

TECHNICAL ASSESSMENT PAPER:

**RELATIONSHIP BETWEEN
ROLLOVER AND
VEHICLE FACTORS**

prepared
by

**THE NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION**

July 1991

Table of Contents

<u>Section</u>	<u>Page</u>
1.0 FOREWORD	1
1.1 INTRODUCTION-GENERAL	1
1.2 THE ROLLOVER ACCIDENT PROBLEM	2
1.3 PREVIOUS ANALYSIS OF FACTORS RELATED TO ROLLOVER CRASH INVOLVEMENT	3
1.3.1 Analyses Conducted Prior to the Submission of the Wirth Rollover Propensity Petition	3
1.3.2 Agency Analyses Conducted Since Submission of the Wirth Rollover Propensity Petition	5
1.4 CURRENT AGENCY ACTIVITIES	8
2.0 PREVIOUS AGENCY ACTIVITIES RELATED TO ROLLOVER	10
2.1 PREVIOUS RULEMAKING ACTIVITIES	10
2.1.1 Advance Notice of Proposed Rulemaking	10
2.1.2 Petitions for Rollover Prevention Rulemaking	10
2.2 DEFECT INVESTIGATION PETITIONS	11
3.0 VEHICLE SELECTION	12
3.1 INTRODUCTION	12
3.2 VEHICLE SELECTION CRITERIA AND PROCEDURE	12
3.3 VEHICLES SELECTED	13
4.0 VEHICLE ROLLOVER STABILITY METRICS	27
4.1 INTRODUCTION	27
4.2 ROLLOVER STABILITY METRICS	27
4.2.1 Untripped Rollover Stability Metrics	28
4.2.2 Tripped Rollover Stability Metrics	34
4.3 TESTING	36
4.3.1 Vehicle Parameter Measurement	36
4.3.2 Special Tilt Table Ratio Measurement with Fully Loaded Vehicles	39
4.4 DISCUSSION OF ERRORS IN THE MEASUREMENT OF VEHICLE METRIC DATA	40
4.4.1 Comparisons of Metric Measurement Methodologies at VRTC and STI	41
4.4.2 General Discussion of Center of Gravity Measurement Accuracy and Effects on SSF and SPR	43
4.4.3 Comparisons of Tilt Table Ratio for Pairs of Vehicles	45
4.4.4 Summary - Errors in Determining Vehicle Metric Data	46
4.5 RELATIONSHIP BETWEEN STABILITY METRICS	47

4.6	OTHER STABILITY METRICS	47
4.6.1	Wheelbase	49
4.6.2	Percent of Total Vehicle Weight on the Rear Axle	49
4.6.3	Braking Stability	49
5.0	ACCIDENT DATA	54
5.1	DATA COLLECTION AND PROCESSING	54
5.1.1	VIN Correction Procedure	54
5.1.2	Accident Definitions	56
5.2	LOGISTIC REGRESSION ANALYTICAL METHODOLOGY	57
5.2.1	Results of Logistic Data Analysis for 5 States	59
5.2.2	Additional Models Based on Michigan Data	65
5.2.3	Additional Detailed Models Based on Michigan Data	70
5.2.4	Analysis of Michigan Data By Vehicle Class	76
5.2.5	Analysis of Michigan Data Using Age, Sex, and Alcohol Cells	80
5.2.6	Discussion of Analysis of VIN Correction Process	84
5.3	LINEAR MODELS OF THE NCSA STATE ROLLOVER DATA	87
5.3.1	Purpose of the Linear Models	87
5.3.2	Data	87
5.3.3	Antilock Brake Analysis	89
6.0	REGISTRATION DATA	93
6.1	DEVELOPMENT OF VEHICLE REGISTRATION DATA BASE	93
6.2	DEVELOPMENT OF ACCIDENT PER REGISTERED VEHICLE DATA	94
6.3	ANALYSIS OF ACCIDENT PER REGISTERED VEHICLE DATA	95
6.4	REGISTRATION DATA	96
7.0	DYNAMIC DIRECTIONAL CONTROL AND STABILITY DATA	106
7.1	VRTC VEHICLE SIMULATION AND METRIC COMPUTATION	106
7.2	USE OF DYNAMIC DIRECTIONAL CONTROL AND STABILITY METRICS	107
8.0	SUMMARY OF RESULTS	108
8.1	RESULTS OF TESTS MEASURING ROLLOVER STABILITY METRICS	108
8.2	RESULTS OF ACCIDENT DATA ANALYSIS AND CORRELATIONS WITH VEHICLE METRICS AND ACCIDENT DEMOGRAPHIC VARIABLES	109
8.3	FURTHER TESTING AND ANALYSIS ACTIVITIES	109
8.3.1	"Accuracy" of Vehicle Rollover Stability Metrics	110
8.3.2	Additional Data Gathering and Analyses	111
8.3.3	Development of Compliance Test Procedure	112

9.0	REFERENCES	113
	APPENDIX A	115
	APPENDIX B	122
APPENDIX C	LINEAR REGRESSION MODELS	124
C-1	Appendix C: LINEAR ANALYSIS AND RESULTS	124
C-1.1	Analysis Over the Entire Range of Make/Models	124
C-1.2	Linear Models of a Restricted Range of Make/Models	127
C-2	Appendix C: VEHUSE SAS (extraction program)	141
C-3	Appendix C: ACCIDENT CHARACTERISTICS	148
C-4	Appendix C: VEHTYPE SAS (linear regression program)	151

List of Tables

<u>Table</u>	<u>Page</u>
Table 1. Vehicle Make/models and Sister Vehicles.	15
Table 2. Companion Vehicles Make/Models.	20
Table 3. Metric Data for Tested Vehicles, Ordered by Type of Vehicle.	50
Table 4. Ranking of Metric Data, Ordered by SSF Data.	52
Table 5. Loaded Vehicle Tilt Table Test Results.	40
Table 6. Unmodified Vehicle Comparison.	45
Table 7. Modified Vehicle Comparison.	46
Table 8. Relationship of Static Stability Factor to other Rollover Stability Metrics.	47
Table 9. Sample Sizes For Various States.	59
Table 10. Correlation Matrix of Vehicle Metrics.	60
Table 11. Results of Initial Model Estimation.	62
Table 12. Summary of Model Coefficients for TILT TABLE RATIO and CRITICAL SLIDING VELOCITY/ROLLOVER PREVENTION METRIC.	63
Table 13. Results of Models Using Individual Vehicle Metrics.	65
Table 14. Summary R-squared Statistics.	69
Table 15. Rollover and Accident Data by Vehicle Class.	71
Table 16. Summary of Analysis of Vehicle Classes.	77
Table 17. Results of Cell Analysis.	83
Table 18. Corrected and Uncorrected GA Data file Summary.	85
Table 19. Comparison of Corrected and Uncorrected GA Data File Coefficients.	86
Table 20. Rollovers per Single-Vehicle Accident, by Eight Driver and Roadway Factors; by State and Combined 5 State	91
Table 21. Chi-square test for affect of antilock brakes on RO/SVA for four vehicles. . .	92
Table 22. Registration and Accident data for Make/Models in Sample	99
Table C-1. Results for Linear Regression Model.	131
Table C-2. Regression-Based Adjustment of Rollovers per Registered Vehicle for the Five States Combined.	135
Table C-3. Regression-Based Adjustment for the Tilt Table Ratio - Range 0.90-1.08. .	139
Table C-4. Accident Characteristics, 5 State Average.	148

List of Figures

<u>Figure</u>	<u>Page</u>
Figure 1. Tilt Table Test Setup.	30
Figure 2. Side Pull Test Setup.	32
Figure 3. Vehicle Axis System of Coordinates.	37
Figure 4. Measurement of Vehicle CG Heights at Various Test Facilities.	43
Figure 5. Relationship between Stability Factor and Metrics: Tilt Table and Side Pull Ratio.	48
Figure 6. Relationship between Tilt Table Metric and Side Pull Ratio.	48
Figure 7. Predicted Rollover Rate vs. Tilt Table for 5-States, Normalized to 5-State Average.	64
Figure 8. Michigan Accident Data vs. Tilt Table.	67
Figure 9. Michigan Accident Data vs, Stability Factor.	68
Figure 10. Michigan Accident Data vs. Side Pull Ratio.	69
Figure 11. Michigan Accident Data vs. Critical Sliding Velocity.	70
Figure 12. Tilt Table Ratio Squared Model Results.	72
Figure 13. Vehicle Class/Drive Configuration Results.	73
Figure 14. Single Vehicle Rate Results.	74
Figure 15. Single Vehicle Rate and Vehicle Class/Drive Configuration Results.	75
Figure 16. Passenger Cars - RO/SVA vs. TTR.	78
Figure 17. Vans - RO/SVA vs. TTR.	79
Figure 18. Pickup Trucks - RO/SVA vs. TTR.	80
Figure 19. Sport Utility Vehicles - RO/SVA vs. TTR.	81
Figure 20. Sample Size of Michigan Data Base sorted by TTR.	82
Figure 21. Georgia Uncorrected Data; Actual vs. Predicted Rollover Rates.	87
Figure 22. Georgia Corrected Data; Actual vs. Predicted Rollover Rates.	88
Figure 23. Rollovers per Single-Vehicle Accident for Five States.	89
Figure 24. Rollovers per Single-Vehicle Accident by Sex and Age for Five States.	90
Figure 25. Number of Single Vehicle Accidents per Registered Vehicle, 5 State data file.	96
Figure 26. Number of Single Vehicle Rollover Accidents per Registered Vehicle, 5 State data.	97
Figure 27. Number of Single Vehicle Rollover Accidents per Single Vehicle Accident, 5 State file.	98
Figure C-1. Regression-Based Adjustment for the Five States Combined Rollovers.	125
Figure C-2. Regression Based Adjusted Data for RO/RV.	128
Figure C-3. Regression Based Adjusted Data for RO/RV when TTR is Limited from 0.90 to 1.08.	130

1.0 FOREWORD

The activities documented in this report were initiated in response to two petitions for rulemaking requesting the development of a standard for rollover stability. They were submitted to the National Highway Traffic Safety Administration (NHTSA) over the past five years. The first, received by the agency in September 1986, was submitted by Senator (then Congressman) Timothy E. Wirth, and the second, received in June 1988, was submitted by the Consumers Union of United States, Inc. (CU). Although the agency denied the Wirth petition (Reference 1), which asked the agency to propose a specific rollover stability standard, NHTSA in its April 1988 denial (Appendix A) indicated that it intended to conduct additional testing and analysis to investigate the problem of rollover of light duty vehicles and that those efforts might lead to rulemaking. The CU petition (Reference 2), which asked that NHTSA investigate the rollover problem and then propose appropriate rulemaking, was granted in a September 1, 1988 letter (Appendix B), based upon the commitment made in the Wirth denial to investigate the rollover issue.

1.1 INTRODUCTION-GENERAL

Rollover accidents occur for many reasons. As with any accident, all three components of the driver/vehicle/environment system play a part in the development of the situation that results in a crash. However, there are extremes wherein a factor or factors related to one of the parts of the system is predominant in the causation of the accident. In the case of the driver, take the "extreme" example of a driver falling asleep at the wheel; for the environment, consider an unexpected patch of ice on an otherwise clear roadway resulting in a skid; and for the vehicle, a vehicle which has a such a low level of rollover stability that a simple, but severe, steering input by the driver as part of an accident avoidance maneuver results in the vehicle's rolling over.

The vast majority of crashes are caused by the interaction of factors from all three parts of the driver/vehicle/environment system. This rulemaking program attempts to accurately define and measure a vehicle performance factor(s) that is influential in the causation of rollover accidents - to the degree that a regulation based on that factor can significantly reduce the number and/or consequences of rollover crashes.

The goal of this rulemaking program is to determine the feasibility of developing a viable and appropriate standard or standards related to vehicle rollover stability that would reduce the likelihood of rollovers and/or to reduce the casualties associated with vehicle rollover crashes. In order to achieve that goal, a number of research and analysis tasks were planned and conducted. The purpose of these research and analysis tasks was to develop a measure of a vehicle's rollover stability that can be used to predict the vehicle's likelihood of rolling over given involvement in a crash. This document summarizes those efforts and results (which only comprise one aspect of the potential vehicle rulemaking) and discusses the adequacy of the results to accurately predict the rollover accident involvement rate of vehicles. The various alternatives for vehicle stability rulemaking action, and the

implications of the research and analysis results on those alternatives, are then discussed. Also addressed are additional testing, analysis and evaluation activities being undertaken by the agency to improve its understanding of rollover accident causation.

1.2 THE ROLLOVER ACCIDENT PROBLEM

This project addresses the crash avoidance aspects of rollover accidents that involve light duty vehicles, which includes passenger cars, and light trucks and vans (LTV's). This latter group includes compact and full-size pickup trucks, mini and full-size passenger and cargo vans, and sport utility vehicles (SUV's). SUV's are passenger vehicles with special features (usually four-wheel-drive) that allow for off-road operation. It should be noted that in the agency's Consumer Information Regulation (49 CFR 575.105) "Utility Vehicles", utility vehicles are defined as "multipurpose passenger vehicles (other than those which are passenger car derivatives) which have a wheelbase of 110 inches or less and special features for occasional off-road operation." Of the SUV's on the market today three, the Toyota Land-Cruiser with a wheelbase of 112.2 inches, the Lamborghini LM002 with a wheelbase of 122.4 inches and the Chevrolet/GMC Suburban with a wheelbase of 129.5 inches, do not fall in both categories.

Rollover crashes are of particular interest since rollover accidents are the most dangerous collision type for all classes of light vehicles, measured by either fatalities or incapacitating injuries per involved occupant. In terms of fatalities per registered vehicle, rollovers are second only to frontal crashes in their level of severity. These results are reported in a 1986 report documenting analyses conducted by NHTSA's National Center for Statistics and Analysis (Reference 3). These high injury/fatality rates are even more alarming given the fact that rollovers are by far the least frequent crash mode, as measured by accident involvements per registered vehicle. The National Accident Sampling System (NASS) datafile for 1989 estimates 137,600 rollover accidents involving passenger cars. Of these, 124,800 are single-vehicle rollovers, and the vast majority of these, 114,800, occur off the roadway. For LTV's, there are 75,600 rollovers, 65,800 single-vehicle rollovers, of which, 57,200 occur off road. Based on NASS data, nearly 90 percent of rollovers occur in single-vehicle accidents. Various accident data studies have indicated that the vehicle is out of control (skidding sideways or spinning) prior to overturning in from 50 percent to 80 percent of all rollovers.

The rollover problem is generally more serious for the LTV, and in particular, the SUV "portion" of the light vehicle group. State accident data (North Carolina for 1984 and 1985) indicate that although the involvement rate (involvements per registered vehicle) for LTV's in all types of collisions is only 68 percent that of passenger cars, their involvement rate in accidents involving rollover is 127 percent that of passenger cars. Rollover accidents are particularly dangerous for the occupants of SUV's, with their incapacitating injury rate being 28 percent higher than that for all light vehicles combined. This occurs even with similar seat belt usage, as shown in an agency regulatory evaluation on "Rear Lap/Shoulder Belts," where seat belt usage rate in accidents of pickups was estimated to be 70 percent of

passenger cars, but "on/off road" vehicles were estimated to have usage rates "equivalent" to passenger cars (actual rate was 95 percent).

In terms of rollover fatal accidents, 1989 Fatal Accident Reporting System (FARS) data indicate that LTV's have fatalities per registered vehicle rates 104 [94.5 versus 46.3 fatalities per million RV] percent higher than passenger cars, with small pickup trucks and SUV's having the highest comparative rates- 259 [based on 119.8 fatalities per million RV] percent and 254 [based on 117.5 fatalities per million RV] percent that of passenger cars respectively. However, since there are many more passenger cars the LTV's on our nations highways, approximately two-thirds of all rollovers involve passenger cars. Based on 1989 FARS data, 5682 fatalities occurred in passenger car rollovers and 3862 fatalities occurred in LTV rollovers.

Further discussion of the nature and magnitude of the rollover problem of light duty vehicles and of the prior analyses of accident data is found in the "Technical Evaluation of Rulemaking Petition" (for Senator Wirth's petition on rollover propensity-Reference 4) and in a discussion of the petition in Section 2.1.2.

1.3 PREVIOUS ANALYSIS OF FACTORS RELATED TO ROLLOVER CRASH INVOLVEMENT

The following is a basic review of accident data analyses performed by both the agency and others prior to the efforts reported in this document. This summary presents what has been studied to better quantify the relationship between vehicle, driver and environmental factors and rollover accident involvement.

1.3.1 Analyses Conducted Prior to the Submission of the Wirth Rollover Propensity Petition

Several researchers have reported correlations between certain vehicle parameters and various measures of rollover accident involvement. Some of these are discussed in Reference 4. Two vehicle parameters that were shown to have significant correlations with the rate of rollovers in single vehicle accidents were:

1. rollover stability factor, and
2. critical sliding velocity.

Both the rollover stability factor, which is one-half the vehicle's track width divided by the vehicle's center of gravity height, (h_g), and the critical sliding velocity, which is a measure calculated from various vehicle dimensions and mass and inertial properties, will be discussed later in this section and in Section 4.

Various accident condition variables have been shown to exhibit a relationship with rollover rates. These include pre-crash stability (skidding or spinning), vehicle pre-crash condition (skid sideways or spin) and skid type (rear wheel lateral or four wheel lateral).

Various driver- and environment-related accident variables also seem to influence the likelihood of rollover. These include driver age, alcohol involvement, driver error, rural vs. urban roadway, day vs. night, the roadway speed limit, the rollover's occurring on or off the roadway, and accidents occurring where the roadway was straight or curved.

Of all these factors, the one which exhibited the greatest correlation with rollover accident involvement is rollover stability factor. The rollover stability factor's correlation "makes sense" since it has an obvious physical relationship to the dynamics of a rollover accident (this is discussed in detail in Section 4).

Other factors which are very important in determining a vehicle's rollover stability (measured or calculated) and its rollover propensity are those related to the vehicle type or class. This is particularly true of LTV's. LTV's have functional characteristics that are inherently different from passenger cars and that contribute to an inherently lower level of rollover stability. Since these same characteristics of LTV's are, to some extent, vehicle characteristics basic to the use for which these vehicles are designed, potential for improvement in their fundamental rollover stability may be limited. This view was noted in the agency's denial of the rulemaking petition from Senator Wirth (Appendix A). In responding to that petition the agency stated that a regulatory requirement based on the rollover stability factor alone, given the then limited understanding of the overall rollover accident causation issue, was not reasonable or practicable and might be in conflict with certain statutory considerations.

Before proceeding, one feature of a previous study should be noted. In a 1974 paper (Reference 5), I. S. Jones argued that a vehicle which has a relatively low rate of rollover per single vehicle accident might have a relatively high overall rate of rollover accident involvement, when measured per vehicle mile travelled (VMT), or per registered vehicle, because of a high rate of single vehicle accidents per VMT or registered vehicle. Jones argued that this could be particularly confounding to an analysis of vehicle rollover stability when comparing vehicles with significantly different handling characteristics; the reasoning being that vehicle handling characteristics influence a vehicle's involvement in single vehicle accidents and since most rollovers occur in single vehicle accidents, the influence of those handling differences could confound an analysis that examines the correlation between rollover involvement and vehicle rollover stability measures. Based on this, Jones reasons that by using rollovers per single vehicle accident as the accident rate measure, the confounding influence of other vehicle factors, unrelated to vehicle rollover stability, would be significantly reduced. This is also reasonable noting that the vast majority of rollovers occur in single vehicle accidents and as such, the occurrence of the single vehicle accident can be viewed as the opportunity for, and therefore, an exposure measure of, a rollover accident.

1.3.2 Agency Analyses Conducted Since Submission of the Wirth Rollover Propensity Petition

This section reviews the accident data analyses performed by NHTSA subsequent to the submission of the Wirth petition, but prior to the testing and analyses that have been performed for this program and reported herein.

Beginning in late 1986, the agency conducted several analyses designed to better understand the association between vehicle design factors and performance characteristics, and rollover propensity.

The first significant analysis effort was performed by Harwin and Brewer (Reference 6). It began just prior to the submission of the Wirth petition. Their analysis employed the then recently developed CARDfile (Crash Avoidance Research Data file). The CARDfile database is constructed from information from police accident reports from several states, and is documented in a report by Mark L. Edwards titled "A Database for Crash Avoidance Research" (Reference 7). A portion of the CARDfile database was used in the Harwin and Brewer analysis, and includes data from Maryland and Texas for accident years 1984 and 1985 and from Washington state for accident years 1983 through 1985.

Their database included accident data for a series of forty vehicle make/models (some of which were different "nameplate" versions of the same vehicle model, e.g., Chevrolet Citation and Oldsmobile Omega) which represented nineteen unique passenger car models, including both foreign and domestic models, and eight utility vehicle models. The vehicles in their sample were selected to cover, without major gaps, the range of stability factors from small utility vehicles to large domestic passenger cars. The data base did not include any pickup trucks or vans. Their research examined various vehicle data, including wheelbase (L), center of gravity height (h_{cg}), half track width (TW/2) and the stability factor ($TW/(2 \cdot h_{cg})$).

The regression of the CARDfile data between the stability factor and the percent of rollovers in single vehicle accidents shows a strong correlation, with R^2 values ranging between 0.57 and 0.86 for the various State/year combinations. This regression shows a continuous trend of rollovers per single vehicle accident over a broad range of stability factors, as opposed to the two clusters of vehicles that are indicated in a report by L.S. Robertson and A.B. Kelley titled "The Role of Stability In Rollover-Initiated Fatal Motor Vehicle Crashes Under On-Road Driving Conditions," (Robertson/Kelley-Reference 8). That report, which was submitted with and in support of the Wirth petition (Reference 1), shows one group of high stability factor vehicles with low rollover per single vehicle accident rates and another group of low stability factor vehicles with high rollover per single vehicle accident rates, indicating that there is some specific value of stability factor above which vehicles are "safe" and below which they are "unsafe". In the case of the Wirth petition, the petitioner suggested 1.20 as that value. The CARDfile analysis instead shows a generally linear distribution of rollovers

per single vehicle accident over a wide range of stability factors with no obvious ranges of "safe" or "unsafe" vehicles.

Harwin and Brewer's research also included a stepwise multivariate regression analysis of the Maryland and Texas data to control for differences in driver and vehicle use. They showed R^2 values for the combination file of Maryland and Texas as well as the Maryland file only. Their final regression equation had an R^2 value of 0.91 for data base combinations with stability factor, percent drivers under 25, percent male drivers, and percent accidents occurring on rural roads included in the regression model.

In summary, Harwin and Brewer indicated that the rollover stability factor statistically explained much of the difference in the rollover rate (computed as the number of rollovers per single-vehicle accident (RO/SVA)) between different vehicle make/models.

Mengert, Salvatore, DiSario, and Walter (Reference 9) re-analyzed the Harwin and Brewer data using logistic regression techniques. This process considers the likelihood of rollover at the accident level rather than at the make/model level as was done in the Harwin/Brewer report. This allows each accident to be treated as a data point (rather than using the summary information from each vehicle make/model as a data point).

This database included over 39,000 single vehicle accidents of which 4,910 were rollover accidents. Several models were developed to relate vehicle metrics and accident conditions. Analysis was conducted at both the accident level and make/model level. At the accident level, the ability of the models to predict rollover versus nonrollover was found to be dependent on stability factor and where the accident occurred, urban or rural. The models were used to predict rollover rates at the make/model level. The index of agreement (R^2) exceeded 0.9 when stability factor was included in the regression, but dropped to approximately 0.5 when stability factor was removed from the analysis. Mengert's plots of the actual versus predicted rollover rate using his 11-factor model showed excellent relationships between rollover rate and stability factor.

These results verified the importance of controlling for confounding differences in vehicle use and driver demographics, and again showed that the stability factor was associated with rollover propensity.

Salvatore, Mengert, DiSario, and Walter expanded the analysis by including pickup trucks and vans in the analysis. Unfortunately, the work was not completed because of the death of the primary author. However, the results they presented suggested that there might be vehicle or driver factors that were inadequately controlled for in the analysis, and that these factors were associated with the particular class to which a vehicle belonged, i.e., passenger car, utility vehicle, pickup truck, or van.

Also, analyses of data from CARDfile and the Fatal Accident Reporting System (FARS) were performed by the agency in response to the Wirth petition. One interesting result is the

significant correlations that were found between rollover accident involvement rates and vehicle wheelbase. These are documented in Reference 4, (referred to previously) and in a report by A.C. Malliaris (Reference 10). Malliaris found that reducing wheelbase at a fixed vehicle weight leads to a significant increase in fatal rollover accident involvement, whereas reducing the vehicle weight at a fixed wheelbase leads to a significant reduction in fatal rollover accident involvement.

Unlike the rollover stability factor, whose correlation with rollover accident involvement rate "makes sense", the correlation with wheelbase does not have such an intuitive relationship with the rollover phenomenon. Several possible explanations have been put forth to explain this wheelbase-to-rollover accident involvement correlation. Perhaps this relationship is due to a correlation of wheelbase with vehicle pre-crash stability, pre-crash condition and/or skid type mentioned above.

It has been hypothesized that the wheelbase is acting as a surrogate for the vehicle's yaw stability characteristic. Such a hypothesis is not unreasonable given that vehicles with longer wheelbases have higher yaw moments of inertia and both factors, wheelbase and yaw moment of inertia, influence a vehicle's yaw damping and yaw stability. If the hypothesis of a relationship between wheelbase and directional stability is valid, the connection to an increased likelihood of rollover is supported by results documented in a report by Malliaris, Nicholson, Hedlund and Scheiner (Reference 11) which indicated a relationship between loss of stability and an increased likelihood of rollover. In that report, an analysis of data from NHTSA's National Crash Severity Study found that a vehicle's pre-crash condition in single vehicle accidents was related to the likelihood of that vehicle's rolling over in the accident. The pre-crash condition of "skidding sideways" existed in about 56 percent of passenger car single vehicle rollover crashes, but in only 29 percent of all passenger car single vehicle accidents. For light trucks and vans, the "skidding sideways" pre-crash condition was indicated in about 52 percent of single vehicle rollovers, in only 34 percent of all single vehicle accidents, and the "spin" pre-crash condition was indicated in about 9 percent of single vehicle rollovers, but in only 3.4 percent of all single vehicle crashes. For passenger cars, the lighter cars (less than 3500 pounds curb weight), which would also tend to have shorter wheelbases, were 2.2 times more likely to have a pre-crash condition of skidding sideways than were the heavier cars.

Another explanation of the relationship between rollover propensity and wheelbase is that wheelbase is related to a vehicle's roll stability measurement, because of the general geometric relationship between track width and wheelbase with respect to vehicle size. Also, a causal relationship may exist between rollover accident involvement and critical sliding velocity, and the correlation between a vehicle's wheelbase and its roll moment of inertia, which is a primary factor in the critical sliding velocity, may result in the wheelbase to rollover accident involvement correlation. However, more analyses and testing are needed to verify these hypotheses. Reference 4 includes additional discussion of the level of understanding and the unanswered questions that existed at the initiation of this program.

The effort by Salvatore et al. and those by agency staff motivated the work reported here. A larger number of explanatory factors were considered, a larger number of vehicle models were included, additional accident data from states were used, and additional vehicle design factors were measured and evaluated in statistical analyses for their association with rollover propensity.

Again, vehicle design measures (the stability factor and other stability measures) were found to be statistically useful in estimating the rollover propensity that remained, after controlling for driver and vehicle use factors.

There is remarkable consistency in the results of all of these analyses done over the past three years. Each study shows that confounding non-vehicle factors are important in understanding rollover propensity, but that there is a large portion of the remaining problem that is associated with vehicle factors related to vehicle rollover stability. This association is not surprising since it is consistent with engineering studies of what happens during a rollover. Where the statistical analysis is especially useful is in verifying that the relationship exists, even after confounding factors have been controlled for, quantifying the effect of rollover propensity on safety. Also, such analyses assist in projecting the likely benefits of any changes that manufacturers might make.

1.4 CURRENT AGENCY ACTIVITIES

The agency's recent activities have been directed at improving its understanding of rollover accident causation by expanding the number of parameters that are examined for possible correlation with a vehicle's rollover propensity, and increasing the number and diversity of the vehicles for which vehicle parameters are examined.

The remainder of the report is organized as follows:

Section 2 discusses the background and history of the agency's past rulemaking and defect investigation actions related to rollover of light duty vehicles.

Section 3 discusses the vehicles that were selected for inclusion in these analyses and the process used in their selection.

Section 4 discusses the vehicle rollover stability metrics that were included in these analyses, the procedures used in their measurement, and the errors associated with their measurement or the measurement of parameters involved in their calculation.

Section 5 discusses the generation of the accident databases used in the RO/SVA rate analyses, the various statistical analysis techniques used and the results of those analyses.

Section 6 discusses the vehicle registration data that was used to estimate vehicle exposure based on vehicle population, the method used to calculate vehicle population estimates from that data and results of analyses of accident data using registered vehicle years as the exposure measure.

Section 7 discusses the dynamic directional control and stability data, the method used in calculating that data and analyses that are planned using that data.

Section 8 discusses the various rulemaking alternatives that are available to the agency to address the rollover safety issue, and discusses the implications of the results of the accident data analyses on those rulemaking alternatives. Also discussed are additional accident data gathering, vehicle testing and data analyses that are planned to further support the agency's rulemaking activities.

2.0 PREVIOUS AGENCY ACTIVITIES RELATED TO ROLLOVER

The following discussion reviews the history and background of previous rulemaking and defect investigation actions taken by NHTSA concerning the rollover safety of light duty vehicles.

2.1 PREVIOUS RULEMAKING ACTIVITIES

2.1.1 Advance Notice of Proposed Rulemaking

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

2.1.2 Petitions for Rollover Prevention Rulemaking

In September 1986, the National Highway Traffic Safety Administration (NHTSA) received a petition (Reference 1) from Congressman Timothy E. Wirth (now Senator Wirth) to issue a Federal Motor Vehicle Safety Standard (FMVSS) to "limit the rollover propensity of passenger automobiles, utility vehicles, and pickup trucks."

That petition requested that the agency take the following actions:

1. Propose an FMVSS to require that the rollover propensity of light duty vehicles, including passenger cars, light trucks and multipurpose passenger vehicles (MPV), be limited by requiring that they have a minimum stability factor, defined as the vehicle's half-track width divided by the vehicle's center of gravity height, of a specified value. The petitioner recommended that the agency consider a value of 1.2 for that minimum stability factor.
2. Conduct a defect investigation of those existing light duty vehicles whose stability factor does not meet the minimum required by the above FMVSS.
3. Obtain and publish stability factor information for vehicles being manufactured for sale in the U.S. and make it available to the public.

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

The petitioner alleged that the rollover propensity of vehicles whose stability factor is less than 1.2 is so great and that the relative numbers of deaths and injuries are so high that their manufacture should be prohibited. This conclusion is based on an analysis contained in the Robertson/Kelley report (Reference 8) which was submitted with the Wirth petition. That petition was denied in April 1988.

In June, 1988, the Consumers Union of United States, Inc. (CU), submitted a petition for rulemaking (Reference 2) to the agency that requested the establishment of "a minimum stability standard to protect against unreasonable risk of rollover." That petition was granted in September 1988, and it is that action which the current rulemaking activity addresses.

2.2 DEFECT INVESTIGATION PETITIONS

In October 1979, and in July 1981, the Office of Defects Investigation received two petitions to conduct investigations concerning the stability of Jeep CJ-5 vehicles. Both of these petitions were denied in part due to a lack of specific information indicating that there is a distinct vehicular defect that causes rollover accidents.

In February 1988, the Office of Defects Investigation received a petition to conduct investigations concerning the stability of Suzuki Samurai vehicles. After a review of accident data, that petition was denied. That denial was based in part on the results of an analysis of accident data which indicated that the involvement of Suzuki Samurai vehicles in fatal rollover accidents was no greater than other similar vehicles. However, those same results indicated that Ford Bronco II vehicles seemed to have a significantly higher rate of involvement in fatal rollover accidents. As a result, a defect investigation petition regarding Ford Bronco II vehicles, that was received in August 1988, was granted in February 1989. Another petition for defect investigation concerning Jeep CJ vehicles was received in 1990 and, after an accident data analysis which was more exhaustive than any that had previously been conducted, the Jeep CJ petition was denied in October 1990 (petition denial- Reference 12, Technical Report supporting denial- Reference 13). The Ford Bronco II case was closed in November 1990 (Engineering Analysis Closing Report- Reference 14). Both investigations were closed in part due to the lack of data to support action against any vehicle. Based on analysis of accident data, these vehicles were statistically no different than many other vehicles in the utility vehicle population. Refer to references 12, 13, and 14 for additional details.

3.0 VEHICLE SELECTION

This section discusses the first step in the testing, data gathering and analysis activities performed during this rulemaking program. For the vehicles selected, accident data and vehicle parameters and performance characteristics were gathered to be used in various statistical analyses of the relationship between vehicle factors and rollover accident involvement.

3.1 INTRODUCTION

The selection of the vehicle sample to be used in the accident data versus vehicle metrics analysis was performed prior to the efforts to generate the accident data base and before the testing program to determine the vehicle metrics. The vehicle sample was selected to encompass all classes of light vehicles, i.e., all ranges of passenger cars; small and large pickup trucks; mini and full size vans; and open, small, and large utility vehicles. They were selected to encompass the entire range of market class designations, usage classifications, and size classes. For each of these classifications, an attempt was made to obtain 1) a set representative of the full spectrum of rollover rates, and 2) a set representative of the full spectrum of vehicle parameters. The vehicles selected encompassed the lowest to the highest rollover to single vehicle accident rates. With regard to vehicle parameters, the selections were made to include the complete range of vehicles from the low slung sports cars and full size sedans to the tall narrow utility vehicles with short, medium and long wheelbases.

3.2 VEHICLE SELECTION CRITERIA AND PROCEDURE

A summary of single vehicle accident and single vehicle rollover accident counts was prepared using the Maryland portion of the CARDfile accident data base for 1986 through 1988. This list was then reviewed using the following criteria (each of the criteria is followed by a short description of the basis for it).

1. **MODEL YEARS 1981 OR LATER:** Model years previous to 1981 did not have a standardized VIN (Vehicle Identification Number) scheme.
2. **ADEQUATE DATA AVAILABLE:** Data from the Maryland 1986-1988 CARDfile was used to determine the exposure of different vehicles. The minimum number of observations was set at 20.
3. **VEHICLES WITH HIGH ROLLOVER PROPENSITY:** Evaluate the rollover rates of these vehicles relative to the rest of the sample population.
4. **HIGH CURRENT SALES VOLUMES:** Vehicles which represent a growing segment of the current vehicle fleet.

5. HIGH REGISTRATION POPULATIONS: Vehicles well represented in the vehicle fleet.

6. PREVIOUSLY TESTED: Vehicles for which dependable sidepull or parameter measurement data either existed, or was planned to be measured in ongoing programs.

A list of 60 vehicles that satisfied one or more of the above criteria was prepared. Forty-five of the vehicles on this list were then accepted for evaluation and testing. Additionally, 11 vehicles that did not meet any of the above requirements, and therefore were not on the original list, were chosen for testing. The additional vehicles were chosen to expand the range of vehicle types, such as several short wheelbase front- and rear-wheel drive subcompact passenger cars, a European sport sedan, large utility vehicle, and a shorter wheelbase version of a vehicle included from the original list.

3.3 VEHICLES SELECTED

The vehicles selected include vehicles in the following categories:

- Sport utility vehicles
- Light (compact) pick-up trucks
- Full size pick-ups trucks
- Mini-vans
- Full-size vans
- Small (subcompact and compact) passenger cars
- Intermediate size passenger cars
- Full-size passenger cars

Table 1 details the list of the vehicles which were actually tested to determine their metrics, i.e., physical measurements were taken by NHTSA or a contractor, and the sister vehicles which were analyzed in this project. Sister vehicles are vehicles of different make/models that are built about the same chassis as that of the tested vehicle, e.g., a Chevrolet S-10 Blazer was tested and the GMC Jimmy S-15 was considered as a sister vehicle. In this table, the tested vehicles are designated with an entry for model year in the "Model Year (Test Vehicle)" column. Hence, Table 1 contains two sets of vehicles, 1) the actual vehicles tested, and 2) a set of sister vehicles for which the test data from the tested vehicles could be applied.

After this group of vehicles was chosen, a second list, presented in Table 2, was prepared for which only accident data would be gathered. This list is called the companion vehicle set. The accident data for the vehicles contained in this second list were gathered to allow comparisons to confirm that the vehicles included in the sample as "average" vehicles were representative of vehicles in their respective size/market/usage class. Comparisons of vehicles in similar classes could help in determining if any vehicles in a class have

unexpectedly high accident rates. An examination of those vehicles' characteristics might aid in gaining a better understanding of what factors can influence accident involvement.

Other vehicles in this accident data-only list were included to allow comparisons of the accident rates between certain sub-classes of vehicles, such as: station wagons vs. sedans/coupes, passenger vans vs. cargo vans, and pickup trucks and vans equipped with anti-lock braking systems vs. pickup trucks and vans that are not so equipped.

Due to some incompatibilities between the two sources of vehicle registration data (which is discussed in Section 6), several other vehicle make/models were added to this list to allow accident involvement rates per registered vehicle year to be determined for all the vehicle make models of interest. In the accident data-only vehicle list these vehicles can be identified by their National Center for Statistical Analysis (NCSA) ID number being followed by an asterisk (*).

Table 1. Vehicle Make/models and Sister Vehicles.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0011	Jeep	CJ-5 w/ stabilizer bar	81	81-83
0013	Jeep	CJ-5-w/o stabilizer bar	81	72-75
0021	Jeep	CJ-7-wide track w/stabilizer bar	85	82-86
0023	Jeep	CJ-7-narrow track w/stabilizer bar	81	81
0031	Jeep	Wrangler	89	87-
0041	Jeep	Cherokee (4WD)	84	84-
0051	Ford	Bronco II	83	83-86
0052	Ford	Bronco II w/ABS		87-
0061	Ford	Bronco	85	81-86
0062	Ford	Bronco w/ABS		87-
0071	Chevrolet	Blazer S10	83	83-88
0072	Chevrolet	Blazer S10 w/ABS		89-
0073	GMC	Jimmy S-15		83-88
0074	GMC	Jimmy S-15 w/ABS		89-
0081	Chevrolet	K10 Blazer		83-86
0082	Chevrolet	R10 Blazer		87-
0083	GMC	K1500 Jimmy	85	83-86
0084	GMC	R1500 Jimmy		87-
0091	Toyota	4Runner-MPV	86	84-
0092	Toyota	4Runner-Truck		84-
0101	Suzuki	Samurai-MPV- '85-88-E	88-E	85-87

Table 1. Vehicle Make/models and Sister Vehicles.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0106	Suzuki	Samurai-Truck- '85-'88-E		85-87
0111	Isuzu	Trooper II-MPV	84	84-
0112	Isuzu	Trooper II-Truck		84-
0121	Ford	F150 4x4	87	81-86
0122	Ford	F150 4x4 w/ABS		87-
0131	Ford	F150 4X2	87	81-86
0132	Ford	F150 4X2 w/ABS		87-
1141	Ford	F250	81	81-86
1142	Ford	F250 w/ABS		87-
0151	Ford	Ranger 4x4	86	83-88
0152	Ford	Ranger 4x4 w/ABS		89-
0161	Ford	Ranger	88	83-88
0162	Ford	Ranger w/ABS		89-
0181	Chevrolet	C-10	76	81-86
0182	Chevrolet	R-10		87-
1183	Chevrolet	C-1500 w/ABS		88-
1173	Chevrolet	K-1500 w/ABS	91	88-
0184	GMC	C-1500		81-86
0185	GMC	R-1500		87-
1186	GMC	C-1500 w/ABS	91	88-
1176	GMC	K-1500 w/ABS		88-
0191	Chevrolet	C-20	84	81-86
0192	Chevrolet	R-20		87-

Table 1. Vehicle Make/models and Sister Vehicles.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0194	GMC	C-2500		81-86
0195	GMC	R-2500		87-
0201	Chevrolet	T-10		82-88
0202	Chevrolet	T-10 w/ABS		89-
0203	GMC	T-1500	86	82-88
0204	GMC	T-1500 w/ABS		89-
0211	Chevrolet	S-10	83	82-88
0212	Chevrolet	S-10 w/ABS		89-
0213	GMC	S-1500		82-88
0214	GMC	S-1500 w/ABS		89-
0221	Toyota	4x4 Pick Up-LWB	80	81-83
0241	Toyota	4X2 Pick Up-SWB	86	84-88
0251	Nissan	4x4 Pick Up	88	81-
0261	Nissan	4X2 Pick Up	85	81-
0271	Ford	E-150 Pass. Van	84	81-
0281	Chevrolet	G10 Sportsvan	88	81-
0283	GMC	G-1500 Rally		81-
0291	Ford	Aerostar-Pass. Van	88	86-
0301	Chevrolet	Astro-Pass. Van	88	85-88
0305	GMC	Safari-Pass. Van		85-88
0311	Dodge	Caravan Van		84-
0316	Plymouth	Voyager Van	89	84-
0321	Toyota	Minivan-Pass. Van	86	84-
0331	Volkswagen	Vanagon Van	84	81-

Table 1. Vehicle Make/models and Sister Vehicles.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0341	Ford	Escort	89	81-85
0351	Ford	Thunderbird	87	83-88
0361	Chevrolet	Chevette	80	81-87
0371	Pontiac	Fiero	84	84-88
0381	Buick	Skyhawk		82-
0382	Chevrolet	Cavalier	85	82-
0383	Oldsmobile	Firenza		82-
0384	Pontiac	J-2000/Sunbird		82-
0391	Buick	Century		82-
0392	Chevrolet	Celebrity		82-
0393	Oldsmobile	Cutlass Ciera	85	82-
0394	Pontiac	6000		82-
0401	Buick	Le Sabre	80	81-85
0402	Chevrolet	Caprice/Impala		81-85
0403	Oldsmobile	Delta 88		81-85
0411	Dodge	Omni	83	78-
0416	Plymouth	Horizon		78-
0420	Toyota	Starlet	82	81-84
0430	Toyota	Camry	83	83-86
0441	Datsun	510	77	78-81
0451	Datsun	200SX	80	80-84
0461	Nissan	Sentra	83	83-86
0471	Nissan	Stanza	85	82-86

Table 1. Vehicle Make/models and Sister Vehicles.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0481	Honda	Civic (4 door-LWB)	82	81-83
0491	Honda	Civic Hatch Back	84	84-86
0501	Honda	Civic CRX	84	84-85
0511	Hyundai/ Mitsubishi	Excel/ Precis	87	84-
0520	BMW	320i	81	78-83
0531	Renault	Le Car	77	79-83
0541	Volkswagen	Jetta	83	81-83
1272	Ford	E-150 Cargo Van		81-
1282	Chevrolet	G10 Cargo Van		81-
1292	Ford	Aerostar-Cargo Van		86-
1302	Chevrolet	Astro-Cargo Van		85-88
1303	Chevrolet	Astro-Pass. Van w/ABS		89-
1304	Chevrolet	Astro-Cargo Van-w/ABS		89-
1306	GMC	Safari-Cargo Van		85-88
1307	GMC	Safari-Pass. Van w/ABS		89-
1308	GMC	Safari-Cargo Van w/ABS		89-
1322	Toyota	Minivan-Cargo Van		84-

This is the end of Table 1.

Table 2. Companion Vehicles Make/Models.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
0042	JEEP	WAGONEER (4WD)		84-
0171	CHEVROLET	K-10 (4WD)		81-86
0172	CHEVROLET	V-10 (4WD)		87-
0174	GMC	K-10 (4WD)		81-86
0175	GMC	V-10 (4WD)		87-
0231	TOYOTA	PICKUP SWB (4WD)		84-88
1012	JEEP	CJ-5-STABILIZER BAR UNKNOWN		76-80
1022	JEEP	CJ-7-NARROW TRACK-STABILIZER BAR UNKNOWN		76-80
1046	JEEP	CHEROKEE (2WD)		85-
1056	FORD	BRONCO II (2WD)- non-ABS		86
1057	FORD	BRONCO II (2WD)- ABS		87-
1076	CHEVROLET	T-10 BLAZER (4WD)- non-ABS		83-88
1077	CHEVROLET	T-10 BLAZER (4WD)- ABS		89-
1078	GMC	T-15 JIMMY (4WD)- non-ABS		83-88
1079	GMC	T-15 JIMMY (4WD)- ABS		89-
1086	CHEVROLET	C-10 BLAZER (2WD)		83-86
1087	CHEVROLET	R-10 BLAZER (2WD)		87-
1088	GMC	C-10 JIMMY (2WD)		83-86

Table 2. Companion Vehicles Make/Models.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
1089	GMC	R-10 JIMMY (2WD)		87-
1102	SUZUKI	SAMURAI-MPV- '88-L		88
1103	SUZUKI	SAMURAI-MPV-'89		89
1107	SUZUKI	SAMURAI-TRUCK- 88-L		88
1108	SUZUKI	SAMURAI-TRUCK- '89		89
1173	CHEVROLET	K-10 (4WD)- ABS		88-
1176	GMC	K-10 (4WD)- ABS		88-
1177	CHEVROLET	K-20 (4WD)		81-86
1178	CHEVROLET	V-20 (4WD)		87-
1179	CHEVROLET	K-20 (4WD)- ABS		88-
117A	GMC	K-20 (4WD)		81-86
117B	GMC	V-20 (4WD)		87-
117C	GMC	K-20 (4WD)- ABS		88-
1183	CHEVROLET	C-10 (2WD)- ABS		88-
1186	GMC	C-10 (2WD)- ABS		88-
1193	CHEVROLET	C-20 (2WD)- ABS		88-
1196	GMC	C-20 (2WD)- ABS		88-
1222	TOYOTA	4X4 PICK UP-SWB		81-83
1223	TOYOTA	PICKUP LWB (2WD)		81-83
1224	TOYOTA	PICKUP SWB (2WD)		81-83
1276	FORD	E-250 CLUB WAGON- PASS. VAN		81-

Table 2. Companion Vehicles Make/Models.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
1277	FORD	E-250- CARGO VAN		81-
1284	GMC	G1500 Cargo Van		81-
1286	CHEVROLET	G-20 SPORTVAN- PASS. VAN		81-
1287	CHEVROLET	G-20- CARGO VAN		81-
1288	GMC	G-20 SPORTVAN- PASS. VAN		81-
1289	GMC	G-20- CARGO VAN		81-
1386	BUICK	SKYHAWK- Station Wagon		88-89
1387	CHEVROLET	CAVALIER- Station Wagon		82-
1396	BUICK	CENTURY- Station Wagon		82-
1397	CHEVROLET	CELEBRITY- Station Wagon		82-
1398	OLDSMOBILE	CIERA- Station Wagon		82-
1406	BUICK	LE SABRE- Station Wagon		81-85
1407	CHEVROLET	IMPALA/CAPRICE- Station Wagon		81-85
1408	OLDSMOBILE	DELTA 88- Station Wagon		81-85
1482	HONDA	CIVIC (2 DOOR-SWB)		81-83
1542	VOLKSWAGEN	JETTA		85-
1551	FORD	FAIRMONT- non- Station Wagon		81-83

Table 2. Companion Vehicles Make/Models.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
1552	MERCURY	ZEPHYR- non- Station Wagon		81-83
1556	FORD	FAIRMONT- Station Wagon		81-83
1557	MERCURY	ZEPHYR- Station Wagon		81-83
1561	BUICK	SKYLARK- non- Station Wagon		81-85
1562	CHEVROLET	CITATION		81-85
1563	OLDSMOBILE	OMEGA		81-84
1564	PONTIAC	PHOENIX		81-84
1566	BUICK	SKYLARK- Station Wagon		81-85
1571	DODGE	ARIES- non- Station Wagon		81-86
1572	PLYMOUTH	RELIANT- non- Station Wagon		81-86
1576	DODGE	ARIES- Station Wagon		81-86
1577	PLYMOUTH	RELIANT- Station Wagon		81-86
1581	TOYOTA	TERCEL		83-86
1591	TOYOTA	MR2		85-
1601	HONDA	PRELUDE		84-86
1611	VOLKSWAGEN	RABBIT- except convertible		81-83
1612	VOLKSWAGEN	RABBIT- convertible		81-83

Table 2. Companion Vehicles Make/Models.

NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
1621	VOLKSWAGEN	GOLF- except convertible		85-
1622	VOLKSWAGEN	GOLF CABRIOLET		85-
1631	AUDI	4000		80-84
2091*	TOYOTA	4-RUNNER- ALL		84-
2101*	SUZUKI	SAMURAI- ALL		85-87
2102*	SUZUKI	SAMURAI- ALL		88
2103*	SUZUKI	SAMURAI- ALL		89
2111*	ISUZU	TROOPER II- ALL		84-
2173*	CHEVROLET	K-10 EXTENDED CAB (4WD)- ABS		88-
2176*	GMC	K-10 EXTENDED CAB (4WD)- ABS		88-
2179*	CHEVROLET	K-20 EXTENDED CAB (4WD)- ABS		88-
217C*	GMC	K-20 EXTENDED CAB (4WD)- ABS		88-
2183*	CHEVROLET	C-10 EXTENDED CAB (2WD)- ABS		88-
2186*	GMC	C-10 EXTENDED CAB (2WD)- ABS		88-
2191*	CHEVROLET	C-20 CREW CAB (2WD)		81-86
2192*	CHEVROLET	R-20 CREW CAB (2WD)		87-
2193*	CHEVROLET	C-20 EXTENDED CAB (2WD)- ABS		88-
2194*	GMC	C-20 CREW CAB (2WD)		81-86
2195*	GMC	R-20 CREW CAB (2WD)		87-

Table 2. Companion Vehicles Make/Models.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
2196*	GMC	C-20 EXTENDED CAB (2WD)- ABS		88-
2201*	CHEVROLET	T-10 EXTENDED CAB (4WD)- non-ABS		82-88
2202*	CHEVROLET	T-10 EXTENDED CAB (4WD)- ABS		89-
2203*	GMC	T-10 EXTENDED CAB (4WD)- non-ABS		82-88
2204*	GMC	T-10 EXTENDED CAB (4WD)- ABS		89-
2211*	CHEVROLET	S-10 EXTENDED CAB (2WD)- non-ABS		82-88
2212*	CHEVROLET	S-10 EXTENDED CAB (2WD)- ABS		89-
2213*	GMC	S-10 EXTENDED CAB (2WD)- non-ABS		82-88
2214*	GMC	S-10 EXTENDED CAB (2WD)- ABS		89-
2281*	CHEVROLET	G-10- UNKNOWN VAN		81-
2282*	CHEVROLET	G-20- UNKNOWN VAN		81-
2283*	GMC	G-10- UNKNOWN VAN		81-
2284*	GMC	G-20- UNKNOWN VAN		81-
2291*	FORD	AEROSTAR- PASS. VAN-EXTENDED CAB		86-
2291*	FORD	AEROSTAR- ALL VANS		86-
2292*	FORD	AEROSTAR- CARGO VAN-EXTENDED CAB		86-

Table 2. Companion Vehicles Make/Models.				
NCSA ID No.	Vehicle		Model Year (Test Vehicle)	Model Year(s) (Accident Data)
	Make	Model/Series		
2301*	CHEVROLET	ASTRO- INCOMPLETE VEH.- non-ABS		85-88
2302*	CHEVROLET	ASTRO- INCOMPLETE VEH.- ABS		89-
2303*	GMC	SAFARI- INCOMPLETE VEH.- non-ABS		85-88
2304*	GMC	SAFARI- INCOMPLETE VEH.- ABS		89-
3251*	NISSAN/ DATSUN	PICKUP (DRIVE-?) excludes King Cab		81-

This is the end of Table 2.

4.0 VEHICLE ROLLOVER STABILITY METRICS

4.1 INTRODUCTION

NHTSA conducted static vehicle tests in support of the rulemaking effort on light vehicle rollover. The basic vehicle parameter testing included vehicle mass, inertial and suspension parameter measurements. It also included measurement of the side pull force and tilt table angle. These two measurements are discussed in detail later in this section.

The results of these tests were used to determine values for the vehicle rollover stability metrics that would be used in correlation analyses with rollover accident data. The rollover stability metrics are discussed in the following section.

4.2 ROLLOVER STABILITY METRICS

Two basic types of rollover phenomena, tripped and untripped rollover, were considered in selecting the rollover stability metrics that would be evaluated with regard to their correlation with vehicle rollover accident involvement. The distinction between these two phenomena is that a tripped rollover involves an abrupt impact with a rigid or nearly rigid object at the vehicle's tires or wheels which induces a rotary motion to the vehicle that results in rollover. In the case of an untripped rollover, the vehicle is exposed to a gradual, or at least not an abrupt, increase of force at the tire/ground contact area which, when coupled with the vehicle's dynamics and physical properties, results in a lift of the vehicle's wheels off the ground leading to a rollover. The latter case also involves situations where the vehicle encounters a downslope or embankment. In such a case, the vehicle's being tilted by that slope reduces the forces necessary to initiate rollover. Untripped rollover also occurs when the vehicle's tires gradually furrow into soft ground. This builds up enough resistive force to lead to a rollover.

These two types of rollover phenomenon were examined to determine what vehicle design and/or performance characteristics are likely to correlate with accident data given their relationship to the actual physics of a rollover situation. Different metrics which characterize a vehicle's rollover stability are appropriate to each of these rollover types. Because of the lack of detail in the accident data files, it is not known which of these phenomena are involved in any individual accident and, as a consequence, which are the most frequent in rollover accidents involving light duty vehicles. If more detailed accident data were available, it would probably be possible to examine the correlation of accidents involving only one type of rollover phenomenon with rollover stability metrics appropriate to the type of rollover that occurred in those accidents. However, as it is not possible to determine, from the accident data used in these analyses, the type of rollover phenomenon involved in particular accidents, the metrics derived from the examination of these two types of rollover phenomenon would be examined for correlation with accident data representing all rollover accidents involving those vehicles in the data set.

The metrics used in this program to quantify the rollover propensity of vehicles were chosen for several reasons. The static stability factor has been used in the past by many researchers and found to have a good correlation with the accident data. Its inclusion in this research continues this effort. Side pull ratio was included since it used to measure roll propensity and has good scientific merit. The tilt table metric was included in this program since it is being proposed in the European community, thus it would allow some possibilities of harmonization between the U.S. and the Europeans, if selected as the best metric. Other metrics, such as rollover prevention and critical sliding velocity were selected for completeness and based on their scientific merit. Several metrics were used for yaw stability measures, since vehicles yaw stability may be important in determining vehicle attitude prior to the accident, and leaving the road sideways could lead to more rollover accidents.

4.2.1 Untripped Rollover Stability Metrics

Three metrics characteristic of the untripped rollover phenomenon were selected for correlation with rollover accident involvement. These are the static stability factor, the tilt table ratio, and the side pull ratio.

4.2.1.1 Vehicle Parameter Definitions

Before discussing the individual rollover stability metrics, two basic vehicle parameters need to be defined.

These are:

Center of Gravity Height, Vertical: The height, in inches, of the center of mass of the entire vehicle measured vertically from and normal to the plane on which the vehicle rests.

Vehicle Track Width: The average of the lateral distance between the centerlines of the two front tires and the two rear tires of the vehicle.

4.2.1.2 Static Stability Factor

For untripped rollover, the most basic metric is the static stability factor mentioned earlier. The static stability factor (SSF) is then determined as:

$$SSF = \frac{TW}{2 \cdot h_{cg}} \quad (1)$$

where: TW = Track width
 h_{cg} = Vertical cg height

If a vehicle were a rigid body with no tire or suspension deflections or motions, this measure would be equal to the level of lateral acceleration at which the vehicle would begin to lift its inside (of a turn) tires off the ground and if forces at the tires were not reduced, the vehicle would roll over.

However, vehicles are not rigid and there are two other measures which take into account the motions of the vehicle's sprung mass (the body and chassis less the suspension and tires) relative to tire contact area. These are the tilt table test angle (the result of this test is usually represented as the tangent of that angle and is called the tilt table ratio) and the side pull force ratio.

These measures are more representative of a vehicle in an actual turning maneuver since they take into account effects of the vehicle's suspension kinematics and its tire and suspension deflections. These effects result in motion of the vehicle's cg relative to the vehicle's tires (where the forces that result in a rollover are generated). These motions change both the cg height (above the ground) and the lateral distance between the cg and the tires on the outside of the turn. In other words, in a real cornering situation, the vehicle's rollover stability is still characterized by "the distance from the lateral cg to the tire contact patch" divided by "the height of the cg." However, the static stability factor, SSF, is calculated based on the static cg height and the track width discounting any change in the cg's position due to the vehicle's suspension and tires.

4.2.1.3 Tilt Table Ratio

The tilt table test involves placing the vehicle on a platform which is then tilted about an axis parallel to the vehicle's longitudinal axis and the vehicle's rollover stability is characterized by the angle at which the tires on the upper side of the platform lose contact with the platform and the vehicle begins to fall off the platform. The tilt table test is shown graphically in Figure 1. As can be seen from this figure, the tangent of this angle is equal to the ratio of the lateral distance between the tire and the lateral center of gravity location to the height of the center of gravity. This ratio approximates the static stability factor and thus, the tangent of the tilt table angle, called the Tilt Table Ratio (TTR), is:

$$TTR = \frac{Mg \cdot \sin \phi}{Mg \cdot \cos \phi} = \tan \phi \quad (2)$$

where: ϕ (phi) = the angle of the tilt table at the point where both wheels lift off the table.

M = vehicle mass, slugs

g = acceleration due to gravity, 32.2 ft/sec²

The TTR is an approximation of the level of lateral acceleration at which the vehicle would roll over. The tilt table test more accurately simulates a vehicle negotiating a steady turn at high lateral acceleration or a vehicle on an embankment or side slope than does the rigid vehicle model upon which the static stability factor is based. However, the total force acting on the vehicle is only equal to the vehicle's total weight. In a real cornering maneuver, the force would be the resultant of both the vehicle's weight and the lateral acceleration times the vehicle's mass. For most light duty vehicles, the force acting on a vehicle on the tilt table,

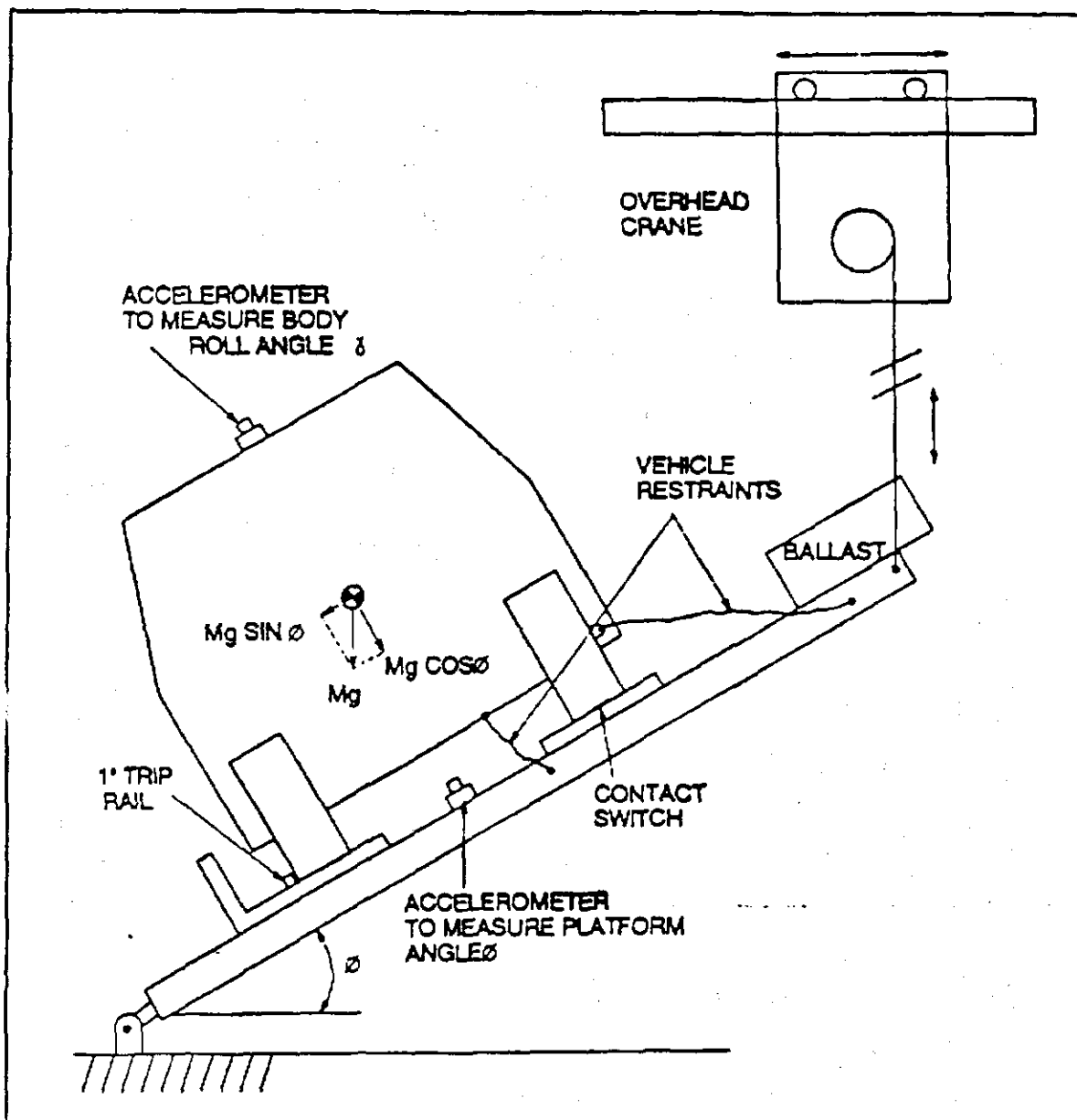


Figure 1. Tilt Table Test Setup.

at its "rollover" angle, would only be 60% to 80% of that which would be acting on a vehicle in a turn at the point of rollover. This lower force has two effects on the tilt table "rollover stability factor" estimate. First, this lower force results in smaller lateral movement of the sprung mass, which decreases the effective half-track width by a smaller amount than would be observed under a real rollover situation, and, therefore, would tend to result in a higher estimate of the lateral acceleration rollover threshold than in an actual rollover. Second, this lower force effectively reduces the level of gravity acting on the vehicle since the "vertical" (relative to the vehicle) force is also reduced. This raises the vehicle cg (relative to the platform) due to the reduction of the load on the vehicle's springs, and, therefore, reduces the estimated rollover threshold. But on the other hand, the tilt table test should be an excellent predictor of a vehicle's possibility to rollover when a vehicle negotiates a side slope of embankment.

Since the overall impact of these two effects is dependent upon the lateral suspension stiffness (that involve both roll and lateral motions that lead to changes in the effective half-track width) and vertical suspension stiffness (that lead to changes in the cg height) of a particular vehicle, the overall effect compared to the real vehicle maneuvering situation cannot be easily estimated. However, although the technique may not actually duplicate the exact physics of a real world rollover during high lateral cornering, the metric may represent the vehicle's rollover propensity with sufficient accuracy due to its excellent representation of side slope rollovers, to proceed with a rollover stability standard based on this metric.

In 1990, a tilt table test was proposed by the United Kingdom (UK), and in revised form by other European nations, to the GRRF (acronym for the French title "Meeting of Experts on Brakes and Running Gear") of the Economic Community for Europe (ECE) as a standard for "four wheel drive multipurpose vehicles." The U.K. proposal includes a recommended requirement level of a minimum tilt angle of 40 degrees (TTR = 0.839) at both "unladen" (driver only) and "laden" [manufacturer's recommended maximum or Gross Vehicle Weight Rating (GVWR)] load conditions.

As will be discussed further in Section 4.3, the vehicle rollover stability metric data gathered for use in the agency's analyses were measured in the driver only load condition. In order to evaluate the impact of the GVWR load condition of the UK proposal on the TTR of the vehicles in NHTSA's vehicle sample, NHTSA measured the TTR for eleven vehicles in a GVWR load condition similar, but not identical to, those contained in the original UK proposal. Data on these tests are presented in Section 4.3.2.

At a GRRF meeting in February 1991, it was agreed that the proposal would be extended to be applicable to ECE vehicle classes M₁ and N₁ which together represent basically all light duty vehicles. Also, at that meeting, it was suggested that the laden load condition in the UK proposal be replaced by that contained in the Union of Soviet Socialist Republic's proposal which would require that "the load beds of goods (cargo carrying) vehicles shall be ballasted...in such a way that the center of mass of the ballast lies on a level with the middle of the sides of the load bed."

As a result of these most recent actions by the ECE/GRRF and the UK, additional tests under several load conditions, including full passenger complement, and 2 versions of the G load condition, are being conducted by NHTSA to examine the effect of these load conditions on the relative TTR ranking of different vehicles.

4.2.1.4 Side Pull Ratio

The side pull test involves applying a horizontal (lateral) force to the vehicle, through sufficient to just lift the vehicle's wheels opposite the pull force off the ground. The pull test setup is shown in Figure 2. The Side Pull Ratio (SPR) is:

$$SPR = \frac{\text{Lateral Force}}{\text{Vehicle Weight}}$$

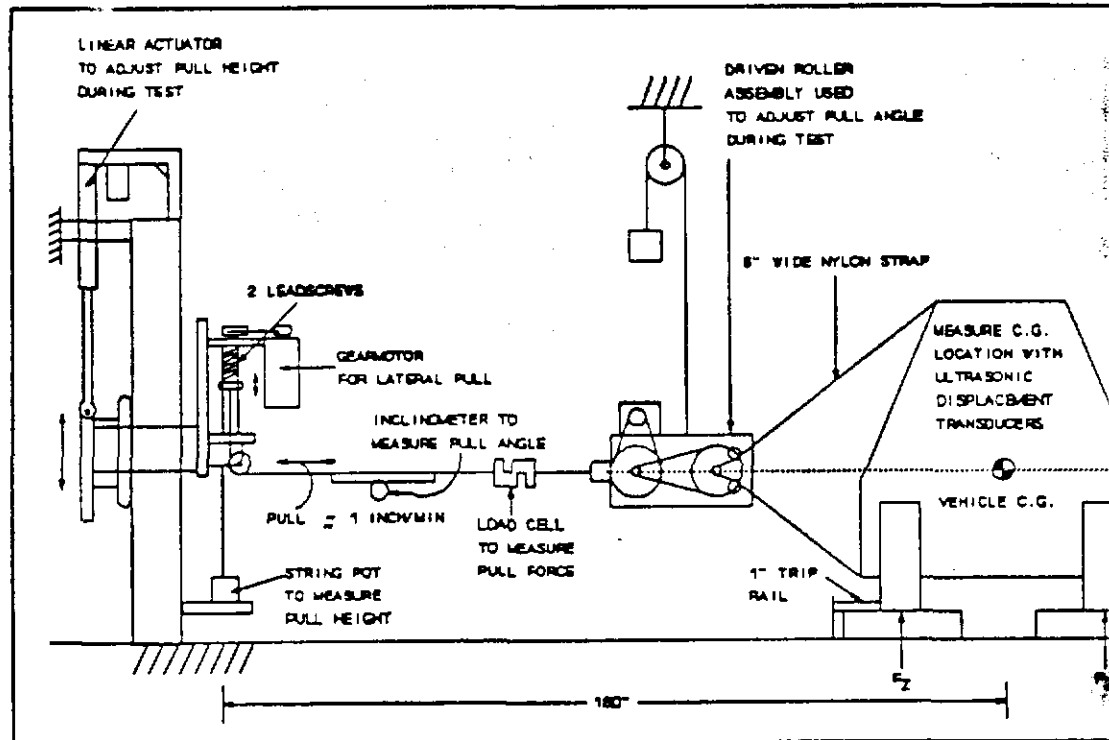


Figure 2. Side Pull Test Setup.

This ratio of the side pull force to the weight of the vehicle is an approximation of the acceleration necessary to initiate a rollover, and, as in the case of the tangent of the tilt angle, is also an approximation of the ratio of the effective half-track to cg height at the point of incipient rollover. This technique's strong point is that it attempts to replicate the forces acting on the vehicle at the point of incipient rollover more accurately than the tests used to determine either the static stability factor or the tilt table ratio. Because of this, the

$$RPM = 100 \frac{T_0 - T_1}{T_0} \quad (4)$$

where:

$$T_0 = \frac{1}{2} M V_y^2 \quad (5)$$

$$T_1 = \frac{1}{2} \frac{M^2 V_y^2 h_{cg}^2}{I_{oxx}} \quad (6)$$

$$I_{oxx} = I_{xx} + M \left(\frac{TW^2}{4} + h_{cg}^2 \right) \quad (7)$$

V_y = vehicle lateral velocity

I_{xx} = roll mass moment of inertia of the vehicle.

It is of note that even though V_y appears in the equations for T_0 and T_1 , RPM is not a function of V_y since it cancels out in the formulation of RPM.

4.2.2.2 Critical Sliding Velocity

The critical sliding velocity metric is a measure of the minimum lateral velocity required to initiate rollover, when the vehicle is in a tripping orientation. It is determined by equating the vehicle energy prior to the tripped impact with the energy needed to raise the vehicle cg to the point where it is just above the assumed pivot point which the vehicle is rolling about. In a tripped rollover, the roll motion is assumed to occur about the point or axis where the tire(s) have contacted the tripping object. Critical sliding velocity (reference 5) is a function of the vehicle's roll mass moment of inertia, vertical cg height, track width, and coefficient of restitution (e); has direct linkage to SSF, since both use track width and h_{cg} in their derivation; and is determined as follows, for inelastic impacts where $e=0$:

$$CSV = \sqrt{\frac{2gI_{\text{oxx}}}{Mh_{cg}^2} \left(\sqrt{\frac{TW^2}{4} + h_{cg}^2} - h_{cg} \right)} \quad (8)$$

where I_{oxx} is defined as in Section 4.2.2.1 above.

4.3 TESTING

Vehicles were tested at two test facilities, Vehicle Research and Test Center (VRTC), NHTSA's test facility in East Liberty, Ohio, and Systems Technology Incorporated (STI). At both VRTC and STI, tests were performed to determine the static stability factor, side pull ratio and other properties which were used in a dynamic directional response simulation model. Each of these sites measured these properties for a subset of the total vehicle test sample. At VRTC, tilt table ratios were determined for all the vehicles in the test sample and the dynamic model was run for all the vehicles to obtain simulated dynamic directional responses to steering inputs.

In all, vehicle measurements were obtained for 54 different make/models. The project at VRTC tested 16 vehicles and that at STI tested 41 vehicles, however, three of the same make/model vehicles were tested at both facilities and for three vehicle make/models tilt table tests were not conducted. Two of these duplicate make/models were used as control vehicles and were shipped from one site to the other for repeat testing. The third was a repeat vehicle using a similar make/model. For these three duplicate make/models, the vehicle data measured at VRTC were used in the accident data analyses. Also at VRTC, two additional vehicle make/models had only their static stability factors and tilt table ratios measured; therefore SSF's were available for 56 different make/models and TTR's were available for 53 different make/models. The results of the comparison of the STI and VRTC test results are discussed later.

At VRTC, the inertial and side pull test matrices were designed to examine test repeatability and the effects of vehicle passenger loading, fuel loading and tire inflation pressure. Both types of tests were performed on twelve vehicles, with a total of fifty-nine test configurations. The similar data obtained for the 41 vehicles tested at STI represents vehicles in only one load configuration. The tilt table testing conducted at VRTC was performed in the one occupant (driver) configuration for 53 vehicle make/models and in the fully loaded (GVWR) configuration for 11 vehicles.

4.3.1 Vehicle Parameter Measurement

The following sections describe the test procedures used in the determination of the static parameters. They are described in generic terms, since the equipment used by the two test labs varied, but the physical measurements were the same. Measurements of the vehicle's

static stability factor, tilt table ratio, and side pull ratio are presented in Table 3, located at the end of this chapter. Table 4, also at the end of the chapter, presents the rankings of the vehicles based on the metric data in Table 3.

4.3.1.1 Center of Gravity Measurement

The longitudinal and lateral location of the vehicle's center of gravity (cg) were determined using the individual wheel weights along with their associated geometry. VRTC and STI used different procedures to determine the center of gravity height. At STI, the vertical cg height was determined by raising the front wheels of the vehicle and measuring the load distribution and changes in vehicle trim height under known increments of front wheel elevations. STI tilted the vehicle through an axis parallel to the vehicle's pitch (y-y) axis. VRTC measured vehicle center of gravity height using their Inertial Parameter Measurement Device (IPMD), which places the vehicle on a stable simple pendulum. A known torque is applied to the pendulum and the resulting angle and vehicle movement are measured. This information together with the test and calibration data, allows computation of the center of gravity height. VRTC also pivots the vehicle about an axis parallel to the y-y axis. (See reference 15 for details on both procedures, as well as error analysis of each.) The vehicle axis system is depicted in Figure 3.

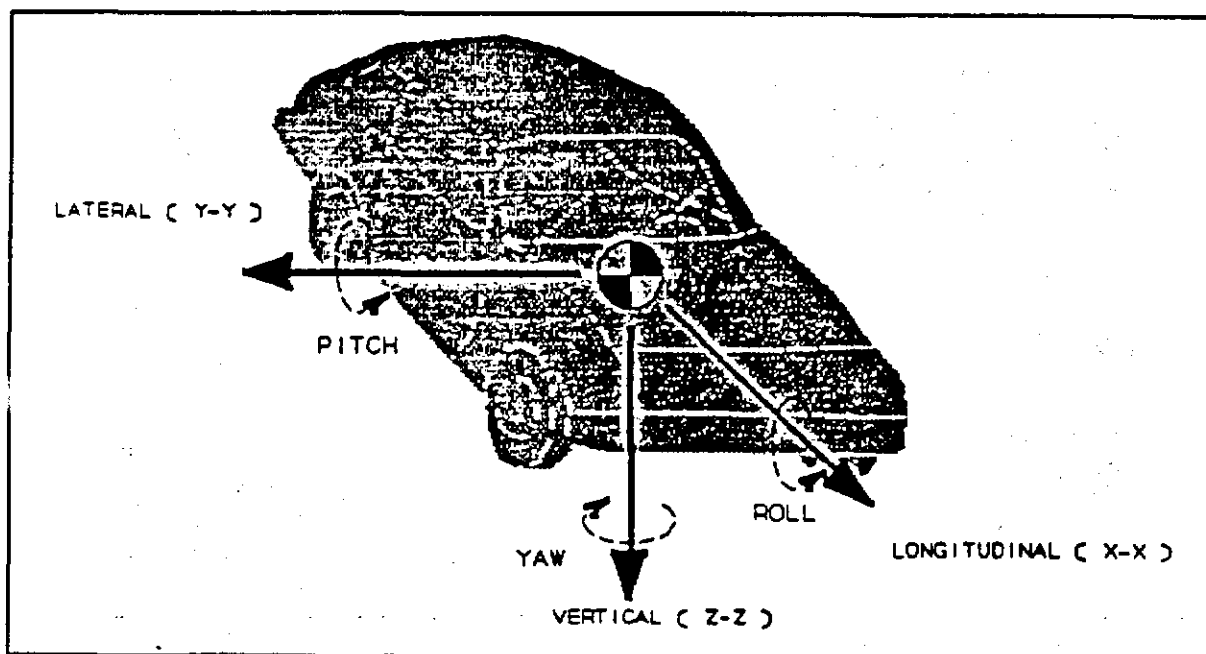


Figure 3. Vehicle Axis System of Coordinates.

4.3.1.2 Static Stability Factor Determination

The static stability factor is the average half track width divided by vertical cg height. The front and rear track widths were measured, added together and divided by two to determine

the average half track width. From the standpoint of its measurement, the static stability factor's strong point is simplicity, in that it requires only static dimensional and mass parameter measurements, albeit the measurement of the vertical cg height needs to be performed carefully to achieve reasonable accuracy (Reference 15).

4.3.1.3 Tilt Table Ratio Measurement

Tilt table ratio gets its name from the fact that the vehicle is placed on a table which is then tilted about an axis parallel to the vehicle's x-x axis. The vehicle is placed on the table with the tires on one side against a short curb. The table is then lifted while the tilt angle of the table is measured. When both tires on the high side lift off the table, the tilt angle of the table is measured. The point of wheel lift is determined using contact switches to detect when the wheels lose contact with the platform. The tilt table ratio, the tangent of the table angle, is then determined as the output of the tilt table test.

The tilt table test procedure has the advantage of not relying on other measurements for the setup of its test conditions. Also, the test itself is quite simple to conduct and quite repeatable. The tilt table testing showed the tilt table ratio results to be comparable to the side pull ratio results. Comparison of the tilt table ratio and side pull ratio data shows their vehicle rankings to be similar (see Table 4). Some test data has indicated that for some vehicles there can be significant variation in the tilt table ratio values for a vehicle model, especially for light trucks and utility vehicles. This is discussed in detail in Section 4.4.3.

The tilt table test has advantages over the side pull test due to its simplicity and the fact that it does not rely on center of gravity height measurements, thus reducing possible sources of error. In addition, the side pull test can damage vehicle body work, which is not a problem with the tilt table test.

4.3.1.4 Side Pull Ratio Determination

Side pull ratio is determined as the ratio of the lateral force acting through the vehicle cg required to lift the opposite side tires off the ground divided by the vehicle weight. The test is performed using wide straps, and in some cases chains, to apply the pull force to the vehicle body. Extreme care needs to be taken and adjustments to the pulling mechanism are made during the test to assure that the line of action of the force is horizontal, and that pull force vector passes through the vehicle's cg, as the vehicle rolls on its suspension and deflects laterally and vertically, causing the vertical and horizontal location of the cg to change.

Its major shortcoming is the complexity of the test and the extraordinary amount of equipment required to perform the test. This complicated setup can lead to errors and inconsistencies in the data.