Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

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This report quantifies the characteristics of ran-off-road crashes and identifies appropriate impact conditions for use in full-scale crash testing. Many of the decisions related to design guidelines and policies can benefit from better information on the impact conditions of ran-off-road crashes. The report will be of particular interest to personnel responsible for the design of roadside safety features.

The primary goal of roadside design is to limit the number of serious injuries and fatalities associated with ran-off-road crashes. Roadside geometrics and safety features have a strong influence on the frequency and severity of crashes. To design optimum roadside geometrics and to determine which roadside safety features are appropriate, it is imperative to identify impact characteristics associated with serious injury and fatal crashes. This information has a direct bearing on safety evaluation criteria used to assess the performance of roadside safety features. However, the impact speeds, angles, and orientations used in the current testing procedures are selected to represent a practical worst-case situation. It is unclear to what degree this practical worst-case situation represents real-world conditions. Consequently, it is important to have definitive data on whether there are real relationships between the selected test impact conditions and actual crashes involving serious injuries and fatalities.

Crash data will be useful in refining guidelines for roadside safety countermeasures and calibrating roadside safety models [e.g., Roadside Safety Analysis Program (RSAP)] and crash and vehicle dynamics simulation models. It will also be helpful in focusing designers' attention on the roadside features that are involved in the greatest number of serious injury and fatal crashes. Crash data will help designers spend safety dollars on improvements that will have the greatest likelihood of reducing serious injuries and fatalities.

Under NCHRP Project 17-22, “Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes,” the Midwest Roadside Safety Facility identified the data needs, developed a data collection plan, conducted a retrospective data collection effort of crashes selected from the National Automotive Sampling System, developed a relational database suitable for future research, and proposed an implementation plan for a long-term data collection effort (The long-term data collection effort is continuing under NCHRP Project 17-43).

The data from this study was used in the evaluation of the guardrail runout length calculation procedures and compared to the recommended runout lengths contained in the 2006 AASHTO Roadside Design Guide. The evaluation provides support for reducing the length of guardrail used in advance of roadside obstacles.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction

1.1 Background

Single-vehicle, ran-off-road crashes are a major cause of serious injuries and fatalities along our nation's highways. Approximately 12,000 motorists lose their lives each year as a result of these crashes. Most of the efforts to reduce this carnage have been focused on designing more forgiving roadsides by removing or relocating hazards and designing better safety features to mitigate the severity of those hazards that cannot be removed or relocated. The fact that the total number of single-vehicle, ran-off-road crashes has remained relatively stable and even declined in recent years while the number of vehicle miles traveled has increased steadily indicates that these efforts have been successful.

The safety performance of roadside features is evaluated primarily through full-scale crash testing. The purpose of this testing is to observe and evaluate the performance of safety features under impact conditions that are either similar or more severe than those associated with real-world crashes resulting in serious injuries and fatalities. Important crash test parameters, such as impact speed and angle, point of impact, and vehicle orientation have been selected based on findings from limited studies of ran-off-road accidents (*1, 2, 3*). Although full-scale crash test data provides a small window into the nature of ran-off-road crashes, it does not provide sufficient data to identify the impact conditions associated with serious injury and fatal crashes. The research program described herein is undertaken primarily to identify appropriate impact conditions for use in full-scale crash testing guidelines.

However, knowledge of the characteristics of ran-off-road crashes has many more applications than just selecting impact conditions for full-scale crash testing guidelines. Many of the decisions related to design guidelines and policies could benefit significantly by better information on the impact conditions of ran-off-road crashes. For example, while the concept of multiple performance levels is embraced by the roadside safety community, highway designers are having difficulty determining when and where to use various roadside safety devices. The multiple-performance-level concept involves selecting a roadside safety feature to match the range of expected impact conditions in the area where it is to be installed. Under this design philosophy, roadside safety features are developed to meet one of several different performance levels or impact capacities. Lower capacity—and presumably less costly—safety devices are installed at sites where the risks of high-energy impacts are lower. Although the multiple-performance-level concept has been largely embraced by the roadside safety community, a significant amount of uncertainty remains regarding how performance levels should be defined and where the various performance-level designs should be installed. Detailed data on ran-off-road crashes could provide a sound basis for determining appropriate performance levels for different classes of highway included in the study.

Safety performance evaluation criteria, such as occupant impact velocity (OIV) and ridedown acceleration (RA), are used as surrogate measures of the risk of injury for vehicle occupants during full-scale crash tests. OIV is a theoretical estimate of the speed at which the head of an unbelted occupant would strike the dash board. RA is calculated as the maximum 10 ms average vehicle acceleration measured after occupant impact occurs. These measures are intended as indicators of the risk that an occupant will be seriously injured during an impact with a roadside safety device. Unfortunately, these measures of occupant risk have never been successfully linked to actual injuries. The difficulty associated with establishing this link is the lack of available data where both the actual injuries and occupant risk measures can be determined. Detailed accident investigations that provide calculations of the occupant risk parameters and include crash injury information should provide the basis for determining the merits of the current safety performance evaluation procedures.

Another measure of occupant risk includes occupant compartment deformation and intrusion. *NCHRP Report 350* (*4*) requires that "Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted." This requirement is relatively subjective and has been interpreted differently by the various crash testing agencies. The requirements are quantified under the *Manual on Assessment of Safety Hardware* (MASH; *5*) based on limited National Automotive Sampling System (NASS) data and engineering judgment. Nevertheless, a database with detailed information on ran-off-road crashes would provide the needed data to develop a link between the location and magnitude of vehicle intrusion and the severity of occupant injury. Any such link would provide an objective basis for establishing limits on occupant compartment deformation and intrusion.

Vehicle stability is also used as a measure of occupant risk. Although crash data clearly shows that the risk of injury increases when a vehicle rolls over, some engineers believe that the risk of injury for occupants of vehicles that only roll 90 degrees is relatively low. Unfortunately, no data are available that can be used to explore this possibility. If data on sufficiently large numbers of ran-off-road crashes are collected, it may be possible to test this hypothesis.

Guidelines on the selection and placement of roadside safety features can also benefit from a detailed crash study such as the one described herein. Most current guidelines are based on benefit/cost analysis techniques and rely heavily on crash severity estimates. These crash severity estimates are based on both the estimated impact conditions, including speed, angle, and vehicle orientation at impact, as well as the severity resulting from any given impact condition. Data collected in this study would be extremely valuable if collected in a sufficiently representative manner to allow an estimate of impact conditions associated with all ran-off-road crashes. Furthermore, if data are collected in a representative manner, detailed crash reconstructions could also provide a wealth of crash severity data with which to validate procedures for relating impact conditions to occupant risk.

Placement guidelines provide procedures for selecting and designing safety features to accommodate the characteristics of specific sites. For example, guardrail installation guidelines recommend procedures for calculating length-of-need and flare configurations based on the characteristics of the specific site where the barrier is to be located. Many facets of safety hardware installation guidelines are based on the expected vehicle trajectories and impact conditions at the given site. For example, procedures for selecting guardrail runout lengths included in the Roadside Design Guide (RDG; *6*) are based on vehicle trajectories measured in a study of encroachments into the medians of divided highways during the 1960s (*7*). Vehicle trajectory data collected in the current study should provide a significant source of additional data regarding such information as the trajectories and the distances vehicles travel along the roadside during a crash. Guardrail placement guidelines also make recommendations regarding maximum flare rates. Increasing the flare rate raises the vehicle impact angles and thereby increases crash severity. Detailed crash data, coupled with injury severity information, should shed some light on this relationship and thereby provide a better foundation for making recommendations on maximum flare rate.

Finally, guidelines on grading requirements are provided for guardrail terminals and crash cushions, including limits on slopes in front of and behind these systems. These guidelines are based mostly on data from limited full-scale crash tests without information from real-world crashes. Also, the RDG provides guidelines as to roadside slopes that merit guardrail protection. Again, these guidelines are based on limited testing and simulation. Detailed data on roadside topography for ran-off-road crashes would provide additional insight into the currently accepted guidelines.

1.2 Objective

The specific objectives for this study included the following:

1. Identify the vehicle types, impact conditions, and site characteristics associated with serious injury and fatal crashes involving roadside features and safety devices;
2. Create a robust relational database for future research; and
3. Develop an implementation plan for a long-term data collection effort.

The first objective pertains to the collection of detailed information on serious injury and fatal crashes involving roadside features and safety devices. The data were then analyzed to identify the vehicle types, impact conditions, and site characteristics associated with these crashes.

The second objective was to create a relational database suitable for future research. The database consists of crash data from prior and current studies that have in-depth crash data and will include future data collection efforts as well.

The third objective was to develop an implementation plan for a long-term data collection effort on detailed data for ran-off-road crashes. As discussed previously, there are many additional applications for such detailed crash data beyond the current study, from performance evaluation of selected roadside safety features and devices to the formulation of policies regarding roadside safety. Thus, a long-term continuing effort to collect detailed data on ran-off-road crashes would be highly desirable.

1.3 Scope

The scope of work for this study was specifically formulated to address the three objectives and consisted of the following major tasks:

1. Identify the data needs for addressing the specific objectives of this study. A literature review was conducted on previous studies involving in-depth crash data collection, impact conditions of ran-off-road crashes, data needs for study of ran-off-road crashes, and reconstruction of ran-off-road crashes.
2. Develop a work plan to collect the needed data. Various data collection alternatives were evaluated and a retrospective supplemental data collection approach was selected for use with the current study. An appropriate data collection protocol was developed, including the sampling plan, data collection forms and field procedures, as well as manual review and reconstruction procedures.
3. Conduct a retrospective supplemental data collection effort of approximately 400 crashes selected from the 2000 and 2001 NASS Crashworthiness Data System (CDS) data. Supplemental field data were collected to gather additional information about the crash sites and roadside features. In addition, these crashes were reconstructed to estimate the impact conditions, including speed, angle, and vehicle orientation.
4. Develop a relational database suitable for future research. The database was first developed with data from the current study. Similar data from previous studies, including NCHRP Project 17-11 and the Federal Highway Administration (FHWA) Rollover Study, were then manually reviewed and reconstructed prior to incorporation into the database.
5. Analyze the database to address the specific objectives of this study, including identification of the vehicle types, impact conditions, and site characteristics associated with serious and fatal crashes.
6. Develop a proposed implementation plan for a long-term data collection effort. The implementation plan outlined a long-term effort to continue collecting detailed data on representative ran-off-road crashes and the flexibility to conduct special studies on specific roadside safety features and devices. Data collection protocols for the continuous data collection and a selected special study were developed. Also, a pilot program was conducted to demonstrate the feasibility of the long-term data collection effort and to iron out the details and identify any potential problems.

1.4 Report Organization

This report summarizes the results of the work conducted under the study. Chapter 2 presents a summary of the literature review and other ongoing and future research and data collection efforts. Chapter 3 outlines the study approach, including data collection alternatives, data collection plan, and development of the database. Results of the analyses are presented in Chapter 4. The proposed plan for a long-term data collection effort is outlined in Chapter 5. Finally, a summary of the study findings and conclusions are presented in Chapter 6.

Some of the details too voluminous for the main body of the report are included as appendices. Appendix A presents the critical review of individual references. Appendix B summarizes the results of the analysis of the 1997-2001 NASS CDS data, including the list of 2000 and 2001 cases to be sampled for supplemental field data collection. Appendix C outlines the protocol for the supplemental field data collection and manual review used for the current study. The details of database elements are shown in Appendix D. Additional tables, plots, and analysis results too voluminous for the main report are shown in Appendix E. Finally, the field data collection forms and the corresponding coding instructions and field procedures for the proposed long-term data collection effort are presented in Appendix F. These appendices are available from the *NCHRP Report 665* blurb page on the TRB website (www.trb.org) by searching for "NCHRP Report 665".

CHAPTER 2

Literature Review

A detailed literature review was conducted to identify studies relevant to the identification of impact conditions for ran-off-road crashes. The review identified numerous studies pertaining to ran-off-road crashes that could have some bearing on this project. However, upon review, most of these studies utilized only police-level crash data, which do not have the required details or information to assess the impact conditions of ran-off-road crashes. An annotated bibliography is shown as Appendix A, and a summary of related ongoing research studies are presented in Appendix B. Only a summary of results of the literature review is presented in this chapter. The literature review is presented under four general headings:

1. In-depth crash data collection
2. Impact conditions of ran-off-road crashes
3. Data needs for study of ran-off-road crashes
4. Reconstruction of ran-off-road crashes

2.1 In-Depth Crash Data Collection

Crash data collection can be grouped into three general levels of detail:

1. Police-reported level
2. Enhanced police-reported level
3. In-depth level

More detailed discussions on these three categories of crash data collection are presented in this section with examples. It should be noted, however, that these examples are intended as illustrations only and are by no means all inclusive. There have been so many studies using crash data over the years that it would not be feasible to include even a fraction of the studies in this review.

The police-reported level is the most common type of crash data available. State and local police officers are required by law to investigate all reportable crashes and complete police accident reports on these crashes. The data are then coded and entered into state crash data files. Crash data on the police-reported level are generally very limited in detail. Occasionally, more detailed data are collected on selected crashes, such as those resulting in fatalities and severe injuries, but such detailed investigations constitute only a small fraction of crashes.

Most of the collected data elements are intended for identification and record-keeping purposes—such as date, time, and location of crash; vehicle(s) and driver(s) involved; damage to the involved vehicle(s) and other property; injury sustained by driver(s) and occupant(s) of vehicle(s); and a brief description of what happened in the crash. The crash data may be merged with other data files for additional information. For example, the Highway Safety Information System (HSIS) combines crash data with other roadway and vehicle-related data files, such as roadway inventory, traffic, alignment, bridge inventory, vehicle identification and registration, etc., to expand the information database for use in various analyses.

Even with the merged files, crash data on the police-reported level still lack the detail needed for analysis beyond problem identification and are of little use from the standpoint of estimating impact conditions of single-vehicle, ran-off-road crashes or evaluating the impact performance of roadside safety features. Thus, studies pertaining to police-reported level crash data are not included in the literature review.

Crash data on the enhanced police-reported level are used in selected research studies in which additional data elements are collected to supplement the police-reported data. The supplemental data collected vary from study to study depending on the objective(s) of the study. Most of the supplemental data pertain to items of specific interest to the studies, such as details of roadside conditions, inventory of a particular roadside object(s), etc. However, there have been a few studies in which the investigating officers were asked to provide information on departure and impact conditions.

In a study by Garrett and Tharp, the investigating officers were asked to provide estimates on impact speed and angle on

324 crashes that occurred on the Ohio Turnpike over a period of five months during the summer and fall of 1967 (*8*). Similarly, in a study by Perchonok et al. to assess the relationships between single-vehicle, ran-off-road crash frequency, severity, and roadway and roadside features, data on over 9,000 crashes were collected from six states (*2*). The investigating police officers were asked to complete supplemental field forms, including data pertaining to impact conditions, such as impact speed and angle.

While enhanced police-reported level crash data provide more detailed information, its utility on estimating impact conditions is limited by a number of factors:

1. Expertise and experience of the investigating police officers. Most police officers receive some basic training in crash investigation, but only a small proportion of the officers receive the highly specialized training in crash reconstruction needed to accurately estimate impact conditions. The quality of data collected by police officers without the specialized training may be questionable.
2. Knowledge of the impact performance of roadside safety features. Even for trained officers, reconstruction of single-vehicle, ran-off-road crashes pose special problems unless the person is also knowledgeable of the impact performance of roadside features. Most reconstructions are based on energy dissipation and balance. For many ran-off-road crashes, energy dissipated by the struck object constitutes a significant portion of the energy equation and must be properly accounted for. This in turn will require knowledge on the impact performance of roadside features, which is beyond the training received by police officers.
3. Time and effort required. To properly reconstruct a crash to estimate its impact conditions would require time and effort beyond those available to an investigating officer. Thus, it is reasonable to expect that estimates of impact conditions would be based mostly on the judgment of the officers and less so on step-by-step reconstruction of the crashes.

In summary, enhanced police-reported level crash data, which uses investigating officers to collect supplemental data, could provide more detailed information on the impact conditions of single-vehicle, ran-off-road crashes. However, as discussed above, there are serious limitations to this approach that could not be easily overcome. Thus, the use of enhanced police investigation to estimate impact conditions is not recommended.

To properly estimate the impact conditions of single-vehicle, ran-off-road crashes, an in-depth level of crash investigation is required. The required data would include detailed data on the roadway, vehicle trajectory, object(s) struck and damage sustained, vehicle and damage measurements, and driver and occupant injury levels. The cost associated with in-depth crash investigation is, as may be expected, very high and there have only been a few ad hoc studies that incorporated such in-depth crash data, i.e., the data collection was designed specifically for the study.

The most notable study involving in-depth crash data is perhaps the study on crashes involving pole support structures (*9*). A stratified random sample of over 1,000 crashes involving utility poles, breakaway and nonbreakaway luminaires, and sign supports were investigated in-depth, and the crashes were reconstructed to estimate the impact conditions. The in-depth crash data were then analyzed in conjunction with police-reported level data on all crashes and all pole crashes, enhanced police-reported level data on unreported crashes, and pole inventory data to address the study objectives. The results of the study include the extent of the pole crash problem; the characteristics of pole crash sites, vehicle damage, and occupant injuries; assessments on the performance of various pole types; and a cost-effectiveness evaluation of the breakaway modification as a safety treatment.

Another study of crashes on highway narrow bridges involved in-depth investigation of 124 crashes that occurred on bridges (*10*). Again, the in-depth crash data were analyzed in conjunction with police-reported level data on crashes that occurred on 11,880 bridges from five states and supplemental field data on a sample of 1,989 bridges to address the study objectives. The results of the study include extent of the narrow bridge crash problem and the associated crash frequencies and rates; relationships between various bridge physical and operational characteristics to crash rates and severities; and the characteristics and relationships between crash and injury severity for crashes at bridges.

Other studies have utilized data from various in-depth crash investigation programs conducted by the National Highway Traffic Safety Administration (NHTSA). Since its inception in late 1960, NHTSA has sponsored numerous programs to collect in-depth crash data. The programs changed over the years, from the multidisciplinary accident investigation (MDAI) program in the late 1960s in which a small convenient sample of crashes were studied in great detail to the current NASS CDS that investigates a nationally representative stratified random sample of crashes in lesser detail. However, these in-depth data collection programs are designed to meet the data needs of NHTSA and the emphasis is, therefore, on data pertaining to the vehicle, occupant, and injury severity. Unfortunately, data pertaining to roadway and roadside characteristics are mostly lacking, which limits the use of the data for highway-related research, such as the current study.

In order to make use of the NASS CDS data, supplemental data collection is necessary to gather information required for the specific study. The supplemental data collection can be prospective or retrospective in nature. The NASS program has a special study subsystem that allows for prospective collection of supplemental data in addition to the standard data elements collected under CDS. For instance, three special studies were designed to collect in-depth crash data on longitudinal barriers, pole support structures, and crash cushions (*11, 12, 13*). These special studies were met with different degrees of success. Nearly 1,200 cases were collected under the Longitudinal Barrier Special Study (LBSS) while only a negligible number of cases were collected under the pole and crash cushion special studies. The LBSS cases were subsequently reconstructed using the conservation of energy approach and the data were analyzed to examine the severity of barrier length-of-need (LON) crashes versus barrier-end impacts. Cases involving failure of the barrier system were reviewed clinically (*14*).

Crashes involving concrete barriers were selected from the LBSS data file for use with an FHWA study on rollovers caused by concrete barriers (*15*). Of the 130 crashes involving concrete barriers, 31 resulted in rollovers. In addition to comparing the characteristics of crashes resulting in rollovers to those of non-rollovers, the rollover crashes were also clinically analyzed to identify potential causes for the rollovers.

These studies illustrated the potential application of the special studies as well as the problems associated with their conduct. This special study approach was not again utilized until the recent Large Truck Crash Causation Special Study, sponsored by the Federal Motor Carrier Safety Administration (FMCSA). The purpose of this study was to determine specific causes of large truck (trucks with gross vehicle weight rating of over 10,000 lbs) crashes. These crash causation data will help to identify crash countermeasures the FMCSA can undertake with regard to interstate motor carriers, their drivers, and their vehicles; and in cooperation with other DOT agencies and state governments with regard to the non-commercial vehicles, pedestrians, and pedal cycles involved in the crashes.

Another approach is to supplement the NASS CDS data retrospectively with additional field data collection. Data elements of specific interest to the study, but not covered under NASS CDS, are identified and collected using supplemental field data collection. The key limitation of this approach is that the supplemental data elements should not change over time since the supplemental data are collected one to two years subsequent to the occurrence of the crashes. This is not a bad assumption for most data elements pertaining to highway and roadside characteristics since they typically do not change except during major construction or reconstruction.

This retrospective approach was utilized in ongoing NCHRP Project 17-11, “Recovery-Area Distance Relationships for Highway Roadside” (*16*). The objective of the study is to develop relationships between recovery-area distance, roadway and roadside features, vehicle factors, encroachment parameters, and traffic conditions for the full range of highway functional classes and design speeds. Part of the research involved clinical analysis of 338 NASS CDS cases from 1997 and 1998. Field data on roadway and roadside characteristics of crash sites were collected to supplement the standard NASS CDS data elements.

These sampled cases (e.g., police accident reports, field forms, scaled diagrams, and photographs) were then manually reviewed to glean additional information beyond the computerized data elements. The crashes were then reconstructed to estimate impact conditions and vehicle trajectories from the manual review such as impact sequence, pre- and post-impact vehicle trajectories, impact angle, etc.

The same retrospective approach and data collection protocol used in NCHRP Project 17-11 were used in the rollover study (*17*) sponsored by FHWA, except that the cases were sampled from the 1999 NASS CDS data file. The objectives of this study were to determine the specific causes of rollover events associated with the full range of passenger vehicle collisions in which such an event occurred. In fact, the data from NCHRP Project 17-11 were utilized in this study with additional in-depth clinical reconstruction on the 180 rollover crashes contained in the database. In addition, new data from 175 NASS CDS cases from 1999 were added to the database.

However, NHTSA recently changed its privacy policy to discard police accident reports after only one year. This policy change effectively eliminates this retrospective approach since the only means of identifying the crash sites was from the police accident reports. The prospective special study is the only viable approach for future studies using the NASS CDS program.

A new emerging technology may provide a totally new and better source of data on impact conditions. Automobile manufacturers have installed Event Data Recorders (EDRs) in selected vehicle lines in recent years. The EDR is designed as a controller for monitoring airbag deployment and seatbelt usage and recording data pertaining to the crash event in case of a crash. Data elements recorded include crash pulse, seatbelt usage, and pre-crash information, such as speedometer reading and engine performance parameters. In the future, EDR data may simplify reconstruction of crashes to estimate impact conditions and could become and an invaluable supplement to in-depth crash investigation.

NHTSA is currently collecting available EDR data under its NASS CDS and Special Investigations (SCI) programs and compiling the data into a national database. While the EDR technology is relatively new and little actual data are currently available, its potential in the future is very promising:

- EDRs are now deployed in all vehicle lines, so more data should become available.
- The number of data elements and the length of recording period are somewhat limited now. However, with rapid

advances in electronics, many more data elements could be incorporated into the EDRs and the recording period could increase significantly.

- In addition to the interest of NHTSA, the highway roadside safety community has also shown great interest in the EDR data. A study, NCHRP Project 17-24, "Use of Event Data Recorder (EDR) Technology for Roadside Crash Data Analysis," was conducted to review and recommend a minimum set of EDR data elements for roadside safety analysis as well as procedures to retrieve, store, and use the data (*18*).

While the EDR technology is very exciting and promising, there is still much development to be done and impediments to overcome before it can reach its potential, including:

- Engineering issues. There are no current standards governing the design and use of EDRs, such as data elements to be included, data format, data retrieval, etc. Such standards are needed if data are to be collected on a large scale. Also, current EDR data elements are, as expected, focused on vehicle parameters with no specific consideration for information pertaining to ran-off-road crashes.
- Institutional barriers. EDR data are intended for the data needs of vehicle manufacturers, which may be reluctant to share their proprietary designs for competitive and legal considerations. Inputs from governmental agencies and research institutions are needed in the early planning and design stages if the EDR data are to be expanded into the roadside safety area.
- Legal consideration. There are still questions pertaining to ownership of the EDR data, privacy issues, use of EDR data in tort claims, etc. Until such concerns are addressed and resolved, large-scale collection of EDR data appears unlikely.

2.2 Impact Conditions of Ran-Off-Road Crashes

Despite the large number of studies on ran-off-road crashes, there are relatively few studies that actually attempted to estimate the impact conditions. The main reason for the lack of such effort is that, in order to estimate the impact conditions, an in-depth level of crash investigation is required, including detailed data on the roadway, vehicle trajectory, object(s) struck and damage sustained, vehicle and damage measurements, and driver and occupant injury levels. The costs associated with in-depth crash investigation are, as may be expected, very high and there have only been a few studies that incorporated such in-depth crash data. Another limitation is that some of the studies, such as the LBSS data, were not based on a representative sample and the resulting distributions of impact conditions could be biased, probably toward the more severe crashes.

Some earlier work relied on reconstruction of impact speed and angle by the investigating officers, such as the studies by Garrett and Tharp (*8*), Perchonok et al. (*2*), and Lampela and Yang (*1*). As discussed previously, the use of enhanced police-reported level crash data to estimate impact conditions is limited by a number of factors, such as expertise and experience of the investigating police officers, availability of time for the officers, and lack of officers' knowledge on the impact performance of roadside safety features. Thus, while the results from these studies provide some insights into impact conditions, their accuracy is somewhat questionable.

Under the pole and narrow bridge studies (*9, 10*), impact conditions were estimated from in-depth investigations and presented in the reports. Mak et al. took the data from these studies and developed statistical models for the distributions of impact speeds and angles (*3*). After screening, a total of 596 cases were available for analysis. The authors found that the gamma function provides the best fit for univariate impact speed and impact angle distributions. Statistical models for impact speed and angle distributions were then developed using the gamma function for the following five functional classes:

- Freeway
- Urban arterial
- Urban collector/local road
- Rural arterial
- Rural collector/local road

For some roadside features, such as longitudinal barriers, impact conditions are defined by both impact speed and angle. However, there is no known means of mathematically expressing a joint gamma distribution. The authors tested various known joint (bivariate) distributions, but with no success. They then proceeded by assuming that the impact speed and impact angle are independent of each other and estimated combined probability distributions for impact speed and angle stratified by functional class and based on the gamma distribution. These impact speed and angle distributions were used in some of the cost-effectiveness analysis procedures, including the Texas Transportation Institute (TTI) ABC model (*19*). The distributions were adjusted to reflect the current higher speed limits under NCHRP Project 22-14 (*20*). The revised impact condition distributions were used with the Roadside Safety Analysis Program (RSAP) (*21*).

Other sources of impact conditions include data from ongoing NCHRP Project 17-11 and the FHWA Rollover Study (*16, 17*). A total of 559 NASS CDS cases from 1997 through 1999 were selected under these two studies. Supplemental field data were collected on these cases, which were then reconstructed to estimate the impact conditions. The impact speed and angle distributions developed under these two studies were significantly different from previous findings. However, it was later found that the scales on some of the diagrams used for the impact angle reconstructions might be distorted. In order to fit the scale diagrams onto a web page, the longitudinal and lateral scales were compressed differently, thus leading to incorrect impact angle estimates. Plans are underway to reconstruct these cases again to correct the errors and reanalyze the revised data.

It should be mentioned that in order to properly establish the distribution of impact conditions, the data source needs to be either the population (i.e., all ran-off-road crashes) or a representative sample. Some databases, such as the LBSS, are sampled on the basis of a comparative analysis and are not suitable for determining impact condition distributions.

2.3 Data Needs for Study of Ran-off-Road Crashes

There have been a number of studies that looked into the data needs for studying ran-off-road crashes. A study by Mak and Sicking identified issues and gaps in the state of the knowledge needed to improve the cost-effectiveness analysis procedure and to develop data collection plans for those issues and gaps that could be addressed with crash data. The research proposed five studies and developed data collection plans for those studies:

- Validation of encroachment frequency/rate
- Determination of encroachment frequency/rate
- Effect of roadside conditions on impact probability and severity
- Distributions of impact conditions
- Relationships of impact conditions, performance limits, and injury probability and severity

These study plans were reviewed by a panel of experts and their comments taken into consideration. The recommended study on the distributions of impact conditions focuses on impact speed, angle, and vehicle orientation in addition to vehicle size, weight, and the nature of the roadside object/feature. The plan for this study includes the following tasks:

- Select sample roadway segments for each of the six highway types
- Set up data collection protocol, including sampling plan, accident notification scheme, data collection forms, etc., and familiarize and train investigators with the protocol through a small pilot study
- Investigate in-depth a representative sample of single-vehicle, ran-off-road accidents on these selected roadway segments
- Reconstruct the sampled accidents to determine impact conditions
- Compile descriptive statistics on vehicle trajectory and impact conditions
- Develop mathematical models for the distributions of impact speeds and angles

These proposed studies and data collection plans are over 10 years old, but they still are applicable today and of great interest to the current study.

Miaou proposed a method to estimate vehicle roadside encroachment rates using accident-based models (*22*). Miaou concluded that the proposed method could be a viable approach to estimating roadside encroachment rates without actually collecting the encroachment data in the field, which can be expensive and technically difficult. A pilot study was conducted by Daily et al. (*23*) to examine the feasibility of this approach. Data were collected on 56 km (35 mi) of tangent sections of rural two-lane highways in Idaho, including detailed roadside, crash, and traffic data. Encroachment rates were estimated from the collected crash data and found to be in the same order of magnitude as previous research. It was concluded that this approach is feasible, although it is limited by the current state of knowledge with respect to data on the trajectories of vehicles involved in ran-off-road, fixed-object accidents. An experimental plan for future research that would produce improved estimates of encroachment rates was developed, but not recommended for immediate implementation.

While this study has no direct bearing on the current study, it could be of interest in future data collection efforts. Data on encroachment rates are over 25 years old and may be outdated in light of the significantly changed conditions in the intervening years, including improvements made to the safety design of highways (e.g., clear zone concept and improved barriers and terminals) and vehicles (e.g., front and side airbags, antilock brakes, and crush management), and other safety countermeasures (e.g., mandatory seatbelt law, tightened blood-alcohol-content law). If a major data collection effort is to be implemented in the future, encroachment data may be one of the objectives.

A list of suggested data elements for use with the current NASS CDS program was proposed by Eskandarian et al. in a study to assess the compatibility between vehicle design characteristics and roadside safety hardware (*24*). These data elements pertain to the design characteristics, pre-impact conditions, and impact conditions of struck features and assessment of impact performance of features. While the suggested data needs pertain mostly to the issue of compatibility between vehicle design and roadside safety features, the information would be helpful to establishing the data needs for the data collection effort under the current study.

Under the recently completed NCHRP Project 17-24 on the potential use of EDR data for roadside safety evaluation, the authors examined the data needs for roadside safety analysis and assessed whether the data needs can be satisfied with EDR data. A list of new data elements for EDR was proposed. As mentioned previously, the EDR technology is very exciting and promising. However, until such time that these new EDR data elements become available, in-depth crash investigation will remain the primary means of obtaining such detailed crash data.

2.4 Reconstruction of Ran-off-Road Crashes

There are a number of existing procedures that have been developed for reconstructing special types of ran-off-road, fixed-object crashes (*14, 15, 25*), including:

- Semi-rigid and flexible barrier
- Rigid barrier
- Pole support structure

These reconstruction procedures are based on the general principle of identifying the energy loss parameters during the collision and summing the total to determine the change in velocity from point of impact to point of final rest. The components of the energy loss in a typical crash include:

- Vehicle crush
- Deformation/damage of roadside feature
- Vehicle trajectory

Energy due to vehicle crush can be estimated manually using equations from Campbell (*26*) or using a computerized reconstruction procedure, such as CRASH3. Energy loss due to post-impact vehicle trajectory is estimated using equations of motion. Adjustments are made to account for skidding and sliding. For rotating vehicles, the distance traveled is based on the angle of rotation and the radius and the energy loss calculated accordingly. Energy loss due to vehicle trajectory can also be estimated using a computerized reconstruction procedure, such as CRASH3. These two energy loss items can be standardized and incorporated into a single reconstruction procedure. Unfortunately, energy loss due to deformation/damage of the roadside feature varies greatly among the roadside features and impact configurations, e.g., barrier length-of-need versus barrier end impact. Thus, there is not a single procedure that can be used to reconstruct all ran-off-road crashes. Instead, different reconstruction procedures are needed to accommodate the wide variety of roadside features.

A reconstruction procedure for semi-rigid and flexible barriers was developed for the LBSS data (*14*). The procedure utilizes similar techniques for estimating vehicle crush and trajectory energy losses. Energy loss associated with the deformation of semi-rigid barriers is estimated from a series of computer simulations that correlate impact severity to maximum barrier deflection. The impact severity (IS), calculated using the following equation, has been shown to be a good indicator of the degree of loading and maximum deflection of a barrier during an impact.

$$IS = \tfrac{1}{2} * M * (V * \sin\theta)$$

where:

IS = Impact Severity
M = Vehicle mass
V = Vehicle velocity
θ = Impact angle

The IS value, in conjunction with the impact angle, can then yield a direct estimate of impact speed. The impact speed calculated from barrier deflection should be verified by energy loss calculations to make sure that the estimates using both approaches are consistent.

Another procedure was developed for reconstructing rigid barrier impacts under the study to assess rollovers on concrete barriers (*15*). For impacts involving concrete barriers, there is typically no deformation/damage to the barrier. However, it was found that vehicle/barrier friction was a major source of energy dissipation during a crash. Thus, energy loss due to deformation/damage to the barrier is replaced by vehicle/barrier friction, which is estimated as a function of the length of barrier contact. Total energy loss is then calculated as the sum of energy losses due to vehicle crush, vehicle/barrier friction, post-impact vehicle trajectory, and the impact speed calculated accordingly.

As a means of verification, the vehicle crush energy is matched to the energy associated with the lateral velocity of the impacting vehicle. If both energy estimates are comparable, the procedure is believed to be reasonably accurate. If not, the vehicle crush energy would be adjusted appropriately and a new estimate of the impact speed generated. This iterative procedure was found to give reasonably good estimates of impact speed when used to evaluate findings from full-scale crash tests.

Another computerized reconstruction procedure was developed for ran-off-road crashes involving pole support structures, including breakaway and non-breakaway utility poles, luminaire supports, and sign supports (*25*). Energy losses due to vehicle crush and post-impact vehicle trajectory are estimated using the CRASH3 program. Energy loss associated with breaking or fracture of the pole is estimated based on empirical test data. Impact speed is then calculated from the total energy loss.

CHAPTER 3

Study Approach

3.1 General

To accomplish the study objectives, the following major tasks were undertaken in this study:

- Identify data needs
- Evaluate data collection alternatives
- Develop data collection protocol
- Conduct supplemental data collection, manual review, and reconstruction
- Create relational database
- Incorporate data from previous studies into database

Details of these tasks are presented in the following sections. The database was then analyzed to address the study objectives and the results are presented in Chapter 4. Finally, a proposed implementation plan for a long-term data collection effort was developed and outlined in Chapter 5.

3.2 Data Needs

The primary goal to be achieved under the current study is to identify the distribution of impact conditions associated with serious injury and fatal ran-off-road accidents, including speed, angle, and vehicle orientation at impact. It is hoped that this information can then be used to select impact conditions to be used in full-scale crash testing of roadside hardware. In order to address this issue, the needed data elements were identified and are listed in Table 1. The data elements are categorized as available from:

1. Basic NASS CDS data. These data elements are already available as part of the basic CDS data.
2. Supplemental field data collection. These data elements will require field data collection.
3. Reconstruction. These data elements will require reconstruction of the crashes.

The data collection plan presented in this chapter covers the data elements requiring supplemental field data collection and reconstruction.

3.3 Data Collection Alternatives

Three basic alternatives were considered for the data collection effort in the current study:

1. New data collection system
2. Prospective special study under the NASS CDS program
3. Retrospective supplemental data collection for existing NASS CDS cases

More detailed discussions of these alternatives are presented below.

3.3.1 New Data Collection

The first alternative was to establish a totally new data collection system. The major activities required in the setup of a new data collection system at multiple sites include, but are not limited to, the following:

- Establish data collection teams. This would require hiring of new personnel, establishing and furnishing the offices, purchasing the necessary equipment for conducting crash investigation, etc.
- Train investigators in the basics of in-depth level crash investigation. The newly hired investigators would need to be trained extensively to acquire the required level of expertise, including both classroom and on-the-job training. This training would need to be extensive and comparable to what is used with the NASS CDS program.
- Develop procedures for obtaining authorization to collect medical records.

Table 1. Data needs for current study.

Variable	Availability
Case Screening Criteria	
• Area type - PSU	1
• Crash type - Single-vehicle, ran-off-road crashes	1
• Vehicle type - Passenger vehicles only	1
• Completeness of data on key variables	1
• Injury severity - Serious and fatal injury	1
Variables of Primary Interest:	
• Encroachment conditions at point of departure	
- Action prior to leaving travelway	1
- Speed	3
- Angle	3
• Pre-impact vehicle trajectory	
- Vehicle path	3
- Maximum lateral extent of encroachment	3
- Total longitudinal distance	3
• General impact data	
- Impact sequence	1
- Object struck	1
- Rollover occurrence	1
- Post-impact trajectory	3
• Impact conditions – first harmful event	
- Impact speed	3
- Impact angle	3
- Vehicle orientation	3
• Impact conditions – most harmful event	
- Impact speed	3
- Impact angle	3
- Vehicle orientation	3
• Driver action	
- Evasive action	1
- Steering – vehicle path	3
- Braking	3
Controlling Variables:	
• Highway type	
- Functional class	2
- Roadway type	1
- Speed limit	1
• Travelway characteristics	
- Number of lanes	2
- Lane width	2
- Horizontal curvature - Point of departure and maximum	2
- Vertical grade - Point of departure and maximum	2
• Roadside characteristics	
- Shoulder type and width	2
- Roadside slopes – widths and rates of slopes	2
- Median type, width, and slope	2
• Traffic characteristics	
- ADT	2
- Percent truck	2
• Struck object characteristics	
- Object type	2
- Impact performance	3
• Vehicle characteristics	
- Type	1
- Make and model	1
- Curb weight	1
- Vehicle damage	1
- Occupant compartment deformation and intrusion	1
• Highest occupant injury severity	
- Abbreviated Injury Scale (AIS)	1
- Police Injury Code (PIC)	1
• EDR data	1

(continued on next page)

Table 1. (Continued).

Variable	Availability
Variables of Secondary Interest:	
• Time	
- Day of week	1
- Time of day	1
• Environmental conditions	
- Light	1
- Weather	1

*Legends for Data Availability:
1. Existing NASS CDS data
2. Supplemental field data collection
3. Reconstruction

- Establish cooperation with local agencies. This would include law enforcement agencies for the notification system, vehicle towing and repair facilities for access to the involved vehicles, hospitals and clinics for medical records/information on injury severity, and transportation agencies for highway-related information.
- Establish quality control procedures. To assure proper data collection in terms of validity and accuracy, appropriate quality control procedures would need to be established, similar to the Zone Centers in the NASS program.

After the data collection system was established, additional activities would be required to establish the specific data collection effort, including:

- Develop data collection protocol. The field forms and accompanying coding and instruction manuals, data collection procedures, data submission processes, and quality control procedures would have to be developed for the specific data collection effort.
- Train investigators in specific data collection effort. The investigators would have to be trained in the details of the specific data collection effort. This would be in addition to the basic training mentioned above.
- Conduct pilot study. A pilot study would have to be conducted to work out any unforeseen problems in the data collection protocol.

It is evident from the above discussion that the alternative of establishing a new data collection system was not a viable option for this study due to funding constraints. The startup costs would be prohibitive for such a short-term data collection effort. However, this remains a viable alternative for a long-term data collection effort.

3.3.2 Prospective NASS CDS Special Study

The second alternative was to establish a special study under the NASS CDS program. The special study would be prospective in nature (i.e., data would be collected on new crashes) and could be within sample (i.e., only crashes that are already sampled under the NASS CDS program would be eligible) or outside of sample (i.e., all crashes are eligible). Again, this alternative is not viable for this study due to time and funding constraints. First, it will take a minimum of 12 to 18 months to set up a special study under the NASS CDS program. Second, this assumes that the NASS CDS program can accommodate a new special study on short notice, which is rarely the case. Because the CDS system itself requires a certain number of crashes to be investigated and the researchers can handle only so many crashes (1 ½ to 2 cases per week per researcher), the ability of the system to conduct special studies is limited. This limitation can be overcome by hiring new investigators specifically to handle the special study, such as in the case of the special study on large-truck crash causation. The addition of new investigators is not as time consuming or costly as establishing new data collection teams, but would still require more time and funding than available for the current study. However, this alternative remains viable for a long-term data collection effort.

3.3.3 Retrospective Supplemental Data Collection

The third alternative was to conduct a retrospective study using previously investigated NASS CDS cases. This approach was similar to that successfully used in NCHRP Project 17-11 and the FHWA Rollover Study. In those studies, single-vehicle, ran-off-road crashes were selected from 1997 through 1999 NASS CDS cases. Since NASS CDS cases are oriented toward vehicle crashworthiness and occupant injury and lack details pertaining to the highway and roadside characteristics, supplemental field data collection and manual review and reconstruction of the cases were used to fill in the data gaps. A total of 559 cases were sampled under these studies.

This approach can be implemented within a short period of time since it involves only existing NASS CDS cases. Supplemental field data collection protocol and manual review and reconstruction procedures had already been developed and field investigators at the Primary Sampling Units (PSUs) and the Zone Center personnel were already familiar with the protocol and procedures. Thus, this approach could be easily implemented for this study within the time and funding constraints. Also, this alternative would allow cases from the previous studies to be incorporated into the database with the new cases collected under this study.

This third alternative of retrospective supplemental field data collection and manual review and reconstruction of existing NASS CDS cases was, therefore, selected for this study. However, it should be noted that NHTSA had changed its policy, starting with the 2003 data, to keep police accident reports in the file for only one year. This in effect eliminates the location information on existing NASS CDS cases. Thus, this alternative of retrospective supplemental field data collection and manual review and reconstruction of existing NASS CDS cases is no longer a viable option. For the long-term data collection effort in the future, only the alternatives of a new data collection effort or a special study under the NASS CDS system could be considered.

3.4 Data Collection Protocol

As discussed previously, the plan for the current study was based on a retrospective supplemental data collection approach. This retrospective approach involved collecting supplemental field data and manual review and reconstruction of existing NASS CDS cases. The major components of the data collection protocol are summarized as follows:

- Sampling plan
- Supplemental field data collection
- Manual review of sampled cases
- Reconstruction of crashes to estimate impact speed

Brief descriptions on activities pertaining to the supplemental field data collection are presented in this section.

3.4.1 Sampling Plan

As discussed previously, a similar retrospective supplemental field data collection approach was used in two previous studies: NCHRP Project 17-11 and the FHWA Rollover Study. Supplemental field data were collected on NASS CDS cases from 1997 through 1999 in these two studies, as follows:

- NCHRP Project 17-11
  - 1997: 138 cases
  - 1998: 200 cases
- FHWA Rollover Study
  - 1999: 221 cases

The scope of the supplemental data collection effort for this study was, therefore, selected to include 2000 and 2001 NASS CDS cases. To maintain consistency among the three studies, the sampling criteria remained the same as the two previous studies. The sampling criteria included the following parameters:

- Area type—rural and suburban. Urban PSUs were excluded from the sample because urban roadways tend to have lower speed limits and the roadsides are typically cluttered with fixed objects. More importantly, inspections at urban crash sites are generally less detailed with a higher percentage of incomplete data due to hazardous working conditions and traffic congestion.
- Single-vehicle, ran-off-road crashes. Only single-vehicle, ran-off-road crashes were included in the sample. Single-vehicle crashes that occurred on the roadway, or involving parked vehicles, animals, or pedestrians, were excluded since the nature of the crashes is different from that of a ran-off-road crash. Similarly, multiple-vehicle crashes were excluded from the sample.
- Passenger-type vehicles. Only passenger-type vehicles, i.e., passenger cars and light trucks with a gross vehicle weight (GVW) of less than 4,536 kg (10,000 lbs), were included in the NASS CDS sample. Heavy trucks, i.e., single-unit trucks with higher GVW and tractor-trailers, present very different problems than passenger vehicles. Also, reconstruction of crashes involving heavy trucks is much more difficult than those involving passenger-type vehicles.
- Speed limit of 72 km/h (45 mph). Only crashes that occurred on highways with speed limits of 72 km/h (45 mph) or higher were included. Low-speed roadways tend to have lower design standards and have crash characteristics that are significantly different from those of high-speed highways. Thus, it is not desirable to mix crashes from both low-speed and high-speed highways.
- Complete vehicle inspection, vehicle trajectory, and injury severity data. It would not be possible to reconstruct crashes without vehicle inspection and trajectory data, and those crashes would be of little interest to the proposed study. Thus, only crashes with complete vehicle inspection and trajectory data were included. Also, the emphasis of the study was on serious and fatal injury crashes, so the injury severity should, therefore, be known for the sampled cases.

Table 2 shows a breakdown of the 2000 and 2001 CDS cases by the first four sampling criteria. In year 2000, there were a total of 4,307 cases, 2,929 (68.0%) of which occurred in the 16 rural and suburban PSUs, and 1,518 (51.8%) of which occurred on highways with speed limits above 72 km/h (45 mph). Of these crashes, 603 (39.7%) were single-vehicle, ran-off-road crashes. In year 2001, there were a total of

Table 2. Breakdown of 2000 and 2001 NASS CDS cases by screening criteria.

Year	Total No. of Cases	16 Rural and Suburban PSUs	Speed Limit ≥ 45 mph	Passenger Vehicle/ Single-Vehicle Ran-Off-Road Crashes
2000	4307	2929	1518	603
2001	4090	2833	1500	593
Total	8397	5762	3018	1196

4,090 cases, 2,833 (49.3%) of which occurred in the 16 rural and suburban PSUs, and 1,500 (52.9%) of which occurred on highways with speed limits above 72 km/h (45 mph). Of these crashes, 593 (39.5%) were single-vehicle, ran-off-road crashes. Combining data from the two years, there were a total of 1,196 eligible cases that occurred in rural and suburban PSUs on highways with speed limits above 72 km/h (45 mph), and involving single-vehicle, ran-off-road crashes.

As shown in Table 3, of the 1,083 eligible cases with known injury severity, 348 (32.13%) resulted in serious to fatal injuries [Abbreviated Injury Scale (AIS) ≥ 3], 229 (21.14%) resulted in moderate injury (AIS = 2), 385 (35.55%) resulted in minor injury (AIS = 1), and 121 (11.17%) incurred no injury (AIS = 0). However, it should be noted that the sampling scheme for NASS CDS is biased toward the more serious crashes. When the cases are weighted according to the sampling scheme, the distribution of injury severity is very different: 43.64% no injury, 40.15% minor, 8.32% moderate; and 7.90% serious to fatal injury. Thus, all analyses shown herein show both unweighted and weighted frequencies and percentages.

Table 4 shows the distribution of the eligible cases by the number of lanes. The vast majority of the cases, 998 (83.44%), occurred on highways with two or three lanes. Another 38 (3.18%) occurred on one-lane roadways (i.e., ramps). The remaining 160 cases (13.38%) occurred on highways with four or more lanes. The weighted distributions are similar, 3.45% for one lane, 82.02% for two or three lanes, and 14.53% for four or more lanes. The similarity between the unweighted and weighted percentages suggests that the severity of crashes is similar for different highway types, though slightly higher for highways with two or three lanes.

Table 5 shows the distribution of the eligible cases by vehicle type. Passenger cars accounted for the majority, 696 (58.19%), of the eligible cases, followed by pickup trucks, 247 (20.65%), and sport utility vehicles, 198 (16.56%). The weighted distributions show a higher percentage for passenger cars (64.60%) and lower percentages for the other vehicle types. This sug-

Table 3. Eligible cases by maximum abbreviated injury scale.

Abbreviated Injury Scale	Unweighted		Weighted	
	Number	Percentage	Number	Percentage
No Injury (0)	121	11.17	280,985	43.64
Minor Injury (1)	385	35.55	258,559	40.15
Moderate Injury (2)	229	21.14	53,554	8.32
Serious Injury (3)	175	16.16	23,074	3.58
Severe Injury (4)	80	7.39	20,846	3.24
Critical Injury (5)	68	6.28	5,190	0.81
Maximum Injury (6)	25	2.31	1,712	0.27
Total	1,083	100.00	643,920	100.00

* Missing Cases = 113 unweighted (45,970 weighted)

Table 4. Eligible cases by number of lanes.

Number of Lanes	Unweighted		Weighted	
	No.	Percentage	No.	Percentage
1	38	3.18	23,809	3.45
2 & 3	998	83.44	565,855	82.02
≥ 4	160	13.38	100,227	14.53
Total	1,196	100.00	689,891	100.00

gests that a higher proportion of crashes involving passenger cars had lower injury severity.

The final screening criteria include documentation of vehicle trajectory, complete vehicle inspection, and known injury severity data. Of the 1,196 eligible cases, only 437 (36.54%) met all three criteria. Table 6 shows the distribution of these 437 cases by PSU. Note that three of the PSUs (4, 73, and 81) do not have any complete cases. Two other PSUs (5 and 43) have only two and four complete cases, respectively. Also, three other PSUs (8, 9, and 75) have less than 20 complete cases.

Since the targeted sample size was only 400 cases, it was decided to eliminate seven PSUs (4, 5, 8, 9, 43, 73, and 81) from the sampling due to overly small number of cases, which renders the data collection effort inefficient. The number of sample cases was thus reduced from 437 to 404 cases. Distribution of the 404 sampled cases by PSU is also shown in Table 6.

In order to make sure that the sampled cases are reasonably representative of the NASS CDS cases, and thus the overall crash population nationwide, a check was conducted on a few key variables, including highest injury severity, number of lanes, and vehicle type.

As shown in Table 7, of the 404 sampled cases, 139 (34.41%) resulted in serious to fatal injuries (AIS ≥ 3), 94 (23.27%) in moderate injury (AIS = 2), 142 (35.15%) in minor injury (AIS = 1), and 29 (7.18%) with no injury (AIS = 0). The distribution of the sampled cases was quite similar to that of the eligible cases shown previously in Table 3 with a slight decrease in the percentage of crashes with no injury. The same is true for the weighted distributions.

Table 8 shows the distribution of the eligible cases by number of lanes. The dominance of highways with two or three lanes is even more pronounced for the sampled cases with the weighted percentages, increasing from the 82.02% for the eligible cases (see Table 4) to 90.36% for the sampled cases. The proportion of crashes on one-lane roadways also increased slightly. Correspondingly, the weighted percentages of crashes on highways with four or more lanes dropped from 14.53% to only 5.69%. This drop in the proportion of cases occurring on highways with four or more lanes is not surprising given that only three of the sampled PSUs are in suburban areas, where multi-lane facilities are more common.

As shown in Table 9, the distributions of the sampled cases by vehicle type are similar to those of the eligible cases, shown previously in Table 5. Passenger cars accounted for about 65% for both the eligible and sampled cases. The proportions of sport utility vehicles and vans/minivans decreased somewhat for the sampled cases while the percentage of pickup trucks increased.

Overall, the distributions of these key variables for the sampled cases were reasonably similar to those of the eligible

Table 5. Eligible cases by vehicle type.

Vehicle Type	Unweighted		Weighted	
	No.	Percentage	No.	Percentage
Passenger Car	696	58.19	445,651	64.60
Sport Utility Vehicle	198	16.56	103,434	14.99
Van/Minivan	55	4.60	26,138	3.79
Pickup Truck	247	20.65	114,668	16.62
Total	1,196	100.00	689,891	100.00

Table 6. Eligible, complete, and sampled cases by primary sampling unit.

Area Type	PSU	Eligible Cases		Complete Cases		Sampled Cases	
		No.	Percentage	No.	Percentage	No.	Percentage
Rural	2	59	4.93	31	7.09	31	7.67
	4	35	2.93	0	0.00	0	0.00
	11	145	12.12	59	13.50	59	14.60
	13	130	10.87	86	19.68	86	21.29
	43	100	8.36	4	0.92	0	0.00
	48	114	9.53	40	9.15	40	9.90
	76	109	9.11	41	9.38	41	10.15
	78	85	7.11	43	9.84	43	10.64
	Subtotal	777	64.97	304	69.57	300	74.26
Suburban	5	16	1.34	2	0.46	0	0.00
	8	28	2.34	15	3.43	0	0.00
	9	64	5.35	12	2.75	0	0.00
	12	94	7.86	47	10.76	47	11.63
	45	60	5.02	38	8.70	38	9.41
	73	48	4.01	0	0.00	0	0.00
	75	57	4.77	19	4.35	19	4.70
	81	52	4.35	0	0.00	0	0.00
	Subtotal	419	35.03	133	30.43	104	25.74
Total		1,196	100.00	437	100.00	404	100.00

Table 7. Sampled cases by highest injury severity.

Abbreviated Injury Scale	Unweighted		Weighted	
	Number	Percentage	Number	Percentage
No Injury (0)	29	7.18	88,968	41.15
Minor Injury (1)	142	35.15	87,723	40.58
Moderate Injury (2)	94	23.27	16,063	7.43
Serious Injury (3)	69	17.08	11,387	5.27
Severe Injury (4)	30	7.43	9,966	3.68
Critical Injury (5)	32	7.92	3,056	1.41
Maximum Injury (6)	8	1.98	1,024	0.47
Total	404	100.00	218,187	100.00

Table 8. Sampled cases by number of lanes.

Number of Lanes	Unweighted		Weighted	
	No.	Percentage	No.	Percentage
1	14	3.47	8,531	3.95
2 & 3	356	88.12	195,360	90.36
≥ 4	34	8.42	12,296	5.69
Total	404	100.00	216,187	100.00

Table 9. Sampled cases by vehicle type.

Vehicle Type	Unweighted		Weighted	
	No.	Percentage	No.	Percentage
Passenger Car	212	52.48	140,692	65.08
Sport Utility Vehicle	64	15.84	67,169	11.25
Van/Minivan	23	5.69	3,502	1.62
Pickup Truck	105	25.99	45,511	21.05
Total	404	100.00	256,874	100.00

cases, given that the sampled cases are not truly a representative sample of the eligible cases. Rather, it is a sample of convenience to make sure that the sampled cases have complete documentation of the vehicle trajectory, vehicle inspection, and information on injury severity.

3.4.2 Supplemental Field Data Collection

Data elements requiring supplemental field collection are shown in Table 10. The protocol for the supplemental field data collection effort was developed, including the field forms and the accompanying coding and instruction manuals. The field forms were used by the PSU investigators during the actual data collection while the manual provided definitions of the data elements, field data collection procedures, and coding instructions.

Note that given the retrospective nature of the data collection approach, there was an implicit assumption that the data elements would not change significantly with time. This is a reasonable assumption for most of the supplemental data elements, such as roadway, traffic, and roadside characteristics. As for the struck-object characteristics, there was an additional assumption that any damaged objects would be replaced in kind, i.e., the replaced object or feature would have the same characteristics as the original that was damaged. The investigators would compare the site and struck-object characteristics at the time of supplemental data collection to those at the time of the crash, using photographs from the case files to make sure that these assumptions were accurate. Cases in which the site and/or struck-object/feature characteristics had been changed significantly would be deleted from the sample.

Table 10. Data elements requiring supplemental field data collection.

- Highway type
  - Functional class
- Highway characteristics
  - Number of lanes
  - Lane width
  - Horizontal curvature - Point of departure and maximum
  - Vertical grade - Point of departure and maximum
- Roadside characteristics
  - Shoulder type and width
  - Roadside slopes – widths and rates of slopes
  - Median type, width, and slope
- Traffic characteristics
  - ADT
  - Percent truck
- Struck-object characteristics
  - Object type
  - Impact performance

There were two sets of field data collection forms:

- Supplemental Highway Data Collection Form
- Object Struck Data Collection Form

A complete copy of the field forms and the accompanying coding and instruction manuals are included as Appendix C and will not be repeated here.

The Supplemental Highway Data Collection Form was completed for each sampled case. The form contains 20 data elements under four general headings:

- Case Identification:
  1. Year
  2. Primary Sampling Unit
  3. Case Number-Stratum
- General Highway Data:
  4. Land Use
  5. Class Trafficway
  6. Access Control
  7. Average Lane Width
  8. Roadway Alignment at Point of Departure
  9. Radius of Curve
  10. Roadway Profile at Point of Departure
  11. Vertical Grade
- Roadside Data:
  12. Curb Presence
  13. Curb Height
  14. Shoulder Type
  15. Shoulder Width
- Slope Data:
  16. Roadside Cross Section at Point of Departure
  17. Number of Slopes
  18. Lateral Offset to Beginning of Slope
  19. Rate of Slope
  20. Width of Slope

An Object Struck Data Collection Form was completed for each object involved in the crash. The form contains seven data elements under four general headings:

- Case Identification:
  1. Year
  2. Primary Sampling Unit
  3. Case Number-Stratum
- General Struck Object Data:
  4. Impact Number
  5. Object Type
  6. Material
- Dimensions of Struck Object—annotation
- Photography:
  7. Photographs Taken?

Due to the large number of potential roadside objects and features, the variables are necessarily very general without specific details. Instead, investigators were asked to provide annotations or descriptions and photographs of the struck object.

Since the data collection protocol was similar to that of NCHRP Project 17-11 and the FHWA Rollover Study, the Zone Center staff and PSU investigators were already familiar with the data collection protocol. Thus, the data collection experienced little problem or difficulty. The actual field data collection was conducted by PSU investigators under the direction of the Zone Centers: Veridian Corporation for Zone Center 1 and KLD Associates for Zone Center 2. After a quality check was conducted by Zone Center personnel for accuracy, the completed data were forwarded to KLD Associates, which was a subcontractor for this study. The supplemental field data were then combined with the regular NASS data in the manual review of the cases.

3.4.3 Manual Review of Sampled Cases

Additional data elements not available from the computerized data file or supplemental field data collection were gleaned from manual review of hard copies (in electronic form) and reconstruction of the sampled cases. The data elements coded from this manual review are shown in Table 11. Part of the review included verification of data elements that were already coded under existing NASS CDS or supplemental data collection, such as:

- Highway data—highway type, number of lanes, divided/undivided, presence/absence of shoulder, and impact sequence
- Roadside feature impacted—guardrail, tree, ditch, etc.
- Driver input—steering and/or braking

Table 11. Data elements requiring reconstruction.

- Encroachment conditions at point of departure
  - Speed
  - Angle
- Pre-impact vehicle trajectory
  - Vehicle path
  - Maximum lateral extent of encroachment
  - Total longitudinal distance
- General impact data
  - Post-impact trajectory
- Impact conditions – first harmful event
  - Impact speed
  - Impact angle
  - Vehicle orientation
- Impact conditions – most harmful event
  - Impact speed
  - Impact angle
  - Vehicle orientation
- Driver action
  - Steering – vehicle path
  - Braking

The main function of the manual review was to conduct detailed reconstruction of the crashes to estimate parameters such as:

- Vehicle encroachment conditions—angle and orientation
- Vehicle trajectory after encroachment—vehicle path
- Impact conditions—angle and orientation
- Impact performance of struck roadside safety feature

With the exception of the reconstruction of impact speed, which was performed by the project staff, the manual review and reconstruction were conducted by Zone Center personnel from KLD Associates. Two reconstruction coding forms were designed specifically for coding of these manual review and reconstruction data elements: one for the first event or impact, and one for subsequent events or impacts. Copies of the reconstruction coding forms and the accompanying coding and instruction manual are shown in Appendix C and will not be repeated here. Zone Center personnel were trained on the manual review procedure and the coding of the data elements.

Under the reconstruction coding form for the first event, there are 20 data elements under six general categories:

- Case Identification:
  1. Year
  2. Primary Sampling Unit
  3. Case Number-Stratum
- Encroachment Data:
  4. Departure Angle
  5. Vehicle Heading Angle
- Vehicle Trajectory Data:
  6. Driver Action
  7. Longitudinal Distance of Travel
  8. Number of Trajectory Profile Points
  9. Lateral Offset of Trajectory Profile Points
  10. Maximum Lateral Offset
- Impact Conditions—First Event:
  11. Location of Impact
  12. NASS CDS Data
  13. Impact Angle
  14. Vehicle Heading Angle at Impact
- Separation Conditions—First Event:
  15. Location of Separation
  16. Separation Angle
  17. Vehicle Heading Angle at Separation
- Subsequent Event/Final Rest
  18. Subsequent Event
  19. Location of Final Rest
  20. Vehicle Heading Angle at Final Rest

Under the reconstruction coding form for subsequent events, there are also 20 data elements under six general categories:

- Case Identification:
  1. Year
  2. Primary Sampling Unit
  3. Case Number-Stratum
- Current Event Identification:
  4. Current Event Number
  5. Current Event Location
- Vehicle Trajectory Data:
  6. Driver Action
  7. Longitudinal Distance of Travel
  8. Number of Trajectory Profile Points
  9. Lateral Offset of Trajectory Profile Points
  10. Maximum Lateral Offset
- Impact Conditions—Current Event:
  11. Location of Impact
  12. NASS CDS Data
  13. Impact Angle
  14. Vehicle Heading Angle at Impact
- Separation Conditions—Current Event:
  15. Location of Separation
  16. Separation Angle
  17. Vehicle Heading Angle at Separation
- Subsequent Event/Final Rest
  18. Subsequent Event
  19. Location of Final Rest
  20. Vehicle Heading Angle at Final Rest

The completed case, including data from the regular NASS CDS data collection, the supplemental field data collection, and the manual review and reconstruction, was then sent to the project staff for final quality control and reconstruction to estimate the impact speeds.

3.4.4 Reconstruction of Impact Speed

As mentioned above, the completed cases from KLD Associates went through one final quality check by the project staff to assure completeness and accuracy. The cases were then reconstructed to estimate the impact speeds. Reconstruction of single-vehicle, ran-off-road crashes is greatly complicated by the wide variety of roadside objects. For example, Table 12 shows a list of first harmful events caused by objects struck from the 1999 Fatality Analysis Reporting System (FARS) data. It is obvious from the list that the object struck varies widely, from impacts with roadside hazards (e.g., trees and utility poles) to roadside safety devices (e.g., guardrails and crash cushions) to terrain features (e.g., embankments and ditches). In order to accurately identify impact conditions associated with these accidents, it is critical to implement crash reconstruction procedures appropriate for each of the hazards listed.

In general, reconstructions of single-vehicle, ran-off-road crashes primarily involve calculating energy losses and gains

Table 12. Object struck as first harmful event from 1999 FARS data.

Object	Frequency	Percentage
Tree	2,997	26.09
Embankment	1,213	10.56
Guardrail	1,078	9.39
Utility Pole	1,018	8.86
Ditch	887	7.72
Curb	681	5.93
Culvert	592	5.15
Fence	490	4.27
Sign Support	368	3.20
Other Post/Support	308	2.68
Concrete Barrier	275	2.39
Bridge Rail	158	1.38
Bridge Pier/Abutment	155	1.35
Wall	119	1.04
Luminaire Support	103	0.90
Boulder	79	0.69
Building	79	0.69
Shrubbery	56	0.49
Bridge Parapet	36	0.31
Equipment	26	0.23
Fire Hydrant	25	0.22
Other Longitudinal Barrier	23	0.20
Snow Bank	23	0.20
Traffic Signal Support	22	0.19
Unknown	22	0.19
Impact Attenuator	11	0.10
Other Fixed Object	506	4.41
Other Object (not fixed)	135	1.18
Total	11,485	100.00

after leaving the roadway. Energy changes during ran-off-road crashes can generally be attributed to one or more of these seven categories:

- Vehicle crush
- Damage to roadside feature
- Tire braking
- Tire side slip
- Vehicle rollover
- Change in vehicle elevation
- Friction between vehicle and roadside feature

Key data elements needed to accurately estimate these energy changes include, but are not limited to:

- Impact sequence
- Vehicle crush profile
- Impact angle/principal direction of force during crash
- Vehicle trajectory, including tire mark measurement and description
- Driver action, i.e., steering/braking
- Roll distance and number of quarter roll
- Changes in elevation along the vehicle path
- Extent of damage to roadside feature

It should be noted that these data elements pertain to perishable evidence that have to be collected at the time of the crash investigation. For a prospective study in which data are collected on crashes as they occur, the study can be designed to properly document the required data elements. However, in the case of a retrospective study like the current project, the data availability and quality is limited by what was actually collected and could be lacking for some of the data elements. The availability and quality of the data elements can be divided into the following general categories:

- Data elements that are well documented and coded in the NASS CDS cases, such as impact sequence, vehicle crush profile, principal direction of force, and number of quarter rolls. The quality of these data elements is typically high and no further work is needed.
- Data elements that are documented and coded in the CDS cases, but the quality of the data may be somewhat questionable, e.g., driver action. These data elements would need to be checked against other available evidence, such as the scaled diagram, annotated remarks, and photographic documentation, to verify the accuracy of the coded data.
- Data elements are documented, but not coded, and the quality of the data may vary greatly from case to case, e.g., vehicle trajectory, tire marks, impact angle, and roll distance. These data elements would have to be gleaned from the scaled diagram, annotated remarks, and photographic documentation.
- Data elements that are not documented. The two areas where existing NASS CDS cases may not contain sufficient information are elevation changes along the vehicle path and the characteristics and sustained damage of the impacted roadside feature(s). These data elements would have to be gleaned from the photographic documentation to the extent possible or the information collected in the supplemental data collection effort. It should be noted, however, that the implicit assumption was that the data from the supplemental data collection were the same as at the time of the crash, which may or may not be true.

Although deformation of roadside features is an important source of energy dissipation for some crashes, many ran-off-road crashes would not involve deformable fixed objects. For the limited number of cases where this energy dissipation factor is important, it may be necessary to make estimates of deformation from case photographs and supplemental site investigations. Change in elevation during a crash is generally not an important source of energy change unless the vehicle has traversed a very deep roadside embankment. Elevation changes along the vehicle path can be estimated by recording the dimensions of the various side slopes.

While the general principle of identifying the energy loss parameters during the collision and summing the total to determine the change in velocity from the point of impact to the final resting position is rather straightforward, the actual reconstruction is greatly complicated by the wide variety of roadside features. There is not a single procedure that can be used to reconstruct all ran-off-road crashes. Instead, different reconstruction procedures are needed to accommodate the wide variety of roadside features and types of impact.

There are a number of existing procedures that have been developed for reconstructing special types of ran-off-road, fixed-object crashes, including:

- Pole support structure (*25*)
- Rigid barrier (*15*)
- Semi-rigid and flexible barrier (*14*)

These roadside features accounted for about 55% of all ran-off-road, fixed-object fatal crashes, as shown in Table 12. For the remaining 45% of crashes, the vast majority can be grouped into one of the following five categories:

- Roadside terrain
- Rigid hazards
- Drainage structures
- Buildings and walls
- Fences and shrubbery

New reconstruction procedures were developed for these five categories of roadside features. Brief discussions on reconstruction procedures for the various roadside features are presented in the following sections.

3.4.4.1 Pole Support Structures

A computerized reconstruction procedure was developed for ran-off-road crashes involving pole support structure, including breakaway and nonbreakaway utility poles, luminaire supports, and sign supports (*25*). Energy loss is grouped into three major categories:

- Vehicle crush. The CRASH3 (*27*) reconstruction program was utilized to estimate vehicle crush energy based on vehicle crush measurements.
- Fracture of pole. Energy associated with breaking or fracture of the pole was estimated based on empirical test data.
- Post-impact vehicle trajectory. The CRASH3 reconstruction program was also utilized, to the extent possible, for estimating the energy or speed loss associated with the post-impact vehicle trajectory. Otherwise, manual calculations were performed for the reconstruction.

This procedure was utilized whenever possible for reconstruction of crashes involving pole support structures, e.g., utility poles; luminaire, sign, and traffic signal supports; other post/supports; and fire hydrants.

3.4.4.2 Rigid Barrier

Another procedure was developed for reconstructing rigid barrier impacts during a study to assess rollovers on concrete barriers (*15*). This study found that vehicle/barrier friction was a major source of energy dissipation during a crash. Again, energy loss is grouped into three major categories:

- Vehicle crush. The CRASH3 (27) reconstruction program was utilized to estimate vehicle crush energy based on vehicle crush measurements.
- Friction. Energy loss associated with vehicle/barrier friction was estimated as a function of the length of barrier contact.
- Post-impact vehicle trajectory. The CRASH3 reconstruction program was also utilized, to the extent possible, for estimating the energy or speed loss associated with the post-impact vehicle trajectory. Otherwise, manual calculations were used for the reconstruction.

The vehicle crush energy was then matched to the energy associated with the lateral velocity of the impacting vehicle. If both energy estimates are comparable, the procedure was believed to be reasonably accurate. If not, the vehicle crush energy would be adjusted appropriately and a new estimate of the impact speed was generated. This iterative procedure has been found to give reasonably good estimates of impact speed when used to evaluate findings from full-scale crash tests.

3.4.4.3 Semi-Rigid and Flexible Barrier

A reconstruction procedure for semi-rigid and flexible barriers was developed in a study of ran-off-road crashes (*14*). This procedure utilized similar techniques for estimating vehicle crush and trajectory energy losses. Energy loss associated with the deformation of semi-rigid barriers was estimated from a series of computer simulations that correlated impact severity to maximum barrier deflection. The impact severity is calculated using the following equation:

$$IS = \frac{1}{2} * M * (V * \sin\theta)^2$$

where:

IS = Impact Severity
M = Vehicle mass
V = Vehicle velocity
θ = Impact angle

The IS value has been shown to be a good indicator of the degree of loading and maximum deflection of a barrier during an impact. Unfortunately, the maximum barrier deflection after a crash is seldom measured during a NASS CDS investigation. Thus, the permanent barrier deflection was estimated from available photographic documentation. The measured or estimated permanent barrier deflection was then related to the maximum dynamic deflection, which in turn was used to estimate the IS value from the impact.

The impact speed could be estimated from IS value along with the impact angle or by traditional energy loss calculations, including vehicle crush, barrier deformation, and post-impact trajectory. An iterative procedure similar to that used to reconstruct rigid barrier crashes was developed for this application.

The procedure from Erinle et al. (*14*) was refined and updated for use in the current study. The revised procedure also included techniques for reconstructing impacts with guardrail terminals and crash cushions.

3.4.4.4 Roadside Terrain

Impacts involving embankments and ditches could be reconstructed if detailed information is available on the terrain and any associated gouges in the terrain along with the vehicle crush. Efforts to model vehicles traversing hazardous roadside terrains have established reasonable measures of the forces and energy associated with vehicle undercarriage components gouging into the terrain (*28*). Furthermore, for crashes involving vehicles plowing into steep embankments virtually head on, vehicle crush measurements would produce a good estimate of the total force generated between the embankment and the vehicle. Finally, energy losses associated with rollover accidents have been investigated through computer simulation for a variety of passenger vehicles (*29*). Hence, impact speeds for crashes involving roadside terrain could be estimated by combining conventional trajectory analyses, such as that used in the CRASH3 reconstruction program, and incorporating procedures for estimating the effects of terrain gouging and vehicle rollover.

3.4.4.5 Rigid Hazards

For rigid obstacles, such as bridge piers and parapets, boulders, and heavy construction equipment, there is little energy dissipated by the rigid hazards themselves. Thus, reconstructions could be based almost entirely on vehicle crush energy and post-impact trajectories. These procedures would be similar to those used by Mak and Labra (*25*) to reconstruct pole crashes in which the poles remained intact.

3.4.4.6 Drainage Structures

Drainage structures, such as culverts and curbs, are often traversed during a ran-off-road accident without a significant speed reduction. Full-scale crash testing and computer simulation have shown that speed losses during curb impacts are very low (*30*). These simulation and test findings were used to obtain gross estimates of the total speed loss associated with curb impacts. Thereafter, other reconstruction techniques could be used to estimate the total energy lost during the post-impact trajectory of the vehicle.

Culverts offer significantly greater challenges. Cross-drainage culverts with high headwalls can act as a rigid hazard and could be reconstructed based largely on vehicle crush as described in the previous section. Crash tests of cross-drainage culverts that have been cut to match the slope and/or grated to reduce the severity of crashes have shown that these hazards provide very little energy dissipation (*31*). This low level of energy dissipation would allow crashes involving these hazards to be reconstructed based on the post-impact trajectory alone. Unfortunately, reconstruction of crashes involving parallel drainage structures were somewhat more difficult. Crash testing has indicated that vehicles striking culverts under driveways or intersecting streets are frequently subjected to violent rollovers. Where possible, procedures for estimating energy losses during vehicle rollover formed the basis for reconstructing rollover crashes associated with culvert accidents. Conventional trajectory analyses were used whenever the vehicles remained upright after striking the culvert.

3.4.4.7 Buildings and Walls

When buildings and walls are struck in a more or less head-on configuration, conventional reconstruction techniques are applicable only if the building or wall is relatively rigid. No procedure has been developed that can effectively estimate the energy required to break through a building or wall. However, if the structures remain intact, the building or wall was treated as either a rigid hazard or a rigid longitudinal barrier, depending on the nature of the impact.

3.4.4.8 Fences and Shrubbery

Most fences, including chain link and wooden privacy fences, provide relatively little energy dissipation when struck by an automobile traveling at a high rate of speed. Similarly, small shrubs do not offer significant resistance to an impacting vehicle. Therefore, crashes involving these hazards were reconstructed using conventional procedures unless the fence had an unusual construction or the shrubs were large enough to pose a major obstacle to a vehicle.

In summary, by utilizing and refining available reconstruction techniques, it was possible to produce accurate estimates of the impact conditions for most ran-off-road crashes. The reconstruction procedures discussed above should account for almost 90% of the serious injury and fatal ran-off-road crashes.

3.4.5 Conduct of Data Collection

The work on supplemental field data collection, quality control, and manual review and reconstruction of the sampled cases was conducted over a period of approximately 12 months. Of the 404 sampled cases, 15 were found to have major construction/reconstruction at the crash sites and thus were eliminated from the sample. One additional case was eliminated because it involved two vehicles. Thus, the final sample size was reduced from 404 to 388.

3.5 Data from Previous Studies

NCHRP Project 17-11 and FHWA's Rollover Study incorporated the same data collection procedures as used in the current study and included at total of 485 cases from NASS CDS for the years 1997 through 1999. These studies were conducted by the Texas Transportation Institute (TTI) and therefore the data from the two studies will be referred to collectively as "TTI data." Because the TTI data was collected and processed using the same protocol as the data collected in this (17-22) study, it was believed to be appropriate to combine the two data sets into a single file. Unfortunately, upon comparison of basic crash data, such as departure velocity and angle, it became apparent that the two data sets were not sufficiently similar to be combined. The biggest differences were found in departure and impact angles. For example, the average departure angle for the TTI data was found to be 19.9 degrees, compared to 17.2 degrees for the 17-22 data. This 15% difference in average departure angle was considered to be excessive. When a simple T-test was applied to compare the two data sets, differences in departure angle were found to be significant at the $p = 0.001$ level. These findings prompted a more careful examination of the differences between the TTI data set and the NCHRP 17-22 data set. It was discovered that the TTI cases were reconstructed from scene diagrams downloaded from the NASS CDS website. These scene diagrams had been converted to PDF format before being posted on the website. Unfortunately, the process of converting the scene diagrams to PDF changed the scaling of the drawings. The compression in the longitudinal direction was found to be greater than the compression in the lateral direction. As a result, all angle measurements were corrupted.

3.5.1 Manual Review and Crash Reconstruction of Prior Cases

In order to salvage the 485 cases included in the TTI data set, it was necessary to obtain the original scene diagrams and repeat the reconstruction process for all of the cases. Unfortunately, supplemental data forms for 35 of the TTI cases were lost in transit from College Station, Texas, to Lincoln, Nebraska. Although reconstructions were possible for these 35 cases, much of the supplemental information such as roadside topography, land use, highway classification, and highway alignment could not be determined.

3.5.2 Incorporation of Prior Data into Database

After the reconstructions and manual reviews were repeated for the TTI cases, the TTI and 17-22 data sets were subjected to a comprehensive evaluation to determine the appropriateness of combining them into a single data set. Each important variable was tested to determine the significance of differences between the two data sets. Whenever a variable was found to be significantly different at the $p = 0.05$ level, all 877 cases were re-examined to identify the source of the error. In some cases, the errors were found to be related to the way a specific parameter was measured. For example, the heading angle at departure was measured from –180 to 180 degrees in the 17-22 data and from 0 to 360 degrees in the TTI data. These errors were easily corrected. Other data elements were found to have been poorly recorded on the supplemental data forms. For example, in some cases, the roadside slope was recorded as the highway grade. In this situation, the research team was forced to re-examine every case to compare photographs at the scene with the recorded highway grade. Whenever there was reasonable evidence of an error, the entire file was examined for evidence of the highway grade. In some cases, the highway grade was found in investigator notes on the supplemental data forms. In other situations, the elevation changes along the roadway were recorded between the point of departure and at a point where the vehicle re-entered the roadway. These elevation changes were then used to estimate highway grade at the crash site. Unfortunately, there were many cases where the highway grade could not be identified and the variable had to be labeled as unknown. This type of examination was undertaken for a large number of data elements that were found to be significantly different in the two data sets.

As shown in Table 13, most variables with significant differences between the two data sets were corrected and the two data sets could be considered to be relatively similar. Unfortunately, significant differences remained for some variables, including speed limit, vehicle weight, height and width of object struck, rollover, and vehicle class. Differences in speed limit and vehicle weight are believed to be appropriate. The national speed limit law was repealed in late 1995 and was not implemented immediately in many states. In fact, 18 states had not implemented any change in speed limit before the end of 1997. Many of these states eventually raised speed limits.

Table 13. Comparison of 17-22 and TTI data.

Variable	Units	17-22 Data			TTI Data			P Value
		Mean	Std Dev.	SEM	Mean	Std Dev.	SEM	
Dep. velocity	km/h	80.00	26.00	1.32	78.70	25.30	1.15	0.48
Dep. angle	deg.	17.20	11.90	0.60	16.90	10.20	0.47	0.70
IS value	kJ	41.70	59.60	3.02	36.90	74.90	3.41	0.31
Degree of curvature	deg.	2.27	7.50	2.65	2.65	6.72	0.32	0.45
Driver action		3.92	3.03	0.15	4.16	3.09	0.15	0.27
Month		6.68	3.45	0.17	6.39	3.00	0.14	0.20
Access control		2.27	0.92	0.05	2.28	0.94	0.04	0.82
Accident time		0.48	0.30	0.02	0.52	0.40	0.02	0.10
Alignment		1.53	0.79	0.04	1.61	0.80	0.04	0.17
Curb height	mm	5.59	29.23	1.48	8.24	39.31	1.86	0.27
Curbs		0.09	0.40	0.02	0.08	0.36	0.02	0.64
Departure side		1.49	0.50	0.03	1.43	0.50	0.02	0.07
Divided/undivided		1.43	0.50	0.03	1.38	0.49	0.02	0.14
Grade	%	1.50	1.67	0.08	1.39	1.49	0.07	0.10
Highway speed limit	mph	57.45	9.24	0.47	55.68	9.44	0.43	0.006
Land use		1.76	0.43	0.02	1.70	0.47	0.02	0.06
Lane width	m	3.69	0.55	0.03	3.64	0.52	0.02	0.18
Lat distance from departure to rest	m	0.07	13.45	0.68	1.24	13.22	0.60	0.20
Lateral travel	m	0.37	12.22	0.62	1.02	12.93	0.59	0.45
Heading angle at point of rest	deg.	166.15	111.15	5.63	165.27	111.47	5.21	0.91
Long. distance from dep. to rest	m	46.40	37.83	1.91	44.84	40.05	1.82	0.56
Long. travel, 1st encroachment	m	39.14	30.89	1.56	39.79	34.71	1.58	0.78
Material of object struck		5.02	2.60	0.13	4.70	2.29	0.11	0.06
No. of slopes		4.11	1.81	0.09	3.94	1.59	0.08	0.15
Object diameter	cm	33.54	26.55	2.81	29.44	38.90	2.66	0.36
Object height	cm	475.84	699.70	62.33	215.86	240.01	17.60	0.0001
Object length	cm	2937	6326	922.8	1145	2229	388.1	0.12
Object width	m	68.91	292.38	19.15	292.38	433.98	38.97	0.0003
Road class		2.77	2.86	1.29	2.86	1.43	0.07	0.33
Road condition		1.36	0.82	0.04	1.31	0.72	0.03	0.32
Road profile		0.52	0.82	0.04	0.53	0.89	0.04	0.90
Road surface		1.21	0.65	0.03	1.25	0.75	0.03	0.46
Rollover		0.59	0.49	0.02	0.50	0.50	0.02	0.008
Shoulder type		1.27	0.74	0.04	1.30	0.84	0.04	0.55
Shoulder width	m	1.77	1.31	0.07	1.86	1.40	0.07	0.37
Sideslip angle	deg.	-1.02	38.61	1.38	0.63	38.59	1.76	0.46
Vehicle weight	lb	3348.32	861.96	43.59	3154.16	738.30	33.52	0.0003
Weather		1.24	0.69	0.03	1.20	0.57	0.03	0.32
X-section at departure		5.43	2.66	0.13	5.45	2.67	0.13	0.89

Recall that the TTI data included crashes from 1997 through 1999 while the 17-22 study included data from 2000–2001. Thus, it is not surprising that speed limits were found to increase between the time of data collection for the TTI and 17-22 data sets. Similarly, the average weight of the vehicle fleet increased dramatically during the 1990s. In the early 1990s, the 5th and 95th percentile passenger vehicle weights were 1,800 and 4,400 lb respectively. By 2002, the 5th and 95th percentile weights had increased to 2,500 and 5,200 lb, respectively. This dramatic increase in vehicle weight would be expected to cause the average weight of crash vehicles to be higher in 2000 and 2001 than during the 1997 through 1999 period. Hence, the nearly 200 lb increase in average weight between the TTI and 17-22 data sets is not unexpected.

Careful examination of the two data sets revealed that the differences in the width and height of the object struck between the two data sets could be attributed to overrepresentations in the number of tall trees impacted in the 17-22 data and of wide ditches in the TTI data. Note that the increase in the number of trees or the number of ditches was not sufficient to produce statistically significant differences in the object-struck category. However, the number of very tall trees (15 m or more) in the 17-22 data was sufficient to produce significant differences in the height of the object struck. Further, a relatively small number of wide ditches in the TTI data produced significant differences in the width of the object struck.

The number of rollovers in the 17-22 data was found to be significantly greater than in the TTI data. As shown in Table 13, 59% of the cases from 17-22 involved vehicle rollover compared to only 50% for the TTI data. A careful evaluation of each case in both data sets could not provide any explanation for the magnitude of the difference in rollover frequency. The only possible explanations for the high rollover rate is that the 17-22 data also had 47% light-truck involvement compared to 38% for TTI data. Although light-truck sales were growing during the 1997 through 2001 time frame, the 9% increase in light-truck involvement is unexpectedly high. Further, even though light trucks are known to have a higher risk of rollover, the overrepresentation of light trucks is insufficient to explain the full magnitude of the difference in rollover rate. The rollover rates for both cars and light trucks were found to be significantly higher in the 17-22 data than in the TTI data. The 17-22 data had 50% and 69% rollover rates for cars and light trucks, respectively, while the comparable numbers from the TTI data were 44% and 59%. Unfortunately, the fundamental differences in rollover rate could neither be eliminated nor explained.

In spite of the differences found in the six variables described above, differences between the two data sets were not statistically significant for the vast majority of data elements. Based upon this finding, combining the two data sets was deemed acceptable. Note that finding differences not to be statistically significant does not necessarily imply that the data sets are similar. Users should use caution whenever using the combined database to examine highway or crash characteristics that are close to the threshold of statistical significance.

3.6 Relational Database

The design of a relational database for the purpose of storage and retrieval of crash data was developed and implemented. In addition to the data collected under this study, the crash database also stored data from NCHRP 17-11 and the FHWA Rollover Study.

The crash database design revolved around the Oracle server, which is an object-relational database management system providing an open, comprehensive, and integrated approach to data management. The crash database was composed of a data file containing different types of elements (e.g., CASE_NUM, CASE_ID, DEPARTURE ANGLE, etc.). A user process (or a client process) and a server process were used for successful communication between users and the crash database. Together these two processes enabled users to run various queries on the database.

Access to the crash database could be obtained by directly issuing SQL commands or through the use of an application that contains SQL statements. The Oracle crash database processes the commands and returns results to the users. It is physically located on a server residing at the Nebraska Transportation Center of the University of Nebraska–Lincoln. Currently, logging in directly on the host computer is supported, i.e., the computer running the Oracle crash database server is used for database access. The communication pathway is established using the inter-process communication mechanisms available on the host computer. Logging in via a two-tiered (client-server) connection, where the machine on which the user is logged in is connected directly to the machine running the Oracle crash database server, and via a three-tiered connection, where users will connect to the Oracle crash database server via network server(s) by using a customized application, are possible but have not been implemented. However, remote access to the database is available using Windows® Remote Desktop Connection (password protected). Data element names and definitions are presented in Appendix D.

CHAPTER 4

Results

4.1 General

The following chapter presents an overview of the data set developed under the current study. A brief comparison of the content of the 17-22 and TTI data set is presented below. Descriptive statistics for the combined data set are then presented followed by a detailed evaluation of the impact conditions and comparison of the current data and historical studies. Encroachment lengths from the combined data set are then compared to historical studies and implications of the new data on the calculation of appropriate guardrail length is discussed. Additional tables and plots describing the basic characteristics of the combined data set are presented in Appendix E.

4.1.1 Comparison of 17-22 and TTI Data

A summary of the efforts to compare the 17-22 and TTI data sets was presented previously in Section 3.5. As shown in Table 13, differences between the two data sets were found to be statistically insignificant for the vast majority of the important variables. Vehicle weight, highway speed limit, rollover frequency, and vehicle class were exceptions to this finding. The modest changes observed in vehicle weight and roadway speed limits could be explained by changes in the vehicle fleet and elimination of the national speed limit law. Unfortunately, the magnitude of the change in vehicle class and the rollover rates between the 17-22 and TTI data could not be adequately explained.

Most other important variables correlated very well between the two data sets. As shown in Table 14, injury and fatality rates for the two studies are virtually identical. Departure speeds and angles are also very similar as shown in Figures 1 and 2. Vehicle heading angle distributions were also found to be very similar, as shown in Figure 3. Although the IS distributions, shown in Figure 4, were not as similar as the other comparisons, the differences were not statistically significant. Recall that IS was defined in Chapter 2 as:

$$IS = \tfrac{1}{2} * M * (V * \sin\theta)$$

where:

IS = Impact Severity
M = Vehicle mass
V = Vehicle velocity
θ = Impact angle

Table 14 and Figures 1 through 4 clearly illustrate that injury rates and departure conditions from the TTI and 17-22 data are sufficiently similar to allow the data to be combined into a single database. As discussed in the prior chapter, the similarity between the two data sets for the vast majority of important data elements is sufficient to justify combining them into a single database. Nevertheless, database users should be cognizant of the differences in rollover rates and vehicle classes when developing data queries. Additional comparisons between the 17-22 and TTI data sets are presented in Appendix E.

4.2 Descriptive Statistics

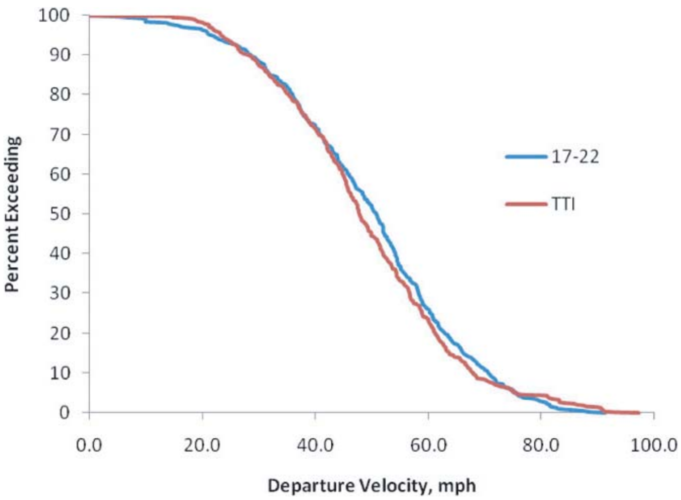
When combined into a single data set, the 17-22 and TTI data included a total of 877 cases. The following sections provide a basic description of the combined data set.

4.2.1 Characteristics of Sampled Cases

As shown in Table 15, rural highways make up approximately 72% of the accident cases with the remaining 28% of cases located in urban areas. Table 16 shows that the data set includes a significant representation of cases on Interstate highways, US routes, state routes, and county roads. The

Table 14. Injury severity by study.

Injury Type	17-22 Data		TTI Data		Total Data	
	No.	Percentage	No.	Percentage	No.	Percentage
Fatal	55	14.0%	74	15.3%	129	14.7%
A-injury	228	58.2%	279	57.5%	507	57.8%
B-injury	40	10.2%	49	10.1%	89	10.2%
C-injury	33	8.4%	42	8.7%	75	8.6%
PDO	36	9.2%	41	8.5%	77	8.8%
Total	392	100.0%	485	100.0%	877	100.0%



Note: Many of the figures in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color version as submitted by the contractor.

Figure 1. 17-22 and TTI departure velocity distributions.

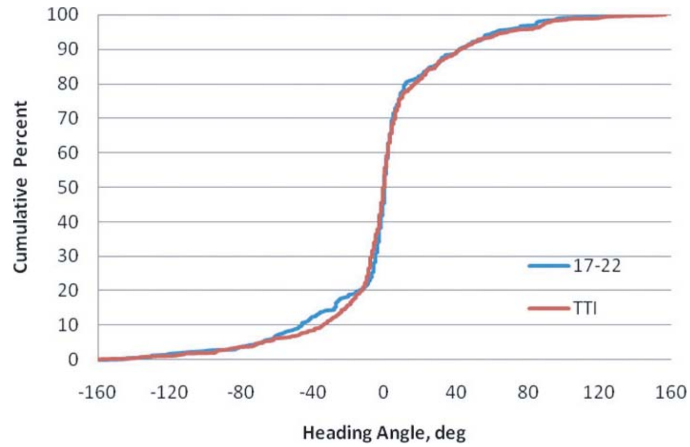


Figure 3. 17-22 and TTI heading angle distributions.

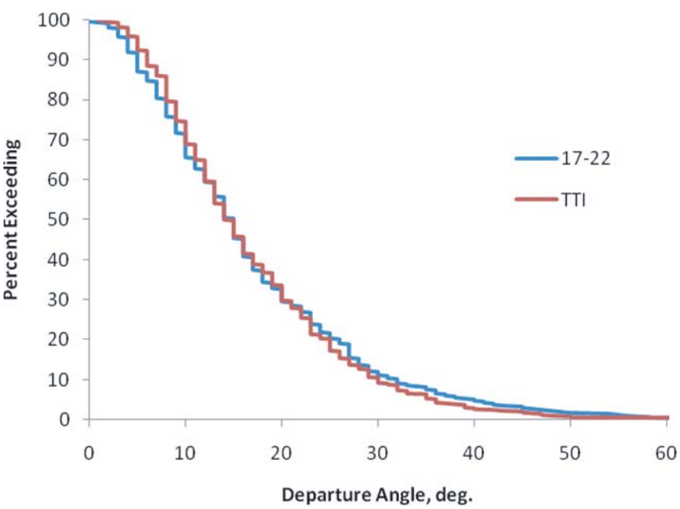


Figure 2. 17-22 and TTI departure angle distributions.

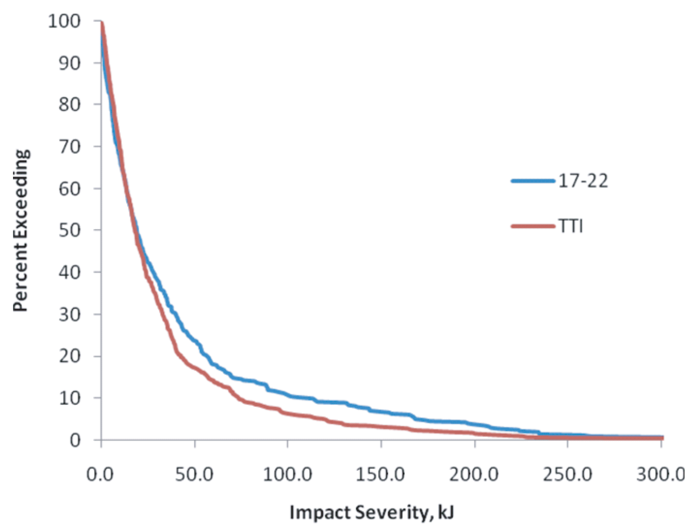


Figure 4. 17-22 and TTI IS distribution.

Table 15. Case distribution by land use.

	No. of Cases	Percentage
Urban	235	27.94%
Rural	606	72.06%
Total	841	100.00%

Table 16. Highway classification.

Hwy Class	No. of Cases	Percentage
Interstate	195	23.16%
US Route	160	19.00%
State Route	161	19.12%
County Road	275	32.66%
City Street	43	5.11%
Other	8	0.95%
Total	842	100.00%

Table 17. Speed limit.

Speed Limit	Cases	
	No.	Percentage
75	58	6.7%
70	114	13.1%
65	75	8.6%
55	361	41.4%
50	68	7.8%
45	195	22.4%
Total	871	100.0%

largest number of cases, 275 (32.7%), occurred on county roads and 195 (23.2%) cases were on Interstate highways. The number of cases on US and state routes are approximately the same at 160 (19.0%) and 161 (19.1%) cases, respectively. As would be expected for crashes collected from these highway types, the data set includes a wide distribution of speed limits ranging from 45 to 75 mph, as shown in Table 17. Table 18 presents this distribution of speed limit by highway class. As expected, most of the data collected from high-speed facilities involved Interstate highways and the majority of cases involving low-speed facilities were collected on county roads. Tables 19 and 20 show the number of lanes at the accident site for divided and undivided highways, respectively.

Surprisingly, even though a large proportion of crashes involved Interstates and US routes, very few cases involved vehicles departing from a portland cement pavement surface. As shown in Table 21, the vast majority of the cases, 773 (88.1%), occurred on asphalt with only 45 (5.1%) involving portland cement concrete.

As shown in Table 22, winter months were significantly underrepresented in the data. Only 132 (15.1%) crashes occurred during the winter months from December through February. The low proportion of crashes during the winter provided an explanation for the low numbers of crashes with ice, 28 (3.2%), or snow, 25 (2.9%), on the roadway surface, as shown in Table 23. This table also shows that almost 80% of all of the crashes in the data set occurred on dry roadways. These findings correlated with the weather conditions at the time of the crash, shown in Table 24. More than 85% of the crashes occurred in clear weather and less than 10% occurred in the rain.

A total of 529 of the 877 cases were recorded as having struck an object on the roadside. As shown in Table 25, more than 37% of these fixed-object crashes involved trees and another 7% involved utility pole impacts. More than 18% of the fixed-object crashes involved longitudinal barrier impacts. Thus, approximately 62% of fixed-object crashes involved impacts that would be expected to significantly reduce vehicle speed or redirect it back toward the roadway. The remaining 38% of crashes involved fixed objects that would be less likely to significantly reduce the speed of the impacting vehicle (e.g. embankments, ditches, curbs, breakaway sign and luminaire supports, fences, mailboxes and culverts).

Table 18. Highway class vs. speed limit.

	Speed Limit (mph)											
	75		70		65		55		50		45	
Hwy Class	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Interstate	57	98.3	63	56.3	25	34.2	41	11.9	2	3.2	5	2.7
US Route	0	0.0	46	41.1	34	46.6	50	14.5	11	17.5	18	9.7
State Route	1	1.7	2	1.8	13	17.8	95	27.5	20	31.7	29	15.6
County Road	0	0.0	0	0.0	0	0.0	153	44.3	27	42.9	94	50.5
City Street	0	0.0	0	0.0	0	0.0	2	0.6	3	4.8	38	20.4
Other	0	0.0	1	0.9	1	1.4	4	1.2	0	0.0	2	1.1
Total	58	100.0	112	100.0	73	100.0	345	100.0	63	100.0	186	100.0

Table 19. Number of lanes—divided highways.

	Number of Lanes		
Hwy Class	1 - 2	3 - 4	More than 4
Interstate	67 (38.3%)	86 (49.1%)	22 (12.6%)
US Route	29 (30.9%)	56 (59.6%)	9 (9.6%)
State Route	17 (37.8%)	25 (55.6%)	3 (6.7%)
County Road	1 (33.3%)	2 (66.7%)	0 (0.0%)
City Street	7 (58.3%)	5 (41.7%)	0 (0.0%)
Other	0 (0.0%)	1 (100.0%)	0 (0.0%)

Table 20. Number of lanes—undivided highways.

	Number of Lanes		
Hwy Class	1 - 2	3 - 4	More than 4
Interstate	18 (94.7%)	1 (5.3%)	0 (0.0%)
US Route	54 (81.8%)	7 (10.6%)	5 (7.6%)
State Route	101 (87.8%)	11 (9.6%)	3 (2.6%)
County Road	237 (98.8%)	3 (1.3%)	0 (0.0%)
City Street	20 (64.5%)	7 (22.6%)	4 (12.9%)
Other	6 (100.0%)	0 (0.0%)	0 (0.0%)

Table 21. Distribution by roadway material.

Roadway Surface	No. of Cases	Percentage of Total
Asphalt	773	88.1%
Portland Cement	45	5.1%
Dirt	31	3.5%
Gravel	28	3.2%
Total	877	100.0%

Table 22. Case distribution by month.

Month	Number of Occurrences	Percentage
January	37	4.2%
February	50	5.7%
March	102	11.6%
April	87	9.9%
May	82	9.4%
June	101	11.5%
July	83	9.5%
August	86	9.8%
September	76	8.7%
October	71	8.1%
November	57	6.5%
December	45	5.1%
Total	877	100.0%

Table 23. Distribution by surface condition.

Surface Condition	No. of Cases	Percentage of Total
Dry	695	79.2%
Wet	121	13.8%
Ice	28	3.2%
Snow	25	2.9%
Other	8	0.9%
Total	877	100.0%

Table 24. Weather condition.

Weather Condition	No. of Cases	Percentage
Clear	750	85.81%
Rain	82	9.38%
Snow	30	3.43%
Fog	6	0.69%
Hail	3	0.34%
Sleet	2	0.23%
Sandstorm	1	0.11%
Total	874	100.00%

Table 26 presents the distribution of vehicle classes included in the data set. Almost 58% of vehicles included in the data set were classified as "car." Further, another 28% of vehicles fell into the compact light truck class including compact pickups, compact utility vehicles, and minivans. Only 13% of vehicles included in the database were full-size pickups, utility vehicles, or vans.

4.2.2 Crash Severity

As expected, the data set is biased toward higher severity crashes. As shown in Table 27, roughly 15% of the cases

Table 25. First impact.

Object/Feature Struck	No.	Percentage
Tree	197	37.2%
Guardrail	71	13.4%
Embankment	65	12.3%
Sign and Luminaire Support	39	7.4%
Utility Pole	37	7.0%
Culvert	30	5.7%
Concrete Barrier	25	4.7%
Ditch	24	4.5%
Mailbox	18	3.4%
Fence	13	2.5%
Curb	10	1.9%
Total	529	100.0%

Table 26. Vehicle class.

Vehicle Class		No. of Cases	Percentage by Veh. Subclass	Percentage of Total
Car	Subcompact Car	145	28.7%	16.5%
	Compact	167	33.0%	19.0%
	Intermediate	117	23.1%	13.4%
	Full-Size Sedan	55	10.9%	6.3%
	Large Size	22	4.3%	2.5%
	Subtotal	506	100.0%	57.7%
Pickup Truck	Compact Pickup	99	52.4%	11.3%
	Large Pickup	87	46.0%	9.9%
	Other Pickup Type	3	1.6%	0.3%
	Subtotal	189	100.0%	21.5%
Utility Vehicle	Compact Utility	120	83.9%	13.7%
	Large Utility	15	10.5%	1.7%
	Stationwagon Utility	8	5.6%	0.9%
	Subtotal	143	100.0%	16.4%
Van	Minivan	27	69.2%	3.1%
	Large Van	10	25.6%	1.1%
	Full-Size Van	2	5.2%	0.2%
	Subtotal	39	100.0%	4.4%
	Total	877		100.0%

involved a fatality (denoted "K") and approximately 73% of all cases involved either an A-injury or a fatality (A+K). A recent study of single-vehicle crashes on controlled-access freeways in Kansas found a fatality rate of only 0.73% and an A+K rate of only 3.8% (*32*). From the data in Table 27, the fatality rate for Interstate highways in the data set was 17.9% and the A+K rate was 73.8%. These fatality and A+K rates were 25 and 19 times higher, respectively, than the values for controlled-access freeways in Kansas. This degree of bias is associated with the original case-selection criteria used to identify the NASS CDS cases and therefore cannot be avoided. This inherent bias toward increased severity may be masking the relationship between highway functional class and crash severity for this database. As shown in Table 27, the A+K rates for all highway functional classes is approximately the same with a minimum of 69% for county roads and a high of 75% for US routes.

This same bias toward higher severity crashes is also evident in Tables 28 through 31. Table 28 presents the relationship between specific vehicle class and crash severity. There appears to be no consistent trend between vehicle size and crash severity. Table 29 condenses this information to produce crash severity by overall vehicle type. Again there appears to be only modest differences in crash severity as a function of overall vehicle type. Tables 30 and 31 also illustrate that the severity bias masks the effects of rollover and the object struck on crash severity, respectively. For example, fatality rates for tree and guardrail impacts are found to be very similar at 13.2% and 12.7% respectively. Thus, Tables 27 through 31 clearly illustrate

Table 27. Highway class vs. crash severity.

	Maximum Severity									
	Fatality		Injury Type A		Injury Type B		Injury Type C		PDO	
Hwy Class	No.	%	No.	%	No.	%	No.	%	No.	%
Interstate	35	17.9%	109	55.9%	15	7.7%	20	10.3%	16	8.2%
US Route	19	11.9%	102	63.8%	11	6.9%	15	9.4%	13	8.1%
State Route	26	16.1%	93	57.8%	18	11.2%	11	6.8%	13	8.1%
County Road	40	14.5%	150	54.5%	36	13.1%	23	8.4%	26	9.5%
City Street	7	16.3%	30	69.8%	3	7.0%	1	2.3%	2	4.7%
Other	0	0.0%	4	50.0%	1	12.5%	3	37.5%	0	0.0%
All	127	15.1%	488	58.0%	84	10.0%	73	8.7%	70	8.3%

Table 28. Crash severity by vehicle class.

Vehicle Class		No. of Cases	Maximum Injury (%)				
			Fatal	A-injury	B-Injury	C-Injury	PDO
Car	Subcompact	145	13.1	53.8	11.0	12.4	9.7
	Compact Car	167	16.2	52.1	10.8	10.2	10.8
	Intermediate	117	13.7	63.2	9.4	6.0	7.7
	Full-Size Sedan	55	14.5	54.5	12.7	10.9	7.3
	Large Size	22	4.5	68.2	13.6	0.0	13.6
Pickup Truck	Compact Pickup	99	19.2	57.6	7.1	8.1	8.1
	Large Pickup	87	10.3	64.4	5.7	10.3	9.2
	Other Pickup Type	3	33.3	33.3	0.0	0.0	33.3
Utility Vehicle	Compact Utility	120	14.2	59.2	14.2	5.0	7.5
	Large Utility	8	0.0	75.0	12.5	0.0	12.5
	Stationwagon Utility	15	13.3	60.0	6.7	13.3	6.7
Van	Minivan	27	22.2	63.0	7.4	3.7	3.7
	Large Van	2	50.0	50.0	0.0	0.0	0.0
	Full-Size Van	10	30.0	50.0	10.0	10.0	0.0

Table 29. Crash severity by vehicle type.

Vehicle Type	No. of Cases	Maximum Injury (%)				
		Fatal	A-injury	B-Injury	C-Injury	PDO
Automobile	506	14.0%	56.1%	10.9%	9.5%	9.5%
Pickup	189	15.3%	60.3%	6.3%	9.0%	9.0%
Utility	143	13.3%	60.1%	13.3%	5.6%	7.7%
Van	39	25.6%	59.0%	7.7%	5.1%	2.6%

Table 30. Rollover and crash severity.

	Maximum Injury	No. of Cases	Percentage by Roll Result	Percentage of Total
Rollover	Fatality	79	16.7%	9.0%
	A-injury	274	57.9%	31.2%
	B-injury	48	10.1%	5.5%
	C-injury	40	8.5%	4.6%
	PDO	32	6.8%	3.6%
	Subtotal	473	100.0%	53.9%
No Rollover	Fatality	50	12.4%	5.7%
	A-injury	233	57.7%	26.6%
	B-injury	41	10.1%	4.7%
	C-injury	35	8.7%	4.0%
	PDO	45	11.1%	5.1%
	Subtotal	404	100.0%	46.1%
	Total	877		100.0%

Table 31. First impact vs. crash severity.

Object/Feature Struck	No. of Cases	Fatal		A-Injury		B-Injury		C-Injury		PDO	
		No.	%	No.	%	No.	%	No.	%	No.	%
Tree	197	26	13.2%	127	64.5%	16	8.1%	14	7.1%	14	7.1%
Guardrail	71	9	12.7%	36	50.7%	7	9.9%	6	8.5%	13	18.3%
Embankment	58	6	10.3%	34	58.6%	9	15.5%	4	6.9%	14	24.1%
Vertical Support	37	6	16.2%	19	51.4%	6	16.2%	1	2.7%	5	13.5%
Utility Pole	37	9	24.3%	17	45.9%	7	18.9%	3	8.1%	1	2.7%
Concrete Barrier	27	5	18.5%	13	48.1%	2	7.4%	4	14.8%	3	11.1%
Culvert	27	3	11.1%	20	74.1%	1	3.7%	2	7.4%	1	3.7%
Ditch	25	2	8.0%	15	60.0%	2	8.0%	5	20.0%	1	4.0%
Mailbox	18	2	11.1%	10	55.6%	2	11.1%	2	11.1%	2	11.1%
Fence	13	2	15.4%	8	61.5%	0	0.0%	3	23.1%	0	0.0%
Curb	10	0	0.0%	7	70.0%	1	10.0%	1	10.0%	1	10.0%
Total	520	70	13.5%	306	58.8%	53	10.2%	45	8.7%	55	10.6%

Table 32. Crash severity by departure velocity.

Departure Velocity (mph)	No. of Cases	Injury Severity Levels									
		Fatal		Injury A		Injury B		Injury C		PDO	
		No.	%	No.	%	No.	%	No.	%	No.	%
< 30	103	3	2.9%	50	48.5%	10	9.7%	17	16.5%	23	22.3%
30–45	240	18	7.5%	135	56.3%	35	14.6%	23	9.6%	29	12.1%
45.1–60	313	52	16.6%	192	61.3%	30	9.6%	26	8.3%	13	4.2%
60.1–75	166	40	24.1%	98	59.0%	9	5.4%	8	4.8%	11	6.6%
> 75	48	15	31.3%	26	54.2%	5	10.4%	1	2.1%	1	2.1%

Table 33. Crash severity by vehicle size for departure velocities of 60–75 mph.

Vehicle Class	Injury Severity Levels									
	Fatal		Injury A		Injury B		Injury C		PDO	
	No.	%	No.	%	No.	%	No.	%	No.	%
Car	15	19.5%	47	58.4%	5	6.5%	3	3.9%	7	9.1%
Pickup	10	22.7%	26	59.1%	3	6.8%	2	4.5%	3	6.8%
Utility	13	33.3%	21	53.9%	1	2.6%	3	7.7%	1	2.6%
Van	2	33.3%	4	66.7%	0	0.0%	0	0.0%	0	0.0%

that the database described herein cannot be used to evaluate the severity of different types of crashes whether it involves crash outcome such as rollover, vehicle class, or object struck.

However, the purpose of this database is not to provide relative comparisons of crash severities available from conventional databases, but rather to provide the basis for developing a relationship between crash conditions and severity for various types of hazards. Table 32 illustrates the strong relationship between departure velocity and crash severity. Both fatality rate and A+K rate increased with each increment in departure velocity. Tables 33 and 34 show injury severity and rollover risk, respectively, by vehicle type for departure velocities from 60 to 75 mph.

Table 35 shows the relationship between impact velocity and crash severity for W-beam guardrails. Again, there appears to be a strong correlation between impact speed and probability of fatal and serious injury. Table 36 provides a comparison between impact angle and crash severity for W-beam guardrails. Although at first glance, there appears to be a general trend for lower impact angles to produce higher crash severities, when A+K severities are considered, the apparent relationship disappears and impact angle appears to have little correlation with severity. Even in light of the very limited amount of data, this finding was quite surprising. The relationship between IS value and crash severity, shown in Table 37, was also quite surprising. After further investigation, it was discovered that the guardrail impact was not the most harmful event for most of the serious injuries associated with low angle and low IS crashes. Tables 38 and 39 present crash severity versus impact angle and IS value for crashes where the guardrail impact was the most severe event. These tables display the expected correlation between impact angle and IS versus crash severity.

Table 34. Rollover risk by vehicle size for departure velocities of 60–75 mph.

Vehicle Class	Rollover			
	Yes		No	
	No.	%	No.	%
Car	51	66.2%	26	33.8%
Pickup	35	79.6%	9	20.5%
Utility	35	89.7%	4	10.3%
Van	5	83.3%	1	16.7%

4.3 Departure Conditions

One of the primary objectives of developing the database described herein was to identify the departure conditions associated with serious ran-off-road crashes. The encroachment conditions described below are associated with a database that has an A+K rate of more than 70%. Clearly, this database is heavily biased and it can be considered to be representative of serious ran-off-road crashes.

4.3.1 Departure Speed and Angle Distributions

As shown in Table 40, the mean departure speed was found to be 49.26 mph. This value was higher than the mean value

Table 35. Crash severity vs. impact speed for W-beam guardrail.

		Maximum Injury									
		Fatalities		A-Injuries		B-Injuries		C-Injuries		PDO Crashes	
Impact Speed	Cases	No.	%	No.	%	No.	%	No.	%	No.	%
< 25 mph	1	0	0	0	0	0	0	0	0	1	100
25-40 mph	2	1	50	1	50	0	0	0	0	0	0
40-55 mph	12	0	0	8	67	2	17	0	0	2	17
55-70 mph	9	1	11	5	56	0	0	1	11	2	22
70-85 mph	5	3	60	1	20	1	20	0	0	0	0
≥ 85 mph	3	2	67	1	33	0	0	0	0	0	0
Unknown	4	0	0	3	75	0	0	0	0	1	25

Table 36. Severity by impact angle of crashes involving guardrails.

		Maximum Injury									
		Fatal		A-Injury		B-Injury		C-Injury		PDO	
Impact Angle	Cases	No.	%	No.	%	No.	%	No.	%	No.	%
0-6 deg	4	2	50%	2	50%	0	0%	0	0%	0	0%
6-12 deg	11	3	27%	5	45%	0	0%	0	0%	3	27%
12-18 deg	7	2	29%	2	29%	1	14%	1	14%	1	14%
18-24 deg	2	0	0%	2	100%	0	0%	0	0%	0	0%
≥ 24 deg	12	0	0%	8	67%	2	17%	0	0%	2	17%

Table 37. Severity by IS value of crashes involving guardrails.

		Maximum Injury									
		Fatal		A-Injury		B-Injury		C-Injury		PDO	
Impact Severity	Cases	No.	%	No.	%	No.	%	No.	%	No.	%
0-5 kJ	4	0	0%	4	100%	0	0%	0	0%	0	0%
5-13 kJ	4	2	50%	1	25%	0	0%	0	0%	1	25%
13-30 kJ	5	1	20%	2	40%	0	0%	0	0%	2	40%
30-90 kJ	10	4	40%	3	30%	1	10%	1	10%	1	10%
≥ 90 kJ	9	0	0%	6	67%	2	22%	0	0%	1	11%

Table 38. Crash severity by impact angle when guardrail impact was most harmful event.

		Maximum Injury			
		Fatalities		A-Injuries	
Impact Angle	Cases	No.	%	No.	%
0-6 deg	0	0	N/A	0	N/A
6-12 deg	0	0	N/A	0	N/A
12-18 deg	3	2	67	1	33
18-24 deg	3	0	0	3	100
≥ 24 deg	9	1	11	8	89

Table 39. Crash severity vs. IS when guardrail impact was most harmful event.

		Maximum Injury			
		Fatalities		"A" Injuries	
Impact Severity	Cases	No.	%	No.	%
0-5 kip-ft	0	0	N/A	0	N/A
5-13 kip-ft	0	0	N/A	0	N/A
13-30 kip-ft	1	0	0	1	100
30-90 kip-ft	7	3	43	4	57
≥ 90 kip-ft	4	0	0	4	100
Unknown	3	0	0	3	100

Table 40. Velocity and angle descriptive statistics.

Variable	Mean	Median	Standard Deviation	Minimum	Maximum	10th percentile	90th percentile
Velocity	49.3	49.2	15.91	5.00	97.2	28.5	69.3
Angle	16.9	15.0	10.49	0.00	84.0	5	30

Table 41. Velocity Comparison with Mak et al. (*3*).

	Velocity (mph)					
	Mean		70th Percentile		90th Percentile	
Highway Class	17-22	Pole Study	17-22	Pole Study	17-22	Pole Study
All	49.3	31.3	57.4	39.1	69.3	59.4
Freeway	56.3	43.9	63.2	51.2	75.5	65.9
Urban Arterial	44	25.3	52	30.4	62.6	44
Rural Arterial	49.1	37.4	56	45.5	65.8	64.1
Urban Loc/Col	44.2	20.8	49.2	25	61.4	37
Rural Loc/Col	44.6	29.1	51.1	35.6	62.4	48.2

found by Mak et al. (*3*) in the 1980s. Table 41 presents a comparison of velocity data from the current study and Mak et al.'s Pole Study. In order to compare the two studies, it was necessary to adjust the roadway classifications in this study to match the functional classes in Mak et al. All fully controlled access roadways were classified as freeways and US and state routes were classified as arterials. County roads and city streets were then placed into the collector/local category. Although this classification scheme is not perfect, it did place all roadways with high volume and most medium-volume roadways in the arterial category. Note the velocity distributions from this study are significantly higher than those found by Mak et al. (*3*). This finding is believed to arise from three factors: (1) the elimination of the national speed limit law; (2) the bias in the current study toward severe crashes; and (3) the Mak data is for impacts while the data from the current study is from departure conditions. Figure 5 graphically illustrates the differences between the velocity distributions on freeways in the two studies.

The mean departure angle shown in Table 42 is also higher than the corresponding angle from the Pole Study. A simple cornering analysis would indicate that higher departure speeds should produce lower departure angles. Thus, the increase in both departure speed and departure angle is unexpected. The most plausible explanation for this finding would be the wide implementation of antilock brakes. In the late 1970s, very few passenger cars had antilock brakes and by the late 1990s, the majority of the vehicle fleet was so equipped. In theory, antilock brakes are intended to allow drivers to continue to steer through emergency braking procedures. Unfortunately, research has not been able to identify any significant reduction in crash risk or crash severity associated with the use of antilock brakes. This finding may indicate that allowing drivers to continue to steer through emergency situations does not necessarily reduce the angle of departure from the roadway. Figure 6 shows a graphical comparison of freeway departure angles for the 17-22 database, encroachment data from Cooper (*33*) and Hutchinson and Kennedy (*7*), and impact angles from the Pole Study. Note that the angle distributions from the current study are very near those found by Cooper. Table 42 presents a comparison between departure angles from the 17-22 data and impact angles from the Pole Study for all roadway classes. Notice that with the exception of urban local/collector, all measures of departure angle for the current study were higher than impact angles from the Pole Study. However, the magnitude of the differences was found to be relatively modest.

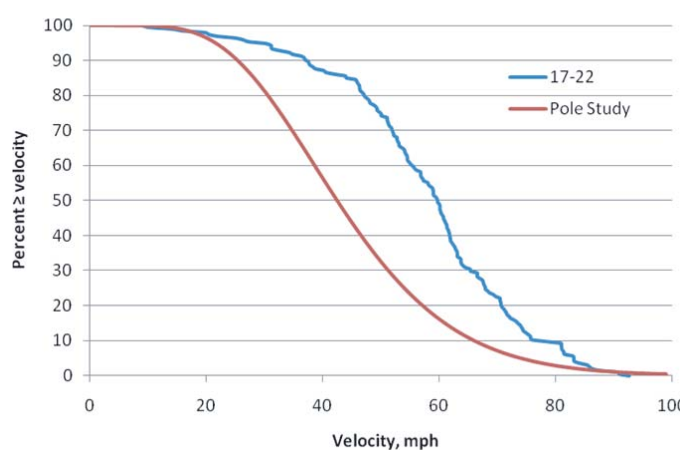


Figure 5. Freeway velocity distributions from Pole Study and 17-22.

Table 42. Angle comparison with Mak et al. (*3*).

	Departure Angle (deg)					
	Mean		70th Percentile		90th Percentile	
Highway Class	17-22	Pole Study	17-22	Pole Study	17-22	Pole Study
All	16.9	15.9	20	19.2	30	29.4
Freeway	16.8	15.5	20	18.7	29	28.4
Urban Arterial	16.6	15.5	17	18.9	29.3	29.5
Rural Arterial	16.3	15.0	20	18.4	30	30.3
Urban Loc/Col	15.4	16.5	18.0	19.8	28.4	28.7
Rural Loc/Col	16.6	15.4	19.5	18.8	29.5	30.4

4.3.2 Theoretical Modeling of Departure Speed and Angle Distributions

Tables 43 and 44 show descriptive statistics for departure velocity and angle respectively, segregated by road class. Note that with the exception of the Interstate classification, the mean velocities were quite similar. Further departure angle did not vary significantly from one road classification to the next. These findings lead to the conclusion that roadway classification may not be the best discriminator for departure conditions.

Tables 45 and 46 show descriptive statistics for departure velocity and angle respectively, segregated by speed limit. Note that the mean velocities now show more significant variation and the trend is correlated with speed limit. There is also more discrimination in the mean angle when the data are segregated by speed limit. Although prior studies showed that functional class was the best discriminator for departure speed, functional class was not identifiable in the current database. Findings from Tables 43 through 46 indicate that the surrogate measures used to indicate functional class may not be appropriate. However, speed limit does appear to provide a significant degree of discrimination for both departure speed and angle.

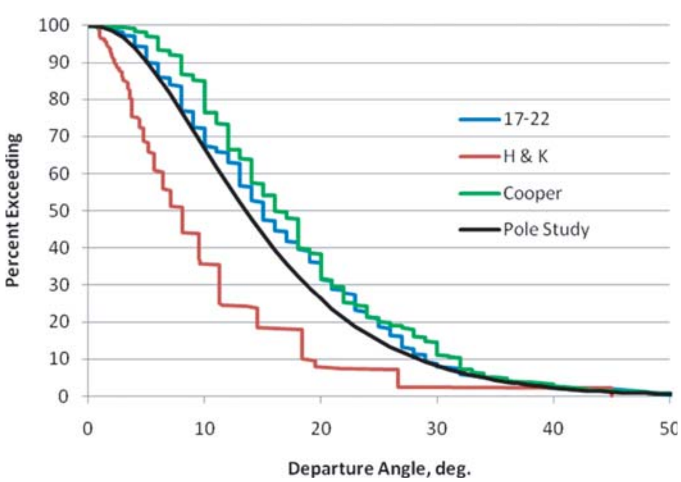


Figure 6. Comparison of freeway departure angle distributions.

Tables 43 through 46 also present skewness values for velocity and angle data. Note that mean skewness for velocity data is near zero while mean skewness for angle data is above 1.0. These skewness measures indicate that the velocity data may best be modeled with a normal distribution while angle data would be more likely to fit a gamma model.

Angle and velocity data from the Pole Study were found to fit a gamma distribution while other studies (*1*) found that the speed data fit a normal distribution. As a first step to modeling departure conditions, normal and gamma distributions were fit to departure speed and angle data for the total database and for each speed limit range as shown in Tables 47 and 48. Table 47 shows that the velocity distributions for the total database and all categories of speed limit were found to fit a normal distribution quite well. Although the gamma distribution was found to fit most speed limit categories acceptably well, p-values for both the total data set and the 50 mph speed limit category were below 0.05, indicating a poor fit to the data. Figure 7 shows the quality of fit for normal and gamma distribution to velocity data for the total database. Notice that the gamma distribution does not match the data very well.

Table 48 shows that neither normal nor gamma distributions provided an acceptable fit to departure angle data for all speed limit categories. Figure 8 shows the poor quality of fit for these distributions to the departure angle data from the total data set. In light of the poor quality of the normal and gamma distribution fits to the departure angle data, 53 other distributions were then fit to the departure angle data from all speed limit categories. Unfortunately, it was found that no single distribution adequately fit all speed limit categories. In fact, the gamma distribution was found to come as close to fitting all data categories as any of the distributions. In order to produce an acceptable fit to departure angle data, it was decided to utilize the square root of the departure angle as the independent variable. Using the square root of the departure angle shifts the distribution to the left and reduces the accuracy of predictions at the high end of the curve. However, adjusting the independent variable in this manner is an acceptable method for improving statistical fits to measured

Table 43. Departure velocity statistics by highway class.

Road Class	Speed Limit (mph)	No. of Cases	Min. Vel (mph)	Mean Vel. (mph)	Max. Vel (mph)	Standard Deviation	Skewness
All	45-75	870	5	49.3	97.2	15.913	-0.09537
Interstate	45-75	194	10	58.24	92.6	15.587	-0.44254
U.S. Highway	45-75	155	5	48.679	97.2	16.775	-0.09055
State Highway	45-65	159	10	49.494	89.9	15.39	0.08016
County Road	45-55	274	14.5	44.668	90.6	13.666	0.82561

Table 44. Departure angle statistics by highway class.

Road Class	Speed Limit (mph)	No. of Cases	Min. Ang. (deg)	Mean Ang. (deg)	Max. Ang. (deg)	Standard Deviation	Skewness
All	45-75	877	0	16.9	84	10.949	1.5728
Interstate	45-75	194	0	16.5	56	9.7802	1.0612
U.S. Highway	45-75	157	2	16.5	55	10.159	1.2036
State Highway	45-65	161	3	16.7	59	10.828	1.422
County Road	45-55	274	0	16.6	84	11.05	1.7913

Table 45. Departure velocity statistics by speed limit.

Speed Limit (mph)	No. of Cases	Min. Vel. (mph)	Mean Vel. (mph)	Max. Vel (mph)	Standard Deviation	Skewness
75	58	42	66.045	92.6	11.081	0.37389
70	112	7.5	54.951	90.8	16.206	-0.13195
65	75	10	53.939	88.5	16.539	-0.90328
55	357	13.8	47.331	97.2	14.894	0.24393
50	68	18.7	46.231	81.9	13.632	0.06293
45	194	5	43.999	91.1	14.741	0.5794

Table 46. Departure angle statistics by speed limit.

Speed Limit (mph)	No. of Cases	Min. Ang. (deg)	Mean Ang. (deg)	Max Ang. (deg)	Standard Deviation	Skewness
75	58	2	14.2	32	8.3183	0.43907
70	114	2	18	56	11.128	1.2138
65	75	3	14.9	49	9.0404	1.4983
55	361	0	17.3	76	11.389	1.4225
50	68	4	17.0	84	13.94	2.4057
45	195	0	17.2	76	10.011	1.5565

Table 47. Normal and gamma distribution fits to speed data.

Speed Limit (mph)	No. of Cases	Mean Vel. (mph)	Standard Deviation	Chi Squared – Normal			Gamma Dist.		Chi Squared – Gamma		
				DOF	Chi Stat.	P-Value	Alpha	Beta	DOF	Chi Stat.	P-Value
All	870	49.3	15.913	9	2.3071	0.9856	9.5964	5.137	9	23.917	0.0044
75	58	66.045	11.081	5	0.96147	0.9615	35.526	1.859	5	1.4802	0.9153
70	112	54.951	16.206	6	6.9659	0.3240	11.498	4.7792	6	7.7562	0.2565
65	75	53.939	16.539	5	7.7495	0.2570	10.637	5.071	5	7.7209	0.1723
55	357	47.331	14.894	8	6.8966	0.5478	10.099	4.6867	8	19.862	0.0109
50	68	46.231	13.632	6	4.7869	0.5714	11.501	4.0198	5	6.5352	0.2576
45	194	43.999	14.741	7	5.61	0.5860	8.908	4.9388	7	1.6949	0.9748

Table 48. Normal and gamma distribution fits to angle data.

Speed Limit (mph)	No. of Cases	Mean Angle (deg)	Standard Deviation	Chi Squared – Normal			Gamma Dist.		Chi Squared - Gamma		
				DOF	Chi Stat.	P-Value	Alpha	Beta	DOF	Chi Stat.	P-Value
All	877	16.936	10.949	9	133.04	0.0001	2.6183	6.483	9	17.895	0.0364
75	58	14.224	8.3183	7	12.754	0.0783	13.961	4.1716	7	12.962	0.0731
70	114	18	11.128	6	9.2486	0.1601	2.6166	6.8791	6	3.4874	0.7456
65	75	14.88	9.0404	5	5.4896	0.3591	2.7091	5.4925	6	8.1237	0.2292
55	361	17.263	11.389	8	47.362	$1x10^{-7}$	2.4615	7.0327	8	13.894	0.0846
50	68	17.044	13.94	4	19.612	$6x10^{-4}$	1.495	11.400	6	21.943	0.0012
45	195	17.195	10.011	7	13.412	0.0627	2.9502	5.8285	7	7.70539	0.4233

data. As shown in Table 49, the gamma distribution was found to fit the square root of the departure angle for all speed limit categories. The p-value of 0.0754 found for the gamma distribution fit to the total data set indicates that this fit is relatively marginal. Note however that the p-values for all individual speed limit categories were found to be 0.27 or higher, which indicates a reasonably good fit to the data. Figure 9 illustrates the use of a gamma distribution fit to the square root of the departure angle to model departure angle data.

Tables 47 and 49 provide parameters for fitting normal and gamma distributions to departure speed and square root of departure angle, respectively. The next step in modeling departure conditions involved exploring the dependence of speed and angle. A chi-square test for independence was employed for this evaluation. Table 50 shows a contingency table for all departure speed and angle combinations and Table 51 presents expected frequencies if speed and angle are independent. A chi-square goodness-of-fit test was then used to measure the appropriateness of the independence assumption using the following equation to calculate the chi-square statistic.

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

where:

χ = Chi-square measure of error between the two contingency tables
O_i = Observed frequency in cell i
E_i = Expected frequency in cell i
k = number of cells in table.

The chi-square statistic calculated from Tables 50 and 51 was found to be 30.54. The number of degrees of freedom for this test is one less than the number of rows times one less than the number of columns. In the example of the entire data base, the 6 x 6 contingency table shown in Table 48 has 25 degrees of freedom. The chi-square statistic of 30.54 and 25 degrees of freedom produce a p-value of 0.205. This magnitude of the p-value indicates that angle and speed data can be considered to be independent. The relationship between speed and angle of departure can be graphically illustrated by plotting the distribution of departure angle for three different

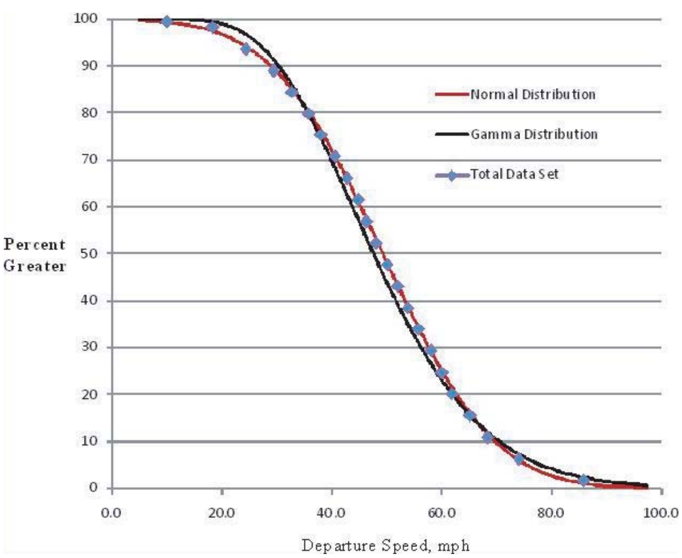


Figure 7. Normal and gamma distribution fits to departure speed.

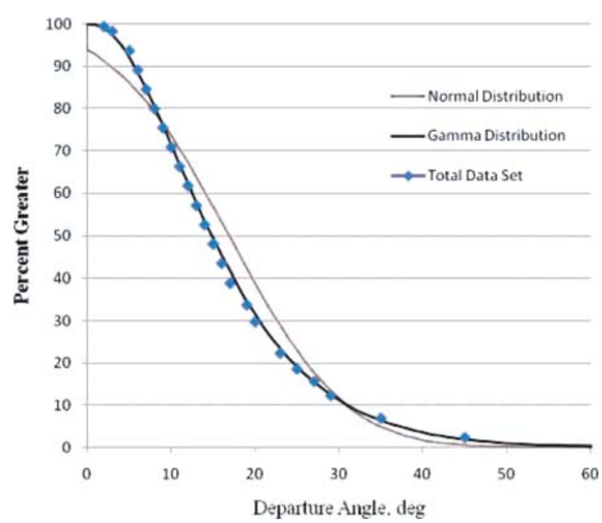


Figure 8. Normal and Gamma Distribution Fits to Departure Angle (all data).

Table 49. Gamma distribution fit to square root of departure angle.

Speed Limit (mph)	No. of Cases	Square Root Angle		Gamma Distribution		Chi Squared - Gamma		
		Mean	Std. Dev.	Alpha	Beta	DOF	Chi Stat.	P-Value
All	877	3.916	1.266	9.6039	0.40868	9	15.613	0.0754
75	58	3.5992	1.1366	10.028	0.35892	5	4.2553	0.51327
70	114	4.0482	1.2754	10.074	0.40183	6	6.066	0.41583
65	75	3.6995	1.0998	11.316	0.32693	6	6.5419	0.3653
55	361	3.9405	1.3184	8.9338	0.44108	8	9.837	0.27665
50	68	3.8812	1.4177	7.4944	0.51788	5	6.3047	0.2777
45	195	3.9755	1.1822	11.309	0.35132	7	6.3246	0.5024

speed ranges as shown in Figure 10. Note that the angle distribution for the low-speed range was found to be higher than the middle- or high-speed range, while differences in departure angle distribution for high- and middle-speed ranges were found not to be statistically significant. The fact that the differences between departure angle distributions for the middle- and high-speed ranges were not statistically significant further reinforces the finding that the correlation between speed and angle is sufficiently weak to treat them as independent.

In view of the finding of limited dependence between departure speed and angle for the total database, the chi-square test for independence was applied to the speed and angle of departure data for each speed limit category. The resulting p-values from these analyses were found to be much higher as shown in Table 52. With all of the p-values greater than 0.05, it is impossible to reject the assumption that the velocity and angle data are independent whenever cases are segregated by speed limit. Based upon the finding of, at most, a very limited degree of dependence between departure speed and angle, the normal distribution fit to velocity data and the gamma distribution fit to square root angle data can be applied independently to produce speed and angle probability distributions for each speed limit category as shown in Tables 53 through 59.

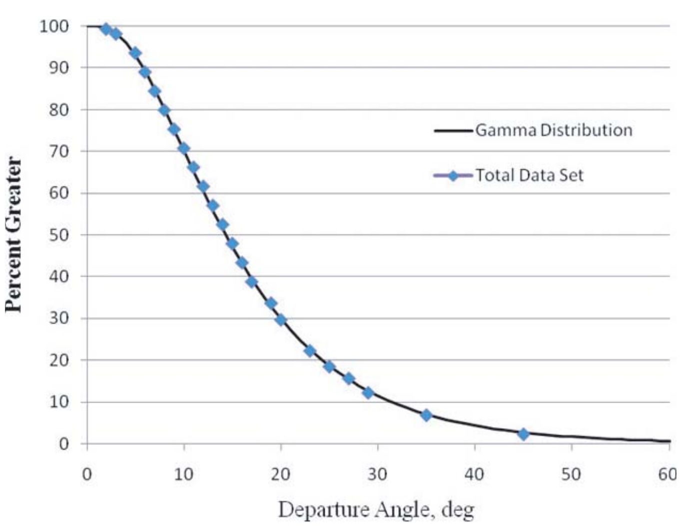


Figure 9. Square root of departure angle used to model departure angle (all data).

Chi-square tests were then conducted to compare predicted and observed frequencies for each speed limit category. As shown in Table 60, the predicted frequencies compared reasonably well with the observed values for most speed limit categories. These findings indicate that it is acceptable to model departure speed and angle as independent variables. Further, departure speed can be modeled using the normal distribution parameters shown in Table 47 and departure angle can be modeled using the gamma distribution fits to square root of departure angle presented in Table 49. These models produce the departure conditions shown in Tables 53 through 59.

Table 50. Observed departure conditions.

Departure Velocity (mph)	Departure Angle (deg.)					
	<6	6 - 12	12 - 18	18 - 24	24-30	>30
<25	4	15	16	10	7	13
25 - 35	9	24	29	15	12	16
35 - 45	15	40	43	31	30	20
45 - 55	25	65	62	31	21	19
55 - 65	13	45	46	32	15	18
>65	22	41	30	19	12	12

Table 51. Expected departure velocity and angle frequencies.

Departure Velocity (mph)	Departure Angles (deg.)					
	<6	6 - 12	12 - 18	18 – 24	24-30	>30
<25	6.52	17.05	16.75	10.23	7.19	7.26
25 - 35	10.54	27.54	27.06	16.52	11.61	11.73
35 - 45	17.96	46.94	46.13	28.17	19.80	20.00
45 - 55	22.38	58.48	57.47	35.09	24.66	24.92
55 - 65	16.96	44.32	43.55	26.59	18.69	18.88
>65	13.65	35.67	35.05	21.40	15.04	15.20

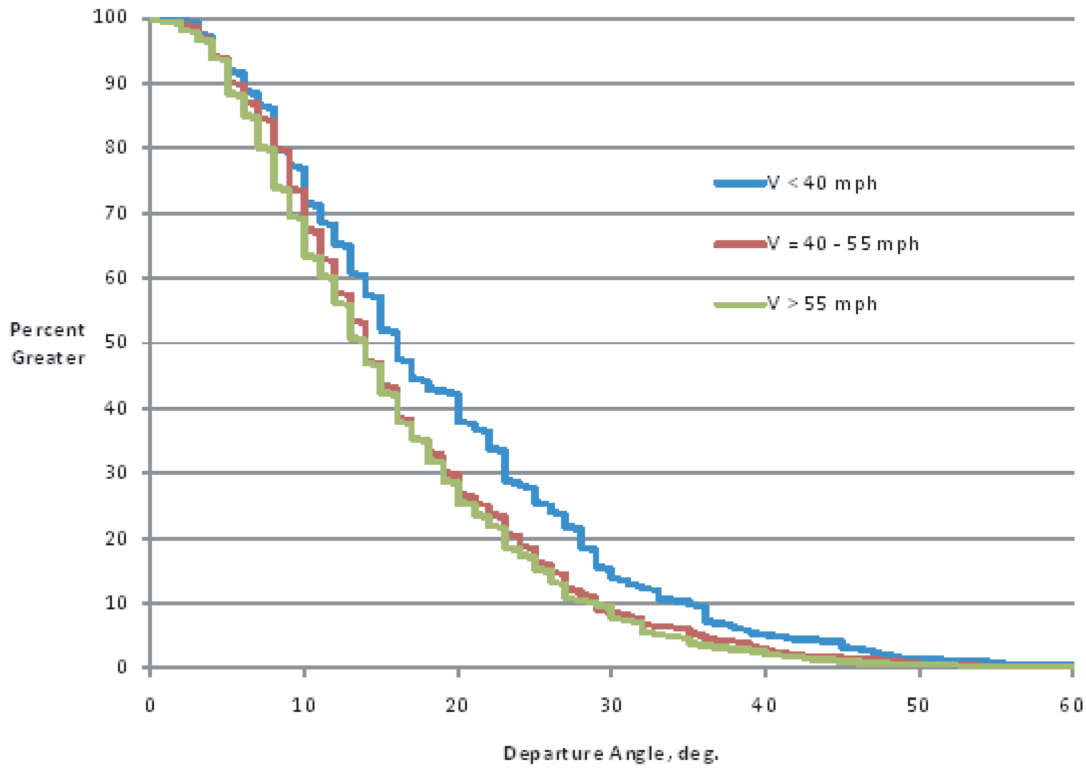


Figure 10. Departure angle distribution for three departure speed categories.

4.4 Impact Conditions

Whereas departure conditions described the vehicle velocity, angle, and orientation at the point the vehicle leaves the roadway, impact conditions describe the same characteristics at the point where an errant vehicle encounters a roadside hazard. Note that a number of the crashes included in the database involved vehicles rolling over without striking an identifiable hazard. Therefore, for the purpose of the analysis described below, impact was defined as the onset of the first harmful event. This definition assigns the impact point to either the point at which the vehicle began to roll over or the point at which it struck a fixed object, whichever occurred first. This definition was selected to produce impact conditions that were representative of the point at which a vehicle's occupants began to be exposed to significant risk of injury.

Table 52. Results of independence tests.

Speed Limit (mph)	No. of Cases	Deg. of Freedom	Chi-square Statistic	P-value
75	58	4	2.69	0.611
70	114	4	3.57	0.467
65	75	1	3.37	0.066
55	361	9	10.55	0.308
50	68	4	3.56	0.469
45	195	9	11.98	0.214

Most of the applications for encroachment speeds and angles described above are more appropriately addressed with impact conditions rather than departure conditions. For example, safety features need to be designed to accommodate impact conditions rather than roadway departure speeds and angles. Similarly, benefit/cost analyses utilize impacts speed and angle to estimate the probability of injury during a ran-off-road crash.

4.4.1 Impact Speed and Angle Distributions

Table 61 compares departure conditions to impact conditions for the first harmful event. Notice the significant change in velocity from roadway departure to the first impact. The mean departure velocity was reduced by approximately 20% or 10 mph from departure to impact. Although at first glance this difference appears to be excessive, the difference becomes more understandable with the application of a simple braking formula to explore the lateral distance required to slow vehicles down from the mean departure velocity to the mean impact speed. A vehicle departing the roadway at the mean speed of 49.3 mph subjected to an effective friction of 0.7 due to braking would need to travel 30 ft before it slowed by 10 mph. If this vehicle was encroaching at the mean departure angle of 16.9 degrees, it would travel only 8 ft laterally as it slowed from 49 mph to 39 mph. Since most of the roadways

Table 53. Departure condition distribution for all speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<20	0.00227	0.00516	0.00984	0.00564	0.00374	0.00236	0.00379
20 - 30	0.00552	0.01256	0.02394	0.01372	0.00910	0.00575	0.00921
30 - 40	0.01154	0.02627	0.05006	0.02869	0.01903	0.01202	0.01926
40 - 50	0.01647	0.03748	0.07142	0.04093	0.02715	0.01714	0.02748
50 - 60	0.01603	0.03649	0.06954	0.03985	0.02644	0.01669	0.02676
60 - 70	0.01065	0.02425	0.04620	0.02647	0.01756	0.01109	0.01778
>70	0.00668	0.01522	0.02900	0.01662	0.01102	0.00696	0.01116

Table 54. Departure condition distribution for 75 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<30	0.00006	0.00016	0.00014	0.00009	0.00005	0.00003	0.00004
30 - 40	0.00087	0.00251	0.00219	0.00141	0.00082	0.00045	0.00055
40 - 50	0.00638	0.01838	0.01604	0.01031	0.00597	0.00332	0.00405
50 - 60	0.02166	0.06242	0.05447	0.03502	0.02027	0.01127	0.01376
60 - 70	0.03432	0.09888	0.08629	0.05548	0.03211	0.01785	0.02180
70 - 80	0.02540	0.07318	0.06387	0.04106	0.02377	0.01321	0.01613
>70	0.01029	0.02964	0.02587	0.01663	0.00963	0.00535	0.00654

Table 55. Departure condition distribution for 70 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<30	0.00336	0.01268	0.01405	0.01103	0.00759	0.00492	0.00821
30 - 40	0.00631	0.02384	0.02643	0.02074	0.01427	0.00925	0.01545
40 - 50	0.01096	0.04139	0.04588	0.03600	0.02477	0.01606	0.02682
50 - 60	0.01315	0.04968	0.05507	0.04322	0.02973	0.01928	0.03219
60 - 70	0.01092	0.04124	0.04572	0.03587	0.02468	0.01600	0.02672
70 - 80	0.00627	0.02367	0.02624	0.02059	0.01416	0.00918	0.01534
>70	0.00332	0.01253	0.01389	0.01090	0.00750	0.00486	0.00812

Table 56. Departure condition distribution for 65 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<30	0.00533	0.01975	0.01927	0.01293	0.00756	0.00418	0.00486
30 - 40	0.00908	0.03362	0.03281	0.02201	0.01288	0.00711	0.00827
40 - 50	0.01488	0.05512	0.05379	0.03608	0.02111	0.01166	0.01356
50 - 60	0.01712	0.06338	0.06185	0.04149	0.02427	0.01341	0.01559
60 - 70	0.01381	0.05112	0.04989	0.03347	0.01958	0.01081	0.01258
70 - 80	0.00781	0.02892	0.02823	0.01893	0.01108	0.00612	0.00712
>70	0.00415	0.01538	0.01501	0.01007	0.00589	0.00325	0.00378

Table 57. Departure condition distribution for 55 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<20	0.00253	0.00749	0.00741	0.00553	0.00373	0.00241	0.00416
20 - 30	0.00678	0.02004	0.01984	0.01481	0.00998	0.00645	0.01114
30 - 40	0.01440	0.04255	0.04211	0.03143	0.02119	0.01368	0.02364
40 - 50	0.01980	0.05849	0.05789	0.04321	0.02913	0.01881	0.03250
50 - 60	0.01763	0.05209	0.05155	0.03849	0.02594	0.01675	0.02894
60 - 70	0.01017	0.03005	0.02974	0.02220	0.01497	0.00966	0.01670
>70	0.00488	0.01441	0.01426	0.01064	0.00718	0.00463	0.00801

Table 58. Departure condition distribution for 50 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<20	0.00284	0.00634	0.00566	0.00411	0.00279	0.00184	0.00357
20 - 30	0.00939	0.02093	0.01870	0.01359	0.00922	0.00609	0.01181
30 - 40	0.02165	0.04827	0.04312	0.03134	0.02125	0.01405	0.02723
40 - 50	0.02983	0.06651	0.05942	0.04319	0.02929	0.01935	0.03752
50 - 60	0.02457	0.05479	0.04895	0.03557	0.02413	0.01594	0.03091
60 - 70	0.01210	0.02697	0.02410	0.01751	0.01188	0.00785	0.01522
>70	0.00425	0.00947	0.00846	0.00615	0.00417	0.00276	0.00534

Table 59. Departure condition distribution for 45 mph speed limits.

Velocity (mph)	Departure Angle Range						
	0° - 5°	5° - 10°	10° - 15°	15° - 20°	20° - 25°	25° - 30°	>30°
<20	0.00250	0.01104	0.01263	0.00970	0.00638	0.00392	0.00559
20 - 30	0.00578	0.02546	0.02913	0.02237	0.01472	0.00904	0.01289
30 - 40	0.01074	0.04733	0.05415	0.04158	0.02737	0.01681	0.02397
40 - 50	0.01282	0.05650	0.06465	0.04963	0.03267	0.02006	0.02861
50 - 60	0.00983	0.04331	0.04956	0.03805	0.02505	0.01538	0.02194
60 - 70	0.00484	0.02132	0.02439	0.01873	0.01233	0.00757	0.01080
>70	0.00188	0.00829	0.00949	0.00728	0.00479	0.00294	0.00420

Table 60. Goodness-of-fit test results.

Speed Limit (mph)	No. of Cases	Deg. of Freedom	Chi-square Statistic	P-value
All	870	31	40.61	0.116
75	58	4	4.47	0.346
70	114	11	11.82	0.377
65	75	4	8.01	0.091
55	361	20	19.73	0.475
50	68	4	3.18	0.528
45	195	9	10.37	0.324

included in the study had at least a modest shoulder, an average lateral movement of 8 ft is certainly not excessive.

There was very little change in angle between roadway departure and the first impact as shown in Table 61. This finding is not surprising and may be an indication that drivers are more likely to be effective applying the brakes than steering the vehicle back to the roadway.

Table 62 shows descriptive statistics for impact speed for the total data set and segregated by highway class and speed limit. It is not surprising that Interstate highways were found to have the highest impact speeds and that impact speeds for state and US routes were quite similar. Perhaps the most surprising observation that can be gleaned from Table 62 is that highways with 60 to 65 mph speed limits had higher impact speeds than roadways with 70 to 75 mph speed limits.

T-tests were conducted to identify which highway classes and speed ranges could be classified as statistically unique. The purpose of this effort was to identify the most appropriate method for segregating impact speed data. As shown in Table 63, impact speeds from Interstate highways were found to be statistically different from all of the other classes, while US Routes were found not to be statistically different from state routes. Similarly, the T-test showed that county roads and city streets could not be considered to have unique impact speeds. When this approach was applied to impact speed data segregated by speed limit, it was found that most speed limit ranges were not statistically different from the adjacent range. Only the 50–55 and 60–65 speed limit ranges

Table 61. Descriptive statistics for impact conditions.

Variable		Mean	Median	Std. Deviation	Minimum	Maximum	90th Percentile
Speed (mph)	Departure	49.3	49.2	15.91	5	97.2	69.3
	Impact	39.13	38.8	16.45	4.2	93.6	59.04
Angle (degree)	Departure	16.9	15	10.49	0	84	30
	Impact	16.96	15	11.68	0	86	32

Table 62. Descriptive statistics for impact speed (mph).

Highway Class	N	Mean	Median	Std. Deviation	Minimum	Maximum	90th Percentile
Interstate	180	45.34	47.00	16.47	6.20	84.10	66.00
US Route	144	38.78	36.65	17.63	4.20	92.80	60.28
State Route	142	39.78	40.00	16.36	7.50	87.90	57.47
County Road	230	34.90	34.40	14.79	8.30	93.60	54.22
City Street	36	26.29	26.65	4.65	13.60	65.50	32.15
Speed Limit (mph)	**N**	**Mean**	**Median**	**Std. Deviation**	**Minimum**	**Maximum**	**90th Percentile**
35-45	163	35.12	34.30	14.71	9.70	73.10	55.66
50-55	375	37.29	36.30	15.97	4.20	93.60	56.88
60-65	72	46.12	48.00	16.69	12.60	87.90	66.08
70-75	161	43.95	45.00	16.76	6.20	84.10	65.00

were found to be statistically dissimilar. The T-test findings indicated that segregating impact speed data by highway class may be more appropriate than segregation by speed limit range.

Table 64 shows descriptive statistics for impact angle segregated by both highway class and speed limit. Notice that the variation in mean impact angle is relatively small for all categories of highway class and speed limit range. Further, note that all mean impact angles shown in the table are above the 15 degree value reported by Mak et al. Prior studies have reported a modest negative correlation between impact speed and impact angle, meaning higher impact speeds tend to be associated with somewhat smaller impact angles (*12*). Such a relationship is expected based on the reduction in vehicle cornering capability associated with an increase in speed. Note however that the Interstate classification, believed to have the highest operating speed of any highway class, was found to have the highest mean impact angle. Further, the second-highest speed limit range, 60–65 mph, had the highest mean impact angle of any speed limit range. However, when impact angle data sets from the various classes of highway and speed limit ranges were compared using T-tests as shown in Table 65,

Table 63. T-tests for impact speed.

	Sample 1	Sample 2	P-value	Statistically Different
By Highway Class	Interstate	US Route	0.0006	Yes
	Interstate	State Route	0.0028	Yes
	US Route	State Route	0.6196	No
	US Route	County Road	0.0224	Yes
	State Route	County Road	0.0032	Yes
	County Road	City Street	0.8384	No
	Sample 1	**Sample 2**	**P-value**	**Statistically Different**
By Speed Limit	35-45	50-55	0.1339	No
	50-55	60-65	< 0.0001	Yes
	60-65	70-75	0.3624	No

Table 64. Descriptive statistics for impact angle (degree).

Highway Class	N	Mean	Median	Std. Deviation	Minimum	Maximum	90th Percentile
Interstate	183	18.02	17	10.59	0	68	30.80
US Route	161	17.84	16	12.50	0	51	36.00
State Route	162	15.83	14	11.36	0	61	30.90
County Road	269	16.52	14	12.40	0	86	30.20
City Street	42	15.93	16	7.44	0	32	25.00
Speed Limit (mph)	**N**	**Mean**	**Median**	**Std. Deviation**	**Minimum**	**Maximum**	**90th Percentile**
All combined	858	17.44	15.0	12.28	0	86	32.0
35-45	194	17.81	15.5	13.00	0	86	31.0
50-55	422	16.91	14.0	12.45	0	84	34.0
60-65	73	18.66	19.0	11.04	0	45	32.0
70-75	166	17.66	17.0	11.34	0	68	30.5

Table 65. Two-sample T-tests for impact angle by highway class.

Sample 1	Sample 2	P-value	Statistically Different
Interstate	US Route	0.8869	No
Interstate	State Route	0.0643	No
US Route	State Route	0.013	No
US Route	County Road	0.2871	No
State Route	County Road	0.5601	No
County Road	City Street	0.7623	No

differences between the data sets were found to be statistically insignificant. Thus, this data would indicate that any correlation between impact angle and operating speed is likely to be weak.

Table 66 shows descriptive statistics for impact speed and impact angle segregated by access control. Impact speeds were found to be higher on highways with full and partial access control than on highways with no access control. Table 67 shows that T-tests verified this finding by indicating that impact speeds on highways with full or partial access control are significantly different from impact speeds on highways with no access control.

4.4.2 Impact Speed and Angle Models

As mentioned above, impact speed and angle have traditionally been believed to be correlated because of the reduction in cornering associated with higher speeds. The first step in modeling impact speed and angle data was devoted to exploring the existence of any association between these two variables. A chi-square independence test was utilized for this effort. As shown in Table 68, when the test was applied to the total data set, a strong dependence was identified between impact speed and angle (i.e., p-value = 0.0014). The Pearson correlation coefficient was found to be negative at –0.19, meaning that, as speed increased, the impact angle tended to decrease. In fact, the 95% confidence interval indicates that there is significant evidence that the correlation is negative. However the magnitude of this correlation is relatively low.

The total database incorporates crash records from widely varying highway classes, ranging from fully access-controlled rural Interstates to constricted county roads and city streets. The causes and nature of crashes associated with such widely varying highway types would be expected to be quite different. Therefore, the same chi-square test for independence was conducted on each highway classification and each of the four speed limit ranges examined in the previous section. These tests would eliminate some of the wide variations in highway geometrics, operating conditions, and crash causation associated with the total data set.

Table 66. Descriptive statistics for impact conditions segregated by access control.

	Access Control	N	Mean	Median	Std. Deviation	Minimum	Maximum	90th Percentile
Impact Speed (mph)	All combined	738	39.15	38.9	16.45	4.2	93.6	59.1
	Full	252	43.65	45.0	16.71	4.2	84.1	64.9
	Partial	54	40.41	42.0	17.65	7.0	87.9	60.7
	Uncontrolled	432	36.37	35.9	15.56	5.0	93.6	55.0
Impact Angle (degree)	All combined	821	16.96	15	11.67	0	86	32.0
	Full	262	18.95	17.00	12.22	0	86	33.9
	Partial	56	16.91	16	10.96	0	51	29.5
	Uncontrolled	503	15.93	14	11.33	0	84	29.8

Table 67. T-tests for impact speed and angle segregated by access control.

	Sample 1	Sample 2	P-value	Statistically different
Speed data	Full control	Partial control	0.201	No
	Full control	Uncontrolled	< 0.0001	Yes
	Partial control	Uncontrolled	0.0772	Yes
Angle data	**Sample 1**	**Sample 2**	**P-value**	**Statistically different**
	Full control	Partial control	0.2504	No
	Full control	Uncontrolled	0.0007	Yes
	Partial control	Uncontrolled	0.5365	No

Table 68. Test of independence results.

Impact Speed (mph) \ Impact Angle (degree)	<6	6–12	13–18	19–24	25–30	>30	Total
<25	0.0339 (24.1767) / 0.0224 (16)	0.0612 (43.6129) / 0.0463 (33)	0.0465 (33.1837) / 0.0533 (38)	0.0372 (26.5740) / 0.0393 (28)	0.0296 (21.0954) / 0.0407 (29)	0.0286 (20.3843) / 0.0351 (25)	0.2370 (169) / 0.2370 (169)
25–35	0.0259 (18.4544) / 0.0281 (20)	0.0467 (33.2903) / 0.0463 (33)	0.0355 (25.3296) / 0.0337 (24)	0.0284 (20.2637) / 0.0238 (17)	0.0226 (16.1024) / 0.0238 (17)	0.0218 (15.5596) / 0.0252 (18)	0.1809 (129) / 0.1809 (129)
35–45	0.0289 (20.6003) / 0.0196 (14)	0.0521 (37.1613) / 0.0477 (34)	0.0397 (28.2749) / 0.0407 (29)	0.0317 (22.6199) / 0.0393 (28)	0.0252 (17.9748) / 0.0281 (20)	0.0244 (17.3689) / 0.0266 (19)	0.2020 (144) / 0.2020 (144)
45–55	0.0315 (22.4600) / 0.0309 (22)	0.0568 (40.5161) / 0.0617 (44)	0.0432 (30.8275) / 0.0393 (28)	0.0346 (24.6620) / 0.0393 (28)	0.0275 (19.5975) / 0.0252 (18)	0.0266 (18.9369) / 0.0238 (17)	0.2202 (157) / 0.2202 (157)
55–65	0.0140 (10.0140) / 0.0295 (21)	0.0253 (18.0645) / 0.0281 (20)	0.0193 (13.7447) / 0.0224 (16)	0.0154 (10.9958) / 0.0070 (5)	0.0123 (8.7377) / 0.0042 (3)	0.0118 (8.4432) / 0.0070 (5)	0.0982 (70) / 0.0982 (70)
>65	0.0088 (6.2945) / 0.0126 (9)	0.0159 (11.3548) / 0.0281 (20)	0.0121 (8.6396) / 0.0070 (5)	0.0097 (6.9116) / 0.0084 (6)	0.0077 (5.4923) / 0.0028 (2)	0.0074 (5.3072) / 0.0028 (2)	0.0617 (44) / 0.0617 (44)
Total	0.1431 (102) / 0.1431 (102)	0.2581 (184) / 0.2581 (184)	0.1964 (140) / 0.1964 (140)	0.1571 (112) / 0.1571 (112)	0.1248 (89) / 0.1248 (89)	0.1206 (86) / 0.1206 (86)	1.0000 (713) / 1.0000 (713)

Legend: Expected Percentage (Expected Freq.) / Observed Percentage (Observed Freq.)

Chi Square = 51.4564
Degree of Freedom = 25
pval = 0.0014
Correlation = −0.1948
95% CI for Correlation = (−0.1209; −0.2598)

When the crash data was segregated by highway class and the chi-square independence testing was repeated, the findings were quite different. Table 69 presents results from this chi-square testing. County road was the only highway class where any significant degree of dependence was detected. Table 69 also shows that all of the highway classes were found to have weak negative correlations between impact speed and impact angle.

With the chi-square testing showing that impact speed and angle can be considered independent for most highway classes, it was decided to develop independent models for the impact speed and impact angle data. If impact speed and angle are truly independent for the segregated data, it should then be possible to combine the independent speed and angle distributions to create a joint probability distribution to fit the raw data.

Several different distributions were fit to both the impact angle and speed data. Although several distributions were found to fit one or more of the data sets, the normal distribution was found to fit the largest number of data sets. The normal distribution provided adequate fits to most of the impact speed data sets and many of the impact angle classifications. Unfortunately, when these fits were used to model speed and angle data from the various highway classifications, the approach failed most of the goodness-of-fit tests. The angle data was then adjusted using a square-root transformation, and new fits were developed. This approach provided acceptable goodness-of-fit tests for all highway classes except Interstate. However, the Interstate highway classification had shown an acceptable goodness-of-fit test using normal distribution fits and untransformed angle data. Figures 11 and 12 present normal distribution fits to impact speed and square-root impact angle data, respectively, to illustrate how close these estimated distributions are to the raw data.

Since it was found that normal distributions provided quality fits for both impact speed and impact angle data, calculations of the joint probabilities for these two variables would

Table 69. Test of independence results for data segregated by highway class.

Highway Class	Chi-square	Degrees-of-freedom	P-value	Correlation
Interstate	25.8015	25	0.4183	-0.1582
US Route	21.744	20	0.3528	-0.2300
State Route	28.2857	20	0.1028	-0.2095
County Road	26.4712	15	0.0334	-0.2752
City Street	5.4704	6	0.4850	-0.0903

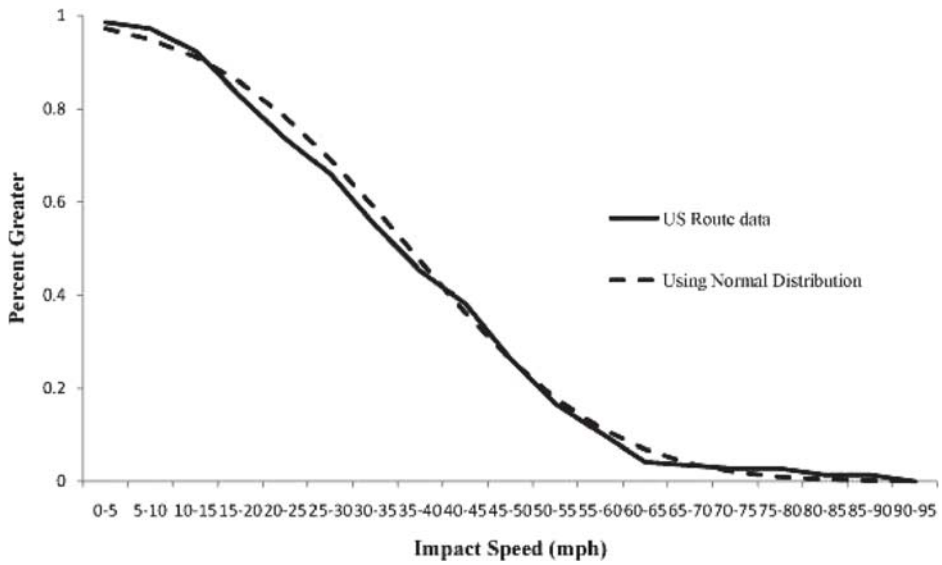


Figure 11. ***Normal distribution fit to impact speed.***

be mathematically possible by adopting the bivariate normal distribution. The probability of an impact falling into any cell can be calculated by solving the double integral of f(x,y) as shown below.

$$f(x,y)=\frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}\exp\left\{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{x-\mu_x}{\sigma_x}\right)^2+\left(\frac{y-\mu_y}{\sigma_y}\right)^2 - 2\rho\left(\frac{x-\mu_x}{\sigma_x}\right)\left(\frac{y-\mu_y}{\sigma_y}\right)\right]\right\}\int_y\int_x f(x,y)\,dxdy$$

where:

μ_x = impact speed mean
μ_y = impact angle mean
σ_x = impact speed standard deviation
σ_y = impact angle standard deviation
ρ = Pearson's correlation coefficient

Two basic assumptions are necessary in order to apply the bivariate normal distribution to model impact and speed data: (1) both impact speed and impact angle distributions

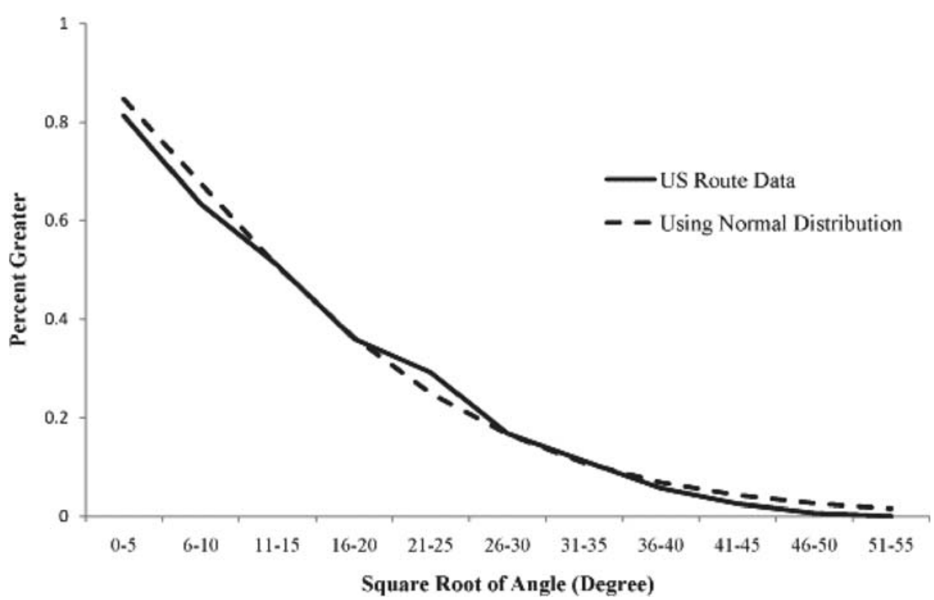


Figure 12. ***Normal distribution fit to impact angle.***

Table 70. Goodness-of-fit results for speed data.

Highway Class	Data Transformation	Distribution	P-value	Coefficients	
Interstate	Untransformed data	Normal	0.2396	mean = 45.105	Std. dev. = 16.731
US Route	Untransformed data	Normal	0.1470	mean = 38.592	Std. dev. = 17.694
State Route	Untransformed data	Normal	0.4398	mean = 39.601	Std. dev. = 16.055
County Road	Untransformed data	Normal	0.5233	mean = 35.017	Std. dev. = 14.782
City Street	Untransformed data	Normal	0.8558	mean = 35.541	Std. dev. = 13.336

Table 71. Goodness-of-fit results for angle data.

Highway Class	Data Transformation	Distribution	P-value	Coefficients	
Interstate	Untransformed data	Normal	0.9857	mean = 18.287	Std. dev. = 10.681
	Transformed data	Normal	0.4191	mean = 4.0628	Std. dev. = 1.3399
US Route	Transformed data	Normal	0.7474	mean = 3.9115	Std. dev. = 1.614
State Route	Transformed data	Normal	0.9999	mean = 3.7777	Std. dev. = 1.4812
County Road	Transformed data	Normal	0.6831	mean = 3.8163	Std. dev. = 1.4558
City Street	Transformed data	Normal	0.9418	mean = 3.9511	Std. dev. = 0.908

are normal, and (2) impact speed and impact angle can be considered as linear combinations of two independent variables. The second assumption can be considered to be satisfied if speed and angle data pass a test for independence as illustrated previously. Tables 70 and 71 show the goodness-of-fit results of the impact speed and angle data. The untransformed data was used for the impact speed. The transformed data was used for the impact angle, except for Interstate data. It was found that, for Interstate, the normal distribution fitted the untransformed impact angle data better than the transformed data. A bivariate normal distribution was then fitted to the speed and angle data for each of the five highway classes using mean and standard deviation values shown in Tables 70 and 71 and correlation coefficients shown in Table 69.

Table 72 summarizes results of goodness-of-fit tests of the bivariate normal distribution fits to the speed and angle data. This table shows that all of the models provided acceptable fits to the raw data. County road was the only highway class that had a goodness-of-fit measure that could be classified as marginal with $p = 0.0747$ compared to the generally accepted limit of $p = 0.05$. This finding is not surprising since impact speed and angle were found to be dependent for this roadway class and independence is one of the assumptions required for application of the bivariate normal distribution. Tables 73 through 77 show estimated impact speed and impact angle distributions for each highway class included in the study. Note that the probability distribution tables generated by the bivariate normal distribution did not initially sum to 1.0. This finding arose because tails of some of the fits to the angle and speed distributions extended below zero. This problem was eliminated with normalization of Tables 73 through 77 by dividing the contents of each cell by the sum of all cells.

When the data was segregated by speed limit range instead of highway classification, two of the four ranges were found to have significant dependency between impact speed and angle. Speed limit ranges of 60–65 and 70–75 mph were found to have p values of 0.0315 and 0.0153, respectively. When the analysis was carried further, it was found that normal distributions fit all of the speed data and all of the angle data after a square-root transformation was applied. Further, neither the normal distributions nor any other distributions

Table 72. Goodness-of-fit results for the bivariate normal distributions.

Highway Class	Chi-square	df	P-value
Interstate	34.1654	31	0.318
US Route	28.4489	25	0.2876
State Route	26.9054	25	0.3606
County Road	28.4740	19	0.0747
City Street	7.8278	7	0.3480

Table 73. Joint speed and angle distribution for Interstate freeways.

Speed (mph)	Angle (degree)						Total
	< 6	6 - 12	12 - 18	18 - 24	24 - 30	> 30	
< 25	0.006	0.014	0.022	0.026	0.022	0.023	0.114
25 - 35	0.011	0.022	0.034	0.037	0.030	0.028	0.161
35 - 45	0.018	0.035	0.050	0.052	0.039	0.034	0.227
45 - 55	0.020	0.038	0.051	0.051	0.037	0.029	0.226
55 - 65	0.016	0.029	0.037	0.035	0.024	0.018	0.159
> 65	0.014	0.023	0.027	0.024	0.015	0.010	0.114
Total	0.085	0.160	0.221	0.224	0.167	0.142	1.000

Table 74. Joint speed and angle distribution for US routes.

Speed (mph)	Angle (degree)						Total
	< 6	6 - 12	12 - 18	18 - 24	24 - 30	> 30	
< 25	0.025	0.037	0.039	0.034	0.026	0.049	0.211
25 - 35	0.030	0.040	0.039	0.032	0.023	0.038	0.202
35 - 45	0.040	0.048	0.044	0.034	0.024	0.036	0.225
45 - 55	0.038	0.042	0.036	0.026	0.018	0.025	0.184
> 55	0.045	0.043	0.034	0.023	0.014	0.018	0.178
Total	0.178	0.211	0.192	0.149	0.105	0.165	1.000

Table 75. Joint speed and angle distribution for state routes.

Speed (mph)	Angle (degree)						Total
	< 6	6 - 12	12 - 18	18 - 24	24 - 30	> 30	
< 25	0.019	0.033	0.036	0.031	0.023	0.035	0.177
25 - 35	0.030	0.045	0.044	0.034	0.023	0.031	0.208
35 - 45	0.044	0.058	0.052	0.038	0.024	0.029	0.246
45 - 55	0.043	0.051	0.042	0.029	0.017	0.019	0.201
> 55	0.046	0.046	0.033	0.021	0.012	0.011	0.169
Total	0.181	0.233	0.208	0.153	0.099	0.125	1.000

Table 76. Joint speed and angle distribution for county roads.

Speed (mph)	Angle (degree)						Total
	< 6	6 - 12	12 - 18	18 - 24	24 - 30	> 30	
< 25	0.023	0.044	0.050	0.044	0.032	0.049	0.243
25 - 35	0.036	0.057	0.055	0.043	0.028	0.035	0.253
35 - 45	0.047	0.063	0.055	0.039	0.024	0.026	0.253
> 45	0.066	0.069	0.051	0.032	0.017	0.016	0.251
Total	0.171	0.233	0.212	0.157	0.101	0.126	1.000

Table 77. Joint speed and angle distribution for city streets.

Speed (mph)	Angle (degree)			Total
	< 12	12 - 18	> 18	
< 25	0.059	0.069	0.082	0.211
25 - 35	0.078	0.089	0.102	0.270
35 - 45	0.083	0.092	0.103	0.279
> 45	0.074	0.079	0.086	0.240
Total	0.295	0.330	0.374	1.000

Table 78. Descriptive statistics for impact severity.

Road Class	N	Mean	Median	Std. Dev.	Minimum	Maximum	90th Percentile	95th Percentile
All classes combined	868	38.91	18.46	57.34	0.00	584.50	98.54	143.31
Interstate	194	51.06	32.13	66.70	0.70	584.50	123.15	159.89
US Route	157	32.63	14.52	43.60	0.20	234.45	80.41	121.74
State Route	159	43.66	19.92	61.53	0.90	392.15	113.65	180.34
County Road	273	28.68	14.78	42.52	0.00	343.14	69.45	100.90
City Street	42	23.15	15.83	24.70	0.40	127.47	48.95	62.04

could be identified that pass goodness-of-fit testing for combined angle and speed distributions. This analysis clearly demonstrated that, for impact conditions, roadway classification provided a better discriminator for impact speed and angle than did speed limit range. Mak et al. obtained similar results when he studied data collected under the national speed limit law. Recall that departure data was found to be more sensitive to speed limit range than highway class. These findings may be a reflection on the effects of clear zones on a driver's ability to slow down before striking a hazard.

4.4.3 Impact Severity

Impact severity has been found to be strongly correlated with the magnitude of loading during longitudinal barrier impacts. IS is defined as shown below:

$$IS = \frac{1}{2} m (v \sin\theta)^2$$

where:

IS = Impact severity
m = Vehicle mass
v = Impact velocity
θ = Impact angle

Table 78 presents descriptive statistics for impact severity from the first harmful event. IS has been accepted as the primary measure of the magnitude of a barrier crash and it is used in MASH to set limits for minimum crash conditions. The target IS value found in MASH for Test Level 3 is 156 kJ. As shown in Table 78, the 95th percentile IS value from Interstate highways was found to be 160 kJ, very near the target value for Test Level 3. Thus, the IS values recommended by MASH for longitudinal barrier testing appear to be appropriate.

4.4.4 Vehicle Orientation at Impact

Vehicle orientation at impact has been linked to crash severity (*15*). Further, this parameter is also used to estimate crash costs in benefit/cost models RSAP (*21*). Basic descriptive statistics for vehicle orientation are shown in Table 79. Figure 13 presents a plot of vehicle orientation distribution from the ran-off-road crash database. Note that less than 40% of crashes were found to have heading angles between –20 and +20 degrees.

4.5 Encroachment Length

The distance that a vehicle travels along the roadside is an important input to the design of guardrail installations. For the last 30 years or more, guardrail designs were based upon findings from a study of roadside encroachments by Hutchinson and Kennedy (H&K) (*7*). More recently, data from an encroachment study by Cooper (*33*) have shown longitudinal travel distances to be much shorter than those measured by H&K. This discrepancy has been attributed to two fundamental differences between the two studies (*34, 35*). The Cooper study involved highways with speed limits of 59–62 mph (95–100 km/h), while the H&K study involved speed limits of 70 mph. The other explanation for differences in longi-

Table 79. Descriptive statistics for vehicle orientation.

Road Class	N	Mean	Median	Std. Dev.	Minimum	Maximum	90th Percentile
All Classes	842	3.3	4	69.52	-168	180	102
Interstate	188	7.29	9	80.42	-159	171	129
US Route	163	-4.12	0	70.73	-165	180	96.8
State Route	165	4.44	1	67.6	-168	180	105
County Road	275	3.96	4	64.72	-164	180	90
City Street	44	13.2	11.5	47.44	-149	115	75

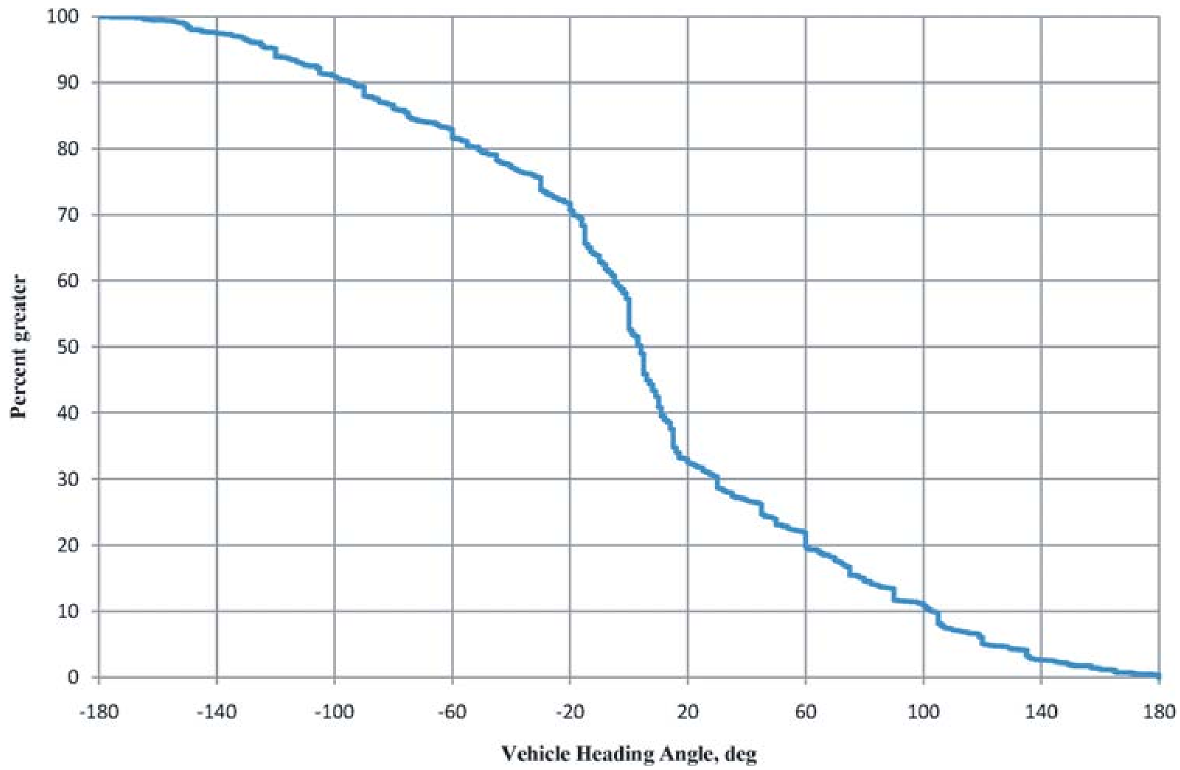


Figure 13. Vehicle orientation angle distribution.

tudinal travel distances is the overrepresentation of low-angle encroachments in the H&K data. Recall that as shown in Figure 6, the angle of departure data from the current study was found to be quite similar to that from Cooper and the Pole Study, while departure angles from H&K were found to be much lower. When H&K data are adjusted to eliminate the bias toward low-angle encroachments, the differences between the Cooper and H&K longitudinal travel distances were reduced to a level that could easily be explained by differences in speed limit.

The database described herein should provide some clarification of which of the two encroachment studies is most appropriate for use in determining guardrail length. Note that the 17-22 database has been constructed from reported accidents, many of which involved impacts with roadside objects. It is reasonable to conclude that many of these vehicles would have traveled farther if the obstacle had not been impacted. However, as described above, the crashes included in this study are strongly biased toward serious injury and fatal crashes. In effect, the data included herein was taken from the very types of roadside crashes guardrail is intended to prevent. Thus, designing guardrail configurations to withstand these crashes is more appropriate than relying on roadside encroachment data that includes very few reported crashes and undoubtedly includes many controlled encroachments that would never produce a crash.

4.5.1 Raw Data

The first step in the process of evaluating longitudinal travel distances from the current study was to compare encroachment length data from Cooper and H&K to longitudinal travel distances from the current study as shown in Figure 14. For this figure, the data from the current study was limited to access-controlled freeways with speed limits of 70–75 mph. The Cooper data were restricted to divided highways with

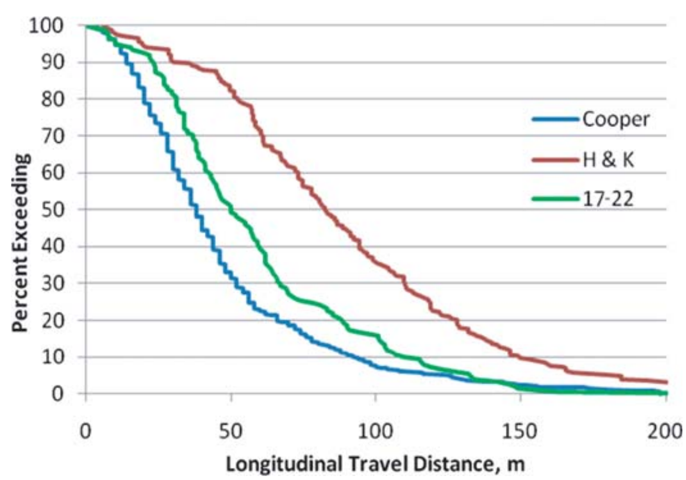


Figure 14. Encroachment lengths for different studies.

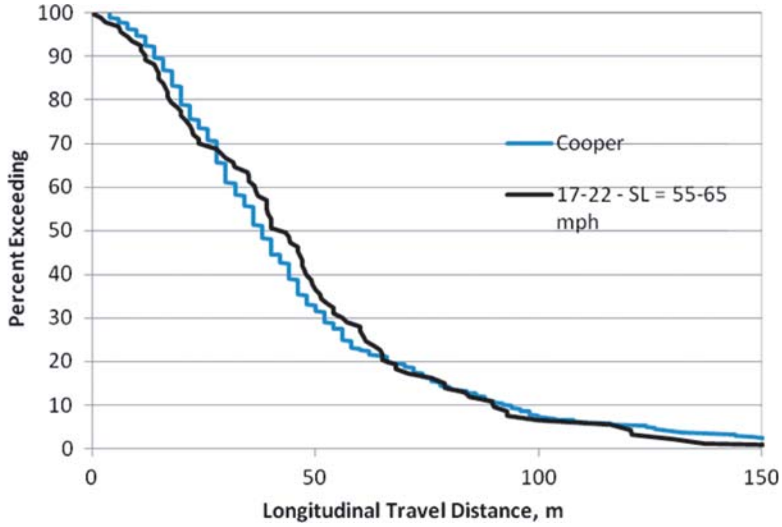


Figure 15. Cooper and 17-22 (55-65 mph) encroachment data comparison.

59–62 mph (95–100 km/h) speed limits and the H&K data were collected on rural Interstate highways with a 70 mph speed limit. Notice that the 17-22 travel distances are close to those from Cooper and that the differences can be explained by the higher speed limits associated with the current study. Figure 15 illustrates the effects of speed limit by comparing data from the current study collected on access-controlled highways with 55–65 mph speed limits to the Cooper data taken from divided highways with 59–62 mph (95–100 km/h) speed limits. These two distributions are not only visually similar; a two tailed T-test analysis indicated that the differences are not statistically significant with a p-value of 0.966. The excellent comparison between Cooper's data and the 17-22 data supports the hypothesis that the long encroachments observed in the H&K study are associated with the overrepresentation of low-angle encroachments in the study.

Procedures contained in the 2006 AASHTO Roadside Design Guide identify the required length of a guardrail in terms of a runout length parameter, which is based upon the distribution of encroachment lengths from the H&K study. As shown in Table 80, the runout length associated with high-volume, high-speed roadways was based upon the 85th percentile encroachment length while lower volume roadways were assigned runout lengths based upon a lower percentile encroachment length. Note that 92% of the encroachments collected by H&K were from highways with a 70 mph design speed and traffic volumes less than 6000 vehicles per day. Hence the traffic volume categories shown in Table 80 were based upon the source of the H&K data. The data from Table 80 was then extrapolated to lower design speeds. A more recent study of guardrail length-of-need utilized this same approach to apply Cooper's data to this problem (*36*). Table 81 presents comparable results from the Cooper data. Thus, encroachment length distributions, presented in tabular form as shown in Tables 80 and 81 have been used to develop the recommended values for the guardrail runout length parameter. The 17-22 longitudinal encroachment lengths will therefore be presented in this same format.

Table 80. RDG runout lengths for 70 mph design speed.

Traffic Volume (ADT)	>6000	2000-6000	800-2000	<800
Design Runout Length, m	146.3	134.1	121.9	109.7
Enc. Length Percentile	85%	80%	75%	70%

Table 81. Encroachment length distributions.

Source	Average Speed Limit	Encroachment Length Percentile				
		90%	85%	80%	75%	70%
Cooper	60.5 mph	96.3	78.6	69.2	57.3	52.4
	50.3 mph	54.9	46.9	42.4	38.4	34.7

Table 82. Departure length segregated by speed limit.

Speed Limit	No. of Cases	Departure Length Percentile					
		90%	85%	80%	75%	70%	50%
70-75	169	109.9	101.0	85.4	73.8	66.3	49.5
55-65	424	77.0	65.4	57.0	50.0	46.5	33.8
55	353	74.4	62.0	52.0	47.0	44.7	32
45-50	253	63.1	50.0	43.2	38.8	34.8	24
45	186	60.8	47.1	41.8	37.0	33.0	24

Table 83. Departure length segregated by traffic volume.

Volume Class	No. of Cases	Departure Length Percentile					
		90%	85%	80%	75%	70%	50%
High	189	92.1	80.9	70.2	61.2	57	38
Medium	207	95.3	84	71.2	64.6	61.8	42.6
Low	388	65.2	53	47	43.6	40	26.6

Longitudinal departure length data from the 17-22 data set were first examined when categorized by speed limit, access control, and traffic volume. Table 82 presents departure length data segregated by speed limit. Note that there were too few cases with 65 and 50 mph to reliably establish the tail of the distributions. These cases were lumped with the next lower speed limit categories to illustrate the general trend between speed limit and departure length. Table 82 shows that there is a relatively strong trend for departure length to increase with higher speed limits.

The effects of traffic volume and access control on departure lengths were then explored as shown in Tables 83 and 84, respectively. Notice that there is no clear trend between traffic volume category and departure length and there appears to be a strong relationship between access control and departure length. However, there is also correlation between speed limit and access control. In order to isolate the importance of access control on departure length, it is necessary to isolate the evaluation to a constant speed limit. This type of evaluation could not be conducted on the tail of the departure length distribution as shown in Tables 82 through 84 because of the small sample sizes at any one speed limit. Therefore, the effect of access control was evaluated at the median for a 55 mph speed limit. The median departure lengths for a 55 mph roadway were found to be 45.2 m and 32.0 m for full and no access control, respectively. The nearly 50% increase in median departure length demonstrates that full access control has a significant effect beyond its correlation with speed limit.

In light of the finding that traffic volume had no consistent effect on departure length, this parameter was eliminated from further consideration. Departure length data was then segregated by access control and speed limit as shown in Table 85. Note that for the 55–65 mph category, there were

Table 84. Departure length segregated by access control.

Access Control	No. of Cases	Departure Length Percentile					
		90%	85%	80%	75%	70%	50%
Full	263	102.7	89.3	76.5	68	62.8	45.4
None	493	66.7	54	47	43.5	40	28

Table 85. Departure length segregated by speed limit and access control.

Speed Limit	Access Control	No. of Cases	Departure Length Percentile					
			90%	85%	80%	75%	70%	50%
70-75	Full	151	109.1	101.1	88	75.1	66.7	50
55-65	Full	98	89.6	76.9	65	60.5	54	40
55-65	None	284	68.7	57.8	49.2	46	43	32
45-50	None	205	61	49	42.9	37	33	24.8

Table 86. Departure lengths excluding barrier impacts.

Speed Limit	Access Control	No. of Cases	Departure Length Percentile					
			90%	85%	80%	75%	70%	50%
70-75	Full	137	111	101.6	88.7	77.2	67	52.5
55-65	None	263	67.9	55.6	49	46	43	31.8
45-50	None	201	61.8	48.4	41.8	36.8	32.6	24.7

sufficient data to provide departure lengths for both full and no access control.

4.5.2 Screened Data

The data shown in Table 85 provides measures of the length of vehicle departures for several speed limit and access control categories. Although this table represents the actual travel distances associated with serious injury and fatal crashes, the data may be distorted by the placement of longitudinal barriers. Barriers placed adjacent to the travelway are designed to redirect vehicles away from roadside obstacles and toward the travelway. Thus, longitudinal barriers are likely to reduce the length of travel along the roadside and the departure length data shown in Table 85 may be artificially shortened. The effects of longitudinal barriers on the length of roadside travel were investigated by removing all crashes involving barrier impacts. The data shown in Table 85 was then adjusted by excluding all crashes involving barrier impacts and is presented in Table 86. Note that the number of cases in the 55–65 mph, full access-control category was reduced to the point that the tail of the distribution could not be reliably determined. Further, eliminating barrier impacts increased longitudinal travel distance values for access control freeway by an average of 2% and decreased lengths for roadways without access control by approximately 1%. The minor differences between Tables 85 and 86 appear to indicate that longitudinal barriers do not produce a significant reduction in the distances that vehicles travel along the roadway during ran-off-road events. This finding may indicate that, for most impacts, longitudinal barriers do not redirect cars back onto the roadway, but rather allow impacting vehicles to rub along the face of the barrier.

There was also a concern that rigid objects may have an effect on longitudinal travel distances. This concern is based on the assumption that, for most crashes involving a rigid obstacle, impacting vehicles are brought to a premature stop. In this situation, the length the vehicle travels along the roadside would be artificially reduced. This effect was again explored by removing crashes involving rigid obstacles from the data set and re-tabulating the data as shown in Table 87. Again, the effects of removing rigid obstacle crashes from the database were extremely minor. The average change in departure length between Tables 86 and 87 was found to be less than 0.5%. Based upon the minor differences in Tables 85, 86, and 87, it can be concluded that the upper tails of the roadside departure length distributions from the 17-22 database are not significantly affected by the presence of roadside barriers or rigid obstacles. Thus it is recommended that Table 85 be used in the evaluation of guardrail runout length calculation procedures.

4.6 Significance for Guardrail Runout Length

As mentioned previously, guardrail length-of-need is determined based upon the design runout length. This length is used to identify locations along the roadway in advance of a roadside object where barriers must begin to be effective. Table 88 shows the recommended runout lengths contained in the 2006 AASHTO Roadside Design Guide. As mentioned above these values are based on the H&K encroachment data (*7*). Table 89 presents runout length recommendations from a 1996 study that applied Cooper's data (*33*) to the design of guardrail layouts. Note that the runout length recommendations were based upon the upper tail of encroach-

Table 87. Departure lengths excluding barrier and rigid obstacle impacts.

Speed Limit	Access Control	No. of Cases	Departure Length Percentile					
			90%	85%	80%	75%	70%	50%
70-75	Full	136	111.5	101.7	88.9	78.2	67.4	53
55-65	None	262	67.9	55.7	49	46	43	31.6
45-50	None	196	62.3	48	41.7	36	32.2	24.6

Table 88. Runout length recommendations from the RDG.

	Traffic Volume ADT			
	6000	2000-6000	800-2000	<800
Design Speed (mph)	Runout Length (m)	Runout Length (m)	Runout Length (m)	Runout Length (m)
70	146	134	122	110
60	122	112	101	91
50	98	89	81	73
40	73	67	61	55
30	49	45	41	37

ment length distributions from H&K and Cooper. For Table 88, the top row of runout lengths were obtained from the 85th, 80th, 75th, and 70th percentile runout lengths from the H&K study. Because the Cooper study contained no highways with 70 mph speed limits, the top row of Table 89 was obtained by extrapolating the 90th, 85th, 80th, and 75th percentile encroachment lengths from the divided highways with 59–62 mph speed limits included in the Cooper study.

When the data from the 17-22 study shown in Table 85 is compared with RDG runout length guidelines, it is clear that existing guardrail design procedures greatly overestimate guardrail lengths. Note the 90th percentile departure length shown in Table 85. Note that the recommended runout length for high traffic volumes with a 70 mph design speed is approximately one-third greater than the 90th percentile departure length found along access-controlled freeways with speed limits from 70 to 75 mph. The difference between the 17-22 departure lengths and the H&K–based runout lengths increases further until it reaches 46% for traffic volumes of less than 800 average daily traffic (ADT), which were intended to correlate with the 70th percentile encroachment length. Thus, 17-22 data indicates that the guardrail length recommendations contained in the RDG grossly overstate guardrail need. It is important to note that guardrail is a roadside hazard that produces approximately 1200 fatalities per year. Therefore, there is a penalty for placing too much guardrail adjacent to the roadway and excessive guardrail length is likely to produce greater numbers of serious injuries and fatalities than would be associated with shorter installations.

Note that findings from the 17-22 data compare much better to guardrail length guidelines developed from Cooper. The 90th percentile departure length for 70–75 mph speed limits with full access control is virtually identical to the recommended guardrail runout length for a 70 mph design speed and high traffic volume. However, the recommended runout lengths for lower traffic volumes appear to drop faster than would be indicated from the 17-22 accident data shown in Table 85. However, the recommended lengths do match up well with the 80th, 75th, and 70th percentile departure length from Table 85. Recall that the original guardrail length guidelines were developed based on the 85th through 70th encroachment lengths from the H&K data. The approach was shifted slightly to utilize the 90th through 75th percentile encroachment length when Cooper data was utilized in place of the H&K study. This adjustment was implemented because Cooper's data did not include any highways with speed limits greater than 62 mph. When the entire history of guardrail length determination is considered, the guardrail runout length recommendations for a 70 mph design speed shown in Table 89 are found to compare very well with the 17-22

Table 89. Runout length recommendations from Wolford & Sicking (*36*).

	Traffic Volume ADT			
	10,000	5,000-10,000	1,000-5,000	<1,000
Design Speed (mph)	Runout Length (m)	Runout Length (m)	Runout Length (m)	Runout Length (m)
70	110	91	79	67
60	79	64	55	49
50	64	52	46	40
40	49	40	34	30
30	34	27	24	21

departure length distribution for access-controlled freeways with 70–75 mph speed limits.

Note that for design speeds of 60 mph, guardrail runout lengths shown in Table 89 appear to be midway between the full access control and no access control data for 55–65 mph speed limits. If it is assumed that fully access-controlled freeways are designed to a 70 mph or higher design speed, guardrail runout length recommendations shown in Table 89 can be considered to be conservative. However, if fully access-controlled roadways utilize a 60 mph design speed, the recommended guardrail lengths should probably be extended. Recommended guardrail runout lengths for a 50 mph design speed also compare well with departure lengths from roadways with speed limits of 45–50 mph and no access control. Note that the recommended runout lengths are consistently 3 m longer than the measured departure lengths shown in Table 85.

In summary, with the exception of highways with a design speed of 60 mph and full access control, guardrail length recommendations based on Cooper's data compare surprisingly well with departure length data described herein. Therefore, it is recommended that AASHTO consider adding a recommendation that guardrails placed along fully access-controlled freeways should be designed for 70 mph, regardless of the actual design speed.

CHAPTER 5

Long-Term Data Collection Plan

5.1 General

The primary goal of the current study is to identify the distribution of impact conditions—including speed, angle, and vehicle orientation—of serious injury and fatal ran-off-road crashes. However, there remain many other questions and issues that need to be addressed, some of which are as follows:

1. Identify distributions of impact conditions—including speed, angle, and vehicle orientation—as a function of highway functional class. These data would provide inputs for benefit/cost (B/C) analysis codes and development of hardware performance-level selection guidelines.
2. Develop a link between occupant compartment deformation and occupant risk in ran-off-road crashes. These data would be helpful in establishing intrusion limits for crash testing guidelines. The magnitude and location of intrusion would need to be identified in order to establish reasonable limits.
3. Quantify the occupant risk associated with partial rollovers by vehicle class. Large trucks are allowed to roll 90 degrees during a crash test, but the test is deemed a failure if a small car or a light truck rolls 90 degrees. Data correlating degree of rollover with occupant injury would be helpful.
4. Establish a link between impact conditions and probability of injury for common safety features and roadside hazards. These data would provide a link between crash conditions and accident severity that would be invaluable in refining B/C analysis techniques.
5. Identify distribution of all vehicle trajectories. These data could be used to incorporate curvilinear paths into the Roadside Safety Analysis Program (RSAP) and to develop guardrail length-of-need calculation procedures.
6. Identify the effects of roadside slopes on vehicle trajectories. This information would contribute to the refinement of B/C analysis tools and the development of length-of-need calculations.
7. Identify the relationship between impact angle and crash severity for longitudinal barriers. These data would contribute to the refinement of B/C analysis tools that in turn would be useful in identifying optimum flare rates for longitudinal barriers.
8. Identify the effects of curbs, ditches, and other terrain irregularities placed in front of safety hardware on the probability of injury during a crash.

This list of questions and issues is by no means exhaustive, but it serves to illustrate the many unanswered questions that can be addressed with in-depth crash data. The database created from the current study may provide answers to some of these questions, but the sample size and the level of detail would limit its applications. There remains a need for a long-term effort to collect in-depth data on single-vehicle, ran-off-road crashes in a continuous and systematic manner.

This long-term data collection effort will require a sponsoring agency with continuing funding sources. The sponsoring agency would ideally be national in scope and have sufficient resources to provide the needed funding on a long-term basis. One possible sponsoring agency is the FHWA. However, given the situation with the research budget in recent years, it is unlikely that the FHWA will sponsor such a long-term data collection effort. Another alternative is to establish a multistate pooled fund study, similar to the Mid-States Pooled Fund Program administered by the Nebraska Department of Roads. While this is a viable approach, the required funding per year and the commitment for a long-term effort may be too much for individual states to handle.

The most logical choice is for AASHTO to sponsor the effort and the program to be administered through NCHRP. There is no question that AASHTO and NCHRP have the required organization and resources to carry out this long-term data collection effort. For example, this current study was requested by the AASHTO Technical Committee on Roadside Safety (TCRS) and administered through NCHRP.

This chapter outlines a proposed plan for such a long-term data collection effort. Unlike the work plan for the current study, this proposed long-term data collection plan is more at the conceptual level. If and when this proposed plan is adopted for implementation, it will then be necessary to develop a more detailed data collection plan.

5.2 Data Collection Alternatives

As discussed previously, there were three basic alternatives for the data collection effort in the current study:

1. New data collection system
2. Prospective special study under the NASS CDS program
3. Retrospective supplemental data collection for existing NASS CDS cases

The retrospective approach is too limited in terms of data items that can be collected and in flexibility. Some of the desired data elements are perishable, i.e., lost after a period of time. For example, data on the struck object would be lost after repair of the object. This information could be necessary to assess the pre-impact characteristics and conditions of the object as well as to determine its impact performance. The sampling scheme is dictated by the CDS since only sample cases within it are available. For certain types of crashes, a very long time would be required before the sample size becomes sufficiently large for proper analysis. Furthermore, NHTSA changed its policy in 2003 so that police accident reports are no longer a part of the final NASS case. Police reports are maintained at the Zone Centers for only one year to allow for quality control procedures. This change in policy will, in essence, eliminate the use of the retrospective approach.

The establishment of a new data collection system is a viable, but expensive approach. As discussed previously, there will be an initial setup cost for the data collection teams, such as hiring of new personnel, establishing and furnishing the offices, purchasing the necessary equipment for conduct of crash investigation, etc. The investigators will then have to be trained extensively in the basics of in-depth level crash investigation, including both classroom and on-the-job training. Then, there is the need to establish cooperation with the local agencies, such as law enforcement agencies for the notification system, vehicle towing and repair facilities for access to the involved vehicles, hospitals and clinics for medical records/information on injury severity, and transportation agencies for highway-related information. It is also necessary to establish quality control procedures to assure that the data collection effort is conducted properly in terms of validity and accuracy.

The most efficient and economical approach is to make use of the existing NASS data collection system. First, the initial setup cost will be greatly reduced since the NASS data teams are already in place. Depending on the nature of the data collection, new investigators may have to be hired and trained and there may be requirements for additional office space and equipment. However, the setup costs should be only a fraction of the cost required to establish a new data collection system. Second, with supplemental field data collection, the portion of the CDS cases involving single-vehicle, ran-off-road crashes will be available for use at a relatively low cost. Third, under the NASS special study subsystem, cases may be selected outside of the CDS sample to address specific types of crashes under study.

The proposed long-term data collection plan is, therefore, built around the NASS CDS data collection system, including both within-sample supplemental data collection and outside-sample special studies. Note that while NHTSA has maintained the philosophy of allowing the NASS infrastructure to be used for other data collection needs, there are requirements that the special study:

- Should not have an adverse affect on normal NASS operations
- Should not reduce the current NASS CDS caseload for researchers
- Should not have any impact on current CDS data collection procedures and data elements being collected
- Should not have any impact on NASS operational costs
- Must cover all costs associated with the development and operation of the study
- Should be within the interests and expertise of the National Center for Statistics and Analysis (NCSA)
- Must conform with NHTSA privacy guidelines regarding collected data
- Must use existing NASS contractors for all data collection and quality control operations
- Should use a feasibility study to appraise the likely impact and success of the study
- Should use a pilot study in the development of formalized procedures
- Should present to NHTSA an analysis plan, i.e., what research questions are to be answered

These considerations are addressed in the development of the proposed data collection plan presented in the following section.

5.3 Proposed Data Collection Plan

The proposed data collection plan would have two major subsystems, both of which would be prospective in nature (i.e., the cases would be sampled from new crashes):

1. Continuous sampling subsystem within the CDS sample, and
2. Special study subsystem outside the CDS sample.

The continuous sampling subsystem is intended for a general database to address items of interest pertaining to single-vehicle, ran-off-road crashes. This general database would be similar to the database developed under this study. This continuous sampling subsystem would consist of selecting eligible cases from within the CDS sample and supplementing the basic CDS data with additional field data on roadway, roadside, and struck-object characteristics. In addition, the cases would be reconstructed to the extent possible to estimate impact conditions and vehicle trajectories.

The special study subsystem would be ad hoc in nature, intended to address specific questions or roadside safety features. For example, a special study may be designed to assess the impact performance of guardrail terminals. In order to assure a sufficient sample size to properly assess the field impact performance, the special study may have to select cases from outside as well as within the CDS sample. In addition to the basic CDS data and the supplemental field data on roadway and roadside characteristics, detailed information would be collected on the safety device of interest. Again, the cases would be reconstructed to the extent possible to estimate impact conditions and vehicle trajectories.

More detailed descriptions of these two subsystems are presented in the following sections.

5.3.1 Continuous Sampling Subsystem

As mentioned above, the continuous sampling subsystem is intended for a general database on single-vehicle, ran-off-road crashes. The cases would be selected from within the NASS CDS sample using sampling criteria similar to those used with the retrospective approach in the current study, i.e.,

- Area type—rural and suburban
- Single-vehicle, ran-off-road crashes
- Passenger-type vehicles only—passenger cars and light trucks
- Speed limit ≥ 75 km/h (45 mph)

The sampling criteria may be modified periodically to change the range of eligible cases. For example, the area type may be expanded to include urban areas with speed limits of 65 km/h (40 mph) and slower, or the vehicle type may be expanded to include single-unit trucks and tractor-trailers, depending on the questions to be addressed with the data. Also, since the cases would be selected within the CDS sample, the notification system would be the same as the CDS.

The basic data elements collected under NASS CDS are very extensive in areas pertaining to the vehicle and occupants, but are lacking in detail in the areas of:

1. Roadway and traffic characteristics
2. Roadside characteristics
3. Struck-object characteristics

For the type of questions that are of interest to the roadside safety community, information on the roadway, traffic, roadside, and struck-object characteristics would be needed for the analyses. Thus, it would be necessary to collect supplemental field data on these data elements. Some of the supplemental data, such as highway type, functional class, and traffic characteristics, would be obtained from the local or state transportation agencies, and cooperation would need to be established with these agencies.

Note that even with the supplemental data collection, the level of detail on struck-object characteristics would still be limited. First, there are simply too many roadside features to include in the data collection protocol for any details to be collected on a particular roadside feature. Second, given the intent of a general database on single-vehicle, ran-off-road crashes, overly detailed information on struck objects would be overkill. Furthermore, it would be very difficult and costly to train the investigators on the details of all these roadside features. The special study subsystem is the more appropriate vehicle for collecting detailed information on selected roadside features.

It is anticipated that the supplemental field data elements for the continuous sampling subsystem would be similar to those used in the current study, with perhaps a few more data elements and additional photographs. It is also anticipated that there would be additional coding on information pertaining to impact conditions and vehicle trajectories based on the basic CDS data, scaled diagram, and supplemental field data. Finally, the cases would be reconstructed to estimate the impact speeds.

One key consideration is how the supplemental field data would be collected. There are basically two approaches for the data collection:

- Existing NASS investigators
- Newly hired and specially trained investigators

For the continuous sampling subsystem, the use of existing NASS investigators would be the more logical and cost-effective means of collecting supplemental field data. Based on previous experience with the retrospective studies, the additional time required to collect and code the supplemental field data is estimated to be no more than two hours per case. For a given Primary Sampling Unit (PSU), the number of eligible cases is likely to be less than 50 per year. Thus, the additional time devoted to the supplemental data collection would not be more than 100 hours per year per PSU, or less than two hours per week per PSU. It is evident from the estimated workload that it would not be cost effective to hire an additional investigator per participating PSU for this supplemental field data collection.

On the other hand, if the special study subsystem is implemented with the continuous sampling subsystem, then one new investigator per participating PSU would make imminent sense. This additional investigator would be responsible for collecting both the supplemental data on the continuous sampling cases as well as the special study cases, although the majority of the investigator's time would be devoted to special study cases.

5.3.2 Special Study Subsystem

The general database developed under the continuous sampling subsystem will be invaluable to addressing general trends and questions on single-vehicle, ran-off-road crashes. However, it lacks the detail and sample size to address specific questions, such as the impact performance of guardrail terminals. As discussed previously, the level of detail on struck-object characteristics will be limited for the supplemental data collected under the continuous sampling subsystem. Also, the number of cases involving a specific roadside feature will be relatively small since the cases are sampled within the CDS sample and it will likely take a very long time before a sufficient sample size becomes available.

The special study subsystem is designed to handle these ad hoc studies. In contrast to the continuous sampling subsystem, a special study is tailored to a specific roadside feature. Thus, the data elements, particularly those pertaining to the roadside feature, can be designed to the desired level of detail. Also, the sampling of the cases would be outside of the CDS sample, thus assuring a sufficient sample size within a reasonable period of time.

As mentioned previously, a new investigator would be hired specifically for the data collection effort at each participating PSU. The investigator would first receive training similar to that of a NASS investigator so that the investigator can collect the basic data elements for a CDS case. In addition, the investigator would receive special training to collect and code the new data elements for the continuous sampling subsystem and the special study being conducted.

5.3.3 Quality Control

Two Zone Centers currently provide the quality control and oversight of the PSUs in the CDS data collection effort. It is envisioned that the Zone Centers would serve the same role in the continuous sampling subsystem and the special study subsystem.

One question is whether the additional coding on information pertaining to impact conditions and vehicle trajectories should be handled at the PSU level by the designated investigators or by Zone Center personnel. Either approach is workable, but it may be more appropriate for the Zone Center personnel to handle this task. First, the task requires considerable expertise and experience, which may be beyond the capability of the PSU investigators, particularly the new hires with little or no experience. Second, the work would likely be more accurate and consistent if handled by Zone Center personnel. Third, one or more new persons can be hired at each of the two Zone Centers specifically for this task of quality control and coding of the additional information. This would minimize the concern of adversely impacting the CDS operation.

5.3.4 Project Management

It is envisioned that an outside contractor would be hired by the sponsoring agency to coordinate with NASS on the data collection effort. The key responsibilities for this contractor would include, but not be limited to:

- Design of the data collection protocol for both the continuous sampling subsystem and the special study subsystem
- Reconstruction of the cases to estimate the impact speeds and conditions
- A second level of quality control of the supplemental data collected
- Maintenance of the general database and special study database
- Analysis of the data to address specific questions

A project panel or a technical advisory committee, composed of management-level personnel from the sponsoring agency and NASS, would oversee the overall conduct of the study. The panel would provide guidance and direction to the contractor and review the study progress and results.

5.4 Pilot Study

A pilot study was conducted to demonstrate the feasibility of such a long-term data collection effort to both the potential sponsor and to NHTSA. Specifically, the objectives of this pilot study were to:

- Demonstrate the feasibility of integrating this long-term data collection effort on ran-off-road crashes into the regular NASS CDS program.
- Identify and resolve any potential problems associated with this long-term data collection effort.
- Estimate time and manpower requirements associated with this long-term data collection effort.

5.4.1 Scope

The pilot study covered only the continuous sampling subsystem within the CDS sample. The feasibility and costs of the special study subsystem outside of the CDS sample would vary greatly depending upon the specific nature of the study to be undertaken. Therefore, evaluation of the special study subsystem is beyond the scope of the current study. The scope of the pilot study involved the conduct of a supplemental data collection effort at a small number of PSUs for a limited period of time. The same data collection protocol used for the current retrospective study was employed for this pilot study for the sake of simplicity. This eliminated the need to develop a new data collection protocol and to retrain the PSU researchers and Zone Center (ZC) personnel.

It should be pointed out that the integrated supplemental field data collection and reconstruction effort are actually easier and more efficient than the current retrospective study:

- No wasted effort to re-familiarize the researchers and ZC personnel with details of the old cases.
- No additional time to travel and locate the crash site.
- Scene evidence (e.g., damage to roadside hardware) available for documentation.
- ZC staff can perform the reconstruction in conjunction with their regular quality control effort in less time and with greater accuracy.

More detailed descriptions of the pilot study are presented in the next section, followed by results of the study and conclusions and recommendations.

5.4.2 Data Collection Protocol

As mentioned previously, the same data collection protocol used for the current retrospective study was employed for the pilot study with minor modifications. Highlights of the data collection protocol are summarized as follows.

Based on the frequency of single-vehicle, ran-off-road crashes and availability of trained researchers, two PSUs were selected for participation in the pilot study: PSU 48 and PSU 78. The time period for the pilot study was the nine weeks from October 4, 2004, to December 4, 2004.

The cases were selected from within the CDS sample, i.e., from cases that were already included in the CDS sample. The sampling criteria were the same as the current supplemental data collection effort except for the completion requirement, i.e., single-vehicle, ran-off-road crashes on roadways with speed limit greater than or equal to 45 mph. In order to avoid disruptions to the regular CDS data collection effort, each researcher was limited to no more than one case per week. However, all eligible cases were documented for the report. Thus, the maximum expected number of eligible cases was limited to four per week, two cases per week from each PSU.

The same data collection forms and procedures as the current effort were used for the pilot study, including:

- Supplemental Data Collection Form
- Object Struck Data Collection Form
- Reconstruction Coding Form
- Scene photographs

A log form was developed to identify each case and its status (i.e., active or not active); track the additional time spent on the supplemental field data collection at the PSU level and on quality control and reconstruction at the ZC level; and document any problems and provide comments. No training for the PSU researchers or ZC personnel was deemed necessary since they were already familiar with the data collection protocol.

The supplemental data collection forms and reconstruction coding forms were completed and submitted in hard copies. The CDS data elements of the selected cases were obtained from preliminary approved cases posted on the NHTSA website with a time lag of approximately six to eight weeks.

5.4.3 Pilot Study Results

As shown in Table 90, there were a total of 22 eligible cases during the nine-week study period, 16 cases for PSU 48 and 6 cases for PSU 78. Of these 22 eligible cases, 16 cases (72.7%) were actually sampled, 11 cases (68.8%) for PSU 48 and 5 cases (83.3%) for PSU 78.

For each sampled case, the PSU and Zone Center personnel were asked to complete a log form, documenting the time required to collect, process, and quality control the additional field data and to reconstruct the cases except for impact speed, including:

- PSU
  - Field time to collect the additional data
  - Office time to process the additional data
- Zone Center
  - Time to quality control the additional data
  - Time to reconstruct the impact conditions other than impact speed

Note that these times pertain to only the additional data elements and not the time required for the NASS CDS data collection effort. In addition, the researchers were asked to note any problems or unusual events encountered in the field or office on the log form.

Table 91 summarizes the additional time required for each of these 16 sampled cases and their averages. As may be expected, the additional time varies greatly on a case-by-case basis, depending on the complexity of the crash and, to some extent, the efficacy and expertise of the individual investigators. Overall, the time required for the additional work on the supplemental data collection ranges from 60 to 255 minutes per case with an average of 135.3 minutes per case.

Table 90. Number of eligible and sampled cases.

Week Beginning	No. of Eligible Cases			No. of Sampled Cases		
	PSU 48	PSU 78	Total	PSU 48	PSU 78	Total
October 4	0	2	2	0	1	1
October 11	4	0	4	2	0	2
October 18	2	1	3	1	1	2
October 25	1	0	1	1	0	1
November 1	4	1	5	2	1	3
November 8	2	1	3	2	1	3
November 15	1	0	1	1	0	1
November 22	1	0	1	1	0	1
November 29	1	1	2	1	1	2
Total	16	6	22	11	5	16

Table 91. Additional time required.

Case Number	Additional Time Required (Minutes)				
	PSU		Zone Center		Total
	Field	Office	Quality Control	Recon-struction	
04-48-235J	60	20	10	40	130
04-48-238K	30	45	5	25	105
04-48-246D	20	30	5	35	90
04-48-253H	60	120	5	35	220
04-48-254B	50	50	5	10	115
04-48-259K	30	20	5	15	70
04-48-262C	20	20	10	30	80
04-48-265K	40	40	10	20	110
04-48-267J	60	20	10	50	140
04-48-274J	25	5	5	25	60
04-48-280K	60	120	10	65	255
PSU 48 Average	41.4	44.6	7.3	31.8	125.0
04-78-134D	60	60	10	35	165
04-78-140K	120	0	10	35	165
04-78-143K	90	60	10	20	180
04-78-144J	60	60	10	30	160
04-78-148K	60	0	10	50	120
PSU 78 Average	78.0	36.0	10.0	34.0	158.0
Combined Average	52.8	41.9	8.1	32.5	135.3

At the PSU level, the additional field time for collection of the supplemental data ranges from 20 to 120 minutes with an average of 52.8 minutes. The processing time in the office ranges from 0 to 120 minutes with an average of 41.9 minutes. The combined field and office time at the PSU level ranges from 30 to 180 minutes with an average of 94.7 minutes.

At the Zone Center level, the additional time for quality control of the supplemental data ranges from 5 to 10 minutes with an average of 8.1 minutes. The time needed to reconstruct the impact conditions (except for impact speeds) ranges from 15 to 65 minutes with an average of 32.5 minutes. The combined time at the Zone Center level ranges from 15 to 75 minutes with an average of 40.6 minutes.

The researchers were asked to report any problems or unusual events encountered during different phases of this supplemental data collection effort for this pilot study. To ensure completeness, the researchers were asked to enter "None" if there are no problems or comments. The comments are tabulated in Table 92. Overall, there are no major comments of concern. Some of the comments pertain to common operational issues, such as scene evidence, photography, and interference from traffic and Visio printer setup, which are not specifically related to the supplemental data collection. Other comments pertained to definitions and procedural issues that can be easily remedied with some training, including:

- Multiple impacts
- Impacts with more than one object in close proximity
- Reference framework for lateral distance measurements of trajectory

Table 92. Summary of comments.

Case No.	PSU Comments	Zone Center Comments
04-48-235J	I had to go back to the scene and redo my lateral measurements because I forgot to separate the rollover initiation, but that was the researcher's fault. Other than that, no problems.	Visio printer setup. Had to "grab" missing images from case.
04-48-238K	None.	Visio printer setup.
04-48-246D	None.	Had to create an object form for 2nd object struck. Visio printer setup.
04-48-253H	Two utility poles situated close beside each other were struck and coded as one event.	Visio printer setup. 2 extra object forms added for Events 2 and 3.
04-48-254B	Another crash occurred in same area / deciphering evidence.	In-house Visio issue.
04-48-259K	None.	In-house Visio issue.
04-48-262C	Difficult to place ID card in images on scene due to Interstate traffic.	Reconstruction – changed angle of departure off barrier, so re-calculated FRP. (No scene evidence at FRP.)
04-48-265K	Vehicle departed right road edge and returned to road to rollover. Slope measurements taken at road departure.	None.
04-48-267J	None.	Visio did not migrate properly. Had to create from printout copy.
04-48-274J	None.	Visio printer software issues.
04-48-280K	Multiple events and scene evidence being contaminated made it difficult to determine impacts and locations.	Same Visio printer setup problem. Listed 3 events (that affected CG) only (not 6). Laterals on a curve were changed to be perpendicular to the curved road edge.
04-78-134D	None.	Had to annotate POD, etc. on Visio. Advised researcher how to do that "next time".
04-78-140K	Had a hard time placing the cones in a straight line from road edge to final rest.	12 laterals taken from POD to FRP, not POD to POI. Had to re-calculate these from Visio.
04-78-143K	Heavy rain and it caused delays in getting out to take images.	None.
04-78-144J	None.	Researcher took 12 laterals from POD to FRP. Re-computed 6 laterals from POD to POI.
04-78-148K	Researcher unsure how to fill in the reconstruction form for events 2 and 3.	Filled in subsequent reconstruction form for researcher.

5.4.4 Summary of Findings and Recommendations

The following is a summary of findings and recommendations gleaned from the pilot study:

- The study clearly demonstrated the feasibility of incorporating a long-term data collection effort on ran-off-road crashes into the existing NASS CDS program. However, note that the study included only the continuous data collection subsystem. Thus, the study results would not apply to the special study subsystem.
- It took an average of 135 minutes per case for the supplemental data collection effort, consisting of 95 minutes at the PSU level and 40 minutes at the Zone Center level. Furthermore, it is reasonable to expect that the time would decrease slightly once the researchers are trained and become familiar with the data elements and procedures.
- There were no major issues of concern regarding the data collection or reconstruction of the cases.

5.5 Data Collection Protocol—Continuous Sampling Subsystem

The data collection protocol for the proposed continuous sampling subsystem is essentially unchanged from that of the current retrospective study or the pilot study. Detailed descriptions of the data collection protocol are provided previously in Chapter 1 and Section 5.4 and will not be repeated herein. Only the highlights of the data collection protocol are summarized in this section.

5.5.1 Sampling Plan

The cases for the continuous sampling subsystem would be selected from within the NASS CDS sample, using the same notification system. The sampling criteria may include, but are not limited to, the following:

- Area type—rural and suburban
- Single-vehicle, ran-off-road crashes
- Passenger-type vehicles only—passenger cars and light trucks
- Speed limit ≥ 75 km/h (45 mph)

The actual sampling criteria used may vary, depending on the specific questions to be addressed with the data. For example, the area type may be expanded to include urban areas with speed limits of 65 km/h (40 mph) and slower, or the vehicle type may be expanded to include single-unit trucks and tractor-trailers, depending on the questions to be addressed in the study. On the other hand, the actual sample size and the PSUs to be included in the data collection effort is merely a question of available funding.

5.5.2 Data Collection Forms

The proposed data collection forms and procedures for the continuous sampling subsystem are similar to those used in the current effort and the pilot study, but with some enhancements based on experience gained in this study, including:

- Supplemental Highway Data Collection Form
- Object Struck Data Collection Form:
  - Barrier
  - Crash Cushion
  - Embankment
  - Pole Support
  - Tree
  - Other Struck Object
- Reconstruction Coding Form:
  - First Harmful Event
  - Subsequent Harmful Event
- Performance Assessment Form
- Scene Photographs

Copies of these proposed data collection forms and the corresponding coding and field procedures manuals are included in Appendix F.

5.5.3 Organization

The data collection effort is best sponsored by AASHTO and administered through NCHRP. An outside contractor would be hired to conduct the study and to coordinate the data collection effort with NASS. A project panel, or a technical advisory committee composed of management-level personnel from the sponsoring agency and NASS, would oversee the overall conduct of the study, provide guidance and direction to the contractor, and review the study progress and results.

If only the continuous sampling subsystem is to be implemented, then the most logical and cost-effective arrangement is for the field data to be collected by existing NASS investigators and quality controlled by Zone Center personnel, assuming the additional work load would not adversely affect the regular CDS operation. Based on previous experience with the retrospective studies, the additional time required to collect and code the supplemental field data is estimated to be no more than two hours per case. For a given PSU, the number of eligible cases is likely to be less than 50 per year. Thus, the additional time devoted to the supplemental data collection would not be more than 100 hours per year per PSU, or less than two hours per week per PSU. It is evident from the estimated workload that it would not be cost-effective to hire an additional investigator per participating PSU for this supplemental field data collection.

Coding of additional information and reconstruction of the cases as well as the performance assessment would be handled by the outside contractor so as to minimize the time required of the PSU and Zone Center personnel.

5.6 Data Collection Protocol—Special Studies Subsystem

Under the special study subsystem, single-vehicle, ran-off-road crashes involving specific roadside safety features or devices would be selected from both within and outside the CDS sample. The data to be collected under this special study subsystem would include:

1. Selected CDS data
2. Supplemental highway data for the continuous sampling subsystem
3. Detailed information on the roadside feature or device under study

The special study cases would then be reconstructed to estimate impact conditions and vehicle trajectories, and the impact performance of the specific roadside feature/device under study will be assessed.

The specific data collection protocol will differ from special study to special study. Thus, the discussions will be more general in nature to cover the key considerations.

5.6.1 Sampling Plan

As mentioned previously, it is impossible to devise a specific sampling plan that works for all special studies. Thus, the discussions will be more general in nature to cover the key considerations in developing the sampling plan.

Sample Size. The number of cases to be investigated would first have to be determined. This is usually determined by study/analysis requirements and the available funding.

Study Location. PSUs with the most eligible cases would first be identified. The most appropriate PSUs would be selected for participation in the special study, based on the required sample size and factors such as: number of eligible crashes, the number and experience of the investigators, geographical location, work load, etc. It is critical that the PSUs are selected in conjunction with NHTSA and the two Zone Centers. Every effort should be made to avoid interference with the regular NASS CDS work of the selected PSUs.

Study Period. Again, this is a function of the required sample size and the number of eligible cases from the participating PSUs.

Sampling Plan. The special study subsystem would typically select cases from both within and outside the NASS CDS sample. The sampling plan should take into account key considerations as those for the selection of PSUs including number of eligible crashes, the number and experience of the investigators, geographical location, work load, etc. Again, it is critical to develop the sampling plan in conjunction with NHTSA and the two Zone Centers. Every effort should be made to avoid interference with the regular NASS CDS work of the selected PSUs.

Notification System. A special notification system is needed for cases to be selected from outside the NASS CDS sample. Care should be taken to make sure that the notification system for the special study would not interfere with the CDS or add too much work to the cooperating agencies. Depending on the nature of the special study, another consideration is the time lag from the time the crash occurred to the time the PSU is notified of the crash. For certain types of crashes, the time lag may need to be relatively short in order to gather the needed scene evidence. In such cases, the notification system would have to be devised to reduce the time lag to an acceptable level.

5.6.2 Data Collection Forms

The general structure of the data collection forms and procedures for the special study subsystem would be similar to those used with the continuous sampling subsystem, including but not limited to:

- Supplemental Highway Data Collection Form
- Object Struck Data Collection Form
- Reconstruction Coding Form
- Performance Assessment Form
- Scene Photographs

However, the forms would be tailored to the specific roadside feature/object under study. The Supplemental Highway Data Collection Form would likely remain mostly unchanged. The other data collection forms would have to be modified to address the specific roadside feature/object with more specific and greater details.

5.6.3 Organization

The sponsorship and organization of a special study data collection effort would be similar to those of the continuous sampling subsystem. The program is best sponsored by AASHTO and administered through NCHRP. The conduct of the study would be handled by an outside contractor and coordinated with NASS while a project panel or a technical advisory committee would provide guidance and direction to the contractor and review the study progress and results.

If both the continuous sampling subsystem and the special study subsystem are implemented, then the most logical arrangement is to hire a new investigator for each participating PSU since the special study cases are mostly sampled outside of CDS cases. Similarly, new personnel would have to be hired at the two Zone Centers to handle the quality control of the collected data and coding of additional information for the special study. The additional staff at the PSUs and Zone Centers would ensure that the regular CDS operation will not be adversely affected. The outside contractor would continue to handle the coding of additional information, reconstruction of the cases, and the performance assessment.

In addition to the training required for the regular CDS data collection and the continuous sampling subsystem, both PSU investigators and Zone Center personnel assigned to the special study data collection effort would require special training in order to collect and quality control the specific and detailed data for the special study. The training would be conducted by the outside contractor on data elements, coding instructions, and field procedures specific to the special study data collection effort. The training should include both classroom lectures and field training as well as on-the-job training.

5.7 Summary

A long-term data collection plan on single-vehicle, ran-off-road crashes is proposed. The proposed plan is built around the NASS CDS data collection system, including both within-sample supplemental data collection and outside-sample special studies. The efforts would be prospective in nature, i.e., the cases would be sampled from new crashes and consist of two major subsystems or components:

1. A continuous sampling subsystem intended for a general database to address items of interest pertaining to single-vehicle, ran-off-road crashes. The cases would be selected from within the CDS sample and supplement the basic CDS data with additional data on roadway, roadside, and struck-object characteristics. In addition, the cases would be reconstructed to estimate impact conditions and vehicle trajectories.
2. An ad hoc special study subsystem intended to address specific questions or roadside safety features. The cases would be selected from both within and outside the CDS sample to assure sufficient sample size within a reasonable period of time. In addition to the basic CDS data and the supplemental field data on roadway and roadside characteristics, detailed information would be collected on the safety device of interest. Again, the cases would be reconstructed to the extent possible to estimate impact conditions and vehicle trajectories.

The data collection effort is best sponsored by AASHTO and administered through NCHRP. An outside contractor would be hired to conduct the study and to coordinate the data collection effort with NASS. A project panel, or a technical advisory committee composed of management-level personnel from the sponsoring agency and NASS, would oversee the overall conduct of the study, provide guidance and direction to the contractor, and review the study progress and results.

If only the continuous sampling subsystem is to be implemented, then the most logical arrangement is for existing NASS investigators to collect the data since the additional time for the supplemental data would not be sufficient to require new staff. Quality control would be conducted by Zone Center personnel. It may be necessary to hire new Zone Center staff to handle the additional work. Coding of additional information, reconstruction of the cases, and assessment of the impact performance would be handled by the outside contractor. It is important to make sure that the additional work would not adversely affect the regular CDS operation.

If both the continuous sampling subsystem and the special study subsystem are to be implemented, then the most logical arrangement is to hire a new investigator for each participating PSU. This new investigator would be trained not only in the collection of CDS data, but also supplemental data pertaining to the continuous sampling subsystem and the special study subsystem. Similarly, new personnel would be hired at the two Zone Centers to handle the quality control of the collected data and coding of additional information. The completed cases would then be forwarded to the outside contractor for additional quality control and reconstruction.

CHAPTER 6

Summary of Findings

6.1 Study Approach

Data was collected under three different studies: the FHWA Rollover Study, NCHRP 17-11, and NCHRP 17-22. Each of these studies involved a retrospective data collection and analysis of historical NASS CDS cases. Supplemental site information was collected to identify characteristics of the roadway, roadside, and objects struck during the crash. This supplemental information was then utilized to reconstruct each crash in order to determine vehicle departure and impact conditions. The data was then compiled into a relational database that can be used to analyze the data.

6.2 Findings

A relational database of ran-off-road crashes has been developed. The database includes detailed characteristics of the vehicle, trajectory, roadway, roadside, objects struck, and crash result for 877 crashes. The data are strongly biased toward serious crashes with 15% fatal and 72% A+K crashes. The database can be used for many different purposes, including identification of roadway departure and roadside impact conditions, and ran-off-road trajectories. The database can also be used to develop a relationship between impact conditions and crash severity for some common obstacles, such as trees and poles.

Although prior studies showed departure velocity to be most closely associated with highway functional class, this roadway classification was not available in the current database. In the absence of highway functional class, speed limit was found to provide the best discriminator for departure velocity and angle. Departure velocities were found to be accurately modeled with a normal distribution while no single common distribution provided a good fit to departure angles for all speed limit classes. However, the gamma distribution was found to fit the square root of the departure angle for all speed limit classes. The dependency between departure angle and velocity was found to be relatively insignificant for all individual speed limit classes. Chi-square tests for independence showed that departure velocity and angle could be considered independent for all speed limit classes. Further, combined velocity and angle distributions developed based on the assumption of independence were subjected to chi-square tests for goodness-of-fit. These tests showed that the differences between predicted and measured distributions of departure velocities and angles were not statistically significant at the $p = 0.05$ level for any speed limit class. Thus, the models of departure velocity and square root of departure angle can be reliably used to develop distributions for a variety of speed limit classes included in the study.

Further, the database provides definitive support for reducing the length of guardrail used in advance of roadside obstacles. The distributions of longitudinal departure lengths included in the data set correlated surprisingly well with recommended guardrail runout lengths generated from Cooper's encroachment data. The only significant difference between the longitudinal departure length distributions and the modified runout length guidelines was associated with the use of a 60 mph design speed for a full access-controlled freeway. In this situation, modified runout length guidelines were found to be shorter than longitudinal travel distances found in the data set. Therefore, it is recommended that states either use a design speed of 70 mph for all controlled access roadways, or an additional category should be added to the guardrail runout length table to accommodate 60 mph design speeds with full access control.

6.3 Long-Term Data Collection

A detailed work plan for a long-term data collection system was developed and pilot tested. The plan involves implementing a continuous sampling subsystem and possibly a special study subsystem within the NASS CDS. The continuous sampling subsystem would provide a steady stream of new cases that would be very similar to the existing database while a special study would focus on one particular type of crash such as W-beam guardrail impacts.

If implemented, the long-term data collection plan could provide information that would allow development of the relationships between impact severity and crash conditions for a wide variety of roadside features. Further, such a study would provide greater information regarding the causation of injuries and fatalities during crashes involving roadside safety hardware. This information will provide the foundation for the next generation roadside safety features designed to dramatically reduce injuries and fatalities associated with ran-off-road crashes.

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Appendices

Appendices A through F are available on the *NCHRP Report 665* summary web page on the TRB website. To find them, go to www.trb.org and search for "NCHRP Report 665". Titles of Appendices A through F are as follows:

Appendix A: Annotated Bibliography
Appendix B: 1997–2001 NASS CDS Cases
Appendix C: Supplemental Data Collection Protocol
Appendix D: Database Content
Appendix E: Additional Tables, Plots, and Analysis Results
Appendix F: Proposed Data Collection Forms Continuous Sampling Subsystem

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation