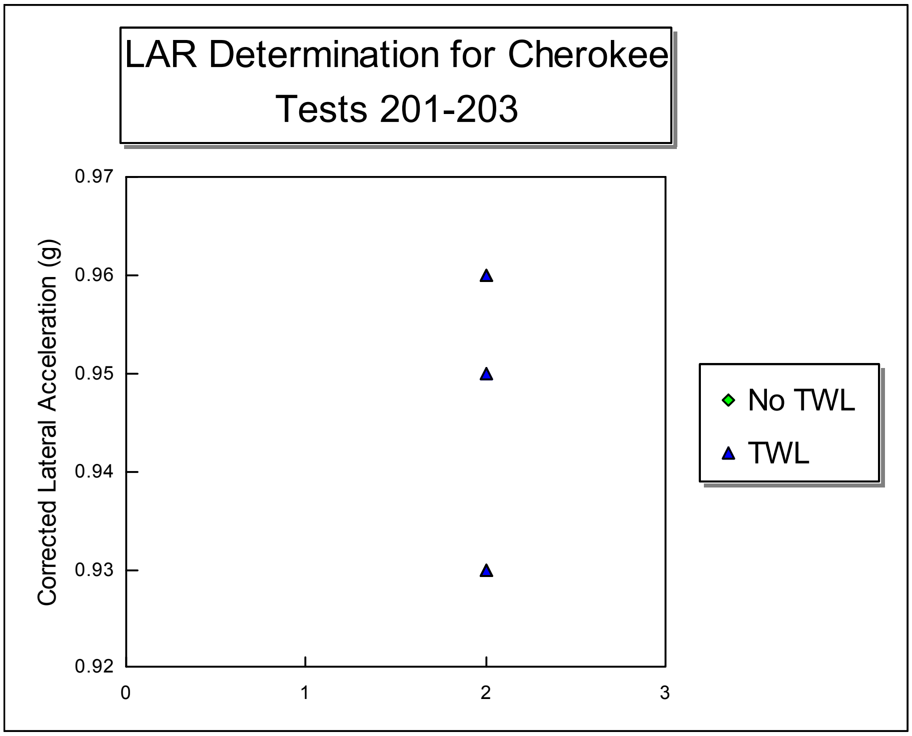

Figure 11.11 -- LAR Determination for Cherokee Tests 201-203

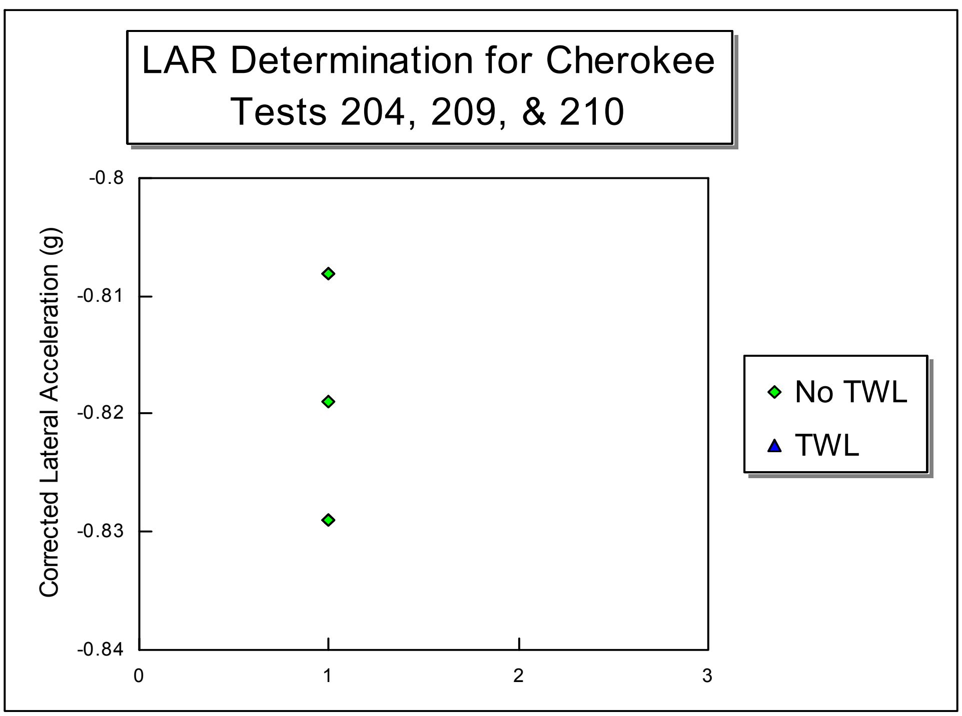

Figure 11.12 -- LAR Determination for Cherokee Tests 204, 209 and 210

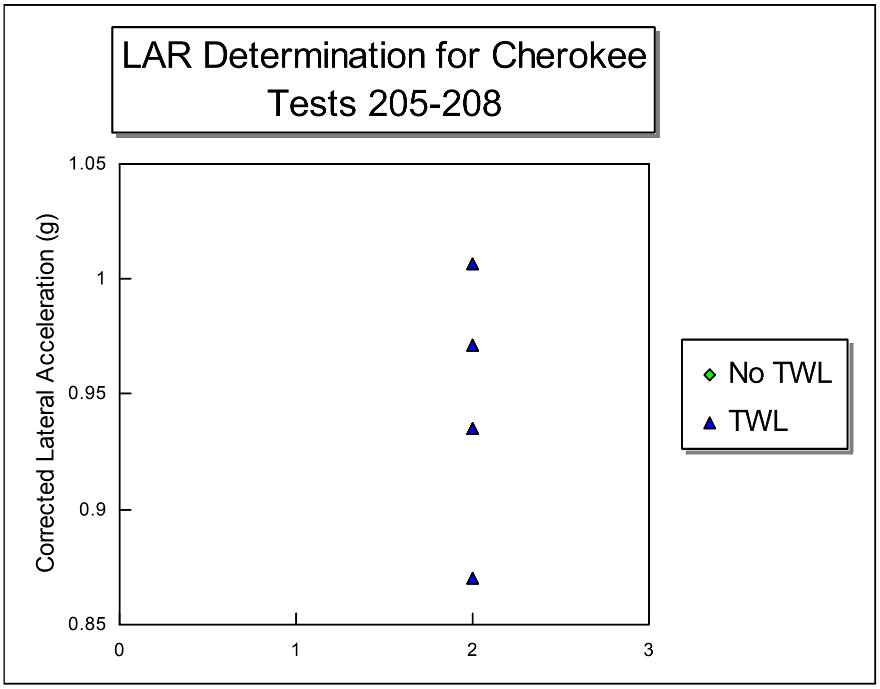

Figure 11.13 -- LAR Determination for Cherokee Tests 205-208

Tests 205 through 208 were also conducted with an initial left then right steering input after all four tires were replaced. The Used Maximum Corrected Lateral Accelerations are plotted in Figure 11.13. All four of these tests produced two-wheel lift. Therefore, an LAR value cannot be determined from this set of tests.

Data from the three Jeep Cherokee sets with an initial left then right steering input (Sets 2, 3, and 5) can be combined to produce an LAR value. For these tests, the smallest Used Maximum Corrected Lateral Acceleration that produced two-wheel lift was 0.87 g and the largest Used Maximum Corrected Lateral Acceleration that did not produce two-wheel lift was 0.82 g. The average of these two numbers is the LAR, giving a value of 0.85 g.

Since two-wheel lift did not occur during either of the two Jeep Cherokee sets (Sets 1 and 4) with an initial right then left steering input, an LAR value for this direction of steering cannot be determined even by combining data from these sets of tests. However, the LAR value for this direction of steering should exceed the largest Used Maximum Corrected Lateral Acceleration from either set. Therefore, the LAR value for the initial right then left steering input exceeds 0.85 g.

To produce a complete LAR value, according to the Toyota test procedure, the lower of the two LAR values from the two initial directions of steering is the LAR value for the vehicle. Since the LAR value for the initial left then right steering input is 0.85 g and the LAR value for the initial right then left steering input exceeds 0.85 g, the LAR value for the Jeep Cherokee is 0.85 g.

11.4 The Toyota Fishhook and Rollover Propensity

Two-wheel lift occurred for all three vehicles tested.

For the Toyota 4Runner eight of 12 test runs produced two-wheel lift. “Minor”, “Moderate”, and “Major” two-wheel lift were all noted. The no two-wheel lift runs were made with Initial speeds of up to 34.8 mph, the “Minor” two-wheel lift runs had Initial Speeds of 36.0 to 36.9 mph, the “Moderate” two-wheel lift runs had Initial Speeds of 38.0 to 38.9 mph, and the “Major” two-wheel lift runs had Initial Speeds of 38.0 to 38.4 mph. Note that there was non-repeatability as to whether an Initial Speed of approximately 38 mph would produce “Moderate” or “Major” two-wheel lift.

For the Ford Bronco II, three of 15 test runs produced “Major” two-wheel lift. The no two-wheel lift runs were made with Initial Speeds of 36.7 to 46.9 mph and the “Major” two-wheel lift runs had Initial Speeds of 42.3 to 45.0 mph. The runs that produced two-wheel lift were performed after significant tire shoulder wear had occurred. The overlap of the no two-wheel lift and the “Major” two-wheel lift runs Initial Speeds supports the belief that tire shoulder wear was responsible for the occurrence of the “Major” two-wheel lifts. The Bronco II did have very large front-wheel lift for many of the tests.

For the Jeep Cherokee, seven of 21 test runs produced two-wheel lift. “Minor” and “Moderate” two-wheel lift were both noted. The no two-wheel lift runs were made with Initial Speeds of up to 52.1

mph, the “Minor” two-wheel lift runs had Initial Speeds of 50.4 to 52.4 mph, and the “Moderate” two-wheel lift runs had Initial Speeds of 52.2 to 54.4 mph. Note that there is a small amount of overlap between each of these ranges, indicating some non-repeatability for this vehicle.

In general, increasing the Toyota Fishhook’s severity by increasing the Initial Speed resulted in increasing maximum corrected lateral accelerations and roll angles up to the point of limit response. All three vehicles experienced two-wheel lift as a limit condition. Tire shoulder wear seemed to be responsible for this limit condition for the Ford Bronco II, but not for the Toyota 4Runner or the Jeep Cherokee.

The maximum lateral accelerations for tests that produced two-wheel lift were higher than for those that did not for the Toyota 4Runner and the Jeep Cherokee. This was not the case for the Ford Bronco II which only produced two-wheel lift after significant tire shoulder wear. For the Bronco II, the tests that did produce two-wheel lift had lower maximum lateral accelerations than did some tests that did not generate two-wheel lift.

11.5 Repeatability of the Toyota Fishhook

A steering stop was not used during this testing to assist the driver in making repeatable initial steering movements. The initial steer for the Toyota Fishhook was specified to be 270 degrees. The actual initial steering inputs generated during this testing ranged from 210 to 342 degrees. Since all of these initial steering angles are quite large, they are expected to saturate (or, as per the discussion in Section 7.4, almost saturate) the tires’ lateral force production capability. Therefore, the observed variation in the magnitudes of the initial steering inputs is expected to have only minor influence on the motions of the test vehicles.

For the second steering input, the test driver was supposed to turn the steering wheel until the vehicle’s built-in mechanical stop was reached. Unfortunately, he did so consistently only for the Toyota 4Runner testing. Therefore, the Toyota 4Runner testing has a very repeatable end-point for the second steering input. The end-point for the second steering input for the other two vehicles was not repeatable. However, the effects of this non-repeatability are expected to be small because the second steering movement was always large enough to saturate the tires' lateral force production capability.

The timing of the steering inputs also varied from run-to-run. Figure 11.14 shows the steering angle as a function of time for each of the Toyota Fishhook runs that were made for the Jeep Cherokee. Note that the initial left then right steering inputs have been inverted so that a direct comparison can be made with the initial right then left inputs.

As Figure 11.14 shows, there is quite a lot of run-to-run non-repeatability in the timing of the Toyota Fishhook steering inputs. For example, among the 21 Jeep Cherokee runs, the time of the first zero crossing varied from 0.92 seconds to 1.55 seconds.

For the Jeep Cherokee, the lateral acceleration values for the right then left steering inputs were generally lower than those for the left then right steering inputs. One possible explanation is the timing of the steering inputs. Note that in Figure 11.14 the initial left then right steering inputs were generally much quicker than those for the initial right then left inputs. This quicker steering input may cause the vehicle to change more rapidly from leaning in one direction to leaning in the other which would result in a larger angular momentum. This larger angular momentum could be the difference between producing and not producing two-wheel lift. Other explanations could include, but not be limited to, suspension geometry changes from one side of the vehicle to the other, suspension stiffness or damping characteristics that are different from one side to the other, roll stiffness or damping characteristics that are different as the vehicle rolls left-to-right versus right-to-left, or weight distribution. A more thorough examination of the effects of steering input timing will require the use of a steering controller that can more accurately reproduce steering profiles than can a human driver.

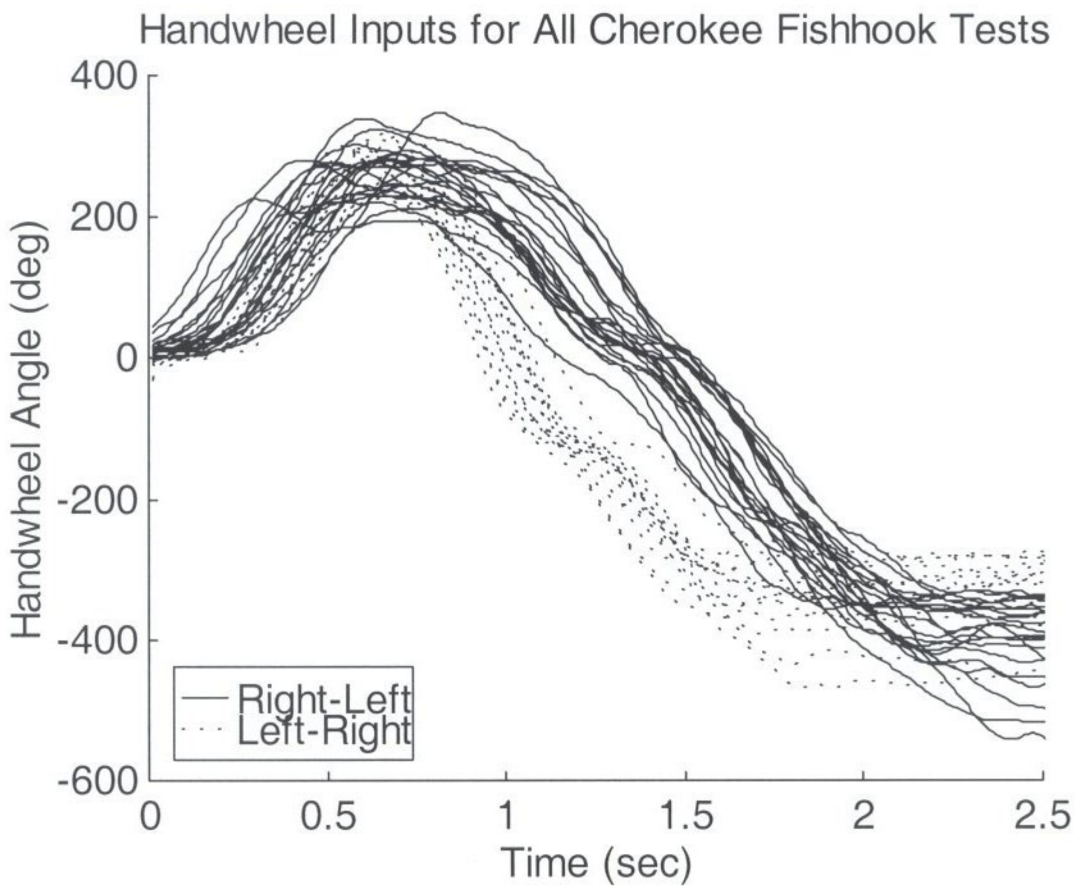

Figure 11.14 -- Comparison of Right Then Left and Left Then Right Steering Inputs

To further examine the repeatability of the Toyota Fishhook maneuver, comparisons between matched pairs of test runs were made. Matched run pairs were selected for a test vehicle based on values of three primary input descriptor variables, Initial Speed, First Steering Input, and Second Steering Input. Note that this is a simplification since the timing of the steering input certainly affects the measured data from a test run. However, the greatest timing differences were between tests with Right Then Left steering inputs and tests with Left Then Right steering inputs. Therefore, despite neglecting steering timing effects, the matched run pair comparisons are thought to provide valuable information about maneuver repeatability.

With three primary input descriptor variables, Initial Speed, First Steering Input, and Second Steering Input, no repeated runs with exactly the same input descriptor variables and only a few runs with close to the same input descriptor variables were made. The pair of runs for each test vehicle which came closest to the same Initial Speed and First and Second Steering Inputs were found and analyzed for repeatability.

The matching pair of test runs for the Toyota 4Runner are Test Numbers 708 and 709. These tests had Initial Speeds of 38.3 and 38.4 mph, respectively, First Steering Inputs of 316 and 324 degrees, respectively, and Second Steering Inputs of -630 degrees for both tests. The Second Steering Inputs are identical because the test driver turned the steering wheel until the vehicle's mechanical steering stop was reached for this steering movement. Since the differences between these two runs' input descriptor variables were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

The two tests had different amounts of two-wheel lift, "Moderate" for Test 708 and "Major" for Test 709. Looking at the post-first steer data from these runs, Test 709's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 708 by 2.9 percent. The absolute value of the Maximum Roll Angle from the First Steer was 9.0 percent larger for Test 709. The Maximum Corrected Lateral Acceleration result is in line with the 2.5 percent increase in the First Steer Input and the 0.3 percent increase in Initial Speed from Test 708 to Test 709. (However, for the large First Steer input that was used, the tires' lateral force production capability should be saturated. Therefore, it is not clear why the Maximum Corrected Lateral Acceleration result should track the difference in the First Steer input.) Looking at the post-second steer data from these runs, the absolute value of the Maximum Corrected Lateral Acceleration from the Second Steer decreased 2.4 percent from Test 708 to Test 709. However, the Maximum Roll Angle from the Second Steer increased by 25.9 percent (3.0 degrees) between the tests. Clearly, there is considerable non-repeatability in roll angle between these two runs. The authors believe that this non-repeatability occurred because the vehicle becomes unstable in roll near its rollover threshold, i.e., near the point when "Major" two-wheel lift occurs.

The matching pair of test runs for the Ford Bronco II are Test Numbers 82 and 91. These tests had Initial Speeds of 40.8 and 40.7 mph, respectively, First Steering Inputs of 282 and 263 degrees, respectively, and Second Steering Inputs of -492 and -509 degrees, respectively. Since the differences between these two runs' input descriptor variables were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

Both tests had the same amount of two-wheel lift, "None". Looking at the post-first steer data from these runs, Test 91's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 82 by 4.1 percent. The absolute value of the Maximum Roll Angle from the First Steer was 8.5 percent larger for Test 91. Both of these results are in the opposite direction than the 7.3 percent decrease in the First Steering Input and the 0.3 percent decrease in Initial Speed from Test 91 to Test 82. Looking at the post-second steer data from these runs, the absolute value of the Maximum Corrected Lateral Acceleration from the Second Steer is 12.7 percent larger for Test 91 than for Test 82. The Maximum Roll Angle from the Second Steer was 8.5 percent larger for Test 91. While the reasons for these differences are not conclusively known, the authors believe that they are due to tire wear. Test 82 was the second test performed after mounting a new set of tires onto the vehicle. Test 91 was the eleventh test performed with this set of tires (allowing for some runs with bad data that are not shown in Table 11.2) and the run before tire shoulder wear is thought to have caused "Major" two-wheel lift to occur. Therefore, Test 82 was performed with unworn tires while Test 91 was performed with worn tires which had a higher side force generation capability. This increase in tire side force generation capability explains the higher Maximum Corrected Lateral Accelerations and Maximum Roll Angles that are seen for Test 91.

The matching pair of test runs for the Jeep Cherokee are Test Numbers 202 and 203. These tests had Initial Speeds of 52.4 and 52.2 mph, respectively, First Steering Inputs of -332 and -318 degrees, respectively, and Second Steering Inputs of 334 and 335 degrees, respectively. Since the differences between these two runs' input descriptor variables were fairly small, it is reasonable to compare data from these two runs to get a measure of maneuver repeatability.

The two tests had different amounts of two-wheel lift, “Minor” for Test 202 and “Moderate” for Test 203. Looking at the post-first steer data from these runs, the absolute value of Test 203's Maximum Corrected Lateral Acceleration from the First Steer exceeded that of Test 202 by 2.2 percent. The Maximum Roll Angle from the First Steer was 6.0 percent smaller for Test 203. The Maximum Corrected Lateral Acceleration result is in the opposite direction than the 4.4 percent decrease in the absolute value of the First Steer Input and the 0.4 percent decrease in Initial Speed from Test 202 to Test 203. However, the Maximum Roll Angle change is in line with the change in the input parameters between the runs. Looking at the post-second steer data from these runs, the Maximum Corrected Lateral Acceleration from the Second Steer increased 3.2 percent from Test 202 to Test 203. The absolute value of the Maximum Roll Angle from the Second Steer increased by 11.6 percent (1.0 degree) between the tests. Clearly, there is considerable non-repeatability in roll angle between these two runs.

11.6 Summary of Toyota Fishhook Results

This testing found that for some, but not all, sets of input parameters all three Phase I-A test vehicles had two-wheel lift for the Toyota Fishhook maneuver. The difference between non-two-wheel lift and two-wheel lift input parameters was primarily faster Initial Speeds.

The Ford Bronco II’s rollover propensity seemed to be highly related to tire wear (particularly shoulder wear) effects. This vehicle would only produce two-wheel lift after significant tire wear was observed. Testing with new tires at speeds higher than those that produced two-wheel lift with worn tires, did not result in two-wheel lift, although large front wheel lift was noted.

The Jeep Cherokee’s rollover propensity seemed to be an asymmetrical phenomenon, depending on the direction of steering input (this vehicle only had two-wheel lift with initial left then right steering inputs). Differences in the steering rates that were achieved for the two directions of steering could be a possible explanation. Further and more refined testing would be required to conclusively determine the reasons for the differences between initial left then right versus initial right then left steering inputs for the Cherokee.

The amount of two-wheel lift generally increased with Initial Speed. However, there were exceptions. In particular, for the Ford Bronco II, "Major" two-wheel lift occurred for runs with very similar Initial Speeds to runs for which no two-wheel lift occurred. The authors believe this to be due to tire wear. Less obvious non-repeatabilities also occurred for both the Jeep Cherokee and the Toyota 4Runner. The authors do not have a full explanation as to why these non-repeatabilities occurred. Several possibilities include timing of handwheel inputs, speed differences, and longitudinal acceleration differences.

Looking at three pairs of matched runs, one for each test vehicle, some unexpected run-to-run changes were seen. The largest, unanticipated, differences were found for the Ford Bronco II and are thought to be due to tire wear. For the Jeep Cherokee and Toyota 4Runner, unexpected differences between the pairs of matched runs in Maximum Corrected Lateral Acceleration were quite small. The largest unexpected run-to-run change in Maximum Corrected Lateral Acceleration was 2.9 percent (0.02 g) for the Toyota 4Runner and 3.2 percent (0.03 g) for the Jeep Cherokee. Larger unexpected differences between the pairs of matched runs in Maximum Roll Angle were seen for these two vehicles. The largest unexpected run-to-run change in Maximum Roll Angle was 25.9 percent (3.0 degrees) for the Toyota 4Runner and 11.6 percent (1.0 degree) for the Jeep Cherokee. The authors think that these larger roll angle differences occurred because vehicles become unstable in roll near their rollover threshold. Such instability would magnify observed experimental differences.

Overall, the repeatability of the Toyota Fishhook maneuver is thought to be acceptable. More repeatable control of the handwheel steering inputs should improve maneuver repeatability. However, because vehicles become unstable in roll very near their rollover thresholds, large run-to-run roll angle differences are inevitable if tests are performed right at the rollover threshold.

Although not as simple to conduct as the J-Turn maneuver, the Toyota Fishhook is a relatively easy test to conduct. It was able to induce two-wheel lift for all three vehicles tested. The results for certain vehicles appear to be affected by tire wear. Further consideration of this maneuver during later phases of NHTSA's Light Vehicle Dynamic Rollover Research program is recommended.

Future Toyota Fishhook research needs to focus on driver effects, tire wear issues, and the timing of the steering reversal. The authors believe that a steering controller will be necessary to achieve a consistent steering profile that can be used to evaluate a wide range of vehicles.

12.0 DOUBLE LANE CHANGE TEST RESULTS AND ANALYSIS

12.1 Tests Performed for Each Vehicle

12.1.1 Toyota 4Runner

A total of 49 double lane change tests with valid data, using three double lane change courses, were conducted with the Toyota 4Runner. Each course had different values for the course geometry parameters L1, L2, and W (these parameters were defined in Figure 6.6). Appendix A contains, in Tables A.1, A.2, and A.3, a run-by-run summary of the 4Runner data for each of the three double lane change courses.

Table 12.1 summarizes, for each course, the number of tests performed, the number of tests with two-wheel lift, the range of maximum corrected lateral accelerations both with and without two-wheel lift, the range of initial test speeds, again with and without two-wheel lift, the number of "clean" runs (i.e., runs for which contact with any of the cones delineating a double lane change course was avoided) made, and the highest initial test speed at which a "clean" run was made. Of the 49 runs, only nine were "clean". The low frequency of "clean" runs gives an indication of how difficult the double lane change maneuver was to perform for limit or near limit speeds and accelerations, as the path-following demands placed on the test driver were very high.

The 60/60/12 double lane change course, the tightest of the three courses, had ten tests with two-wheel lifts out of 19 runs with valid data which were performed with the Toyota 4Runner. Of the ten 60/60/12 course two-wheel lift tests, none had "Major" lifts, four had "Moderate" lifts, and six had "Minor" two-wheel lifts.

Figure 12.1 presents the range of maximum corrected lateral accelerations recorded during Toyota 4Runner 60/60/12 double lane change course testing and indicates whether two-wheel lift occurred. Figure 12.1 shows that a minimal (0.01 g) maximum corrected lateral acceleration overlap exists between tests that resulted in two-wheel lift and those that did not. On this course, for the Toyota 4Runner, two-wheel lift occurred when the maximum corrected lateral acceleration was greater than or equal to 0.84 g.

Table 12.1 -- Summary of Double Lane Change Testing for the Toyota 4Runner

Course Layout (ft)			Number of Tests	Number of Tests with TWL	Max. Cor. Lat. Acc.* Ranges (g)		Initial Speed Ranges (mph)		Number of "Clean" Runs	Highest "Clean" Run Initial Speed (mph)
L1	L2	W			without TWL	with TWL	without TWL	with TWL		
60	60	12	19	10	0.68 to 0.84	0.84 to 0.92	30.3 to 39.0	37.8 to 41.8	5	37.0
70	70	12	17	11	0.51 to 0.84	0.81 to 0.91	39.3 to 47.4	41.9 to 46.1	2	42.6
70	70	14	13	8	0.73 to 0.88	0.86 to 0.96	35.3 to 43.0	42.3 to 50.0	2	36.6

* – The corrected lateral acceleration data was obtained after the first steering reversal (the second steering input), but prior to the second reversal.

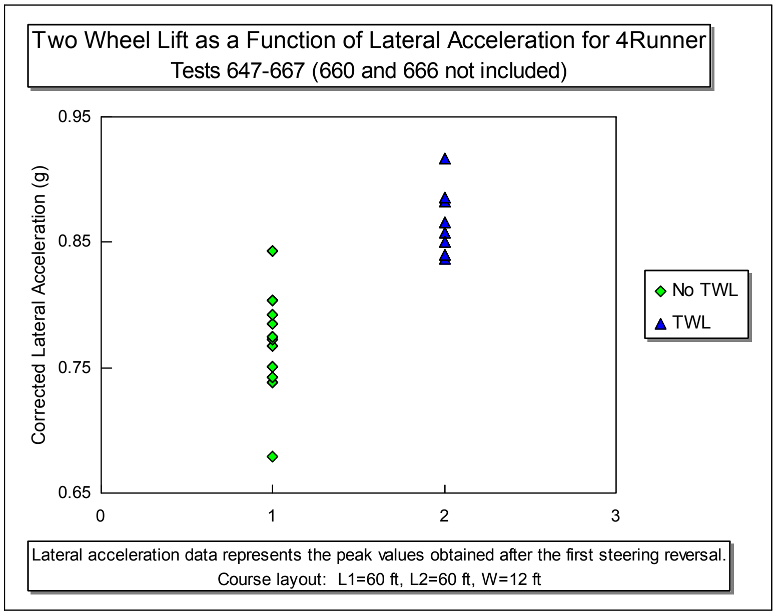

Figure 12.1 -- Toyota 4Runner Double Lane Change Maximum Corrected Lateral Accelerations With and Without Two-Wheel Lift for the 60/60/12 Course

The 70/70/12 double lane change course layout resulted in 11 two-wheel lifts out of 17 runs with valid data which were performed with the Toyota 4Runner. All of the two-wheel lifts on the 70/70/12 course were “Minor”.

Figure 12.2 presents the range of maximum corrected lateral accelerations recorded during Toyota 4Runner 70/70/12 double lane change course testing and indicates whether two-wheel lift occurred. This figure shows an increase in the overlap of maximum corrected lateral accelerations (0.03 g) for tests that resulted in two-wheel lift and those that did not compared to the 60/60/12 course. On this course, for the Toyota 4Runner, two-wheel lift occurred when the maximum corrected lateral acceleration was greater than or equal to 0.81 g. This 0.81 g value was the lowest maximum corrected lateral acceleration to produce two-wheel lift with the 4Runner for any of the three double lane change course layouts used during the Phase I-A testing.

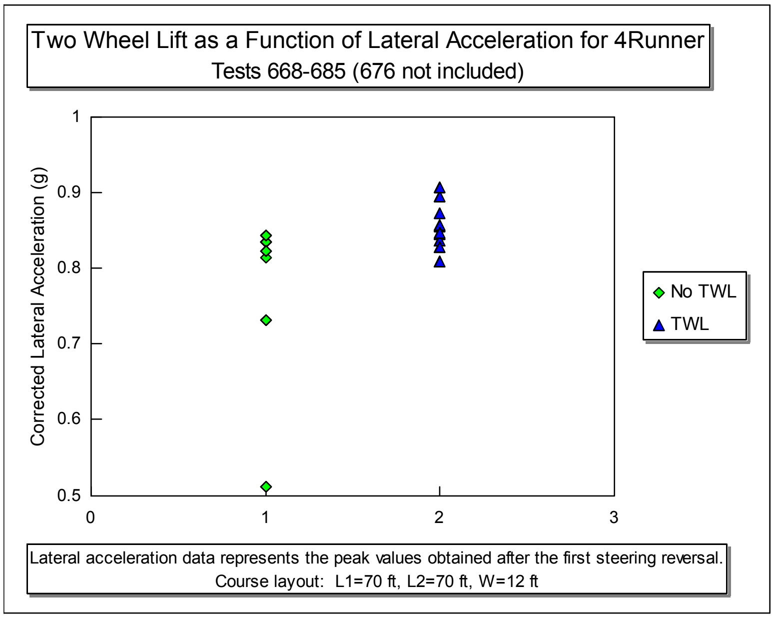

Figure 12.2 -- Toyota 4Runner Double Lane Change Maximum Corrected Lateral Accelerations With and Without Two-Wheel Lift for the 70/70/12 Course

The highest maximum corrected lateral acceleration generated for the Toyota 4Runner on the 70/70/12 double lane change course without two-wheel lift was 0.84 g. This is identical to the 0.84 g maximum corrected lateral acceleration without two-wheel lift result obtained during 60/60/12 course testing. Note that use of the 70/70/12 course yielded a significant increase in the maximum without two-wheel lift speed over the 60/60/12 course: up 21.5 percent to 47.4 mph. The 47.4 mph speed is the highest entrance speed used on the three double lane change course layouts that did not produce two-wheel lift with the 4Runner.

The Toyota 4Runner's highest "clean" run speed of 42.6 mph occurred during testing on the 70/70/12 double lane change course. The test run that yielded this speed is of particular interest, as it was the only "clean" double lane change that also produced two-wheel lift for any of the three test vehicles.

The 70/70/14 double lane change course had eight tests with two-wheel lifts out of 13 runs with valid data which were performed using the Toyota 4Runner. Of the eight 70/70/14 course two-wheel lift tests, one had “Major” lift, two had “Moderate” lifts, and five had “Minor” two-wheel lifts.

Figure 12.3 presents the range of maximum corrected lateral accelerations recorded during Toyota 4Runner 70/70/14 double lane change course testing, and indicates whether two-wheel lift was observed. This figure shows a 0.02 g overlap in the maximum corrected lateral accelerations between tests that resulted in two-wheel lift and those that did not. On this course, for the Toyota 4Runner, two-wheel lift occurred when the maximum corrected lateral acceleration was greater than or equal to 0.86 g. The minimum value for two-wheel lift, 0.86 g, of the maximum corrected lateral acceleration was the highest of the three course layouts for the 4Runner.

The highest maximum corrected lateral acceleration without two-wheel lift with the Toyota 4Runner that was generated on the 70/70/14 double lane change course was 0.88 g, 4.8 percent greater than the 0.84 g maximum no two-wheel lift results obtained during the 60/60/12 and 70/70/12 course testing of this vehicle.

During double lane change testing on all three courses, the Toyota 4Runner mostly exhibited “Minor” two-wheel lifts. Out of a total of 29 runs with two-wheel lift, there was one run with “Major” two-wheel lift, six runs with “Moderate” two-wheel lift, and 22 runs with “Minor” two-wheel lift.

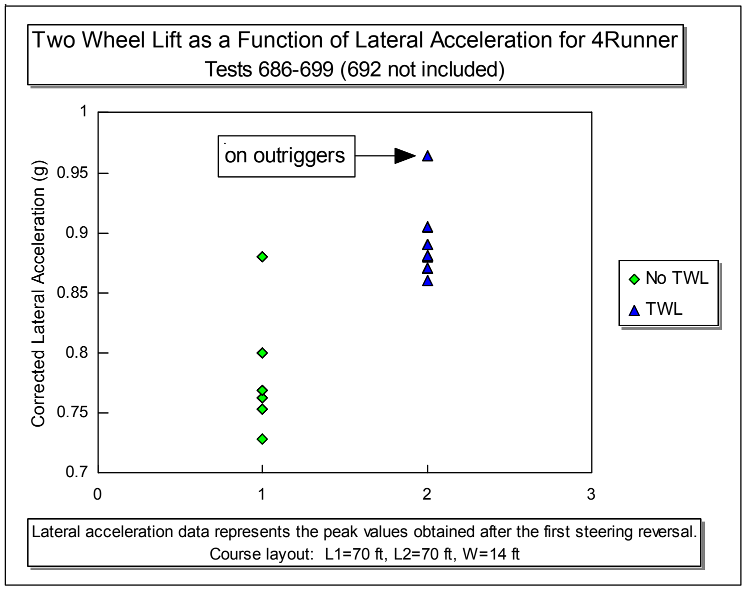

Figure 12.3 -- Toyota 4Runner Double Lane Change Maximum Corrected Lateral Accelerations With and Without Two-Wheel Lift for the 70/70/14 Course

When “Minor” two-wheel lift occurred for the Toyota 4Runner, there were few differences between roll angle and corrected lateral acceleration data from two-wheel lift and no two-wheel lift runs with nearly identical entrance lane speeds and driver steering inputs on the same double lane change course. Figure 12.4 compares data from two runs (Tests 691 and 697) which did not have two-wheel lift to data from a run with “Minor” two-wheel lift (Test 694). Note the similarity of the data traces from these three runs.

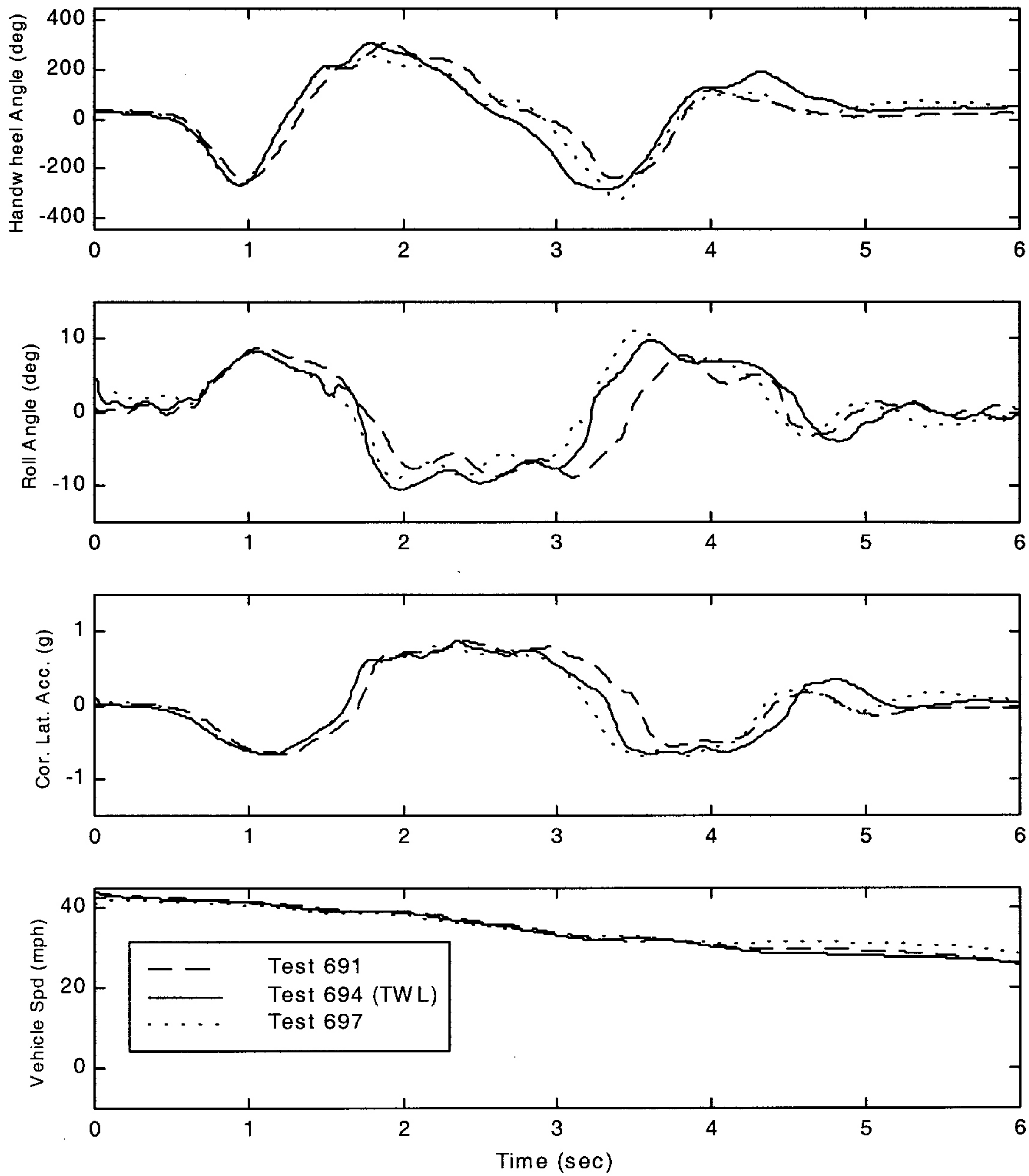

Figure 12.4 -- Toyota 4Runner Double Lane Change Data for Runs With and Without Two-Wheel Lift on the 70/70/14 Double Lane Change Course

12.1.2 Ford Bronco II

A total of 45 double lane change tests with valid data, using three double lane change courses, were conducted with the Ford Bronco II. Each course had different values for the course geometry parameters L1 and L2 (these parameters were defined in Figure 6.6). However, the lane offset, W, was held constant at 14 feet for all Bronco II tests. Appendix A contains, in Tables A.4, A.5, A.6, and A.7, a run-by-run summary of the Bronco II data for each of the three double lane change courses. Note that there are four tables for the three courses because testing on the 70/70/14 course was performed on two different days. Data from each day of testing is reported separately, in Tables A.5 and A.6, in case the day when the testing was performed affected the results.

Table 12.2 summarizes, for each course, the number of tests performed, the number of tests with two-wheel lift, the range of maximum corrected lateral accelerations both with and without two-wheel lift, the range of initial test speeds, again with and without two-wheel lift, the number of "clean" runs (i.e., runs for which contact with any of the cones delineating a double lane change course was avoided) made, and the highest initial test speed at which a "clean" run was made. Of the 45 runs, only six were "clean". The low frequency of "clean" runs gives an indication of how difficult the double lane change maneuver was to perform for limit or near limit speeds and accelerations, as the path-following demands placed on the test driver were very high.

The 60/60/14 layout was the tightest of the three courses used for Ford Bronco II double lane change testing, and resulted in the lowest maximum attainable "clean" run initial speed. Only seven runs were conducted, and none resulted in two-wheel lift. The maximum test speed used for this course was lower than for the other two primarily due to the shorter gate length. The largest maximum corrected lateral acceleration attained during testing on this course was 0.80 g.

Table 12.2 -- Summary of Double Lane Change Testing for the Ford Bronco II

Course Layout (ft)			Number of Tests	Number of Tests with TWL	Max. Cor. Lat. Acc.* Ranges (g)		Initial Speed Ranges (mph)		Number of "Clean" Runs	Highest "Clean" Run Initial Speed (mph)
L1	L2	W			without TWL	with TWL	without TWL	with TWL		
60	60	14	7	0	0.67 to 0.80	None	31.8 to 40.4	None	2	35.5
70	70	14	7 (day 1)	0	0.57 to 1.00	None	29.3 to 48.1	None	2	39.1
70	70	14	11 (day 2)	0	0.74 to 0.82	None	39.8 to 47.7	None	2	39.8
70	80	14	20	1	0.71 to 0.80	0.78**	41.3 to 47.0	45.5**	2	43.2

* – The corrected lateral acceleration data was obtained after the first steering reversal (the second steering input), but prior to the second reversal.

** – Wheel lift could not be determined from video data for Tests 126, 127, and 131 (all run on the 70/80/14 course).

A total of 18 tests were conducted with the Ford Bronco II using the 70/70/14 double lane change course layout. Two-wheel lift was not observed during any run. Roll angle and lateral acceleration data for Tests 50, 53, and 54 are not shown in Appendix A, as instrumentation malfunctions prevented accurate data acquisition.

Twenty tests were conducted with the Ford Bronco II using the 70/80/14 double lane change course layout. Testing on this course resulted in one two-wheel lift which was "Major". Note that information about possible two-wheel lifts is not available for Tests 126, 127, and 131 as video data is unavailable for these tests.

Figure 12.5 presents the range of maximum corrected lateral accelerations recorded during Ford Bronco II 70/80/14 double lane change course testing, and indicates whether two-wheel lift was observed. As the figure shows, a minimal (0.02 g) overlap in maximum corrected lateral accelerations exists between tests that resulted in two-wheel lift and the one that did not. However, due to limited data (a single two-wheel lift data point), a reasonable assessment of two-wheel lift likelihood for a given maximum corrected lateral acceleration for the Bronco II on the 70/80/14 course is not possible.

After the "Major" two-wheel lift occurred, new tires were installed on the Ford Bronco II. After the tire change, two-wheel lift did not occur again, even for tests with nearly identical steering inputs

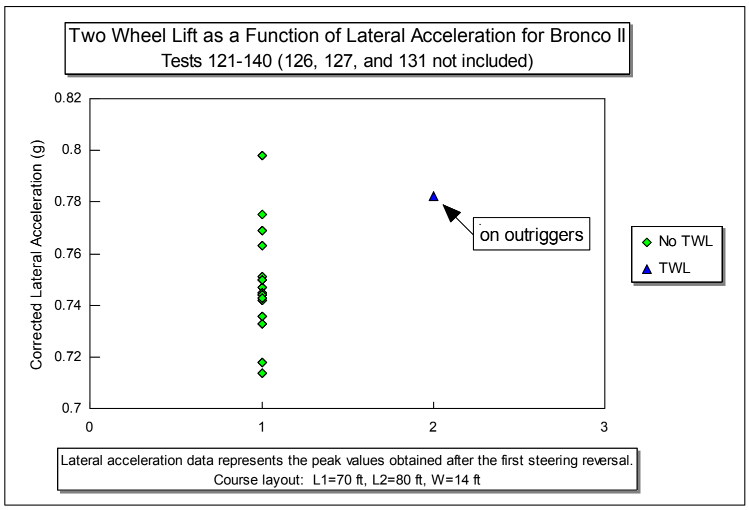

Figure 12.5 -- Ford Bronco II Double Lane Change Maximum Corrected Lateral Accelerations With and Without Two-Wheel Lift for the 70/80/14 Course

and initial test speeds to the one for which the "Major" two-wheel lift happened. Figure 12.6 demonstrates this observation by comparing data collected during three tests. "Major" two-wheel lift occurred for Test 124, while Tests 127 and 137 did not have two-wheel lift. Tests 127 and 137 were performed using the second (new) Bronco II tire set.

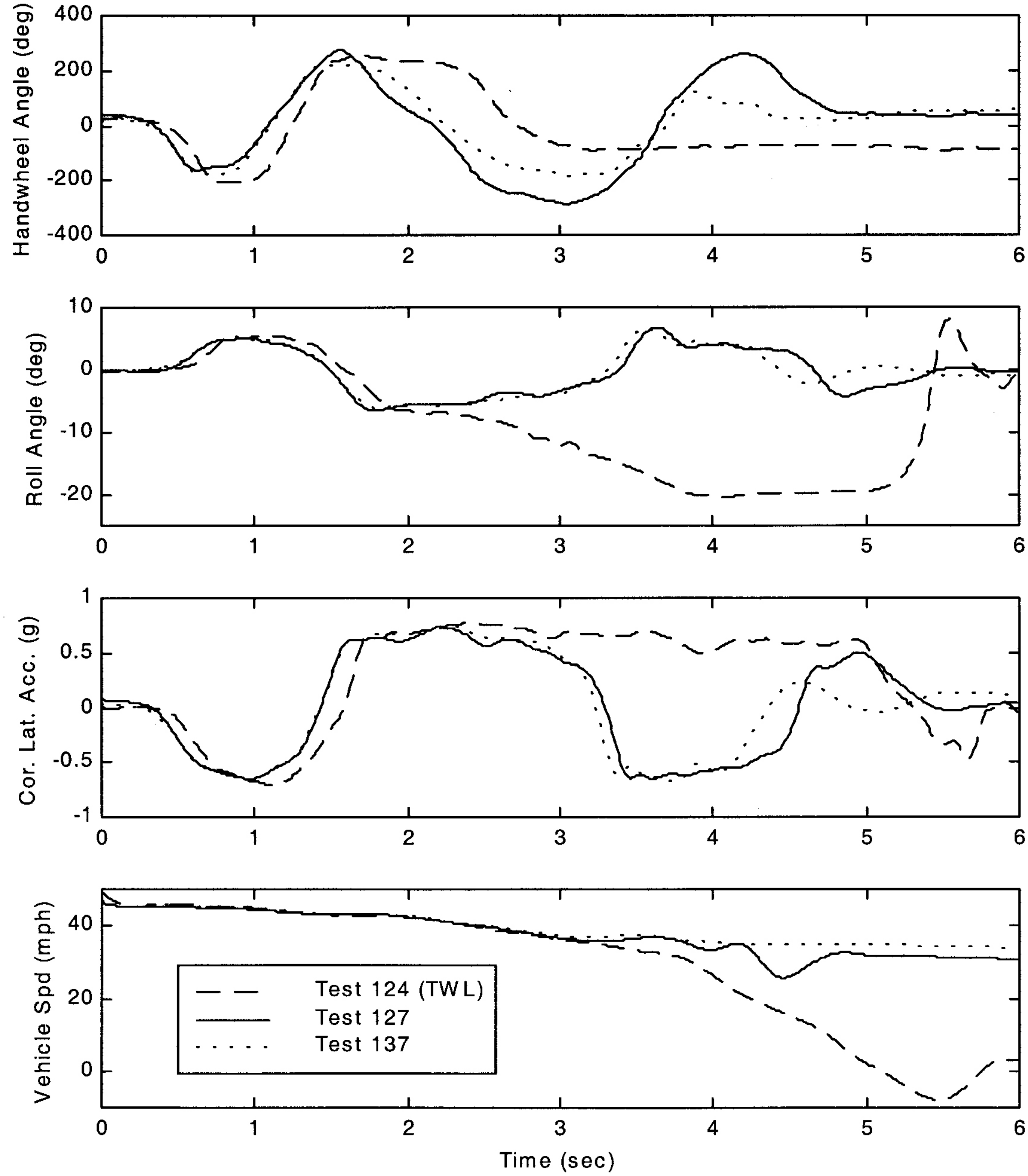

Figure 12.6 -- Comparison of Ford Bronco II Double Lane Change Data From One Test With Major Two-Wheel Lift and Two Tests Without Two-Wheel Lift on the 70/80/14 Course

Tire wear, specifically on the tread blocks just above the tires' shoulders, appears to be the cause of the "Major" two-wheel lift observed during Ford Bronco II testing on the 70/80/14 double lane change course. This influence of tire wear on the Bronco II's rollover propensity was also observed for other Phase I-A maneuvers (see, in particular, the discussion in Chapter 11 of the Ford Bronco II tire wear that was observed during Toyota Fishhook testing).

12.1.3 Jeep Cherokee

A total of 28 double lane change tests with valid data, using five double lane change courses, were conducted with the Jeep Cherokee. Each course had different values for the course geometry parameters L1 and L2 (these parameters were defined in Figure 6.6). However, the lane offset, W, was held constant at 14 feet for all Cherokee tests. Appendix A contains, in Tables A.8, A.9, A.10, A.11, and A.12, a run-by-run summary of the Cherokee data for each of the five double lane change courses.

Table 12.3 summarizes, for each course, the number of tests performed, the number of tests with two-wheel lift, the range of maximum corrected lateral accelerations both with and without two-wheel lift, the range of initial test speeds, again with and without two-wheel lift, the number of "clean" runs (i.e., runs for which contact with any of the cones delineating a double lane change course was avoided) made, and the highest initial test speed at which a "clean" run was made. Of the 28 runs, only four were "clean". The low frequency of "clean" runs gives an indication of how difficult the double lane change maneuver was to perform for limit or near limit speeds and accelerations, as the path-following demands placed on the test driver were very high.

Table 12.3 -- Summary of Double Lane Change Testing for the Jeep Cherokee

Course Layout (ft)			Number of Tests	Number of Tests with TWL	Max. Cor. Lat. Acc.* Ranges (g)		Initial Speed Ranges (mph)		Number of "Clean" Runs	Highest "Clean" Run Initial Speed (mph)
L1	L2	W			without TWL	with TWL	without TWL	with TWL		
60	60	14	6	0	0.82 to 0.86	None	38.6 to 44.9	None	1	38.6
70	70	14	6	0	0.85 to 0.89	None	45.0 to 49.1	None	1	45.2
80	80	14	8	0	0.85 to 0.90	None	45.4 to 54.2	None	1	45.3
70	80	14	5	0	0.88 to 0.92	None	44.8 to 51.1	None	1	44.8
70	90	14	3	0	0.89 to 0.92	None	49.1 to 51.9	None	0	None

* – The corrected lateral acceleration data was obtained after the first steering reversal (the second steering input), but prior to the second reversal.

Two-wheel lift did not occur for the Jeep Cherokee on any of the five double lane change courses, even at very high lateral accelerations. As L1 and L2 were increased from 60 to 80 ft, the maximum corrected lateral accelerations, attainable initial speeds while remaining approximately on the course, and the highest attainable "clean" initial speeds generally all increased. The highest Cherokee maximum corrected lateral acceleration, 0.92 g, was observed on both the 70/80/14 and 70/90/14 courses. The highest "clean" initial speed for the 70/80/14 course was 44.8 mph, less than that observed for either the 70/70/14 or 80/80/14 courses. None of the three 70/90/14 course runs were "clean".

Figure 12.7 provides a comparison of data collected for the Jeep Cherokee during three tests on the 70/70/14 double lane change course. Test 120 was a "clean" run, while Tests 119 and 123 were not.

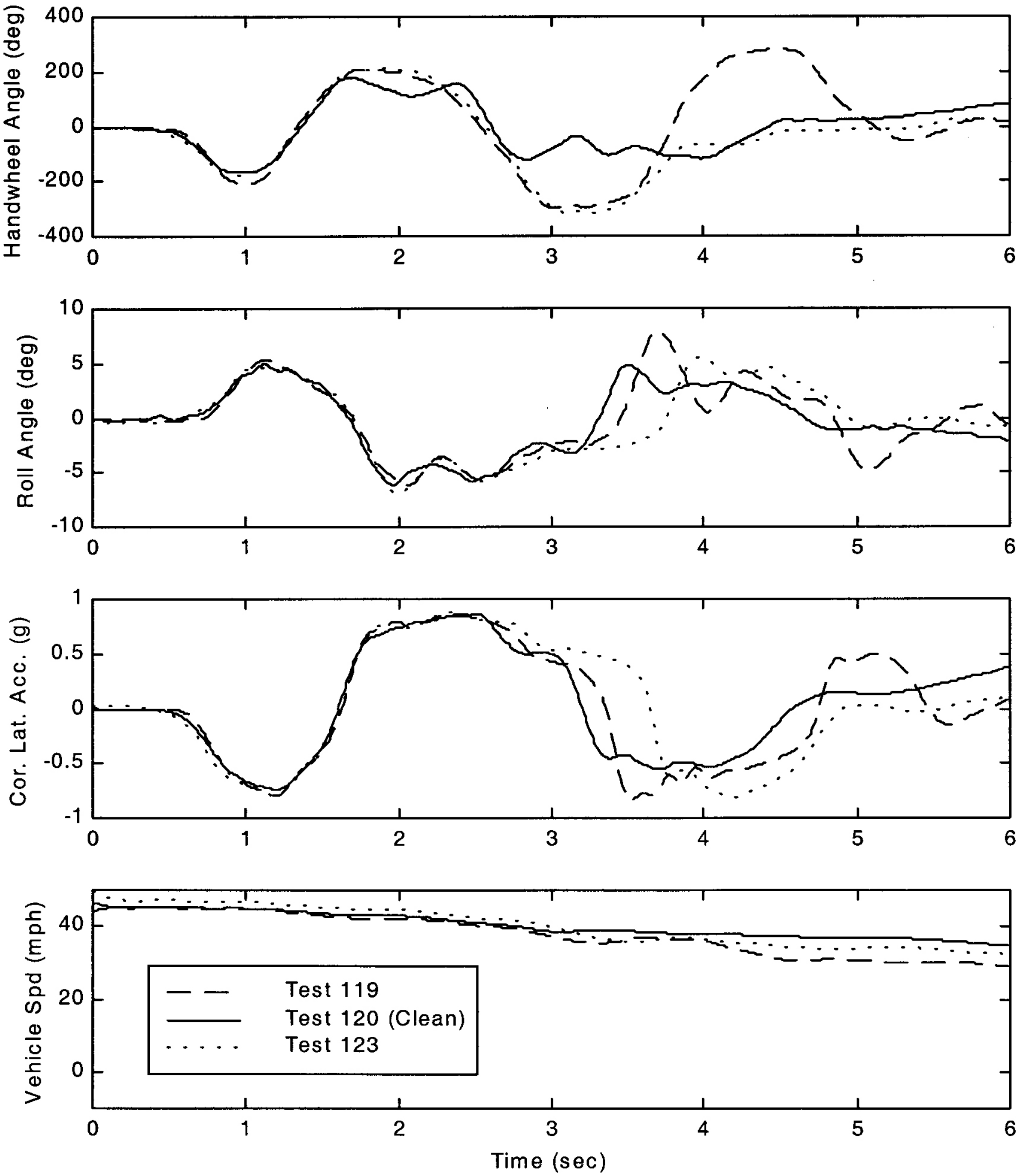

Figure 12.7 -- Typical Jeep Cherokee Double Lane Change Data From Testing on the 70/70/14 Course

12.2 The Double Lane Change and Rollover Propensity

Two of the three vehicles experienced two-wheel lift while performing the double lane change maneuver.

The Toyota 4Runner had two-wheel lift on all three of the courses on which it was tested. It mostly exhibited “Minor” two-wheel lifts. Out of a total of 29 runs with two-wheel lift, there was one run with “Major” two-wheel lift (on the 70/70/14 course), six runs with “Moderate” two-wheel lift, and 22 runs with “Minor” two-wheel lift.

Only one two-wheel lift occurred during double lane change testing with the Ford Bronco II. It was a “Major” lift, and happened on the 70/80/14 course. Tire wear may have been the cause of this two-wheel lift. The sole two-wheel lift for the Bronco II occurred while testing with a set of tires that had been used for numerous double lane change test runs. After four new tires were installed (identical to those which they replaced in size and manufacturer), the same course that produced “Major” two-wheel lift no longer did so - even with identical initial test speeds and nearly identical handwheel steering inputs.

The Jeep Cherokee did not exhibit two-wheel lift during testing on any double lane course layout, even for runs with very high maximum corrected lateral accelerations and with steering inputs and initial speeds nearly identical to those used for the other vehicles.

In general, increasing Double Lane Change severity by increasing the Initial Speed on a given course, resulted in increasing maximum corrected lateral acceleration and roll angles up to the point of limit response. The two-wheel lifts that did occur were at Initial Speeds well above the maximum attained “clean” run Initial Speeds for a given course.

During this testing, two-wheel lifts generally occurred just after the first steering reversal. Sometimes a two-wheel lift would occur just after the second steering reversal; however, this happened only when a two-wheel lift also occurred just after the first steering reversal.

When the Initial Speed is so high that the test driver can no longer drive a "clean" run, the driver is no longer following the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle. When the driver is no longer following the prescribed course, the first and second steering inputs become very similar to those of a Toyota Fishhook test. This makes the Double Lane Change a "muted" Toyota Fishhook test: muted in that the second steer is not held, but instead followed by another steering reversal. Note that the Toyota Fishhook was able to produce two-wheel lift for all three vehicles compared to only two with the Double Lane Change maneuver.

12.3 Repeatability of the Double Lane Change

Due to the path-following nature of the double lane change maneuver, successfully completing a given course can be very driver-dependent as there are infinite combinations of steering inputs that could be utilized. The "technique" one driver chooses to employ may be very different than another driver, yet they may both complete the maneuver successfully. Previous NHTSA research has investigated the relationship between test driver and two-wheel lift propensity, and confirmed the occurrence of this phenomenon [6].

Figure 12.8 demonstrates the technique used by two drivers in the 70/70/14 course, and compares the steering inputs, roll angles, lateral accelerations, and vehicle speeds associated with the highest speed "clean" runs. The lateral accelerations and roll angles achieved by Driver DP are much higher than those for Driver GH.

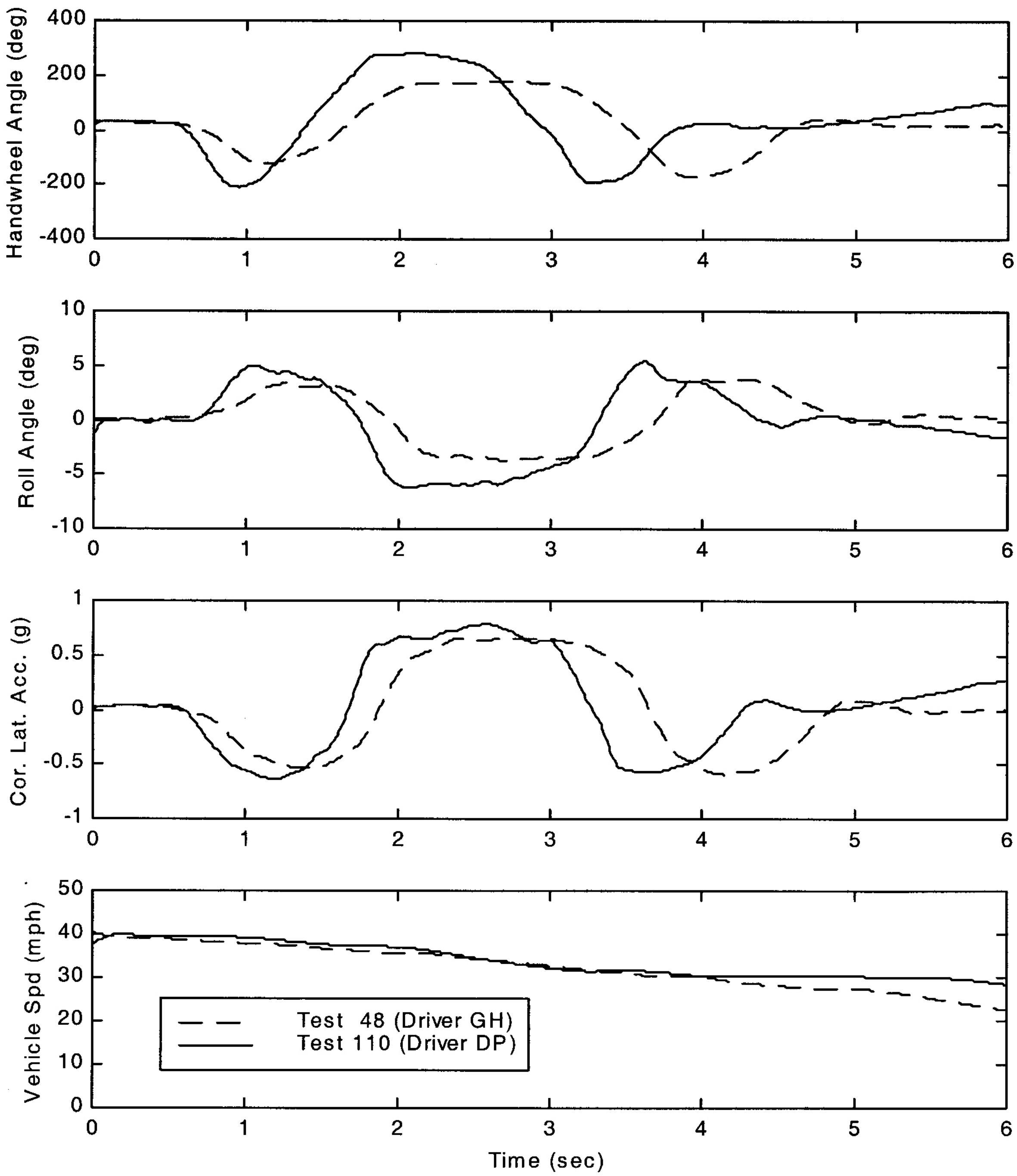

Figure 12.8 -- Driver Inputs and Vehicle Outputs for Two Test Drivers for Ford Bronco II Double Lane Change Testing on the 70/70/14 Course

Repeatability is expected to degrade even further when the Initial Speed is so high that the test driver can no longer drive a "clean" run. In this situation, the driver is no longer following the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

These two problems, that there are multiple driver "techniques" for driving through the course and that at the higher Initial Speeds the driver is no longer following the prescribed course, makes the repeatability of the Double Lane Change lower than that of some of the other Phase I-A maneuvers.

Unlike the Toyota Fishhook, the variability in Double Lane Change steering inputs is very difficult to minimize using a steering controller. Programming the controller to follow a prescribed course is much more difficult to implement than simply providing a particular steering handwheel profile as a function of time as is the case for the Toyota Fishhook maneuver since following a set course requires path control feedback.

As was done for most of the other Phase I-A maneuvers, double lane change maneuver repeatability was studied by making comparisons between matched tests. The double lane change testing had two independent variables, Test Vehicle and Course, and one primary input variable, Initial Speed. With only one primary input variable, many pairs of tests with either exactly the same input or close to the same input were made. Data from matched pairs of tests are shown in Tables 12.4, 12.5, and 12.6 for the Toyota 4Runner, Ford Bronco II, and Jeep Cherokee, respectively. The Test Course, Initial Speed, First and Second Test Numbers, and the differences between the two tests for the First, Second, and Third Peaks for Handwheel Angle, Corrected Lateral Acceleration, and Roll Angle are given in each table. The 4Runner and Bronco II Initial Speeds for the two tests were within 0.2 mph of each other for each pair. They were within 0.3 mph for the Cherokee. The Initial Speed values listed in the table are an average of the two tests.

There were seven pairs of tests that were within 0.2 mph of each other for the Toyota 4Runner. Each pair is listed in Table 12.4.

In general, for the Toyota 4Runner, the First Handwheel Angle peaks had smaller run-to-run differences than either the Second or Third Handwheel Angle peaks. The two notable exceptions are for pairs containing Test Numbers 674 & 683 and 690 & 697. All of the other test pairs contain tests that were run either consecutively or with one intervening test. The First Handwheel Angle run-to-run differences for the other test pairs range from 2 to 21 degrees while the differences for 674 & 683 and 690 & 697 are 50 and 66 degrees respectively. These larger differences suggest that as the driver makes more attempts through a course, he or she may try different strategies to try and produce a "clean" run (no contact with cones). The average run-to-run differences for the Second Handwheel Angle peaks, 38 degrees, is slightly larger than the average differences for the Third Handwheel Angle peaks, 33 degrees.

The Corrected Peak Lateral Acceleration differences ranged from 0.00 to 0.12 g. The run-to-run differences generally increased from peak-to-peak with the average First Peak differences, 0.02 g, being less than the average of the Second Peak differences, 0.03 g, which, in turn were less than the average of the Third Peak differences, 0.05 g. However, there was great variability in the pattern of these differences with one pair, Test Numbers 688 & 689, having the smallest run-to-run Corrected Peak Lateral Acceleration difference occurring for the Third Peak. For all of the run pairs and peaks, Test Numbers 690 & 697 had the largest run-to-run Corrected Peak Lateral Acceleration difference which occurred at the Third Peak. Test 690 had moderate two-wheel lift while Test 697 did not have two-wheel lift. The Initial Speed difference for these two runs was only 0.2 mph (with Test 690 having the slightly higher speed). This suggests that the difference in the Handwheel Angle Peaks, which were relatively large for these two tests compared to all other test pairs, can produce very different results.

Table 12.4 -- Measures of Maneuver Repeatability From Matched Pairs of Toyota 4Runner Double Lane Change Tests

Test Course	Initial Speed (mph)	First Test No.	Second Test No.	Handwheel Angle (deg)			Cor. Lateral Acceleration (g)			Roll Angle (deg)		
				First	Second	Third	First	Second	Third	First	Second	Third
60/60/12	36.9	651	653	2	40	26	0.00	0.01	0.01	0.4	0.3	0.2
60/60/12	37.8	655	656	2	73	34	0.02	0.03	0.07	0.8	1.3	0.5
70/70/12	43.2	670	671	5	15	5	0.01	0.04	0.05	0.5	0.1	0.5
70/70/12	42.6	672	673	10	26	39	0.01	0.04	0.05	0.3	0.3	1.4
70/70/12	46.1	674	683	50	11	23	0.04	0.02	0.02	0.5	0.3	1.2
70/70/14	39.3	688	689	21	26	26	0.03	0.01	0.00	1.2	0.7	0.5
70/70/14	42.2	690	697	66	75	71	0.02	0.06	0.12	0.4	2.5	0.9

The Roll Angle Peak differences ranged from 0.1 to 2.5 degrees. Unlike Corrected Lateral Acceleration, the run-to-run differences generally remained (approximately) constant from peak-to-peak with the average First Peak differences, 0.6 degrees, being close to the average of the Second Peak differences, 0.8 degrees, and the average Third Peak differences, 0.7 degrees. Again, Test Numbers 690 & 697 had the largest run-to-run difference in Peak Roll Angle of any test run pair. For Roll Angle, this difference was the largest for the Second Peak, not the Third (as was the case for Corrected Lateral Acceleration). Again, this suggests that the difference in the Handwheel Angle Peaks, which were relatively large for these two tests compared to all other test pairs, can produce very different results.

There were eight pairs of tests that were within 0.2 mph of each other for the Ford Bronco II. Each pair is listed in Table 12.5.

As was the case with the 4Runner, the run-to-run Handwheel Angle peak differences increased from peak-to-peak. However, the average increase was fairly small from the First Peak to the Second Peak (20 degrees to 28 degrees) and much larger from the Second Peak to the Third Peak (28 degrees to 92 degrees). Three of the Third Handwheel Angle peaks had very large differences (greater than 100 degrees). These were from pairs for which the driver essentially lost control of the vehicle during one of the two runs. This loss of control resulted in highly non-repeatable Third Handwheel Angle peaks.

As was the case for the 4Runner, the test pairs containing runs that were performed either consecutively or close to consecutively had generally smaller differences for the First Handwheel Angle Peak. The most notable exception to this generalization are Tests 127 & 128 which had a difference of 34 degrees. Again, these larger differences for runs that were performed farther apart in time suggest that as the driver makes more attempts through a course, he or she may try different strategies to try and produce a “clean” run (no cones knocked down).

Table 12.5 -- Measures of Maneuver Repeatability From Matched Pairs of Ford Bronco II Double Lane Change Tests

Test Course	Initial Speed (mph)	First Test No.	Second Test No.	Handwheel Angle (deg)			Cor. Lateral Acceleration (g)			Roll Angle (deg)		
				First	Second	Third	First	Second	Third	First	Second	Third
70/70/14	42.2	111	112	1	32	1	0.03	0.02	0.13	0.2	0.1	2.0
70/70/14	47.6	119	120	14	25	105	0.03	0.06	0.65	0.1	1.6	5.8
70/80/14	41.6	121	122	5	55	143	0.03	0.02	0.25	0.3	0.9	3.8
70/80/14	45.5	124	131	35	22	243	0.03	0.04	0.27	0.6	13.6	0.6
70/80/14	45.1	127	128	34	26	34	0.03	0.00	0.22	0.2	0.2	2.7
70/80/14	45.5	131	132	23	18	61	0.01	0.03	0.37	0.2	0.5	4.0
70/80/14	45.2	127	133	42	28	78	0.02	0.00	0.03	0.2	0.7	1.7
70/80/14	45.8	136	139	4	18	69	0.01	0.01	0.25	0.3	0.2	2.7

The Bronco II Corrected Lateral Acceleration run-to-run differences for the First Peak were relatively small ranging from 0.01 to 0.03 g with an average of 0.02 g. The Second Peaks had slightly larger differences ranging from 0.00 to 0.06 g although the average was still 0.02 g. The Third Peaks had much larger differences which ranged from 0.03 to 0.65 g with an average difference of 0.27 g. For six of the eight pairs of runs, the difference exceeded 0.20 g. Three of these pairs are ones for which the large differences in the Third Peak Handwheel Angle input occurred. However, the Third Peak Corrected Lateral Acceleration run-to-run differences do not appear to be correlated to the Third Peak Handwheel Angle run-to-run differences since the run with the smallest difference in the Third Peak Corrected Lateral Acceleration (0.03 g) had a relatively large difference in the Third Peak Handwheel Angle (78 degrees).

The Bronco II First Roll Angle peak differences had a relatively small range of 0.1 to 0.6 degrees with an average value of 0.3 degrees. The Second Peak differences ranged from 0.1 to 13.6 degrees. In one pair of tests, Test 131 had major two-wheel lift while Test 124 did not, resulting in the 13.6 degree difference. As discussed previously, this major two-wheel lift may have been related to tire wear issues. Even if this pair of tests is not included, the Second Peak differences ranged from 0.1 to 1.6 degrees with an average difference of 0.6 degrees which is much greater than the First Peak data. The Third Peak run-to-run Roll Angle differences were much larger ranging from 0.6 to 5.8 degrees with an average difference of 2.9 degrees. For seven of the eight pairs of runs, the difference exceeded 1.0 degrees. Interestingly, the smallest run-to-run Third Peak Roll Angle difference occurred for the Test Numbers 124 & 131 pair which had the largest Third Peak Handwheel Angle difference.

There were six pairs of tests that were within 0.3 mph of each other for the Jeep Cherokee. (A larger speed range, 0.3 mph, was used for the Cherokee than the 0.2 mph range that was used for the Toyota 4Runner or the Ford Bronco II because only a couple of pairs of Cherokee runs met the 0.2 mph criterion.) Each pair is listed in Table 12.6.

Table 12.6 -- Measures of Maneuver Repeatability From Matched Pairs of Jeep Cherokee Double Lane Change Tests

Test Course	Vehicle Speed (mph)	First Test No.	Second Test No.	Handwheel Angle (deg)			Cor. Lateral Acceleration (g)			Roll Angle (deg)		
				First	Second	Third	First	Second	Third	First	Second	Third
60/60/14	43.3	116	117	23	13	76	0.01	0.00	0.32	0.4	0.0	2.3
70/70/14	45.2	119	120	37	28	175	0.06	0.01	0.28	0.5	0.1	3.1
70/70/14	47.2	121	123	25	12	13	0.05	0.01	0.57	0.8	0.4	4.1
80/80/14	52.1	129	130	29	43	125	0.08	0.02	0.57	0.1	1.2	4.1
70/80/14	49.2	135	136	15	11	25	0.01	0.01	0.08	0.1	0.6	0.4
70/90/14	51.8	139	140	6	8	41	0.01	0.01	0.01	0.6	0.0	0.1

Unlike the Toyota 4Runner and the Ford Bronco II, for the Jeep Cherokee the run-to-run Handwheel Angle peak differences did not increase from the First to the Second Peak. The average run-to-run difference remained essentially constant for the First and Second Peaks (23 degrees versus 21 degrees). As was the case for the other two vehicles, the average Third Peak run-to-run differences were much larger (76 degrees). Two of the Third Handwheel Angle peaks had very large differences (greater than 100 degrees). These were from pairs for which the driver essentially lost control of the vehicle during one of the two runs. This loss of control resulted in highly non-repeatable Third Handwheel Angle peaks.

The Jeep Cherokee Corrected Lateral Acceleration run-to-run differences for the First Peak were relatively small ranging from 0.01 to 0.08 g with an average of 0.03 g. The Second Peaks had very small differences ranging from 0.00 to 0.02 g with an average of 0.01 g. The Third Peaks had much larger differences which ranged from 0.01 to 0.57 g with an average difference of 0.31 g. For four of the six pairs of runs, the difference exceeded 0.20 g. Two of these pairs are ones for which the large differences in the Third Peak Handwheel Angle input occurred. However, the Third Peak Corrected Lateral Acceleration run-to-run differences do not appear to be correlated to the Third Peak Handwheel Angle run-to-run differences since the run with the smallest difference in the Third Peak Handwheel Angle (13 degrees) had one of the largest differences in the Third Peak Corrected Lateral Acceleration (0.57 g).

The Jeep Cherokee First Roll Angle peak differences had a relatively small range of 0.1 to 0.8 degrees with an average value of 0.4 degrees. The Second Peak differences had a slightly larger range of 0.1 to 1.2 degrees but the same average value, 0.4 degrees. The Third Peak run-to-run Roll Angle differences were much larger ranging from 0.1 to 4.1 degrees with an average difference of 2.4 degrees. For four of the six pairs of runs, the difference exceeded 1.0 degree.

Looking at data from all three vehicles, the repeatability of the Double Lane Change maneuver became much worse later in the maneuver (i.e., Third Peak variability was much greater than Second Peak variability which, in turn, was slightly worse than First Peak variability). In particular, Third

Peak variability grew very large when loss of control occurred during test runs, especially since not every test run resulted in a loss of control. Test run pairs for which the driver lost control during only one of the two runs had, not surprisingly, the largest variability.

Since the goal of the Double Lane Change maneuver is to test the vehicle in the limit regime, and since there is substantial run-to-run variability in the control inputs generated by the test driver, test runs that result in a loss of vehicle control are inevitable. Therefore, the runs with a loss of control cannot be discarded as "outliers" and must be retained when examining the repeatability of this maneuver.

Table 12.7 -- Run-to-Run Variability for the Double Lane Change Maneuver Compared to Other, Retained Maneuvers

Maneuver	Cor. Lateral Acc. Variability (g)	Roll Angle Variability (deg)
J-Turn	0.04	0.5
J-Turn with Pulse Braking	0.07	0.9
Toyota Fishhook	0.09*	3.0**
Double Lane Change	0.65***	5.8†

* – This corrected lateral acceleration variability may have been due to tire wear. Excluding this run pair, the worst corrected lateral acceleration non-repeatability was 0.03 g.

** – This large roll angle variability is believed to have occurred because vehicle was tested right at its rollover threshold where a vehicle becomes unstable in roll. One run was above threshold and the other one was below.

*** – Third peak variability.

† – Roll angle variability for the Ford Bronco II run pair with major two-wheel lift not included since two-wheel lift was believed to have occurred due to tire wear.

Table 12.7 compares the run-to-run variability of the Double Lane Change maneuver with the run-to-run variability of the three maneuvers, the J-Turn, the J-Turn with Pulse Braking, and the Toyota Fishhook, that were retained at the end of the Phase I-A research. As this table shows, the Double Lane Change maneuver had far more variability than did the three maneuvers that were retained for further development.

12.4 Double Lane Change Testing Problems

The principal testing problem with the Double Lane Change maneuver is in making "clean" runs (i.e., runs for which contact with any of the cones delineating a double lane change course was avoided) at limit or near limit conditions. When the Initial Speed is so high that the test driver can no longer drive a "clean" run, the driver is no longer following the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

For all three vehicles, 21 "clean" runs were made out of 122 Double Lane Change tests with valid data. A higher percentage of "clean" runs could have been achieved by reducing the Initial Speed of runs. However, our primary interest is vehicle behavior at the highest attainable lateral accelerations and roll angles. Performing this limit/near limit testing requires that Initial Speeds be pushed up to the point where "clean" runs are extremely difficult for drivers to perform.

Multiple data trigger problems occurred during this testing. The data trigger generally picked up a false cue and started the data collection at the wrong time. For the tests that this occurred, the data is missing in the tables given in Appendix A. The Amount of Two-Wheel Lift is listed though since video data was available for these tests.

12.5 Summary of Double Lane Change Results

For the Double Lane Change maneuver, the test driver steers the vehicle through an entrance lane, turns left to avoid the single cone in the second lane, turns right to return to the original lane, and then straightens the vehicle to leave the course via an exit lane.

The principal testing problem with the Double Lane Change maneuver is in making "clean" runs (i.e., runs for which contact with any of the cones delineating a double lane change course was avoided) at limit or near limit conditions. When the Initial Speed is so high that the test driver can

no longer drive a "clean" run, the driver is no longer following the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

Two of the three vehicles, the Toyota 4Runner and the Ford Bronco II, experienced two-wheel lift while performing the Double Lane Change maneuver. Tire wear appears to have been the cause of the two-wheel lift for the Ford Bronco II. Two-wheel lift was observed only once for this vehicle, and was achieved on a tire set that had been used to complete numerous runs. After four new tires were installed, two-wheel lift could not be achieved even with identical vehicle speeds and nearly equivalent handwheel inputs.

For both vehicles for which two-wheel lift occurred, the two-wheel lifts occurred at Initial Speeds that were well above the maximum "clean" run Initial Speeds which were achieved for a given course. At these speeds, the driver really has no opportunity to follow the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

When the driver is no longer following the course, the first and second steering inputs are very similar to those of a Toyota Fishhook test. This makes the Double Lane Change a "muted" Fishhook test: muted in that the second steer is not held, but instead followed by a third steering reversal. (For the testing performed during this program, sufficient speed scrubbed off prior to the third steering reversal so that the third steering reversal did not cause two-wheel lift to occur. For testing using higher Initial Speeds, and having the proper severity and timing for the third steering reversal, the Double Lane Change maneuver may be of comparable severity to the Toyota Fishhook. An example of this situation is given in [10].) The Toyota Fishhook generated two-wheel lift for all three Phase I-A test vehicles compared to only two for the Double Lane Change maneuver.

Due to the path-following nature of the Double Lane Change maneuver, successfully completing a given course can be very driver-dependent, as there are infinite combinations of steering inputs that could be utilized. The "technique" one driver chooses to employ may be very different than another driver, yet they both may complete the maneuver successfully.

The path-following nature of the Double Lane Change maneuver resulted in handwheel steering inputs that become less-and-less repeatable during the course of a maneuver. As was shown above, the first two steering reversals are typically reasonably repeatable (with a run-to-run variability of less than 30 degrees) while the third reversal may have run-to-run differences that exceed 100 degrees.

This growing non-repeatability in handwheel steering inputs results in growing non-repeatability in output measures such as Third Peak Corrected Lateral Acceleration and Third Peak Roll Angle. As has been shown above, there is far more variability in the Corrected Lateral Acceleration and the Roll Angle for the Double Lane Change maneuver than there is for the J-Turn, J-Turn with Pulse Braking, and Toyota Fishhook maneuvers.

Unlike the Toyota Fishhook, the variability in Double Lane Change steering inputs is very difficult to minimize using a steering controller. Programming the controller to follow a prescribed course is much more difficult to implement than simply providing a particular steering profile as is the case for a Fishhook maneuver. Following a set course would require path control feedback which would be costly and difficult to implement.

There are an infinite number of possible Double Lane Change courses. One course geometry may excite undesirable frequency dependent responses for one particular vehicle, but not for others. Another course may be at the frequency needed to excite undesirable frequency dependent responses for another vehicle, but not for the vehicle that had poor performance on the first course. Therefore, there is no one "best Double Lane Change" course geometry. Instead, vehicles need to be tested using a broad range of Double Lane Change course geometries.

Due to the repeatability problems associated with the Double Lane Change maneuver, the need to perform Double Lane Change maneuvers over a range of courses, and that the Double Lane Change maneuver seems to affect the vehicle like a "muted" Toyota Fishhook, the authors recommend that the Double Lane Change Maneuver not be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

13.0 SPLIT-MU OFF ROAD RECOVERY SIMULATION TEST RESULTS AND ANALYSIS

13.1 Tests Performed for Each Vehicle

A total of 38 Split-Mu maneuver tests with valid data were performed with the Toyota 4Runner. Table 13.1 summarizes the Split-Mu testing performed with the 4Runner. The table lists, for each run, the Test Number, Initial Speed, the First and Second Steering Input magnitudes, (note that during the Second Steering Movement the steering wheel is actually turned through the sum of the First and Second Steering Input magnitudes that are shown in the table), whether or not the steering stop was used, the Maximum Corrected Lateral Acceleration associated with each steering input, the Maximum Roll Angle associated with each steering input, and the Amount of Two-Wheel Lift (if any). The same nomenclature is used to categorize the amount of two-wheel lift that occurred (if any) as is described in Section 7.1 for the J-Turn (without pulse braking).

The Steer Stop Used? column is present in Table 13.1 because some Toyota 4Runner Split-Mu testing was conducted using a steering stop to produce more repeatable initial steering input. During testing the magnitude of the Second Steering Input required to produce two-wheel lift appeared to be greater than could be generated with the steering stop present. Consideration was given to having the test driver disconnect the steering stop during the maneuver (i.e., after the First Steering Movement but before the Second Steering Movement). However, adding the workload of disconnecting the steering stop design then being used to the demands of performing this difficult maneuver proved to be beyond the capacity of the test driver. The steering stop design has since been modified; future Split-Mu testing (if any) will be able to utilize a steering stop to make the First Steering Movement more repeatable while still permitting very large Second Steering Input magnitudes.

Of the 38 tests listed in Table 13.1, only one produced two-wheel lift (Test 639). There were a couple of other test runs that produced two-wheel lift, but instrumentation data was not collected for these tests (therefore, these tests are **not** included in Table 13.1). The reason for this lost data will be discussed further in Section 13.4, Split-Mu Off Road Recovery Simulation Testing Problems. Video data is available for these tests.

A summary of the Initial Speed and Corrected Lateral Acceleration levels achieved during the Toyota 4Runner testing are shown in Table 13.2. The data presented in this table will be discussed further in Section 13.3, Repeatability of the Split-Mu Off Road Recovery Simulation.

Table 13.1 -- Summary of Split-Mu Testing for the Toyota 4Runner

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
566	37.7	-47	43	Yes	-0.22	0.18	2.7	-3.6	None
567	39.6	-86	163	Yes	-0.46	0.65	4.3	-7.5	None
568	41.1	-107	135	Yes	-0.51	0.53	4.5	-6.3	None
569	42.9	-146	152	Yes	-0.57	0.55	5.4	-7.1	None
570	42.8	-156	185	Yes	-0.53	0.62	5.0	-9.9	None
571	41.7	-176	132	Yes	-0.56	0.53	5.5	-7.1	None
572	43.6	-197	145	No	-0.55	0.67	5.0	-7.7	None
573	42.5	-170	149	No	-0.55	0.66	4.8	-7.6	None
574	39.4	-201	116	No	-0.50	0.63	5.0	-6.5	None
575	42.3	-268	246	No	-0.59	0.74	5.7	-7.2	None
576	39.6	-268	184	No	-0.58	0.64	5.3	-7.1	None
577	42.4	-253	217	No	-0.60	0.78	5.6	-8.5	None
578	41.2	-286	255	No	-0.59	0.64	4.9	-7.6	None
579	44.9	-295	186	No	-0.60	0.61	5.3	-8.6	None
591	45.3	-78	121	Yes	-0.46	0.56	4.2	-5.7	None
592	44.7	-107	135	Yes	-0.56	0.61	4.9	-7.1	None
593	44.7	-128	195	Yes	-0.55	0.64	5.1	-6.8	None
594	45.8	-148	138	Yes	-0.59	0.53	5.1	-6.5	None
595	46.9	-168	176	Yes	-0.59	0.73	5.4	-6.7	None
596	45.1	-197	144	Yes	-0.63	0.72	5.7	-7.7	None

Table 13.1 -- Summary of Split-Mu Testing for the Toyota 4Runner (continued)

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
597	47.0	-204	139	Yes	-0.58	0.71	5.3	-7.7	None
598	45.5	-214	132	Yes	-0.58	0.72	5.2	-7.8	None
599	49.2	-227	118	Yes	-0.66	0.62	5.6	-6.8	None
601	43.5	-211	119	No	-0.66	0.67	5.7	-7.3	None
626	42.3	-281	279	No	-0.59	0.78	5.8	-9.4	None
627	44.7	-322	240	No	-0.62	0.64	6.1	-8.9	None
628	45.7	-343	199	No	-0.62	0.66	6.3	-8.3	None
629	48.8	-253	197	No	-0.59	0.70	5.6	-7.8	None
630	52.8	-233	212	No	-0.58	0.74	5.6	-9.0	None
631	55.1	-274	182	No	-0.59	0.56	5.0	-8.0	None
632	55.5	-232	190	No	-0.61	0.65	5.9	-8.6	None
634	52.6	-192	169	No	-0.64	0.45	5.7	-5.0	None
635	52.2	-275	194	No	-0.61	0.76	5.6	-6.9	None
636	54.0	-234	331	No	-0.53	0.70	5.6	-8.3	None
637	49.8	-233	304	No	-0.53	0.64	5.3	-7.4	None
638	47.4	-291	251	No	-0.62	0.61	6.4	-7.3	None
639	49.6	-300	328	No	-0.60	0.88	6.0	-9.7	Minor
640	52.7	-330	-330	No	-0.70	0.63	7.1	-7.8	None

Table 13.2 -- Summary of Toyota 4Runner Split-Mu Test Results

Initial Speed Ranges (mph)		Corrected Lateral Acceleration Ranges (g)	
Without Two-Wheel Lift	**With Two-Wheel Lift**	**Without Two-Wheel Lift**	**With Two-Wheel Lift**
37.7 to 55.5	49.6	0.18 to 0.78	0.88

A total of 8 Split-Mu maneuver tests with valid data were performed with the Ford Bronco II. Table 13.3 summarizes the Split-Mu testing performed with the Bronco II. Note that the steering stop was not used during the Bronco II Split-Mu testing.

None of the eight tests listed in Table 13.3 produced two-wheel lift. A ninth test (Bronco II Test 99) did produce two-wheel lift, but instrumentation data was not collected for this test (therefore, this test is **not** included in Table 13.3). The reason for this lost data will be discussed further in Section 13.4, Split-Mu Off Road Recovery Simulation Testing Problems. Video data is available for this test. The test run that produced two-wheel lift is thought to have had an Initial Speed of between 48 and 50 mph. Tire wear may have been responsible for this two-wheel lift as was the case with this vehicle for other maneuvers.

A summary of the Initial Speed and Corrected Lateral Acceleration levels achieved during the Ford Bronco II testing are shown in Table 13.4. The data presented in this table will be discussed further in Section 13.3, Repeatability of the Split-Mu Off Road Recovery Simulation.

Table 13.3 -- Summary of Split-Mu Testing for the Ford Bronco II

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
93	38.6	-336	251	No	-0.58	0.63	4.1	-4.8	None
94	42.0	-340	244	No	-0.60	0.59	4.9	-5.9	None
95	41.1	-314	317	No	-0.57	0.68	4.0	-6.3	None
96	43.7	-338	234	No	-0.62	0.66	4.8	-6.4	None
97	43.6	-349	287	No	-0.62	0.68	5.0	-6.4	None
98	50.6	-323	282	No	-0.58	0.70	4.2	-4.7	None
101	49.4	-338	331	No	-0.54	0.74	4.1	-6.5	None
102	48.0	-337	345	No	-0.51	0.74	3.5	-6.5	None

During Tests 101 and 102, the Ford Bronco II re-entered the low coefficient of friction surface after the driver had tried to complete the off-road recovery. As it re-entered the low coefficient surface, the vehicle spun very rapidly; approximately 180 deg/sec. The yaw rate channel Test 101 is plotted in Figure 13.1 (Test 102's yaw rate channel is similar). This channel has a maximum range of +/- 55 deg/sec. As can be seen in Figure 13.1, the channel remained clipped for a long period of time as the vehicle was spinning.

Table 13.4 -- Summary of Bronco II Split-Mu Test Results

Vehicle Speed Ranges (mph)		Corrected Lateral Acceleration Ranges (g)	
Without Two-Wheel Lift	With Two-Wheel Lift	Without Two-Wheel Lift	With Two-Wheel Lift
38.6 to 50.6	48 to 50*	0.51 to 0.74	No Data

* - Only one test for which no data was collected.

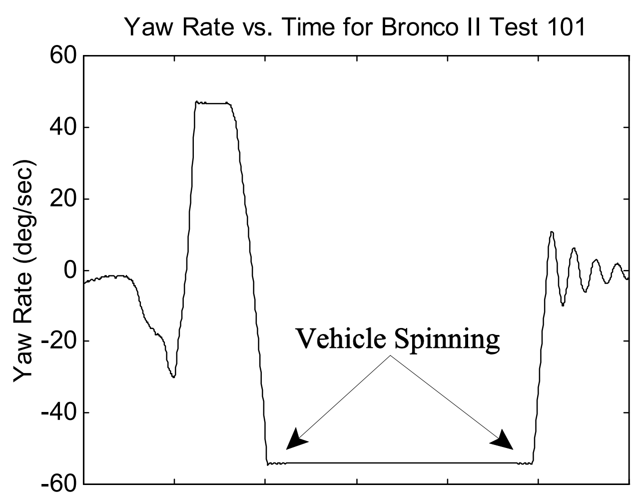

Figure 13.1 -- Yaw Rate as a Function of Time For Bronco II Test 101

A total of 12 Split-Mu maneuver tests with valid data were performed with the Jeep Cherokee. Table 13.5 summarizes the Split-Mu testing performed with the Cherokee. Note that the steering stop was not used during the Cherokee Split-Mu testing.

None of the twelve tests listed in Table 13.5 produced two-wheel lift even though the steering inputs were of similar magnitude for the other two test vehicles and the lateral accelerations produced were very high.

A summary of the Initial Speed and Corrected Lateral Acceleration levels achieved during the Jeep Cherokee testing are shown in Table 13.6. The data presented in this table will be discussed further in Section 13.3, Repeatability of the Split-Mu Off Road Recovery Simulation.

13.2 The Split-Mu Off Road Recovery Simulation and Rollover Propensity

The Split-Mu Off Road Recovery maneuver produced two-wheel lifts for two of the test vehicles. The Toyota 4Runner had minor two-wheel lift for one test with valid instrumentation data plus a couple of tests without valid instrumentation data. Major two-wheel lift occurred for one Ford Bronco II test for which valid instrumentation data was not collected. (Tire wear may have been responsible for this two-wheel lift as was the case with this vehicle for other maneuvers.) The Jeep Cherokee did not produce two-wheel lift for this maneuver at Initial Speeds of up to 60 mph.

Table 13.5 -- Summary of Split-Mu Testing for the Jeep Cherokee

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
222	51.8	-312	261	No	-0.74	0.78	4.0	-6.0	None
223	52.5	-332	306	No	-0.70	0.85	4.0	-7.0	None
224	55.2	-353	369	No	-0.70	0.90	3.8	-7.2	None
225	55.6	-339	345	No	-0.71	0.85	3.9	-7.2	None
226	56.1	-343	373	No	-0.65	0.88	3.5	-6.7	None
228	56.9	-334	296	No	-0.70	0.77	4.1	-6.3	None
229	58.6	-352	274	No	-0.64	0.74	3.8	-5.5	None
230	60.3	-352	277	No	-0.68	0.73	3.8	-5.4	None
231	60.3	-342	154	No	-0.56	0.80	2.9	-6.1	None
232	59.3	-352	217	No	-0.64	0.63	3.7	-4.5	None
233	60.5	-352	251	No	-0.70	0.74	3.7	-5.4	None
234	60.6	-337	256	No	-0.61	0.56	3.2	-4.3	None

Table 13.6 -- Summary of Jeep Cherokee Split-Mu Test Results

Vehicle Speed Ranges (mph)		Corrected Lateral Acceleration Ranges (g)	
Without Two-Wheel Lift	**With Two-Wheel Lift**	**Without Two-Wheel Lift**	**With Two-Wheel Lift**
51.8 to 60.6	None Occurred	0.56 to 0.90	None Occurred

During processing, it was noted that the data collected from the Split-Mu testing resembled the data from the Steering Reversal testing. While no tests were performed with the intent of specifically comparing the maneuvers with each other, several Toyota 4Runner tests had initial and secondary inputs of similar magnitude and timing. Figure 13.2 highlights two of these test runs. The initial handwheel steering inputs are nearly identical, but the Steering Reversal test produced a greater roll angle than the Split-Mu test. This would be expected because the initial steering input during the Split-Mu test is performed with the right side tires on a low coefficient of friction surface. During the Steering Reversal, when the vehicle returns to the higher coefficient surface, the Split-Mu test does achieve a comparable amount of lateral acceleration to the Steering Reversal test, though the roll angle is still of lesser magnitude.

Figure 13.3 shows two other test runs and demonstrates that even with a reduced steering input, the Split-Mu roll angle is still exceeded by the Steering Reversal roll angle in the initial input. In this case, the secondary inputs are of similar magnitude, and the resulting roll angle measurements are of similar magnitude as well. This input occurs when the vehicle is on the higher coefficient of friction surface for both maneuvers. It was noted that for similar handwheel steering inputs, the steering reversal maneuver typically created a higher degree of roll, and therefore was probably a more severe test for rollover propensity.

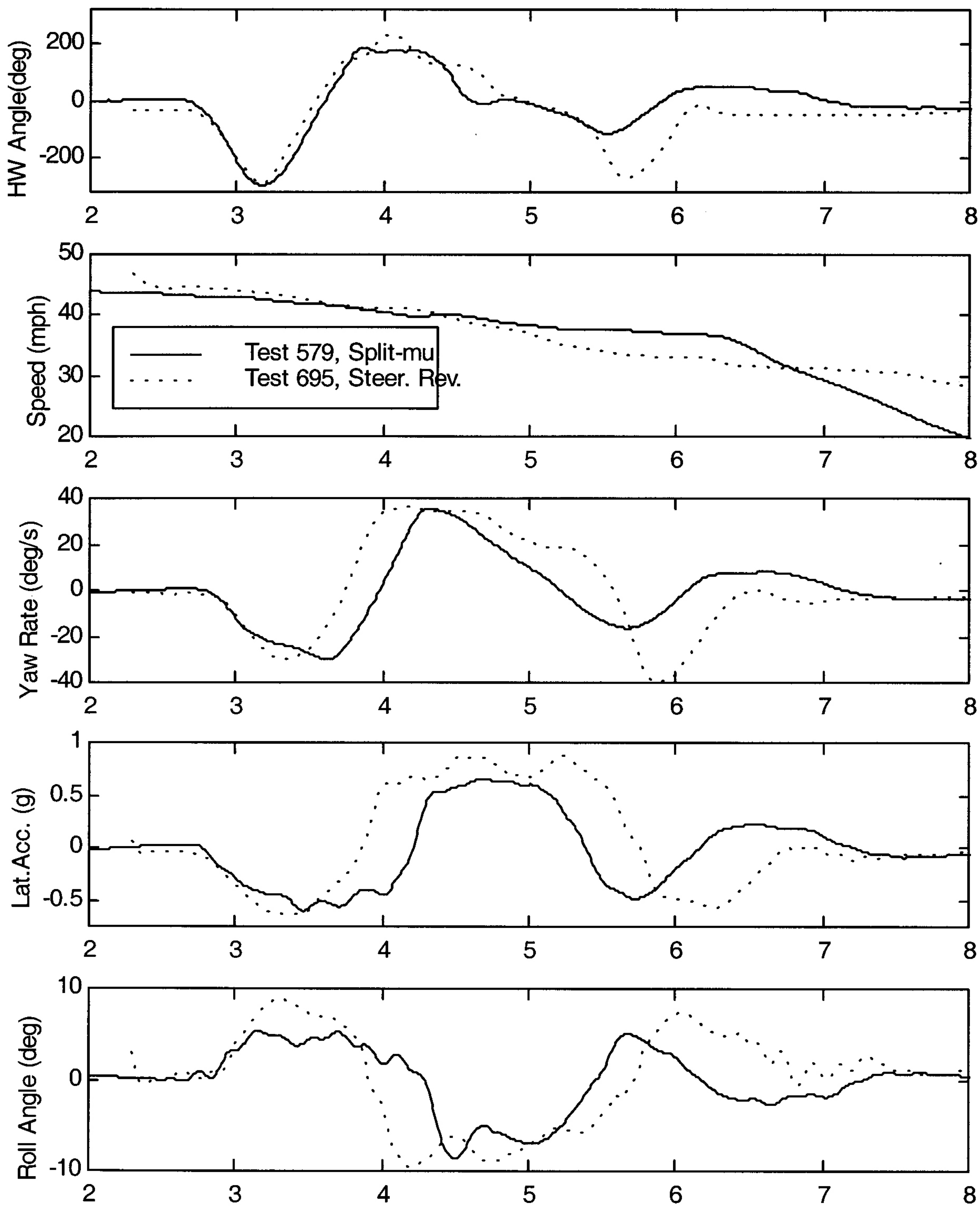

Figure 13.2 -- Split-Mu Test 579 and Steering Reversal Test 695 for the Toyota 4Runner

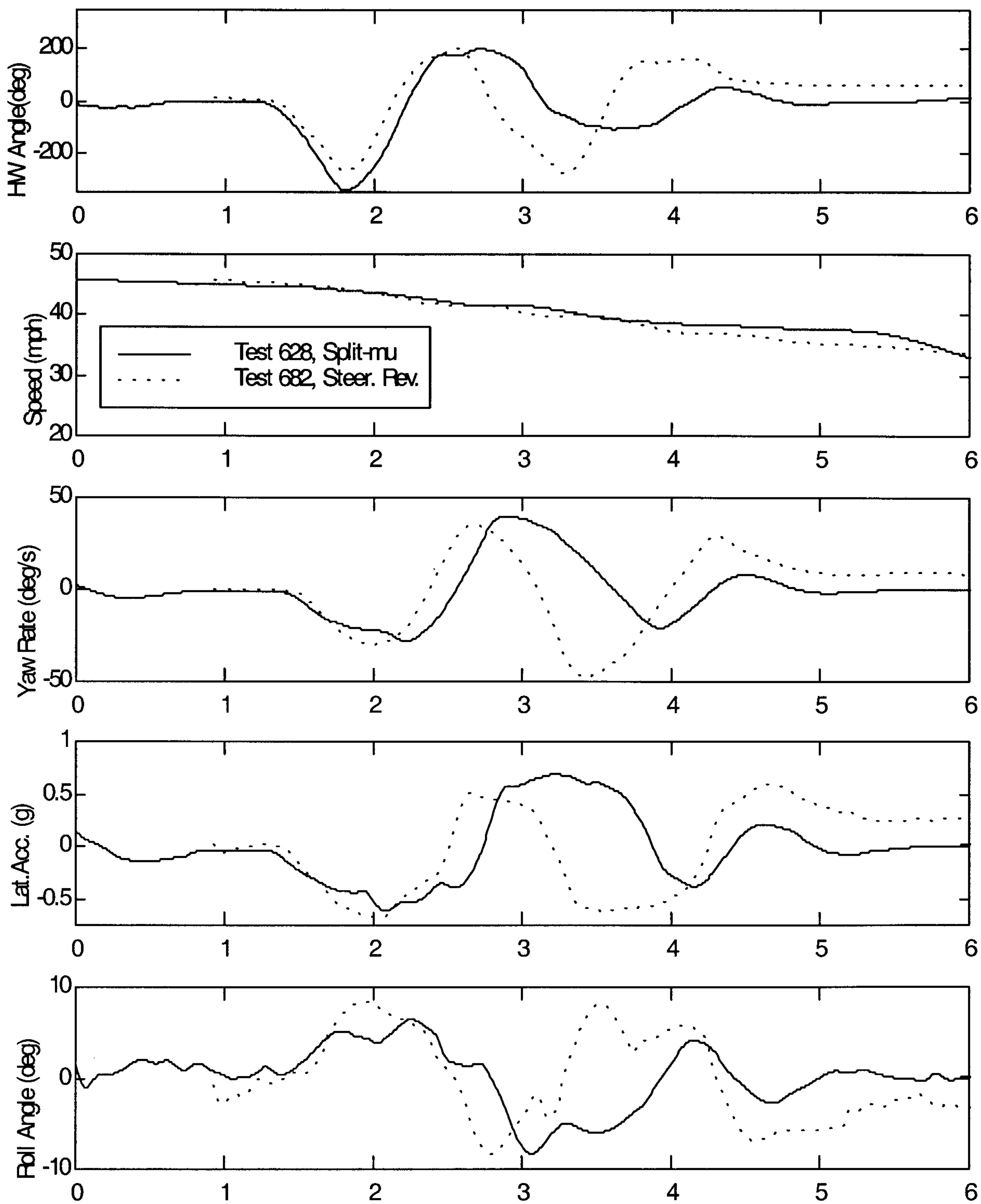

Figure 13.3 -- Split-Mu Test 628 and Steering Reversal Test 682 for the Toyota 4Runner

Vehicle yaw effects on a split-mu surface may potentially increase rollover propensity, but this was not observed in this study. Further specific correlation between the two types of tests cannot be concluded without a specific test plan with the intent of comparing the maneuvers, including the use of a steering controller.

The Toyota Fishhook maneuver was able to produce two-wheel lift for all three vehicles compared to only two for the Split-Mu maneuver. The Toyota Fishhook was also able to produce two-wheel lift on a more consistent basis.

13.3 Repeatability of the Split-Mu Off Road Recovery Simulation Maneuver

The Split-Mu Off-Road Recovery Simulation was developed to try and simulate a scenario that has been documented in the rollover crash data collected by NHTSA. This maneuver simulates the return of a vehicle that has two wheels off the road to having all four wheels on the road surface. As was explained in Section 6.7, "Split-Mu Off-Road Recovery Simulation Maneuver Test Procedure," for this maneuver the vehicle is driven onto a split-coefficient-of-friction (split-mu) surface, i.e., the tires on the right side of the vehicle are on a low coefficient-of-friction, wet-epoxy surface and the tires on the left side are on a higher coefficient-of-friction dry-asphalt surface. The driver then turns the vehicle to the left to bring all four tires on to the dry-asphalt surface. This is followed by a turn to the right to try to maintain control while keeping the vehicle within a two lane width boundary (24 feet). As such, driver steering subsequent to the initial steering movement was a reaction to the trajectory being followed by the vehicle.

In an attempt to reduce test variability, a mechanical steering stop was used to control the magnitude of the First Steering Movement (when the vehicle was turned to drive off of the wet-epoxy surface) for some of the early Toyota 4Runner tests. This version of the steering stop was very cumbersome; therefore, later Toyota 4Runner and all of Ford Bronco II and Jeep Cherokee tests were performed without the use of a steering stop. For these tests, no electronic or mechanical assistance was given to help the driver make the initial steering movement repeatable.

For the Toyota 4Runner testing, the magnitude of the First Steering Movement was intentionally varied to achieve higher or lower levels of test severity. The Second Steering Movement was permitted to vary as needed for the test driver to try to maintain control while keeping the vehicle within a two lane width boundary. The Initial Speed was also raised or lowered to vary test severity.

Therefore, two Toyota 4Runner tests which were run at the same (or almost the same) Initial Speeds might or might not have been attempting to achieve the same test severity. One comparison that can be made is between two runs that attempted to achieve the same severity. One such pair of runs is 4Runner Tests 572 & 601.

These two tests had almost the same Initial Speeds, 43.6 mph for Test 572 and 43.5 mph for Test 601. Test 601's First Steering Input magnitude at -211 degrees was slightly larger (in absolute value) than Test 572's First Steering Input magnitude of -197 degrees. However, the two First Steering Input magnitudes are close enough that similar maneuver severities are expected. Both tests were performed without use of the Steering Stop.

Time histories for the Handwheel Steering Angle, Corrected Lateral Acceleration, and Roll Angle for Toyota 4Runner Tests 572 & 601 are shown in Figure 13.4. As this figure and the Maximum Corrected Lateral Acceleration and Maximum Roll Angle Columns in Table 13.1 show, these two tests actually resulted in quite different vehicle motions. The Maximum Corrected Lateral Acceleration due to the First Steering Movement of Test 601 is 20 percent greater than that of Test 572 even though the magnitudes of the First Steering Inputs only increase by 7 percent from run-to-run. This is because Test 601's First Steering Movement lasted longer than did the First Steering Movement of Test 572. Similarly, the Maximum Roll Angle due to the First Steer of Test 601 is 14 percent larger than that of Test 572. The magnitude of the Second Steering Input for Test 572 is 22 percent greater than that of Test 601. The Maximum Corrected Lateral Accelerations due to the Second Steering Movement of Tests 572 & 601 are the same; however, the Corrected Lateral Accelerations have quite different time histories during and following the Second Steering Movement. The Maximum Roll Angle due to the Second Steer of Test 601 is 5 percent less (in absolute value) than that of Test 572. Again, the Roll Angles have quite different time histories during and following the Second Steering Movement.

The use of the Steering Stop was expected to reduce variability due to the First Steering Movement. To confirm this expectation, Toyota 4Runner Tests 569 & 570 were examined. These two tests had almost the same Initial Speeds, 42.9 mph for Test 569 and 42.8 mph for Test 570. Test 570's First Steering Input magnitude at -156 degrees was slightly larger (in absolute value) than Test 569's First Steering Input magnitude of -146 degrees. However, the two First Steering Input magnitudes are close enough that similar maneuver severities are expected.

Peak values for Toyota 4Runner Tests 569 & 570 are shown in Table 13.1; time histories for the Handwheel Steering Angle, Corrected Lateral Acceleration, and Roll Angle for these tests are shown in Figure 13.5. The Maximum Corrected Lateral Acceleration due to the First Steering Movement of Test 570 is 8 percent less than that of Test 569 even though the magnitudes of the First Steering Inputs increased by 7 percent from run-to-run. This is due to differences in the duration of the First Steering Movement between the two tests. Similarly, the Maximum Roll Angle due to the First Steer of Test 570 is 8 percent less than that of Test 569. Looking at the numbers, the use of the Steering Stop does not appear to have improved repeatability. Variations in maneuver timing that can still occur even when a Steering Stop is used appear to strongly affect the results.

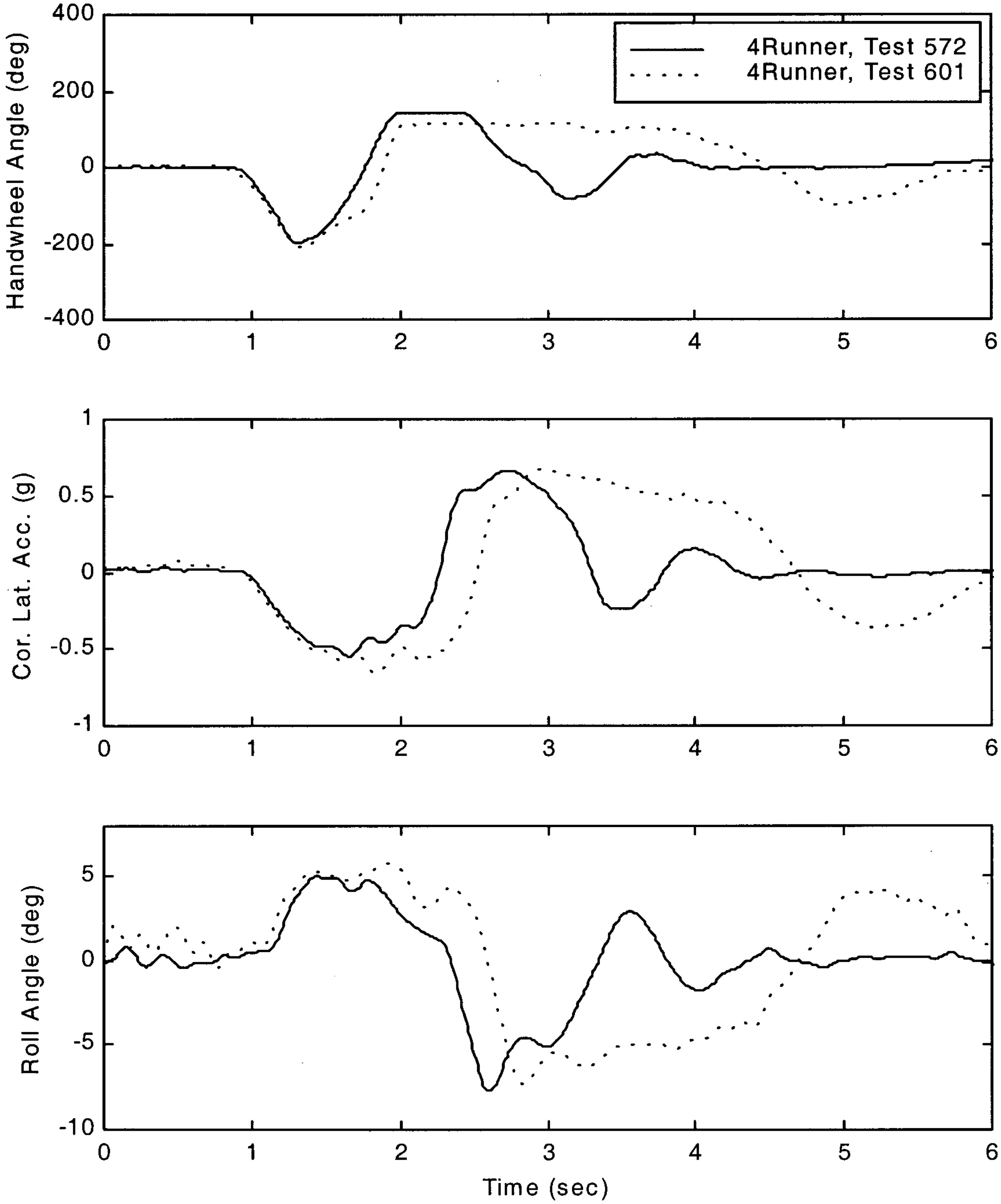

Figure 13.4 -- Toyota 4Runner Split-Mu Test Comparison for Tests 572 & 601

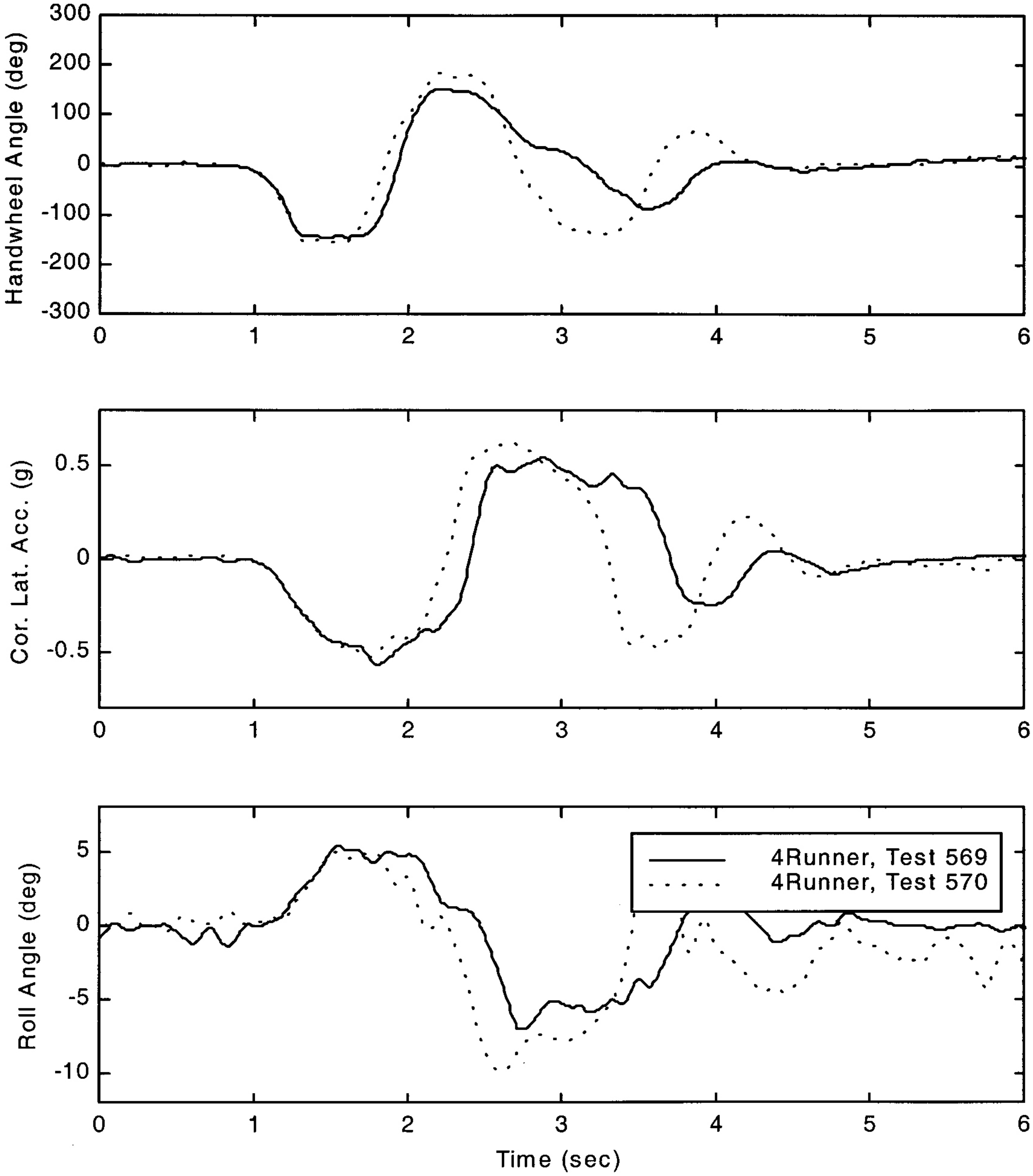

Figure 13.5 -- Toyota 4Runner Split-Mu Test Comparison for Tests 569 & 570

Turning to the second portion of these maneuvers, the magnitude of the Second Steering Input for Test 570 is 22 percent greater than that of Test 569. The Maximum Corrected Lateral Accelerations due to the Second Steering Movement of Tests 569 & 570 differ by 13 percent with, in line with the increase in the magnitude of the Second Steering Input, Test 570 having the larger value. However, the Maximum Roll Angle due to the Second Steer of Test 570 is a very large 39 percent greater (in absolute value) than that of Test 569. Again, the use of the Steering Stop does not appear to have improved repeatability during the second portion of the maneuver for this pair of tests.

For the Ford Bronco II and the Jeep Cherokee testing, the driver generated a First Steering Input magnitude between -300 and -360 degrees for all of the test runs. As was shown in Section 7.4, "Effects of Magnitude of Steering Input on J-Turn Results," the lateral force production capacity of the Toyota 4Runner tires is saturated at these Handwheel Steering angles; the Ford Bronco II and Jeep Cherokee tires are expected to behave similarly. Therefore, the First Steering Input magnitude is **not** expected to have significantly influenced maneuver severity for these tests. This reduces the number of primary input variables to one, Initial Speed, for these vehicles.

Even with only one primary input variable, there were only a few pairs of tests with either exactly, or almost exactly, the same Initial Speed for the Ford Bronco II and the Jeep Cherokee. This was primarily due to the limited number of tests conducted with these vehicles. Examination of Table 13.3 shows that only one pair of matched tests (Tests 96 & 97) exists for the Ford Bronco II. Table 13.5 shows that there are two pairs of matched runs for the Jeep Cherokee, Tests 230 & 231 and Tests 233 & 234. Since all four of these runs have very similar Initial Speeds, Tests 230 & 233 can also be used to form a matched pair of runs. Comparisons of these matched tests are contained in Table 13.7.

Table 13.7 -- Split-Mu Matched Test Run Pair Results

Test Number	Initial Speed (mph)	First Steering Input (deg)	Second Steering Input (deg)	Steer Stop Used?	Max. Corrected Lateral Acc., First Steer (g)	Max. Corrected Lateral Acc., Second Steer (g)	Maximum Roll Angle from First Steer (deg)	Maximum Roll Angle from Second Steer (deg)	Amount of Two-Wheel Lift
Bronco II Results									
96	43.7	-338	234	No	-0.62	0.66	4.8	-6.4	None
97	43.6	-349	287	No	-0.62	0.68	5.0	-6.4	None
Difference	0.1	11	53	None	0.00	0.02	0.2	0.0	
Cherokee Results									
230	60.3	-352	277	No	-0.68	0.73	3.8	-5.4	None
231	60.3	-342	154	No	-0.56	0.80	2.9	-6.1	None
Difference	0	10	123	None	0.12	0.07	0.9	0.7	
233	60.5	-352	251	No	-0.70	0.74	3.7	-5.4	None
234	60.6	-337	256	No	-0.61	0.56	3.2	-4.3	None
Difference	0.1	16	5	None	0.09	0.18	0.5	1.1	
230	60.3	-352	277	No	-0.68	0.73	3.8	-5.4	None
233	60.5	-352	251	No	-0.70	0.74	3.7	-5.4	None
Difference	0.2	0	26	None	0.02	0.01	0.1	0.0	

Examining the results for Bronco II Tests 96 & 97 in Table 13.7 show that this test appeared to have produced very similar results. The First Steering Inputs were only 11 degrees different, while the Second Steering Inputs had larger magnitude differences (53 degrees). The resulting First and Second Maximum Corrected Lateral Accelerations and Roll Angles for these two tests are very similar.

The Handwheel Steering Angle, Corrected Lateral Acceleration, and Roll Angle traces for Ford Bronco II Tests 96 & 97 are shown in Figure 13.6. The Handwheel Angle traces for these two tests are very similar up to approximately 2.5 seconds and again from 3.9 to 4.5 seconds. It is interesting to note that the Corrected Lateral Acceleration and Roll Angle traces start to diverge much earlier (at approximately 2.0 seconds) and then converge at approximately 3.8 seconds.

Examination of the video for these tests showed that during Test 96, the rear portion of the Ford Bronco II traveled approximately two full lanes (24 feet) laterally after leaving the lower coefficient-of-friction surface. During Test 97, the Bronco II only traveled approximately 1.5 lanes laterally. The results presented in Figure 13.6 are consistent with this observation, i.e., the longer duration first peak lateral acceleration for Test 96 caused the vehicle to travel further laterally.

The rear end of the Ford Bronco II tended to spin-out quite a bit during both of these tests. The first yaw rate peak is higher and of longer duration (potentially greater degree of spin-out) for Test 96, which may explain why the vehicle did not respond as quickly to the second steer for this test as it did for Test 97.

Jeep Cherokee Tests 230 & 231 and Tests 233 & 234 provided two matched pairs of tests (similar Initial Speeds). In fact, all four of these tests had similar speeds. For this reason, and others to be explained later, Tests 230 & 233 were also examined as a matched pair as well. The differences between specific vehicle inputs and responses for each of these pairs are given above in Table 13.7.

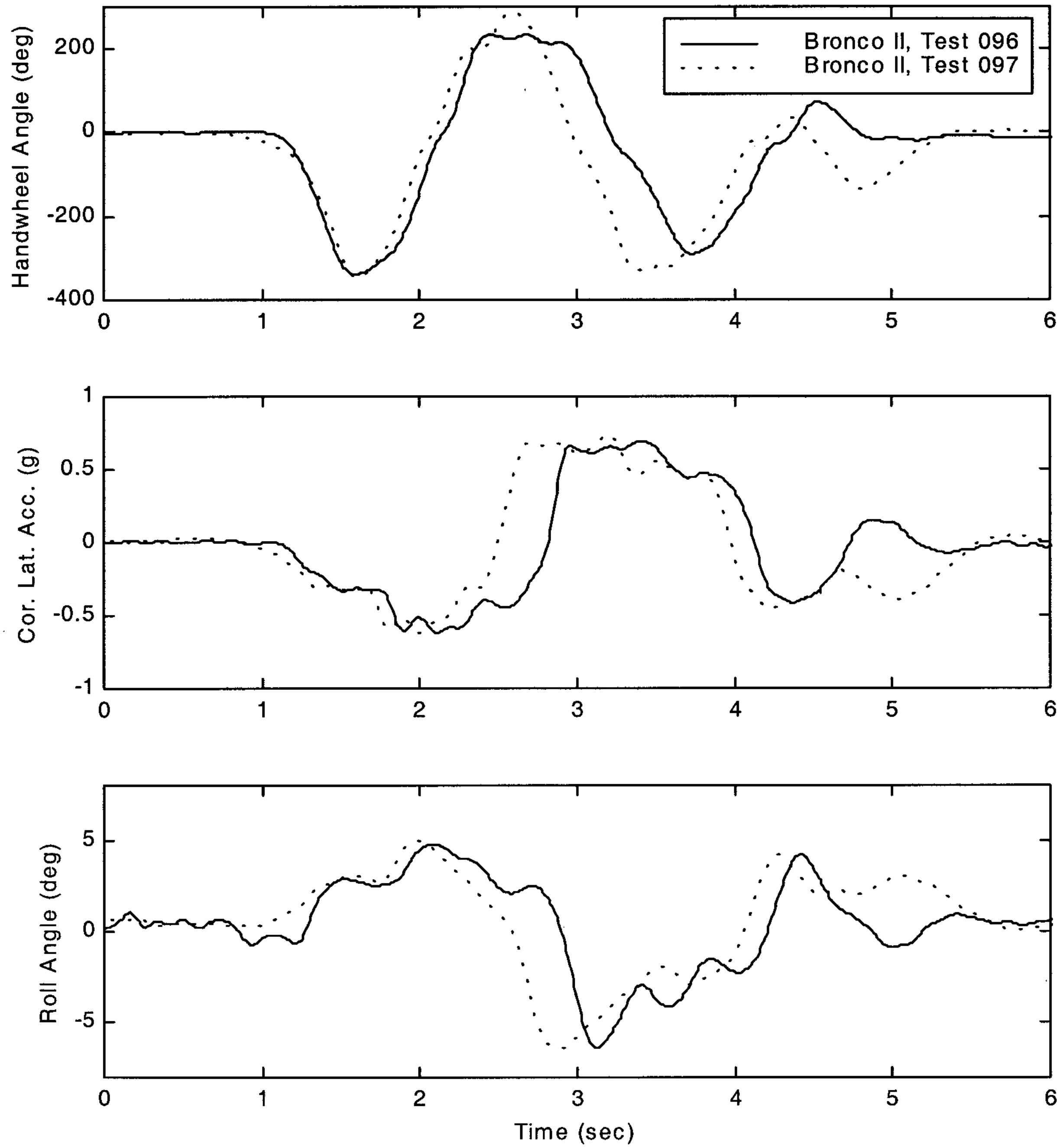

Figure 13.6 -- Ford Bronco II Split-Mu Test Comparison for Tests 096 and 097

Jeep Cherokee Tests 230 & 231 had a First Steering Input magnitude difference of only 10 degrees. The Second Steering Input magnitude difference was fairly large (123 degrees). Despite this very small First Steering Input difference (which, due to tire side force capacity saturation, should not have had any effect), the Maximum Corrected Lateral Acceleration and Maximum Roll Angle due to the First Steer differences for these tests are relatively large (0.12 g and 0.9 degree, respectively). These differences are larger than the corresponding Maximum Corrected Lateral Acceleration and Maximum Roll Angle due to the Second Steer differences (0.06 g and 0.7 degree) despite the Second Steering Input magnitude difference being so large.

Jeep Cherokee Tests 233 & 234 had First and Second Steering Input magnitude differences of only 16 and 5 degrees, respectively. Despite these very small differences, the Maximum Corrected Lateral Acceleration due to the First and Second Steer differences were 0.09 and 0.18 g, respectively. The Maximum Roll Angle due to the First and Second Steer differences were 0.6 and 1.1 degrees.

Noting these large differences for both pairs of tests, the video was examined to try to develop a better understanding as to why these differences occurred. The degree of lane deviation was the main difference found in examining the video. For Test 230, the rear end of the Jeep Cherokee moves laterally slightly more than two lane widths (24 feet) from the edge the lower coefficient-of-friction surface. In Test 231, the Cherokee only moves about 1.5 lane widths. Test 233 had very similar lateral movement to that found in Test 230 (two lane widths). Test 234 moved a little more than 1.5 lane widths laterally. Since Tests 230 and 233 had similar lateral lane deviations and they had Initial Speeds that were within 0.2 mph of each other, these two tests were also examined for repeatability.

As shown in Table 13.7, Jeep Cherokee Tests 230 & 233 had identical First Steering Input magnitudes and the Second Steering Input magnitude difference was 26 degrees. The Maximum Corrected Lateral Accelerations due to the First and Second Steers had differences of only 0.02 and

0.01 g, respectively. The Maximum Roll Angles due to the First and Second Steers had corresponding small differences as well (0.1 and 0.0 degrees).

The Handwheel Steering Angle, Corrected Lateral Acceleration, and Roll Angle traces for all three pairs of Jeep Cherokee tests are displayed in Figures 13.7 through 13.9.

Jeep Cherokee Tests 230 & 231 time histories are plotted in Figure 13.7. The First Steering Movements for these two tests are very similar in magnitude and duration. The Second Steering Movement for Test 231 has a much lower magnitude, but a longer duration, than that of Test 230. This longer duration allows the lateral acceleration and roll angle to achieve higher magnitudes in Test 231. There is a relatively large difference between the roll angles at the very beginning of the test. This data probably isn't valid (just during the first part of the test) and may be due to sensor problems associated with the wet epoxy surface.

Jeep Cherokee Tests 233 & 234 time histories are plotted in Figure 13.8. The First Steering Movements for these two tests are very similar in magnitude but not in duration. Test 233 has a longer dwell time near the initial negative peak prior to reversing the direction of steering movement. After the dwell, the steering profiles are fairly similar up to 2.8 seconds except for a time delay caused by the initial dwell of Test 233. The dwell time contributes to the larger (in absolute value) Maximum Corrected Lateral Acceleration and Maximum Roll Angle due to the First and Second Steer values for Test 233. The longer duration and higher magnitude of the lateral acceleration for Test 233 is consistent with the larger vehicle lateral movement seen for this test (compared to Test 234).

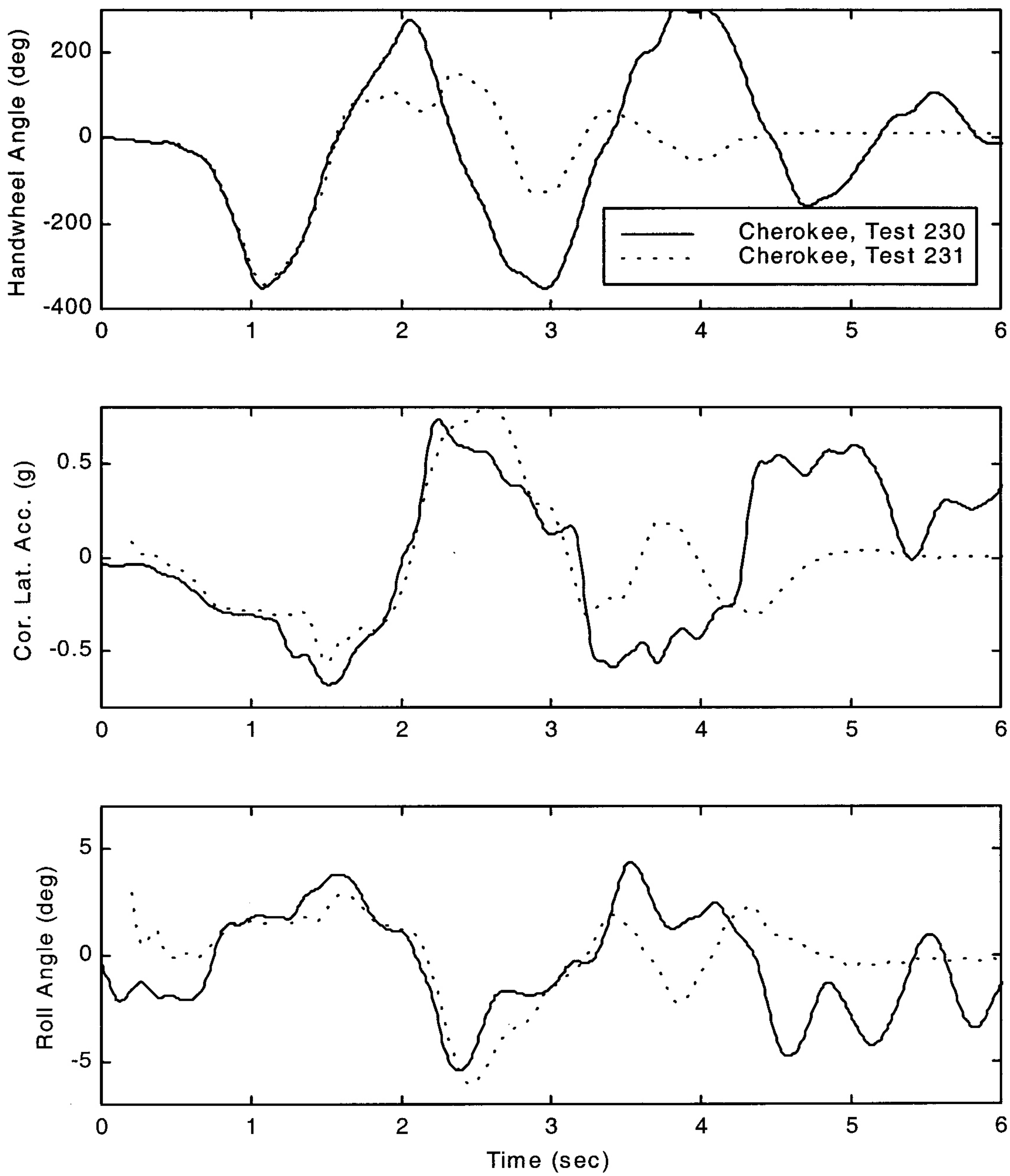

Figure 13.7 -- Jeep Cherokee Split-Mu Test Comparison for Tests 230 and 231

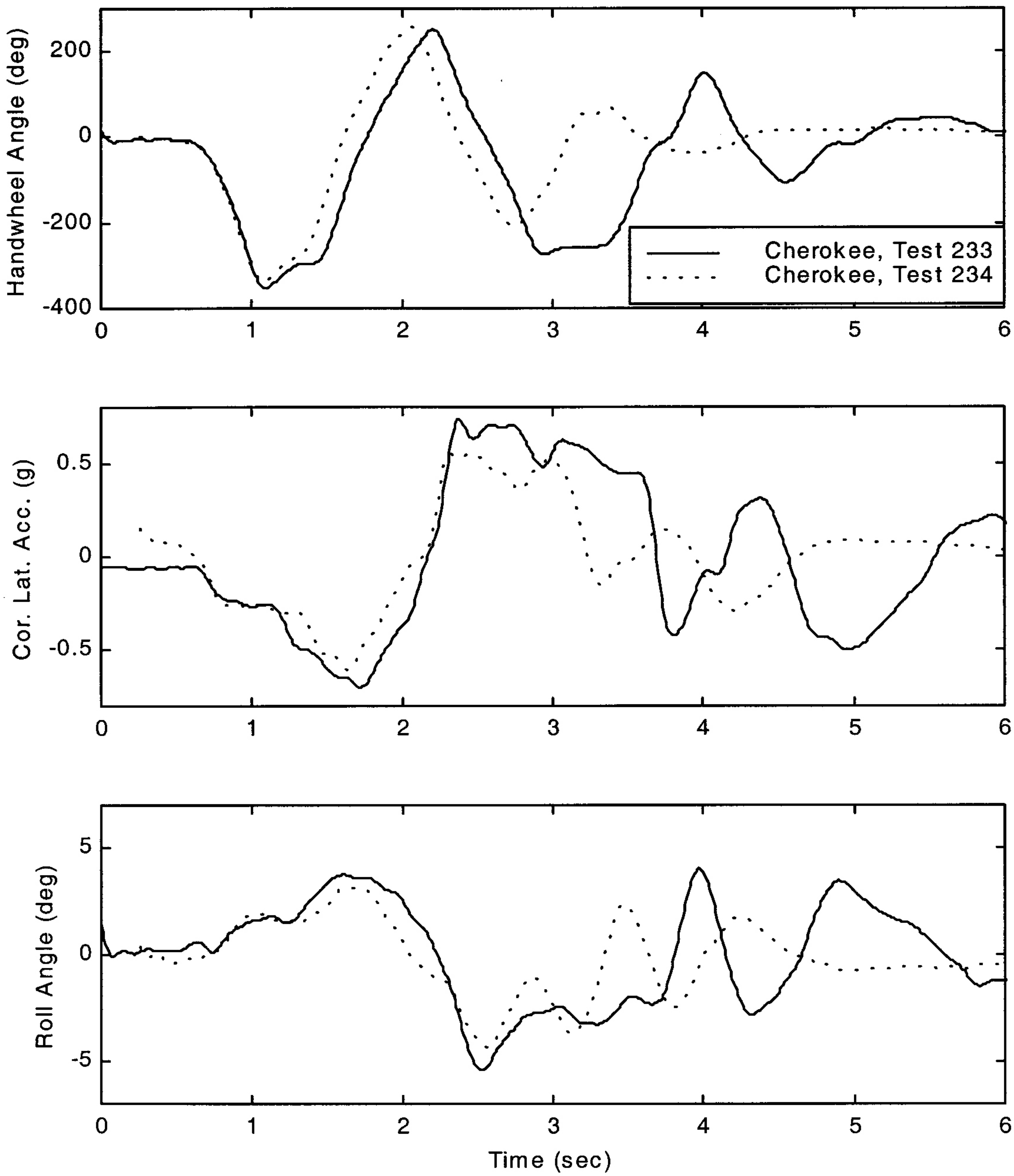

Figure 13.8 -- Jeep Cherokee Split-Mu Test Comparison for- Tests 233 and 234

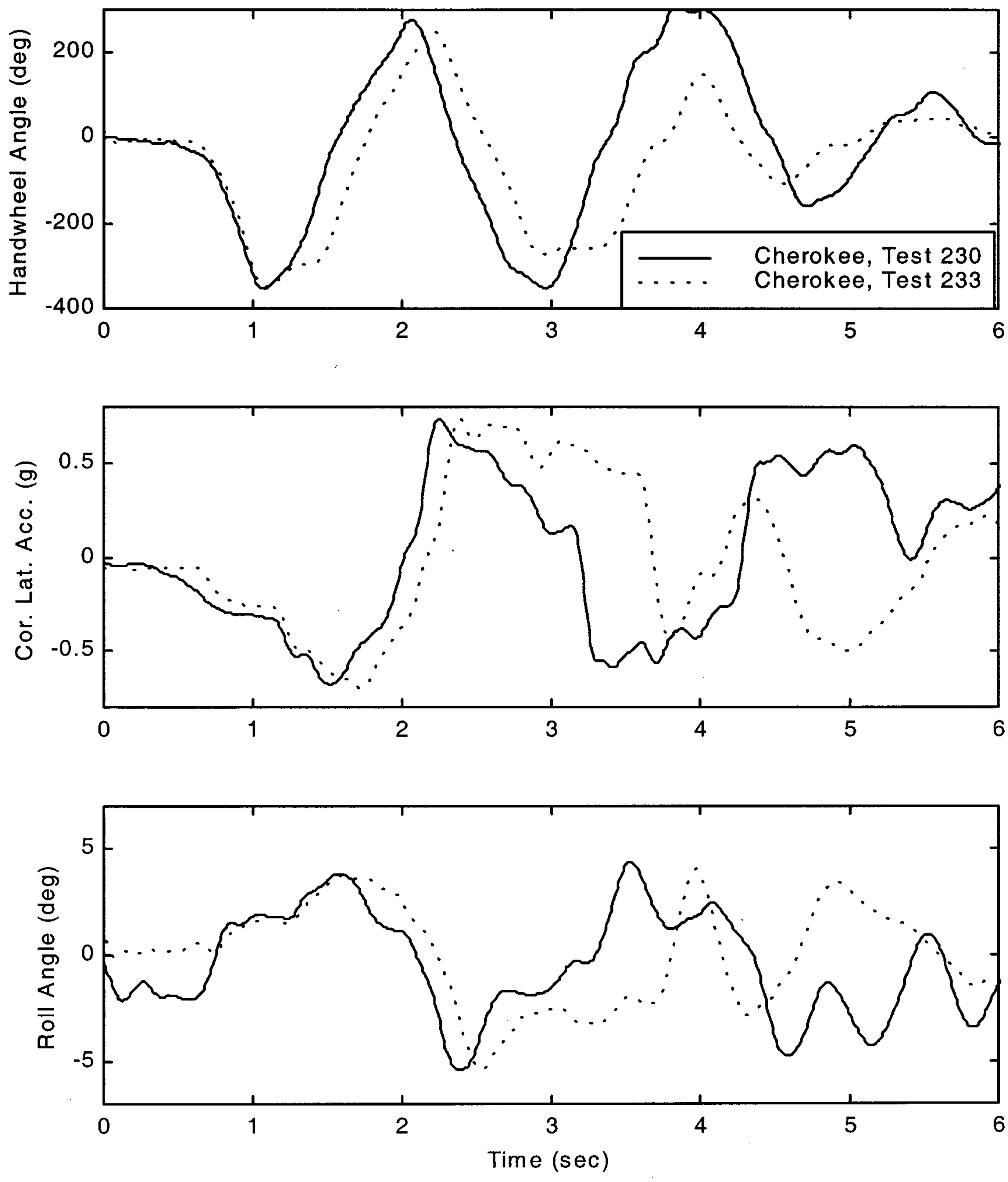

Figure 13.9 -- Jeep Cherokee Split-Mu Test Comparison for Tests 230 and 233

Since Jeep Cherokee Tests 230 & 233 had the most similar lateral movement and maximum vehicle responses, these tests were also examined as a pair and are plotted in Figure 13.9. As was the case when compared to Test 234, compared to Test 230, Test 233 has a longer dwell time near the initial negative peak, prior to reversing direction. After the dwell, the steering profiles are fairly similar up to 2.8 seconds except for the delay caused by the dwell of Test 233. The magnitudes of the peak vehicle responses are very similar for the two tests, but they are delayed for Test 233 (compared to Test 230) due to the dwell. These results are somewhat counter to what was seen when comparing Tests 233 & 234 (larger accelerations and roll angles for Test 233). This further confirms how variable Split-Mu testing can be.

These matched pairs of tests clearly show how variable the magnitude and timing of the driver input can be for this test. Even for tests for which variability in the magnitude of the driver input is not expected to have an effect (due to tire lateral side force capacity saturation), the variability in timing can produce very different run-to-run test results. A better steering stop could be used to control the magnitude of the First Steering Movement, but, even then, the driver has a lot of freedom in how to perform the Second (and subsequent) Steering Movements.

The path-following problems associated with the Double Lane Change maneuver are also evident for the Split-Mu maneuver. Driver influences, although not evaluated in this study, would probably make the Split-Mu maneuver performed by multiple test drivers even less repeatable than what was seen in this study.

13.4 Split-Mu Off Road Recovery Simulation Testing Problems

During Ford Bronco II Test 99, the vehicle had two-wheel lift, but no data was collected. The Bronco II has a manual transmission and after the vehicle lifted and then spun, the engine stalled. The data acquisition system will continue to collect data if there is sufficient battery power. There is enough power even if the engine is shut off temporarily, but when the driver started the engine, all the power was diverted to the starter and the computer shut down prior to saving the data. The engine stalled on several other tests, but the driver always made sure the software was finished saving data prior to re-starting the engine.

One side of the Split-Mu test area is a wet epoxy surface. The wet surface and/or the off-white epoxy surface would cause the data system to trigger falsely at times. This problem can be corrected by adjusting the sensitivity of the triggering device.

13.5 Summary Split-Mu Off Road Recovery Simulation Results

Two of the three vehicles, the Toyota 4Runner and the Ford Bronco II, experienced two-wheel lift while performing the Split-Mu maneuver. Each vehicle had only one test run that resulted in two-wheel lift. The Toyota 4Runner had a Minor two-wheel lift and the Ford Bronco II had a Major two-wheel lift. Tire wear may well have been the cause of the two-wheel lift for the Ford Bronco II. The single two-wheel lift that occurred for this vehicle happened with a tire set that had been used to complete numerous other runs.

During processing, the data collected during Split-Mu testing seemed very similar to that collected during Steering Reversal testing. The Split-Mu maneuver appears to be a "muted" Steering Reversal (or Toyota Fishhook) test: muted in that the second steer is not held, but instead followed by a third steering reversal. A comparison of similar tests from these two maneuver types suggests that the Steering Reversal maneuver (and hence the Toyota Fishhook) is at least as severe, if not more so, than the Split-Mu maneuver. Vehicle yaw effects on a split-mu surface may potentially increase rollover propensity, but this was not observed in this study.

During the Split-Mu maneuver, driver steering subsequent to the First Steering Movement is a reaction to the trajectory being followed by the vehicle. Due to the trajectory-following nature of this portion of the Split-Mu maneuver, handwheel steering inputs become less-and-less repeatable during the course of a maneuver. A better steering stop design could be used to better control the magnitude of the First Steering Movement, but even then the driver has a lot of freedom in how to perform the Second (and subsequent) Steering Movements because the vehicle path is not heavily constrained. Also, even when using a steering stop, the analyses have shown that there was still substantial variability in the timing of the First Steering Movement which significantly affected subsequent vehicle motions.

Unlike the Toyota Fishhook, the variability in Split-Mu steering inputs is very difficult to minimize using a steering controller. Programming the controller to recover from an initial, prescribed, severe disturbance is much more difficult to implement than simply providing a particular steering profile as is the case for a Fishhook maneuver.

As has been shown above, there is far more variability in the Corrected Lateral Acceleration and the Roll Angle for the Split-Mu maneuver than there is for the J-Turn, J-Turn with Pulse Braking, and Toyota Fishhook maneuvers. This is in part because the driver inputs were not controlled enough to produce repeatable results. However, this test also required two different test surfaces. Since test surface friction ratings can change with time, weather, amount of water applied to the low coefficient surface, etc., the variability in results from this test is expected to be higher than the variability of a test performed on a single road surface.

Due to the repeatability problems associated with the Split-Mu maneuver, that the split-mu surface properties did not appear to increase rollover propensity for the vehicles tested (as was initially thought might be the case), and that the Split-Mu maneuver seems to affect the vehicle like a "muted" Toyota Fishhook, the authors recommend that the Split-Mu Maneuver not be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

14.0 TOYOTA FISHHOOK WITH PULSE BRAKING TEST RESULTS AND ANALYSIS

14.1 Tests Performed for Each Vehicle

The Toyota 4Runner had two-wheel lift during the Toyota Fishhook (without pulse braking) testing. Therefore, no Toyota Fishhook with Pulse Braking tests were conducted using this vehicle.

Even though the Ford Bronco II had two-wheel lift during Toyota Fishhook without pulse braking testing, the two-wheel lift appeared to be related to tire wear. Therefore, Toyota Fishhook with Pulse Braking tests were conducted using this vehicle.

Two sets of Toyota Fishhook with Pulse Braking tests were performed with the Ford Bronco II. These tests were all run with an initial steering input to the right followed by a steering input to the left. A total of 14 Toyota Fishhook with Pulse Braking test runs were made for this vehicle. Of these 14, four produced two-wheel lift that ranged from minor to major.

Table 14.1 summarizes the data for all 14 valid Toyota Fishhook with Pulse Braking tests performed with the Ford Bronco II. This table lists the Test Number, Initial Speed, the magnitude of the First and Second Steering Inputs, the maximum Brake Pedal Force achieved during pulse braking, the Maximum Corrected Lateral Accelerations at three times, due to the First Steering Input, due to the Second Steer Input but before the brake pulse, and after the brake pulse, the Maximum Roll Angles at the same three times, and the Amount of Two-Wheel Lift (if any). The two-wheel lift categorization method used in this table is the same as was described in Section 7.1 for the J-Turn maneuver.

Table 14.1 -- Ford Bronco II Toyota Fishhook with Pulse Braking Results

Test Number	Initial Speed (mph)	First Steer Input (deg)	Second Steer Input (deg)	Max. Brake Pedal Force (lbs)	Max. Cor. Lat. Acc. due to First Steer (g)	Max. Cor. Lat. Acc., Second Steer to Pre-Brake (g)	Max. Cor. Lat. Acc., Post-Brake (g)	Max. Roll Angle due to First Steer (deg)	Max. Roll Angle, Second Steer to Pre-Brake (deg)	Max. Roll Angle, Post-Brake (deg)	Amount of Two-Wheel Lift
23	42.2	266	-394	30	0.69	-0.60	-0.91	-4.3	5.7	18.7	Major
24	36.1	301	-377	28	0.69	-0.56	-0.70	-4.4	4.8	7.2	None
25	40.6	273	-432	19	0.71	-0.69	-0.91	-4.2	6.0	11.3	Moderate
26	41.1	253	-374	27	0.68	-0.67	-0.77	-4.4	5.7	9.9	None
27	41.1	290	-452	20	0.72	-0.71	-0.66	-4.4	7.5	4.7	None
29	43.8	253	-376	27	0.71	-0.68	-0.66	-4.7	6.5	5.1	None
70	32.8	288	-478	39	0.69	-0.74	-0.70	-4.2	4.9	6.5	None
71	35.9	269	-636	60	0.67	-0.71	-0.64	-4.3	4.8	6.7	None
72	38.8	281	-452	54	0.72	-0.75	-0.68	-4.4	5.6	6.8	None
73	38.6	224	-415	56	0.70	-0.74	-0.70	-4.1	5.3	7.2	None
74	41.1	236	-412	48	0.70	-0.78	-0.83	-4.5	5.9	8.6	None
75	44.3	250	-385	72	0.73	-0.81	-0.93	-4.5	5.4	15.9	Moderate
76	40.9	243	-441	73	0.72	-0.75	-0.79	-4.6	6.4	9.5	None
77	41.4	296	-392	60	0.74	-0.80	-0.98	-4.8	9.5	9.9	Minor

An initial Toyota Fishhook with Pulse Braking run, Test 23, was performed that produced major two-wheel lift. As discussed in Section 6.5, the Toyota Fishhook with Pulse Braking is run starting with relatively low course entry speeds. The course entry speed is then gradually increased for each successive run until several runs with two-wheel lift are produced. A group of test runs, starting at a low course entry speed and working up until a termination condition occurs is referred to as a "set". Because two-wheel lift had not been achieved with the Toyota Fishhook (without pulse braking) test procedure unless significant tire wear was present with this vehicle, the initial test speed for this test set was relatively high. After the major two-wheel lift occurred, the initial test speed was reduced to a level where two-wheel lift would not be achieved. While this test is technically not part of a set (it was not part of a sequence of runs for which Initial Speed was being systematically increased), for purposes of Lateral Acceleration for Rollover (LAR) determination it has been included in the first set.

The first set of Toyota Fishhook With Pulse Braking tests conducted with the Ford Bronco II consisted of Tests 23 through 29. These tests were performed at Initial Speeds ranging from 36.1 to 43.8 mph. One of these tests produced moderate two-wheel lift and the initial test (23) produced major two-wheel lift.

The second set of Toyota Fishhook With Pulse Braking tests conducted with the Ford Bronco II consisted of Tests 70 through 77. These tests were performed at Initial Speeds ranging from 32.8 to 44.3 mph. One of these tests produced moderate two-wheel lift and one produced minor two-wheel lift.

Tests 76 and 77 were performed at Initial Speeds of 40.9 and 41.4 mph. Even though these tests had lower Initial Speeds than those for Test 75 (44.3 mph), they are included in the test set. After a moderate or major two-wheel lift, the driver would tend to decrease the speed slightly to see if two-wheel lift could be achieved at a lower speed.

Two sets of Toyota Fishhook with Pulse Braking tests, plus a few runs that were not part of a set, were also performed with the Jeep Cherokee. Tests were run both with an initial steering input to the right followed by a steering input to the left and with an initial steering input to the left followed by a steering input to the right. A total of 16 Toyota Fishhook with Pulse Braking test runs were made for this vehicle. Of these 16, three produced minor two-wheel lift.

Table 14.2 summarizes the data for all 16 valid Toyota Fishhook with Pulse Braking tests performed with the Jeep Cherokee.

Tests 107 and 108 were conducted with the vehicle's anti-lock braking system functioning. The maximum roll angle for both runs occurred prior to the initiation of the pulse braking and neither test resulted in two-wheel lift. Since the pulse braking did not influence the significant test results for these runs, these two tests have been combined with the non-pulse braking data in Chapter 11. They are not included in either of the Jeep Cherokee's Toyota Fishhook with Pulse Braking sets.

All Jeep Cherokee Toyota Fishhook with Pulse Braking tests other than Tests 107 and 108 were performed with the vehicle's antilock braking system disabled.

The first set of Toyota Fishhook With Pulse Braking tests conducted with the Jeep Cherokee consisted of Tests 154 through 163. These tests were performed with an initial steering input to the right followed by a steering input to the left at Initial Speeds ranging from 44.5 to 56.9 mph. None of these tests produced two-wheel lift. For all but three of these tests (Tests 155 through 157), the maximum roll angle (in absolute value) during the entire test occurred prior to the start of pulse braking.

Table 14.2 -- Jeep Cherokee Toyota Fishhook with Pulse Braking Results

Test Number	Initial Speed (mph)	First Steer Input (deg)	Second Steer Input (deg)	Max. Brake Pedal Force (lbs)	Max. Cor. Lat. Acc. due to First Steer (g)	Max. Cor. Lat. Acc., Second Steer to Pre-Brake (g)	Max. Cor. Lat. Acc., Post-Brake (g)	Max. Roll Angle due to First Steer (deg)	Max. Roll Angle, Second Steer to Pre-Brake (deg)	Max. Roll Angle, Post-Brake (deg)	Amount of Two-Wheel Lift
ABS											
107	44.4	210	-371	189	0.81	-0.81	-0.78	-5.0	6.6	5.1	None
108	44.1	275	-370	176	0.83	-0.81	-0.81	-4.9	6.9	6.0	None
No-ABS											
154	45.0	306	-427	153	0.89	-0.87	-0.84	-5.6	7.4	6.2	None
155	44.5	229	-384	174	0.86	-0.86	-0.87	-5.3	7.3	7.7	None
156	47.4	264	-401	96	0.85	-0.88	-0.83	-5.3	7.6	7.7	None
157	48.0	257	-423	169	0.86	-0.85	-0.84	-5.5	7.9	8.9	None
158	50.8	217	-408	145	0.86	-0.89	-0.80	-5.1	7.2	6.7	None
159	52.7	253	-381	178	0.87	-0.81	-0.83	-5.6	6.9	5.2	None
160	51.5	204	-375	174	0.87	-0.82	-0.81	-5.0	7.5	6.1	None
161	54.3	283	-638	210	0.85	-0.81	-0.82	-5.6	6.8	5.3	None
163	56.9	263	-638	120	0.88	-0.87	-0.85	-5.9	8.6	5.6	None
195	45.5	-248	372	207	-0.81	0.89	0.83	5.1	-8.1	-8.5	Minor
196	46.8	-272	294	194	-0.87	0.89	0.87	5.2	-8.1	-7.4	None
197	50.2	-274	315	194	-0.89	0.83	0.83	5.0	-7.9	-7.0	None
198	54.4	-303	303	209	-0.90	0.91	0.87	5.1	-9.2	-7.6	Minor
199	51.9	-329	314	67	-0.90	0.91	0.84	5.5	-8.5	-7.2	Minor

The second set of Toyota Fishhook With Pulse Braking tests conducted with the Jeep Cherokee consisted of Tests 195 through 199. These tests were performed with an initial steering input to the left followed by a steering input to the right at Initial Speeds ranging from 45.5 to 54.4 mph. Three of these tests produced minor two-wheel lift. The two-wheel lifts occurred prior to the start of pulse braking during the steering reversal. The brake pulse began while the Cherokee had two-wheel lift. The brake pulse brought the two wheels back down. The Cherokee did not have two-lift wheel lift occur again, after the pulse braking. Because the Cherokee was having two-wheel lift before braking began, Tests 201 through 203 were then conducted without pulse braking. Results from these tests were presented in Chapter 11.

14.2 Lateral Acceleration for Rollover Determination for Each Vehicle

The Lateral Acceleration for Rollover (LAR) was calculated from each of the Toyota Fishhook with Pulse Braking sets. Section 11.2 discusses the techniques used to determine the Used Maxiumum Corrected Lateral Acceleration values that are needed for this calculation. Note that, for this research, data from Toyota Fishhook (without pulse braking) tests was not combined with data from Toyota Fishhook with Pulse Braking runs when computing LAR values (except for one special case, Jeep Cherokee Tests 107 & 108 which were run without disabling the vehicle's antilock braking system).

The Ford Bronco II Used Maximum Corrected Lateral Acceleration values for Tests 23 through 29 are plotted in Figure 14.1. Two of these tests produced two-wheel lift (Tests 23 and 25) with Used Maximum Corrected Lateral Acceleration values of -0.91 g for each test. The tests without two-wheel lift had Used Maximum Corrected Lateral Acceleration values ranging from -0.68 to -0.77 g. The average of the largest absolute value of Used Maximum Corrected Lateral Acceleration value without two-wheel lift and the smallest absolute value of Used Maximum Corrected Lateral Acceleration value with two-wheel lift is the LAR, giving a value of 0.84 g. To produce a complete LAR value, testing would also have to be conducted in the other direction (initial left then right steering input) and a second LAR value calculated. According to the Toyota test procedure, the lower of these two LAR values is the LAR value for the vehicle.

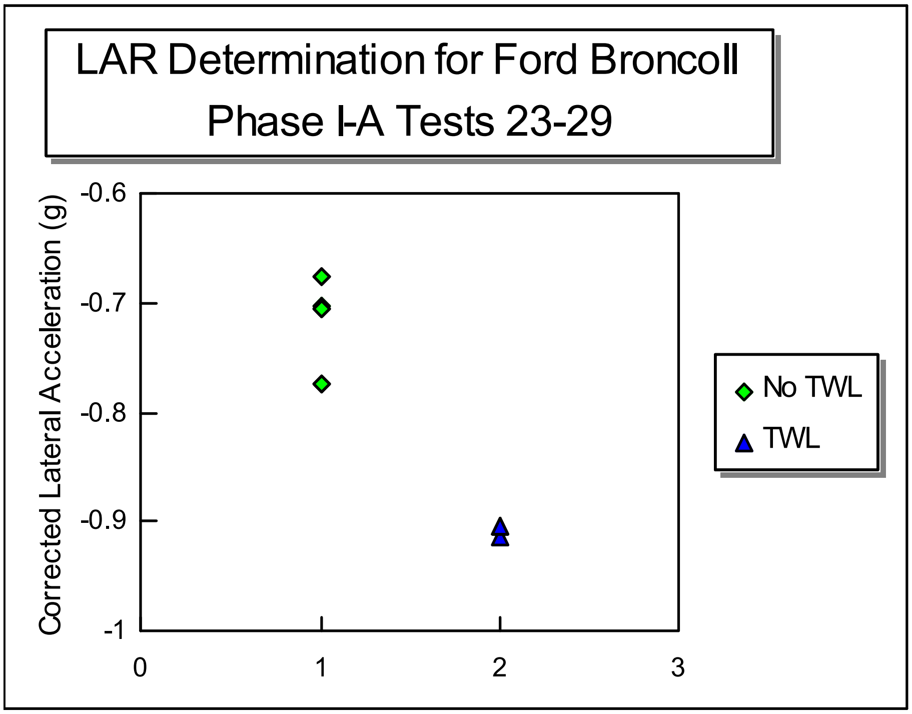

Figure 14.1 -- Ford Bronco II LAR Determination from Tests 23 through 29

The Ford Bronco II Used Maximum Corrected Lateral Acceleration values for Tests 70 through 77 are plotted in Figure 14.2. Two of these tests produced two-wheel lift (Tests 75 and 77) with Used Maximum Corrected Lateral Acceleration values of -0.93 and -0.98 g respectively. The tests without two-wheel lift had Used Maximum Corrected Lateral Acceleration values ranging from -0.71 to -0.83 g. The average of the largest absolute value of Used Maximum Corrected Lateral Acceleration value without two-wheel lift and the smallest absolute value of Used Maximum Corrected Lateral Acceleration value with two-wheel lift is the LAR, giving a value of 0.88 g. Again, to produce a complete LAR value, testing would also have to be conducted in the other direction (initial left then right steering input), a second LAR value calculated, and the minimum value taken.

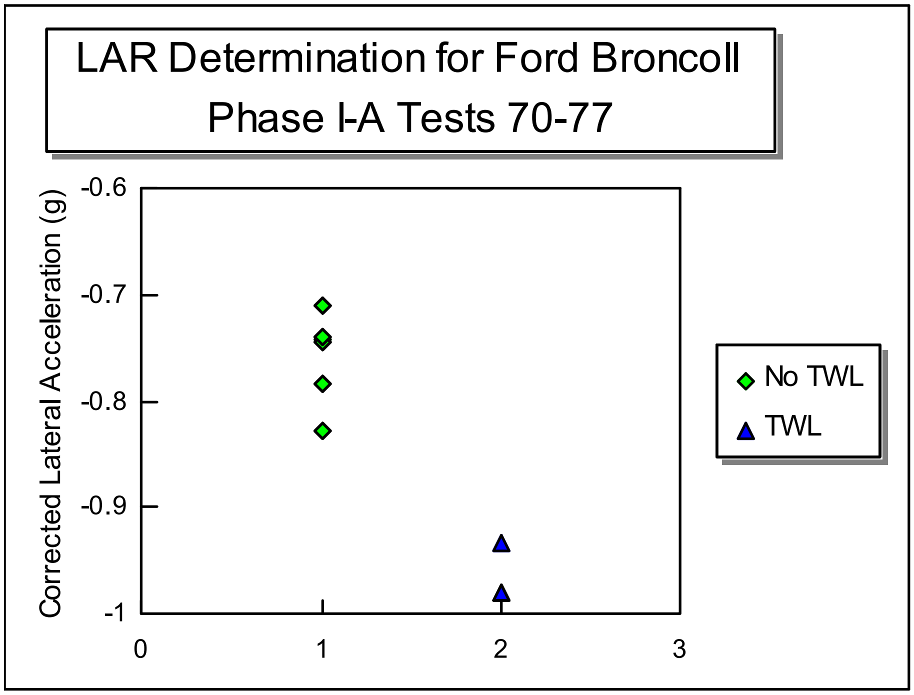

Figure 14.2 -- Ford Bronco II LAR Determination from Tests 70 through 77

The Jeep Cherokee Used Maximum Corrected Lateral Acceleration values for Tests 154 through 163 are plotted in Figure 14.3. None of these tests produced two-wheel lift. The tests without two-wheel lift had Used Maximum Corrected Lateral Acceleration values ranging from -0.82 to -0.89 g. Since no two-wheel lifts occurred, an LAR value cannot be determined from this set of tests.

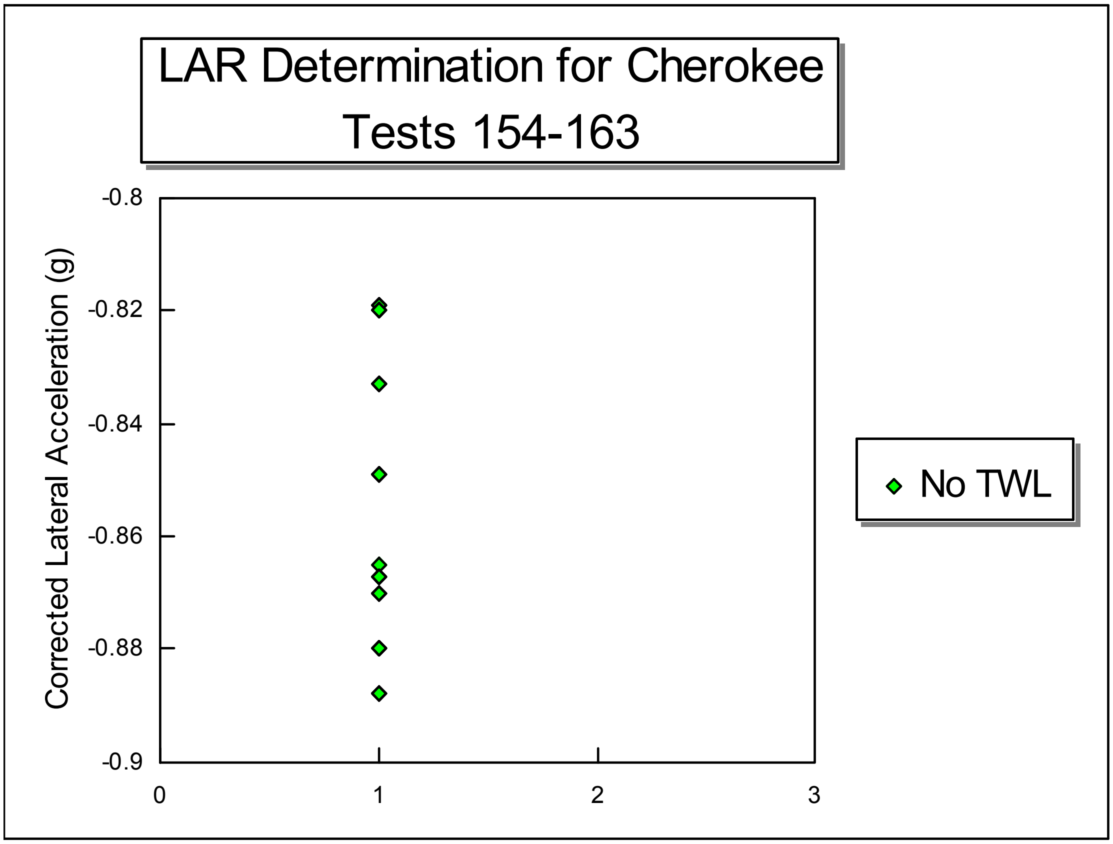

Figure 14.3 -- Jeep Cherokee LAR Determination from Tests 154 through 163

The Jeep Cherokee Used Maximum Corrected Lateral Acceleration values for Tests 195 through 199 are plotted in Figure 14.4. Three of these tests produced two-wheel lift (Tests 195, 198, and 199) with Used Maximum Corrected Lateral Acceleration values ranging between 0.89 and 0.91 g. The runs without two-wheel lift, Tests 196 & 197, had Used Maximum Corrected Lateral Acceleration values of 0.89 and 0.83 g, respectively. The average of the largest absolute value of Used Maximum Corrected Lateral Acceleration value without two-wheel lift and the smallest absolute value of Used Maximum Corrected Lateral Acceleration value with two-wheel lift is the LAR, giving a value of 0.90 g. Again, to produce a complete LAR value, testing would also have to be conducted in the other direction (initial right then left steering input), a second LAR value calculated, and the minimum value taken.

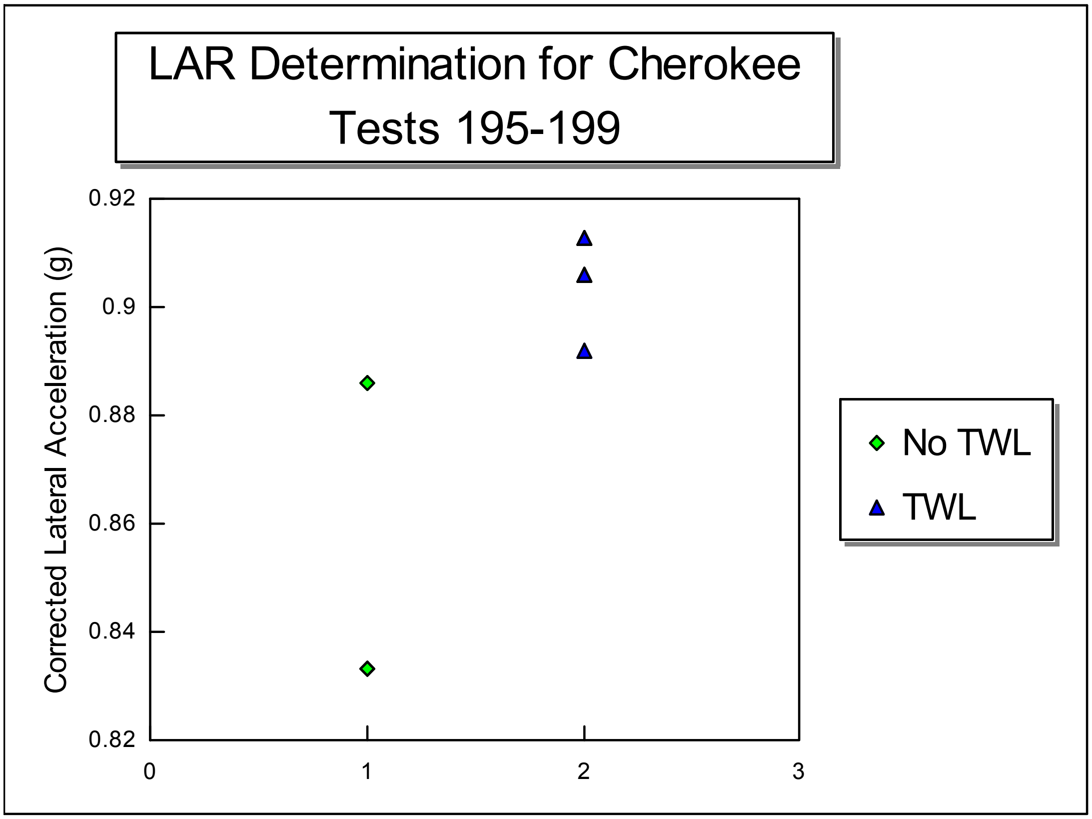

Figure 14.4 -- Jeep Cherokee LAR Determination from Test 195 through 199

14.3 The Toyota Fishhook with Pulse Braking and Rollover Propensity

For both vehicles tested, the Ford Bronco II and the Jeep Cherokee, two-wheel lifts were observed during the Toyota Fishhook with Pulse Braking testing.

The Ford Bronco II had minor, moderate, and major two-wheel lifts while the Jeep Cherokee only had minor two-wheel lifts. The two-wheel lifts that occurred for the Bronco II did not appear to be related to tire wear like the two-wheel lifts that occurred for this vehicle with the Toyota Fishhook (without pulse braking). The degree of two-wheel lift was greater for the Toyota Fishhook with Pulse Braking maneuver than it was for the J-Turn with Pulse Braking maneuver for the Bronco II.

The two-wheel lifts that occurred for the Jeep Cherokee happened prior to the onset of the braking pulse. Therefore, the braking pulse did not produce the two-wheel lifts. In fact, the brake pulse tended to bring the vehicle back down from the two-wheel lifts and the vehicle did not have two-wheel lift again after the pulse was concluded. Testing at higher speeds may produce a different result. The Cherokee also had two-wheel lift in the J-Turn with Pulse Brake and the Toyota Fishhook (without pulse braking) maneuvers. As was the case with the Toyota Fishhook (without pulse braking) maneuver, only a left then right steering input produced two-wheel lift.

The Toyota Fishhook with Pulse Braking does not appear to give any better indication of rollover propensity than the combination of the Toyota Fishhook (without pulse braking) and the J-Turn with Pulse Braking. The Ford Bronco II did have a higher level of two-wheel lifts for the Toyota Fishhook with Pulse Braking maneuver than it did for the J-Turn with Pulse Braking maneuver in Phase I-A testing; however, two-wheel lifts did occur for both maneuvers.

14.4 Repeatability of the Toyota Fishhook with Pulse Braking Maneuver

As was done for most of the other Phase I-A maneuvers, Toyota Fishhook with Pulse Braking maneuver repeatability was studied by making comparisons between matched tests. The Fishhook with Pulse Braking testing had one independent variable, Test Vehicle. The Toyota Fishhook with Pulse Braking has even more primary input variables than the J-Turn with Pulse Brake: Initial Speed, magnitude of the First Steering Input, magnitude of the Second Steering Input, Maximum Brake Pedal Force, Brake Pulse Width, and Time of Pulse Start. All of these inputs create a very difficult maneuver for the driver to perform repeatably. All of the factors that create the variability seen in the J-Turn with Pulse Braking and the Toyota Fishhook without pulse braking are present with this maneuver.

With multiple primary input variables, a large number of tests would have to be performed to find matched pairs with similar values for all of the primary input variables. Relatively few tests were performed with this maneuver, so it was decided to match tests that just had similar Initial Speeds for this repeatability analysis and accept differences in the other primary input variables. There were only a few pairs of tests with either exactly the same Initial Speed or close to the same Initial Speed for the Ford Bronco II and Jeep Cherokee. In fact, the closest pair of Initial Speeds for the Cherokee had a 0.5 mph difference. Examination of Table 14.1 shows that three pairs of matched tests for the Bronco II exist: Tests 26 & 27, 72 & 73, and 74 & 76 . From Table 14.2, the closest pair of tests for the Cherokee are 154 & 155 (Tests 161 and 198 have similar speeds, but the direction of the First Steering Input for these two tests are the opposite of each other). The results from each matched pair of tests, and the differences between them, are shown in Table 14.3.

Ford Bronco II Tests 26 & 27 had the same Initial Speed. The First and Second Steering Inputs differed by 37 and 78 degrees, respectively. However, both steering inputs are large enough that they should have saturated the side force generation capability of the vehicle's tires. Therefore, these relatively large differences are in steering input magnitudes are expected to have only minimal effects on the Bronco II's responses. The Maximum Brake Pedal Force is relatively low for both tests and varied by a moderate 7 pounds (14%). The Maximum Corrected Lateral Acceleration due to the First and due to the Second Steer but before the start of braking are fairly similar with only a 0.04 g difference for both values. These small differences occur even though there are large differences in the steering magnitudes because of the saturation of the vehicle's tire side force generation capability. The Maximum Corrected Lateral Accelerations, Post-Brake had a larger difference (0.11 g). A similar trend is also seen with the Roll Angle values. The Maximum Roll Angles due to the First Steer are the same, the Second Steer to Pre-Brake values are 1.8 degrees different, and the Post-Brake values are 5.3 degrees different. The reasons for these differences can be better explained by examining the data traces from these tests.

Table 14.3 -- Fishhook with Pulse Braking Matched Pair Test Results

Test Number	Initial Speed (mph)	First Steer Input (deg)	Second Steer Input (deg)	Max. Brake Pedal Force (lbs)	Max. Cor. Lat. Acc. due to First Steer (g)	Max. Cor. Lat. Acc., Second Steer to Pre-Brake (g)	Max. Cor. Lat. Acc., Post-Brake (g)	Max Roll Angle due to First Steer (deg)	Max Roll Angle, Second Steer to Pre-Brake (deg)	Max Roll Angle, Post-Brake (deg)	Amount of Two-Wheel Lift
Ford Bronco II Results											
26	41.1	253	-374	27	0.68	-0.67	-0.77	-4.4	5.7	9.9	None
27	41.1	290	-452	20	0.72	-0.71	-0.66	-4.4	7.5	4.7	None
Difference	0	37	78	7	0.04	0.04	0.11	0	1.8	5.2	
72	38.8	281	-452	54	0.72	-0.75	-0.68	-4.4	5.6	6.8	None
73	38.6	224	-415	56	0.70	-0.74	-0.70	-4.1	5.3	7.2	None
Difference	0.2	57	37	2	0.02	0.01	0.02	0.3	0.3	0.4	
74	41.1	236	-412	48	0.70	-0.78	-0.83	-4.5	5.9	8.6	None
76	40.9	243	-441	73	0.72	-0.75	-0.79	-4.6	6.4	9.5	None
Difference	0.2	7	29	25	0.02	0.03	0.04	0.1	0.5	0.9	
Jeep Cherokee Results											
154	45.0	306	-427	153	0.89	-0.87	-0.84	-5.6	7.4	6.2	None
155	44.5	229	-384	174	0.86	-0.86	-0.87	-5.3	7.3	7.7	None
Difference	0.5	77	43	21	0.03	0.01	0.03	0.3	0.1	1.5	

The handwheel steering angle, brake pedal force, corrected lateral acceleration, and roll angle data from Ford Bronco II Tests 26 & 27 are plotted in Figure 14.5. The handwheel steering angle traces for these two tests have a very similar shape with Test 27 having higher peak values. The brake pulse shape for these two tests are fairly different. The pulse for Test 26 occurs much earlier than Test 27. Test 26 also has a higher magnitude. Both tests have a double peak for the brake pulse. This is fairly atypical and is probably a function of being two of the earliest tests conducted with this maneuver. The roll angle and corrected lateral acceleration traces are very similar for these two tests up to the point of brake pulse application. Because the brake application is much later for Test 27, the pre-pulse roll angle magnitude achieves a higher value for this test. The pre-pulse lateral accelerations are fairly similar. The post-pulse roll angle and corrected lateral acceleration peak magnitudes are much higher for Test 26. This is primarily due to the larger brake force magnitude. These two tests clearly demonstrate how brake pulse magnitude and timing (relative to the steering inputs) can have an effect on test results.

From Table 14.3, Ford Bronco II Tests 72 & 73 had a 0.2 mph difference in Initial Speed. The First and Second Steering Inputs differed by 57 and 37 degrees, respectively. Again, both steering inputs are large enough that they should have saturated the side force generation capability of the vehicle's tires. Therefore, these relatively large differences in steering input magnitudes are expected to have only minimal effects on the Bronco II's responses. The Maximum Brake Pedal Forces varied by a minimal 2 pounds (4 %). The Maximum Corrected Lateral Acceleration for the First Steer, Second Steer to Pre-Brake, and Second Steer Post-Brake are fairly similar with only a 0.02 g or less difference for all three values. The First Steer, Second Steer to Pre-Brake, and Post-Brake Maximum Roll Angles are very similar as well (0.4 degree difference or less).

The handwheel steering angle, brake pedal force, corrected lateral acceleration, and roll angle data for Ford Bronco II Tests 72 & 73 are plotted in Figure 14.6. The handwheel steering angle traces for these two tests have a very similar shape with Test 72 having higher peak values. The brake pulse shapes for these two tests are very similar, but the pulse for Test 73 occurs earlier than for Test 72. The roll angle and corrected lateral acceleration traces are also very similar for these two tests except for the timing of the dip in the traces caused by the pulse brake application. The results for Test 72 & 73 are much more similar than those for Tests 26 & 27 even though both pairs of tests had different timings for the brake pulse. In both Tests 72 & 73, the pulse brake occurred after the vehicle attained its maximum roll angle for the given steering inputs. This was not the case in Test 26. This explains why the timing differences for Tests 72 & 73 had less of an effect on the Second Steer to Pre-Brake data than was seen for Tests 26 & 27. The magnitudes of the brake pulses for these tests are very similar and the resulting post-pulse corrected lateral acceleration and roll angle peaks are too.

From Table 14.3, Ford Bronco II Tests 74 & 76 had a 0.2 mph difference in Initial Speed. The magnitudes of the First and Second Steering Inputs differed by 7 and 29 degrees, respectively. Again, both steering inputs are large enough that they should have saturated the side force generation capability of the vehicle's tires. Therefore, these relatively large differences in steering input magnitudes are expected to have only minimal effects on the Bronco II's responses. The Maximum Brake Pedal Forces varied by a large amount, 25 pounds (52 %). The Maximum Corrected Lateral Acceleration due to the First Steer, Second Steer to Pre-Brake, and Post-Brake are all fairly similar with only a 0.04 g or less difference for all three values. The First Steer, Second Steer to Pre-Brake, and Post-Brake Maximum Roll Angles had differences of 0.1, 0.5 and 0.9 degrees ,respectively. The larger Post-Brake Maximum Roll Angle is consistent with the larger Maximum Brake Pedal Force.

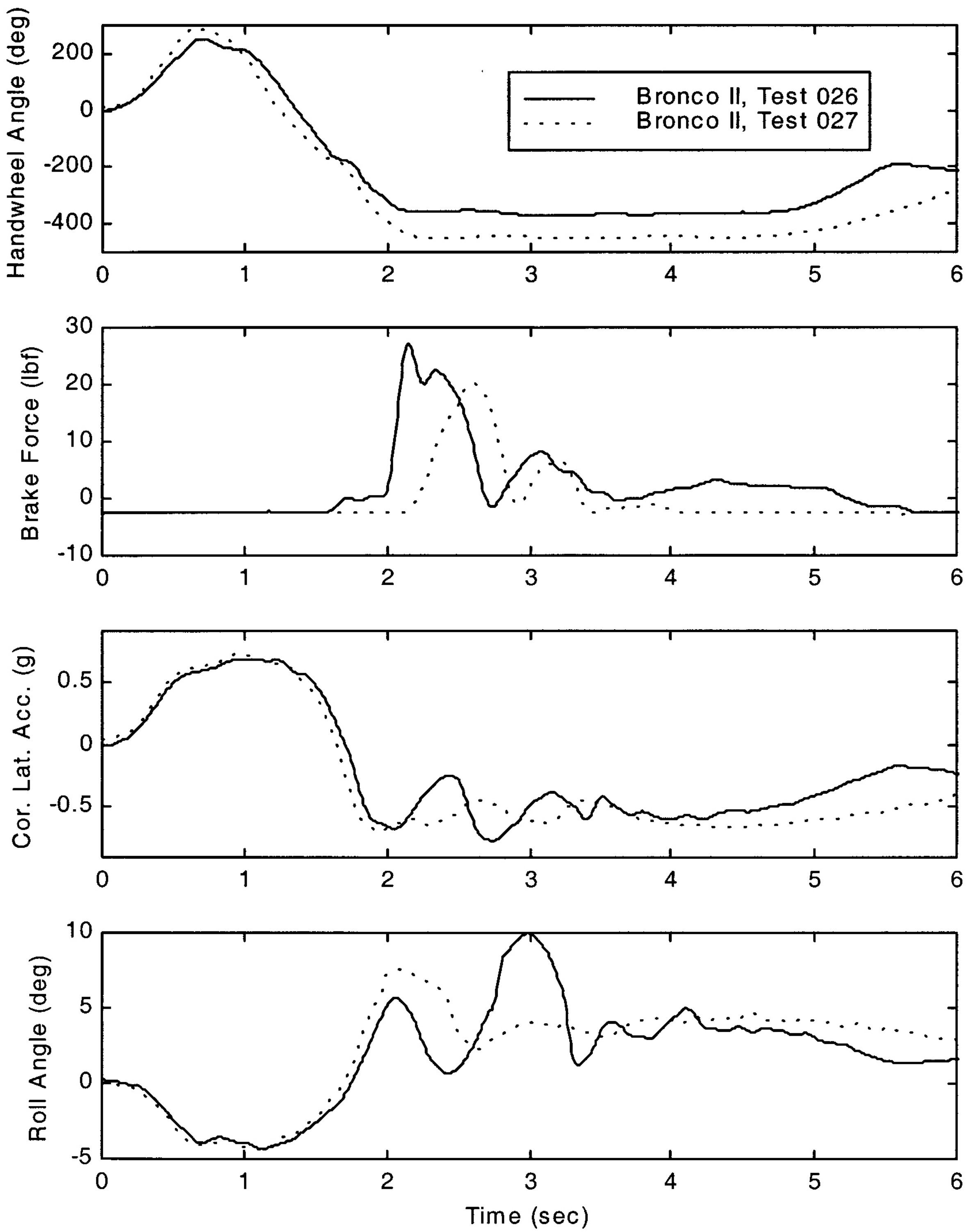

Figure 14.5 -- Ford Bronco II Toyota Fishhook with Pulse Brake Comparison for Tests 26 and 27

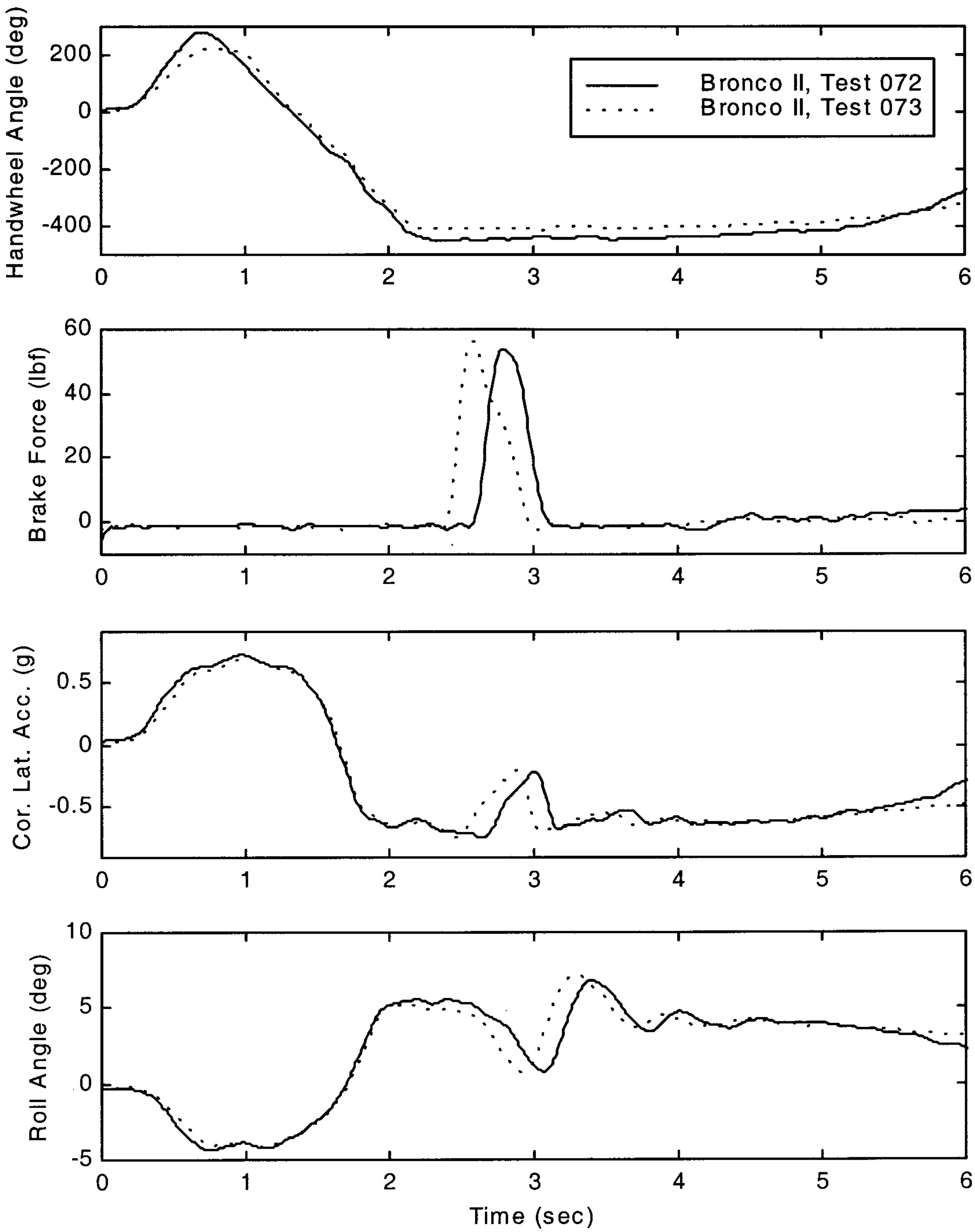

Figure 14.6: Ford Bronco II Toyota Fishhook with Pulse Brake Comparison for Tests 72 and 73

The handwheel steering angle, brake pedal force, corrected lateral acceleration, and roll angle data from Ford Bronco II Tests 74 & 76 are plotted in Figure 14.7. The handwheel steering angle traces for these two tests have a very similar shape with Test 76 having slightly higher peak values. The brake pulse shape for these two tests are somewhat different. The pulse for Test 74 occurs earlier and has a lower magnitude than that for Test 76. The corrected lateral acceleration and roll angle traces are very similar up to the start of the brake pulse. The pre-pulse metrics for Tests 74 & 76 are much more similar than were those for Tests 26 & 27 even though both pairs of tests had different timings for the brake pulse. In both Tests 74 & 76, the pulse brake occurred after the vehicle had attained its maximum corrected lateral acceleration and roll angle (or near maximum) for the given steering inputs. The larger pulse brake magnitude for Test 76 (compared to Test 74) resulted in a larger dip in corrected lateral acceleration and roll angle. The Maximum Roll Angle, Post-Brake, is also noticeably higher for this test.

From Table 14.3, Jeep Cherokee Tests 154 & 155 had a 0.5 mph difference in Initial Speed. The magnitudes of the First and Second Steering Inputs differed by 77 and 43 degrees, respectively. Again, both steering inputs are large enough that they should have saturated the side force generation capability of the vehicle's tires. Therefore, these relatively large differences in steering input magnitudes are expected to have only minimal effects on the Jeep's responses. The Maximum Brake Pedal Forces varied by a moderate, 21 pounds (14 %). The Maximum Corrected Lateral Acceleration for the First Steer, Second Steer to Pre-Brake, and Post-Brake are fairly similar with only 0.03 g or less difference for all three values. The First Steer, Second Steer to Pre-Brake, and Post-Brake Maximum Roll Angles had differences of 0.3, 0.1, and 1.5 degrees respectively. The larger Post-Brake Maximum Roll Angle is consistent with the larger Maximum Brake Pedal Force.

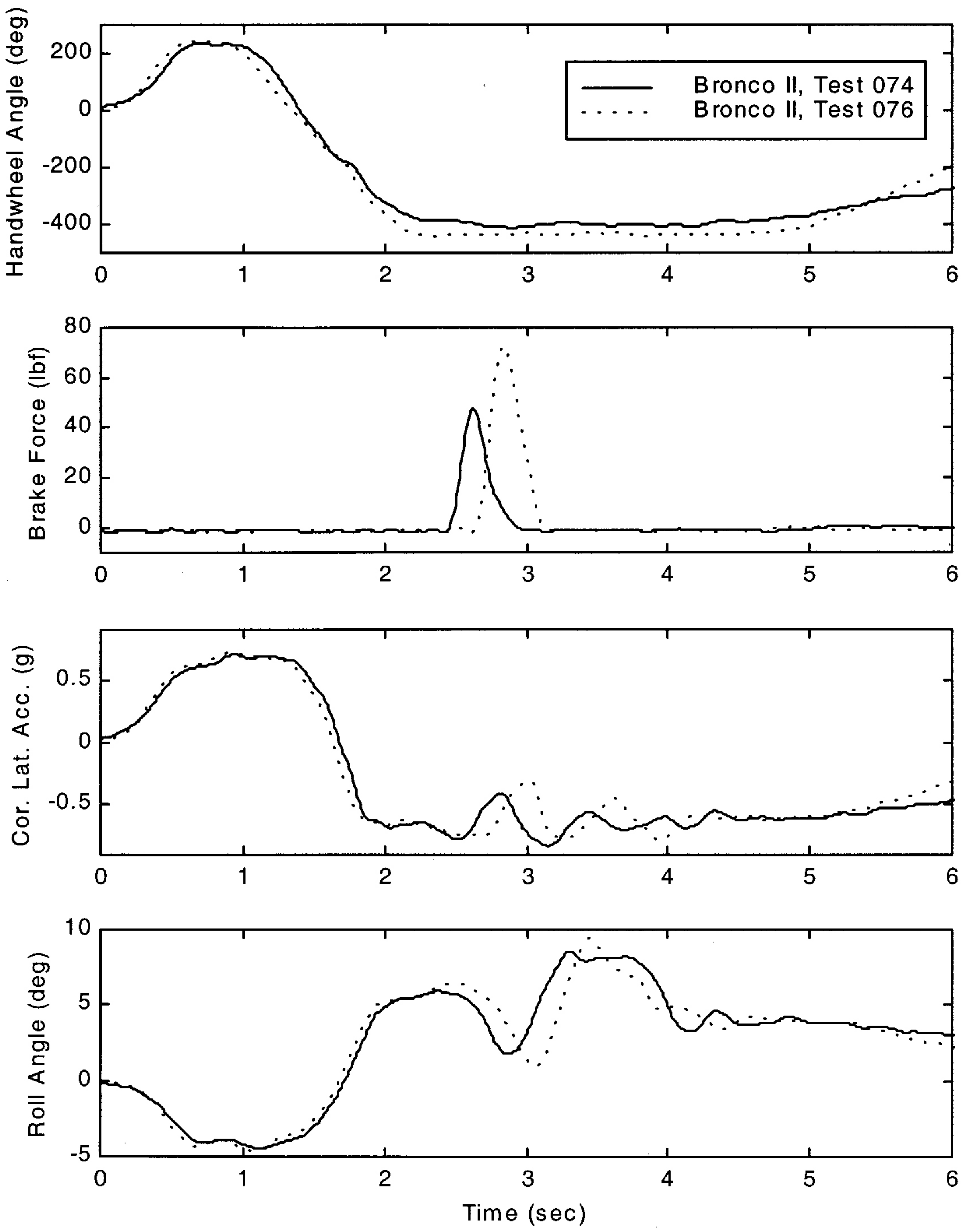

Figure 14.7 -- Ford Bronco II Toyota Fishhook with Pulse Brake Comparison for Tests 74 and 76

The handwheel angle, brake pedal force, corrected lateral acceleration, and roll angle data for Jeep Cherokee Tests 154 & 155 are plotted in Figure 14.8. The handwheel steering angle traces for these two tests have very similar shapes with Test 154 having higher peak values. The brake pulse shapes for these two tests are somewhat different. The pulse for Test 155 occurs earlier and has a higher magnitude than that for Test 154. The corrected lateral acceleration and roll angle traces are very similar for these two tests up to the start of the pulse brake application. As was the case with Bronco II Tests 72 & 73 and 74 &76, the pre-pulse brake results for Cherokee Test 154 & 155 are much more similar than those for Bronco II Tests 26 & 27 even though both pairs of tests had different timings for the brake pulse. In both Tests 154 & 155, the pulse brake occurred after the vehicle had attained its maximum corrected lateral acceleration and roll angle (or near maximum) for the given steering inputs. The larger pulse brake magnitude for Test 155 (compared to Test 154) resulted in a larger dip in roll angle. The Maximum Roll Angle, Post-Brake, is also noticeably higher for this test.

Finally, the two Ford Bronco II test series produced fairly similar Lateral Acceleration for Rollover values: 0.84 and 0.88 g.

Based on the preceding analyses, if the magnitude and timing of the brake pulse inputs can be better controlled, then the Toyota Fishhook with Pulse Braking maneuver is expected to produce repeatable results. In particular, the resulting corrected lateral accelerations and roll angles should be fairly repeatable. Further study would be required to verify this expectation.

14.5 Summary of Toyota Fishhook with Pulse Braking Results

The Toyota 4Runner had two-wheel lift during Toyota Fishhook (without pulse braking) testing, therefore, Toyota Fishhook with Pulse Braking tests were **not** conducted with this vehicle.

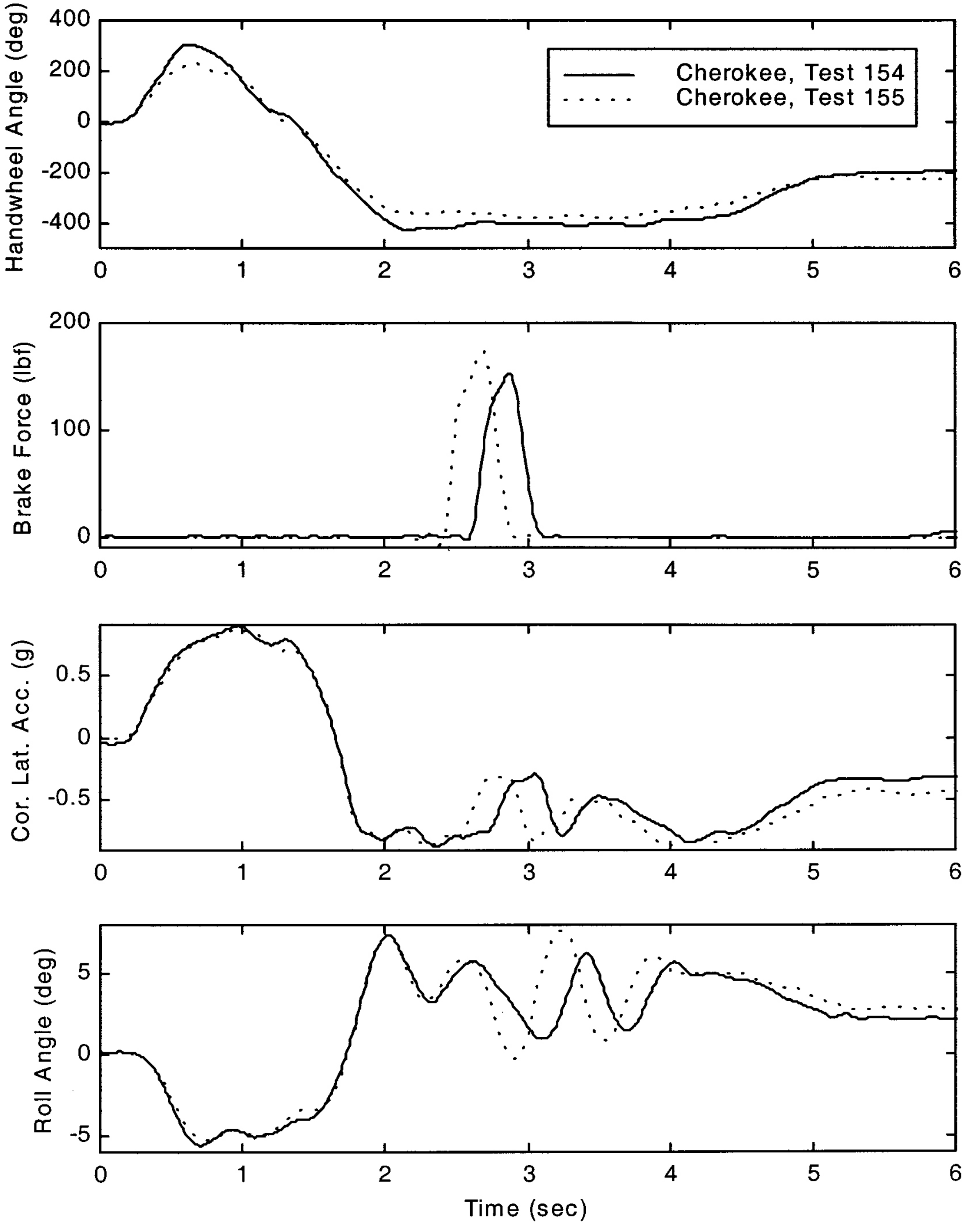

Figure 14.8 -- Cherokee Toyota Fishhook with Pulse Brake Comparison for Tests 154 and 155

Even though the Ford Bronco II had two-wheel lift during Toyota Fishhook (without pulse braking) testing, that two-wheel lift appeared to be related to tire wear. Therefore, Toyota Fishhook with Pulse Braking tests were conducted with this vehicle. Two-wheel lift was readily achieved for the Bronco II when pulse braking was added to the Toyota Fishhook. This is not surprising given that pulse braking also caused two-wheel lift for this vehicle when it was added to the J-Turn maneuver.

During Toyota Fishhook with Pulse Braking testing, the Jeep Cherokee had two-wheel lift prior to the start of pulse braking during the steering reversal. In these cases the brake pulse occurred during the two-wheel lift. The pulse resulted in bringing the two wheels back down. The Cherokee did not lift two wheels later in the maneuver.

The Toyota Fishhook with Pulse Braking does **not** appear to give any more information about a vehicle's rollover propensity than the combination of the Toyota Fishhook (without pulse braking) and the J-Turn with Pulse Braking maneuvers. One minor exception to this is that the Ford Bronco II did have a major two-wheel lift (as well as multiple moderate two-wheel lifts) for the Toyota Fishhook with Pulse Braking maneuver while it only had multiple moderate two-wheel lifts for the J-Turn with Pulse Braking maneuver. This difference may be due to the limited number of tests that were performed or due to how the outrigger heights were set (maybe too low for some conditions).

The Toyota Fishhook with Pulse Braking has more primary input variables than either the J-Turn with Pulse Brake or the Toyota Fishhook (without pulse braking) maneuvers. Having all of these inputs creates a more difficult maneuver for the driver to perform and decreases maneuver repeatability. All of the factors that created the variability seen in the J-Turn with Pulse Braking and the Toyota Fishhook (without pulse braking) maneuvers are also present with this maneuver.

Despite the statements in the preceding paragraph, the repeatability of the Toyota Fishhook with Pulse Braking was about the same as that of the J-Turn with Pulse Braking. Pre-pulse repeatability was about the same as that of the Toyota Fishhook (without pulse braking) maneuver. The repeatability of the post-pulse metrics was worse than that attained for the pre-pulse metrics, but no worse than then repeatability that was attained for the post-pulse J-Turn with Pulse Braking metrics. The two Ford Bronco II test series produced fairly similar Lateral Acceleration for Rollover values: 0.84 and 0.88 g.

Based on the preceding analyses, if the magnitude and timing of the brake pulse inputs can be better controlled, then the Toyota Fishhook with Pulse Braking maneuver is expected to produce repeatable results. In particular, the resulting corrected lateral accelerations and roll angles should be fairly repeatable. Further study would be required to verify this expectation.

Although there are many complexities to the Toyota Fishhook with Pulse Braking maneuver, it also has many advantages. The maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. The repeatability of the maneuver appears to be reasonable. Therefore, the authors recommended that this maneuver be further evaluated during Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. A focus of the Phase I-B research for this maneuver should be to see if the Toyota Fishhook with Pulse Braking maneuver provides any more information than is obtainable from the simpler Toyota Fishhook (without Pulse Braking) and J-Turn with Pulse Braking maneuvers. If not, the Toyota Fishhook with Pulse Braking maneuver should be dropped from this research program.

15.0 CONCLUSIONS AND RECOMMENDATIONS

15.1 J-Turn Maneuver Conclusions and Recommendations

The J-Turn (without pulse braking) maneuver consists of a single steering input. For this research, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the J-Turn tests. These large steering angles were chosen to saturate the tires of all of the test vehicles. J-Turns maneuvers were performed with turns to both the left and to the right. The inputs for this test maneuver are very repeatable due to the simple, single steering motion, the mechanical steering stop that was used, and the minimal requirements that this maneuver imposes on the driver.

This research found that the magnitude of the J-Turn steering input should exceed 250 degrees. No reduction in Maximum Corrected Lateral Acceleration or Maximum Roll Angle was seen due to increasing the Steering Input. Therefore, the largest steering input that can easily be generated with a steering stop, ±330 degrees, is recommended for future testing.

For two of the vehicles tested, the Ford Bronco II and the Jeep Cherokee, no two-wheel lifts were observed during the J-Turn tests. For the Toyota 4Runner, minor and moderate two-wheel lifts were observed. In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, results in increasing lateral acceleration and roll angle up to the point of limit response. For the Bronco II and Cherokee the limit responses observed were plow outs, while the 4Runner had two-wheel lift.

The J-Turn tests conducted were found to be very repeatable. For any given vehicle, all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum lateral accelerations varied by, at most, 0.04 g. and the maximum roll angles varied by, at most, 0.5 degrees.

The J-Turn maneuver is a simple test to conduct relative to other vehicle rollover propensity tests. It appears to induce two-wheel lift for some vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. For the above reasons, the J-Turn maneuver is a good candidate for use in a potential dynamic rollover propensity test procedure. As such, further consideration of this maneuver during later phases of NHTSA's Light Vehicle Dynamic Rollover Research program is recommended.

15.2 J-Turn with Pulse Braking Maneuver Conclusions and Recommendations

The J-Turn With Pulse Braking maneuver adds pulse braking to the J-Turn (without pulse braking). J-Turn With Pulse Braking uses the same steering input as a function of time as does the J-Turn. The test procedure differs from the test procedure for the J-Turn in that after the driver has turned the steering handwheel through the specified steering movement, a short duration, hard pulse force was applied to the brake pedal. As was the case with the J-Turn (without pulse braking) maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used. J-Turn With Pulse Braking maneuvers were performed with turns to both the left and to the right.

The braking pulse momentarily decreases the lateral force capabilities of the tires, thereby decreasing the vehicle's lateral acceleration. When the braking pulse ends, the lateral force capabilities of the tires increase very rapidly. This sometimes produces vehicle lateral acceleration levels and/or roll angles which surpass those achieved prior to the onset of braking. These larger lateral accelerations and/or roll angles can result in two-wheel lift for some vehicles that do not have two-wheel lift for the J-Turn (without pulse braking) maneuver.

The Toyota 4Runner had two-wheel lift in the J-Turn (without Pulse Braking) maneuver and therefore was not tested using the J-Turn with Pulse Braking maneuver. Both the Ford Bronco II and the Jeep Cherokee had minor to moderate lift during the course of J-Turn with Pulse Braking testing. Major lift for the Bronco II may have been prevented by the rear outriggers being set too low.

The effects of different brake pulse magnitudes and durations on vehicle responses were determined. Two measures of vehicle response due to the brake pulse were focused on. One of these was Delta Ay which is defined as the largest (in absolute value) post-pulse corrected lateral acceleration minus the largest (in absolute value) pre-pulse corrected lateral acceleration. The other was Delta Roll Angle which is defined as the largest (in absolute value) post-pulse roll angle minus the largest (in absolute value) pre-pulse roll angle. This research found that both Delta Ay and Delta Roll Angle increase with increasing values of Maximum Pedal Force during the pulse. Further research on this issue was conducted in Phase I-B, but based on this research it appears that a 200 pound value for Maximum Pedal Force would be appropriate.

This research found that Delta Ay was essentially independent of Brake Pulse Width. The effect of Brake Pulse Width on Delta Roll Angle varied between the two vehicles. However, the average Brake Pulse Width achieved naturally by the test driver (approximately 0.50 seconds) appeared to be a good value for the Brake Pulse Width to cause substantial roll angle effects for both vehicles. Therefore, having a test driver manually generate the brake pulse appeared to be adequate for future light vehicle dynamic rollover testing.

The above analyses (using less sophisticated post-test processing to calculate roll angles than was subsequently developed) were originally performed while the Phase I-B testing was being performed. Based on these analyses, a decision was made to have the test driver manually pulse the brakes during the Phase II light vehicle dynamic rollover testing. The only actions that were taken to improve brake pulse repeatability were that the test driver practiced attaining a Maximum Pedal Force of 200 pounds and a timer/buzzer was installed in each test vehicle to make the time to the start of the brake pulse more constant.

No attempt was made to use the Phase I-A data to study the effects on vehicle rollover propensity of varying the timing of the brake pedal application relative to the initial steering input. This report is actually being written after the Phase II testing has been completed and all of the Phase II test data analyzed. Based on the Phase II data, the authors believe that a vehicle's behavior during the J-Turn With Pulse Braking maneuver is quite sensitive to the timing of the brake pedal application relative to the initial steering input. Therefore, the authors now recommend that any pulse braking performed during future light vehicle dynamic rollover testing be performed using a brake machine that can precisely time both the start of the pulse relative to the initiation of steering input and the Brake Pulse Width.

The J-Turn With Pulse Braking tests were less repeatable than were the J-Turn (without pulse braking) tests. The J-Turn With Pulse Braking maneuver has five primary input variables: Initial Speed, Steering Input, Maximum Pedal Force, Brake Pulse Width, and Time of Pulse Start as compared to two for J-Turn (without Pulse Braking) maneuver: Initial Speed and Steering Input. The Maximum Pedal Force, Brake Pulse Width, and Time of Pulse were difficult for the driver to control in a precise and repeatable fashion. However, maneuver repeatability is still felt to have been acceptable. For any given vehicle, all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum lateral accelerations varied by, at most, 0.07 g. and the maximum roll angles varied by, at most, 0.9 degrees.

Further testing is required to better define and understand the J-Turn With Pulse Braking test. In particular, testing with more consistent brake pulse magnitudes and durations is needed to more carefully determine the effects of the severity of the brake pulse on vehicle responses.

The J-Turn With Pulse Braking maneuver is expected to induce two-wheel lift for many vehicles. The repeatability of the maneuver appears to be acceptable. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. For these reasons, the J-Turn With Pulse Braking maneuver should be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

15.3 Brake and Steer Maneuver Conclusions and Recommendations

The Brake and Steer maneuver increases maneuver complexity by adding sustained braking to the J-Turn (without pulse braking). Brake and Steer uses the same steering input as a function of time as does the J-Turn. For all but two of these tests, the brakes were applied at the same time as the steering input. For the other two tests, the brakes were applied well after the steering handwheel had reached the steering stop. As was the case with the J-Turn maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the Brake and Steer tests. No electronic or mechanical assistance was given to help the driver make the brake application repeatable.

During analysis of the first vehicle's Brake and Steer testing, it became apparent that, since applying and maintaining hard braking during steering decreases the lateral force capabilities of the tires, the lateral acceleration of the vehicle and the potential for two-wheel lift are reduced by the sustained braking. Therefore, only the Toyota 4Runner was tested using this maneuver.

Under hard braking the roll angle, yaw rate, and lateral acceleration decrease rapidly. These responses first overshoot the zero value and then return to zero as the vehicle plows to a stop. Delayed braking allows the roll angle and lateral acceleration to build up to greater levels than the simultaneous steering and braking cases, to the point where two-wheel lift can occur. However, upon the initiation of heavy braking the roll angle, yaw rate, and lateral acceleration reduce to zero as the vehicle plows to a stop.

The Brake and Steer maneuver did not result in two-wheel lift when the brakes were applied simultaneously with the start of steering even though the vehicle tested had two-wheel lift for the J-Turn maneuver. Since this maneuver reduces the chances of two-wheel lift occurring relative to the J-Turn, it is not expected to discriminate between vehicles with different rollover propensities (i.e., hardly any vehicles will experience two-wheel lift due to this maneuver). This being the case, further consideration of this maneuver during the dynamic rollover research program is not recommended.

15.4 Steering Reversal Maneuver Conclusions and Recommendations

The Steering Reversal maneuver consists of two steering inputs; the steering handwheel is first turned in one direction and then is rapidly reversed resulting in a turn in the opposite direction. The initial steering movement can be either to the left or to the right. There are an infinite number of combinations of initial and second steering magnitudes that can be used with this test procedure. Test severity can be increased by increasing the magnitudes of the steering inputs, raising the initial vehicle speed, or both. Initial testing for this maneuver was performed using the mechanical steering stop. Unfortunately, the mechanical steering stop was found to hinder the driver's ability to perform the maneuver. No electronic or mechanical assistance was given to help the driver make the steering inputs repeatable. As a result the steering movements were not as repeatable as the steering inputs for the J-Turn.

This testing found that for some, but not all, sets of input parameters the Steering Reversal maneuver resulted in two-wheel lift for the Toyota 4Runner. The difference between non-two-wheel lift and two-wheel lift input parameters were faster Initial Speeds and larger First and Second Steering Inputs.

This testing found good repeatability for the Steering Reversal maneuver. Data changed from run-to-run as expected based upon changes in the input parameters. The largest, unanticipated, differences that were found by looking at three pairs of matched runs were 0.02 g for maximum corrected lateral acceleration and 0.4 degrees for maximum roll angle. There were no unanticipated differences in the amount of two-wheel lift that was seen

This testing used only a small sampling of the large number of First and Second Steering Input magnitudes that could have been performed with the Steering Reversal maneuver. A thorough examination of a significant number of these possibilities would require more resources than were available to perform this research. While contemplating how best to perform the Steering Reversal maneuver, the authors were fortunately made aware of the Toyota Fishhook maneuver. The Toyota Fishhook (without pulse braking) is a form of the Steering Reversal maneuver with selected values for the First and Second Steering Input magnitudes. Toyota Motor Corporation has performed a substantial amount of work to determine good values for the Fishhook's steering input magnitudes. We did not wish to repeat this work. Furthermore, the Toyota Fishhook maneuver uses large steering magnitudes for both the initial and second steering movements. The large steering input magnitudes of the Fishhook result in the vehicle's tires being saturated for most of the maneuver. This is expected to improve maneuver repeatability. Therefore a decision was made to try running the Toyota Fishhook maneuver for the Toyota 4Runner. Once the Fishhook maneuver had been run successfully for this vehicle, a decision was made to use the Toyota Fishhook as the only form of Steering Reversal performed for the other two test vehicles.

While the Steering Reversal maneuver is a more complex test to perform than the J-Turn maneuver, it is still a good candidate for use in a potential dynamic rollover propensity test procedure. It appears to induce two-wheel lift for some vehicles. The initial test speed and the magnitudes of the steering inputs appear to be measures that can be used to quantify a vehicle's rollover propensity. The maneuver seems to be quite repeatable.

The authors decided to focus on one particular set of First and Second Steering Input magnitudes for the Steering Reversal maneuver, the ones developed by Toyota for the Fishhook, for the remainder of this research.

15.5 Toyota Fishhook Maneuver Conclusions and Recommendations

The Toyota Fishhook maneuver is detailed in Toyota Engineering Standard TS-A1544. This test procedure is designed to produce two-wheel lift by imparting to the vehicle a rapid steering reversal that causes the vehicle to be at or near maximum lateral acceleration in one direction due to the initial steer and then rapidly taken to maximum or near maximum lateral acceleration in the other direction. This rapid change in lateral acceleration direction also imparts a large angular momentum change to the chassis due to the vehicle leaning at a relatively large angle to one side and then being forced to lean in the opposite direction. The combination of the change in direction for lateral acceleration and the large roll angular momentum can produce two-wheel lift. The initial handwheel steering input used for this research was approximately 270 degrees. The second steer is to (or close to) the steering lock in the opposite direction from the initial steer. The Toyota Fishhook is run starting with relatively low course entry speeds. The course entry speed is then gradually increased for each successive run until several runs with two-wheel lift are produced. If two-wheel lift cannot be produced at any speed with just steering input, then pulse braking can be added. The addition of pulse braking is discussed in the Section 15.8.

This testing found that for some, but not all, sets of input parameters all three Phase I-A test vehicles had two-wheel lift for the Toyota Fishhook maneuver. The difference between non-two-wheel lift and two-wheel lift input parameters was primarily faster Initial Speeds.

The Ford Bronco II’s rollover propensity seemed to be highly related to tire wear (particularly shoulder wear) effects. This vehicle would only produce two-wheel lift after significant tire wear was observed. Testing with new tires at speeds higher than those that produced two-wheel lift with worn tires, did not result in two-wheel lift, although large front wheel lift was noted.

The Jeep Cherokee’s rollover propensity seemed to be an asymmetrical phenomenon, depending on the direction of steering input (this vehicle only had two-wheel lift with initial left then right steering inputs). Differences in the steering rates that were achieved for the two directions of steering could be a possible explanation. Further and more refined testing would be required to conclusively determine the reasons for the differences between initial left then right versus initial right then left steering inputs for the Cherokee.

The amount of two-wheel lift generally increased with Initial Speed. However, there were exceptions. In particular, for the Ford Bronco II, "Major" two-wheel lift occurred for runs with very similar Initial Speeds to runs for which no two-wheel lift occurred. The authors believe this to be due to tire wear. Less obvious non-repeatabilities also occurred for both the Jeep Cherokee and the Toyota 4Runner. The authors do not have a full explanation as to why these non-repeatabilities occurred. Several possibilities include timing of handwheel inputs, speed differences, and longitudinal acceleration differences.

Looking at three pairs of matched runs, one for each test vehicle, some unexpected run-to-run changes were seen. The largest, unanticipated, differences were found for the Ford Bronco II and are thought to be due to tire wear. For the Jeep Cherokee and Toyota 4Runner, unexpected differences between the pairs of matched runs in Maximum Corrected Lateral Acceleration were quite small. The largest unexpected run-to-run change in Maximum Corrected Lateral Acceleration was 2.9 percent (0.02 g) for the Toyota 4Runner and 3.2 percent (0.03 g) for the Jeep Cherokee. Larger unexpected differences between the pairs of matched runs in Maximum Roll Angle were seen for these two vehicles. The largest unexpected run-to-run change in Maximum Roll Angle was 25.9 percent (3.0 degrees) for the Toyota 4Runner and 11.6 percent (1.0 degree) for the Jeep Cherokee. The authors think that these larger roll angle differences occurred because vehicles become unstable in roll near their rollover threshold. Such instability would magnify observed experimental differences.

Overall, the repeatability of the Toyota Fishhook maneuver is thought to be acceptable. More repeatable control of the handwheel steering inputs should improve maneuver repeatability. However, because vehicles become unstable in roll very near their rollover thresholds, large run-to-run roll angle differences are inevitable if tests are performed right at the rollover threshold. (This is also the case for all of the other maneuvers studied; the issue is raised here because it was most noticeable during Toyota Fishhook testing.)

Although not as simple to conduct as the J-Turn maneuver, the Toyota Fishhook is a relatively easy test to conduct. It was able to induce two-wheel lift for all three vehicles tested. The results for certain vehicles appear to be affected by tire wear. This maneuver appears to have good potential for evaluating the on-road, untripped rollover propensity of vehicles and should be further studied and developed. Therefore, further consideration of this maneuver during later phases of NHTSA's Light Vehicle Dynamic Rollover Research program is recommended.

Future Toyota Fishhook research needs to focus on driver effects, tire wear issues, and the timing of the steering reversal. The authors believe that a steering controller will be necessary to achieve a consistent steering profile that can be used to evaluate a wide range of vehicles.

15.6 Double Lane Change Maneuver Conclusions and Recommendations

For the Double Lane Change maneuver, the test driver steers the vehicle through an entrance lane, turns left to avoid the single cone in the second lane, turns right to return to the original lane, and then straightens the vehicle to leave the course via an exit lane. An infinite number of cone placements are possible for a Double Lane Change maneuver. Note that picking a single Double Lane Change course for all vehicles may not be advisable since any given course geometry may excite the natural frequency of some, but not all, vehicles. This type of test can produce dramatically different results depending on the test driver's "steering style" for negotiating the course.

The principal testing problem with the Double Lane Change maneuver is in making “clean” runs (i.e., avoided) at limit or near limit conditions. When the Initial Speed is so high that the test driver can no longer drive a "clean" run, the driver is no longer following the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

For all three vehicles, 21 "clean" runs were made out of 122 Double Lane Change tests with valid data. A higher percentage of "clean" runs could have been achieved by reducing the Initial Speed of runs. However, our primary interest is vehicle behavior at the highest attainable lateral accelerations and roll angles. Performing this limit/near limit testing requires that Initial Speeds be pushed up to the point where "clean" runs are extremely difficult for drivers to perform.

Two of the three vehicles, the Ford Bronco II and the Toyota 4Runner, experienced two-wheel lift while performing the Double Lane Change maneuver. The Jeep Cherokee did not exhibit two-wheel lift in any course layout, even at very high lateral accelerations and with steering inputs nearly identical to those used for the other vehicles.

Tire shoulder wear appears to have been the cause of the two-wheel lift for the Ford Bronco II. Two-wheel lift was observed only once for this vehicle, and was achieved on a tire set that had been used to complete numerous runs. After four new tires were installed (equivalent to those which they replaced in dimension and manufacturer), two-wheel lift could not be achieved even with identical vehicle speeds and nearly equivalent handwheel inputs.

All three courses utilized for Toyota 4Runner testing produced two-wheel lift, although it was usually minor. One 70/70/14 test, however, did produce major two-wheel lift with the 4Runner.

For both vehicles for which two-wheel lift occurred, the two-wheel lifts occurred at Initial Speeds that were well above the maximum "clean" run Initial Speeds which were achieved for a given course. At these speeds, the driver really has no opportunity to follow the prescribed course and is really just providing two relatively rapid steering reversals to the vehicle.

When the driver is no longer following the course, the first and second steering inputs are very similar to those of a Toyota Fishhook test. This makes the Double Lane Change a "muted" Fishhook test: muted in that the second steer is not held, but instead followed by a third steering reversal. (For the testing performed during this program, sufficient speed scrubbed off prior to the third steering reversal so that the third steering reversal did not cause two-wheel lift to occur. For testing using higher Initial Speeds, and having the proper severity and timing for the third steering reversal, the Double Lane Change maneuver may be of comparable severity to the Toyota Fishhook. An example of this situation is given in [10].) The Toyota Fishhook generated two-wheel lift for all three Phase I-A test vehicles compared to only two for the Double Lane Change maneuver.

Due to the path-following nature of the Double Lane Change maneuver, successfully completing a given course can be very driver-dependent, as there are infinite combinations of steering inputs that could be utilized. The "technique" one driver chooses to employ may be very different than another driver, yet they both may complete the maneuver successfully. Previous NHTSA research has investigated the relationship between test driver and two-wheel lift propensity, and confirms the occurrence of this phenomenon [6]. Steering inputs found to induce two-wheel lift in one vehicle, may not induce the same response from another vehicle.

The path-following nature of the Double Lane Change maneuver results in handwheel steering inputs that become less-and-less repeatable during the course of a maneuver. As was shown, the first two steering reversals are typically reasonably repeatable (with a run-to-run variability of less than 30 degrees) while the third reversal may have run-to-run differences that exceed 100 degrees.

This growing non-repeatability in handwheel steering inputs results in growing non-repeatability in output measures such as Third Peak Corrected Lateral Acceleration and Third Peak Roll Angle. There is far more variability in the Corrected Lateral Acceleration and the Roll Angle for the Double Lane Change maneuver than there is for the J-Turn, J-Turn with Pulse Braking, and Toyota Fishhook maneuvers.

Unlike the Toyota Fishhook, the variability in Double Lane Change steering inputs is very difficult to minimize using a steering controller. Programming the controller to follow a prescribed course is much more difficult to implement than simply providing a particular steering profile as is the case for a Fishhook maneuver. Following a set course would require path control feedback which would be costly and difficult to implement.

There are an infinite number of possible Double Lane Change courses. One course geometry may excite undesirable frequency dependent responses for one particular vehicle, but not for others. Another course may be at the frequency needed to excite undesirable frequency dependent responses for another vehicle, but not for the vehicle that had poor performance on the first course. Therefore, there is no one "best Double Lane Change" course geometry. Instead, vehicles need to be tested using a broad range of Double Lane Change course geometries.

Due to the repeatability problems associated with the Double Lane Change maneuver, and the need to perform Double Lane Change maneuvers over a range of courses, the authors recommend that the Double Lane Change Maneuver not be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

15.7 Split-Mu Off-Road Recovery Simulation Maneuver Conclusions and Recommendations

The Split-Mu Off-Road Recovery Simulation was developed to try and simulate a scenario that has been documented in the rollover crash data collected by NHTSA. This maneuver simulates the return of a vehicle that has two wheels off the road to having all four wheels on the road surface. A more realistic simulation would require the two wheels off the road surface to climb a lip as they re-entered the road surface. This lip was not simulated to reduce test complexity and variability. For this maneuver, the vehicle is driven onto a split-coefficient-of-friction (split-mu) surface, i.e., the tires on the right side of the vehicle are on the low coefficient-of-friction, wet-epoxy surface and the tires on the left side are on the higher coefficient-of-friction dry-asphalt surface. The driver then turns the vehicle to the left to bring all four tires on to the dry-asphalt surface. This is followed by a turn to the right to try and keep the vehicle within a two lane width boundary (24 feet).

Two of the three vehicles, the Toyota 4Runner and the Ford Bronco II, experienced two-wheel lift while performing the Split-Mu maneuver. Each vehicle had only one test run that resulted in two-wheel lift. The Toyota 4Runner had a Minor two-wheel lift and the Ford Bronco II had a Major two-wheel lift. Tire wear may well have been the cause of the two-wheel lift for the Ford Bronco II. The single two-wheel lift that occurred for this vehicle happened using a tire set that had been used to complete numerous other runs.

During processing, the data collected during Split-Mu testing seemed very similar to that collected during Steering Reversal testing. The Split-Mu maneuver appears to be a “muted” Steering Reversal (or Toyota Fishhook) test: muted in that the second steer is not held, but instead followed by a third steering reversal. A comparison of similar tests from these two maneuver types suggests that the Steering Reversal maneuver (and hence the Toyota Fishhook) is at least as severe, if not more so, than the Split-Mu maneuver. Vehicle yaw effects on a split-mu surface may potentially increase rollover propensity, but this was not observed in this study.

During the Split-Mu maneuver, driver steering subsequent to the First Steering Movement is a reaction to the trajectory being followed by the vehicle. Due to the trajectory-following nature of this portion of the Split-Mu maneuver, handwheel steering inputs become less-and-less repeatable during the course of a maneuver. A better steering stop design could be used to better control the magnitude of the First Steering Movement, but even then the driver has a lot of freedom on how to perform the Second (and subsequent) Steering Movements because the vehicle path is not heavily constrained. Also, even when using a steering stop, the analyses have shown that there was still substantial variability in the timing of the First Steering Movement which significantly affected subsequent vehicle motions.

Unlike the Toyota Fishhook, the variability in Split-Mu steering inputs is very difficult to minimize using a steering controller. Programming the controller to recover from an initial, prescribed, severe disturbance is much more difficult to implement than simply providing a particular steering profile as is the case for a Fishhook maneuver.

As has been shown, there is far more variability in the Corrected Lateral Acceleration and the Roll Angle for the Split-Mu maneuver than there is for the J-Turn, J-Turn with Pulse Braking, and Toyota Fishhook maneuvers. This is in part because the driver inputs were not controlled enough to produce repeatable results. However, this test also requires two different test surfaces. Since test surface friction ratings can change with time, weather, amount of water applied to the low coefficient surface, etc., the variability in results from this test is expected to be higher than the variability of a test performed on a single road surface.

Due to the repeatability problems associated with the Split-Mu maneuver, that the split-mu surface properties did not appear to increase rollover propensity for the vehicles tested (as was initially thought might be the case), and that the Split-Mu maneuver seems to affect the vehicle like a "muted" Toyota Fishhook, the authors recommend that the Split-Mu Maneuver not be further developed in later phases of NHTSA's Light Vehicle Dynamic Rollover Research program.

15.8 Toyota Fishhook with Pulse Braking Maneuver Conclusions and Recommendations

The Toyota Fishhook With Pulse Braking uses the same course and steering input as a function of time as does the Toyota Fishhook Without Pulse Braking. The test procedure differs from the test procedure for the Toyota Fishhook Without Pulse Braking in that after the driver has completed the second steering movement, a short duration, hard pulse was applied to the brake pedal. The pulse braking causes a sharp decrease in the lateral acceleration capabilities of the tires as the brakes are applied and then a sharp increase as the brakes are released. This rapid increase in the lateral acceleration can produce lateral accelerations that are significantly higher than the lateral acceleration prior to the application of the brakes. Pulse braking can also produce large angular momentum changes because the chassis roll angle decreases as the brakes are applied and can rapidly increase as the brakes are released.

The Toyota 4Runner had two-wheel lift during Toyota Fishhook (without pulse braking) testing, therefore, Toyota Fishhook with Pulse Braking tests were **not** conducted with this vehicle.

Even though the Ford Bronco II had two-wheel lift during Toyota Fishhook (without pulse braking) testing, that two-wheel lift appeared to be related to tire wear. Therefore, Toyota Fishhook with Pulse Braking tests were conducted with this vehicle. Two-wheel lift was readily achieved for the Bronco II when pulse braking was added to the Toyota Fishhook. This is not surprising given that pulse braking also caused two-wheel lift for this vehicle when it was added to the J-Turn maneuver.

During Toyota Fishhook with Pulse Braking testing, the Jeep Cherokee had two-wheel lift prior to the start of pulse braking during the steering reversal. In these cases the brake pulse occurred during the two-wheel lift. The pulse resulted in bringing the two wheels back down. The Cherokee did not lift two wheels later in the maneuver.

The Toyota Fishhook with Pulse Braking does **not** appear to give any more information about a vehicle's rollover propensity than the combination of the Toyota Fishhook (without pulse braking) and the J-Turn with Pulse Braking maneuvers. One minor exception to this is that the Ford Bronco II did have a major two-wheel lift (as well as multiple moderate two-wheel lifts) for the Toyota Fishhook with Pulse Braking maneuver while it only had multiple moderate two-wheel lifts for the J-Turn with Pulse Braking maneuver. This difference may be due to the limited number of tests that were performed or due to how the outrigger heights were set (maybe too low for some conditions).

The Toyota Fishhook with Pulse Braking has more primary input variables than either the J-Turn with Pulse Brake or the Toyota Fishhook (without pulse braking) maneuvers. Having all of these inputs creates a more difficult maneuver for the driver to perform and decreases maneuver repeatability. All of the factors that created the variability seen in the J-Turn with Pulse Braking and the Toyota Fishhook (without pulse braking) maneuvers are also present with this maneuver.

Despite the statements in the preceding paragraph, the repeatability of the Toyota Fishhook with Pulse Braking was about the same as that of the J-Turn with Pulse Braking. Pre-pulse repeatability was about the same as that of the Toyota Fishhook (without pulse braking) maneuver. The repeatability of the post-pulse metrics was worse than that attained for the pre-pulse metrics, but no worse than then repeatability that was attained for the post-pulse J-Turn with Pulse Braking metrics. The two Ford Bronco II test series produced fairly similar Lateral Acceleration for Rollover values: 0.84 and 0.88 g.

Based on the preceding analyses, if the magnitude and timing of the brake pulse inputs can be better controlled, then the Toyota Fishhook with Pulse Braking maneuver is expected to produce repeatable results. In particular, the resulting corrected lateral accelerations and roll angles should be fairly repeatable. Further study would be required to verify this expectation.

Although there are many complexities to the Toyota Fishhook with Pulse Braking maneuver, it also has many advantages. The maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. The repeatability of the maneuver appears to be reasonable. Therefore, the authors recommended that this maneuver be further evaluated during Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. A focus of the Phase I-B research for this maneuver should be to see if the Toyota Fishhook with Pulse Braking maneuver provides any more information than is obtainable from the simpler Toyota Fishhook (without Pulse Braking) and J-Turn with Pulse Braking maneuvers. If not, the Toyota Fishhook with Pulse Braking maneuver should be dropped from this research program.

16.0 REFERENCES

1. Heitzman, E., Research News #4, Automotive Testing, Inc / Heitz Chassis Lab, December 1997.

2. Congressional Report: Rollover Prevention and Roof Crush, National Highway Traffic Safety Administration, Office of Vehicle Safety Standards, April 1992.

3. Technical Assessment Paper: Relationship Between Rollover and Vehicle Factors, National Highway Traffic Safety Administration, Office of Vehicle Safety Standards, July 1991, available from Docket 91-68-N01.

4. Potential Reductions in Fatalities and Injuries in Single Vehicle Rollover Crashes as a Result of a Minimum Rollover Stability Standard, National Highway Traffic Safety Administration, Office of Vehicle Safety Standards, December 1991, available from Docket 91-68-N03.

5. Petition Analysis DP96-011: Petition for Defects Investigation Concerning Rollover Propensity of MY 1995-96 Isuzu Trooper and 1996 Acura SLX Vehicles, National Highway Traffic Safety Administration, Office of Defects Investigation, June 1997.

6. Howe, J. G., Tests Concerning Rollover Propensity of 1995-96 Isuzu Trooper and 1996 Acura SLX, National Highway Traffic Safety Administration, Vehicle Research and Test Center, Report VRTC-76 0424, May 1997, available from Docket DP96-011.

7. Garrott, W. R., Rollover Research Activities at the Vehicle Research and Test Center – Frequency Response Testing, National Highway Traffic Safety Administration, Vehicle Research and Test Center, NHTSA Technical Report DOT HS 807 993, June 1992.

8. SAE J266 - Surface Vehicle Recommended Practice, “Steady State Directional Control Test Procedures for Passenger Cars and Light Trucks,” 1996.

9. Ervin, R. D., Grote, P., Fancer, P. S., MacAdam, C. C., Segal, L., “Vehicle Handling Performance Volumes 1 and 2 Research Study,” HSRI 27085 and 27086, November 1972.

10. Larsen, R. E., Smith, J. W., Werner, S. M., and Fowler, G. F., “Vehicle Rollover Testing Methodologies in Recreating Rollover Collisions,” SAE Paper 2000-01-1641, May 2000.

APPENDIX A

DOUBLE LANE CHANGE TEST RESULTS

Table A.1: Toyota 4 Runner Double Lane Change Data
L1 = 60 , L2 = 60, W = 12, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3
647	30.250	-269.348	286.002	-268.415	-835.492	1012.278	-1025.842	-0.717	0.806	-0.701	-0.620	0.679	-0.599
648	33.439	-324.758	341.138	-370.033	-921.045	1257.503	-1452.637	-0.770	0.873	-0.790	-0.658	0.751	-0.673
649	34.245	-332.032	319.691	-278.221	-889.251	1190.125	-1270.252	-0.775	0.865	-0.750	-0.663	0.738	-0.628
650	34.583	-316.888	316.741	-305.272	-914.454	1182.383	-1267.053	-0.767	0.864	-0.788	-0.662	0.742	-0.671
651	36.970	-333.142	327.016	-293.401	-873.228	1180.833	-1374.744	-0.783	0.937	-0.790	-0.677	0.785	-0.662
652	36.098	-337.106	324.674	-320.816	-946.970	1259.401	-1210.248	-0.792	0.917	-0.791	-0.691	0.767	-0.694
653	36.853	-335.072	367.293	-319.142	-974.535	1137.126	-1392.800	-0.790	0.946	-0.800	-0.675	0.792	-0.675
654	39.026	-304.991	311.790	-381.228	-874.817	1229.661	-1218.853	-0.786	0.986	-0.902	-0.667	0.843	-0.728
655	37.934	-345.432	268.610	-385.780	-914.239	1261.953	-1399.150	-0.793	0.952	-0.892	-0.688	0.804	-0.788
656	37.775	-343.618	341.676	-351.859	-933.634	1339.250	-1306.066	-0.796	1.024	-0.866	-0.669	0.837	-0.720
657	41.110	-345.583	310.835	-408.297	-877.379	1332.725	-1194.749	-0.814	1.044	-0.972	-0.706	0.882	-0.770
658	41.761	-330.963	318.578	-378.365	-832.350	1363.860	-1241.738	-0.809	1.024	-0.735	-0.667	0.857	-0.613
659	40.041	-292.911	266.216	-352.797	-893.854	1292.030	-1407.899	-0.764	1.016	-0.894	-0.645	0.840	-0.707
660													
661	39.544	-341.866	319.167	-417.318	-875.411	1340.823	-1226.398	-0.807	1.098	-0.758	-0.674	0.916	-0.715
662	40.395	-330.165	316.271	-363.943	-857.896	1244.368	-1169.607	-0.802	1.056	-0.783	-0.684	0.885	-0.649
663	39.993	-330.978	308.163	-428.548	-876.083	1478.138	-1223.485	-0.790	1.024	-0.767	-0.666	0.866	-0.635
664	37.692	-317.580	275.660	-236.838	-959.493	1322.810	-846.865	-0.778	0.910	-0.679	-0.664	0.772	-0.576
665	38.339	-330.218	244.729	-353.458	-953.959	1342.568	-861.553	-0.790	0.936	-0.883	-0.662	0.775	-0.713
666													
667	39.248	-345.852	292.736	-292.973	-912.658	1329.014	-1268.333	-0.812	1.016	-0.665	-0.681	0.850	-0.544

Table A.1: Toyota 4 Runner Double Lane Change Data
L1 = 60 , L2 = 60, W = 12, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
647*	19.473	-29.424	26.688	-27.605	32.952	-25.827	6.161	-7.628	6.520	0	0
648	21.644	-36.543	28.199	-29.978	32.703	-31.479	6.863	-8.414	7.526	0	XR1
649	21.936	-37.381	27.854	-30.754	31.305	-29.705	7.116	-8.190	7.071	0	XR1
650	21.893	-36.202	31.142	-30.152	31.811	-30.461	6.805	-8.444	6.849	0	0
651	22.605	-36.790	31.986	-30.637	31.555	-33.829	7.299	-8.523	7.637	0	0
652	22.961	-34.828	30.047	-30.533	32.515	-33.682	7.037	-8.579	8.135	0	0
653	22.885	-36.968	31.635	-30.909	33.493	-35.005	7.727	-8.811	7.807	0	0
654	24.132	-36.999	38.259	-29.351	36.473	-41.293	8.354	-9.296	9.616	0	XL1
655	22.568	-38.018	32.020	-30.811	34.053	-40.896	7.542	-9.094	8.573	0	XR2, 3, 4
656	23.587	-36.997	39.089	-30.795	35.721	-43.773	8.289	-10.356	9.086	1	NL5
657	22.331	-36.504	43.557	-29.921	38.720	-51.555	7.528	-10.204	11.315	2	NL5, XR3, 5, XL1, 2
658	23.270	-39.036	37.753	-29.745	38.379	-51.529	8.658	-10.825	8.205	2	LC, XL2, XR2
659	21.591	-41.918	41.717	-29.040	36.885	-51.282	7.576	-9.994	10.524	1	LC, XL1, 2, 3, 4
660										2	NL5, XR2, 5
661	20.938	-38.662	50.861	-30.950	39.256	-51.459	8.471	-10.115	8.424	1	LC, XL1
662	23.876	-37.866	35.174	-30.520	39.093	-51.291	8.177	-10.346	8.689	1	NL5, XR2, 4, XL1
663	21.823	-39.082	35.694	-30.974	39.450	-51.584	7.871	-9.682	9.176	1	NL5, LC
664	21.352	-41.209	28.571	-31.005	33.717	-33.985	7.509	-9.178	7.157	0	NL5
665	22.388	-38.252	36.546	-31.364	36.026	-40.066	8.151	-9.546	9.285	0	XR2
666										2	LC, XR2, 3, XL1--No Trigger
667	21.560	-37.560	42.368	-31.524	38.850	-43.760	8.429	-10.319	7.911	1	NL5, XL1, 2, 3

Table A.2: Toyota 4 Runner Double Lane Change Data
L1 = 70 , L2 = 70, W = 12, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
668	41.062	-291.599	243.897	-292.599	-897.996	1287.877	-1281.183	-0.763	0.948	-0.832	-0.624	0.813	-0.679
669	39.261	-341.276	249.870	-310.966	-1008.703	1255.209	-906.747	-0.795	0.995	-0.865	-0.679	0.835	-0.703
670	43.139	-318.135	215.259	-366.729	-821.277	1346.565	-1134.241	-0.790	0.986	-0.786	-0.665	0.835	-0.633
671	43.307	-322.763	230.506	-372.226	-829.091	1322.414	-961.901	-0.788	1.032	-0.842	-0.658	0.873	-0.681
672	42.586	-324.187	237.059	-334.151	-817.051	1312.237	-1174.545	-0.793	1.001	-0.716	-0.660	0.855	-0.573
673	42.621	-314.256	263.056	-372.831	-873.361	1309.899	-1183.616	-0.797	1.049	-0.808	-0.670	0.895	-0.626
674	46.058	-336.712	235.807	-327.929	-832.688	1319.422	-902.850	-0.818	0.990	-0.660	-0.699	0.844	-0.559
675	44.911	-330.923	282.919	-438.437	-865.681	1321.755	-1316.425	-0.808	0.975	-0.760	-0.682	0.836	-0.622
676													
677	43.565	-322.714	258.192	-375.997	-901.091	1278.045	-1115.806	-0.788	1.073	-0.724	-0.670	0.906	-0.582
678	43.732	-301.794	237.174	-337.348	-832.583	1248.809	-1007.915	-0.766	0.990	-0.760	-0.637	0.828	-0.603
679	44.910	-321.335	212.710	-310.916	-841.687	1212.415	-886.184	-0.802	0.954	-0.687	-0.677	0.808	-0.629
680	42.990	-326.884	264.109	-394.736	-879.627	1060.722	-1163.387	-0.802	1.037	-1.042	-0.668	0.857	-0.876
681	41.906	-316.668	249.004	-328.502	-872.605	1226.871	-1032.274	-0.780	0.997	-0.841	-0.657	0.846	-0.663
682	45.488	-296.525	174.207	-307.794	-832.903	1217.509	-1174.088	-0.801	0.614	-0.762	-0.676	0.511	-0.620
683	46.059	-287.147	224.333	-304.935	-792.331	1415.007	-1253.325	-0.776	0.987	-0.669	-0.659	0.823	-0.541
684	46.627	-278.804	234.446	-307.853	-771.910	1249.653	-1000.690	-0.771	1.005	-0.893	-0.635	0.843	-0.706
685	47.380	-332.657	176.870	-110.849	-800.484	1258.812	-599.028	-0.840	0.866	-0.426	-0.731	0.732	-0.319

Table A.2: Toyota 4 Runner Double Lane Change Data
L1 = 70 , L2 = 70, W = 12, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
668**	23.017	-43.522	31.826	-29.521	36.613	-42.311	8.453	-8.934	8.555	0	LC, NR5
669	23.292	-38.464	35.461	-31.094	34.953	-33.175	8.085	-9.329	8.751	0	0
670	21.826	-34.817	43.817	-30.429	36.287	-51.459	8.034	-9.418	9.061	0	LC, XL1, 4, 5
671	22.631	-37.066	41.675	-30.030	38.451	-51.481	8.537	-9.473	8.590	1	XR1, 5
672	22.426	-41.888	33.081	-30.253	36.599	-51.282	8.263	-9.789	8.368	1	XR5
673	23.098	-41.000	48.047	-30.096	38.632	-51.464	8.603	-10.083	9.735	1	0
674	21.419	-38.035	26.990	-30.012	37.497	-51.216	7.954	-9.546	6.706	1	NL5, XR3, 4
675	22.036	-41.813	33.264	-30.427	42.574	-51.568	8.372	-10.439	8.225	1	XR2, 5
676										1	NL5, XR1--No Trigger--#1; XL1, XR3, 4, 5No Trigger--#2
677	22.028	-43.464	42.463	-30.257	38.463	-51.509	7.889	-10.079	8.964	1	XR2, 3, 4
678	22.401	-41.828	38.257	-29.629	36.255	-51.403	8.379	-10.757	8.892	1	LC, XR2, 3, 4
679	23.774	-42.407	28.067	-30.961	37.243	-48.780	7.874	-10.508	6.754	1	XR2, 3, 5
680	22.824	-41.055	46.601	-31.510	40.038	-51.518	8.633	-10.947	10.954	1	XL1, XR2, 5
681	20.633	-41.388	30.540	-30.087	36.208	-50.199	8.191	-9.607	9.189	1	XR1
682	20.812	-36.149	39.138	-29.854	34.973	-47.460	8.353	-8.409	8.189	0	OOPS
683	21.515	-44.818	41.566	-29.443	36.725	-46.831	7.467	-9.830	7.853	0	NL5, GATE
684	20.882	-45.150	42.984	-29.725	34.367	-48.137	7.958	-9.914	9.846	0	NL5, GATE, XR2, 3, 4
685	23.120	-40.106	28.058	-30.085	36.877	-17.668	8.230	-8.845	5.866	0	mssd whl exit lane

Table A.3: Toyota 4 Runner Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
686	35.346	-340.281	228.056	-210.363	-948.999	1065.575	-667.249	-0.802	0.863	-0.551	-0.671	0.728	-0.457
687	36.578	-316.560	220.451	-287.250	-897.721	1058.755	-1048.773	-0.788	0.899	-0.749	-0.652	0.753	-0.606
688	39.335	-264.449	245.182	-322.561	-815.667	1242.042	-666.044	-0.787	0.952	-0.841	-0.682	0.762	-0.666
689	39.218	-285.094	219.130	-296.604	-864.230	1213.742	-977.951	-0.779	0.946	-0.822	-0.654	0.769	-0.671
690	42.301	-260.799	274.336	-311.055	-736.058	1212.845	-719.080	-0.814	1.032	-0.959	-0.697	0.860	-0.812
691	42.953	-309.341	255.145	-297.271	-816.078	1093.397	-1105.544	-0.795	0.997	-0.689	-0.674	0.880	-0.557
692													
693	43.385	-317.274	267.955	-328.971	-803.371	1218.558	-1251.048	-0.800	1.028	-0.620	-0.672	0.890	-0.501
694	42.664	-324.658	251.828	-342.460	-944.943	1258.705	-955.001	-0.791	1.032	-0.848	-0.665	0.870	-0.668
695	44.439	-289.811	229.867	-267.710	-794.791	1028.143	-966.941	-0.767	1.027	-0.657	-0.638	0.880	-0.570
696	43.630	-291.993	254.161	-322.667	-805.176	1044.441	-1176.088	-0.774	1.065	-0.623	-0.640	0.905	-0.488
697	42.095	-326.894	199.710	-382.109	-925.681	1157.330	-871.172	-0.798	0.937	-0.899	-0.674	0.800	-0.690
698	45.542	-324.147	255.418	-311.488	-866.688	1202.278	-780.293	-0.814	1.047	-0.704	-0.690	0.881	-0.626
699	50.029	-317.941	227.711	-43.532	-917.013	1042.461	-614.011	-0.817	1.183	-0.136	-0.697	0.964	-0.127

Table A.3: Toyota 4 Runner Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
686	20.361	-31.717	16.579	-32.468	31.396	-24.220	8.221	-9.002	5.454	0	0
687	19.982	-36.324	30.448	-31.603	31.932	-35.171	8.445	-9.617	8.250	0	0
688	18.628	-37.477	40.904	-28.715	34.195	-40.283	6.975	-10.405	9.525	0	NL5,
689	21.656	-39.892	35.470	-29.528	33.489	-37.807	8.214	-9.736	9.044	0	LC
690	19.248	-37.442	47.379	-28.129	38.503	-49.461	7.688	-11.585	10.340	2	XR2
691	23.053	-40.277	28.767	-30.357	36.779	-46.399	8.809	-8.669	7.767	0	LC, XR2, 4; XL1
692										1	XL1
693	21.378	-38.016	33.116	-30.915	38.105	-44.710	8.566	-9.921	6.832	1	LC, XR1, 2
694	20.662	-39.619	31.883	-31.185	38.420	-51.330	8.221	-10.576	9.853	1	XR2, 4
695	21.948	-39.020	22.887	-30.100	36.419	-40.095	8.891	-9.519	7.369	1	LC, Drove thru Rt. side cones
696	20.810	-39.323	30.272	-30.096	36.517	-42.225	8.667	-9.994	7.184	1	XR2, 3
697	20.873	-34.773	41.440	-31.257	33.807	-41.718	8.121	-9.070	11.195	0	LC
698	21.874	-40.478	35.666	-30.114	39.292	-41.544	8.681	-10.567	6.934	2	NL5, XL1, 2
699	20.662	-39.614	48.804	-30.294	42.526	-5.008	8.590	-16.532	1.768	3	Full tip--Rt. side; Left side cones

Table A.4: Ford Bronco II Double Lane Change Data
L1 = 60 , L2 = 60, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
103	31.792	-257.092	246.847	-239.488	-801.757	969.537	-800.582	-0.692	0.746	-0.638	-0.618	0.668	-0.567
104	34.245	-230.750	263.003	-256.146	-928.886	827.336	-936.071	-0.676	0.796	-0.696	-0.605	0.712	-0.619
105	35.503	-248.280	266.699	-263.333	-853.704	1184.661	-890.183	-0.718	0.867	-0.675	-0.635	0.768	-0.596
106	37.692	-245.905	297.920	-250.580	-955.218	1103.637	-1233.764	-0.727	0.888	-0.732	-0.653	0.777	-0.661
107	38.281	-256.822	292.332	-265.179	-964.955	984.560	-1186.318	-0.735	0.904	-0.765	-0.660	0.798	-0.689
108	40.421	-242.811	277.203	-274.806	-900.004	1066.098	-907.114	-0.736	0.913	-0.680	-0.660	0.800	-0.613
109	39.283	-251.170	301.991	-308.516	-900.516	1341.163	-801.478	-0.760	0.920	-0.629	-0.678	0.797	-0.574

Table A.4: Ford Bronco II Double Lane Change Data
L1 = 60 , L2 = 60, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
103	12.373	-18.406	18.493	-34.607	33.364	-32.326	4.900	-4.965	5.058	0	0
104	14.728	-16.106	20.435	-32.336	31.429	-33.107	4.454	-5.144	5.150	0	XR 2, 4
105	14.995	-16.132	21.460	-32.480	40.491	-33.902	5.077	-5.724	4.988	0	0
106	15.830	-24.049	26.959	-32.635	43.389	-36.951	4.924	-6.500	4.708	0	XR 2, 3, 4
107	16.343	-19.352	24.330	-33.330	42.940	-41.297	4.925	-6.037	5.784	0	XL 1, XR 4
108	16.167	-19.597	31.604	-33.293	46.193	-54.165	4.902	-6.432	6.175	0	XL1, XR2, 3, 4
109	16.740	-17.029	28.576	-33.522	46.584	-54.866	5.095	-6.998	5.242	0	XR2

Table A.5: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
43	42.411	-235.638	276.032	-223.445	-915.160	852.371	-978.312	-0.681	0.907	-0.690	-0.624	0.818	-0.623
44	29.342	-178.694	148.465	-132.666	-491.163	637.267	-368.598	-0.554	0.623	-0.378	-0.501	0.568	-0.344
45	34.062	-173.036	208.822	-139.700	-648.339	648.933	-641.119	-0.574	0.747	-0.427	-0.522	0.682	-0.378
46	37.839	-164.345	164.234	-277.337	-446.080	649.578	-743.826	-0.629	0.743	-0.599	-0.574	0.674	--
47	36.722	-161.840	142.327	-135.395	-629.524	569.918	-488.111	-0.599	0.706	-0.498	--	--	--
48	39.056	-148.228	149.343	-201.693	-466.134	524.320	-605.546	-0.589	0.716	-0.650	-0.538	0.657	-0.592
49	43.146	-258.820	328.950	-368.423	-992.456	1180.338	-1054.211	-0.760	0.895	-0.662	--	--	--
50	41.134	-262.859	348.012	-355.349	-966.191	1061.134	-1164.651	-0.728	0.929	-0.750	--	--	--
51	44.276	-289.275	291.066	-337.644	-999.747	1186.126	-1099.963	-0.719	0.879	-0.618	-0.660	0.799	-0.552
52	39.306	-244.101	338.956	-345.673	-779.382	1081.633	-1042.610	-0.701	0.916	-0.766	-0.646	0.824	-0.679
53	42.057	-270.422	332.755	-369.300	-881.611	1216.679	-1215.974	-0.699	0.915	-0.744	--	--	--
54	41.272	-245.635	291.124	-271.197	-904.104	1180.419	-1052.195	-0.767	0.853	-0.507	--	--	--
55	48.063	-252.557	239.885	-408.417	-967.690	1229.582	-940.882	-0.686	0.898	-0.728	-0.627	0.812	-0.645

Table A.5: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
43	13.727	-28.161	19.330	-30.709	41.318	-38.333	4.222	-5.567	4.510	0	XR4, 5
44	7.891	-16.123	6.970	-23.888	25.985	-20.209	3.392	-3.137	2.043	0	0
45	9.577	-16.562	12.422	-25.504	32.655	-20.617	3.215	-3.869	2.962	0	XL1
46	8.094	-18.592	15.039	-24.726	29.768	-33.825	3.463	-3.924	--	0	XR2, 4
47	10.754	-14.935	14.151	-24.112	26.196	-22.129	--	--	--	0	0
48	8.878	-17.186	18.155	-23.445	26.917	-30.034	3.335	-3.668	3.902	0	0
49	16.222	-26.446	23.644	-29.890	48.166	-53.467	--	--	--	0	NL5--Drove Left of exit lane cones
50	15.051	-25.505	30.590	-31.252	48.192	-53.401	--	--	--	0	XL1, XR4, 5. Drove thru Rt. side cones
51	13.125	-27.260	28.924	-30.394	48.146	-50.114	4.357	-5.884	4.063	0	XL4, 5--Drove left of left exit cones
52	13.762	-23.285	27.467	-29.834	44.888	-51.248	4.017	-5.880	5.825	0	XR2, 3
53	13.328	-23.389	28.398	-30.701	47.378	-53.533	--	--	--	0	NL5, XR2, 3; XL3, 4, 5
54	12.926	-25.137	19.189	-30.501	46.788	-42.659	--	--	--	0	LC, Missed whole lane--went left
55	14.145	-27.106	24.236	-30.337	47.379	-53.533	4.232	-5.680	4.643	0	LC, SR3, 4 (?)

Table A.6: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
110	39.846	-236.719	252.052	-222.193	-964.464	776.527	-998.937	-0.702	0.890	-0.652	-0.633	0.785	-0.564
111	42.218	-242.650	264.082	-310.689	-922.361	1052.372	-963.150	-0.747	0.936	-0.673	-0.673	0.818	-0.586
112	42.282	-242.075	231.798	-312.017	-1029.591	1070.461	-1028.171	-0.721	0.905	-0.852	-0.647	0.794	-0.719
113	44.127	-215.481	275.869	-338.220	-826.323	1067.316	-950.784	-0.728	0.911	-0.779	-0.652	0.787	-0.705
114	43.688	-248.808	269.339	-443.028	-942.708	1143.036	-926.259	-0.764	0.887	-0.687	-0.677	0.762	-0.599
115	42.076	-214.190	221.776	-176.090	-767.487	823.914	-659.845	-0.711	0.890	-0.635	-0.638	0.784	-0.557
116	44.548	-219.023	225.340	-270.641	-784.113	846.527	-834.925	-0.734	0.858	-0.772	-0.659	0.738	-0.699
117	43.224	-217.242	211.185	-201.259	-859.487	977.458	-837.997	-0.736	0.889	-0.731	-0.656	0.783	-0.664
118	45.466	-233.484	224.723	-267.291	-928.582	1049.746	-730.284	-0.785	0.850	-0.716	-0.699	0.743	-0.635
119	47.651	-230.058	240.077	-214.325	-1011.290	1130.908	-625.172	-0.774	0.948	-0.190	-0.683	0.799	-0.186
120	47.607	-215.752	214.722	-319.397	-876.201	946.617	-720.490	-0.748	0.889	-0.836	-0.667	0.773	-0.731

Table A.6: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
110	16.527	-24.923	23.246	-32.158	40.477	-41.817	5.039	-6.245	5.404	**0**	0
111	15.585	-21.685	31.654	-31.496	46.560	-54.916	5.264	-6.633	5.624	**0**	XR1, 2
112	14.633	-21.259	33.059	-32.290	44.049	-55.032	5.095	-6.498	7.620	**0**	XR2, 4--5th whl
113	14.360	-27.864	34.960	-30.910	46.570	-55.151	5.259	-7.399	7.853	**0**	XR2, 3, 4
114	15.971	-19.318	32.286	-32.099	46.625	-54.604	5.389	-7.513	6.100	**0**	XR2, 4
115	12.763	-25.906	21.054	-30.587	40.057	-36.855	4.675	-6.044	4.830	**0**	0
116	13.934	-26.792	34.451	-30.425	41.817	-50.808	5.363	-7.268	6.401	**0**	XR2, 3, 4
117	15.409	-18.981	32.962	-30.580	43.426	-45.133	5.068	-6.021	6.304	**0**	XR2, 3
118	14.348	-21.130	30.681	-32.354	44.362	-54.769	5.284	-6.833	5.740	**0**	XL1, XR3
119	17.369	-20.922	18.273	-31.307	46.841	-20.151	5.448	-8.621	2.037	**0**	Drove thru
120	16.149	-23.650	38.704	-30.983	45.494	-55.092	5.390	-7.017	7.855	**0**	XR4

Table A.7: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 80, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
121	41.573	-224.581	282.672	-316.096	-792.364	838.157	-977.536	-0.745	0.905	-0.763	-0.668	0.775	-0.651
122	41.637	-219.772	227.705	-172.826	-918.602	846.975	-744.431	-0.720	0.910	-0.459	-0.641	0.798	-0.404
123	43.187	-204.668	248.465	-273.416	-755.615	948.891	-816.799	-0.755	0.881	-0.562	-0.681	0.747	-0.474
124	45.487	-235.772	232.221	-121.007	-924.709	1159.403	-809.593	-0.793	1.006	-0.580	-0.705	0.782	-0.474
125	41.317	-207.184	229.230	-362.453	-811.474	984.940	-811.413	-0.742	0.858	-0.695	-0.661	0.742	-0.611
126	42.710	-204.470	202.501	-287.653	-775.458	791.153	-678.696	-0.713	0.854	-0.758	-0.643	0.751	-0.684
127	45.269	-189.690	245.732	-315.232	-841.048	809.137	-755.320	-0.737	0.837	-0.773	-0.652	0.733	-0.649
128	45.069	-223.881	219.955	-281.532	-778.071	1140.451	-669.808	-0.754	0.836	-0.467	-0.683	0.733	-0.428
129	44.936	-218.446	238.568	-198.338	-774.588	995.783	-591.440	-0.752	0.884	0.458	-0.676	0.769	0.384
130	45.204	-214.436	242.804	-271.868	-867.508	972.679	-740.389	-0.744	0.834	-0.552	-0.667	0.718	-0.476
131	45.483	-201.199	253.903	-364.027	-760.671	1001.140	-743.697	-0.751	0.860	-0.840	-0.674	0.742	-0.743
132	45.479	-223.884	235.923	-302.945	-932.406	948.545	-787.718	-0.737	0.821	-0.418	-0.665	0.714	-0.375
133	45.101	-231.762	274.008	-237.556	-929.110	909.296	-798.651	-0.755	0.859	-0.694	-0.668	0.736	-0.624
134	43.516	-222.828	247.035	-217.103	-856.778	945.657	-724.852	-0.754	0.864	-0.745	-0.677	0.750	-0.666
135	44.976	-204.714	218.018	-355.439	-873.698	1034.126	-704.894	-0.762	0.864	-0.791	-0.680	0.751	-0.698
136	45.847	-217.785	250.549	-392.728	-867.401	1054.356	-915.733	-0.747	0.869	-0.923	-0.672	0.745	-0.821
137	45.532	-207.187	191.676	-210.772	-843.633	921.498	-610.685	-0.744	0.847	-0.749	-0.666	0.744	-0.667
138	44.709	-192.652	214.328	-272.402	-773.175	795.111	-706.799	-0.727	0.874	-0.803	-0.654	0.763	-0.714
139	45.853	-221.873	232.141	-323.561	-816.543	911.497	-687.977	-0.739	0.876	-0.654	-0.661	0.750	-0.573
140	46.987	-192.170	221.326	-238.758	-689.106	898.113	-603.141	-0.738	0.863	-0.854	-0.657	0.743	-0.750

Table A.7: Ford Bronco II Double Lane Change Data
L1 = 70 , L2 = 80, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
121	15.779	-27.784	34.361	-30.932	44.804	-54.951	5.280	-7.347	7.651	0	XR2, 3, 4
122	14.531	-24.545	16.554	-31.010	41.272	-33.994	4.981	-6.438	3.846	0	0
123	13.724	-21.731	26.638	-30.137	43.393	-44.856	5.006	-7.633	4.941	0	0
124	15.335	-19.161	58.589	-32.048	46.702	-1.085	5.460	-20.380	8.022	3	Full tip--lost focus
125	14.760	-22.045	29.661	-30.823	47.691	-53.709	5.300	-6.501	5.387	0	XR2
126	15.983	-23.743	34.830	-30.268	44.223	-53.835	4.711	-5.929	6.954	no data	XR1, 2, 3
127	16.695	-27.777	35.488	-29.521	47.729	-53.806	5.143	-6.490	6.774	no data	XR2, 3, 4
128	13.539	-21.317	24.431	-30.933	47.860	-41.084	5.314	-6.255	4.091	0	XR2, Drove thru Rt side cones
129	15.023	-21.137	7.996	-31.178	47.932	6.328	4.906	-7.305	-0.079	0	Steering Stop Prob
130	15.781	-23.513	22.140	-31.298	47.913	-29.802	5.045	-7.055	4.477	0	XR1, 2
131	13.922	-22.244	32.321	-29.740	47.975	-53.916	4.881	-6.806	7.464	no data	XR3, Missed lane
132	15.535	-22.304	20.361	-31.628	47.948	-32.598	5.096	-6.333	3.481	0	Missed lane
133	16.661	-25.170	27.260	-32.470	47.970	-46.873	5.310	-7.172	5.085	0	Drove thru Rt. side, Missed lane
134	15.386	-25.504	27.573	-30.484	47.718	-46.362	5.115	-6.652	5.951	0	XR3, 4, 5
135	16.182	-21.444	32.347	-30.476	47.677	-53.665	5.156	-8.238	6.275	0	Drove thru Rt. side cones
136	17.018	-24.609	34.882	-30.703	47.743	-53.972	5.554	-6.961	7.765	0	XR2, 3
137	14.916	-21.712	35.334	-29.734	45.301	-49.642	5.319	-6.124	6.528	0	XR3, 4, 5
138	14.778	-26.557	33.972	-29.945	45.339	-53.539	4.709	-6.435	6.587	0	XR2, 3, 4
139	15.922	-25.171	26.112	-30.562	47.682	-51.545	5.213	-7.115	5.048	0	XR1, 2--Drove thru Rt. side cones
140	13.200	-24.635	36.045	-28.345	47.461	-50.720	5.019	-7.001	6.837	0	Drove thru Rt. side cones

Table A.8: Jeep Cherokee Double Lane Change Data
L1 = 60 , L2 = 60, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
113	42.105	-226.933	237.318	-267.201	-813.948	1047.947	-863.906	-0.911	0.952	-0.461	-0.824	0.848	-0.443
114	38.599	-179.872	252.114	-235.501	-552.755	724.471	-950.225	-0.751	0.917	-0.850	-0.682	0.820	-0.772
115	40.642	-188.907	209.034	-218.169	-818.405	885.033	-786.392	-0.842	0.950	-0.779	-0.770	0.854	-0.715
116	43.312	-200.796	224.138	-259.663	-685.628	934.901	-996.432	-0.888	0.948	-0.489	-0.809	0.838	-0.443
117	43.393	-223.332	237.465	-335.593	-813.589	1146.696	-1164.983	-0.901	0.953	-0.854	-0.818	0.843	-0.767
118	44.913	-203.779	223.387	-333.335	-813.650	1175.070	-905.186	-0.906	0.962	-0.939	-0.829	0.857	-0.868

Table A.8: Jeep Cherokee Double Lane Change Data
L1 = 60 , L2 = 60, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
113	14.196	-26.994	29.286	-36.385	46.419	-40.647	5.097	-7.022	4.447	0	drove betw XR2 & 3
114	10.378	-13.375	28.702	-30.548	37.231	-41.841	4.167	-5.261	6.109	0	0
115	13.536	-25.233	23.893	-33.654	39.776	-45.417	4.381	-6.430	5.043	0	XR 2 & 3
116	14.643	-27.137	28.400	-34.927	45.413	-39.537	4.943	-6.924	4.422	0	XL1; drove betw XR1/2 & 2/3
117	15.993	-28.775	35.244	-36.651	46.348	-54.465	5.308	-6.911	6.728	0	XR3 & 4
118	15.898	-25.892	36.066	-35.494	47.072	-54.453	4.910	-7.053	7.177	0	XR2; drove betw XR1/2 & 2/3

Table A.9: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
119	45.037	-204.314	206.853	-297.322	-746.309	1047.780	-932.706	-0.881	0.932	-0.927	-0.795	0.854	-0.838
120	45.289	-166.917	178.384	-122.044	-533.537	746.607	-1008.913	-0.815	0.966	-0.596	-0.737	0.863	-0.556
121	47.363	-204.447	223.105	-301.837	-794.158	1013.855	-756.927	-0.918	0.955	-0.251	-0.835	0.890	-0.236
122	48.199	-154.082	202.496	-325.774	-509.732	783.097	-835.212	-0.850	0.955	-0.884	-0.776	0.857	-0.847
123	47.098	-179.396	211.056	-314.837	-656.604	834.824	-975.768	-0.859	0.959	-0.866	-0.785	0.876	-0.802
124	49.141	-189.740	201.732	-414.952	-801.022	834.561	-1015.783	-0.860	0.950	-0.931	-0.782	0.874	-0.885

Table A.9: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 70, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
119	15.341	-29.858	37.834	-35.237	44.426	-54.552	5.370	-6.216	7.920	0	LC, XR1 & XR3
120	12.251	-24.763	28.812	-30.781	38.554	-20.907	4.917	-6.169	4.796	0	0
121	16.234	-28.973	22.585	-35.251	47.401	46.849	5.299	-7.232	1.432	0	XL1, XR1 & 2
122	11.654	-27.273	34.584	-28.639	43.459	-54.566	4.401	-6.760	7.216	0	XR2 & 3
123	13.132	-28.168	30.983	-32.193	45.361	-54.409	4.532	-6.835	5.498	0	XR1
124	16.073	-30.347	35.479	-33.207	46.668	-54.493	5.043	-7.059	7.453	0	XL1; XR1 & 2

Table A.10: Jeep Cherokee Double Lane Change Data
L1 = 80 , L2 = 80, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
125	45.399	-171.853	191.744	-234.265	-594.095	779.532	-722.271	-0.833	0.946	-0.693	-0.758	0.853	-0.668
126	47.188	-169.519	172.937	-117.660	-599.691	730.955	-708.724	-0.768	0.937	-0.736	-0.696	0.847	-0.670
127	49.061	-175.188	211.055	-304.614	-574.475	804.271	-928.743	-0.858	0.959	-0.731	-0.782	0.894	-0.686
128	48.235	-170.666	195.398	-262.046	-643.745	767.612	-909.949	-0.854	0.951	-0.829	-0.772	0.873	-0.791
129	51.964	-186.140	239.805	-137.362	-817.430	995.081	-654.601	-0.913	0.990	-0.283	-0.824	0.874	-0.238
130	52.224	-157.379	197.235	-262.039	-581.604	688.397	-777.400	-0.823	0.953	-0.895	-0.744	0.891	-0.804
131	53.491	-176.877	194.281	-208.805	-650.836	846.187	-967.133	-0.888	0.949	-0.317	-0.804	0.876	-0.267
132	54.218	-174.133	201.063	-348.518	-613.875	778.673	-915.349	-0.848	0.965	-0.888	-0.772	0.900	-0.856

Table A.10: Jeep Cherokee Double Lane Change Data
L1 = 80 , L2 = 80, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
125	13.112	-27.452	28.102	-31.530	40.405	-53.251	4.607	-6.362	5.404	0	0
126	12.803	-30.196	23.538	-29.754	32.959	-28.237	4.788	-6.228	4.843	0	XR2
127	13.663	-31.899	30.930	-32.622	45.396	-54.539	5.057	-7.131	6.030	0	XR1
128	13.073	-26.307	37.632	-31.613	42.162	-54.455	5.179	-6.499	7.717	0	XR1
129	14.889	-31.214	30.417	-34.074	47.427	-16.405	5.262	-8.087	3.039	0	XR1 & 2
130	13.424	-29.424	36.282	-29.696	43.726	-52.844	5.326	-6.927	7.178	0	XR2, 3, 4
131	13.827	-26.992	29.578	-32.001	47.262	-15.725	5.204	-7.083	3.615	0	XL1, XR1 & 3
132	13.378	-30.085	38.121	-31.379	47.146	-54.481	4.918	-7.567	7.004	0	XL1; XR3 & 4

Table A.11: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 80, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
133	44.820	-168.063	193.476	-202.432	-533.691	770.596	-738.399	-0.840	0.984	-0.739	-0.770	0.880	-0.660
134	47.692	-170.393	172.660	-210.436	-633.794	737.436	-784.487	-0.835	0.973	-0.872	-0.758	0.891	-0.795
135	49.096	-163.384	195.590	-263.696	-569.809	751.534	-912.170	-0.841	0.973	-0.909	-0.763	0.905	-0.823
136	49.295	-178.514	184.623	-238.942	-526.404	819.649	-644.251	-0.854	0.968	-0.831	-0.774	0.892	-0.740
137	51.132	-172.278	219.766	-341.863	-577.829	821.907	-882.647	-0.871	0.986	-0.646	-0.791	0.920	-0.588

Table A.11: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 80, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
133	12.003	-26.053	28.737	-31.034	40.789	-44.049	4.467	-6.518	5.409	0	0
134	13.827	-26.781	32.956	-31.368	38.536	-50.314	4.971	-6.254	7.482	0	XR4-bmpd
135	12.688	-29.604	37.498	-31.371	43.710	-54.420	4.750	-7.128	6.949	0	XR2 & 5
136	13.480	-26.096	41.589	-32.285	43.865	-47.568	4.836	-6.560	7.300	0	XL1; XR 2 & 3
137	13.735	-32.075	28.111	-32.800	47.054	-54.541	4.966	-8.018	5.118	0	XR1

Table A.12: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 90, W = 14, Page 1 of 2

Run Number	RUN SPEED	Handwheel Angle 1	Handwheel Angle 2	Handwheel Angle 3	Handwheel Rate 1	Handwheel Rate 2	Handwheel Rate 3	Lateral Accel. 1	Lateral Accel. 2	Lateral Accel. 3	Corrected Lateral Accel. 1	Corrected Lateral Accel. 2	Corrected Lateral Accel. 3
138	49.055	-173.414	196.799	-231.204	-625.730	736.765	-767.377	-0.830	0.962	-0.757	-0.750	0.888	-0.673
139	51.728	-181.731	187.123	-322.249	-678.699	922.192	-843.159	-0.876	0.980	-0.837	-0.794	0.911	-0.757
140	51.869	-176.194	179.137	-280.906	-686.290	1050.497	-815.413	-0.887	0.980	-0.810	-0.801	0.917	-0.743

Table A.12: Jeep Cherokee Double Lane Change Data
L1 = 70 , L2 = 90, W = 14, Page 2 of 2

Run Number	Yaw Rate 1	Yaw Rate 2	Yaw Rate 3	Roll Rate 1	Roll Rate 2	Roll Rate 3	Roll Angle 1	Roll Angle 2	Roll Angle 3	TWL	Cones Hit
138	14.528	-29.114	36.342	-31.888	43.103	-48.186	4.875	-7.186	6.752	0	XR1 & 2
139	15.546	-26.496	34.336	-33.383	46.146	-54.442	5.252	-7.138	6.537	0	XR1, 2, 4, 5
140	16.621	-27.700	34.570	-33.754	46.078	-54.436	5.802	-7.126	6.436	0	All on Rt.