U.S. Department
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DOT HS 809 894 November 2005

Technical Report

Rollover Crash Mechanisms and Injury Outcomes for Restrained Occupants

**Published By:
NHTSA's
National Center for Statistics and Analysis**

NCSA

Technical Report Documentation Page

1. Report No.
HS 809 894

2. Government Accession No.

3. Recipients's Catalog No.

4. Title and Subtitle
Rollover Crash Mechanisms and Injury Outcomes for Restrained Occupants

5. Report Date
November 2005

6. Performing Organization Code
NPO-121

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Mathematical Analysis Division, Office of Traffic Records and Analysis
National Center for Statistics and Analysis
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Washington, DC 20590

10. Work Unit No. (TRAIS)n code

11. Contract of Grant No.

12. Sponsoring Agency Name and Address
Mathematical Analysis Division, Office of Traffic Records and Analysis
National Center for Statistics and Analysis
National Highway Traffic Safety Administration
U.S. Department of Transportation
NPO-121, 400 Seventh Street, S.W.
Washington, DC 20590

13. Type of Report and Period Covered
NHTSA Technical Report

14. Sponsoring Agency Code

15.Supplementary Notes
Special thanks to Dr. David Smith, Office of Vehicle Safety, Mr. Dennis Utter, and Dr. Chou-Lin Chen, both of NCSA, for making the completion of this report possible.

16. Abstract

The present study amplified findings presented in “Examination of Rollover Crash Mechanisms” (2003), “Crash Attributes That Influence the Severity of Rollover Crashes” (2003), and “Characterization of Attributes Applicable to a Rollover Crash Severity Metric” (2004) relevant to restrained occupants. Identification of the three crash occupant populations was reviewed: unejected belted, unejected unbelted, and ejected unbelted. Belted occupants involved in multiple-vehicle rollover crashes were studied owing to their elevated serious injury rates. Harm analysis and case reviews were presented for the belted occupants involved in single-vehicle rollover crashes. Two alternate crash populations were studied owing to their injury implications and pure rollover characteristics.

Multiple-vehicle rollover crash belted occupants were selected owing to the elevated injury risk associated with this crash configuration. Among belted rollover crash occupants, the injury rate for multiple-vehicle rollover crash occupants was twice as high as for single-vehicle rollover crash occupants. Among unbelted rollover crash occupants, the difference between the injury rates for the crash configurations was negligible.

Single-vehicle rollover crashes with nonfixed object impacts were selected because these simulated a pure rollover situation. These impacts also excluded abruptly stopped rollover crashes, especially those for which the roof was stopped by a fixed object. From these crashes, representative cases were selected for analyses of HARM, crash mechanisms, and injury patterns.

HARM is a measure of societal cost of injuries sustained by motor vehicle crash occupants. From the HARM analysis, two injured body regions were identified for further study. These were: the head and thorax. Elevated HARM values were noted in rollovers with one roof to ground contact for head injuries and the second roof to ground impact for thoracic injuries.

The final section presented hard-copy case review based upon the identified injuries associated with roof to ground impacts. Head injuries in rollovers with one roof to ground contact were consistent with the work of Burel (2003), who found the highest dummy head accelerations during the first revolution. These results were based upon modeling. Thoracic injuries were divided into near-side and far-side injuries. The near-side occupant thoracic injury source was generally associated with the side hardware and the far-side occupant thoracic injury source was generally associated with the safety belt. Further, tripping acceleration was evident in most of these cases. The present work seeks to outline the tripping acceleration and complex motion phenomena predicated on the injury mechanisms identified in Eigen (2004).

17. Key Words
rollover crashes, quarter turns, MAIS 3+F injuries, tripping acceleration, head injuries, thoracic injuries

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of Pages
44

22. Price

Form DOT F1700.7 (8-72)

Reproduction of completed page authorized

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1 Executive Summary

In continued response to the rollover situation in the United States and parameters identified in subsequent research, more information is available regarding:

- rollover population selection;
- crash configuration and its influences on occupant outcome;
- application of societal costs to injuries sustained by restrained unejected occupants (occupants retained completely within the occupant compartment exclusive of partial or full ejections) in rollover crashes; and
- association of prevalent crash modes and injury characteristics for restrained unejected occupants.

This document will:

- justify the selection of belted unejected occupants;
- discuss societal implications of injuries sustained by this group; and
- identify injury mechanisms and associated crash parameters.

Current findings indicate that:

- head and thorax injuries were the highest contributors to societal cost;
- planar impacts prior to rollover need to include a planar crash severity (delta V) in addition to the rollover severity (Number of roof to ground contacts);
- the magnitude of the trip pulse influences the number of roof to ground impacts and may increase Abbreviated Injury Scale (AIS) 3+ chest injury risk; and
- most Maximum AIS (MAIS) 3+ head injuries occur in rollovers with one roof to ground contact.

2 Introduction

The study of rollover crash severity is dependent upon its ability to be quantified for benefits analysis. Upon determining a societal good coming from a sophisticated benefit cost analysis model, such as HARM, a severity metric may be found to be dependent upon some countermeasure. In general, the early rollover countermeasures continue to be in force. These include:

- ejection prevention;
- intrusion control (roof strength); and
- safety belt improvements.

Pursuant to the review of relevant occupant selection and justification of inclusion, two subgroups were identified for review in this document. Among the restrained occupants, the most numerous group of relevant occupants, the multiple-vehicle configuration and single-vehicle nonfixed-object crashes constituted two opportunities for improvement. Multiple-vehicle belted rollover crash occupants had an injury rate twice as high as for single-vehicle belted rollover crash occupants. Among restrained occupants, the single-vehicle rollover crashes without fixed-object involvements were selected as a surrogate for the pure rollover case.

3 Background

Since the early 1980s, the pursuit of a rollover severity metric has intrigued researchers. McGuigan (1980) and Najjer (1980) considered energy absorption surrogates similar to delta V. The concept of a several-tiered severity metric also emerged when considering the planar and rollover components of the crash. Until 1995, insufficient refinement in the collection of the number of quarter turns disallowed the consideration of roof to ground impacts. Currently, a study of this nature was permissible owing to the detailed data available and the number of years since the inception of this level of detail.

“Examination of Rollover Crash Mechanisms and Occupant Outcomes” (DOT HS 809 692, 2003) examined the first phase of recent rollover severity metric review. It consisted of initial identification of a rollover data set and associated vehicle and occupant parameters. At the conclusion of DOT HS 809 692, issues were identified pursuant to the initial study and future avenues of study were proposed. The areas of study were determined via analysis of National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) data, 1995 through 2001. This work presents the subsequent findings using the NASS CDS data, 1995 through 2002.

DOT HS 809 692 and Digges (2003) both resulted from the data analysis. Both publications presented results prior to significance testing. The significance testing was used to determine whether issues identified in CDS merited further study. The findings of the significance testing shaped the remainder of the project. These results were reported in Eigen (2004).

Upon identifying the populations and establishing a rollover severity metric, a review of cases ensued. The engineering analysis made use of the coded elements, as well as the photographic documentation available from the NHTSA Electronic CDS Case Access.

The final phase, computer modeling, was dependent upon the significant issues and the characteristics associated with these crashes. This information was coupled with test data to further redefine rollover models for restrained passenger car occupants.

4 Methodology

The overall analysis was divided into three components. These were:

- data analysis and test for significance of results;
- review of cases and engineering analysis of crash patterns; and
- computer modeling of crashes based upon supplemental test data.

This phase of the study focused on the restrained occupants who presented the largest opportunity for improvement owing to the magnitude of this population. This population is identified and discussed in subsequent sections. Among restrained occupants, this study identified rollover crash and injury parameters for:

- those crashes closest to the state of pure rollover
- occupants associated with the highest injury risk.

5 Definitions and Population Identification

This section provides the crash severity measures used to analyze the data. Further crash, occupant, and injury definitions are provided. Based upon the quantification of occupants, and crash and injury definitions, the populations of interest are outlined.

5.1 Evaluation of Crash Severity

In assessing the true magnitude of a problem not only its population size must be examined. Also, some quantifiable attributes must be identified to characterize the problem. These are:

- exposed population;
- injury frequency; and
- injury rates.

5.2 Definitions

From the rollover crash population, those occupants sustaining MAIS 3 through 6 and fatally injured occupants sustaining MAIS 1 and 2 injuries were selected (NHTSA, 2000). These injuries will be identified as MAIS 3+F in this document. Occupants subjected to rollovers of quantifiable quarter turns were selected and disaggregated based upon crash configuration.

By virtue of the exposure and the MAIS 3+F injured occupants, a rate of injury could be established. The term risk was used in a similar context, as rate of injury, but was not meant to identify the statistical constructs of relative or absolute risk. The injury risk represented the number of MAIS 3+F injuries sustained for a given rollover subpopulation per 100 occupants exposed to rollovers.

Based upon early rollover studies, roof to ground impacts were proposed as a potential severity metric. From 1988 through 1994, NASS CDS allowed for quantification through the third quarter turn and aggregated quarter turns as of the first roof to ground impact. This precluded any roof to ground impact analysis to be done. In 1995, NASS CDS modified rollover quantification and allowed for 16 quarter turns, four complete revolutions and four roof to ground impacts, to be recorded. A value aggregating any quantifiable rollover beyond 16 quarter turns was also assigned. It was determined that aggregation of 2 or more roof to ground impacts provided an adequate severity measure and accurately increased the size of the cell (Eigen, 2004). Table 1 provides the translation of roof to ground contacts based upon the number of quarter turns.

Table 1: Relationship between Number of Roof to Ground Impacts and Quarter Turns

Number of Roof to Ground Contacts/Impacts	Number of Quarter Turns
Zero	1
One	2, 3, 4, 5
Two-Plus	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 16+

Source: NASS CDS, 1995 - 2002

The number of roof to ground impacts is defined as the number of times the roof brushes, touches, or is suspended over the ground in a rollover. This distinction is made, especially in the case of severe rollover, when the second quarter turn may constitute no contact with the ground or a light brushing.

Tow-away crashes are disaggregated based upon the number of vehicles involved in the crash. Single-vehicle crashes are those in which one vehicle was reported in the crash. Multiple-vehicle crashes consisted of any crash in which more than one vehicle was involved.

5.3 Identification of Populations of Interest and Constraints

Three populations of interest were published in Digges (2003) that were relevant to rollover crashes and were used in this study. These populations were:

- restrained, unejected occupants;
- unrestrained, unejected occupants; and
- unrestrained, completely ejected occupants.

These population groups were identified using NASS CDS data from 1995 through 2001. Adding the 2002 data does not affect the proportion of these populations. The rollover data set represents approximately 1.5 million vehicles transporting nearly 2 million left- and right-front-seat occupants, 12 and older. Approximately 126,000 of these occupants sustained MAIS 3+F injuries. The unweighted data consists of 3,871 vehicles and 5,227 occupants with 1,309 sustained MAIS 3+F injuries.

The data were restricted to the two front outboard seating positions to insure comparability among a variety of vehicle platforms. In this way, the results were not skewed toward vehicles, which could transport several occupants. Upon removing other seating positions, occupancy rates were comparable, as seen in Digges (2003).

It should also be noted that vans constituted a very small segment of the population and distorted the findings. The vans were retained in the general summarizations but were excluded from analysis.

6 Rollover Crash Configuration and Its Influences on Occupant Outcome

This section explains the disaggregation of the number of vehicles involved in a crash. The relationship between the number of vehicles involved and injury severity, and the relationship between the number of vehicles and crash severity are discussed.

6.1 Crash Configuration and Injury Severity

The initial summarization of data provided conclusions on aggregate rollover crashes. The benefit of a large sample masked the effects of multiple vehicles involved in rollover crashes. It was found, however, that the presence of more than one vehicle was highly injurious. Further, concepts of incidental versus serious planar events might be considered in this type of analysis and will be the subject of subsequent technical reports.

Approximately 20 percent of rollover crashes involved more than one vehicle. In multiple-vehicle rollover crashes, the injury rates were nearly double those of single-vehicle rollover crashes. This conclusion was based upon 5.8 MAIS 3+F belted multiple-vehicle rollover-crash-injured occupants per 100 belted occupants exposed to multiple vehicle rollover crashes, as compared with 2.8 MAIS 3+F belted single-vehicle rollover-crash-injured occupants per 100 belted occupants exposed to single vehicle rollover crashes, as reported in Digges (2003).

Belt use was highly correlated with MAIS 3+F injury rates among the unejected. The belted unejected occupants had a very low frequency and carried a low risk of injury. Conversely, the unbelted ejected were vulnerable to MAIS 3+F injury. The disaggregation of the population by restraint use and ejection status highlights the detriment of the unejected unrestrained occupants.

6.2 Crash Configuration and Crash Severity

Single-vehicle rollover crashes are distinctive and complex events. The introduction of one or more vehicles to the crash before or after the rollover can be devastating.

For planar and rollover crashes, a means to assess planar crash severity was devised. This made use of the 1995 coding modifications to delta V reporting in NASS CDS. Prior to 1995, if WINSMASH was unable to perform the damage calculation, for qualified crashes based upon vehicle damage measurements, then the severity would go unreported. Qualified crashes excluded:

- damage due to rollover;
- principal direction of force was non-horizontal;
- collision with a yielding fixed object that broke away early in the collision sequence;
- vehicle struck an easily movable object;
- damage was primarily to the undercarriage of the vehicle;
- vehicle damage was due to gross underride that engaged only the passenger compartment;
- two vehicles involved in an impact never reached a common velocity (sideswipe and endswipe);
- one of the vehicles involved in an impact was a moving, heavy vehicle that incurred significant damage; and
- simultaneous collision of three or more vehicles occurred that could not be separated into distinct collisions involving only one or two vehicles.

In 1995, an estimated delta V parameter was introduced. This provided an estimate of the damage to be used especially when assessing the most severe and second most severe events. In this analysis, the composite interpretation provided a qualitative means for comparing the computer-generated delta V with the estimated delta V. In table 2, the equivalencies used in the analysis are included. In comparing the measured deltaV and the estimated delta V, the results are nearly identical. For this reason, the aggregated delta V measure was accepted, allowing for an enlarged dataset with known values.

Table 2: Analytical Equivalence of Estimated Delta V to Measured Delta V

Estimated Delta V (Planar Crash Severity)	Measured Delta V Equivalent
Low	< 24 kilometers per hour
Medium	>= 24 and <=55 kilometers per hour
High	> 55 kilometers per hour

Source: NASS CDS, 1995 – 2002

Note: This is not an endorsed method by NASS CDS. It is rather an analytical tool used to enlarge the data set based upon comparing measured alone to measured plus estimated results. Note that the WINSMASH algorithm, using vehicle crash measurements, generates measured delta V and estimated delta V is a qualitative crash severity measure assigned based upon researcher experience.

7 Justification for Inclusion of Belted Unejected Occupants

Rollover crashes represented about 10 percent of the tow-away crash population. On average, roughly 220,000 tow-away rollover crashes occur yearly in the United States, calculated using NASS CDS. Approximately, 80 percent of the rollover crashes involve a single vehicle. Of all rollover crash occupants, 68 percent of exposed occupants were belted and involved in a single-vehicle rollover crash. Further, among MAIS 3+F injured occupants involved in rollover crashes, 24 percent of these MAIS 3+F rollover occupants were belted and involved in a single-vehicle rollover crash.

Each population was analyzed to ascertain whether the number of roof to ground impacts was an adequate measure of severity. It was envisioned that injury risk would increase smoothly as the number of roof to ground impacts increased. Due to the scope of this publication, only the belted unejected occupants will be considered. Additional information on this population and the remaining populations of interest may be found in Eigen (2004).

7.1 Belted Unejected Occupants Involved in Single-Vehicle Rollover Crashes

The largest rollover subpopulation was composed of belted unejected occupants involved in single-vehicle rollover crashes. These occupants presented the greatest opportunity for improvement based upon statistical exigencies. For this group, the injury severity increased as the number of roof to ground impacts increased. The annualized frequencies are presented in table 3, as a backdrop to figures 1 and 2.

Table 3: Annualized Number of Occupants Sustaining Rollover Crashes, by Quarter Turns and Vehicle Body Type

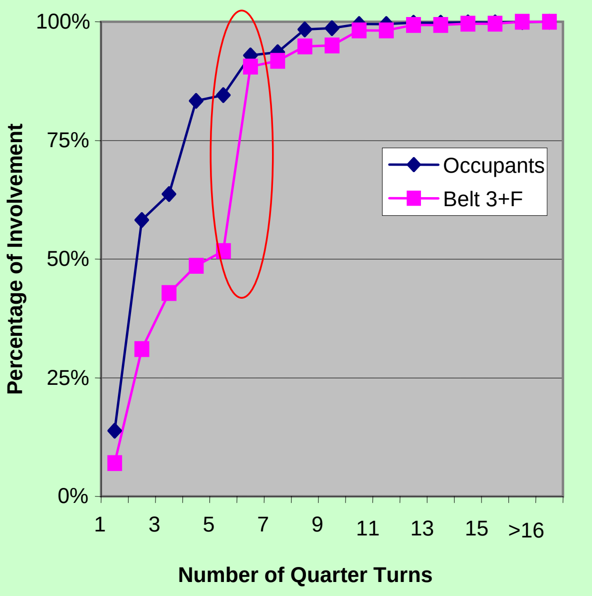
Number of Quarter Turn	Passenger Car	Sports Utility Vehicle	Van	Pick up Truck	Total
1	8,318	5,340	2,336	6,900	22,894
2	33,515	28,397	1,251	10,356	73,519
3	3,445	2,877	1,322	1,379	9,023
4	14,487	12,824	711	4,459	32,481
5	362	526	64	1,090	2,042
6	9,043	2,600	400	1,774	13,817
7	20	918	8	236	1,182
8	6,012	1,515	67	314	7,908
9	76	56	26	297	455
10	1,181	70	99	88	1,438
11	0	0	0	10	10
12	311	103	30	0	444
13	0	0	0	0	0
14	20	13	9	113	155
15	0	0	0	0	0
16	0	2	0	40	42
>16	0	107	18	5	130
End-over-End	550	57	74	44	725
Total	77,340	55,405	6,415	27,105	166,263

Source: NASS CDS, 1995 – 2001

Note: Annualized seven-year frequency.

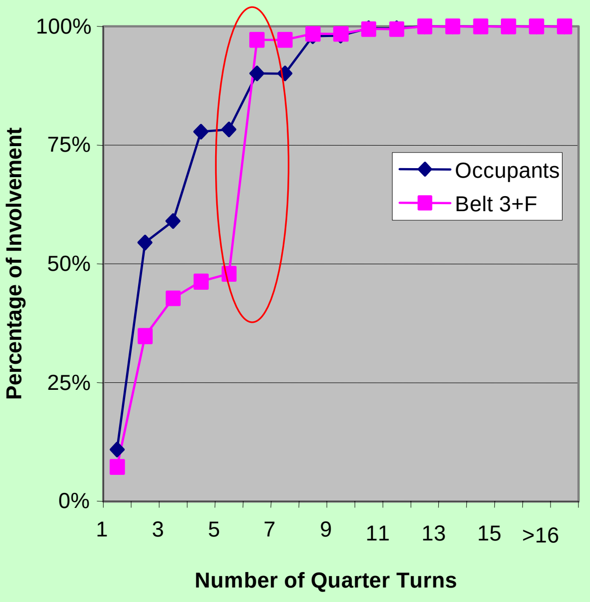
In figures 1 and 2, in rollovers with two roof to ground contacts, coincident with the sixth quarter turn, an increase in the occupant injury rate was noted for all passenger vehicles, as well as passenger cars alone. This was revisited later in the hard-copy case reviews.

Figure 1: Percent Involvement for Restrained Unejected Passenger Car Occupants and Those Sustaining MAIS 3+F Injuries, by Number of Quarter Turns



Source: NHTSA/NCSA/NASS CDS, 1995-2001

Figure 2: Percent Involvement for Restrained Unejected Passenger Car Occupants and Those Sustaining MAIS 3+F Injuries, by Number of Quarter Turns



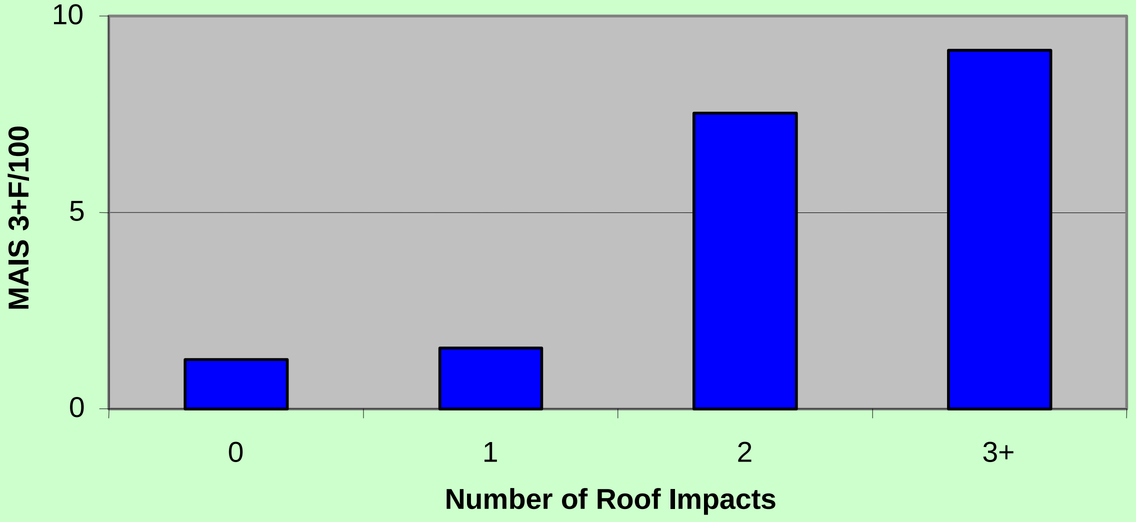
Source: NHTSA/NCSA/NASS CDS, 1995-2001

For this subpopulation, the use of roof to ground impacts was a preferred metric. Further, the aggregation for the two-plus roof to ground impacts was warranted. Based upon information reported in Eigen (2004), added data will be needed to obtain statistical significance for this limited population. Significance was found for the entire rollover population when examining the relationship between injury severity and roof to ground impacts.

In figure 3, the injury risk is plotted over the ascending roof to ground impacts. The number of roof to ground impacts was a good severity measure for belted occupants involved in single-vehicle rollover crashes, since injury severity increased monotonically with respect to increasing roof to ground impacts. It is noted that 48 percent of MAIS 3+F injuries occurred in rollovers with more than one roof to ground impact. The increased risk of injury for occupants in vehicles experiencing more than two roof to ground impacts was small.

When examining quarter turns, injury risk increased with ascending quarter turns but owing to the small sample size, and upon disaggregating, the quarter turn cell sizes became very small. The increase was better defined via roof to ground impacts. The decrease over the fourth through eighth quarter turn might have been attributable to the nature of the sample. The NASS cases are representative crashes selected not because of the quarter turns but by an algorithm subsuming general vehicle and injury characteristics. The increase in risk from two to three roof to ground impacts was small thereby allowing the creation of the two plus roof to ground impact category. Little was gained by leaving the two, three, and four roof to ground impact categories disaggregated. The roof to ground impacts presented a smoothly ascending relationship, as sought in an injury severity metric.

Figure 3: Injury Rate per 100 Exposed for Belted Unejected Front Seat Age 12+ Occupants with MAIS 3+F Injuries in Single Vehicle Rollovers by Number of Roof Impacts



Source: NHTSA/NCSA/NASS CDS, 1995-2001

7.2 Belted Unejected Occupants Involved in Multiple-Vehicle Rollover Crashes

The inclusion of the belted unejected occupants involved in multiple vehicle rollover crashes was dictated by an injury rate twice as high as the single-vehicle case. A disaggregation of the planar and rollover crashes was dictated owing to the difference in crash dynamics experienced in each type of crash. Pursuant to these findings, the specific occupant injuries were studied and the planar crash severity associated with these crashes provided an added measure to a composite crash severity metric.

8 Discussion of Belted Unejected Population

The previous sections provided an examination of the rollover data and its relevant subpopulations pursuant to data extraction and significance testing. The data spanned the years 1995 through 2001, as previously published. The subsequent sections consider 1995 through 2002.

8.1 General Case

This report presents the first subpopulations, as presented in Eigen (2004): the belted unejected rollover occupants 12 and older seated in the outboard front seats involved in a rollover crash. This group constitutes approximately 74 percent of the rollover population and 35 percent of the MAIS 3+F injured occupants. In subsequent phases, the unbelted unejected population will be considered, since they comprise 19 percent of the rollover population and 23 percent of the

MAIS 3+F injured occupants. The unbelted ejected population is the third group of interest, contributing 4 percent of rollover occupants and 33 percent of the of the MAIS 3+F injured occupants, with an injury rate of 49.6 per 100 ejected occupants, per Digges (2003). The restrained population will be examined from two perspectives: injury rates and HARM analysis of pure rollover.

An increased risk of injury has been shown for the multiple-vehicle rollover crash occupants. These crashes were separated into planar and rollover events. Further, the planar events may either have constituted a severe or incidental contact. The severe contact was considered an impact to which the injuries might be attributed whereas the incidental contact was an impact in which the planar event presented little danger to the occupants and the injuries might reasonably be attributed to the rollover sequence. Attribution of an injury to a particular event, however, was beyond the scope of this report and retained for future study.

Cases in which a single-vehicle rollover crash occurred without a prior impact with a fixed object were selected as surrogates for the case of pure rollover. This was envisioned in keeping with constraints of modeling. The HARM analysis allowed a societal cost to be attributed to the injuries. The maximum injury was assigned the cost factor. The maximum injury was determined based upon a hierarchy of injuries: head/face, neck, spine, thorax, abdomen, lower extremity, upper extremity, unspecified body region, and missing values. This hierarchy was selected based upon expected injury patterns occurring in rollover crashes and their severity. This was not meant to be an endorsement of any given hierarchy but a starting point from which other competing hierarchies might be introduced, at the discretion of the analyst. The AIS 3+F, owing to injury specification rather than aggregate occupant severity, level was used to determine the areas of concern. From this analysis, areas of concern were identified and led to case reviews ascertaining physical crash properties and associated injury mechanisms.

8.2 Specific Case: Multiple-Vehicle Rollover Crash Configuration for Belted Occupants

Injury rates in multiple-vehicle collisions were 1.5 times higher than in single-vehicle rollovers, per Digges (2003). Among the unejected occupants involved in multiple-vehicle rollover crashes, the injury rates were 2.2 times higher than in single-vehicle rollover crashes. Planar delta V was used to capture the severity of the planar portion of the crash.

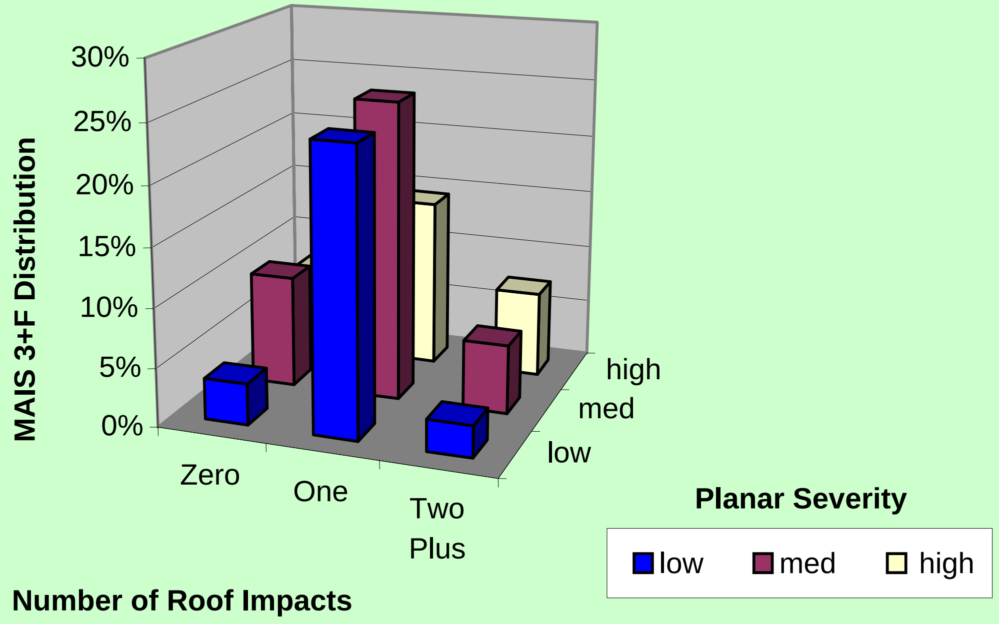
Two delta V measures were used in this study to determine planar severity, measured delta V and estimated delta V. Measured delta V was the value yielded from the WINSMASH algorithm based upon vehicle damage. The estimated delta V, for crashes not able to be calculated using WINSMASH, was made available starting in 1995. These crashes included, but were not limited to, rollover and sideswipe. The estimates carried qualitative values of low, medium, and high crash severity. Table 2 provided a translation for the aggregation of these two values.

Comparisons of delta V by roof to ground contacts were made for all general areas of damage and for aggregated rollover crashes. The results when using only measured delta V and aggregating measured and estimated delta V yielded the same results. This allowed for the following analysis. Results for each of the crash modes and the aggregated case were published in Eigen (2004). Based upon these results, comparisons of body regions injured by the number of roof to ground impacts and the planar crash severity were analyzed.

In figure 4, the distribution of MAIS 3+F occupant injuries was partitioned, by the number of roof to ground contacts and planar crash severity. The injury measure was defined previously to account for serious injury. The roof to ground contacts, synonymous with roof to ground impacts, were also described previously. The planar severity was introduced to disaggregate effects of the rollover and planar events. Figure 5 also contained a similar format, however, substituting MAIS 3+F injury distribution with MAIS 3+F injury risk. The injury risk was described in both graphics over ascending number of roof to ground contacts or planar crash severity. The remaining discussion followed this tact by disaggregating the injury severity and referencing the salient rollover and planar measures of crash severity.

Continuing with the discussion of figure 5, an evident increase was identified over the increasing planar severities for each level of roof to ground impact. The injury risk also increased with increasing roof to ground contacts for low and medium planar severity. A general increase in risk was found with damage extent and roof to ground contacts. The zero roof to ground impacts category was found to have an outlier potentially from a severe event or limited amount of data. This condition was primarily associated with severe side impacts that resulted in one quarter turn. Additional years of crash data might increase the sample and allow for the conditions of the outlier to be more completely identified.

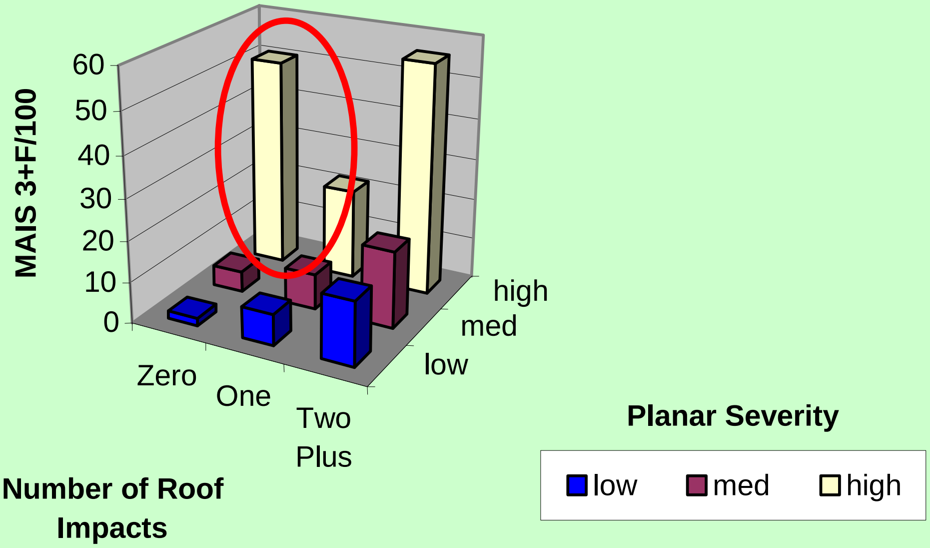
Figure 4: Percentage of Injury, by Planar and Rollover Severity



Source: NHTSA/NCSA/NASS CDS, 1995-2002

As expected, the majority of MAIS 3+F injury percentage distribution falls within the first roof to ground contact. As noted previously, the rollover component was not assigned a delta V reading owing to the algorithm architecture. The linear deformation present in planar crashes was absent in rollover crashes since the forces were not directly proportional to deformation. Delta V was used as the planar severity indicator. Based upon the studies cited above, roof to ground impacts have been selected as the rollover severity indicator. From this point, a mixed indicator evolved. The planar crash severity was dependent upon energy transfer, whereas the number of quarter turns sustained by the vehicle constituted the rollover severity indicator. Roof deformation does not predict the amount of crash energy.

Figure 5: Injury Risk, by Planar and Rollover Severity



Source: NHTSA/NCSA/NASS CDS, 1995-2002

8.3 Analytical Considerations

Among belted occupants, several refinements should be made in analyzing rollover crashes and defining severity. Definitions would reflect the findings of the data analysis to include multiple-vehicle collisions, fixed-object contacts, and roof leading, one-quarter-turn rollover crashes.

For multiple-vehicle collisions occurring prior to rollover, a pre-rollover crash severity measure must be defined with a rollover severity measure. In the previous discussion, delta V was proposed owing to its accessibility and the introduction of the estimated value for the delta V. The dataset was enhanced by including measured and estimated delta V. This was warranted based upon the analysis described previously.

The condition of fixed object contacts, especially for single-vehicle crashes, presented unique scenarios. As was seen in hard-copy case review, multiple-impact crashes constituted an elevated danger, per the work of Bahouth (2004).

The final condition identified for the belted occupants was the rollover interrupted at the first quarter turn. In this roof-leading scenario, great force was being imparted to the vehicle. It was suggested that some coding element be introduced to easily identify this condition.

9 Societal Cost of Injuries to Belted Unejected Occupants Involved in Single-Vehicle, Nonfixed Object Rollover Crashes

The largest segment of the injured population was found to be the belted unejected occupants. Although they constituted a lower injury risk than their unbelted counterparts, their absolute magnitude and their willingness to comply with restraint-use mandates made them a very interesting group. These occupants have benefited from a technology intended for planar crashes and, in most instances, they fared very well. Cases where occupants have opted to comply but have been injured merited further investigation.

A further refinement of this population excluded multiple-vehicle crashes or any crash in which a collision with a fixed object preceded the rollover crash. In this way, unusual, violent conditions imposed by fixed-object crashes would not confuse the pure rollover scenario.

9.1 Description of Chosen Societal Cost Method – HARM

The societal cost of injuries has long been a topic of interest. This has aided in benefit cost analysis for the preparation of rulemaking, research, and development. Analysis and methods developed by Malliaris (1982) have become the basis for such costing. The methodology involved the examination of overall societal costs of injuries attributable to motor vehicle crashes. The injury severity for HARM was based upon the average costs of injured people at each MAIS level. The HARM was expressed in dollars. NHTSA subsequently modified the calculation by dividing the cost by the average cost of a fatality. The resulting HARM was expressed in equivalent fatalities. To calculate HARM for a population, the maximum severity of each injured occupant was multiplied by the HARM factor (in equivalent fatalities) and the results for the population were added together. The HARM provided an overall cost of injuries of different severities in terms of equivalent fatalities.

HARM factors were applied to each injury and the maximum injury sustained by each occupant to obtain proportional costs. Analysis was performed using both methods but the former might tend to overstate injury cost. The benefit rested with the larger data set able to report injuries more completely. The latter method was developed upon assignment of a maximum injury based upon a hierarchy. The hierarchy was defined in descending order as follows: head and face, neck, spine, thorax, abdomen, lower extremities, upper extremities, unspecified, and missing values. Only AIS 3+F injuries were considered in this study. Results for each AIS level were reported in Eigen (2004).

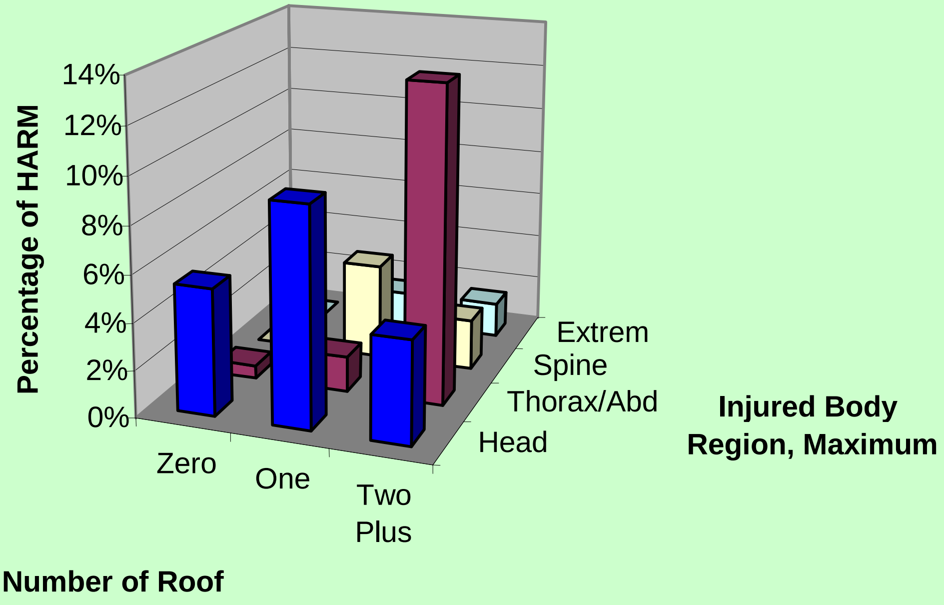
9.2 Results Leading to Case Reviews

The case review parameters were selected based upon comparative data from each of the AIS levels and characterized in figure 6 for AIS 3+F for restrained occupants. In this figure, the percentage of HARM was reported by injured body region and number of roof to ground impacts. Two body regions emerged as the areas of concern within pure rollover crashes when studying the maximum injuries, as defined by the rollover injury hierarchy.

The majority of head injuries occurred in rollovers with one roof to ground contact. This was coincident with findings of Burel (2003). The model of an SUV in a maneuver induced rollover provided insight into the time at which head velocity was the highest for the left and right front belted unejected occupants. The head velocities reached a maximum of about 5 meters per second after the first roof to ground contact. In that research, the maneuver-induced rollover was likened to a pure rollover condition. This occurred in the absence of any fixed object or other vehicle engagement. Among restrained occupants sustaining head injuries, the HARM was second only to those occupants sustaining chest injuries at two plus roof to ground impacts. Head injuries were not disaggregated with regard to intruding components; therefore, these injuries may or may not have been related to roof intrusion.

Chest injuries were most prevalent at two or more roof to ground impacts, as shown in figure 6. The elevated thoracic injuries were unexpected and warranted case reviews. An engineering analysis of the possible crash mechanisms and injury sources was undertaken. The summarized photographic and occupant injury analyses results were presented in the next section. The complete text was published in Eigen (2004).

Figure 6: Percentage of HARM, by Number of Roof Impacts and Most Seriously Injured Body Region



Source: NHTSA/NCSA/NASS CDS, 1995-2002

10 Identification of Case Review Focus

Based upon their HARM contribution as seen in figure 6, the prevalence of chest injuries pursuant to high-severity crashes was evident. The severity, in this case, was the early measure of quarter turns. In general, high tripping was often associated with the two-plus roof to ground impacts. This was particularly true for passenger cars. The static stability factor for this vehicle type ranged from 1.30 to 1.50, indicating a high degree of force to sustain the vehicle through more than six quarter turns and the damage patterns found. The near-side and far-side rollover had distinct chest injury sources. For the near-side rollovers, the most frequent injury source was side hardware; for far-side rollovers, the most frequent injury source was the safety belt. The near-side was selected for this summarization owing to the photographs and data associated with the case and their exemplification of the side force phenomena. Additional information on far-side crashes was published in Eigen (2004).

Approximately, 190 cases were reviewed. These cases were qualified based upon MAIS 3+F injuries sustained by the left- or right-front belted occupant who was at least 12 years old involved in a rollover crash. From these cases, the zero, one, and two-plus roof to ground impact cases were separated. Among each roof to ground impact group, the injuries to body region provided the final division.

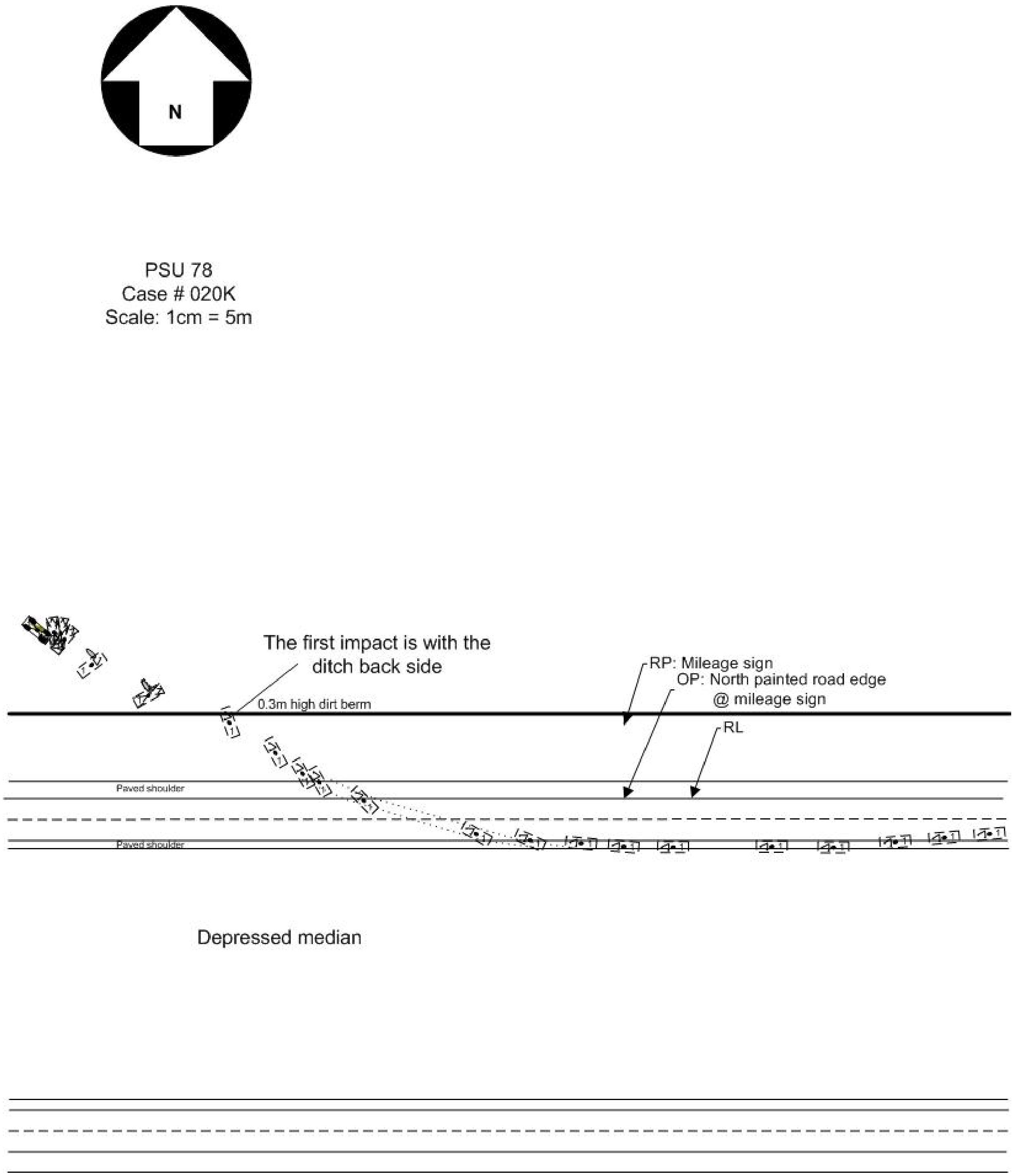
10.1 Four Illustrative Tripping Damage Cases – High Side Force

Review of cases lead to the identification of high side forces. These were identified based upon severe near-side wheel damage and two-plus roof to ground impacts. Further, near-side injuries to restrained, unejected occupants were generally attributed to a side interior contact and resulted in rib fractures and lung injuries. This followed the early findings indicating that thoracic injuries over two or more roof to ground impacts were major contributors to the overall HARM attributable to injuries of the highest severity per occupant, as shown in figure 6. Among the restrained, unejected occupants, a sharp increase in MAIS 3+F injuries was noted in rollovers with two or more roof to ground contacts, per figures 1 and 2.

10.1.1 Case 2001–78-20

The case vehicle, a 1997 Buick Riviera, was traveling in a westerly direction. It experienced a trip-over at the roadside, rolled to the left, and came to rest after six quarter turns. This driver-side-leading rollover occurred pursuant to a departure on the right side of the roadway, per figure 7. The sole occupant was an 86-year-old male driver. He experienced left aspect AIS 3 rib fractures on the right and left sides of the rib cage and a left aspect AIS 3 lung injury with unknown details. The injuries were attributed to the left side vehicle interior.

Figure 7: Case 2001-78-20 Scene Diagram and Crash Summary



Source: NHTSA/NCSA/NASS CDS, 2001

As noted, this was a left side leading rollover crash. Figure 8 depicted the near-side wheel damage as evidence of the high side force. The left front and rear wheels were severed from their respective axles during the crash, highlighting the severity of the crash.

Figure 8: Case 2001-78-20 Indication of Side Force

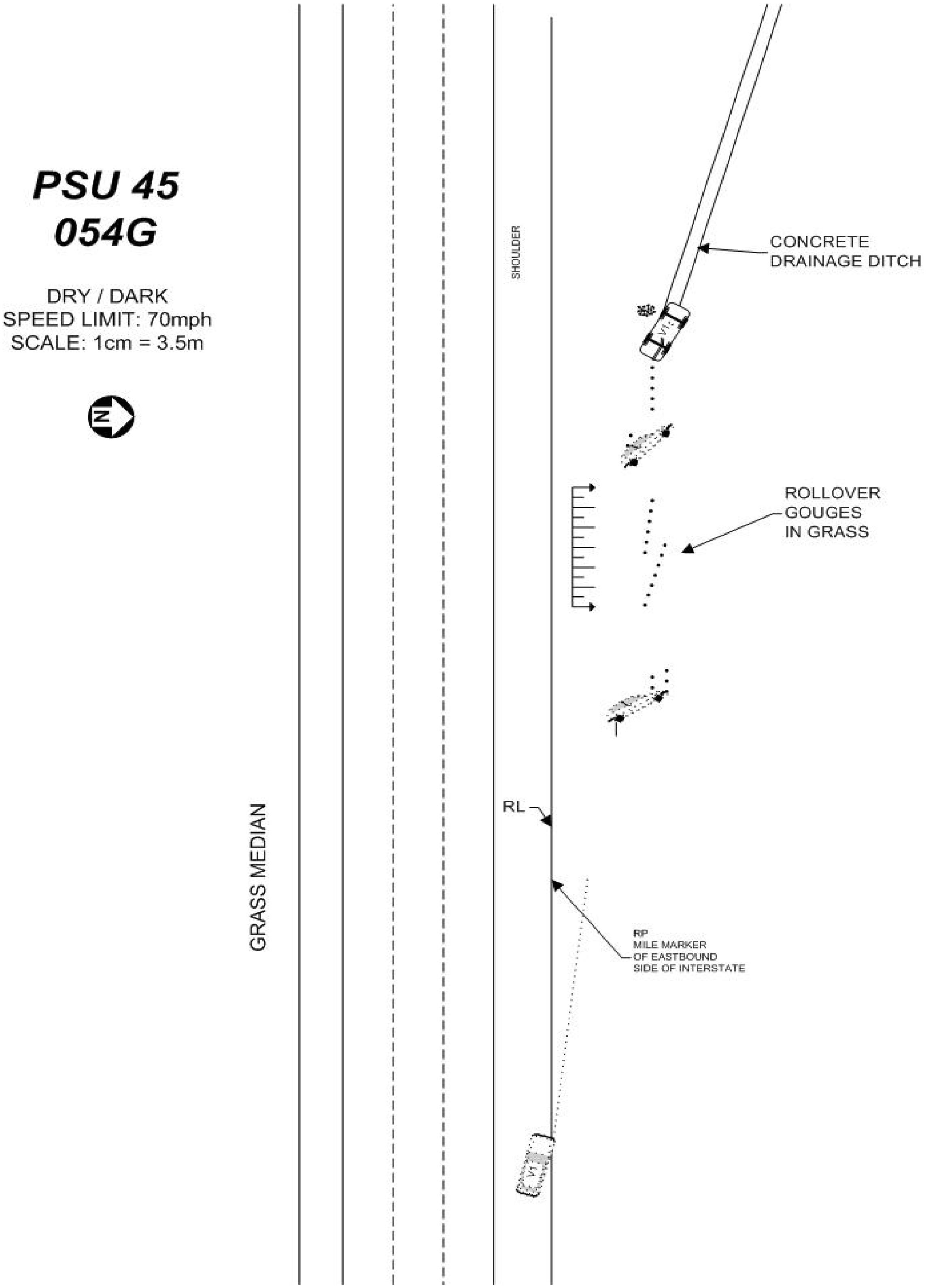
Source: NHTSA/NCSA/NASS CDS, 2001

10.1.1 1998–45–54

The case vehicle, a 1997 Chevrolet Geo Prism, was traveling in a westerly direction and departed the right side of the roadway, as seen in figure 9. It rotated clockwise and was tripped over at the roadside by the ground (possibly on loose dirt, gravel, etc.) The vehicle rolled six quarter turns toward the left in a driver side leading rollover crash. The driver, a 40-year-old female, sustained left aspect AIS 3 rib fractures with hemothorax, a collection of blood in the pleural portions of the thoracic cavity, and pneumothorax, an accumulation of air or gas in the thoracic cavity. These injuries were attributable to the side interior.

In figure 10, the high side force was evident in the front wheel and axle structure. The wheel bent away from the front axle on the near-side of the rollover crash. The severity was accentuated as seen by the bending at the B-pillar.

Figure 9: Case 1998–45–54 Case Summary and Scene Diagram



Source: NHTSA/NCSA/NASS CDS, 1998

Figure 10: Case 1998–45–54 Indication of Side Force

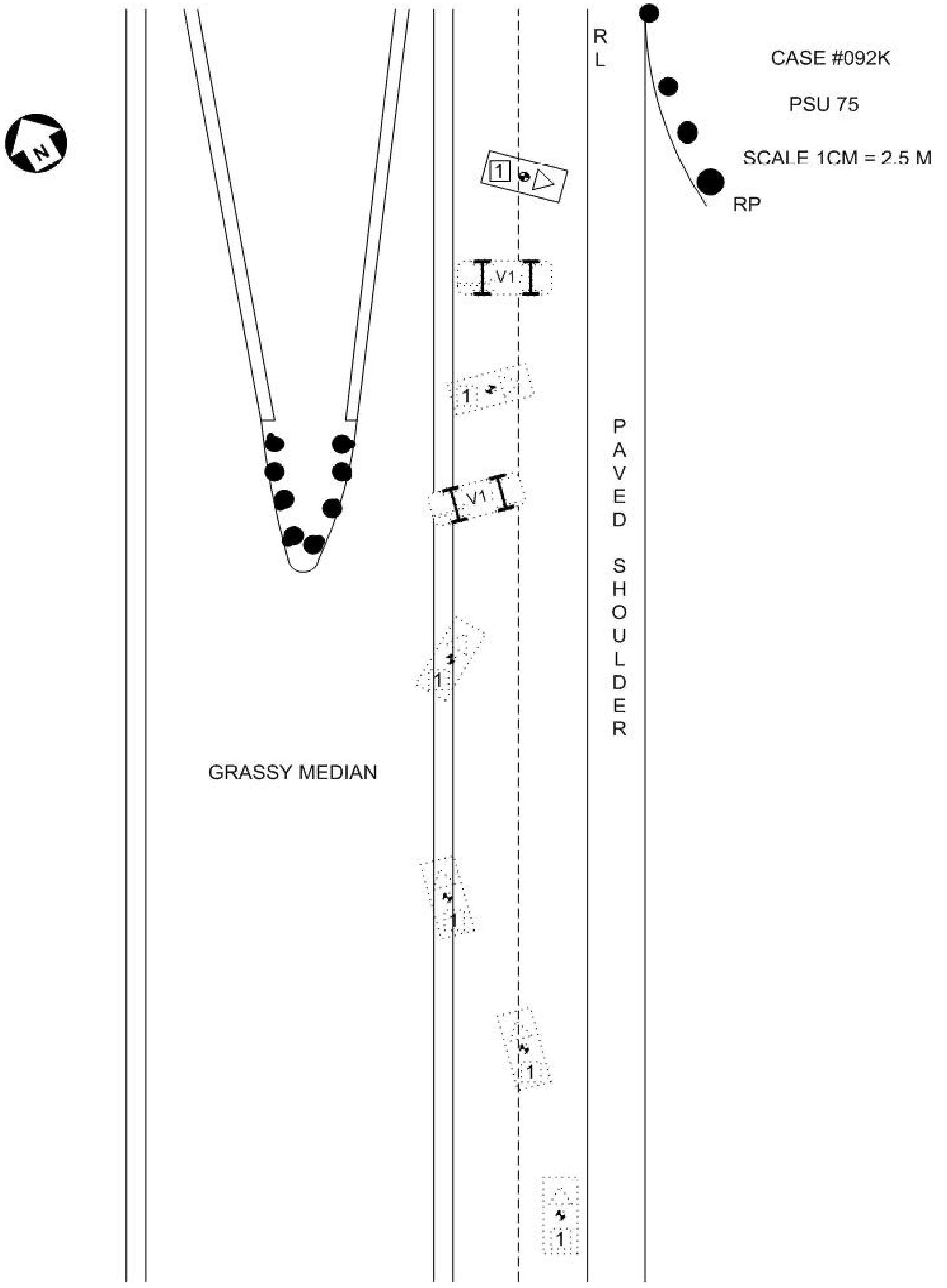
Source: NHTSA/NCSA/NASS CDS, 1998

10.1.3 Case 1998–75–92

The case vehicle, a 1990 Jeep Cherokee, was traveling in an eastbound direction. It hydroplaned and lost control, departing the left side of the roadway, per figure 11. The case vehicle reentered the roadway and rolled to the left eight quarter turns. The vehicle tripped over the ground (possibly on loose dirt, gravel, etc.). The driver, a 53-year-old male, sustained left aspect AIS 3 rib fractures with hemothorax and pneumothorax.

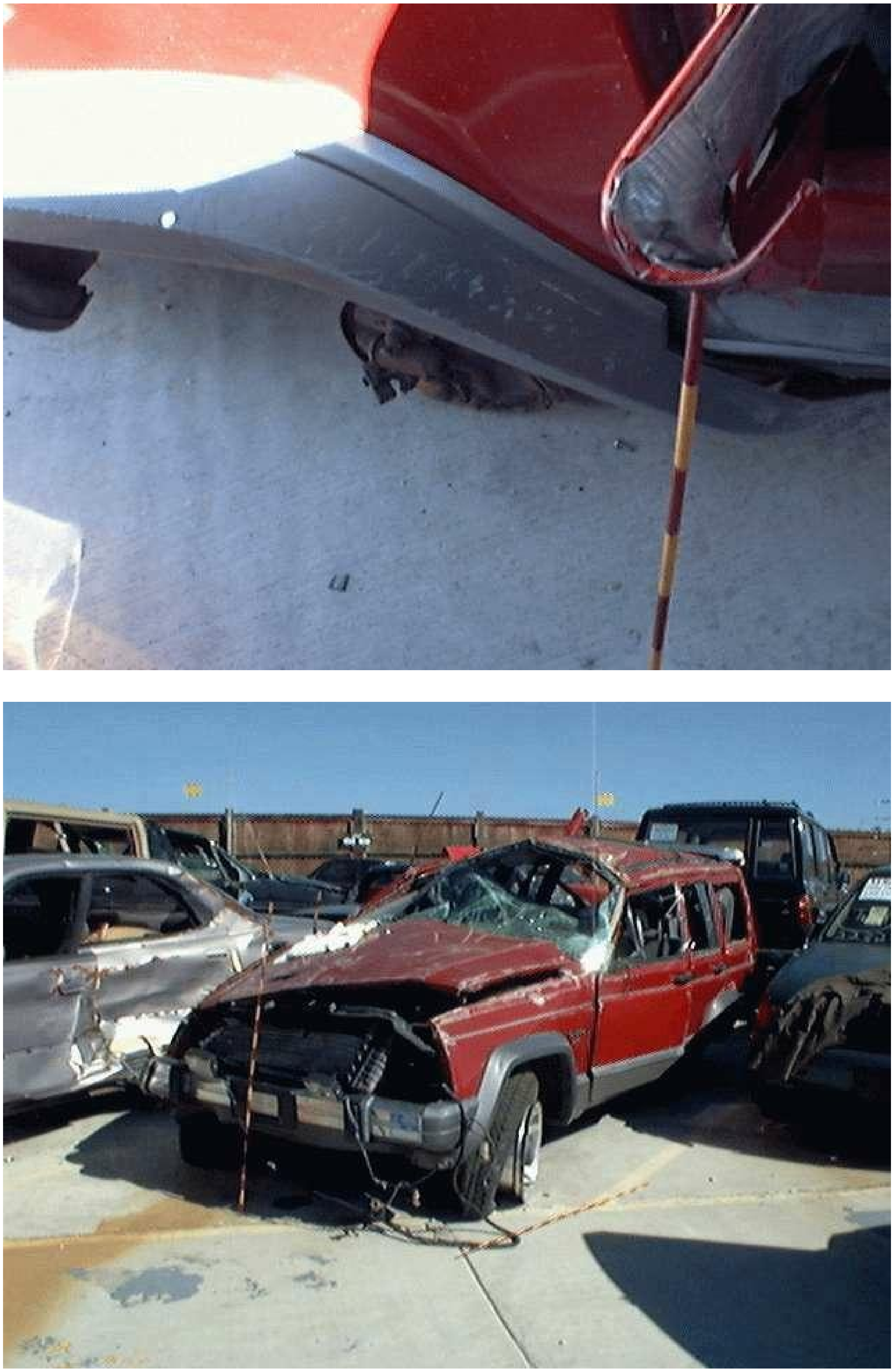
As noted previously, this phenomenon primarily affected passenger cars; however, some SUVs and pickup trucks underwent similar, high side force rollover crashes producing chest injuries, as seen in figure 12. The left rear near-side wheel was severed from the axle. Upon very close examination of the case photographs for the left front near-side, wheel damage was evident at the top near the point where the tire lost contact with the wheel.

Figure 11: **Case 1998–75–92 Case Summary and Scene Diagram**



Source: NHTSA/NCSA/NASS CDS, 1998

Figure 12: Case 1998–75–92 Indication of Side Force

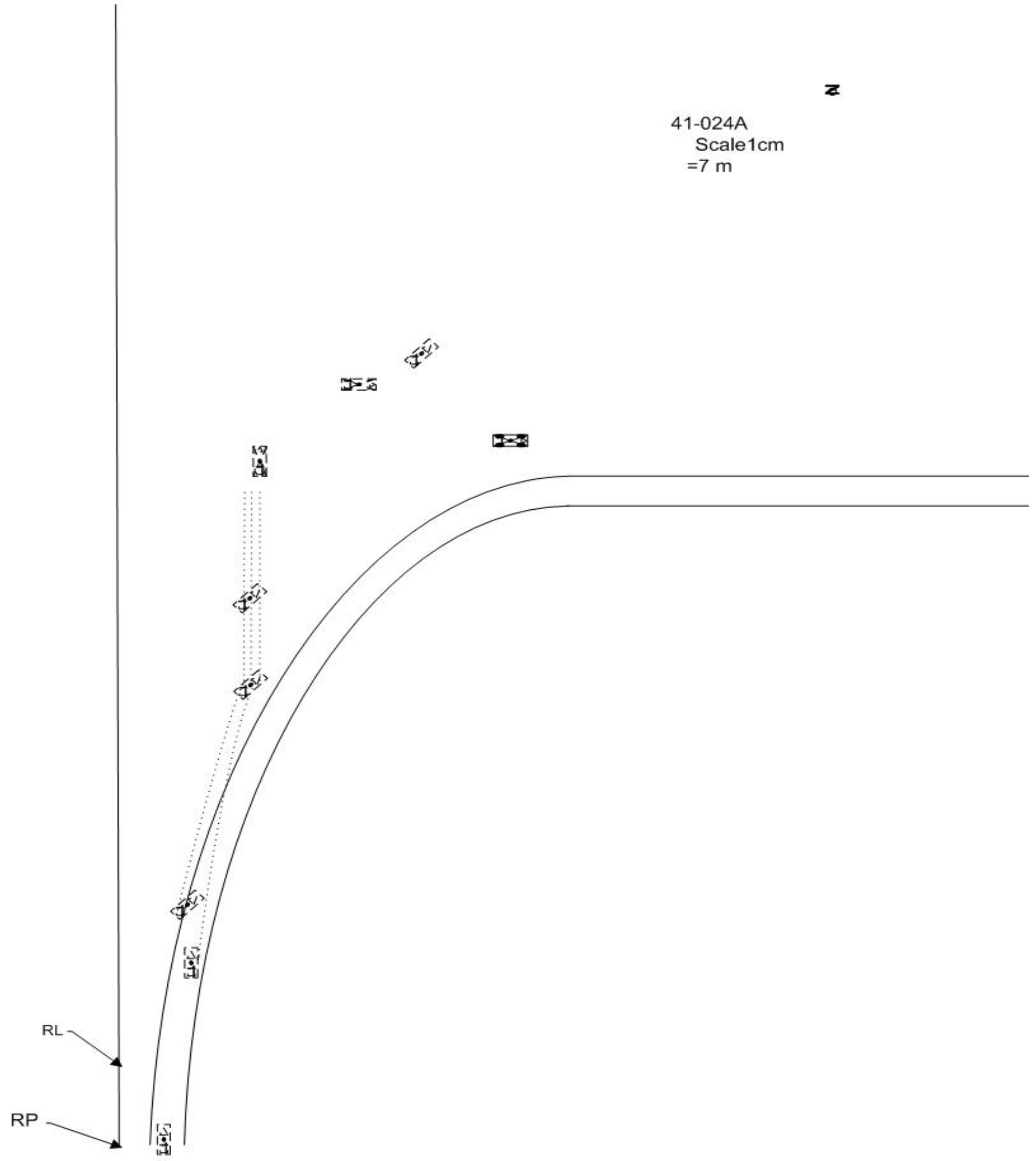


Source: NHTSA/NCSA/NASS CDS, 1998

10.1.4 Case 1999–41–24

The case vehicle, a 1999 Chrysler 300M, was negotiating a right-hand curve in an eastbound direction, per figure 13. The case vehicle traveled down an embankment, rotated clockwise, and tripped at the shoulder/unpaved area. The ground (possibly loose dirt, gravel, etc.) was cited as the object contacted preceding the rollover. The vehicle rolled to the left ten quarter turns, in a driver-side-leading rollover crash. The driver, a 62-year-old male, sustained an AIS 5 bilateral rib cage flail chest, an AIS 3 bilateral pleura laceration with hemothorax and pneumothorax, and a right aspect AIS 3 unilateral lung laceration. In this near-side engagement, the steering column was cited as the injury source. The AIS 5 injury was the medically reported cause of death.

Figure 13: Case 1999–41-24 Case Summary and Scene Diagram



Source: NHTSA/NCSA/NASS CDS, 1999

In figure 14, a very high tripping force was evident, sustaining the rollover through ten quarter turns. As noted previously, it takes great force to initiate the rollover of a passenger car and even greater force must be present to sustain it through ten quarter turns. The high side force was evident in the bent wheel at the front. Further, the wheel was severed from the axle at rear near-side of the rollover crash.

Figure 14: Case 1999–41-24 Indication of Side Force

Source: NHTSA/NCSA/NASS CDS, 1999

10.2 Pre-Rollover Complex Motion

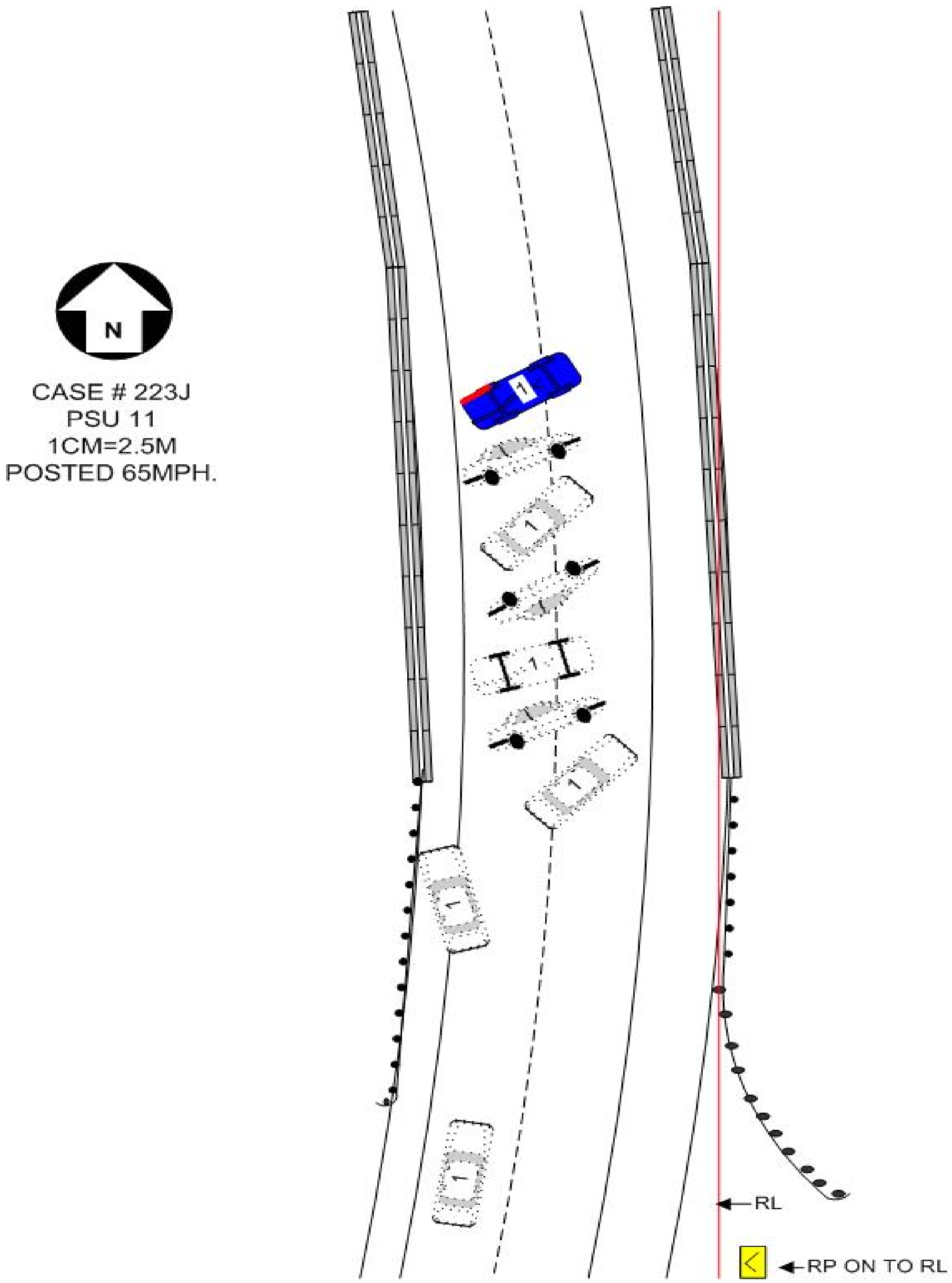
In the next segment pre-rollover events were disaggregated to define planar and rollover events. Further, incidental versus severe planar contacts were considered in describing the crash and the potential attribution of injuries to planar versus rollover events. These injury parameters may be useful in refining a severity metric and will be the subject of future work. Although Bahouth (2004) did not consider rollover crashes, the multiple-impact metric was found to hold true in cases where a planar event was followed by a rollover crash.

10.2.1 Case 1998–11–223

The case vehicle, a 1985 Pontiac Grand Am, was traveling northbound and departed the left side of the roadway, as seen in figure 15. It was redirected back on to the roadway by the guardrail. It proceeded to bounce over the guardrail and rolled over six quarter turns at the roadside. The driver, a 31-year-old female, sustained left aspect AIS 3 rib fractures with pneumothorax and a left aspect AIS 3 unilateral lung contusion, attributable to the side interior. It was suggested that a pre-impact change in direction might have contributed to the injury. This complex pre-crash motion was also postulated to have been a severe planar contact indicating that the injuries might have been sustained prior to the rollover crash.

Subsumed within the scenario of complex motion, evidence of high force continued to exist, per figure 16. Noteworthy, however, was the violence of the planar component of this crash, which upon examination may have been responsible for the injuries sustained by the driver. The severe side force of the rollover crash was inescapable owing to the repeated impact on the left side (rollover initiation side) over the two roof to ground impacts. In the absence of the planar component, neither was it known nor would it have been appropriate to speculate whether these injuries would have been minimized or other types of injuries might have been produced. The redirection, however, was the event that preceded the rollover sequence.

Figure 15: Case 1998–11-223 Case Summary and Scene Diagram



Source: NHTSA/NCSA/NASS CDS, 1998

Figure 16: Case 1998–11-223 Indication of Side Force

Source: NHTSA/NCSA/NASS CDS, 1998

10.3 Discussion of Case Review Results

The case reviews allowed for detection of vehicle damage patterns and injury patterns. The photographic analysis permitted concepts not readily available via coded data to be identified. The high side force was found to be associated with two-plus roof to ground impact crashes inducing chest injuries. A further refinement was the identification of near-side versus far-side orientation in injury patterns. The orientation was dependent upon the occupant seating position and the side of initiation for the rollover crash. The near-side, multiple-roof to ground-impact rollover crash generally resulted in thoracic injuries attributable to the side interior. In contrast the far-side, multiple-roof to ground-impact rollover crash, generally resulted in safety-belt-induced thoracic injuries. Conclusively, it can be said that a great deal of force was required to sustain vehicles through high numbers of roof to ground impacts. This was evidenced by the wheel deformation therefore making the association with the chest injuries more tenable.

10.4 Qualitative Results of Individual Case Analysis

Tripping damage was found to be indicative of chest injuries and higher number of roof to ground impacts. Further, the pre-rollover events that influence injury outcome were found to be complex skidding and spinning motions and impacts with fixed objects and vehicles. In the multiple-vehicle and/or multiple-event rollover crashes, this allowed for disaggregation of the planar event. The planar event could be viewed as an injury producer, severe planar contact, or incidental contact, where the rollover crash was culpable for injuries sustained. Within the larger study, cases existed of crashes where injuries might have been caused both during the planar and rollover events. This is a highly exploratory enterprise dependent upon the experience of the analyst and was devised as a means to stimulate more research in this field.

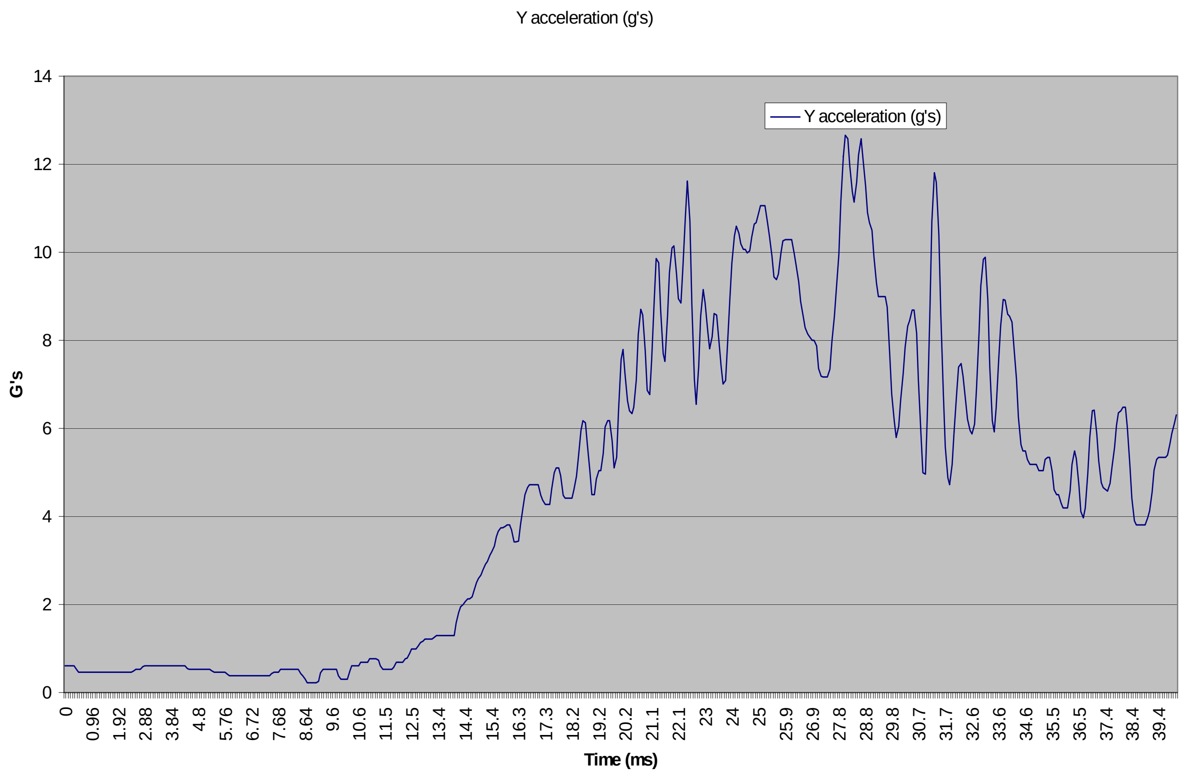
11 Computer Modeling

In order to amplify any study and supplement scanty test data, computer modeling has become an accepted tool. In the case of rollover crashes, however, little data existed for the replication of vehicle tripping at the time of rollover. Owing to the scarcity of data, speculative inputs were used in modeling. Based upon this data many assumptions must be made.

11.1 Discussion of Modeling Results

From the tripping acceleration test data presented in Digges (2004) and seen in figure 17, it was possible to obtain a crash pulse. The test data reached nearly 14 g’s, producing nearly 25 g’s output. For chest injury to occur, 25 g’s has been found to be sufficient. Little other test data existed; therefore, many assumptions were made for modeling.

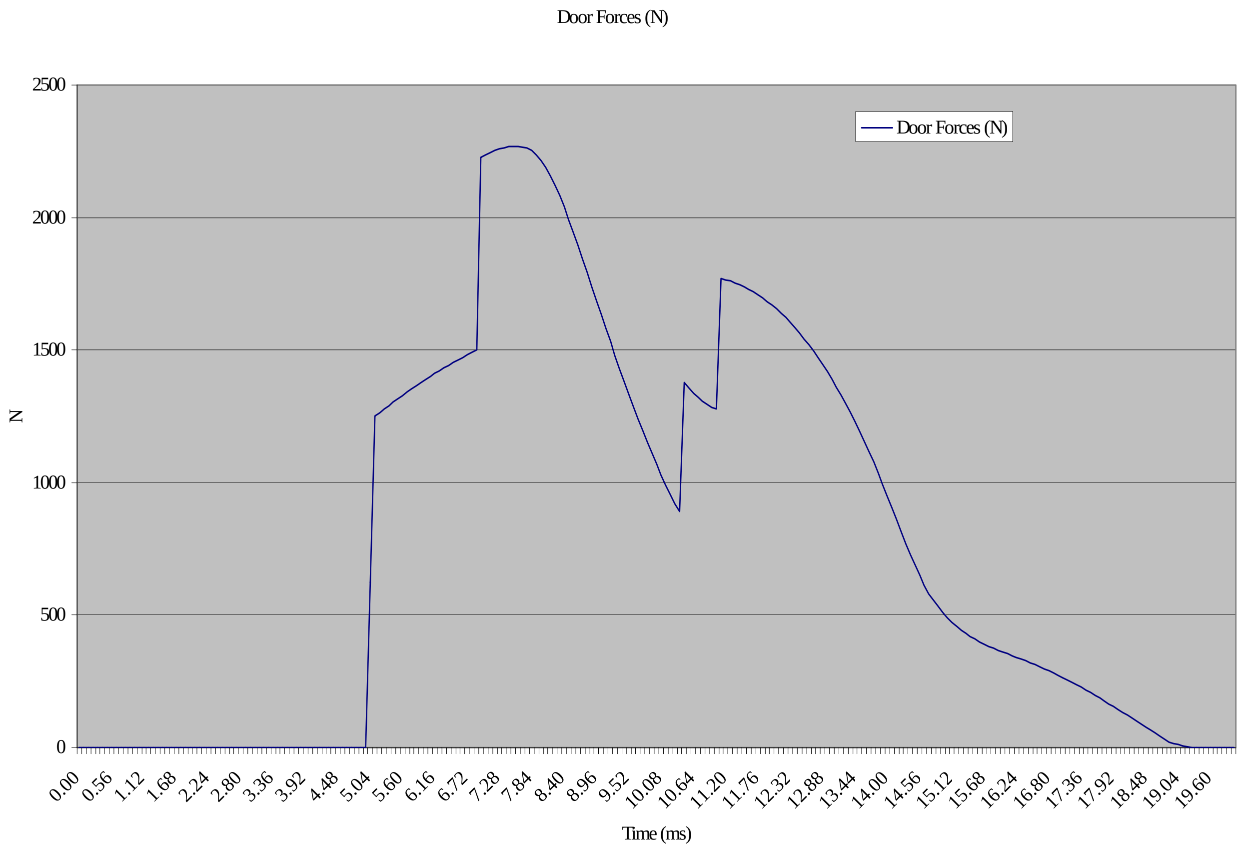
Figure 17: Y Acceleration - Input for MADYMO Simulation



Source: Digges, 2004

Using MADYMO, a model was created using the force inputs. This was done to clarify some of the injury forces. According to the model, a 2,500 Newton force was reached, as described by Dahdah (2004) and reproduced in figure 18. This was considered sufficient to induce chest injury, especially for the elderly population.

Figure 18: Door Forces Generated by MADYMO Simulation



Source: Dahdah, 2004

11.2 Observation Based upon Modeling – Tripping Acceleration

Tripping acceleration was found to be an important factor in rollover crash severity. It was postulated to influence the number of roof to ground impacts. The reviewed cases provided a link between chest injuries and the tripping severity. A paucity of crash pulse data existed, as much of this was proprietary and held by manufacturers and suppliers of air bags. This effort was required for modeling effects but hampered by the proprietary nature of the data. Further, structural force-deformation response data must be added to the model for prediction of severity based upon field measurements.

12 Conclusions

Conclusions are provided for the following subtopics:

- rollover population selection;
- crash configuration and its influences on occupant outcome;
- application of societal costs to injuries sustained by restrained unejected occupants in rollover crashes; and
- association of prevalent crash modes and injury characteristics for restrained unejected occupants.

12.1 General Conclusions Based upon Previous Work

- Number of roof to ground contacts is a good aggregation of quarter-turns for measuring rollover severity.
  The following considerations or exceptions exist when considering roof to ground contacts:
  - quarter turns can be more severe due to planar impacts;
  - impacts to fixed objects with roof leading;
  - severe side and frontal crashes with other vehicles; and
  - end-over-end rollovers.
- Inclusion of planar crash severity (delta V) prior to rollovers in addition to the rollover severity (number of roof to ground contacts) improves understanding of the rollover crash.
- The magnitude of the trip pulse influences the number of roof to ground impacts and may increase AIS 3+ chest injury risk
- Most MAIS 3+ head injuries occur in rollovers with one roof to ground contact. Computer modeling indicates the highest head velocity can occur at that time.

12.2 Rollover Population Selection

The early sections of this publication guided the selection of crashes for detailed review. These included the rationale for their selection based upon frequency and injury rate. The populations of interest were found to be unejected belted, unejected unbelted, and ejected unbelted occupants. This phase of study and the current publication focused on the unejected belted occupants owing to their prevalence and their contribution to serious injury.

12.3 Crash Configuration and Its Influence on Occupant Outcome

Disaggregating rollover crashes by crash configuration and restraint use was the next portion of the analysis. Crash configuration was determined by single-vehicle or multiple-vehicle involvement in the rollover crash. Among belted rollover crash occupants, occupants involved in multiple-vehicle crashes sustained injury rates twice as high as those for occupants involved in single-vehicle crashes.

12.3.1 Application of Societal Costs to Injuries Sustained by Restrained Unejected Occupants in Rollover Crashes

The percentage contribution of HARM was used to describe the societal cost of injuries to the restrained unejected occupants. Rollover crashes similar to the pure rollover case were selected by excluding fixed-object contacts before the rollover crash. Occupants were selected based upon an overall MAIS 3+F injury severity and their most severe injury was selected based upon a hierarchy of injuries. HARM for AIS 3+F injuries highlighted the head and thorax injuries at one roof to ground impact and two-plus roof to ground impacts, respectively.

12.3.2 Association of Prevalent Crash Modes and Injury Characteristics for Restrained Unejected Occupants

Based upon the results of the HARM analysis for the pure rollover case, the head and thoracic injuries were identified as areas of concern. Head injuries have traditionally posed a singular problem for rollover crashes and modeling work complemented the findings of the HARM analysis. The thoracic injuries warranted extra study owing to the high number of quarter turns and the type of vehicles involved. High tripping acceleration was the physical phenomenon associated with these thoracic injuries. These were also studied with regard to crash orientation, finding that thoracic injuries pursuant to a near-side rollover crash were attributable to the side interior, per injury source reporting in NASS CDS. Finally, computer modeling also provided some basis for the concern over thoracic injuries.

13 Recommendations

13.1 Future Work Recommendations

- Continue analysis to obtain statistical significance for all observations.
- Perform further research on tripping acceleration.
- Obtain pulses via crash testing.
- Obtain damage versus force response via static or dynamic testing.
- Provide field measurements of tripping damage.
- Develop/Perform severity calculations like WINSMASH.
- Continue examination of roof to ground impact injury mechanisms.

13.2 Recommendations for NASS Researchers

- Continue collecting number of quarter turns and estimated planar delta V; these were very valuable to analysis.
- Enhance documentation of tripping damage with photography and measurements.
- Identify cases with one quarter turn in which the severity was increased by:
  - Roof leading fixed impact
  - Pre-rollover planar crash

13.3 Recommendation for Rollover Data Analysts

- Aggregate quarter turns by number of roof to ground impacts.
- Disaggregate data by:
  - ejected and unejected;
  - belted and unbelted;
  - single-vehicle and multiple-vehicle rollovers; and
  - severe versus incidental planar contact.
- Augment data analysis with hard copy case reviews and computer modeling.

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DOT HS 809 894
November 2005

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