A STUDY OF VEHICLE RESPONSE ASYMMETRIES
DURING SEVERE DRIVING MANEUVERS

A Thesis

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By

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ABSTRACT

The main objective of this research was to study vehicle response asymmetries during severe driving maneuvers. During Phase VI of the National Highway Traffic Safety Administration's Light Vehicle Rollover Research Program, such response asymmetries occurred during field tests, and consequently, the data collected in Phase VI was used in this study. Of the twenty-six light vehicles tested in Phase VI, three vehicles exhibited significant response asymmetries with respect to left versus right steer maneuvers: the 1996 Acura SLX, 1995 Mitsubishi Montero, and 1993 Ford Aerostar.

An overview and an evaluation of several rollover stability indexes are provided to help explain the vehicle dynamics at the onset of rollover. No known models exist that incorporate vehicle asymmetries other than the lateral center of gravity (CG) offset. As such, this research effort investigates possible vehicle asymmetric characteristics and unintended inputs that may cause vehicle response asymmetries.

The cause of vehicle asymmetric response is quite complex and cannot be narrowed down to one item alone, e.g., CG offset. Careful consideration was given to possible unintended differences in the vehicle inputs that may adversely affect the vehicle response. These unintended vehicle inputs were determined to be either negligible or to have an insignificant impact on the vehicle asymmetric response, and therefore, the cause of vehicle asymmetric response is more likely within the vehicle itself. As such,

suspension and steering tests were conducted on the SLX and the Montero to identify any vehicle components/characteristics that may cause vehicle response asymmetries.

The suspension tests showed that both vehicles exhibited less stiffness in the nonlinear region of suspension compression on the side of the suspension that was opposite to the more severe steer direction in the J-turn maneuver. For example, the SLX experiences two-wheel lift (TWL) at a lower maneuver entrance speed in a left steer versus a right steer J-turn maneuver, and its right side suspension is softer than the left side. The same phenomenon applies to the Montero: it experiences TWL at a lower maneuver entrance speed in a right steer J-turn maneuver, and its left side suspension is softer.

To confirm the trend that the softer side suspension will lead to earlier TWL in the opposite steer direction, a model representative of the SLX was created and evaluated using CarSim™. Using the actual SLX suspension parameters, the model showed some differences between left and right steer response, but the effect of the lateral CG offset dominated the vehicle response.

The response of the shock absorbers was not determined during the suspension and steering tests, but a simulation study was done to evaluate the effect of the shock absorbers on vehicle response. Based on the shock absorber study, it is evident that a change in the damping force response can have a significant effect on the vehicle response.

Dedicated to my parents and Jennifer

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TABLE OF CONTENTS

	<u>Page</u>
Abstract	ii
Dedication	iv
Acknowledgments	v
Vita	vi
List of Figures	ix
List of Tables	xiii
Chapters:	
1. Introduction	1
1.1 General	1
1.2 Objectives	2
1.3 Thesis Overview	3
2. Background	5
2.1 General	5
2.2 Details of Phase VI	7
2.2.1 Test vehicles and configurations	8
2.2.2 Instrumentation	9
2.2.3 Test maneuvers	9
2.2.4 Test results	14
3. Rollover Stability Indexes	20
3.1 Introduction	20
3.2 Overview of Rollover Stability Indexes	20
3.3 Evaluation of SSF and DSI	25
3.4 Modification of SSF and DSI	29
3.5 Conclusions and Recommends of the Rollover Stability Index Study	36
4. Evaluation of the Field Test Data	38
4.1 Introduction	38
4.2 Accuracy and Repeatability of the Collected Data	38
4.2.1 Commanded steering inputs (handwheel position and rate)	39
4.2.2 Initial handwheel angle prior to the maneuver	42

4.2.3 Environmental effects	42
4.2.4 Vehicle Dynamic Area (VDA) test surface	43
4.2.5 Tire wear	44
4.2.6 Vehicle age and wear: worn or damaged suspension components ...	46
4.2.7 Test-to-test variability	46
4.3 Common Vehicle Asymmetries	50
4.4 Understeer and Roll Gradients	51
4.6 Analysis of Field Test Data	59
5. Suspension and Steering Tests	78
5.1 Introduction	78
5.2 Description of Suspension and Steering Tests	78
5.3 Results of the Suspension and Steering Tests	81
5.3.1 SLX tests	82
5.3.2 Montero tests	105
5.4 Physical Suspension Asymmetries	127
6. Vehicle Dynamics Simulation Using CarSim™	129
6.1 Introduction	129
6.2 Validity of CarSim™	129
6.3 The Vehicle Model Created in CarSim™	130
6.4 Simulation Results	135
7. Conclusions and Recommendations	158
7.1 Conclusions	158
7.2 Recommendations	163
List of References	165
Appendix: Miscellaneous Equations and CarSim™ Parsfile	169

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 2.1: Slowly Increasing Steer Maneuver Description	10
Figure 2.2: J-turn Maneuver Description.....	11
Figure 2.3: Road Edge Recovery Maneuver Description	13
Figure 3.1: Forces Acting to Roll Over a Vehicle	22
Figure 3.2: Example of Dynamic Stability Index	24
Figure 4.1: Comparison of SLX Response at ≈ 39 mph, Nominal Load, Left Steer J-turn.....	48
Figure 4.2: Differences in Roll Angle.....	49
Figure 4.3: SLX, Slowing Increasing Steer Maneuver	55
Figure 4.4: Montero, Slowing Increasing Steer Maneuver.....	56
Figure 4.5: Aerostar, Slowing Increasing Steer Maneuver.....	57
Figure 4.6: Aerostar Roll Gain, Slowing Increasing Steer Maneuver	58
Figure 4.7: SLX, Nominal Load, J-turn at Onset of TWL Left Steer at 39.9 mph, Right Steer at 50.2 mph	60
Figure 4.8: SLX, Nominal Load, J-turn at Common Entrance Speed Left Steer at 44.5 mph, Right Steer at 44.2 mph	61
Figure 4.9: SLX, Maximum Occupancy, J-turn at Onset of TWL Left Steer at 34.6 mph, Right Steer at 61.1 mph	62
Figure 4.10: SLX, Maximum Occupancy, J-turn at Common Entrance Speed Left Steer at 36.9 mph, Right Steer at 37.0 mph	63

Figure 4.11: SLX, Nominal Load, Road Edge Recovery at Onset of TWL Left-Right Steer at 39.5 mph, Right-Left Steer at 36.4 mph.....	64
Figure 4.12: SLX, Nominal Load, Road Edge Recovery at Common Entrance Speed Left-Right Steer at 36.4 mph, Right-Left Steer at 36.4 mph.....	65
Figure 4.13: Montero, Nominal Load, J-turn at Common Entrance Speed Left Steer at 60.3 mph, Right Steer at 59.9 mph	66
Figure 4.14: Montero, Maximum Occupancy, J-turn at Onset of TWL Left Steer at 60.1 mph, Right Steer at 30.6 mph	67
Figure 4.15: Montero, Maximum Occupancy, J-turn at Common Entrance Speed Left Steer at 36.1 mph, Right Steer at 35.6 mph	68
Figure 4.16: Montero, Nominal Load, Road Edge Recovery at Onset of TWL Left-Right Steer at 32.7 mph, Right-Left Steer at 40.6 mph.....	69
Figure 4.17: Montero, Nominal Load, Road Edge Recovery at Common Entrance Speed Left-Right Steer at 35.1 mph, Right-Left Steer at 35.6 mph.....	70
Figure 4.18: Aerostar, Nominal Load, J-turn at Common Entrance Speed Left Steer at 61.6 mph, Right Steer at 61.6 mph	71
Figure 4.19: Aerostar, Maximum Occupancy, J-turn at Onset of TWL Left Steer at 52.1 mph, Right Steer at 59.7 mph	72
Figure 4.20: Aerostar, Maximum Occupancy, J-turn at Common Entrance Speed Left Steer at 37.1 mph, Right Steer at 37.0 mph	73
Figure 4.21: Aerostar, Maximum Occupancy, Road Edge Recovery at Onset of TWL Left-Right Steer at 46.5 mph, Right-Left Steer at 40.8 mph.....	74
Figure 4.22: Aerostar, Maximum Occupancy, Road Edge Recovery at Common Entrance Speed, Left-Right Steer at 37.5 mph, Right-Left Steer at 36.6 mph	75
Figure 5.1: SLX Front Suspension Spring Rate.....	86
Figure 5.2: SLX Front Bump Stop.....	87
Figure 5.3: SLX Rear Suspension Spring Rate.....	88
Figure 5.4: Sketch of SLX Rear Bump Stop (side view).....	88
Figure 5.5: SLX Front Overall Roll Stiffness	91

Figure 5.6: SLX Rear Overall Roll Stiffness	92
Figure 5.7: SLX Front Roll Steer.....	95
Figure 5.8: SLX Front Wheel Lateral Force Steer Compliance	97
Figure 5.9: SLX Front Steering Compliance	100
Figure 5.10: SLX Steering Ratio	102
Figure 5.11: SLX Front Suspension.....	103
Figure 5.12: SLX Rear Suspension.....	104
Figure 5.13: Montero Front Suspension Spring Rate	109
Figure 5.14: Montero Rear Suspension Spring Rate	111
Figure 5.15: Montero Front Overall Roll Stiffness.....	113
Figure 5.16: Montero Rear Overall Roll Stiffness.....	114
Figure 5.17: Montero Front Roll Steer	116
Figure 5.18: Montero Front Wheel Lateral Force Steer Compliance	118
Figure 5.19: Montero Front Steering Compliance.....	120
Figure 5.20: Montero Steering Ratio	122
Figure 5.21: Montero Front Suspension	123
Figure 5.22: Montero Front-Left Suspension	124
Figure 5.23: Montero Rear Suspension	125
Figure 5.24: Montero Rear-Left Suspension	126
Figure 6.1: Coefficient of Friction Study, SLX Model at 40 mph.....	137
Figure 6.2: Big SUV Baseline Model at 40, 50, and 60 mph	138
Figure 6.3: SLX Model: Y vs. X Trajectory, Effect of the Lateral CG Offset	144
Figure 6.4: SLX Model: Effect of Lateral CG Offset at 30 mph.....	145

Figure 6.5: SLX Model: Effect of Lateral CG Offset at 40 mph	146
Figure 6.6: SLX Model: Effect of Asymmetric Suspension at 30 mph, No Lateral CG Offset	147
Figure 6.7: SLX Model: Effect of Asymmetric Suspension at 60 mph, No Lateral CG Offset	148
Figure 6.8: SLX Model: Effect of Asymmetric Suspension Parameters and Lateral CG Offset at 30 mph	149
Figure 6.9: SLX Model: Effect of Asymmetric Suspension Parameters and Lateral CG Offset at 40 mph	150
Figure 6.10: CarSim™ Default Shock Absorber Response.....	151
Figure 6.11: Shock Absorber Study, SLX Model, Default Damping Force for Comparison	152
Figure 6.12: Shock Absorber Study, SLX Model, Decrease the Default Damping Force by 10%.....	153
Figure 6.13: Shock Absorber Study, SLX Model, Increase the Default Damping Force by 10%.....	154
Figure 6.14: Shock Absorber Study, SLX Model, Increase the Default Damping Force by 20%.....	155
Figure 6.15: Shock Absorber Study, SLX Model, Increase the Front Default Damping Force by 10%	156
Figure 6.16: Shock Absorber Study, SLX Model, Increase the Rear Default Damping Force by 10%	157

LIST OF TABLES

<u>Table</u>	<u>Page</u>
Table 2.1: Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia	15
Table 2.2: Minimum Maneuver Entrance Speeds (mph) Required to Produce Two-Wheel Lift	16
Table 2.3: J-Turn Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check	18
Table 2.4: Road Edge Recovery Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check	19
Table 3.1: Analysis of DSI/SSF as TWL Predictors (Phase VI Data).....	28
Table 3.2: Analysis of the Modified DSI/SSF Metrics as TWL Predictors.....	33
Table 3.3: Accuracy of Rollover Stability Indexes.....	34
Table 4.1: Handwheel Controller Angles (deg) and Rates (deg/sec).....	41
Table 4.2: Understeer Gradient, Roll Gradient, and Maximum Lateral Acceleration; Slowly Increasing Steer Maneuver	53
Table 5.1: SLX Suspension and Steering Tests	82
Table 5.2: SLX Suspension Test Summary	83-85
Table 5.3: Montero Suspension and Steering Tests.....	105
Table 5.4: Montero Suspension Test Summary	106-108
Table 6.1: Vehicle Parameters of Actual Vehicles and CarSim™ Models	132
Table 6.2: Shock Absorber Study	143

CHAPTER 1

INTRODUCTION

1.1 General

The majority of vehicle dynamic models and simulations assume that a vehicle is symmetrical about the longitudinal axis (defined by SAE as the X-axis), and that a vehicle responds symmetrically to identical right versus left steer maneuvers. However, during the National Highway Traffic Safety Administration's (NHTSA) research on light vehicle dynamic rollover propensity, field tests have shown several vehicles to have response asymmetries with respect to right versus left steer maneuvers. The test maneuvers have been well developed, are well defined, repeatable given the same driver inputs and environmental conditions, and are claimed to represent actual severe maneuvers a driver may reproduce during accident avoidance.

Some of these response asymmetries may be a result of vehicle lateral center of gravity (CG) offset, steering asymmetries, and/or suspension asymmetries, but further investigation is necessary to fully explain the response asymmetries. Furthermore, asymmetrical vehicle characteristics may support or contradict the asymmetrical vehicle responses observed. For example, a static CG offset toward the driver side will increase the energy needed to roll the vehicle to the right (clockwise rotation) during a left steer maneuver, which reduces the likelihood of rollover. However, the CG offset will

compensate for the normal lateral weight transfer occurring in the turn, which keeps the vertical tire loads more balanced. Given that a balanced pair of tires will produce more lateral grip than an unbalanced pair, the vehicle will achieve more lateral acceleration, and therefore will be more prone to rollover. Thus the issue of asymmetrical vehicle response is a complicated cause and effect investigation.

This research will focus on the vehicle test data gathered at NHTSA's Vehicle Research and Test Center (VRTC) during Phase VI of NHTSA's Light Vehicle Rollover Research Program [1]. The objective of Phase VI was to assess the rollover resistance of a broad range of twenty-six light vehicles (passenger cars, sport utility vehicles (SUVs), light trucks, and minivans). Of the vehicles tested during Phase VI, three vehicles exhibited significant response asymmetries. These vehicles are the 1996 Acura SLX, 1995 Mitsubishi Montero, and the 1993 Ford Aerostar.

1.2 Objectives

The major objectives of this research were to:

1. Evaluate selective rollover stability indexes using the Phase VI data.
2. Analyze the measurements taken (roll angle, lateral acceleration, handwheel angle, etc.) during Phase VI's vehicle field tests.
3. Determine what vehicles responded asymmetrically in Phase VI tests.
4. Identify any vehicle components/characteristics, such as steering system or suspension asymmetries, that may cause the asymmetric response.
5. Use vehicle dynamics computer simulation to evaluate the sensitivity of vehicle response to vehicle asymmetric characteristics.

1.3 Thesis Overview

This thesis consists of seven chapters. This first chapter provides a basic introduction to the study, the objectives of the study, and an overview of the thesis.

The second chapter includes background information on the rollover research by NHTSA, in particular Phase VI of its Light Vehicle Rollover Research Program (“Phase VI”), where the vehicle field test data used in this thesis was collected. A detailed description of the test vehicles and configurations, instrumentation, test maneuvers, and the test results of Phase VI is also given.

An overview and an evaluation of rollover stability indexes are presented in the third chapter. This includes an analysis on modifying two of the indexes to better predict rollover instability.

The fourth chapter provides an evaluation of the field tests in Phase VI. This includes a discussion of the accuracy and repeatability of the collected data, common vehicle asymmetries, vehicle understeer and roll gradients, and an analysis of the field test data.

The fifth chapter accomplishes the fourth objective of this research, which is to identify any vehicle components/characteristics, such as steering system or suspension asymmetries that may cause vehicle asymmetric response. A description of the suspension and steering tests performed along with the results are given in this chapter.

The sixth chapter accomplishes the fifth objective of this research, which is to evaluate the sensitivity of vehicle response to vehicle asymmetric characteristics. The vehicle dynamic simulator used in this evaluation is introduced along with its validity, the vehicle model created, and the simulation results.

The seventh and final chapter presents the conclusions of this research along with recommendations for future work in this area.

CHAPTER 2

BACKGROUND

2.1 General

For over thirty years, NHTSA has been investigating the dynamic rollover propensity of light vehicles (vehicles that have a gross vehicle weight rating (GVWR) of 10,000 pounds or less, excluding motorcycles [2]). Efforts since 1997 include Phase I-A up to Phase VI of NHTSA's Light Vehicle Rollover Research Program, with additional phases yet to be published. The objectives of these phases are as follows:

I-A: Initial, exploratory study of using test track maneuvers to quantify on-road, untripped rollover propensity [2]

I-B: Investigate the effects of driver variability, outrigger, and fuel level on test results; implement the use of a programmable steering controller; and select maneuvers for Phase II testing [3]

II: Test a broad range of light vehicles using the test maneuvers and procedures developed during Phase I-A and I-B; characterize the on-road, untripped rollover

propensities of the vehicles tested; compare the test results with the vehicles' static and dynamic rollover metrics; improve upon the test maneuvers and procedures used [4]

III-A: Determine when to initiate handwheel steering reversal during fishhook maneuver as to maximize the severity of the maneuver with respect to two-wheel lift/rollover [5]

III-B: Implement automated pulse braking in the J-turn maneuver [6]

IV: Evaluate maneuvers to be used to assess on-road, untripped rollover resistance of light vehicles [7]

V: Finalize the test methodology and procedures to be used during Phase VI and investigate the effect of different outrigger designs, ambient temperatures, and test surfaces on vehicle response (yet to be published, see [1] for details)

VI: Assess the rollover resistance of a broad range of twenty-six light vehicles [1]

These efforts serve to meet the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act of 2000 to develop a dynamic test on passenger vehicle rollovers for the purposes of a consumer information program in which the resulting rollover resistance ratings will be part of NHTSA's New Car Assessment Program (NCAP).

The main driving force for the TREAD Act of 2000 and NHTSA's recent rollover research is the fact that a large number of Americans are killed each year in rollover crashes. According to the report, "Traffic Safety Facts 2001" [8], 9866 fatal light vehicle rollover accidents occurred in 2001, which represents 20.5% of the total fatal light vehicle accidents. Of all the fatal SUV accidents, 35.2% were rollovers, as were 15.7% for passenger cars, 25.1% for pickup trucks, and 19.2% for vans. The percentages for fatalities in single vehicle crashes were even higher. Consider the following statistics based on the Fatality Analysis Reporting System (FARS). In 2001, 10,157 people were killed as occupants in light vehicle rollover crashes, of which 8,424 were killed in single vehicle rollovers crashes. The statistics show that of the 2,279 occupants killed in SUV single vehicle crashes, 76% were rollover crashes. Other light vehicle data are 45% for passenger cars, 61% for vans, and 60% for pickup trucks [9].

2.2 Details of Phase VI

As mentioned earlier, the objective of Phase VI of NHTSA's Light Vehicle Rollover Research Program was to assess the rollover resistance of a broad range of twenty-six light vehicles. As determined in earlier phases, two maneuvers (J-turn and fishhook, also referred to as road edge recovery) were used to evaluate the vehicles in both nominal and maximum occupancy load configurations. The remainder of this chapter presents in detail the test vehicles and configurations, instrumentation, test maneuvers, and the test results of Phase VI. For additional information on Phase VI, refer to [1].

2.2.1 Test vehicles and configurations

The twenty-six light vehicles evaluated in Phase VI consisted of nine SUVs, six pickup trucks, five minivans, and six passenger cars. The majority of the vehicles were used vehicles. To ensure performance similar to manufacturer design, the suspension components of the used vehicles were refurbished along with any other components that did not meet the manufacturers standards. Also, a four-wheel alignment was performed before testing.

All of the tires were new, inflated to vehicle manufacturer recommended pressure, and recommended by the vehicle manufacturer as OE equipment or equivalent. Prior to formal testing, the tires underwent a break-in procedure to wear away mold sheen and bring them up to operating temperatures. Since the effect of tire wear can have a strong influence on vehicle response, the tires were changed after each test series, e.g., one test series consisted of both left and right steer J-turn tests in the nominal load condition. The effect of tire wear will be discussed in Chapter 4.

The two vehicle load configurations were nominal load and maximum occupancy. The nominal load configuration consisted of the driver, instrumentation, steering machine, titanium outriggers (attached to the front and rear bumper attachment points), and a full gas tank. In addition to the nominal load configuration, maximum occupancy also consisted of water dummies in each seating position, excluding the front seats. In the case of the pickup trucks where no rear seats existed, a comparable loading condition to that of an SUV was used (water dummies were placed in the pickup truck bed close to the cab).

2.2.2 Instrumentation

Each vehicle was similarly instrumented with sensors, data acquisition system, and a programmable steering machine. The following data were measured (by the given sensor): handwheel angle (angle encoder); brake pedal force (load cell); longitudinal, lateral, and vertical accelerations along with roll, yaw, and pitch rates (multi-axis inertial sensing system); left and right side vehicle ride height (ultrasonic distance measuring system); vehicle speed (radar speed sensor); and wheel lift (analog displacement measuring system). Appropriate measures were taken to correct for any CG offset placement of the accelerometers and the effect of roll angle. All data were sampled at 200 Hz, and signal conditioning consisted of amplification, anti-alias filtering, and digitizing analog signals.

2.2.3 Test maneuvers

The test vehicles were evaluated with a characterization maneuver (slowly increasing steer) and two rollover resistance maneuvers (J-turn and road edge recovery). The slowly increasing steer maneuver was based on the “Constant Speed, Variable Steer” test defined in SAE J266 [10], and the data output from the maneuver was used to determine the handwheel input magnitudes for the J-turn and road edge recovery maneuvers. Hence, it characterized the lateral response of the vehicle, but did not evaluate the vehicle’s rollover resistance. The maneuver was performed at 50 mph in both the left and right steer directions. At time zero, the handwheel angle was linearly increased from 0° to 270° at a rate of $13.5^\circ/\text{sec}$ and then held constant at 270° for two seconds, as shown in Figure 2.1.

Figure 2.1: Slowly Increasing Steer Maneuver Description [1]

The J-turn is a basic, single step steer input. To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, the steering machine initiated the handwheel commands described in Figure 2.2. Following completion of the handwheel ramp, handwheel position was maintained for four seconds and then returned to zero. The J-turn handwheel magnitudes, shown as 'A' in Figure 2.2, were calculated by multiplying the handwheel angle producing an average of 0.3 g in the slowly increasing steer maneuver by a scalar of 8.0. The handwheel rate was 1000°/sec for all test vehicles.

Figure 2.2: J-turn Maneuver Description [1]

The entrance speeds used in the J-turn maneuver ranged from 35 to 60 mph, and were increased in 5 mph increments until either two-wheel lift (TWL) occurred or the maximum entrance speed of 60 mph was reached without TWL having occurred. If TWL was observed, a downward iteration of vehicle speed in 1 mph increments was performed until lift was no longer detected. Once this lowest speed for TWL was isolated, two additional J-turns were performed at that speed to confirm TWL repeatability.

The road edge recovery maneuver is the same as NHTSA's roll rate feedback fishhook used in earlier rollover research phases. The phrase "road edge recovery" was coined because the handwheel inputs are claimed to represent the steering that a startled driver might use to regain lane position on a two-lane road after dropping two wheels off

onto the shoulder. In addition, more people could easily relate to “road edge recovery” versus “fishhook”. However, note that the road edge recovery maneuver is performed on a smooth uniform surface where the wheels never contact or drop off of the shoulder edge of the test surface.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, the steering machine initiated the handwheel commands described in Figure 2.3. Following completion of the countersteer, handwheel position was maintained for three seconds and then returned to zero.

In a manner similar to that used for the J-turn, road edge recovery handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the slowly increasing steer maneuver by a scalar of 6.5, as shown in Figure 2.3 as value ‘A’. The timing of the countersteer is meant to maximize the severity of the maneuver. If a counter-clockwise initial steer was used (left steer), the countersteer following completion of the first handwheel ramp was to occur when the roll velocity of the vehicle was $1.5^{\circ}/\text{sec}$ (considered a left-right steering road edge recovery maneuver). In similar fashion, the right-left steering road edge recovery maneuver’s countersteer was to occur when the roll velocity of the vehicle was $-1.5^{\circ}/\text{sec}$, as shown in Figure 2.3. The handwheel rates of the initial steer and countersteer were $720^{\circ}/\text{sec}$ for all test vehicles. The nominal maneuver entrance speeds used in the road edge recovery maneuver ranged from 35 to 50 mph, and the procedure used to isolate the TWL speed was the same as in the J-turn tests.

Figure 2.3: Road Edge Recovery Maneuver Description [1]

2.2.4 Test results

A list of all the Phase VI vehicles, including the vehicle weight, CG location, static stability factor (SSF, discussed in Chapter 3), and mass moments of inertia is given in Table 2.1.

Two-wheel lift (TWL) is defined as at least two inches of simultaneous front and rear wheel lift for one side of a vehicle. TWL less than two inches was not considered. The minimum maneuver entrance speeds required to produce TWL are reported in Table 2.2, where ten of the twenty-six vehicles experienced TWL. Dashes indicate that TWL did not occur at or below the maximum test speed (50 mph for J-turn and 60 mph for road edge recovery). Refer to [1] for explanations of tests that were not performed (TNP) or terminated early (ET).

Vehicle	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec ²)	Roll (ft-lb-sec ²)	Yaw (ft-lb-sec ²)
1998 Honda CR-V	3371	46.63	25.03	-0.59	1.210	1826	431	1977
1998 Chevrolet Tracker	2625	39.87	24.26	-0.84	1.131	959	262	1044
1997 Jeep Cherokee Sport	3684	44.95	26.38	-0.91	1.102	1838	420	1993
2001 Toyota 4Runner	4239	48.57	27.07	-1.17	1.098	2437	463	2544
1996 Acura SLX	4467	52.13	27.33	-0.51	1.098	2758	572	2874
2001 Ford Explorer XLS	4446	51.38	27.10	-1.45	1.085	2611	497	2685
2001 Ford Explorer Sport	4057	47.55	27.37	-1.48	1.070	2161	466	2247
2001 Chevrolet Blazer	3998	49.10	26.63	-1.00	1.025	2273	429	2384
1995 Mitsubishi Montero	4655	57.55	29.35	-1.13	0.953	2859	581	2920
1992 Ford F-150	4397	56.53	26.50	-0.86	1.225	3638	479	3909
1994 Chevrolet C1500	4273	57.22	26.33	-1.06	1.219	3268	517	3579
1997 Ford F-150	4438	57.02	26.92	-0.86	1.212	3538	572	3774
1995 Chevrolet K1500	4856	53.45	27.74	-1.16	1.152	3645	548	3911
1997 Ford Ranger 4x2	3228	44.02	25.12	-1.85	1.136	1702	336	1821
1997 Ford Ranger 4x4	3723	43.22	27.08	-1.78	1.070	1922	382	2048
1998 Plymouth Voyager	3812	46.92	24.96	-1.34	1.273	2417	581	2609
1995 Ford Windstar GL	3943	46.72	25.34	-0.48	1.258	2757	593	2974
1994 Dodge Caravan	3616	47.03	25.82	-0.93	1.182	2207	475	2377
1995 Chevrolet Astro	4422	50.83	29.01	-1.11	1.126	2778	690	2938
1993 Ford Aerostar	3879	51.46	27.30	-1.21	1.117	2263	537	2389
2002 Chevrolet Corvette	3361	51.45	17.61	-0.55	1.749	1442	341	1637
1992 Honda Civic LX	2529	39.90	19.88	-1.09	1.462	1212	257	1360
1994 Ford Taurus	3407	37.63	21.08	-0.94	1.447	1845	363	2072
1993 Chevrolet Caprice Classic	4097	50.68	22.21	-0.55	1.406	2718	453	3022
1997 Chevrolet Metro	2057	35.41	20.37	-1.46	1.326	782	202	867
1991 Chevrolet Cavalier	2728	36.99	21.19	-0.88	1.310	1333	271	1474

Table 2.1: Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Baseline, Sorted By SSF In Descending Order, Per Vehicle Class) [1]

Vehicle	J-Turn (Maximum Test Speed of 60 mph)				Road Edge Recovery (Maximum Test Speed of 50 mph)			
	Nominal Load		Maximum Occupancy		Nominal Load		Maximum Occupancy	
	Left Steer	Right Steer	Left Steer	Right Steer	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering
1998 Honda CR-V	--	--	55.2 (ET)	-- (ET)	42.4	-- (ET)	43.7 (ET)	TNP
1998 Chevrolet Tracker	--	--	--	--	--	--	43.5	45.4
2001 Toyota 4Runner*	--	--	--	--	--	--	37.2	45.7
1996 Acura SLX	39.9	50.2	34.6	--	39.5	36.4	35.3	35.9
2001 Ford Explorer XLS	--	--	--	--	--	--	37.5	--
2001 Chevrolet Blazer	--	--	52.4	49.0	40.4	39.6	34.9	34.3
1995 Mitsubishi Montero	--	--	--	30.6	32.7	40.6	34.0	29.7
1997 Ford Ranger 4x4	--	--	--	60.9 (ET)	48.8	51.4 (ET)	TNP	
1995 Chevrolet Astro	--	--	--	57.9 (ET)	--	--	34.5	36.2
1993 Ford Aerostar	--	--	52.1	--	43.3	46.5	46.5	40.8

*The electronic stability control (VSC) on the 2001 4Runner was disabled during all Phase VI tests.

Table 2.2: Minimum Maneuver Entrance Speeds (mph) Required to Produce Two-Wheel Lift [1]
 (ET): Early Termination, TNP: Test Not Performed
 (Sorted by Baseline SSF in Descending Order, Per Vehicle Class)

Ideally, the vehicle response should be the same given identical steering and speed inputs as well as surface and environmental conditions. Such is the case with modeling and computer simulation. However, in actual field tests, test-to-test variability can cause small response fluctuations. Even more so, when testing at a vehicle's TWL threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur), the likelihood of TWL is very high, but not guaranteed. Therefore, the results of Phase VI's TWL repeatability evaluation, presented in Tables 2.3 (J-turn) and 2.4 (road edge recovery), should not be surprising. The combination of test-to-test variability and testing at TWL threshold speeds adds to the complexity of analyzing vehicle response, e.g., when comparing left versus right steer vehicle response.

Vehicle	Nominal Load						Maximum Occupancy					
	Left Steer			Right Steer			Left Steer			Right Steer		
	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat
1996 Acura SLX	39.9	39.5 (No TWL) ¹	39.1 (No TWL) ¹	--	--	--	34.8	34.2 (No TWL) ¹	34.6	--	--	--
2001 Chevrolet Blazer	--	--	--	--	--	--	53.7	52.6 (No TWL) ¹	52.4	49.0	49.5	49.6 (No TWL) ²
1995 Mitsubishi Montero	--	--	--	--	--	--	--	--	--	30.6	31.0	31.0
1993 Ford Aerostar	--	--	--	--	--	--	--	--	--	--	--	--

(No TWL)¹ = less than two inches of simultaneous two wheel lift was observed

(No TWL)² = front wheel lift only, no rear wheel lift

Table 2.3: J-Turn Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check [1]

Vehicle	Nominal Load						Maximum Occupancy					
	Left-Right Steering			Right-Left Steering			Left-Right Steering			Right-Left Steering		
	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat	Initial	1 st Repeat	2 nd Repeat
1998 Honda CR-V	42.4	42.5	42.1 (No TWL) ¹	--	--	--	--	--	--	--	--	--
1998 Chevrolet Tracker	--	--	--	--	--	--	43.5	43.4 (No TWL) ²	43.2 (No TWL) ²	45.4	45.9 (No TWL) ¹	45.8 (No TWL) ¹
2001 Toyota 4Runner	--	--	--	--	--	--	37.2	37.6	37.7	45.8	45.8	45.7
1996 Acura SLX	39.5	39.9	39.5	--	--	--	36.0	35.3	35.7	35.9	36.5	36.5
2001 Ford Explorer XLS	--	--	--	--	--	--	38.6	37.5	39.2	--	--	--
2001 Chevrolet Blazer	40.4	40.6	40.7	39.8	40.4	39.6	34.9	35.7	36.8 (No TWL) ¹	35.2	34.3	34.3
1995 Mitsubishi Montero	32.7	32.7	32.9 (No TWL) ³	40.6	40.7	41.0	34.6	34.6	34.0	29.7	30.1	30.1 (No TWL) ³
1997 Ford Ranger 4x4	49.3	49.8	48.8	--	--	--	--	--	--	--	--	--
1995 Chevrolet Astro	--	--	--	--	--	--	34.9	34.6	34.5	36.2	36.8	36.8
1993 Ford Aerostar	44.0	43.3	43.0 (No TWL) ²	46.5	47.0	46.7	47.2	46.6	46.5	40.8	41.1	40.8 (No TWL) ²

(No TWL)¹ = less than two inches of simultaneous two wheel lift was observed

(No TWL)² = front wheel lift only, no rear wheel lift

(No TWL)³ = no front or rear wheel lift

Table 2.4: Road Edge Recovery Maneuver Entrance Speed Versus Two-Wheel Lift Repeatability Check [1]

CHAPTER 3

ROLLOVER STABILITY INDEXES

3.1 Introduction

This chapter begins with an overview of both static and dynamic rollover stability indexes. Then an evaluation of two of the indexes is given based on vehicle field test data collected during Phase VI of NHTSA's Light Vehicle Rollover Research Program. Next is a discussion on the modification of these indexes to better represent the rollover instability threshold, along with an evaluation of the modified indexes. Since this investigation of rollover stability indexes considers but does not focus on asymmetric vehicle response, conclusions and recommendations of this index investigation are given at the end of this chapter instead of being included into the overall conclusion section of this thesis.

3.2 Overview of Rollover Stability Indexes

There are two types of rollover stability indexes: static (time-independent) and dynamic (time-dependent). Three common types of static indexes include the Static Stability Factor (SSF), Side Pull Ratio (SPR), and the Tilt Table Ratio (TTR). Countless dynamic indexes exist, influenced heavily by the dynamic onboard measurements (e.g. yaw rate, lateral acceleration, roll acceleration, etc.) available and the purpose (e.g.

electronic stability controller, active suspension, etc.) of the index. The three static indexes mentioned are based on the estimation of the steady state lateral acceleration needed to cause a vehicle to roll over on a flat road. This lateral acceleration level represents a major, or first order, characteristic in vehicle rollover stability [11].

On May 25, 2000, NHTSA declared that, “after extensive research, NHTSA determined that a vehicle’s ‘static stability factor’ is the most reliable indicator of rollover risk in single-vehicle crashes” [12]. NHTSA then incorporated SSF into a rollover resistance star rating, which can be found at NHTSA’s website (<http://www.nhtsa.dot.gov/NCAP>). SSF has thus become the most popular rollover index. It (nominal SSF) is simply half of the vehicle’s average track width (average of the front and rear) divided by the vehicle’s CG height and is commonly referred to as “t over 2h” [13]. The vehicle is considered to be a rigid body that approaches rollover instability as the lateral acceleration approaches SSF. This rigid body model neglects the effects of the suspension, roll angle of the sprung mass, and deformation of the tires, and it assumes sufficient tire-road friction such that the tires do not slide laterally. The model, including D’Alembert’s force $M \cdot a_y$, is shown in Figure 3.1.

Figure 3.1: Forces Acting to Roll Over a Vehicle [13]

where:

M: entire mass of vehicle

a_y : lateral acceleration

F_y : lateral tire force

F_z : vertical (normal) force on tire

g: gravitational constant

h: total vehicle CG height

subscripts 'i' and 'o' denote inside and outside of turn, respectively.

Consider the moment about the center of contact for the outside tires (assume vehicle is in a steady turn, i.e., no roll acceleration, and the inside tires lose contact with the ground) and then the stabilizing moment is:

$$Mg \frac{t}{2} \quad (3-1)$$

and the overturning (tip-up causing) moment is:

$$Ma_y h \quad (3-2)$$

Setting the two moments equal to each other and modifying the equation yields:

$$SSF : \frac{t}{2h} = \frac{a_y}{g} \quad (3-3)$$

So as the lateral acceleration (in g's) approaches "t over 2h," then the vehicle approaches rollover instability.

In an effort to better model the rollover dynamics of a vehicle, numerous dynamic indexes have been introduced, which account for the higher order effects of vehicle instability and allow for the implementation of active control systems. These dynamic indexes incorporate all of the dynamic test data (i.e., not just a single point) and represent the roll stability of the vehicle at each instance during a maneuver. An example of a dynamic index is given in Figure 3.2.

In 1998, Bernard, Shannan, and Vanderploeg built upon the static rigid model by accounting for the sprung mass body roll and the lateral deflection of the tires during a turning maneuver, which decreases the stabilizing moment given in SSF [14]. Gillespie also has a model that accounts for the roll of the body [13]. Heydinger and Howe introduced a Dynamic Stability Index (DSI) in 2000 that accounts for the roll moment of the sprung mass [15]. In addition to DSI, they suggested a modification of SSF to account for the lateral CG offset of a vehicle. In 2002, Hac considered many modifications to SSF, which include body roll, changes in half-track width due to suspension kinematics and lateral compliance of the tires and suspension, gyroscopic forces due to wheel rotation, and the effect of jacking forces [16]. Yang and Liu (2003) discussed three different dynamic indexes to be used in an active controller [17]. One of the indexes (R_2) mentioned by Yang and Liu is based on energy relationships, which

according to Heydinger and Howe [15] are difficult to accurately model. Given the different nature of ‘ R_2 ’, it was included in the index evaluation documented in Section 3.5.

Figure 3.2: Example of Dynamic Stability Index
1996 Acura SLX, J-turn maneuver (≈ 44 mph) as described in Section 2.2.3

3.3 Evaluation of SSF and DSI

Of the dynamic rollover indexes mentioned, DSI was chosen for this study because of its simplicity and similarity to SSF. The DSI model is based on the SSF model with the addition of the roll moment of the sprung mass ($I_{xxs}\alpha$), where the roll

inertia of the sprung mass (I_{xxs}) is assumed to be 80% of the entire vehicle roll inertia and ‘ α ’ denotes roll acceleration. The tip-up causing moment in Equation 3.2 now becomes:

$$Ma_y h + I_{xxs} \alpha \quad (3.4)$$

In [15], the SSF was modified to account for the lateral CG offset of a vehicle. The effective half-track width of the vehicle is:

$$\left(\frac{t}{2}\right)_{effective} = \left(\frac{t}{2}\right) - CG_offset \quad (3.5)$$

where the sign of the CG offset is based on the SAE vehicle coordinate system.

Therefore, a CG offset toward the driver side of a vehicle would be a negative offset and would increase the effective half-track width during a left steer maneuver and decrease the effective half-track width during a right steer maneuver. The effective SSF for both the left and right steer maneuvers for the 1996 Acura SLX are shown in Figure 3.2. Now, the moment equation for this model is:

$$Mg\left(\frac{t}{2}\right)_{effective} = Ma_y h + I_{xxs} \alpha \quad (3.6)$$

Rearrange the moment equation to get:

$$Effective_SSF : \frac{(t/2)_{effective}}{h} = \frac{a_y}{g} + \frac{I_{xxs} \alpha}{Mgh} : DSI \quad (3.7)$$

Additional notes on DSI [15]:

- Theoretically, in any and all rollovers, DSI exceeds SSF.
- The first-order DSI is derived based on roll moments that are always lower than the “exact” roll moments a vehicle will experience in an actual dynamic maneuver.
- The DSI has to be greater than the SSF for some period of time in order to produce major two wheel lift (TWL).

- As mentioned in the derivation of SSF, it is assumed that the tire contact patch provides adequate friction to achieve enough lateral force to cause vehicle wheel lift. However, during severe maneuvers, some vehicle-tire combinations might plow out and not provide enough lateral force to produce TWL.
- Some vehicles exhibit oscillatory roll response during severe maneuvers. DSI does not account for the oscillating energy transfer in the system (springs, shocks, tires, etc.).

Based on the derivation of DSI, the combination of SSF and DSI (“the metrics”) should predict vehicle rollover (when the stabilizing moment is less than the tip-up causing moment). As mentioned in Chapter 2, NHTSA’s objective in Phase VI was to determine the rollover resistance of a broad range of vehicles, which involved determining the minimum maneuver entrance speed needed to produce TWL. However, TWL does not necessarily result in rollover. Therefore, if during a severe maneuver a vehicle experiences TWL, the metrics should not be expected to predict TWL—unless for that particular case, TWL will result in vehicle rollover. Given this, a better validation test of the metrics would be to consider the field tests where the vehicle outriggers touched the ground, i.e., the vehicle would have rolled over in the absence of the outriggers.

However, if it is desired to use the metrics to predict TWL (which is assumed throughout this analysis), then one must determine a threshold value for DSI/SSF so that $[DSI/SSF > (\text{threshold value})]$ will predict TWL. Currently, if $DSI/SSF > 1$, major TWL and vehicle rollover is expected.

Based on the Phase VI data, ten vehicles experienced TWL. The majority of the field tests for those ten vehicles were considered, for a total of 514 tests, as shown in Table 3.1. The metrics (DSI/SSF) predicted TWL (column 6) 34 out of the 166 tests that produced TWL and did not predict or “underestimated” TWL in the remaining 132 cases. The metrics predicted TWL (column 7) 23 times in which TWL did not occur (“overestimated” TWL).

	Vehicle	# Tests Considered	# Tests that TWL occurred	DSI/SSF predict TWL	DSI/SSF predict TWL and TWL occurred	DSI/SSF predict TWL and TWL did not occur	TWL occurred and DSI/SSF did not predict TWL
1	1991 Chevrolet Cavalier		0				
2	1992 Ford F-150		0				
3	1992 Honda Civic LX		0				
4	1993 Chevrolet Caprice Classic		0				
5	1993 Ford Aerostar	59	13	3	2	1	11
6	1994 Chevrolet C1500		0				
7	1994 Dodge Caravan		0				
8	1994 Ford Taurus		0				
9	1995 Chevrolet Astro	30	12	3	2	1	10
10	1995 Chevrolet K1500		0				
11	1995 Ford Windstar GL		0				
12	1995 Mitsubishi Montero	63	34	0	0	0	34
13	1996 Acura SLX	89	42	8	4	4	38
14	1997 Chevrolet Metro		0				
15	1997 Ford F-150		0				
16	1997 Ford Ranger 4x2		0				
17	1997 Ford Ranger 4x4	38	7	8	7	1	0
18	1997 Jeep Cherokee Sport		0				
19	1998 Chevrolet Tracker	47	8	7	4	3	4
20	1998 Honda CR-V	55	12	7	3	4	9
21	1998 Plymouth Voyager		0				
22	2001 Chevrolet Blazer	58	21	9	3	6	18
23	2001 Ford Explorer Sport 4x2		0				
24	2001 Ford Explorer XLS 4x4	61	8	1	0	1	8
25	2001 Toyota 4Runner	14	9	11	9	2	0
26	2002 Chevrolet Corvette		0				
	Total	514	166	57	34	23	132

Table 3.1: Analysis of DSI/SSF as TWL Predictors (Phase VI Data)

Given that the metrics both under and overestimated TWL, the previously mentioned threshold multiplier would decrease the number of underestimates (desirable) and increase the number of overestimates (undesirable). Instead of introducing a threshold multiplier, the current metrics should be modified to better represent the roll dynamics of the vehicle.

3.4 Modification of SSF and DSI

In the previous rollover index study, the metrics (DSI/SSF) correctly predicted TWL or no TWL 69.8% of the 514 Phase VI tests considered. In order to increase the accuracy of the metrics, an improved model of the vehicle roll dynamics is needed. Two relatively easy modifications to implement are:

1. Account for the decrease in track width due to the lateral deflection of the tires.

This would decrease the effective SSF, which already accounts for the lateral CG offset. This modification would require knowing the lateral tire stiffness (lateral spring rate).

2. Increase the assumed value that the unsprung roll inertia is 80% of the total roll inertia. This modification would increase the DSI value. For a more accurate model, this percentage should be calculated for each vehicle. However, this is not feasible—but perhaps an average value could be determined from several vehicles, in particular an average value found for each type of vehicle (passenger car, SUV, van, and light truck).

In the current study, the assumption that the unsprung roll inertia is 80% of the total roll inertia was replaced by an approximation for the unsprung roll inertia based on the type

of suspension (solid rear axle or independent), total roll inertia of the vehicle, loaded radius of the tire, front and rear track width, unsprung mass, sprung mass, and sprung mass CG. This estimate was reported in “Vehicle Dynamic Stability and Rollover” by Systems Technology Incorporated (STI, June 1992) [18].

Four cases were considered in representing the decrease in track width due to the lateral deflection of the tires. All four cases used the approximation for the unsprung roll inertia suggested by STI. Additional dynamic effects were also considered in CASE 2 and 4.

CASE 1:

Assume tire lateral deflection (in) = Lateral Force * (0.0002 ft/lb) * (12 in/ft). The deflection coefficient (0.0002 ft/lb) is based on static lateral tire stiffness tests performed at S.E.A., Inc. in Columbus, Ohio. During tip up, all mass is on one side of the vehicle; therefore the lateral force on one tire is equal to half the vehicle mass times the lateral acceleration. The lateral deflection of the tire (inches) is:

$$tire_deflect_1 = abs(0.5 * M * a_y * 0.0002 * 12) \quad (3.8)$$

CASE 2:

Another approximation of the lateral tire deflection coefficient is 1.0 to 3.0 inches per g of lateral acceleration, which is based on tire test data [14]. Given that the majority of vehicles in Phase VI that experienced TWL were SUVs and that SUV tires tend to have higher aspect ratios (i.e., more lateral tire deflection), the deflection coefficient was assumed to be 2.5 in/g. Another effect that shortens the moment arm of the stabilizing moment is the sprung mass rolling to the outside of a turn. Based on typical vehicle geometry and roll gain, this reduction is about 1.0 in/g for passenger

cars and utility vehicles [14]. The total reduction of the moment arm is therefore 3.5 in/g, which is equivalent to (inches):

$$tire_deflect_2 = abs(3.5 * a_y) \quad (3.9)$$

CASE 3:

Similar to CASE 2, but assume multiplier of 4.0 instead of 3.5 in/g, so that:

$$tire_deflect_3 = abs(4.0 * a_y) \quad (3.10)$$

CASE 4:

Estimate the combined lateral compliance rate of the tire and suspension based on STI's vehicle model [18]. The combined rate accounts for tire casing lateral compliance, wheel bending, suspension bending, suspension and sub-frame bushing deflection, etc. This rate is estimated to be twice the vertical spring rate of the tire. The vertical spring rates of the tires used in Phase VI testing are unknown; therefore an approximation given in the report by STI was used. To validate the approximation equation for vehicles that showed TWL in Phase VI (mainly light trucks and SUVs), the approximation equation was used to estimate the vertical deflection of a P265/75R15 tire mounted on a 1997 Ford Ranger STX 4x4. The equation estimated the deflection to be about a tenth of an inch. However, the vertical deflection of the tire and vehicle combination based on actual measurements was about one inch. The approximation, based solely on tire dimensions and inflation pressure, greatly overestimated the vertical spring rate of a test vehicle. The approximation formula attempts to represent all passenger vehicle tires, which given the complexity of a tire, is probably unreasonable based solely on tire dimensions and inflation pressure.

Based on the inaccuracies of the tire vertical spring rate calculation, the combined lateral compliance rate approximation (CASE 4) was not used.

In addition to testing the validity of the previously mentioned dynamic rollover indexes, the 'R₂' dynamic rollover index from "A Robust Active Suspension Controller with Rollover Prevention" [17] was considered. It is based on the change of energy of a simplified sprung mass body model and the assumption that "the suspension travel range will not have too much of an impact on the potential energy change at the critical situation when the kinetic energy is to be greater than the potential energy change." The index was calculated for many vehicle runs, in which it failed to represent rollover propensity, and therefore the index was not applied to all Phase VI tests.

The results of the three cases are shown in Table 3.2. The ten vehicles that experienced TWL are shown in the table, and those vehicles that did not experience TWL were omitted. The first column in 'CASE 1' gives the number of times that CASE 1 DSI/SSF predicted TWL. The second column in 'CASE 1' states the frequency that CASE 1 DSI/SSF predicted TWL (first 'Y') and TWL occurred (second 'Y'). The third through fifth columns are similar in nature. The last column of 'CASE 1' states the percentage that CASE 1 DSI/SSF correctly predicted TWL (correct being Y/Y or N/N). The columns in 'CASE 2' and 'CASE 3' follow the same convention as the columns in 'CASE 1.'

				CASE 1						CASE 2						CASE 3					
	Predict TWL: Y/N TWL Occurred: Y/N	# Tests Consid- ered	# Tests that TWL occurred	DSI/SSF 1 predict TWL	Y Y	Y N	N Y	N N	% cor- rect	DSI/SSF 2 predict TWL	Y Y	Y N	N Y	N N	% cor- rect	DSI/SSF 3 predict TWL	Y Y	Y N	N Y	N N	% cor- rect
5	1993 Ford Aerostar	59	13	35	13	22	0	24	62.7	23	10	13	3	33	72.9	25	11	14	2	32	72.9
9	1995 Chevrolet Astro	30	12	24	12	12	0	6	60	19	12	7	0	11	76.7	20	12	8	0	10	73.3
12	1995 Mitsubishi Montero	63	34	29	21	8	13	21	66.7	9	9	0	25	29	60.3	11	10	1	24	28	60.3
13	1996 Acura SLX	89	42	86	40	46	2	1	46.1	62	32	30	10	17	55.1	68	34	34	8	13	52.8
17	1997 Ford Ranger 4x4	38	7	12	7	5	0	26	86.8	9	7	2	0	29	94.7	11	7	4	0	27	89.5
19	1998 Chevrolet Tracker	47	8	18	7	11	1	28	74.5	17	7	10	1	29	76.6	19	7	12	1	27	72.3
20	1998 Honda CR-V	55	12	24	12	12	0	31	78.2	20	12	8	0	35	85.5	24	12	12	0	31	78.2
22	2001 Chevrolet Blazer	58	21	40	20	20	1	17	63.8	31	20	11	1	26	79.3	33	20	13	1	24	75.9
24	2001 Ford Explorer XLS 4x4	61	8	8	5	3	3	50	90.2	3	2	1	6	52	88.5	5	3	2	5	51	88.5
25	2001 Toyota 4Runner	14	9	14	9	5	0	0	64.3	12	9	3	0	2	78.6	13	9	4	0	1	71.4
Total		514	166	290	146	144	20	204	69.3	205	120	85	46	263	76.8	229	125	104	41	244	73.5

Table 3.2: Analysis of the Modified DSI/SSF Metrics as TWL Predictors

The accuracy of each case study considered, including the previous study of DSI/SSF ('Original'), is shown in Table 3.3.

CASE	% Correct (total tests)	% Correct (equal vehicle weight)
Original	69.8	73
1	68.1	69.3
2	74.5	76.8
3	71.8	73.5

Table 3.3: Accuracy of Rollover Stability Indexes

where:

% Correct (total tests) = (total correct)/(total tests considered)

% Correct (equal vehicle weight) = (Sum of % correct for each vehicle) / (number of vehicles)

The “percentage correct using equal vehicle weighting” eliminates the effect that a particular vehicle with a proportionally large number of tests, either well or poorly represented by the index, dominates.

This study is a step in the right direction to better represent the roll dynamics of the vehicle. Unfortunately, the modified indexes show at most a 6.7% increase of accuracy (for CASE 2: $(74.5-69.8)/69.8 * 100\% = 6.7\%$).

As mentioned before, the indexes are limited by the assumptions used. Parameters such as lateral and vertical tire deflection (stiffness), sprung mass inertia, sprung mass CG height, etc. are based on calculations that use coefficients derived from a

limited number of vehicle tests and thus may or may not represent accurately the current vehicle under consideration. This makes predicting TWL very difficult at the TWL threshold. The metrics, with their many assumptions, may well represent the rollover propensity of vehicles during no wheel lift and major wheel lift (more than two inches), but not at the TWL threshold (simultaneous front and rear lift of two inches).

More complex models are needed to fully represent the roll dynamics of the vehicle. For example, a two degree of freedom model (separate sprung and unsprung masses) would represent the sprung mass rolling to the outside of turn, thus shortening the moment arm of the stabilizing moment. However, the two degree of freedom model requires more vehicle parameters to be known, e.g., roll center, suspension kinematics, etc. The current model (CASE 2) accounts for the shift of the sprung mass by assuming a shift of 1.0 inch per lateral g (suggested in [14]). According to Hac [16], other factors that affect the roll dynamics include the change in half-track width due to suspension kinematics and compliance, gyroscopic forces due to wheel rotation (increase the moment needed for rollover), and vertical forces transmitted from the wheels through the suspension that lift the vehicle CG height. These factors along with others that change the lateral forces (by approximately the percentage ranges given) needed to induce rollover are listed below in descending order of effect [16]:

1. lateral displacement of vehicle center of gravity due to body roll; 5 to 12% decrease
2. reduction in half track width due to lateral compliance of the tires; 3 to 8% decrease
3. increase in the center of gravity height resulting from jacking forces; up to 5% decrease
4. increase in half track width as the result of suspension kinematics; up to 5% increase

5. gyroscopic forces due to wheel rotation; 1 to 1.5% increase

3.5 Conclusions and Recommendations of the Rollover Stability Index Study

If the sole purpose of DSI/SSF is to accurately predict when TWL will occur, then the investigation should be continued. However, a more complex model will require knowing more vehicle parameters. At some point, adding more required vehicle parameters (which will require more testing) will outweigh the cost of simply testing the vehicle on the track to determine if and when TWL will occur. Perhaps a more useful purpose of DSI/SSF is to predict vehicle instability (impending wheel lift but not necessarily TWL) for the purpose of on-board vehicle stability control. For example, if DSI/SSF approaches 0.8, then engine power will be reduced, the appropriate brakes will be applied, suspension force actuators will act to reduce the roll angle, etc., such that the vehicle will go from an impending unstable condition to a stable one.

If it is desired to have DSI/SSF more accurately predict TWL, then the following recommendations should be considered:

1. Perform vehicle tests to determine the total reduction of the effective half track width (lateral tire deflection, suspension compliance, etc.) for each vehicle.
2. Incorporate the effect of roll angle into the index.

There have been several field tests where lateral acceleration was relatively low and yet the roll angle was relatively high and TWL occurred. An increase in roll angle is probably the result of increased vertical forces in the suspension. This scenario will be accompanied by an increase in CG height, which reduces the stabilizing moment.

3. Further investigate the role of the suspension kinematics.
4. Modify DSI to account for the oscillatory energy transfer in the system (springs, shocks, tires, etc.), which occurs in vehicles that exhibit significant oscillatory roll response during severe maneuvers.

OR Keep DSI/SSF simple (as the original indexes) and note its limitations at the TWL threshold.

CHAPTER 4

EVALUATION OF THE FIELD TEST DATA

4.1 Introduction

The fourth chapter provides an evaluation of the field tests in Phase VI. This includes a discussion of the accuracy and repeatability of the collected data, common vehicle asymmetries, vehicle understeer and roll gradients, and an analysis of the field test data.

As shown in Table 2.2, during Phase VI testing three vehicles exhibited significant response asymmetries with respect to the minimum maneuver entrance speed required to produce TWL. These vehicles are the 1996 Acura SLX (“SLX”), 1995 Mitsubishi Montero (“Montero”), and the 1993 Ford Aerostar (“Aerostar”).

4.2 Accuracy and Repeatability of the Collected Data

Before analyzing any experimental data, one must be certain that the experiments were executed properly and consistently and that the results are accurate and repeatable. As detailed in Chapter 2, the Phase VI testing protocol was based on a well developed and documented process. Phase VI field tests were carried out according to that protocol and all inputs (speed, handwheel angle, environmental conditions, etc.) were appropriately recorded. The objective of the Phase VI tests was to determine the

minimum maneuver entrance speed at which TWL occurred. Therefore, in addition to measuring the wheel heights (TWL occurrence) onboard, the heights were also verified through video analysis. All other collected data was evaluated to ensure it makes physical sense. In other words, the collected data is accurate and repeatable (with the disclaimer given in Chapter 2 regarding test-to-test variability and TWL threshold vehicle response).

Ideally all tests should be performed according to the test protocol, and all commanded inputs should be executed accordingly. However, in real world testing, especially when dealing with a multibody nonlinear system such as a vehicle, slight differences in the inputs and the system itself over time may affect the system response. If these differences are consistent (e.g. handwheel rates achieved are 5% higher than the commanded rate), then comparisons between tests can easily be made. However, if the differences are inconsistent (e.g. handwheel rates achieved vary from 95% to 105% of the commanded rate), then the differences in the inputs must be considered when comparing similar tests. Possible reasons for unintended differences in inputs/responses are detailed below:

4.2.1 Commanded steering inputs (handwheel position and rate)

A programmable steering machine (handwheel controller) was used to produce the commanded steering inputs (handwheel position and rate). Although steering torque was not measured, it is likely that differences in torque required to rotate the handwheel clockwise (CW) versus counter-clockwise (CCW) exist. If so, then the handwheel controller may not have performed CW and CCW commanded rotation rates equally.

During Phase VI testing [1], J-Turn handwheel angle data were averaged for 1000 ms after the instant the commanded angle was first achieved. Road edge recovery handwheel angle data were averaged from 80 ms after completion of the initial steer to the initiation of the reversal to determine initial steer magnitudes. The reversal steer magnitudes were determined by averaging the handwheel data for 1000 ms after the instant the commanded angle of the reversal was first achieved. The commanded and actual handwheel angle (degrees) and rate (degrees/second) for the J-turn and road edge recovery maneuvers are given in Table 4.1. The percent differences are based on the actual range produced by the handwheel controller. For example, the commanded angle and rate for the J-turn maneuver (both steer directions) for the SLX was 384° at $1000^{\circ}/\text{sec}$, respectively. The actual range (averaged data as previously described) was $384\text{-}386^{\circ}$ (negligible difference: “---”) at $1114\text{-}1146^{\circ}/\text{sec}$ (2.8% difference). The commanded range difference is negligible (even if left versus right steer were at the opposite extremes, i.e., 384° to the left and 386° to the right), however the 2.8% differences in handwheel rate may have an effect on the vehicle response, e.g. yaw rate and lateral acceleration.

Significant differences of handwheel angle and/or rates between left versus right steer maneuvers may contribute to vehicle asymmetric response. Cases to consider further are shaded in Table 4.1 and include the Montero’s handwheel rate for the J-turn and the Aerostar’s handwheel rate for the reversal steer in the road edge recovery maneuver. Note these differences may occur for the same direction of steer, in which case the different handwheel angle and/or rate has no effect on left versus right steer vehicle asymmetric response. For example, the actual rate range limits for the Montero

in the J-turn maneuver (947 and 1030 deg/sec) are both left steer maneuvers in the maximum occupancy load configuration. Vehicle response comparisons made in Section 4.6, “Analysis of Field Test Data,” will consider differences in handwheel angle and rate.

			SLX	Montero	Aerostar	
J-turn			Commanded Angle	384	336	451
			Actual Angle Range	384 - 386	333-334	456 - 458
			% Difference	---	---	---
			Commanded Rate	1000	1000	1000
			Actual Rate Range	1114 - 1146	947 - 1030	1116 - 1135
			% Difference	2.8	8.4	1.7
Road Edge Recovery	Initial Steer	Commanded Angle	312	273	366	
		Actual Angle Range	310 - 312	270 - 272	376 - 377	
		% Difference	---	---	---	
		Commanded Rate	720	720	720	
		Actual Rate Range	739 - 754	712 - 733	745 - 752	
		% Difference	2.0	2.9	0.9	
	Reversal Steer	Commanded Angle	312	273	366	
		Actual Angle Range	312 - 313	270 - 273	369 - 371	
		% Difference	---	---	---	
		Commanded Rate	720	720	720	
		Actual Rate Range	707 - 721	713 - 721	590 - 722	
		% Difference	2.0	1.1	20.1	

Table 4.1: Handwheel Controller Angles (deg) and Rates (deg/sec)
Based on Tables 6.1 – 6.4 from [1]

4.2.2 Initial handwheel angle prior to the maneuver

Prior to a maneuver, the vehicle is driven in a “straight line” at a constant speed. Deviation from the straight line path is difficult for a driver to detect; therefore it is possible that the vehicle may have been driven with slight left or right steer prior to the maneuver. In addition, play/slop in the steering system may offset the actual handwheel angle achieved during the maneuver.

Fortunately, data is recorded for two seconds just before the initial steer is executed, so any deviations from straight line driving and/or play in the handwheel can be detected. During those two seconds, the handwheel angle usually fluctuates between $\pm 2^\circ$. The entire data set is then zeroed based on the mean value of the handwheel angle during the last second prior to the initial steer input. Therefore, a vehicle would have to have considerable play (much greater than 4°) before it had a noticeable effect on vehicle response. For example, if the handwheel had 4° of play, then the vehicle heading would be in a straight line when the handwheel angle was between $\pm 2^\circ$. If during both left and right steer J-turn maneuvers, the handwheel angle was -2° prior to the maneuver with a commanded maximum absolute handwheel angle of 360° , then the effective handwheel angle would be -362° for a left steer maneuver and 358° for a right steer maneuver.

In addition, the handwheel angle, yaw rate, and lateral acceleration were analyzed to ensure the vehicle was driven in a straight line and the instrumentation zero point was the same as the true vehicle zero point.

4.2.3 Environmental effects

Although all of the Phase VI tests for a given vehicle were performed within a short time span (less than 16 days), day-to-day environmental fluctuations may affect the vehicle response. The time period of the tests as well as temperature ranges are as follows (all tests performed on dry pavement):

SLX time period: June 7 –13, 2002 (72 to $92^\circ = 20^\circ$ F difference)

Montero: June 20 – July 3, 2002 (74 to $90^\circ = 16^\circ$ F difference)

Aerostar: September 16 – October 1, 2002 (55 to $84^\circ = 29^\circ$ F difference)

A recent study of the effect of temperature on vehicle response in the J-turn and road edge recovery maneuvers was performed at VRTC [19]. A 2001 Toyota 4Runner 4WD (with and without yaw stability control enabled) and a 2001 Chevrolet Blazer 2WD were tested on the same test track during cold, moderate, and hot ambient temperatures. The temperature averages were 30° F (cold), 76° F (moderate), and 90° F (hot). The vehicles were tested according to the Phase VI protocol (e.g. increase maneuver entrance speed by 5 mph until TWL occurs or maximum test speed is achieved). Out of the eighteen tests performed (essentially three vehicles, two maneuvers, three temperature ranges), the only temperature effect observed was that the Blazer tipped up in the J-Turn in cold weather (29° F) but did not in the moderate (83° F) and hot weather tests (86° F). In all of the other tests, the vehicle/maneuver combination produced TWL at about the same speed in either all temperature ranges or none. Therefore, given that the maximum temperature range in the Phase VI testing was relatively small (29°F for the Aerostar), the effect of temperature on vehicle response is assumed to be negligible.

The maximum allowed wind speed was 15 mph. There is the possibility that a sudden side gust of wind may affect the vehicle response. However, the tests are repeated to isolate the TWL threshold speed, so one particular test may be affected, but that group of tests performed at the TWL threshold speed are still valid.

4.2.4 Vehicle Dynamic Area (VDA) test surface

All Phase VI tests were performed on the VDA. It is an 1800 by 1200 foot, flat, paved surface with a one percent longitudinal grade for drainage. It was constructed to be a smooth, homogeneous surface, and it is constantly monitored (visually and SN

testing). The coefficient of friction (Skid Number—SN) was measured twice a month (weather permitting) and varied very little from month to month. The range of peak SN was 0.95 - 0.99 and sliding SN was 0.83 – 0.88 from May to October of 2003 [1].

Given the consistency of the test surface, it is unlikely that any road irregularities affected the vehicle response. The longitudinal grade may have a slight affect on vehicle response. All J-turn and road edge recovery maneuvers are performed directly climbing the grade (i.e., not across the grade), so any possible effects due to the grade are minimized.

4.2.5 Tire wear

Based on numerous tests performed at VRTC, it has been shown that tire wear during testing tends to increase the maximum lateral force capabilities of the tires and thus increases the maximum lateral acceleration of the vehicle and the vehicle's likelihood to tip up at a given speed. To minimize these effects, the tires were changed after each test series, e.g., one test series consists of both left and right J-turn tests in the nominal load condition. However, the tire change interval may be too long, especially since different tires wear at different rates and in different ways. In addition, the speed at which the tests are performed has a pronounced effect on the severity of the wear (the greater the maneuver entrance speed, the greater the tire wear). The following three studies investigate the number of vehicle tests needed for tire wear to have a noticeable effect on vehicle performance:

To test the effect of tire wear, VRTC performed 22 left-right road edge recovery tests with a 2001 Ford Explorer 4x4 (maximum occupancy) at the same entrance speed of

40 mph (range of 39.4 – 40.8 mph) and using the same steering inputs. The first 18 tests did not produce TWL (some lift, but less than two inches of front and rear wheel lift), but 3 of the last 4 tests did [not published].

In “Assessing the Feasibility of Using ASTM E1136 Standard Reference Test Tires During Road Edge Recovery Maneuvers” [20], 25 left-right road edge recovery tests at 42 mph entrance speed (range of 40.7 – 43.2 mph) were performed with a 1997 Ford Ranger 4x2 (ASTM E1136 Tires, 284lbs of roof ballast, 288° left-right steering). Each of the 25 tests produced at least 3” of front wheel lift after initiation of the steering reversal, and 22 of these tests produced front wheel lift of at least 4”. The eighth test produced minor TWL (front wheel lift of 3” and rear wheel lift of 0.5”). The first test to produce major TWL (at least 2” for the front and rear wheel) was the eleventh test. After the eleventh test, major TWL was observed during 8 of the remaining 14 tests.

According to the study “Tire Shoulder Wear in Repetitive Rollover Testing” by Automotive Testing, Inc. [21], “the effect of tire shoulder wear on a vehicle’s lateral acceleration and on the most-loaded tire’s lateral deformation in 19 identical severe maneuvers was found to be negligible, at least for the vehicle/tire (2001 Chevrolet Tracker with OEM Uniroyal Tiger Paw AWP tires) measured.” The severe maneuver was similar to the road edge recovery maneuver with 180° left/right steer at 50 mph.

Based on the previously mentioned studies and the Phase VI data, tire wear has an effect on vehicle response, but the effect is not noticeable if the number of tests performed on a set of tires is kept small. For some vehicle/tire/test combinations, “small” may be 5 tests, while for other combinations, “small” might be 18 tests (as with the 2001 Ford Explorer 4x4 described earlier).

4.2.6 Vehicle age and wear: worn or damaged suspension components

Before testing any vehicle, especially used vehicles, the vehicle must be inspected to ensure performance similar to manufacturer design. As mentioned in Chapter 2, the suspension components of the used vehicles were refurbished along with any other components that did not meet the manufacturers standards. Also, a four-wheel alignment was performed before testing. At a minimum, the following items were replaced, regardless of their condition:

1. Front and rear shock absorbers / struts
2. Front and rear springs
3. Front and rear shock absorber / strut bump stops
4. Front strut bearings and any related bushings
5. Rear shock bushings
6. Front and rear swaybar bushings

4.2.7 Test-to-test variability

In addition to the variability just mentioned (tire wear, commanded handwheel angle and rate, environment, test surface, etc.), other test-to-test variability may occur. This is especially likely when vehicles are being evaluated at their TWL threshold speeds (the maneuver entry speed for which TWL may or may not occur). When operating at this threshold, the propensity of TWL is very high, but not guaranteed.

Consider Figure 4.1, which compares six, left steer J-turn tests performed consecutively on the same day by the SLX, with speeds ranging from 38.1 to 40.4 mph.

At these threshold speeds, there were significant fluctuations of the lateral acceleration and roll angle, rate, and acceleration, even though all inputs were similar (fairly new tires, entrance speed, steer angle and rates, and environmental conditions).

Figure 4.1: Comparison of SLX Response at ≈ 39 mph, Nominal Load, Left Steer J-turn

Run #	Entry Speed (mph)	Color
33	40.4	red
34--TWL	39.9	black
35	38.1	green
36	37.0	magenta
37--TWL	39.5	blue
38	39.1	cyan

Legend for Figure 4.1

(If viewed as a black & white document, the important note to make is the roll angle plot that is singled out in Figure 4.2.)

The differences in the roll angle are also shown in Figure 4.2. Note that test 34 and 37 produced a maximum roll angle of 22° and 13° , respectively, while the other four tests only reached 10 - 11° of roll. The effect of tire wear was not apparent here.

Figure 4.2: Differences in Roll Angle

According to a 2001 NHTSA report on rollover resistance [19, Notice 2], the authors “estimate that the speed at tip-up [for the J-turn and fishhook (road edge recovery) maneuvers] is repeatable within 2 mph on the same surface.” Thus, the

variation in vehicle response shown in Figure 4.1 is not uncommon, even within the small range of vehicle speed (38.1 to 40.4 mph).

4.3 Common Vehicle Asymmetries

The tire lateral force as a function of load for a pair of wheels on an axle is maximized when the wheels are loaded equally [22]. This is because the tire cornering coefficient (cornering stiffness divided by load) is usually largest at light loads, diminishing continuously as the load reaches its rated value [13]. However, the wheels are usually not loaded equally. Reasons for this unequal load (left versus right wheel on a given axle) include static lateral CG offset, weight jacking (spring preload), and anti-roll bar preload. Other common asymmetries include tire and tire pressure differences.

Vehicles commonly have a static lateral CG offset toward the driver side, primarily due to the steering system and other vehicle controls located on the driver side. The lateral CG offsets for the three vehicles under consideration are (negative indicates offset toward the driver side):

SLX: -0.46" Nominal, -0.55" Max Occupancy

Montero: -1.13" Nominal, -1.08" Max Occupancy

Aerostar: -0.90" Nominal, -1.04" Max Occupancy

Due to the offsets, the loads on the tires are more balanced in a left steer maneuver (the lateral CG offset compensates for the normal lateral weight transfer in a turn).

Consequently, the vehicle should be able to achieve more lateral acceleration steering left.

Weight jacking and roll bar preload affect wheel load distribution but do not affect the CG position. They result in a weight increase on one diagonal (e.g., the right front and left rear) and a corresponding decrease on the opposite diagonal. As such, they change the maximum side force distribution front to rear (i.e., affect over/understeer) [22].

It is common for race cars to have different tires (stagger) and different tire pressures with respect to the left and right side of the vehicle. Although passenger vehicles have seemingly identical tires and tire pressures on the left and right side of the vehicle, the response of “identical” tires is rarely identical. For the purposes of this research, “identical” tires are assumed to perform identically, unless tested otherwise, e.g., vertical spring rates tested at S.E.A., Inc. presented in Chapter 5.

4.4 Understeer and Roll Gradients

The under/oversteer gradient is a measure of the vehicle’s front and rear lateral force response to the handwheel steer angle. An understeer (positive gradient) vehicle loses front wheel traction before the rear wheels, and thus plows out at high lateral accelerations (the front tires become saturated so that an increase in the handwheel angle does not correspond to an increase in lateral acceleration). An oversteer (negative gradient) vehicle loses rear wheel traction before the front wheels, and thus loses directional stability at high lateral accelerations (the vehicle will spin out unless the handwheel angle is reduced).

The roll gradient (gain) is defined as the degrees of body roll per lateral g of acceleration. Large differences between the left and right steer roll gradients are an indication of suspension irregularities.

Both the understeer gradient (deg of wheel steer/g) and the roll gradient (deg of body roll/g) were determined from the slowly increasing steer maneuver. The gradient calculations and the maneuver were based on the “Constant Speed, Variable Steer” test defined in SAE J266 [10]. As described in Chapter 2, the maneuver was performed at 50 mph in both the left and right steer directions. At time zero, the handwheel angle was linearly increased from 0° to 270° at a rate of 13.5°/second and then held constant at 270° for two seconds. The gradients under all test conditions (steer direction and load condition) are given in Table 4.2. Note that each gradient value shown in Table 4.2 is the average gradient based on at least three tests. The understeer and roll gradients of a vehicle refer to the linear range of vehicle response (handwheel angle versus lateral acceleration). As such, the gradients were based on the data from 0.1 to 0.4 g’s of lateral acceleration. Also included in Table 4.2 is the maximum consistent lateral acceleration obtained during the maneuver, i.e., when the vehicle begins to plow out. These differences in maximum lateral acceleration are common. In a recent comparison test by *Automobile Magazine* of four-door passenger cars under \$30,000, nine of the twelve vehicles tested achieved more lateral acceleration cornering left, and the remaining three had equal limits [24]. Three of the vehicles had 0.5-0.6 g’s more cornering left.

A plot of the handwheel angle versus lateral acceleration for each test condition is given in Figures 4.3 – 4.5. Figure 4.3 highlights the linear range used to determine the understeer gradient as well as the corresponding value of the understeer gradient, K.

Since only small differences in the roll gradient between left and right steer directions existed, only one plot of body roll angle versus lateral acceleration is given, Figure 4.6.

Although it is worthwhile to note the response asymmetries in this linear response range, those asymmetries may not be reflected at higher levels of lateral acceleration, e.g. during severe driving maneuvers. Furthermore, all three vehicles, especially the Montero, have lower understeer gradients steering left versus right. This indicates that for a given handwheel angle input, those vehicles will generate more lateral acceleration steering left. Based on that and the rollover models presented in Chapter 2 (where lateral acceleration was a primary effect), it would seem reasonable that both vehicles would be more likely to tip up in a left steer maneuver. According to Table 2.1 however, the SLX tips up at a lower speed in a left steer J-turn maneuver as expected, but the Montero tips up at a lower speed in a right steer J-turn maneuver.

	Steer Direction	SLX		Montero		Aerostar	
		Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy	Nominal Load	Maximum Occupancy
Understeer Gradient (deg/g)	Left	3.0	3.6	2.8	2.5	5.9	6.0
	Right	3.7	3.7	4.6	4.0	7.2	6.7
	%difference	20.9	2.7	48.6	46.2	19.8	11.0
Roll Gradient (deg/g)	Left	8.4	10.0	7.9	9.1	9.0	9.8
	Right	9.2	10.1	7.8	9.5	10.4	10.4
	%difference	9.1	1.0	1.3	4.3	14.4	5.9
Maximum Lateral Acceleration (g)	Left	0.74	0.70	0.71	0.65	0.63	0.65
	Right	0.74	0.65	0.66	0.61	0.65	0.62
	%difference	0.0	7.4	7.3	6.3	3.1	4.7

Table 4.2: Understeer Gradient, Roll Gradient, and Maximum Lateral Acceleration; Slowly Increasing Steer Maneuver

In the report, “Analysis of a Request for a Defect Investigation Submitted by Bridgestone/Firestone, Inc.” [25], Ford evaluated the variability in determining a vehicle’s understeer gradient. Based on the Ford study and other sources of variability, the “ODI [Office of Defects Investigation] believes that unless differences of at least 1°/g are found when comparing the measured understeer gradients of different vehicle models, one cannot confidently state that the vehicles truly have different understeer gradients.” Due to test variability involved in determining the understeer gradient, only those differences greater than 1°/g are considered significant and are consequently highlighted in Table 4.2.

Figure 4.3: SLX, Slowly Increasing Steer Maneuver

Figure 4.4: Montero, Slowly Increasing Steer Maneuver

Figure 4.5: Aerostar, Slowly Increasing Steer Maneuver

Figure 4.6: Aerostar Roll Gain, Slowly Increasing Steer Maneuver

4.6 Analysis of Field Test Data

A comparison between both steering directions for the J-turn maneuver is shown in Figures 4.7 – 4.10 (SLX), 4.13 – 4.15 (Montero), and 4.18 – 4.20 (Aerostar). The comparison covers both load conditions and presents the vehicle response at the minimum maneuver entrance speed for which TWL was produced and at a common maneuver entrance speed. A similar comparison for the road edge recovery maneuver is shown in Figures 4.11 – 4.12 (SLX), 4.16 – 4.17 (Montero), and 4.21 – 4.22 (Aerostar). Since the differences in the minimum maneuver entrance speeds required to produce TWL are not as significant for the road edge recovery relative to the J-turn, only one load condition (that condition that produced more asymmetric response) is shown for the road edge recovery maneuver.

Neither the Montero nor the Aerostar experienced TWL in the J-turn nominal load condition test, therefore only the common maneuver entrance speed results are given. All three vehicles experienced TWL in the J-turn maximum occupancy test in only one steering direction (either left or right, not both); therefore the non-TWL steer direction entrance speed considered was 60 mph (maximum test speed). For ease of comparison, all values are shown as absolute (positive).

Figure 4.7: SLX, Nominal Load, J-turn at Onset of TWL
Left Steer at 39.9 mph, Right Steer at 50.2 mph

Figure 4.8: SLX, Nominal Load, J-turn at Common Entrance Speed
Left Steer at 44.5 mph, Right Steer at 44.2 mph

Figure 4.9: SLX, Maximum Occupancy, J-turn at Onset of TWL

Left Steer at 34.6 mph, Right Steer at 61.1 mph*

*Note TWL did not occur, thus the maximum speed was used.

Figure 4.10: SLX, Maximum Occupancy, J-turn at Common Entrance Speed
Left Steer at 36.9 mph, Right Steer at 37.0 mph

Figure 4.11: SLX, Nominal Load, Road Edge Recovery at Onset of TWL
Left-Right Steer at 39.5 mph, Right-Left Steer at 36.4 mph

Figure 4.12: SLX, Nominal Load, Road Edge Recovery at Common Entrance Speed
Left-Right Steer at 36.4 mph, Right-Left Steer at 36.4 mph

Figure 4.13: Montero, Nominal Load, J-turn at Common Entrance Speed*

Left Steer at 60.3 mph, Right Steer at 59.9 mph

*Note TWL did not occur, thus the maximum speed was used.

Figure 4.14: Montero, Maximum Occupancy, J-turn at Onset of TWL

Left Steer at 60.1 mph*, Right Steer at 30.6 mph

*Note TWL did not occur, thus the maximum speed was used.

Figure 4.15: Montero, Maximum Occupancy, J-turn at Common Entrance Speed
Left Steer at 36.1 mph, Right Steer at 35.6 mph

Figure 4.16: Montero, Nominal Load, Road Edge Recovery at Onset of TWL
Left-Right Steer at 32.7 mph, Right-Left Steer at 40.6 mph

Figure 4.17: Montero, Nominal Load, Road Edge Recovery at Common Entrance Speed
Left-Right Steer at 35.1 mph, Right-Left Steer at 35.6 mph

Aerostar: J-Turn, Common Speed (244,252)

Figure 4.18: Aerostar, Nominal Load, J-turn at Common Entrance Speed*

Left Steer at 61.6 mph, Right Steer at 61.6 mph

*Note TWL did not occur, thus the maximum speed was used.

Figure 4.19: Aerostar, Maximum Occupancy, J-turn at Onset of TWL

Left Steer at 52.1 mph, Right Steer at 59.7 mph*

*Note TWL did not occur, thus the maximum speed was used.

Figure 4.20: Aerostar, Maximum Occupancy, J-turn at Common Entrance Speed
Left Steer at 37.1 mph, Right Steer at 37.0 mph

Figure 4.21: Aerostar, Maximum Occupancy, Road Edge Recovery at Onset of TWL
Left-Right Steer at 46.5 mph, Right-Left Steer at 40.8 mph

Figure 4.22: Aerostar, Maximum Occupancy,
Road Edge Recovery at Common Entrance Speed
Left-Right Steer at 37.5 mph, Right-Left Steer at 36.6 mph

Section 4.2 presented many possible unintended differences in the vehicle inputs that may cause vehicle response asymmetries. The first input mentioned was the commanded steering inputs (handwheel position and rate). As shown in Table 4.1, the limits of the range of the handwheel rate achieved in the J-turn for the Montero and in the road edge recovery for the Aerostar had differences of 8.4% and 20.1%, respectively. In Figure 4.14, the Montero's handwheel rate steering left in the J-turn was 1020.6 deg/s and steering right was 947.3 deg/s (7.4% difference). In Figure 4.21, the Aerostar achieved a handwheel rate in the reversal steer of the road edge recovery of 720.2 deg/s for left-right maneuver and 680.8 deg/s for the right-left maneuver (5.6% difference). These different handwheel rates (for all of the tests, not just those tests plotted in Figures 4.14 and 4.21) did not occur at the same maneuver entrance speed, therefore the effect cannot be singled out. However, all of the other tests shown in Figures 4.7 – 4.22 had negligible differences in the handwheel angle and rates achieved with respect to the comparison being made in each individual figure.

The second input considered was the initial handwheel angle prior to the maneuver and any instrumentation offsets. The average for each data set shown in Figures 4.7 – 4.22 for the second prior to the initial handwheel steer was used to determine if any initial offsets existed. For example, the average values for the first second shown in Figure 4.18 for the left steer J-turn were: 0.02° handwheel angle, 0.02 g of lateral acceleration, 0.43°/sec of yaw, 0.32° of body roll, etc. These values are comparable to the other tests, and therefore the effect of the initial handwheel angle prior to the maneuver and any instrumentation offsets is negligible.

The next two inputs mentioned, the environmental conditions and the test surface, cannot be determined from the available data. However, as stated earlier, the effect on vehicle asymmetric response, if any, is negligible.

The fifth and sixth unintended inputs discussed were the effect of tire wear and worn/damaged suspension components. Given the severity of the tests, it is likely that significant tire and suspension wear occurred. Unfortunately, no measurements of tire wear (tread depth, tread shoulder wear and temperature, etc.) or suspension forces/deflections were made. The magnitude of these effects is less for the simpler, single steer, J-turn maneuver. For example, a left steer J-turn will scrub off some of the right shoulder of the tires. The next set of tests, right steer J-turn, will be on those same used tires, but the effective part of the tire for these tests, the left shoulder, will be relatively unworn compared to the right shoulder. This idea of minimized effect of the tire wear also applies to some extent to the suspension components, e.g., bump stops. Therefore, the J-turn maneuver is considered to be more reliable in indicating vehicle asymmetric response.

The last item presented in Section 4.2, test-to-test variability, is an unfortunate occurrence in real world testing. Although its effect cannot be determined, Phase VI tests were repeated to verify the minimum maneuver entrance speed for which TWL was produced. As such, those speeds listed in Table 2.2 are a clear indication of vehicle asymmetric response.

CHAPTER 5

SUSPENSION AND STEERING TESTS

5.1 Introduction

The fifth chapter accomplishes the fourth objective of this research, which is to identify any vehicle components/characteristics, such as steering system or suspension asymmetries that may cause vehicle asymmetric response. Suspension and steering tests were performed at S.E.A., Inc. in Columbus, Ohio. As discussed in Chapter 4, the J-turn maneuver is considered to be more reliable in indicating vehicle asymmetric response. In addition, the J-turn is a simpler maneuver relative to the road edge recovery; therefore, modeling the dynamics of the J-turn and determining the effect of suspension and/or steering asymmetries is more intuitive for the J-turn. Since the SLX and the Montero exhibited the most differences in left versus right steer J-turn maneuvers, they were chosen for the suspension and steering tests. A description of these tests along with the results is given in this chapter.

5.2 Description of Suspension and Steering Tests

The following types of tests were performed on the SLX and the Montero: bounce, roll, lateral and longitudinal force compliance, steering compliance, and steering ratio. Each type of test was performed in the nominal load configuration, and some

of the tests were repeated for the maximum occupancy load configuration. Typically the compliance tests are performed for one side of the vehicle (e.g. left side longitudinal force compliance), because the other (right) side is assumed to respond identically. However, the SLX and Montero were not assumed to respond symmetrically, so both left and right side tests were performed when applicable. The actual tests performed with respect to the type of test, side of vehicle, and load configuration will be presented in Section 5.3.1 for the SLX and 5.3.2 for the Montero.

During the quasi-static bounce and roll tests, steel cross members were rigidly attached to the chassis of the vehicle. The ends of the cross members (at the sides of the vehicle) were moved up and down in phase to drive the vehicle chassis through its range of bounce motion and out of phase to drive the chassis through its range of roll motion. During the tests, the tires were positioned on free-floating wheel-pad units (commonly referred to as “Hunter pads”) so that no lateral or longitudinal forces, or aligning moments would exist at the tires. For all but the steering ratio test, the steering wheel was locked, and the service and park brakes were applied. During the tests, eleven string potentiometers, six linear displacement transducers, four vertical load scales, an inclinometer, and a load cell were used to measure the quantities necessary to describe the suspension or steering behavior. The transducer signals were appropriately processed to provide the desired engineering quantities.

A pneumatic cylinder was used to generate lateral and longitudinal forces for the translational compliance tests. The lateral compliance tests involved pulling either the right or left wheel pad toward the opposite side of the vehicle using the pneumatic cylinder and a custom attachment to the chassis. The out-of-phase longitudinal

compliance test involved pulling the same side front and rear wheel pads together using the pneumatic cylinder. The steering compliance test involved applying a pure aligning moment to the wheel under consideration using a custom apparatus mounted to the wheel. For all the compliance tests, the forces were measured using a load cell, and the necessary string potentiometers, displacement transducers, and load scales were used to measure the quantities necessary to describe the suspension characteristics under study. The steering ratio test was performed with the engine running, so that the effect of power steering would be included.

All wheel position and orientation measurements were made on both the right and left sides of the vehicle. The standard SAE vehicle dynamics coordinate system (longitudinal X-axis positive forward, lateral Y-axis positive rightward, and vertical Z-axis positive downward) was used to define the directions of the measured quantities. All quantities are measurements made relative to the 'normal' vehicle state prior to testing. For example, the vertical force shown on the graphs is the change in vertical force, not the absolute value of the vertical force. The measured translational quantities are positive directed along the positive X, Y, and Z axes. For example, a positive lateral deflection or force indicates a deflection or force directed to the right. Similarly for rotational quantities, positive rotations and applied torques are defined positive about an axis defined using the right-hand screw rule. Vertical suspension deflection (chassis deflection less tire deflection) is defined as positive for suspension compression and negative for suspension rebound.

5.3 Results of the Suspension and Steering Tests

The Suspension Test Summary tables (5.2 for the SLX and 5.4 for the Montero) contain selected suspension and steering system parameter results. These results are from linear curve fits to the listed suspension characteristic curves. The ranges of the characteristic curves over which the linear curve fits were made are shown in the corresponding graphs following the summary table. For all the graphs, the circles indicate the measured data points, the dashed lines connect the circles to represent the respective characteristic behavior throughout the full test range, and solid lines represent curve fits. For graphs with both left and right side suspension plots (e.g. front suspension spring rate and roll steer), circles are used for the right side suspension characteristics and triangles for the left side.

For brevity, only those graphs that indicate left versus right side suspension asymmetric response are shown, but all graphs corresponding to the steering system (front steering compliance and steering ratio) are shown. Note that unless stated otherwise, plots are based on the nominal load configuration.

5.3.1 SLX tests

Table 5.1 lists the tests performed on the SLX (DNP denotes “did not perform” test). As shown in Table 5.1, “Side” refers to the left (L) or right (R) side of the vehicle tested. These tests only measure one side of the vehicle at a time, unlike the roll, bounce, and steering ratio tests.

Test	Side	Load Configuration	
	L/R	Nominal	Max Occ
Front Bounce		x	DNP
Rear Bounce		x	DNP
Front Roll		x	x
Rear Roll		x	x
Front Lateral Compliance	L	x	x
Front Lateral Compliance	R	x	DNP
Rear Lateral Compliance	L	DNP	x
Rear Lateral Compliance	R	x	x
Out-of-Phase Longitudinal Compliance	L	x	DNP
Out-of-Phase Longitudinal Compliance	R	x	DNP
Front Steering Compliance	L	x	x
Front Steering Compliance	R	x	DNP
Rear Steering Compliance	L	x	x
Rear Steering Compliance	R	x	DNP
Steering Ratio Test		x	DNP

Table 5.1: SLX Suspension and Steering Tests

SLX Front Bounce Test Results		
	Front Right	Front Left
Front Ride Rate Vertical Force vs. Suspension Deflection	160.2 lb/in	159.0 lb/in
Front Bump Stop Stiffness* Vertical Force vs. Suspension Deflection	260 lb/in 1172 lb/in	365 lb/in 1447 lb/in
Front Tire Static Stiffness (30 psi) Vertical Force vs. Tire Deflection	1352 lb/in	1291 lb/in
*Nonlinear, broken up and linearized for 1-2" and 2-3" suspension compression		
SLX Rear Bounce Test Results		
	Rear Right	Rear Left
Rear Ride Rate Vertical Force vs. Suspension Deflection	237.9 lb/in	246.9 lb/in
Rear Bump Stop Stiffness* Vertical Force vs. Suspension Deflection	395 lb/in 1517 lb/in	423 lb/in 1910 lb/in
Rear Tire Static Stiffness (35 psi) Vertical Force vs. Tire Deflection	1412 lb/in	1427 lb/in

*Nonlinear, broken up and linearized for 0.5-1.6" and 1.6-2.2" suspension compression

(continued)

Table 5.2: SLX Suspension Test Summary

Table 5.2, continued

SLX Front Roll Test Results		
First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Front Right	Front Left
Front Roll Steer	0.0269	0.0571
Wheel Steer Angle vs. Roll Angle	0.0085	0.0330
Front Roll Camber	0.846	0.839
Wheel Camber Angle vs. Roll Angle	0.826	0.832
Overall Front Roll Rate	7703 in-lb/deg	
Roll Moment vs. Roll Angle	8218 in-lb/deg	
SLX Rear Roll Test Results		
First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Rear Right	Rear Left
Rear Roll Steer	0.0518	0.0516
Wheel Steer Angle vs. Roll Angle	0.0252	0.0292
Rear Roll Camber	0.0865	0.0845
Wheel Camber Angle vs. Roll Angle	0.112	0.128
Overall Rear Roll Rate	4754 in-lb/deg	
Roll Moment vs. Roll Angle	5832 in-lb/deg	

(continued)

Table 5.2, continued

SLX Front Steering Compliance Test Results First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Front Right	Front Left
Front Steering Compliance (deg/(ft-lb))	0.00501	0.00452
Applied Steering Torque vs. Steer Angle	DNP	0.00451
SLX Steering Ratio Test Results		
	Right	Left
Steering Ratio (fit between $\pm 360^\circ$)	19.76	19.85
Steering Wheel Angle vs. Front Wheel Steer Angle		
Ave. Steering Ratio (fit between $\pm 360^\circ$)	19.80	
Average of Right and Left Measured Ratios		

The results of the front bounce test are shown in Figure 5.1. The linear suspension spring rate was computed based on the suspension deflection from -1.0 to 1.0 inch during the front bounce test. All of the static tire stiffnesses (front and rear of both vehicles) were computed over the range of -0.5 to 0.5 inches of vertical tire deflection. The nonlinear response beyond 1.5 inches of suspension compression is an indication of front bump stop contact with the chassis. This nonlinear region is simply referred to as the bump stop stiffness. The front bump stops were short rubber squares, as shown in the Figure 5.2. The front suspension was a typical torsion bar suspension with a stabilizer bar. Refer to Figure 5.11 for a diagram of the front suspension.

Figure 5.1: SLX Front Suspension Spring Rate

Figure 5.2: SLX Front Bump Stop

As stated in Table 5.2, the linearized front bump stop stiffness from 1 to 2 inches of suspension compression is 365 lb/in and 260 lb/in for the left and right side respectively, and from 2 inches to maximum compression measured, the stiffness is 1445 lb/in and 1172 lb/in for the left and right side respectively.

The results of the rear bounce test are shown in Figure 5.3. The linear suspension spring rate was computed based on the suspension deflection from -1.0 to 1.0 inch. Note the nonlinear bump stop stiffness (about 0.5 to 2.1 inches of suspension deflection). During testing, the rear bump stops contacted the axle at 0.5 inches of suspension compression. A sketch of the rear bump stops is shown in Figure 5.4. The rear suspension consisted of a solid axle with coil springs, stabilizer bar, lateral rod, and trailing links. Refer to Figure 5.12 for a diagram of the rear suspension.

Figure 5.3: SLX Rear Suspension Spring Rate

Figure 5.4: Sketch of SLX Rear Bump Stop (side view)

The linearized bump stop stiffness from 0.5 to 1.6 inches of suspension compression is 423 lb/in and 395 lb/in for the left and right side respectively, and from 1.6 inches to the maximum compression measured, the stiffness is 1910 lb/in and 1517 lb/in for the left and right side respectively.

Although the springs, shock absorbers, and anti-roll bars are always active regardless of the direction of steer or roll angle, the bump stops only have an effect upon contact (i.e., in a severe maneuver), and therefore the bump stops on only one side of the vehicle can be active at a time (unless the vehicle is loaded beyond GVWR). Given that, and the differences in the right versus left bump stop stiffnesses (both front and rear), severe body roll (where the bump stops are compressed) will be greater clockwise (CW), i.e., in a left turn. The differences in the bump stop stiffnesses are likely one of the reasons the SLX experiences TWL at a lower maneuver entrance speed in a left steer versus a right steer J-turn maneuver. The stiffer bump stops absorb more of the energy as the vehicle rolls. During a severe maneuver, the bump stops may be completely compressed, at which point they act as a rigid link connecting the body (sprung mass) to the suspension (unsprung mass). The stiffer side of the suspension will suppress the roll acceleration such that less of an impact will occur when the bump stop is completely compressed. The softer side of the suspension will allow more roll acceleration and thus more of an impact will occur from the momentum of the sprung mass. Upon this faster, harder impact, the body may either rebound abruptly or continue to roll due to the sprung mass momentum.

As mentioned earlier, the nonlinear response region of suspension compression is simply referred to as the bump stop stiffness, and therefore, is not the actual stiffness of the bump stops. The suspension kinematics affect how the suspension deflects under lateral, longitudinal, and vertical load. For instance, the increased stiffness of the left side suspension (Figures 5.1 and 5.3) is likely due to earlier bump stop contact, and therefore, simply replacing or switching the bump stops will not have any effect on the vehicle

response. In addition to the bounce tests, this phenomenon will also affect the roll tests, in particular the roll stiffness of the SLX in CW versus CCW (counter-clockwise) roll.

Other vehicle bounce test data (2000 Kia Sportage and 1998 Chevrolet Malibu LS, [not published]) show that the combined front and rear bump stop stiffnesses are similar with respect to the left and right side of the vehicle. In addition, no known published material exists stating that a passenger vehicle manufacturer (i.e., excluding specialized race cars) purposely designed a suspension with different left versus right side spring and bump stop stiffnesses. Therefore, the SLX's suspension rates are unusual.

Unfortunately, the maximum roll angles achieved during the roll suspension tests were only about $\pm 4^\circ$ (Figure 5.5), while the roll angles in the field tests reached values of -15° (right steer) to 21° (left steer) during TWL. Although the roll stiffness of the vehicle is unknown beyond $\pm 4^\circ$ of roll, the important consideration is how the suspension responded leading up to TWL, i.e., at roll angles less than $\pm 10^\circ$. Both graphs in Figure 5.5 show that beyond $\pm 3^\circ$ roll angle, the front suspension is stiffer in CCW body roll. Linear regression analysis shows that the front roll stiffness is 3.1% greater in CCW versus CW body roll for the nominal load configuration and 12.0% for the maximum occupancy configuration. Note the roll stiffness becomes nonlinear for roll angles beyond -3° , especially in the maximum occupancy configuration. It appears that the bump stops or the anti-roll bar begin to have a predominant effect beyond -3° of roll. As for the rear, the rear roll stiffness is 3.2% greater in CCW versus CW body roll for the nominal load configuration and 2.0% for the maximum occupancy configuration (refer to Figure 5.6).

Figure 5.5: SLX Front Overall Roll Stiffness

Figure 5.6: SLX Rear Overall Roll Stiffness

Figure 5.7 presents the front roll steer for both load configurations. The right wheel had less roll steer than the left wheel for both load configurations. The roll steer was in the opposite rotational direction of the wheel steer needed to create the vehicle roll in a driving situation. For instance, negative wheel steer causes the vehicle to steer left, which causes the vehicle body to roll away from the turn (positive roll), which causes positive roll steer. This countersteer phenomenon is called roll understeer. For example, based on the nominal load test, during a right steer maneuver (roll CCW (-)), both tires exhibited countersteer (-0.20° for the right wheel and -0.24° for the left wheel at about -4° of roll). During a left steer maneuver (roll CW (+)), the countersteer magnitudes were 0.14° for the right wheel and 0.25° for the left wheel at about 4° of body roll. Note the roll steer on the heavier loaded tire during a turn that produces $\pm 4^\circ$ of roll: during a right steer, the left wheel has -0.20° of roll steer, and during a left steer, the right wheel has 0.14° . This phenomenon also occurs in the maximum occupancy configuration, although to a lesser extent.

The differences in the roll steer of the heavily loaded tire indicate that there is less roll countersteer in a left steer maneuver, and thus given identical inputs, a left steer maneuver should produce more lateral acceleration. However, the roll steer magnitudes are very small (less than $\pm 0.3^\circ$ for the roll angles tested) for both load configurations, and thus roll steer has little effect on the amount of lateral force generated by the tires.

In both tests, the vehicle was first rolled CW to 4° and then CCW to -4° and finally CW to 0° . Note in the maximum occupancy test that during the CCW roll, the wheels appeared to “stick” around -0.08° steer angle, and upon the final CW roll motion, they rotated to 0.07° steer angle. Ideally, the steer angle should have returned to 0° once

the roll angle reached 0° . The maximum occupancy roll test was performed twice to verify this response, and the wheels “stuck” even more in the second test.

Unlike the front roll tests, the rear roll tests showed negligible differences for the roll steer between the left and right wheels in both roll directions, and therefore the rear roll steer graphs are not shown. The negligible differences in roll steer are typical for a solid axle rear suspension, where the entire axle yaws slightly during roll causing both wheels to rotate in the same manner.

Figure 5.7: SLX Front Roll Steer

The SLX was tested for front and rear lateral force compliance. Compliances result from flexibility and deflection of the suspension components (mainly rubber bushings). These deflections cause some additional wheel steer and camber angle, as well as changing the effective track width of the vehicle. The front right and left wheel lateral force steer compliances are shown in Figure 5.8.

As the front left wheel is pulled to the right (i.e., in a right turn, top graph in Figure 5.8), the left wheel steers toward the right, and vice versa for the right front wheel (bottom graph in Figure 5.8). The magnitude of the steer angle is negligible though (0.10° for left wheel and -0.01° for right wheel, both under 600 lb of lateral force).

The rear lateral force compliance tests showed negligible differences between the left and right side wheels, and consequently, the graphs for these tests are not shown.

Figure 5.8: SLX Front Wheel Lateral Force Steer Compliance

The results of the nominal load configuration front steering compliance tests are shown in Figure 5.9. The maximum occupancy configuration tests had similar results to the nominal load configuration tests and therefore are not shown. As expected for a solid rear axle suspension, the rear steering compliance showed negligible differences between CW and CCW applied moments, and therefore, no graphs are presented for the rear steering compliance.

The steering rack attachment and the suspension link attachments will determine how much compliance steer there is in each case. Bent steering links (for packaging reasons) are more compliant than straight links, because a bent link in compression or tension will bend more easily. Also, longer links are more compliant than shorter links. Furthermore, during vehicle roll, the wheels move in opposite directions (one up and the other down) and the steering rack has a side force trying to move it to either the left or right [22].

A significant amount of compliance would mean that a given handwheel angle would produce less wheel steer than the steering ratio expectation. However, it is difficult to quantify the effect of compliance steer, since the aligning moment of the tire during a maneuver is unknown for the SLX. Although, published aligning moment data show that magnitudes can reach up to 200 ft-lb for a heavy loaded tire with moderate slip angles (4° to 8°) [13]. This range of aligning moment was also observed in the severe simulation runs that will be presented in Chapter 6.

The SLX's tie rods were connected to the steering arm in front of the wheel center (forward-steer configuration). The track rod and both tie rods were straight (no bends). The pitman arm was on the driver side, and consequently, the left wheel had less

compliance than the right wheel (fewer links connecting the left wheel to the pitman arm).

Based on the nominal load configuration front steering compliance tests, during a right turn, the right front wheel's compliance is 0.00549 deg/(ft-lb) and the left wheel's compliance is 0.00491 deg/(ft-lb); therefore the average is 0.00520 deg/(ft-lb). During a left turn, the right front wheel's compliance is 0.00452 deg/(ft-lb), and the left wheel's compliance is 0.00413 deg/(ft-lb); therefore the average is 0.00433 deg/(ft-lb). Thus, there is 20.1% more compliance in a right turn. Given the same handwheel angle magnitude, a left steer maneuver will produce more wheel steer than a right steer maneuver. However, given that the aligning moment is estimated to be less than 200 ft-lb, the maximum change in steer angle due to steering compliance is 1.04° for a right turn and 0.87° for a left turn, which is negligible.

Figure 5.9: SLX Front Steering Compliance

The results of the steering ratio tests are shown in Figure 5.10. The typical handwheel (steering) angle used in everyday driving is less than $\pm 360^\circ$, and the maximum used for the SLX's rollover tests was $\pm 386^\circ$ (J-turn). Consequently, the steering ratio was computed based on the linear fit between $\pm 360^\circ$ handwheel angle. Still, the handwheel angle was tested from lock-to-lock (732° and -736°) to reflect the performance during low speed maneuvers (e.g. parallel parking).

Although it is not apparent in Figure 5.10, it is common for the steering ratio plots to contain loops, which is a result of hysteresis and means that there is some compliance and/or loss motion (slop) in the steering system.

There was negligible difference between the left and right wheel steering ratios, 19.76 deg/deg and 19.85 deg/deg, respectively. The steering ratio steering right is 20.22 deg/deg and steering left is 19.57 deg/deg (taken as the average of both wheel steer angles versus handwheel angle, where 0° to 360° is right steer and 0° to -360° is left steer). Furthermore, the wheel steer angle of the heavier loaded outside tire at $\pm 360^\circ$ handwheel angle is 17.38° (right steer, left front tire) and -17.63° (left steer, right front tire). All of these values indicate that there is negligible difference in the handwheel angle versus wheel steer angle between a left steer and right steer maneuver.

Figure 5.10: SLX Steering Ratio

Figure 5.11: SLX Front Suspension [26]
Typical Torsion Bar Suspension

Figure 5.12: SLX Rear Suspension [26]

5.3.2 Montero tests

Similar to Table 5.1 for the SLX, Table 5.3 lists the tests performed on the Montero (DNP denotes “did not perform” test).

Test	Side	Load Configuration	
	L/R	Nominal	Max Occ
Front Bounce		x	DNP
Rear Bounce		x	DNP
Front Roll		x	x
Rear Roll		x	x
Front Lateral Compliance	L	x	x
Front Lateral Compliance	R	x	DNP
Rear Lateral Compliance	L	x	x
Rear Lateral Compliance	R	x	DNP
Out-of-Phase Longitudinal Compliance	L	x	DNP
Out-of-Phase Longitudinal Compliance	R	x	DNP
Front Steering Compliance	L	x	x
Front Steering Compliance	R	x	DNP
Rear Steering Compliance	L	x	x
Rear Steering Compliance	R	x	DNP
Steering Ratio Test		x	DNP

Table 5.3: Montero Suspension and Steering Tests

Montero Front Bounce Test Results		
	Front Right	Front Left
Front Ride Rate Vertical Force vs. Suspension Deflection	159.2 lb/in	153.8 lb/in
Front Bump Stop Stiffness* Vertical Force vs. Suspension Deflection	1430 lb/in 5048 lb/in	1403 lb/in 4216 lb/in
Front Tire Static Stiffness (26 psi) Vertical Force vs. Tire Deflection	1096 lb/in	1086 lb/in
*Nonlinear, broken up and linearized for 3.5-4.6" and 4.6"-max suspension compression		
Montero Rear Bounce Test Results		
	Rear Right	Rear Left
Rear Ride Rate Vertical Force vs. Suspension Deflection	216.7 lb/in	209.8 lb/in
Rear Bump Stop Stiffness* Vertical Force vs. Suspension Deflection	504 lb/in 1646 lb/in	540 lb/in 1645 lb/in
Rear Tire Static Stiffness (35 psi) Vertical Force vs. Tire Deflection	1369 lb/in	1356 lb/in

*Nonlinear, broken up and linearized for 2.0-2.6" and 2.6-3.1" suspension compression

(continued)

Table 5.4: Montero Suspension Test Summary

Table 5.4, continued

Montero Front Roll Test Results		
First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Front Right	Front Left
Front Roll Steer	-0.123	-0.166
Wheel Steer Angle vs. Roll Angle	-0.116	-0.156
Front Roll Camber	0.972	1.011
Wheel Camber Angle vs. Roll Angle	0.971	0.989
Overall Front Roll Rate	9336 in-lb/deg	
Roll Moment vs. Roll Angle	8818 in-lb/deg	
Montero Rear Roll Test Results		
First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Rear Right	Rear Left
Rear Roll Steer	-0.016	-0.019
Wheel Steer Angle vs. Roll Angle	-0.038	-0.040
Rear Roll Camber	0.159	0.174
Wheel Camber Angle vs. Roll Angle	0.170	0.173
Overall Rear Roll Rate	7835 in-lb/deg	
Roll Moment vs. Roll Angle	7679 in-lb/deg	

(continued)

Table 5.4, continued

Montero Front Steering Compliance Test Results First value given is Nominal Load Case and the other value is Maximum Occupancy Case		
	Front Right	Front Left
Front Steering Compliance (deg/(ft-lb)) Applied Steering Torque vs. Steer Angle	0.00608 DNP	0.00668 0.00653
Steering Ratio Test Results		
	Right	Left
Steering Ratio (fit between $\pm 360^\circ$) Steering Wheel Angle vs. Front Wheel Steer Angle	18.4	18.3
Ave. Steering Ratio (fit between $\pm 360^\circ$) Average of Right and Left Measured Ratios	18.3	

The results of the front bounce test are shown in Figure 5.13. The linear suspension spring rate was computed based on the suspension deflection from 0.0 to 2.0 inches during the front bounce test. Typically the spring rate is computed from -1.0 to 1.0 inch of suspension deflection, but the Montero's front axle unloaded quickly such that the front wheels were impending lift off at only 1.0 inch of suspension rebound.

Figure 5.13: Montero Front Suspension Spring Rate

Beyond five inches of suspension compression, the left side of the suspension is slightly softer than the right side of the suspension. This slight difference is reflected in the upper linearized bump stop values stated in Table 5.4. Note the nonlinear bump stop stiffness (about 3.0 to 5.3 inches of suspension compression) shown in Figure 5.13. A picture of the front bump stops and a diagram of the front suspension (typical torsion bar suspension with a stabilizer bar) are given in Figures 5.22 and 5.21, respectively.

The results of the rear bounce test are shown in Figure 5.14. The linear suspension spring rate was computed based on the suspension deflection from -1.0 to 1.0 inch. Note the nonlinear bump stop stiffness beyond 2.0 inches of suspension compression. Unlike the front suspension, the rear suspension does not have noticeable differences between the left and right side. A picture of the rear bump stops and a diagram of the rear suspension (solid axle with coil springs, stabilizer bar, lateral rod, and trailing links) are given in Figures 5.24 and 5.23, respectively.

Figure 5.14: Montero Rear Suspension Spring Rate

The differences between the right and left bump stop stiffnesses for the Montero were not as significant as those for the SLX. However, the left side of the suspension is slightly softer than the right side, and therefore the idea proposed earlier that the differences in suspension stiffness contribute to vehicle asymmetrical response is still valid. Furthermore, recall that the SLX experiences TWL at a lower maneuver entrance speed in a left steer versus a right steer J-turn maneuver and its right side suspension is softer than the left side. The same phenomenon applies to the Montero: it experiences TWL at a lower maneuver entrance speed in a right steer J-turn maneuver and its left side suspension is softer.

Unfortunately due to wheel lift off, the maximum roll angles achieved during the nominal load, front roll stiffness test (Figure 5.15) were -4.7° with 6 lbs remaining on the right front tire scale and 5.2° with 80 lbs remaining on left front tire scale. In the maximum occupancy configuration, the test limits due to wheel lift off were -4.7° and 5.7° .

Although the roll stiffness of the vehicle is unknown beyond $\pm 5^\circ$, the important consideration is how the suspension responded leading up to TWL, i.e., at roll angles less than $\pm 10^\circ$. Both nominal load and maximum occupancy Front Roll Stiffness graphs in Figure 5.15 show that the front roll stiffness is slightly stiffer in CW roll (note how the circles begin to deviate from the best fit (solid red) line). Furthermore, linear regression analysis shows that the front roll stiffness is 3.3% greater in CW versus CCW body roll for the nominal load configuration and 1.6% for the maximum occupancy configuration. As for the rear, the rear roll stiffness is 3.5% greater in CW versus CCW body roll for the nominal load configuration and 0.1% for the maximum occupancy configuration (refer to Figure 5.16).

Figure 5.15: Montero Front Overall Roll Stiffness

Figure 5.16: Montero Rear Overall Roll Stiffness

Figure 5.17 presents the front roll steer for both load configurations. The roll steer was in the same rotational direction as the wheel steer needed to create the vehicle roll in a driving situation, i.e., roll oversteer. For example, based on the nominal load test, during a right steer maneuver (roll CCW (-)), both tires exhibited oversteer (0.32° for the right wheel and 0.40° for the left wheel at -4.7° of roll). During a left steer maneuver (roll to right (+)), the roll steer magnitudes were -0.50° for the right wheel and -0.80° for the left wheel at 5.2° of roll. Note the roll steer on the heavier loaded tire during a turn that produces $\pm 4^\circ$ of roll: during a right steer, the left wheel has 0.37° of roll steer, and during a left steer, the right wheel has -0.47° . This phenomenon also occurs in the maximum occupancy configuration.

The differences in the roll steer of the heavily loaded tire for both load configurations indicate that there is more roll steer in a left steer maneuver. However, the differences in the roll steer magnitudes are very small (about 0.1°) for both load configurations, and thus roll steer has little effect on the differences in lateral force generated by the tires in a left versus right steer maneuver.

Unlike the front roll tests, the rear roll tests showed negligible differences for the roll steer between the left and right wheels in both roll directions, and therefore the rear roll steer graphs are not shown.

Figure 5.17: Montero Front Roll Steer

The results of the front lateral force compliance tests are shown in Figure 5.18. As shown in the top graph of Figure 5.18, as the front left wheel is pulled to the right (i.e., in a right turn), the left wheel steers toward the left, and vice versa for the right front wheel (bottom graph of Figure 5.18). The magnitude of the steer angle is negligible though (-0.19° for left wheel and 0.06° for right wheel, both under 600 lb of lateral force). The rear lateral force compliance tests showed negligible differences between the left and right wheels, and consequently, the graphs for these tests are not shown.

Figure 5.18: Montero Front Wheel Lateral Force Steer Compliance

The results of the nominal load configuration front steering compliance tests are shown in Figure 5.19. The maximum occupancy configuration tests had similar results to the nominal load configuration and therefore are not shown. As expected for a solid rear axle suspension, the rear steering compliance showed negligible differences between CW and CCW applied moments, and therefore, no graphs are presented for the rear steering compliance.

Based on the nominal load configuration front steering compliance test, during a right turn, the right front wheel's compliance is 0.00690 deg/(ft-lb) and the left wheel's compliance is 0.00660 deg/(ft-lb); therefore the average is 0.00675 deg/(ft-lb). During a left turn, the right front wheel's compliance is 0.00526 deg/(ft-lb) and the left wheel's compliance is 0.00676 deg/(ft-lb); therefore the average is 0.00601 deg/(ft-lb). Thus, there is 12.3% more compliance in a right turn. Given the same handwheel angle, a left steer maneuver will produce more wheel steer than a right steer maneuver. However, given that the aligning moment is estimated to be less than 200 ft-lb, the maximum change in steer angle due to steering compliance is 1.35° for a right turn and 1.20° for a left turn, of which the difference is negligible.

Figure 5.19: Montero Front Steering Compliance

The results of the steering ratio tests are shown in Figure 5.20. The typical handwheel (steering) angle used in everyday driving is less than $\pm 360^\circ$, and the maximum used for the Montero's rollover tests was $\pm 334^\circ$ (J-turn). Consequently, the steering ratio was computed based on the linear fit between $\pm 360^\circ$ handwheel angle. The handwheel angle was tested from lock-to-lock (609° and -640°) to reflect the performance during low speed maneuvers (e.g. parallel parking).

There was negligible difference between the left and right wheel steering ratios, 18.3 deg/deg and 18.4 deg/deg, respectively. The steering ratio steering right is 18.72 deg/deg and steering left is 18.24 deg/deg (taken as the average of both wheel steer angles versus handwheel angle, where 0° to 360° is right steer and 0° to -360° is left steer). Furthermore, the wheel steer angle of the heavier loaded outside tire at $\pm 360^\circ$ handwheel angle is 18.75° (right steer, left front tire) and -18.25° (left steer, right front tire). All of these values indicate that there is negligible difference in the handwheel angle versus wheel steer angle between a left steer and right steer maneuver.

Figure 5.20: Montero Steering Ratio

Figure 5.21: Montero Front Suspension [26]
Torsion Bar Suspension

Figure 5.22: Montero Front-Left Suspension
(view facing rearward, wheel in rebound)

Figure 5.23: Montero Rear Suspension

Figure 5.24: Montero Rear-Left Suspension
(view looking forward: bump stop, lateral link (connected to axle), and coil spring)

5.4 Physical Suspension Asymmetries

As shown in Figures 5.11 and 5.21, the front suspensions of both the SLX and the Montero were typical torsion bar suspensions with a stabilizer bar. The general layouts of those suspensions were similar and the only significant difference was that the Montero had rebound stops. As for the rear suspensions, shown in Figures 5.12 and 5.23, both vehicles had a solid axle with coil springs, stabilizer bar, lateral rod, and trailing links. Differences between the two rear suspensions include the shape of the bump stops, presence of a center link (SLX only), and the attachment points of the lateral (Panhard) rod. For the SLX, the left side of the rod was attached to the sprung mass (body) and the right side was attached to unsprung mass (solid axle). The attachment points for the Montero were just the opposite. The left side was attached to the axle, and the right side was attached to the body.

The purpose of the Panhard rod is to distribute the lateral force between the sprung and unsprung masses. When the rod is horizontal, the distributed forces are purely lateral, but upon some inclination of the rod, vertical forces are produced. The magnitude and direction of these vertical forces are dependent on the slope of the rod and the direction of vehicle cornering. As such, the vertical forces can either lift or pull down the sprung mass. Furthermore, [22] states that “some considerations in the design of a track bar [Panhard bar] include whether it is normally in tension or compression. For circle track racing, always turning left means that the bar should be attached to the body on the right side and to the axle on the left assuring that it is always in tension when cornering.” This statement supports the rollover tendencies of the SLX and the Montero. For example, the undesired effect of having the bar in compression occurs when the SLX

is steering left and when the Montero is steering right, in which both cases were more prone to vehicle rollover relative to the opposite steering direction. In addition, during severe maneuvers, the roll angles can easily be above 8° (without even producing TWL at 8°), and therefore, the inclination of the rod relative to the axle will produce more of a force coupling effect.

CHAPTER 6

VEHICLE DYNAMICS SIMULATION USING CARSIM™

6.1 Introduction

This chapter accomplishes the fifth objective of this research, which is to evaluate the sensitivity of vehicle response to asymmetric suspension characteristics. The vehicle dynamics simulation, CarSim™, was used for this purpose. More specifically, CarSim™ was used to evaluate the effect of the suspension asymmetries, detailed in Chapter 5, in an effort to explain the vehicle response asymmetries described in Chapter 4. The validity of CarSim™ and the model created in it, as well as the simulation results, are presented in this chapter.

6.2 Validity of CarSim™

CarSim™ is a PC-based program for simulating the dynamic response of a vehicle. It allows the user to create detailed vehicle models based on vehicle dimensions, inertias, suspension setup and response, steering response, and tire parameters. Version 5.15 was used in this simulation study and the model created (independent front suspension and solid axle rear suspension) is represented mathematically by 54 ordinary differential equations that describe its kinematic and dynamic behavior. It is composed of 9 bodies and has 14 multibody degrees of freedom.

It would be ideal to create a CarSim™ model that completely matched the vehicle parameters of the SLX and/or the Montero, perform J-turn tests, and modify the model accordingly until the simulation matched the field test results. Thus the CarSim™ model of the SLX and/or the Montero would represent the actual vehicles well, and the models would be considered validated. However, a “perfect” model is beyond the scope of this research effort, and it is not needed for the current study. The goal of this simulation effort is simply to gain a better understanding of the effect of the suspension asymmetries on vehicle response. Therefore a representative model is sufficient assuming that CarSim™ can accurately evaluate the model to produce meaningful results. The developers of CarSim™, the Mechanical Simulation Corporation (MSC), claim so. MSC states that “CarSim is built on decades of research in characterizing vehicles and reproducing their behavior with mathematical models,” and that “its validity has been well established by many automotive OEMs and Tier 1 suppliers where it is currently being used” [27]. Given that and CarSim’s™ popularity in industry and academic research, this research effort assumes that CarSim™ is capable of representing the vehicle response of mid-sized SUV's like the SLX and the Montero in the J-turn maneuver to evaluate the effect of suspension asymmetries.

6.3 The Vehicle Model Created in CarSim™

As mentioned, a representative model is sufficient for this study. A representative model is assumed to be a model that focuses on the first order effects of the vehicle (e.g., the vehicle masses, CG locations of those masses, and inertias) as well as contain comparable suspension parameters to the actual vehicle. Given the nature of this study,

only one model is needed. The model created was based on CarSim's™ Big SUV model (baseline, front steer only, rear wheel drive, independent front suspension, and solid axle rear suspension). In an effort to represent, not necessarily match, the response of the SLX, the model's masses, inertias, and CG locations were modified to represent those of the SLX in the maximum occupancy configuration. As detailed in Chapter 4, this configuration produced the most asymmetric response by the SLX and the Montero in the J-turn maneuver. Unfortunately, CarSim™ suspension models have only two generic forms: either independent or solid axle. As such, the effect of the Panhard rod as discussed in Section 5.4 cannot be evaluated using CarSim™.

The total vehicle mass, CG location, and inertias (roll, pitch, and yaw) for the SLX and the Montero (as determined by S.E.A., Inc.) and the models used in CarSim™ are given in Table 6.1 (baseline values were first presented in Table 2.1). Instead of using the total vehicle values directly, CarSim™ requires the sprung mass values. CarSim's™ default unsprung mass values (both front and rear) and their respective CG heights were used, but the lateral and longitudinal CG locations were assumed to be at the wheel centers, i.e., four separate masses represent the unsprung masses. The location of the sprung mass CG was calculated using a static moment equation based on the total vehicle CG location and the assumed unsprung masses CG locations. The roll, pitch, and yaw sprung mass moments of inertia required by CarSim™ were calculated based on the parallel axis theorem and the known total vehicle properties, with the assumption that the vehicle inertia can be accurately represented by five separate masses: the sprung mass and the unsprung mass at each wheel center.

Vehicle	Configuration	SSF	Weight	Wheelbase	Mean Track Width	C.G.			Mass Moments of Inertia		
						Longitudinal	Height	Lateral Offset	Pitch	Roll	Yaw
			(lb)	(in)	(in)	(in)	(in)	(in)	(ft-lb-sec ²)	(ft-lb-sec ²)	(ft-lb-sec ²)
1995 Mitsubishi Montero	baseline	0.95	4655	107.2	56.0	57.55	29.35	-1.13	2859	581	2920
	nominal load	0.98	4961	107.2	56.0	57.74	28.56	-0.95	3198	650	3317
	maximum occupancy	0.95	5657	107.2	56.0	63.55	29.58	-0.75	3489	698	3618
1996 Acura SLX	baseline	1.10	4467	108.5	60.0	52.13	27.33	-0.51	2758	572	2874
	nominal load	1.13	4798	108.5	60.0	52.56	26.58	-0.46	3090	640	3246
	maximum occupancy	1.08	5327	108.5	60.0	56.06	27.74	-0.55	3214	677	3397
CarSim™ Big SUV model, default values	total vehicle values	1.28	5401	112.2	63.8	43.50	24.88	0.00	3591	1017	3662
	sprung mass values		4872			42.13	25.98	0.00	3195	917	3195
CarSim™ SLX model, maximum occupancy	total vehicle values	1.08	5325	108.5	60.0	56.06	27.74	-0.55	3217	655	3531
	sprung mass values		4798			56.26	29.18	-0.61	2856	553	3114

Table 6.1: Vehicle Parameters of Actual Vehicles and CarSim™ Models

Upon completion of a simulation run, CarSim™ outputs a summary (“echo”) file that lists all the variables used, including the total vehicle CG locations and inertias. As shown in Table 6.1, these “total vehicle values” for the SLX model are about the same as the actual SLX values (any differences are highlighted), therefore the equations and assumptions used to calculate the sprung mass properties must be similar to those used in CarSim™ to determine the total vehicle properties. All of the equations and additional assumptions used to compute these masses, CG locations, and inertias are provided in the Appendix.

A comparable J-turn maneuver was created in CarSim™ based on the J-turn used in Phase VI for the SLX. For the maximum occupancy load configuration, the SLX’s J-turn handwheel magnitude was 384° and the rate was 1000°/sec. The model’s steering ratio was also modified to that of the SLX to ensure that the model would produce equivalent front wheel steer.

Since CarSim™ assumes the front suspension parameters are the same for the left and right side, the asymmetric SLX suspension values could not be included in one model/run. Given that, the SLX model used either the front right or front left side suspension parameters to represent the entire front suspension. The corresponding left or right side rear suspension values were used for the entire rear. Thus, the SLX model had either the entire “left side” or “right side” suspension setup, as noted in the figures for the SLX model.

The SLX’s suspension spring rates, bump stop stiffnesses, auxiliary roll stiffnesses, and vertical tire stiffnesses were determined from the data presented in Chapter 5 and were included in the model. The actual bounce test data (vertical force

versus suspension deflection as shown in Figures 5.1 and 5.3) were used as lookup tables in CarSim™, therefore utilizing the true suspension response rather than using the linearized spring rate and bump stop stiffness values listed in Table 5.2. The front and rear auxiliary roll stiffnesses were extracted from the overall roll stiffnesses according to the procedure used in [28]. The calculated auxiliary stiffness values were used as the “right side” suspension and increased by 10% for the “left side” values. The front vertical tire stiffnesses were averaged (left and right side) as was the rear tires’ values. Having one vertical tire stiffness value for the front tires and one for the rear tires includes the effect of the different front to rear tire pressures, but ignores the effect of different left to right side values. Based on the bounce test results, the percent differences of the vertical tire stiffness between the front tires is 4.6% and 1.0% for the rear tires. For the rear solid axle suspension model, CarSim™ requires the lateral distance between the springs and the lateral distance between the shocks, of which the SLX values were used. The remaining CarSim™ suspension and tire parameters were not modified. For reference purposes, the CarSim™ parsfile for a particular simulation run with the SLX model is included in the Appendix and lists all the default and modified values for that run.

In addition to the vehicle model, the road surface coefficient of friction (μ) was modified so that the SLX model response would be similar to the field tests with respect to the yaw rate (level off around 40°/sec, refer to Figures 4.7 - 4.10). As shown in Figure 6.1, a μ value of 1.1 minimized the yaw rate (compared to $\mu = 1.0$) and did not produce immediate vehicle rollover (compared to $\mu = 1.2$). As such, μ was set to 1.1 for all the simulation runs. The CarSim™ default Big SUV tire model stated “tire/ground friction

coefficient for this [tire] data” as 0.87 for lateral force data and 0.89 for longitudinal force data. It was assumed that CarSim™ multiplies μ with the tire/ground friction coefficient to get an overall friction coefficient; therefore the overall friction coefficient, with μ of 1.1, is 0.974 for lateral forces and 0.957 for longitudinal forces. This seems reasonable since the VDA’s range of peak SN was 0.95 - 0.99 during the SLX and Montero testing.

6.4 Simulation Results

Given the vast amount of vehicle response variables produced by CarSim™ and the focus of this research on rollover maneuvers (TWL), the format of the graphs shown in this chapter have been modified from the Chapter 4 graphs to include vertical wheel displacements for the front and rear tires (in place of yaw acceleration and roll acceleration plots that were shown previously).

The vertical wheel displacement values are given in the “Front (and Rear) Wheel Lift” plots. Each of these dynamic values is the current wheel center height minus the average of that wheel center height for the first second of the test, i.e., wheel lift is defined as the wheel center height minus the rolling radius of the tire. Given the vertical tire deflection, the stated wheel lift values are not necessarily the distance between the tire tread and the road surface. Based on the average tire stiffness (1370.3 lb/in) and vertical load (1331.8 lb), the average vertical tire deflection is 0.97 inch. Thus, the tire loses lateral grip as the “wheel lift” approaches one inch and upon reaching one inch, loses complete contact with the ground. For ease of comparison, only those wheels that are likely to tip up (inside wheels) are shown in the wheel lift plots, e.g., the left side wheels are shown for the left steer J-turn and vice versa for the right side. A legend is

provided in the wheel lift plots as additional clarification when left and right steer maneuvers are plotted together. For ease of comparison, all values are shown as absolute (positive).

As a basis for comparison, the default CarSim™ Big SUV (baseline, only front steer, rear wheel drive only) model response is shown in Figure 6.2. The modified Big SUV model representing the SLX is referred to as the “SLX model.”

Based on the vehicle response figures and the CarSim™ animation, the abrupt and momentary drop in lateral acceleration between 1.2 and 1.4 seconds is caused by the onset of the inside rear wheel lift. This phenomenon occurred in every J-turn simulation run.

Figure 6.1: Coefficient of Friction Study, SLX Model at 40 mph
 “Right Side” Suspension, No Lateral CG Offset

Figure 6.2: Big SUV Baseline Model at 40, 50, and 60 mph

The lateral CG offset for the SLX model caused the vehicle to drift to the left (toward the CG offset). At 30 mph (top plot in Figure 6.3), the vehicle drifted laterally 0.43 ft (5.2 in) after 40 ft of longitudinal travel. During this time, the initial response values were: roll angle (-0.16° , independent of speed and handwheel steer correction), yaw rate ($-0.08^\circ/\text{sec}$), and lateral acceleration (-0.002 g). Although, the lateral drift is barely noticeable at 30 mph, it becomes more apparent at 60 mph (essentially doubles). A handwheel steer correction of 0.4° (to the right) was used to maintain the vehicle in a straight line before the initial maneuver steer (refer to the bottom plot in Figure 6.3). With the handwheel steer correction, the initial yaw rate ($4.6\text{E-}4^\circ/\text{sec}$) and lateral acceleration ($1.0\text{E-}5\text{ g}$) values were negligible. All runs that include the lateral CG offset also have the handwheel steer correction (except for the top plot in Figure 6.3)

To test the effect of the lateral CG offset, only the “right side” suspension was used. As shown in Figures 6.4 and 6.5, there was a slight difference in response at 30 mph and a significant difference at 40 mph. At that higher speed, both steer directions produced 1.0 g of lateral acceleration, but the right steer also caused vehicle rollover while the left steer only produced 7° of roll.

Given the significant effect of the lateral CG offset, the offset was not used in the evaluation of the effect of the asymmetric suspension parameters. Based on the softer versus stiffer side of the suspension discussion in Chapter 5, the “right side” suspension was used for the left steer maneuver and the “left side” suspension for the right steer. At 30 mph (Figure 6.6), there was no noticeable difference between the left and right steer maneuvers. At 60 mph, the right steer maneuver with the stiffer suspension produced

0.5° less roll and about 0.1 - 0.2 inches less of wheel lift. This slight asymmetric response of the model is negligible when compared to the differences shown in the field test data.

The combined effect of the lateral CG offset and the asymmetric suspension parameters at 30 and 40 mph is shown in Figures 6.8 and 6.9, respectively. There is negligible difference at 30 mph, but at 40 mph the right steer maneuver produces vehicle rollover. When compared to the right steer maneuver at 40 mph with the lateral CG offset and the “right side” suspension (Figure 6.5), the stiffer left suspension (Figure 6.9) delays rollover by 0.5 seconds, but all of the response magnitudes are the same.

Based on this simulation study, the lateral CG offset dominated the vehicle response. Using the actual suspension parameters (spring force versus deflection data, and auxiliary roll stiffness) for the SLX showed some differences between left and right steer response, but to a much lesser extent than the CG lateral offset. The model response in roll either leveled off around 5-7° or completely rolled over. The actual SLX suspension was fairly symmetric in the linear range, but showed differences upon extreme suspension compression (where bump stop contact occurs). Given that, the bump stops may not have had an effect on the model. In the field tests, the SLX frequently experienced roll angles of 10° without TWL and had an oscillatory roll response that is indicative of bump stop contact. It is unfortunate that the model seems to be missing that middle ground, i.e, early level off of response or complete rollover.

Unfortunately due to time and monetary constraints, the response of the shock absorbers was not determined during the suspension and steering tests described in Chapter 5. To study the effect of the shock absorbers on vehicle response, the default

damping force, as shown in Figure 6.10, was decreased by 10% (Figure 6.12) and increased by 10% (Figure 6.13) and 20% (Figure 6.14) for the “left side” suspension. In addition, to test the effect of different front to rear shock absorbers, a series of simulations were performed with only the front (Figure 6.15) or rear (Figure 6.16) damping force increased by 10%. All of the shock absorber study tests included the lateral CG offset and the “left side” suspension for a series of right steer J-turn maneuvers at 40, 50, and 60 mph. This combination was chosen because it is prone to rollover. For comparison purposes, Figure 6.11 shows the vehicle response with the default damping values. In addition to the vehicle response plots shown previously, the figures in this study include a plot of the vehicle’s trajectory.

Compared to the vehicle response with the default damping force, decreasing the damping force by 10% caused the vehicle to roll over about half a second sooner, but increasing the damping force prevented rollover. As shown in Figure 6.13, at 50 mph the model with the 10% increase in damping force achieved TWL and 9° of roll without rolling over, which is a significant difference compared to all of the previous results. Furthermore, the vehicle did not experience TWL when the entrance speed was increased to 60 mph. In Phase VI testing, it was assumed that once TWL occurred, any increase in maneuver entrance speed would also produce TWL. All of the simulation runs support this assumption, except for the current one under consideration (Figure 6.13). In this particular simulation run, the increased speed caused the vehicle to plow out, and thus the additional speed was quickly scrubbed off. It is interesting to note that aside from the yaw rate, the vehicle response at 40 and 60 mph is very similar in Figure 6.13. When

compared to the 10% increase, the 20% increase in damping force prevented TWL and reduced the roll angle achieved in the 50 mph simulation, but had little effect on the other plotted values.

Increasing only the rear default damping force prevented the vehicle from rolling over at 40 mph, but the response was similar at both 50 and 60 mph to the default damping values. Compared to increasing both the front and rear by 10%, the rear increase only simulations had similar results at 40 mph. When compared to the rear increase only, the front increase only simulations produced more wheel lift at 40 mph and delayed rollover by almost half a second in the 50 and 60 mph runs.

Note that given the oscillatory roll response of the SLX observed during the J-turn and road edge recovery maneuvers in Phase VI, it is possible the default damping forces may not have paired well with the spring stiffnesses. If the springs were excessively stiff relative to the shock absorbers, the shocks' damping forces may have been "overpowered" by their respective springs, thereby having a relatively small effect on the overall vehicle response.

Based on the shock absorber study, it is evident that a change in the damping force response can have a significant effect on the vehicle response. A summary of this effect is given in Table 6.2.

Change*	Effect
-10%	vehicle rollover at 2.7 – 3.0 seconds
default	vehicle rollover at 3.0 – 3.5 seconds
+10%	no vehicle rollover, but TWL at 50 mph
+20%	no vehicle rollover, and only slight wheel lift
+10% front	prevent rollover at 40 mph, rollover at 50 and 60 mph at 3.3 – 3.5 seconds
+10% rear	prevent rollover at 40 mph, rollover at 50 and 60 mph at 2.9 – 3.0 seconds

*Change in the CarSim™ Big SUV default damping force values

Table 6.2: Shock Absorber Study

Figure 6.3: SLX Model: Y versus X Trajectory, Effect of the Lateral CG Offset Without (top) and With (top) Handwheel Angle Correction, 30 mph

Figure 6.4: SLX Model: Effect of Lateral CG Offset at 30 mph
“Right Side” Suspension

Figure 6.5: SLX Model: Effect of Lateral CG Offset at 40 mph
“Right Side” Suspension

J-turn: Effect of Asymmetric Suspension

Figure 6.6: SLX Model: Effect of Asymmetric Suspension at 30 mph

No Lateral CG Offset

“Right Side” Suspension for Left Steer and “Left Side” Suspension for Right Steer

Figure 6.7: SLX Model: Effect of Asymmetric Suspension at 60 mph
 No Lateral CG Offset
 “Right Side” Suspension for Left Steer and “Left Side” Suspension for Right Steer

Figure 6.8: SLX Model: Effect of Asymmetric Suspension Parameters and Lateral CG Offset at 30 mph
 “Right Side” Suspension for Left Steer, and “Left Side” Suspension for Right Steer

Figure 6.9: SLX Model: Effect of Asymmetric Suspension Parameters and Lateral CG Offset at 40 mph
 “Right Side” Suspension for Left Steer, and “Left Side” Suspension for Right Steer

Figure 6.10: CarSim™ Default Shock Absorber Response

Figure 6.11: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Default Damping Force for Comparison

Figure 6.12: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Decrease the Default Damping Force by 10%

Figure 6.13: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Increase the Default Damping Force by 10%

Figure 6.14: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Increase the Default Damping Force by 20%

Figure 6.15: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Increase the Front Default Damping Force by 10%

Figure 6.16: Shock Absorber Study, SLX Model
 “Left Side” Suspension with Lateral CG Offset
 Increase the Rear Default Damping Force by 10%

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The main objective of this research was to study vehicle response asymmetries during severe driving maneuvers. During Phase VI of the National Highway Traffic Safety Administration's (NHTSA) Light Vehicle Rollover Research Program, such response asymmetries occurred during field tests, and consequently, the data collected during Phase VI was used in this study. Of the twenty-six light vehicles tested in Phase VI, three vehicles exhibited significant response asymmetries with respect to left versus right steer maneuvers: the 1996 Acura SLX, 1995 Mitsubishi Montero, and the 1993 Ford Aerostar

Ideally, the vehicle response should be the same given identical steering and speed inputs as well as surface and environmental conditions. Such is the case, assuming vehicle symmetry, with modeling and computer simulation. However in actual field tests, test-to-test variability can cause small response fluctuations. Even more so, when testing at a vehicle's TWL threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur), the vehicle response is highly nonlinear and to some extent unpredictable. The combination of test-to-test variability and testing at TWL

threshold speeds adds to the complexity of analyzing vehicle response, e.g., when comparing left versus right steer vehicle response. Additional possible reasons for the asymmetric response were discussed in Chapter 4 and include the accuracy and repeatability of the collected data, common vehicle asymmetries, and vehicle understeer and roll gradients.

The cause of the vehicle asymmetric response is quite complex and cannot be narrowed down to one item alone, e.g., differences in the suspension spring rates. The vehicle responds to all of the inputs (vehicle speed, handwheel angle and rate, environmental conditions, test surface, tires, etc), so evaluating a single factor is difficult in real world testing. Careful consideration was given to possible unintended differences in the vehicle inputs that may cause vehicle asymmetric response. The unintended vehicle inputs evaluated include deviations in the desired commanded steering inputs, fluctuations of the environmental conditions, inconsistencies in the test surface, initial handwheel angle offset prior to the maneuver and any instrumentation offsets, and the effect of tire wear and worn/damaged suspension components as a result of testing. Aside from the tire and suspension wear, these unintended vehicle inputs were determined to be either negligible or to have an insignificant impact on the vehicle asymmetric response.

Given the severity of the tests, it is likely that significant tire and suspension wear occurred. Unfortunately, no measurements of tire wear (tread depth, tread shoulder wear and temperature, etc.) or suspension forces/deflections were made. It was determined that relative to the road edge recovery maneuver, the magnitude of these effects is less for the simpler, single steer, J-turn maneuver, and therefore, the J-turn maneuver was

considered to be more reliable in indicating vehicle asymmetric response. In addition, modeling the dynamics of the J-turn and determining the effect of suspension and/or steering asymmetries is more intuitive for the J-turn.

An attempt was made to minimize the undesirable effect of tire and suspension wear in the Phase VI tests through frequent tire changes and suspension and body inspections. As such, the likely cause of the vehicle response asymmetries is within the vehicle itself and not attributed to the test procedure/conditions. Suspension and steering tests were conducted on the SLX and the Montero to identify any vehicle components/characteristics, such as steering system or suspension asymmetries, that may cause vehicle asymmetric response.

The major suspension response asymmetries occurred in the bounce and roll tests. Both vehicles exhibited lower bump stop and roll (with respect to the top of the vehicle rolling to that side) stiffness values on the side of the suspension that was opposite to the more severe steer direction in the J-turn maneuver. For example, the SLX experiences TWL at a lower maneuver entrance speed in a left steer versus a right steer J-turn maneuver, and its right side suspension is softer than the left side. The same phenomenon applies to the Montero: it experiences TWL at a lower maneuver entrance speed in a right steer J-turn maneuver, and its left side suspension is softer.

Given the nonlinear suspension response upon bump stop contact, it is difficult to quantitatively compare the right and left side of the suspension response during extreme compression. However, linearized values were extracted for the initial bump stop contact and extreme bump stop compression. The linearized bump stop stiffness values were greater for the left side of the suspension by 20 to 40% for the front and 7 to 26% for the

rear of the SLX. The Montero linearized bump stop stiffnesses were greater for the right side by 2 to 20% for the front and negligible for the rear. Based on linear regression analysis, the SLX front roll stiffness values were 3.1% and 12.0% stiffer in counter-clockwise body roll for the nominal load and maximum occupancy configuration, respectively. The Montero front roll stiffness values were 3.3% and 1.6% stiffer in clockwise body roll for the nominal load and maximum occupancy configuration, respectively. There were no noticeable differences in the rear roll stiffness values for either vehicle.

Of the physical suspension asymmetries observed during the suspension tests, the most significant was the attachment points of the Panhard rod used in the rear suspension of both the SLX and the Montero. The rod's configuration supports the rollover tendencies of both vehicles, but the magnitude of the effect is unknown.

To confirm the trend that the softer side suspension will lead to earlier TWL in the opposite steer direction, a model representative of the SLX was created and evaluated using the vehicle dynamics computer simulation, CarSim™. Based on the simulation study, the lateral CG offset has a significant effect on the vehicle response. This supports the rollover model in Chapter 3 and the idea of an “effective SSF”. Interestingly, the lateral CG offset dominated the vehicle response. Using the actual suspension parameters (spring force versus deflection data, and auxiliary roll stiffness) for the SLX showed some differences between left and right steer response, but to a much lesser extent than the lateral CG offset. Given that, the bump stops may not have had an effect on the model. In the field tests, the SLX frequently experienced roll angles of 10° without TWL and had an oscillatory roll response that is indicative of bump stop contact.

It is unfortunate that the model seems to be missing that middle ground, i.e., either early level off of response or complete rollover. Although the simulation results show that the suspension asymmetric response has little effect on the vehicle response, the trend between the J-turn maneuver steer direction and the opposite side suspension relative stiffness cannot be ignored.

The response of the shock absorbers was not determined during the suspension and steering tests described in Chapter 5, but a simulation study was done to evaluate the effect of the shock absorbers on vehicle response. A series of simulation runs were performed with the default damping force as is, decreased by 10%, increased by 10%, and increased by 20%. Also a series of simulations was performed with only the front or rear damping force increased by 10%. Based on the shock absorber study, it is evident that a change in the damping force response can have a significant effect on the vehicle response. As the default damping force was increased from -10% to +20%, the vehicle model went from immediate rollover to delayed rollover to only TWL and finally to slight wheel lift. When compared to the rear increase only, the front increase only simulations (where only the front damping force was increased by 10%) produced more wheel lift at 40 mph but delayed rollover by almost half a second in the 50 and 60 mph runs.

According to Dixon [29], “even when correctly assembled and free of such gross errors, dampers of the same design, and intended to have the same performance, are frequently found to have forces differing by 20% or more.” As such, it is possible that the shocks used in the field tests were different with respect to the left versus right side of the vehicle. Furthermore, the findings of the shock absorber simulation study indicate

that subtle changes to the front/rear force distribution can also have a significant effect on vehicle response. In addition to the shocks, seemingly identical tires can have tire-to-tire variations.

7.2 Recommendations

Based on the significant effect of tire wear discussed in Chapter 4, a new set of tires should be used to verify the minimum maneuver entrance speed for which TWL occurred, with the first test on the new tires being at that isolated speed. This was not the tire change protocol used in Phase VI, but according to a recent NHTSA document [19], future field tests performed by NHTSA will rerun the maneuver with new tires if the maneuver entrance speed that produced TWL was at least 47.5 mph. Upon installing new tires, the first test will be run at 35 mph, and if TWL does not occur, the next test will be at the maneuver entrance speed that produced TWL.

Although the 1993 Ford Aerostar did not exhibit as extreme response asymmetries as the SLX and the Montero during Phase VI testing, the Aerostar should undergo the same suspension and steering tests to further verify the trend between the J-turn steer direction and the opposite side suspension relative stiffness.

Further investigation of the validity of CarSim™ in predicting vehicle rollover should be conducted as well as using other vehicle simulations such as ADAMS to test the effect of the SLX's and Montero's suspension asymmetric responses, including the effect of the Panhard rod as discussed in Section 5.4. In addition, the response of the shock absorbers on both the SLX and the Montero should be tested and incorporated into a representative model in CarSim™ or other simulation package to reevaluate the

model's response with the actual shock absorber response in place of the CarSim™ default values used in the current research effort.

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APPENDIX

MISCELLANEOUS EQUATIONS AND CARSIM™ PARSEFILE

Matlab® Code that determines the sprung mass inertias based on the total vehicle inertias and the CG locations.

```
%% Author: Mike Dorohoff
%% Date: October 14,2003
clc, clear;
format compact

%% known vehicle quantities (all lengths given in meters)
%% use SAE axis convention
Ixx = 917.89; %kg.m^2 for all inertias
Iyy = 4357.6;
Izz = 4605.71;
x_cg = 1423.92/1000; %longitudinal distance from front axle
%y_cg = 0;
y_cg = -13.97/1000; %lateral CG offset from centerline
h_cg = 704.6/1000; %CG height
tr = 1524/1000; %mean track width
wh_b = 2755.9/1000; %wheel base
mass = 2415.46; %total vehicle mass (kg for all masses)
mass_uf = 120; %unsprung front mass
mass_ur = 120; %unsprung rear mass
h_uf = 368.6/1000; %unsprung front mass CG height, CarSim default value
h_ur = 379.7/1000; %unsprung rear mass CG height, CarSim default value

%% calculate the sprung mass CG locations based on static moment equation
% The CG locations of the unsprung masses were assumed to be at the loaded wheel
% centers (i.e., four separate masses represent the unsprung masses). The
% lateral CG distance between the total vehicle CG and the front and rear
% unsprung masses were assumed to be negligible. See the end of this
% code for verification of this.
mass_s = mass - mass_uf - mass_ur; %sprung mass

%sprung mass, longitudinal distance from the front axle
x_scg = (mass*x_cg - mass_uf*0 - mass_ur*wh_b)/mass_s

%lateral sprung mass CG offset (negative toward driver side)
y_scg = (mass*y_cg)/mass_s
```

```

% sprung mass CG height
h_scg = (mass*h_cg - mass_uf*h_uf - mass_ur*h_ur)/mass_s

%% The sprung mass moments of inertia were calculated based on the parallel
% axis theorem, with the assumption that the vehicle inertia can be accurately
% represented by five separate masses: the sprung mass and the unsprung mass
% at each wheel center.

% unsprung mass roll moment of inertia about its own CG
Ixx_u = (mass_uf + mass_ur)*(tr/2)^2

% unsprung mass pitch moment of inertia about its own CG
% assume the mass is centered along the axle
Iyy_u = 0

% unsprung mass yaw moment of inertia about its own CG
% assumed to be symmetrical about the y-axis
Izz_u = Ixx_u

% sprung mass roll moment of inertia about its own CG
Ixx_s = Ixx - Ixx_u - mass_s*((h_scg - h_cg)^2 + (y_scg - y_cg)^2) ...
- mass_uf*(h_uf - h_cg)^2 - mass_ur*(h_ur - h_cg)^2

% sprung mass pitch moment of inertia about its own CG
Iyy_s = Iyy - Iyy_u - mass_s*((h_scg - h_cg)^2 + (x_scg - x_cg)^2) ...
- mass_uf*((h_uf - h_cg)^2 + (x_cg)^2) ...
- mass_ur*((h_ur - h_cg)^2 + (wh_b - x_cg)^2)

% sprung mass yaw moment of inertia about its own CG
Izz_s = Izz - Izz_u - mass_s*((y_scg - y_cg)^2 + (x_scg - x_cg)^2) ...
- mass_uf*((x_cg)^2) - mass_ur*((tr - x_cg)^2)

%% the lateral offset of the total vehicle CG has negligible effect
% on the sprung mass inertia values. Given that the sprung mass
% is almost ten times that of the combined unsprung masses, the
% effect of the lateral CG distance between the total vehicle CG
% and the front and rear unsprung masses is also negligible.
% y_cg = 0; % to evaluate the effect of the lateral CG offset
% Ixx_s = 749.4295
% Iyy_s = 3872.2
% Izz_s = 4221.8

% y_cg = -13.97/1000;
% Ixx_s = 749.4243;
% Iyy_s = 3872.2;
% Izz_s = 4221.8;

```

CarSim™ Parsfile for a particular simulation run with SLX Model (parts deemed unnecessary, e.g. animator information, were deleted)

```
*SLX Model
* Left side suspension
* 40 mph entrance speed
* Left steer J-turn
* CG offset
* Environment friction coefficient of 1.1
* Steering ratio of 19.8
* Modified tire stiffnesses
* default 'Big SUV' damping look-up table

ENTER_PARSFILE Runs\Run377.par
#FullDataName CarSim Run Control`SLX home2 pars output`mike
#VehicleCode Ind_SA
#ModelType Simulink
#Ready

*Animator details deleted...

ENTER_PARSFILE Vehicles\Sprung_Mass\SprMass116.par
#FullDataName Vehicle: Sprung Mass`SLX:inertias_cg`mike
Y_LENGTH 1500
LX_H 4000
H_H 560
H_CG_SU 741.1
L_WHEELBASE 2755.9
LX_CG_SU 1429
M_SU 2175.46
IXX_SU 749.42
IYY_SU 3872.2
IZZ_SU 4221.8
IXZ_SU 0
RX_SGUI 0.5869
RY_SGUI 1.3341
RZ_SGUI 1.3931
Y_CG_SU 15.5
Y_H 0
IXY_SU 0
IYZ_SU 0
Z_LENGTH 1400
Y_LENGTH 1620
#CheckBox0, 1 , Show Radii of Gyration
X_LENGTH 2755.9
iaxle 2
LX_AXLE 2755.9
Title SLX:inertias_cg <mike>
#DataSet : SLX:inertias_cg
#Category: mike
#FileID : SprMass116
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:12:58
#LinkCat Sprung mass
EXIT_PARSFILE Vehicles\Sprung_Mass\SprMass116.par

#BlueLink0, Vehicle: Sprung Mass`SLX:inertias_cg`mike` , sprung mass
#Ready

*Aerodynamics\Aero_Main\Aero105.par details deleted...

*No brakes used, information deleted...

#BlueLink6, Brakes: Four-Wheel System`Big SUV - No ABS` No ABS Control` , Brakes
#Ready

ENTER_PARSFILE Steering\System\StrSys107.par
#FullDataName Steering System`SUV - Gear 19.8`mike
```



```

*RSW_F 19.8
*RSW_R 20.0
*VLOW_STR_COMP(1) 1.5
*VLOW_STR_COMP(2) 1.5
*L1_LKPO 100
*L2_LKPO 100
*R1_LKPO 100
*R2_LKPO 100
*L1_AKPI 12
*L2_AKPI 8
*R1_AKPI 12
*R2_AKPI 8
*L1_ACAST 2
*L2_ACAST 1
*R1_ACAST 2
*R2_ACASTI 1
*L1_XKPO 0
*L2_XKPO 0
*R1_XKPO 0
*R2_XKPO 0
#Ready

```

```

ENTER_PARSFILE Steering\Rear_Steer\RearStr101.par
#FullDataName Steering System: Rear-Wheel Gain`No Rear Steering`
#DiagramOne0
R_STEER_SPEED_TABLE 2
0.000000, 0.000000
5.000000, 0.000000
ENDTABLE
Title No Rear Steering
#DataSet : No Rear Steering
#Category:
#FileID : RearStr101
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:05
#LinkCat Steer Gain vs. Speed
EXIT_PARSFILE Steering\Rear_Steer\RearStr101.par

```

```

#BlueLink6, Steering System: Rear-Wheel Gain`No Rear Steering` , Rear steering gain vs. speed
#Ready

```

```

ENTER_PARSFILE Steering\Str_Wheel_Tq\TqSW107.par
#FullDataName Steering Wheel Torque`1/20`
*3D_XLabel Speed (km/h)
*3D_YLabel Total kingpin moment (N-m)
*3D_ZLabel Steering-wheel torque (N-m)
#DiagramTwo
*3D_DATA 2, 2 --> columns x rows
M_SW_CARPET 3
0, 0.0, 200.0
0.0, 0.0, 0.0
20.0, 1.0, 1.0
ENDTABLE
Title 1/20
#DataSet : 1/20
#Category:
#FileID : TqSW107
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:04
#LinkCat Steering torque
EXIT_PARSFILE Steering\Str_Wheel_Tq\TqSW107.par

```

```

#BlueLink7, Steering Wheel Torque`1/20` , Rear steering gain vs. speed
iaxle 1
iside 1
R_GEAR_STR 19.8
VLOW_STR_COMP 1.5
#Ready

```

```

ENTER_PARSFILE Steering\Compliance\StrCmp100.par
#FullDataName Steering System: Compliance`SUV - 0.002 deg/N-m`
#DiagramOne0
STEER_COMP_TABLE 2
0.000000, 0.000000
1.000000, 0.000500
ENDTABLE
Title SUV - 0.002 deg/N-m
#DataSet : SUV - 0.002 deg/N-m
#Category:
#FileID : StrCmp100
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:10:06
#LinkCat Steering compliance
EXIT_PARSFILE Steering\Compliance\StrCmp100.par

#BlueLink4, Steering System: Compliance`SUV - 0.002 deg/N-m` , F steering system compliance
#Ready

ENTER_PARSFILE Steering\Kinematics\StrKin101.par
#FullDataName Steering System: Kinematics for One Wheel`Example Left Wheel Data`
#DiagramOne0
STEER_KIN_TABLE 2
-22.670000, -21.460000
-19.830000, -18.910000
-17.000000, -16.320000
-14.170000, -13.700000
-11.330000, -11.030000
-8.500000, -8.330000
-5.670000, -5.590000
-2.830000, -2.810000
0.000000, 0.000000
2.830000, 2.850000
5.670000, 5.740000
8.500000, 8.670000
11.330000, 11.630000
14.170000, 14.640000
17.000000, 17.680000
19.830000, 20.750000
22.670000, 23.870000
ENDTABLE
Title Example Left Wheel Data
#DataSet : Example Left Wheel Data
#Category:
#FileID : StrKin101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:10:05
#LinkCat Steering kinematics
EXIT_PARSFILE Steering\Kinematics\StrKin101.par

#BlueLink0, Steering System: Kinematics for One Wheel`Example Left Wheel Data` , L1 steering kinematics
L_KPO 100
A_KPI 12
A_CASTER 2
X_KPO 0
iaxle 2
iside 1
R_GEAR_STR 20.0
VLOW_STR_COMP 1.5
#Ready

ENTER_PARSFILE Steering\Compliance\StrCmp100.par
#FullDataName Steering System: Compliance`SUV - 0.002 deg/N-m`
#DiagramOne0
STEER_COMP_TABLE 2
0.000000, 0.000000
1.000000, 0.000500
ENDTABLE
Title SUV - 0.002 deg/N-m

```

```

#DataSet : SUV - 0.002 deg/N-m
#Category:
#FileID : StrCmp100
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:06
#LinkCat Steering compliance
EXIT_PARSFILE Steering\Compliance\StrCmp100.par

#BlueLink5, Steering System: Compliance`SUV - 0.002 deg/N-m` , R steering system compliance
#Ready

ENTER_PARSFILE Steering\Kinematics\StrKin100.par
#FullDataName Steering System: Kinematics for One Wheel`Linear`
#DiagramOne0
STEER_KIN_TABLE 2
-1.000000, -1.000000
1.000000, 1.000000
ENDTABLE
Title Linear
#DataSet : Linear
#Category:
#FileID : StrKin100
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:05
#LinkCat Steering kinematics
EXIT_PARSFILE Steering\Kinematics\StrKin100.par

#BlueLink1, Steering System: Kinematics for One Wheel`Linear` , L2 steering kinematics
L_KPO 100
A_KPI 8
A_CASTER 1
X_KPO 0
iaxle 1
iside 2
#Ready

ENTER_PARSFILE Steering\Kinematics\StrKin102.par
#FullDataName Steering System: Kinematics for One Wheel`Example Right Wheel Data`
#DiagramOne0
STEER_KIN_TABLE 2
-22.420000, -23.580000
-19.620000, -20.510000
-16.810000, -17.470000
-14.010000, -14.470000
-11.210000, -11.500000
-8.410000, -8.570000
-5.600000, -5.680000
-2.800000, -2.820000
0.000000, 0.000000
2.800000, 2.780000
5.600000, 5.530000
8.410000, 8.240000
11.210000, 10.920000
14.010000, 13.560000
16.810000, 16.160000
19.620000, 18.720000
22.420000, 21.250000
ENDTABLE
Title Example Right Wheel Data
#DataSet : Example Right Wheel Data
#Category:
#FileID : StrKin102
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:05
#LinkCat Steering kinematics
EXIT_PARSFILE Steering\Kinematics\StrKin102.par

#BlueLink2, Steering System: Kinematics for One Wheel`Example Right Wheel Data` , R1 steering kinematics
L_KPO 100

```

```

A_KPI 12
A_CASTER 2
X_KPO 0
iaxle 2
iside 2
#Ready

ENTER_PARSFILE Steering\Kinematics\StrKin100.par
#FullDataName Steering System: Kinematics for One Wheel`Linear`
#DiagramOne0
STEER_KIN_TABLE 2
-1.000000, -1.000000
1.000000, 1.000000
ENDTABLE
Title Linear
#DataSet : Linear
#Category:
#FileID : StrKin100
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:10:05
#LinkCat Steering kinematics
EXIT_PARSFILE Steering\Kinematics\StrKin100.par

#BlueLink3, Steering System: Kinematics for One Wheel`Linear` , R2 steering kinematics
L_KPO 100
A_KPI 8
A_CASTER 1
X_KPO 0
Title SUV - Gear 19.8 <mike>
#DataSet : SUV - Gear 19.8
#Category: mike
#FileID : StrSys107
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:13:00
#LinkCat 4-wheel steer
EXIT_PARSFILE Steering\System\StrSys107.par

#BlueLink7, Steering System`SUV - Gear 19.8` mike` , Steering system
#RingCtrl0, 0`, Powertrain type
OPT_PT 0
#MiscYellow0
#ENDMYellow
iaxle 1
#Ready

ENTER_PARSFILE Suspensions\Independent\Ind116.par
#FullDataName Suspension: Independent System`SLX: Front Left Suspension `mike
M_US 120
L_TRACK 1524
H_RC 130
R_AP 0.077
R_SPRING 1.0
R_DAMPER 1.0
CT_FX 0.43e-3
CS_FY -0.15e-3
CS_MZ 0.19e-2
CC_FX 0
CI_FY 0
CI_MZ 0
IW 1.1
Y_CL_SUSP 0
R_AP_BRAKE 0.077
FS_OFFSET 0
JNC_DESIGN 0
H_WC 368.6
#Ready

ENTER_PARSFILE Suspensions\Springs\Spring115.par
#FullDataName Suspension: Spring`SLX: Front Left`mike

```

```

SPRING_COMP_BETA 2
SPRING_EXT_BETA 2
#DiagramOne0
FS_COMP_TABLE 2
-120.570000, -607.870000
-116.140000, 488.390000
-110.090000, 1019.240000
-99.870000, 1396.000000
-88.630000, 1761.640000
-78.100000, 2099.840000
-66.750000, 2430.030000
-55.290000, 2781.880000
-44.550000, 3107.760000
-33.060000, 3434.610000
-21.650000, 3683.350000
-9.730000, 4058.320000
0.000000, 4500.000000
11.150000, 4853.270000
23.480000, 5129.330000
36.640000, 5566.810000
44.860000, 6321.450000
52.460000, 7303.430000
59.280000, 8468.910000
65.380000, 9848.960000
69.960000, 11516.590000
ENDTABLE
#DiagramOne1
FS_EXT_TABLE 2
-120.570000, -807.870000
-116.140000, 288.390000
-110.090000, 819.240000
-99.870000, 1196.000000
-88.630000, 1561.640000
-78.100000, 1899.840000
-66.750000, 2230.030000
-55.290000, 2581.880000
-44.550000, 2907.760000
-33.060000, 3234.610000
-21.650000, 3483.350000
-9.730000, 3858.320000
0.000000, 4300.000000
11.150000, 4653.270000
23.480000, 4929.330000
36.640000, 5366.810000
44.860000, 6121.450000
52.460000, 7103.430000
59.280000, 8268.910000
65.380000, 9648.960000
69.960000, 11316.590000
ENDTABLE
Title SLX: Front Left <mike>
#DataSet : SLX: Front Left
#Category: mike
#FileID : Spring115
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:16:32
#LinkCat Spring
EXIT_PARSFILE Suspensions\Springs\Spring115.par

#BlueLink0, Suspension: Spring`SLX: Front Left` mike` , Spring
#Ready

ENTER_PARSFILE Suspensions\Shocks\Shock106.par
#FullDataName Suspension: Shock Absorber` Big SUV Damping`
#DiagramOne0
FD_TABLE 2
-1410.000000, -7316.000000
-720.000000, -5019.000000
-390.000000, -3395.000000

```

```

-210.000000, -2618.000000
-90.000000, -1472.000000
-20.000000, -333.000000
20.000000, 333.000000
90.000000, 870.000000
200.000000, 1145.000000
390.000000, 1607.000000
760.000000, 2623.000000
1160.000000, 3740.000000
ENDTABLE
Title Big SUV Damping
#DataSet : Big SUV Damping
#Category:
#FileID : Shock106
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:10:00
#LinkCat Shock absorber
EXIT_PARSFILE Suspensions\Shocks\Shock106.par

#BlueLink1, Suspension: Shock Absorber`Big SUV Damping` `, Damper
#Ready

ENTER_PARSFILE Suspensions\Toe\Toe104.par
#FullDataName Suspension: Toe Angle`Example Front Toe`
#DiagramOne0
TOE_TABLE 2
-70.000000, 1.060000
-60.000000, 0.830000
-50.000000, 0.610000
-40.000000, 0.430000
-30.000000, 0.270000
-20.000000, 0.140000
-10.000000, 0.030000
0.000000, -0.050000
10.000000, -0.100000
20.000000, -0.130000
30.000000, -0.140000
40.000000, -0.110000
50.000000, -0.060000
60.000000, 0.010000
70.000000, 0.120000
ENDTABLE
Title Example Front Toe
#DataSet : Example Front Toe
#Category:
#FileID : Toe104
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:58
#LinkCat Toe
EXIT_PARSFILE Suspensions\Toe\Toe104.par

#BlueLink2, Suspension: Toe Angle`Example Front Toe` `, Toe vs. Jounce
#Ready

ENTER_PARSFILE Suspensions\Camber\Camber101.par
#FullDataName Suspension: Camber Angle`Example Front Camber`
#DiagramOne0
CAMBER_TABLE 2
-70.000000, 0.430000
-60.000000, 0.440000
-50.000000, 0.420000
-40.000000, 0.380000
-30.000000, 0.310000
-20.000000, 0.230000
-10.000000, 0.130000
0.000000, 0.000000
10.000000, -0.150000
20.000000, -0.320000
30.000000, -0.510000

```

```

40.000000, -0.720000
50.000000, -0.950000
60.000000, -1.210000
70.000000, -1.490000
ENDTABLE
Title Example Front Camber
#DataSet : Example Front Camber
#Category:
#FileID : Camber101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:10:02
#LinkCat Camber
EXIT_PARSFILE Suspensions\Camber\Camber101.par

#BlueLink3, Suspension: Camber Angle`Example Front Camber` , Camber vs. Jounce
#Ready

ENTER_PARSFILE Suspensions\Aux_Roll\AuxMx114.par
#FullDataName Suspension: Auxiliary Roll Moment`SLX - Linear left front`mike
*3D_XLabel Axle load (N)
*3D_YLabel Suspension roll (deg)
*3D_ZLabel Auxiliary roll moment (N-m)
#DiagramTwo
*3D_DATA 2, 2 --> columns x rows
MX_AUX_CARPET 3
0, 0.0, 1000.0
0.0, 0.0, 0.0
1.0, 650.4, 650.4
ENDTABLE
Title SLX - Linear left front <mike>
#DataSet : SLX - Linear left front
#Category: mike
#FileID : AuxMx114
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:16:33
#LinkCat Aux. roll moment
EXIT_PARSFILE Suspensions\Aux_Roll\AuxMx114.par

#BlueLink4, Suspension: Auxiliary Roll Moment`SLX - Linear left front` mike` , Aux Roll moment
#RingCtrl0, 1`, Jounce option
OPT_JNC_DESIGN 1
Title SLX: Front Left Suspension <mike>
#DataSet : SLX: Front Left Suspension
#Category: mike
#FileID : Ind116
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:16:33
#LinkCat Independent
EXIT_PARSFILE Suspensions\Independent\Ind116.par

#BlueLink8, Suspension: Independent System`SLX: Front Left Suspension` mike` , Lead unit front suspension
iaxle 2
add_reference_frame Axle 2
set_euler_angles yaw_roll_pitch
set_x_name X_A2
set_y_name Y_A2
set_z_name Z_A2
set_yaw_name Yaw
set_pitch_name Pitch_A2
set_roll_name Roll_A2
x_ref_length 1
y_ref_length 1
z_ref_length 1
x_length 1
y_length 1
z_length 1
#Ready

ENTER_PARSFILE Suspensions\Solid_Axle\SldAx108.par

```

```

#FullDataName Suspension: Solid Axle System`SLX: Rear Left Suspension `mike
H_RC 350
L_TRACK 1473.2
R_AP -0.1
L_SPRINGS 868.7
L_DAMPERS 868.7
R_SPRING 1.0
R_DAMPER 1.0
CT_FX 0
CS_FY -0.56e-5
CS_MZ 0.95e-3
CC_FX 0
CI_FY 0
CI_MZ 0
M_US 120
IA 40
IW 1.1
R_ROLL_STEER 0
Y_CL_SUSP 0
*TOE_L 0
*TOE_R 0
*CAMBER_L 0
*CAMBER_R 0
R_AP_BRAKE -0.1
FS_OFFSET 0
H_WC 379.7
H_CG_AXLE 379.7
#Ready

```

```

ENTER_PARSFILE Suspensions\Springs\Spring116.par
#FullDataName Suspension: Spring`SLX: Rear Left`mike
SPRING_COMP_BETA 2
SPRING_EXT_BETA 2
#DiagramOne0
FS_COMP_TABLE 2
-126.400000, -185.180000
-123.680000, 776.470000
-115.500000, 1421.860000
-104.660000, 1731.190000
-95.320000, 1999.110000
-84.510000, 2310.350000
-73.700000, 2621.720000
-63.110000, 2956.800000
-52.620000, 3266.400000
-41.920000, 3553.970000
-31.040000, 3892.620000
-21.020000, 4231.880000
-10.890000, 4502.900000
-1.020000, 4842.760000
0.000000, 4900.000000
8.620000, 5515.940000
16.860000, 6138.960000
25.840000, 6695.690000
34.020000, 7402.110000
41.200000, 8235.570000
46.310000, 9355.320000
50.510000, 10705.790000
53.340000, 12146.120000
ENDTABLE
#DiagramOne1
FS_EXT_TABLE 2
-126.400000, -385.180000
-123.680000, 576.470000
-115.500000, 1221.860000
-104.660000, 1531.190000
-95.320000, 1799.110000
-84.510000, 2110.350000
-73.700000, 2421.720000
-63.110000, 2756.800000

```



```

-52.620000, 3066.400000
-41.920000, 3353.970000
-31.040000, 3692.620000
-21.020000, 4031.880000
-10.890000, 4302.900000
-1.020000, 4642.760000
0.000000, 4700.000000
8.620000, 5315.940000
16.860000, 5938.960000
25.840000, 6495.690000
34.020000, 7202.110000
41.200000, 8035.570000
46.310000, 9155.320000
50.510000, 10505.790000
53.340000, 11946.120000
ENDTABLE
Title SLX: Rear Left <mike>
#DataSet : SLX: Rear Left
#Category: mike
#FileID : Spring116
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:16:34
#LinkCat Spring
EXIT_PARSFILE Suspensions\Springs\Spring116.par

#BlueLink0, Suspension: Spring`SLX: Rear Left` mike` , Spring
#Ready

ENTER_PARSFILE Suspensions\Shocks\Shock106.par
#FullDataName Suspension: Shock Absorber`Big SUV Damping`
#DiagramOne0
FD_TABLE 2
-1410.000000, -7316.000000
-720.000000, -5019.000000
-390.000000, -3395.000000
-210.000000, -2618.000000
-90.000000, -1472.000000
-20.000000, -333.000000
20.000000, 333.000000
90.000000, 870.000000
200.000000, 1145.000000
390.000000, 1607.000000
760.000000, 2623.000000
1160.000000, 3740.000000
ENDTABLE
Title Big SUV Damping
#DataSet : Big SUV Damping
#Category:
#FileID : Shock106
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:10:00
#LinkCat Shock absorber
EXIT_PARSFILE Suspensions\Shocks\Shock106.par

#BlueLink1, Suspension: Shock Absorber`Big SUV Damping`` , Shock
#Ready

ENTER_PARSFILE Suspensions\Aux_Roll\AuxMx115.par
#FullDataName Suspension: Auxiliary Roll Moment`SLX: Linear Rear Left`mike
*3D_XLabel Axle load (N)
*3D_YLabel Suspension roll (deg)
*3D_ZLabel Auxiliary roll moment (N-m)
#DiagramTwo
*3D_DATA 2, 2 --> columns x rows
MX_AUX_CARPET 3
0, 0.0, 1000.0
0.0, 0.0, 0.0
1.0, 526.6, 526.6
ENDTABLE

```

```

Title SLX: Linear Rear Left <mike>
#DataSet : SLX: Linear Rear Left
#Category: mike
#FileID : AuxMx115
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:16:34
#LinkCat Aux. roll moment
EXIT_PARSFILE Suspensions\Aux_Roll\AuxMx115.par

#BlueLink2, Suspension: Auxiliary Roll Moment`SLX: Linear Rear Left` mike` , Aux Mx
#Ready

#BlueLink12, Suspension: Solid Axle System`SLX: Rear Left Suspension` mike` , Lead unit rear suspension
iaxle 1
iside 1
add_reference_frame L1 Wheel
set_euler_angles yaw_roll_pitch
set_x_name X_L1
set_y_name Y_L1
set_z_name Z_L1
set_yaw_name Yaw_L1
set_pitch_name Rot_L1
set_roll_name Roll_L1
set_scale_var_pitch 360
x_ref_length 1
y_ref_length 1
z_ref_length 1
x_length 1
y_length 1
z_length 1
#Ready

ENTER_PARSFILE Tires\MSC_Model\Tire111.par
#FullDataName Tire: MSC Model`SLX front 275/70R16`mike
add_wheel tire data
set_radius 0.398000
set_radial_line on
set_thickness 0.275000
#BlueLink4, ```, Animator info
WRITE_WHEEL_OFFSET
set_offset_y 0.000000
SET_NUM_POINTS 12
SET_THICKNESS_SGUI 275
set_color black
#CheckBox0, 0 , Toggle solid
set_solid_shade on
#CheckBox1, 0 , animation link
#RingCtrl0, 1`, Model
OPT_TIRE_MODEL 1
RRE 398
IT 0
KT 231.4
FZ_MAX 100000
L_RELAX_X 55
L_RELAX_Y 565
VLOW_ALPHA 15
RR_C .005
RR_V .000029
#Ready

ENTER_PARSFILE Tires\Mz\TireMz104.par
#FullDataName Tire: Aligning Moment`Peak 110N-m, Load 5.8KN`
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Aligning Moment (N-m)
#DiagramTwo
*3D_DATA 3, 13 --> columns x rows
MZ_TIRE_CARPET 4

```

```

0, 2500.0, 4100.0, 5800.0
1.2, 16.0, 36.9, 61.5
2.8, 25.0, 62.9, 109.9
4.3, 22.1, 60.8, 112.1
5.8, 16.4, 48.8, 94.5
7.2, 11.5, 36.4, 73.3
8.9, 7.9, 26.0, 53.9
10.4, 5.6, 19.0, 40.4
11.8, 4.1, 14.1, 30.4
13.3, 3.0, 10.6, 23.2
15.0, 2.2, 8.0, 17.5
16.3, 1.7, 6.3, 14.0
27.6, 0.0, 0.0, 0.0
28.8, 0.0, 0.0, 0.0
ENDTABLE
Title Peak 110N-m, Load 5.8KN
#DataSet : Peak 110N-m, Load 5.8KN
#Category:
#FileID : TireMz104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Tire: Mz
EXIT_PARSFILE Tires\Mz\TireMz104.par

#BlueLink0, Tire: Aligning Moment`Peak 110N-m, Load 5.8KN` ` , Mz
#Ready

ENTER_PARSFILE Tires\Fy\TireFy104.par
#FullDataName Tire: Lateral Force`Slope 0.17, Load 6.7KN`
MU_REF_Y 0.87
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Absolute Lateral Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FY_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
1.2, 993.3, 1344.6, 1579.6
2.9, 2110.3, 2966.7, 3559.0
4.4, 2648.6, 3850.3, 4717.3
6.0, 2888.7, 4296.6, 5346.2
7.6, 2979.9, 4497.3, 5654.9
9.2, 2998.2, 4570.0, 5788.8
10.8, 2979.1, 4567.7, 5812.2
12.4, 2942.7, 4529.6, 5781.7
14.0, 2897.7, 4472.1, 5720.7
15.6, 2844.2, 4398.3, 5635.3
17.0, 2796.6, 4329.8, 5553.1
20.0, 2796.6, 4329.8, 5553.1
ENDTABLE
Title Slope 0.17, Load 6.7KN
#DataSet : Slope 0.17, Load 6.7KN
#Category:
#FileID : TireFy104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:56
#LinkCat Tire: Fy
EXIT_PARSFILE Tires\Fy\TireFy104.par

#BlueLink1, Tire: Lateral Force`Slope 0.17, Load 6.7KN` ` , Fy
#Ready

ENTER_PARSFILE Tires\Fx\TireFx103.par
#FullDataName Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN`
MU_REF_X 0.89
*3D_XLabel Vertical Load (N)
*3D_YLabel Abs. Slip Ratio [Kappa] (-)
*3D_ZLabel Absolute Longitudinal Tire Force (N)
#DiagramTwo

```

```

*3D_DATA 3, 12 --> columns x rows
FX_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
0.009, 335.625, 559.562, 785.36
0.013, 530.107, 883.918, 1240.425
0.027, 1094.347, 1815.034, 2527.206
0.067, 2326.209, 3736.741, 4998.142
0.133, 2930.522, 4581.301, 5944.776
0.2, 2998.326, 4648.622, 5979.575
0.267, 2961.147, 4576.08, 5866.472
0.333, 2900.795, 4475.8, 5728.702
0.4, 2836.935, 4373.485, 5592.818
0.467, 2775.123, 4275.93, 5465.168
0.533, 2716.933, 4184.816, 5346.879
0.6, 2662.641, 4100.222, 5237.549
ENDTABLE
Title Peak 20% Slip, Load 6.7KN
#DataSet : Peak 20% Slip, Load 6.7KN
#Category:
#FileID : TireFx103
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:57
#LinkCat Tire: Fx
EXIT_PARSFILE Tires\Fx\TireFx103.par

#BlueLink2, Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN` `, Fx
#Ready

ENTER_PARSFILE Tires\Camber_Thrust\CamStiff101.par
#FullDataName Tire: Camber Thrust Coefficient`Constant @ -60`
#DiagramOne0
KGAMMA_TABLE 2
0.000000, -60.000000
5000.000000, -60.000000
ENDTABLE
Title Constant @ -60
#DataSet : Constant @ -60
#Category:
#FileID : CamStiff101
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Camber thrust
EXIT_PARSFILE Tires\Camber_Thrust\CamStiff101.par

#BlueLink3, Tire: Camber Thrust Coefficient`Constant @ -60` `, Camber thrust
#BlueLink5, ```, External
Title SLX front 275/70R16 <mike>
#DataSet : SLX front 275/70R16
#Category: mike
#FileID : Tire111
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:13:04
#LinkCat MSC model
EXIT_PARSFILE Tires\MSC_Model\Tire111.par

#BlueLink9, Tire: MSC Model`SLX front 275/70R16` mike`, Lead unit left front tire
inside 2
add_reference_frame R1 Wheel
set_euler_angles yaw_roll_pitch
set_x_name X_R1
set_y_name Y_R1
set_z_name Z_R1
set_yaw_name Yaw_R1
set_pitch_name Rot_R1
set_roll_name Roll_R1
set_scale_var_pitch 360
x_ref_length 1
y_ref_length 1
z_ref_length 1

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```

x_length 1
y_length 1
z_length 1
#Ready

ENTER_PARSFILE Tires\MSC_Model\Tire111.par
#FullDataName Tire: MSC Model`SLX front 275/70R16`mike
add_wheel tire data
set_radius 0.398000
set_radial_line on
set_thickness 0.275000
#BlueLink4, ```, Animator info
WRITE_WHEEL_OFFSET
set_offset_y 0.000000
SET_NUM_POINTS 12
SET_THICKNESS_SGUI 275
set_color black
#CheckBox0, 0 , Toggle solid
set_solid_shade on
#CheckBox1, 0 , animation link
#RingCtrl0, 1`, Model
OPT_TIRE_MODEL 1
RRE 398
IT 0
KT 231.4
FZ_MAX 100000
L_RELAX_X 55
L_RELAX_Y 565
VLOW_ALPHA 15
RR_C .005
RR_V .000029
#Ready

ENTER_PARSFILE Tires\Mz\TireMz104.par
#FullDataName Tire: Aligning Moment`Peak 110N-m, Load 5.8KN`
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Aligning Moment (N-m)
#DiagramTwo
*3D_DATA 3, 13 --> columns x rows
MZ_TIRE_CARPET 4
0, 2500.0, 4100.0, 5800.0
1.2, 16.0, 36.9, 61.5
2.8, 25.0, 62.9, 109.9
4.3, 22.1, 60.8, 112.1
5.8, 16.4, 48.8, 94.5
7.2, 11.5, 36.4, 73.3
8.9, 7.9, 26.0, 53.9
10.4, 5.6, 19.0, 40.4
11.8, 4.1, 14.1, 30.4
13.3, 3.0, 10.6, 23.2
15.0, 2.2, 8.0, 17.5
16.3, 1.7, 6.3, 14.0
27.6, 0.0, 0.0, 0.0
28.8, 0.0, 0.0, 0.0
ENDTABLE
Title Peak 110N-m, Load 5.8KN
#DataSet : Peak 110N-m, Load 5.8KN
#Category:
#FileID : TireMz104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Tire: Mz
EXIT_PARSFILE Tires\Mz\TireMz104.par

#BlueLink0, Tire: Aligning Moment`Peak 110N-m, Load 5.8KN` ` , Mz
#Ready

ENTER_PARSFILE Tires\Fy\TireFy104.par

```

```

#FullDataName Tire: Lateral Force`Slope 0.17, Load 6.7KN`
MU_REF_Y 0.87
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Absolute Lateral Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FY_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
1.2, 993.3, 1344.6, 1579.6
2.9, 2110.3, 2966.7, 3559.0
4.4, 2648.6, 3850.3, 4717.3
6.0, 2888.7, 4296.6, 5346.2
7.6, 2979.9, 4497.3, 5654.9
9.2, 2998.2, 4570.0, 5788.8
10.8, 2979.1, 4567.7, 5812.2
12.4, 2942.7, 4529.6, 5781.7
14.0, 2897.7, 4472.1, 5720.7
15.6, 2844.2, 4398.3, 5635.3
17.0, 2796.6, 4329.8, 5553.1
20.0, 2796.6, 4329.8, 5553.1
ENDTABLE
Title Slope 0.17, Load 6.7KN
#DataSet : Slope 0.17, Load 6.7KN
#Category:
#FileID : TireFy104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:56
#LinkCat Tire: Fy
EXIT_PARSFILE Tires\Fy\TireFy104.par

#BlueLink1, Tire: Lateral Force`Slope 0.17, Load 6.7KN` ` , Fy
#Ready

ENTER_PARSFILE Tires\Fx\TireFx103.par
#FullDataName Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN`
MU_REF_X 0.89
*3D_XLabel Vertical Load (N)
*3D_YLabel Abs. Slip Ratio [Kappa] (-)
*3D_ZLabel Absolute Longitudinal Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FX_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
0.009, 335.625, 559.562, 785.36
0.013, 530.107, 883.918, 1240.425
0.027, 1094.347, 1815.034, 2527.206
0.067, 2326.209, 3736.741, 4998.142
0.133, 2930.522, 4581.301, 5944.776
0.2, 2998.326, 4648.622, 5979.575
0.267, 2961.147, 4576.08, 5866.472
0.333, 2900.795, 4475.8, 5728.702
0.4, 2836.935, 4373.485, 5592.818
0.467, 2775.123, 4275.93, 5465.168
0.533, 2716.933, 4184.816, 5346.879
0.6, 2662.641, 4100.222, 5237.549
ENDTABLE
Title Peak 20% Slip, Load 6.7KN
#DataSet : Peak 20% Slip, Load 6.7KN
#Category:
#FileID : TireFx103
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:57
#LinkCat Tire: Fx
EXIT_PARSFILE Tires\Fx\TireFx103.par

#BlueLink2, Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN` ` , Fx
#Ready

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```

ENTER_PARSFILE Tires\Camber_Thrust\CamStiff101.par
#FullDataName Tire: Camber Thrust Coefficient`Constant @ -60`
#DiagramOne0
KGAMMA_TABLE 2
0.000000, -60.000000
5000.000000, -60.000000
ENDTABLE
Title Constant @ -60
#DataSet : Constant @ -60
#Category:
#FileID : CamStiff101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Camber thrust
EXIT_PARSFILE Tires\Camber_Thrust\CamStiff101.par

#BlueLink3, Tire: Camber Thrust Coefficient`Constant @ -60` , Camber thrust
#BlueLink5, ```, External
Title SLX front 275/70R16 <mike>
#DataSet : SLX front 275/70R16
#Category: mike
#FileID : Tire111
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:04
#LinkCat MSC model
EXIT_PARSFILE Tires\MSC_Model\Tire111.par

#BlueLink10, Tire: MSC Model`SLX front 275/70R16` mike` , Lead unit right front tire
#MiscYellow1
#ENDMYellow
iaxle 2
iside 1
add_reference_frame L2 Wheel
set_euler_angles yaw_roll_pitch
set_x_name X_L2
set_y_name Y_L2
set_z_name Z_L2
set_yaw_name Yaw_L2
set_pitch_name Rot_L2
set_roll_name Roll_L2
set_scale_var_pitch 360
x_ref_length 1
y_ref_length 1
z_ref_length 1
x_length 1
y_length 1
z_length 1
#Ready

ENTER_PARSFILE Tires\MSC_Model\Tire112.par
#FullDataName Tire: MSC Model`SLX rear 275/70R16` mike
add_wheel tire data
set_radius 0.398000
set_radial_line on
set_thickness 0.275000
#BlueLink4, ```, Animator info
WRITE_WHEEL_OFFSET
set_offset_y 0.000000
SET_NUM_POINTS 12
SET_THICKNESS_SGUI 275
set_color black
#CheckBox0, 0 , Toggle solid
set_solid_shade on
#CheckBox1, 0 , animation link
#RingCtrl0, 1`, Model
OPT_TIRE_MODEL 1
RRE 398
IT 0
KT 248.6

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```

FZ_MAX 100000
L_RELAX_X 55
L_RELAX_Y 565
VLOW_ALPHA 15
RR_C .005
RR_V .000029
#Ready

ENTER_PARSFILE Tires\Mz\TireMz104.par
#FullDataName Tire: Aligning Moment`Peak 110N-m, Load 5.8KN`
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Aligning Moment (N-m)
#DiagramTwo
*3D_DATA 3, 13 --> columns x rows
MZ_TIRE_CARPET 4
0, 2500.0, 4100.0, 5800.0
1.2, 16.0, 36.9, 61.5
2.8, 25.0, 62.9, 109.9
4.3, 22.1, 60.8, 112.1
5.8, 16.4, 48.8, 94.5
7.2, 11.5, 36.4, 73.3
8.9, 7.9, 26.0, 53.9
10.4, 5.6, 19.0, 40.4
11.8, 4.1, 14.1, 30.4
13.3, 3.0, 10.6, 23.2
15.0, 2.2, 8.0, 17.5
16.3, 1.7, 6.3, 14.0
27.6, 0.0, 0.0, 0.0
28.8, 0.0, 0.0, 0.0
ENDTABLE
Title Peak 110N-m, Load 5.8KN
#DataSet : Peak 110N-m, Load 5.8KN
#Category:
#FileID : TireMz104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Tire: Mz
EXIT_PARSFILE Tires\Mz\TireMz104.par

#BlueLink0, Tire: Aligning Moment`Peak 110N-m, Load 5.8KN` , Mz
#Ready

ENTER_PARSFILE Tires\Fy\TireFy104.par
#FullDataName Tire: Lateral Force`Slope 0.17, Load 6.7KN`
MU_REF_Y 0.87
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Absolute Lateral Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FY_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
1.2, 993.3, 1344.6, 1579.6
2.9, 2110.3, 2966.7, 3559.0
4.4, 2648.6, 3850.3, 4717.3
6.0, 2888.7, 4296.6, 5346.2
7.6, 2979.9, 4497.3, 5654.9
9.2, 2998.2, 4570.0, 5788.8
10.8, 2979.1, 4567.7, 5812.2
12.4, 2942.7, 4529.6, 5781.7
14.0, 2897.7, 4472.1, 5720.7
15.6, 2844.2, 4398.3, 5635.3
17.0, 2796.6, 4329.8, 5553.1
20.0, 2796.6, 4329.8, 5553.1
ENDTABLE
Title Slope 0.17, Load 6.7KN
#DataSet : Slope 0.17, Load 6.7KN
#Category:

```



```

#FileID : TireFy104
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:56
#LinkCat Tire: Fy
EXIT_PARSFILE Tires\Fy\TireFy104.par

#BlueLink1, Tire: Lateral Force`Slope 0.17, Load 6.7KN` ` , Fy
#Ready

ENTER_PARSFILE Tires\Fx\TireFx103.par
#FullDataName Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN`
MU_REF_X 0.89
*3D_XLabel Vertical Load (N)
*3D_YLabel Abs. Slip Ratio [Kappa] (-)
*3D_ZLabel Absolute Longitudinal Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12  --> columns x rows
FX_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
0.009, 335.625, 559.562, 785.36
0.013, 530.107, 883.918, 1240.425
0.027, 1094.347, 1815.034, 2527.206
0.067, 2326.209, 3736.741, 4998.142
0.133, 2930.522, 4581.301, 5944.776
0.2, 2998.326, 4648.622, 5979.575
0.267, 2961.147, 4576.08, 5866.472
0.333, 2900.795, 4475.8, 5728.702
0.4, 2836.935, 4373.485, 5592.818
0.467, 2775.123, 4275.93, 5465.168
0.533, 2716.933, 4184.816, 5346.879
0.6, 2662.641, 4100.222, 5237.549
ENDTABLE
Title Peak 20% Slip, Load 6.7KN
#DataSet : Peak 20% Slip, Load 6.7KN
#Category:
#FileID : TireFx103
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:57
#LinkCat Tire: Fx
EXIT_PARSFILE Tires\Fx\TireFx103.par

#BlueLink2, Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN` ` , Fx
#Ready

ENTER_PARSFILE Tires\Camber_Thrust\CamStiff101.par
#FullDataName Tire: Camber Thrust Coefficient`Constant @ -60`
#DiagramOne0
KGAMMA_TABLE 2
0.000000, -60.000000
5000.000000, -60.000000
ENDTABLE
Title Constant @ -60
#DataSet : Constant @ -60
#Category:
#FileID : CamStiff101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Camber thrust
EXIT_PARSFILE Tires\Camber_Thrust\CamStiff101.par

#BlueLink3, Tire: Camber Thrust Coefficient`Constant @ -60` ` , Camber thrust
#BlueLink5, `` ` , External
Title SLX rear 275/70R16 <mike>
#DataSet : SLX rear 275/70R16
#Category: mike
#FileID : Tire112
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:05
#LinkCat MSC model

```

EXIT_PARSFILE Tires\MSC_Model\Tire112.par

```
#BlueLink13, Tire: MSC Model\SLX rear 275/70R16` mike` , Lead unit left rear tire
inside 2
add_reference_frame R2 Wheel
set_euler_angles yaw_roll_pitch
set_x_name X_R2
set_y_name Y_R2
set_z_name Z_R2
set_yaw_name Yaw_R2
set_pitch_name Rot_R2
set_roll_name Roll_R2
set_scale_var_pitch 360
x_ref_length 1
y_ref_length 1
z_ref_length 1
x_length 1
y_length 1
z_length 1
#Ready
```

```
ENTER_PARSFILE Tires\MSC_Model\Tire112.par
#FullDataName Tire: MSC Model\SLX rear 275/70R16` mike
add_wheel tire data
set_radius 0.398000
set_radial_line on
set_thickness 0.275000
#BlueLink4, ```, Animator info
WRITE_WHEEL_OFFSET
set_offset_y 0.000000
SET_NUM_POINTS 12
SET_THICKNESS_SGUI 275
set_color black
#CheckBox0, 0 , Toggle solid
set_solid_shade on
#CheckBox1, 0 , animation link
#RingCtrl0, 1`, Model
OPT_TIRE_MODEL 1
RRE 398
IT 0
KT 248.6
FZ_MAX 100000
L_RELAX_X 55
L_RELAX_Y 565
VLOW_ALPHA 15
RR_C .005
RR_V .000029
#Ready
```

```
ENTER_PARSFILE Tires\Mz\TireMz104.par
#FullDataName Tire: Aligning Moment`Peak 110N-m, Load 5.8KN`
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Aligning Moment (N-m)
#DiagramTwo
*3D_DATA 3, 13 --> columns x rows
MZ_TIRE_CARPET 4
0, 2500.0, 4100.0, 5800.0
1.2, 16.0, 36.9, 61.5
2.8, 25.0, 62.9, 109.9
4.3, 22.1, 60.8, 112.1
5.8, 16.4, 48.8, 94.5
7.2, 11.5, 36.4, 73.3
8.9, 7.9, 26.0, 53.9
10.4, 5.6, 19.0, 40.4
11.8, 4.1, 14.1, 30.4
13.3, 3.0, 10.6, 23.2
15.0, 2.2, 8.0, 17.5
16.3, 1.7, 6.3, 14.0
```

```

27.6, 0.0, 0.0, 0.0
28.8, 0.0, 0.0, 0.0
ENDTABLE
Title Peak 110N-m, Load 5.8KN
#DataSet : Peak 110N-m, Load 5.8KN
#Category:
#FileID : TireMz104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Tire: Mz
EXIT_PARSFILE Tires\Mz\TireMz104.par

#BlueLink0, Tire: Aligning Moment`Peak 110N-m, Load 5.8KN` ` , Mz
#Ready

ENTER_PARSFILE Tires\Fy\TireFy104.par
#FullDataName Tire: Lateral Force`Slope 0.17, Load 6.7KN`
MU_REF_Y 0.87
*3D_XLabel Vertical Load (N)
*3D_YLabel Slip Angle [Alpha] (deg)
*3D_ZLabel Absolute Lateral Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FY_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
1.2, 993.3, 1344.6, 1579.6
2.9, 2110.3, 2966.7, 3559.0
4.4, 2648.6, 3850.3, 4717.3
6.0, 2888.7, 4296.6, 5346.2
7.6, 2979.9, 4497.3, 5654.9
9.2, 2998.2, 4570.0, 5788.8
10.8, 2979.1, 4567.7, 5812.2
12.4, 2942.7, 4529.6, 5781.7
14.0, 2897.7, 4472.1, 5720.7
15.6, 2844.2, 4398.3, 5635.3
17.0, 2796.6, 4329.8, 5553.1
20.0, 2796.6, 4329.8, 5553.1
ENDTABLE
Title Slope 0.17, Load 6.7KN
#DataSet : Slope 0.17, Load 6.7KN
#Category:
#FileID : TireFy104
#Product : CarSim Version 5.15 October 2002
#Last update: 10-28-2002 12:09:56
#LinkCat Tire: Fy
EXIT_PARSFILE Tires\Fy\TireFy104.par

#BlueLink1, Tire: Lateral Force`Slope 0.17, Load 6.7KN` ` , Fy
#Ready

ENTER_PARSFILE Tires\Fx\TireFx103.par
#FullDataName Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN`
MU_REF_X 0.89
*3D_XLabel Vertical Load (N)
*3D_YLabel Abs. Slip Ratio [Kappa] (-)
*3D_ZLabel Absolute Longitudinal Tire Force (N)
#DiagramTwo
*3D_DATA 3, 12 --> columns x rows
FX_TIRE_CARPET 4
0, 2900.0, 4800.0, 6700.0
0.009, 335.625, 559.562, 785.36
0.013, 530.107, 883.918, 1240.425
0.027, 1094.347, 1815.034, 2527.206
0.067, 2326.209, 3736.741, 4998.142
0.133, 2930.522, 4581.301, 5944.776
0.2, 2998.326, 4648.622, 5979.575
0.267, 2961.147, 4576.08, 5866.472
0.333, 2900.795, 4475.8, 5728.702
0.4, 2836.935, 4373.485, 5592.818

```

```

0.467, 2775.123, 4275.93, 5465.168
0.533, 2716.933, 4184.816, 5346.879
0.6, 2662.641, 4100.222, 5237.549
ENDTABLE
Title Peak 20% Slip, Load 6.7KN
#DataSet : Peak 20% Slip, Load 6.7KN
#Category:
#FileID : TireFx103
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:57
#LinkCat Tire: Fx
EXIT_PARSFILE Tires\Fx\TireFx103.par

#BlueLink2, Tire: Longitudinal Force`Peak 20% Slip, Load 6.7KN` , Fx
#Ready

ENTER_PARSFILE Tires\Camber_Thrust\CamStiff101.par
#FullDataName Tire: Camber Thrust Coefficient`Constant @ -60`
#DiagramOne0
KGAMMA_TABLE 2
0.000000, -60.000000
5000.000000, -60.000000
ENDTABLE
Title Constant @ -60
#DataSet : Constant @ -60
#Category:
#FileID : CamStiff101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:09:55
#LinkCat Camber thrust
EXIT_PARSFILE Tires\Camber_Thrust\CamStiff101.par

#BlueLink3, Tire: Camber Thrust Coefficient`Constant @ -60` , Camber thrust
#BlueLink5, `` , External
Title SLX rear 275/70R16 <mike>
#DataSet : SLX rear 275/70R16
#Category: mike
#FileID : Tire112
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:05
#LinkCat MSC model
EXIT_PARSFILE Tires\MSC_Model\Tire112.par

#BlueLink14, Tire: MSC Model`SLX rear 275/70R16` mike` , Lead unit right rear tire
#MiscYellow2
#ENDMYellow
Title SLX assembly left <mike>
#DataSet : SLX assembly left
#Category: mike
#FileID : Vehicle156
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:17:00
#LinkCat Ind_SA
EXIT_PARSFILE Vehicles\Assembly\Vehicle156.par

#BlueLink2, Vehicle: Assembly`SLX assembly left` mike` , Vehicle
#Ready

ENTER_PARSFILE Control\Steer\Steer101.par
#FullDataName Control: Steering (Open Loop)`No steer`
OPT_DRIVER_MODEL 0
#DiagramOne0
STEER_SW_TABLE 2
0.000000, 0.000000
1.000000, 0.000000
ENDTABLE
Title No steer
#DataSet : No steer
#Category:

```

```
#FileID : Steer101
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:11:26
#LinkCat Open-loop steer control
EXIT_PARSFILE Control\Steer\Steer101.par
```

```
#BlueLink3, Control: Steering (Open Loop)`No steer` , Input1
#Ready
```

```
ENTER_PARSFILE Control\Braking\ConBrk100.par
#FullDataName Control: Braking`No Braking`
#DiagramOne0
PBK_CON_TABLE 2
0.000000, 0.000000
10.000000, 0.000000
ENDTABLE
Title No Braking
#DataSet : No Braking
#Category:
#FileID : ConBrk100
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:11:32
#LinkCat Brake control
EXIT_PARSFILE Control\Braking\ConBrk100.par
```

```
#BlueLink4, Control: Braking`No Braking` , Input1
#Ready
```

```
*Road Surface information deleted...
*3D_DATA 2, 2 --> columns x rows
MU_ROAD_CARPET 3
0, 0.0, 1.0
0.0, 1.1, 1.1
1.0, 1.1, 1.1
ENDTABLE
Title 1.1 <mike>
#DataSet : 1.1
#Category: mike
#FileID : RdFric113
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:08
#LinkCat Road: friction
EXIT_PARSFILE Roads\Friction\RdFric113.par
```

```
ENTER_PARSFILE Models\Simulink\Cmex108.par
#FullDataName Models: Simulink`J-turn simulink mdl`mike
#RunMdlFile C:\CarSim5\Programs\Simulink_MDL\J_turn_switch.mdl
#AltPath c:\CarSim5\Programs\Simulink_MDL
#RunSimCat Ind_Ind`C:\CarSim5\PROGRAMS\Solvers\S_function\i_i_mex.dll
#RunSimCat Ind_SA`C:\CarSim5\PROGRAMS\Solvers\S_function\i_s_mex.dll
#RunSimCat Ind_SA + SA`C:\CarSim5\PROGRAMS\Solvers\S_function\i_s__s_mex.dll
#RunSimCat Ind_SA + SA_SA`C:\CarSim5\PROGRAMS\Solvers\S_function\i_s__ss_mex.dll
#RunSimCat Ind_Ind + SA_SA`C:\CarSim5\PROGRAMS\Solvers\S_function\i_i__ss_mex.dll
#RunSimCat Ind_Ind + SA`C:\CarSim5\PROGRAMS\Solvers\S_function\i_i__s_mex.dll
*Sim_Code1 Ind_Ind
*Sim_Code2 Ind_SA
*Sim_Code3 Ind_SA + SA
*Sim_Code4 Ind_SA + SA_SA
*Sim_Code5 Ind_Ind + SA_SA
*Sim_Code6 Ind_Ind + SA
*Sim_Path1 C:\CarSim5\PROGRAMS\Solvers\S_function\i_i_mex.dll
*Sim_Path2 C:\CarSim5\PROGRAMS\Solvers\S_function\i_s_mex.dll
*Sim_Path3 C:\CarSim5\PROGRAMS\Solvers\S_function\i_s__s_mex.dll
*Sim_Path4 C:\CarSim5\PROGRAMS\Solvers\S_function\i_s__ss_mex.dll
*Sim_Path5 C:\CarSim5\PROGRAMS\Solvers\S_function\i_i__ss_mex.dll
*Sim_Path6 C:\CarSim5\PROGRAMS\Solvers\S_function\i_i__s_mex.dll
*Sim_Path7 C:\CarSim5\
*Sim_Path8 C:\CarSim5\
```

```

*Sim_Path9 C:\CarSim5\
*Sim_Path10 C:\CarSim5\
*Sim_Path11 C:\CarSim5\
*Sim_Path12 C:\CarSim5\
*Sim_Path13 C:\CarSim5\
*Sim_Path14 C:\CarSim5\
*Sim_Path15 C:\CarSim5\
*Sim_Path16 C:\CarSim5\
*Sim_Path17 C:\CarSim5\
*Sim_Path18 C:\CarSim5\
*Sim_Path19 C:\CarSim5\
*Sim_Path20 C:\CarSim5\
*MDL_PATH C:\CarSim5\Programs\Simulink_MDL\J_turn_switch.mdl
*ALTERNATE_PATH c:\CarSim5\Programs\Simulink_MDL
#RingCtrl0, 6, Ring
N_CODES 6
#MiscYellow0
#ENDMYellow
#Ready

```

```

ENTER_PARSFILE Generic\Lists\GList127.par
#FullDataName Generic Data Lists`simulink Import/Export `mike
#MiscYellow0
OPT_ALL_IMPORT 0
OPT_ECHO_IMPORT 1
begin_set_import
IMP_Steer_SW
end_set_import
#ENDMYellow
#MiscYellow1
OPT_ALL_EXPORT 0
OPT_ECHO_EXPORT 1
begin_set_export
EXP_Ay
EXP_Roll
EXP_Steer_SW
EXP_Vx
EXP_Yo
EXP_Xo
EXP_Z_L1
EXP_Z_L2
EXP_Z_R1
EXP_Z_R2
EXP_AVz
EXP_AVx
end_set_export
#ENDMYellow
#MiscYellow2
#ENDMYellow
Title simulink Import/Export <mike>
#DataSet : simulink Import/Export
#Category: mike
#FileID : GList127
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:13:11
#LinkCat Generic Lists
EXIT_PARSFILE Generic\Lists\GList127.par

#BlueLink0, Generic Data Lists`simulink Import/Export `mike`, Link 1
#Ready

```

```

ENTER_PARSFILE Generic\Lists\GList127.par
#FullDataName Generic Data Lists`simulink Import/Export `mike
#MiscYellow0
OPT_ALL_IMPORT 0
OPT_ECHO_IMPORT 1
begin_set_import
IMP_Steer_SW
end_set_import

```

```

#ENDMYellow
#MiscYellow1
OPT_ALL_EXPORT 0
OPT_ECHO_EXPORT 1
begin_set_export
EXP_Ay
EXP_Roll
EXP_Steer_SW
EXP_Vx
EXP_Yo
EXP_Xo
EXP_Z_L1
EXP_Z_L2
EXP_Z_R1
EXP_Z_R2
EXP_AVz
EXP_AVx
end_set_export
#ENDMYellow
#MiscYellow2
#ENDMYellow
Title simulink Import/Export <mike>
#DataSet : simulink Import/Export
#Category: mike
#FileID : GList127
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:11
#LinkCat Generic Lists
EXIT_PARSFILE Generic\Lists\GList127.par

#BlueLink0, Generic Data Lists`simulink Import/Export` mike` , Link 1
#CheckBox0, 1 , Check box
*MODEL_CHECK_BOX 1
Title J-turn simulink mdl <mike>
#DataSet : J-turn simulink mdl
#Category: mike
#FileID : Cmex108
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:18:11
#LinkCat Simulink
EXIT_PARSFILE Models\Simulink\Cmex108.par

#BlueLink12, Models: Simulink`J-turn simulink mdl` mike` , Model info
#Ready

ENTER_PARSFILE Generic\Group\GData109.par
#FullDataName Generic Data Group`All outputs`Outputs
#MiscYellow0
OPT_ALL_WRITE 1
#ENDMYellow
#MiscYellow1
#ENDMYellow
#MiscYellow2
#ENDMYellow
#MiscYellow3
#ENDMYellow
#MiscYellow4
#ENDMYellow
#MiscYellow5
#ENDMYellow
#MiscYellow6
#ENDMYellow
#MiscYellow7
#ENDMYellow
#MiscYellow8
#ENDMYellow
Title All outputs <Outputs>
#DataSet : All outputs
#Category: Outputs

```

```

#FileID : GData109
#Product : CarSim Version 5.15  October 2002
#Last update: 10-28-2002 12:11:23
#LinkCat Generic group
EXIT_PARSFILE Generic\Group\GData109.par

#BlueLink13, Generic Data Group`All outputs` Outputs` , Output Variables
Opt_SC 2
#Ready

ENTER_PARSFILE Control\Speed_t\SpdTime102.par
#FullDataName Control: Speed vs. Time`drop throttle 40 mph` mike
SPEED_KI 0.157
SPEED_KP 0.141
OPT_VMIN -1
#DiagramOne0
SPEED_TIME_TABLE 2
0.000000, 64.370000
5.000000, 64.370000
5.010000, 0.000000
20.000000, 0.000000
ENDTABLE
Title drop throttle 40 mph <mike>
#DataSet : drop throttle 40 mph
#Category: mike
#FileID : SpdTime102
#Product : CarSim Version 5.15  October 2002
#Last update: 10-27-2003 15:13:12
#LinkCat Speed vs. time
EXIT_PARSFILE Control\Speed_t\SpdTime102.par

#BlueLink7, Control: Speed vs. Time`drop throttle 40 mph` mike` , Speed link
#BlueLink8, Control: Speed vs. Station```, Speed link
Speed 120
TSTOP 20
TSTART -3
Sstart -50
sgui_Sstop 1000
TSTEP 0.001
*TSTEP_OUT 0.01
*FREQ_MODEL 1000
*FREQ_OUT 100
TSTOP_WRITE 20
OPT_WRITE_BASIS 1
iprint 10
Sstop 1000
#RingCtrl0, 2`, Speed Control
#RingCtrl1, 0`, Placeholder
#RingCtrl2, 1`, Stop Station
OPT_SSTOP 1
#RingCtrl3, 0`, Direction of vehicle on road
#CheckBox0, 1 , Multiple Plot
#CheckBox1, 0 , Overlay Plots
#CheckBox2, 1 , Show More Settings
#CheckBox3, 0 , Run RT-Animation
#MiscYellow0
#ENDMYellow
#BlueLink15, Plot: Setup`Vx -- longitudinal speed` Vehicle Motion` , Plot #1
#BlueLink16, Plot: Setup`Ay -- lat. accel. of CG's` Vehicle Motion` , Plot #2
#BlueLink17, Plot: Setup`Roll -- sprung masses` Vehicle Motion` , Plot #3
#BlueLink18, Plot: Setup`Y vs X -- trajectory` Tracking` , Plot #4
#BlueLink19, Plot: Setup`Steer SW -- steering wheel` Steering` , Plot #5
#BlueLink20, Plot: Setup``, Plot #6
#BlueLink21, Plot: Setup``, Plot #7
#BlueLink22, Plot: Setup``, Plot #8
#BlueLink23, CarSim Run Control``, Overlay #1
#BlueLink24,``, Overlay #2
#BlueLink25,``, Overlay #3
Title SLX home2 pars output <mike>

```


#DataSet : SLX home2 pars output
#Category: mike
#FileID : Run377
#Product : CarSim Version 5.15 October 2002
#Last update: 10-27-2003 15:23:17
#LinkCat Run
EXIT_PARSFILE Runs\Run377.par

END