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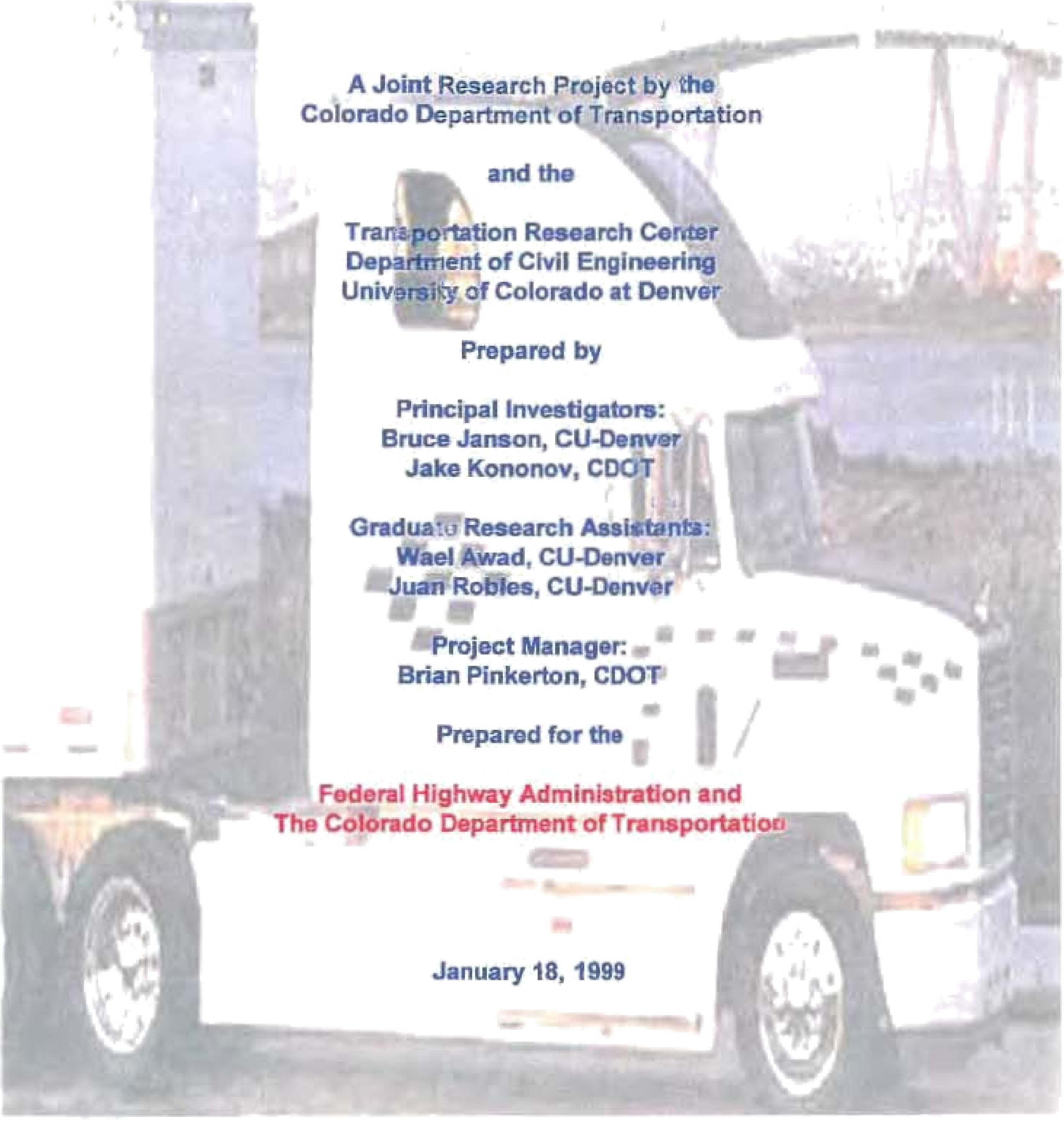
EFFECTS OF GEOMETRIC CHARACTERISTICS OF INTERCHANGES ON TRUCK SAFETY

Final Report



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ABSTRACT (Maximum 200 words)
Relationships between truck accidents and selected geometric characteristics of interchanges are examined. Datasets containing information on truck accidents at interchanges, traffic exposure and selected geometric characteristics are analyzed with an emphasis on interchange and ramp configurations. Most of the data in the report was obtained from the Washington State DOT, with limited data obtained from Colorado and California. In order to assess the impact of merging and diverging maneuvers on safety, the limits of ramp influence zones expressed in terms of accident frequencies were defined on the main line alignments. In addition, a procedure for identifying high-risk locations from the standpoint of truck operations was proposed.

Freeway truck accidents were grouped by ramp type, accident type, and by four conflict areas of each merge or diverge ramp and compared on the basis of truck accidents per location and per truck mile of travel. Truck accident frequencies and rate were not found to be significantly different by ramp type alone, but were significantly different by conflict area and accident type, both between and within ramp types. Truck accident frequencies at ramps were found to be less than proportional to truck volumes, meaning that high volume ramps had lower rates of truck accidents per truck mile of travel. Thus, a ramp's safety risk is related to accident type and conflict area, but not directly to truck volumes, which affects identifications of high-risk locations.

Selected aspects of the AASHTO Policy on Geometric Design were examined from the standpoint of truck operations. This portion of the report was largely conducted as a literature review. In order to develop greater understanding of the relationship between truck accidents and geometrics of interchanges, the study conducted a series of truck driver surveys.

SUBJECT TERMS
geometric design, truck accidents, ramp configurations, truck driver surveys

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Chapter One

INTRODUCTION

Nationally, between 20% and 30% of freeway truck accidents occur near interchanges, even though these areas comprise less than 5% of all freeway lane area (Firestine et al., 1989). "Freeways", as we define them here, are all limited access highways (i.e., interstate highways, expressways, turnpikes, and parkways). This percentage increases to 40% or more if accidents at intersections of ramps and arterial roads are included. These same percentages hold true for many western states. Of nearly 2400 freeway truck accidents in Colorado in the years 1993, 1994, and early 1995, roughly 30% occurred at interchanges, and another 10% occurred at intersections associated with interchanges. For accidents of all vehicle types, Sullivan (1990) found the number of interchange ramps along highway sections in California to be a significant explanatory variable of accident frequency per vehicle mile of travel.

Although driver actions (in both cars and trucks) most often cause highway accidents, inadequate interchange designs for large truck operations may contribute to some of them, along with insufficient safety warnings to commercial drivers at certain locations. Many interchange ramps throughout the U.S. were designed for older truck configurations and not for longer combination vehicles carrying much greater weights. Moreover, even some recently designed ramps do not adequately accommodate current truck configurations.

1.1 PROJECT OBJECTIVES

The objectives of this study were to:

1. Identify significant relationships between interchange design and large truck accidents in Colorado, California, and Washington State. The discovery of such relationships will lead to proposed safety enhancements of interchanges in these and other states.

2. Critically examine the AASHTO Policy on Geometric Design of Highways and Streets (AASHTO, 1990) from the standpoint of truck operations at freeways.

3. Develop short-term and long-term strategies to mitigate problems at Colorado interchanges identified in the study.

1.2 PROJECT NEED AND BENEFITS

Truck accidents are a major consideration for government agencies regulating the design of these facilities. Findings from this project pertaining to design standards will be of important value to other states confronting this issue. The primary benefits sought by this project are to reduce accident risk to all motorists, reduce accident related impacts, and provide greater levels of service on the freeway system.

This project offers significant benefits to the general public as well as the trucking industry. In addition to the obvious risk to truckers, truck accidents are a significant safety risk and expense to highway users and nonusers. Truck accidents may involve other vehicles, cause traffic delays, increase insurance costs, reduce economic productivity, and may hurt the environment. Findings from this project, if used to address safety problems, may reduce future accidents, which translates into greater safety and reduced costs to the traveling public and the trucking industry. With increasing traffic congestion in urban areas, findings from this project can help to mitigate this problem, since improvements to interchange design for trucks will improve traffic flow for all highway users, both passengers and freight.

1.3 RESEARCH BACKGROUND

Previous studies have indicated that AASHTO design standards provide a slim margin of safety for the operation of large trucks through interchanges (Ervin et al., 1986). This degree of risk is attributed to the fact that some of the current geometric design and operational criteria are based on the dimensions and operational characteristics of passenger cars. We'll later discuss current and future trends in truck design and technology, and re-evaluate current AASHTO standards pertaining to large truck operation at interchanges (AASHTO, 1990).

The complex relationship between highway geometrics and truck safety has been examined by numerous researchers, generally yielding mixed results. Difficulties with statistical analyses of truck accidents arise because of the large number of factors contributing to a truck accident, and the relative lack of information about "non-events". Some information is generally available from police accident reports about specific truck accidents, but limited data is available about all the non-accident traffic passing through these same locations.

	Surrounding Area			
Section Type	Rural	Suburb	Urban	Total
With Interchanges	0.57	0.77	3.05	1.22
Without Interchanges	0.49	0.61	2.07	0.90

Note: Accident rates are per million vehicle miles, and include all accidents causing fatalities, injuries, and property damage only.

Table 1.1. Accident Rates on Controlled-Access Highway Sections (Pigman, 1981)

Accident rates vary widely by highway type, location, and by the study in which they are found. Table 1 shows some rates compiled by Pigman (1981) for interstate sections with and without bridges and interchanges. Differences in highway sections that affect accident rates are number of lanes, number of interchanges, number of bridges or tunnels, curvature, grade, and the mix of vehicle types. Although differences in these rates are also partly due to the classification of sample highway sections as freeways, expressways, or interstates, and the criteria by which they were defined to be rural, suburban, or urban, the rates are always greater when road sections with bridges and interchanges are included. An analysis by this research team of truck accident data reported by Goodell-Grivas (1989) also showed that truck accident involvements were significantly higher on freeway sections in the vicinity of interchanges.

General accident rates per vehicle mile of travel (VMT) for all vehicles do not provide an adequate comparison of truck accident rates on different facilities. For both cars and trucks, studies have shown that fewer severe accidents per VMT occur on congested roads of similar design. Thus, on some highways, fewer accidents occur when greater traffic volumes generate greater VMT for some hours of the day. We designed this study to differentiate between accident rates for highways with different geometric designs and traffic characteristics.

1.4 OVERVIEW OF TASKS

Work on this study included (1) a review of past research on truck accident rates in general and truck accidents at interchanges in particular, (2) processing and manipulation of available data into tabulations needed to perform the above tasks, (3) description of alternative relationships to be evaluated, (4) presentation of statistical results, and (5) application of statistical results to procedures for identifying problem locations. The tasks were to:

1.4.1 Task A: Review Past Studies and Assess Available Data

Review literature on past research related to truck safety and highway geometrics.

Review Colorado accident data to identify potential study sites to examine.

Review Colorado traffic reporting system to identify truck exposure data

(e.g., volumes, types, and primary routes).

Review HSIS, HPMS and other national data bases for additional truck exposure data and accident information.

Contact state DOT's and research institutes in other states to identify more detailed datasets.

1.4.2 Task B: Design Analysis Approach and Gather Needed Data

Develop list of key questions we sought to answer regarding truck accidents that we could investigate with data known to be available or obtainable within project resources and time.

Design database and statistical analyses to be performed once the data was assembled.

Develop survey form and survey procedure of truck drivers operating in Colorado to gain additional knowledge of truck safety issues at interchanges from the operators perspective and experience.

Distribute survey and follow-up requests in order to speed returns and ensure a sufficient return rate

Compile results and perform initial interpretation and assessment.

1.4.3 Task C: Assemble Databases and Perform Analyses

Select interchanges in each state where truck accidents were to be examined and used in statistical analyses.

Obtain geometric design drawings and truck accident reports at each selected interchange.

Input and process truck accident data pertaining to truck exposure, roadway characteristics, and traffic volumes for these sites.

Develop statistical comparisons of truck accidents at interchange ramps of different geometric designs and traffic characteristics.

Produce preliminary report of findings, which described the sample design and data gathering process, methods of statistical analysis applied, and development of statistical comparisons.

1.4.4 Task D: Implementation

Apply the statistical findings to identify future accidents risk at selected sites.

Evaluate selected elements of the AASHTO geometric design criteria.

Develop short-term and long-term mitigation measures for select sites.

Produce Final Report describing the principal findings of the project.

An early task of this study was to assess whether national or state databases contained the detailed information on truck accidents needed perform the desired analyses. The Fatal Accident Reporting System (FARS), the National Accident Sampling System (NASS), and the General Estimates System (GES) from NHTSA were the first datasets we examined. Also, a survey of accidents in mid-1985 was collected for FHWA by seven states that may have included more detailed data on truck accidents and the locational attributes where these accidents occurred. We found that none of the national databases contained the detailed data we needed to investigate our questions concerning truck accidents as later described in Chapter 3.

We then surveyed the reports of several safety research institutes (e.g., the University of Michigan, the University of North Carolina, Midwest Research Institute, etc.) and State DOT's to identify more detailed datasets. Of the states we contacted, Washington State had assembled the most comprehensive truck accident database, with coded route mile point locations to cross-reference data files of highway geometrics and traffic volumes, including truck volumes on the ramps and in the freeway lanes. Colorado was able to provide limited data on truck accident at interchanges that we supplemented with data from police accident reports, but no traffic volumes. California provided a dataset of truck accidents at interchanges with traffic volumes and interchange diagrams, but with no information on truck volumes.

In order to fit statistical models of large truck accident rates related to interchange geometrics and traffic characteristics, we created a truck accident database for Washington State that included information about "safe travel" through the same interchanges where truck accidents had occurred. We were not able to gather comparable information for Colorado and California, but we were able to make some overall comparisons as shown at the end of Chapter 5.

Chapter Two

REVIEW OF TRUCK ACCIDENT STUDIES

The complex relationship between interchange geometrics and truck safety has been examined by numerous studies, generally yielding mixed results. The difficulties normally associated with statistical analysis of this relationship are attributed to the large number of interrelated factors contributing to accidents. These factors generally include human behavior, environmental conditions, and vehicle and roadway characteristics. The problem is further complicated by the lack of reliable exposure data on truck traffic at interchanges coupled with difficulties of obtaining detailed geometric design information. Earlier research efforts examined this relationship using different approaches and statistical techniques and yet because of the complexity of the issue and problems with obtaining reliable data no conclusive results have been drawn.

2.1 TRUCK ACCIDENT STUDIES IN GENERAL

A research group at Oak Ridge National Laboratory (Miau, et al., 1993) conducted extensive study of the relationship between truck accidents and roadway geometrics using Highway Safety Information System (HSIS) data base. The objective of the study was to determine the truck accident involvement rate and truck accident probability of a road section, given its geometric design, and other relevant characteristics. The authors of the study made a convincing case for using Poisson and Negative Binomial regression models to capture the relationship between accidents and geometric design variables, instead of conventional multiple linear regression models utilized by earlier studies of similar relationships. It was found that HSIS was a comprehensive and well prepared data base containing useful information on accidents, vehicles, drivers, traffic and roadway geometrics. Each record of the road inventory file represents a homogeneous road section in terms of its cross-sectional characteristics, such as number of lanes, lane width, median type and width, annual average daily traffic (AADT) and percentage of trucks. Each accident record contains information from accident reports which include information on accident type, severity, vehicle type, time of accident and drivers' condition. The database structure of HSIS makes it possible to link truck accident files with road inventory files and conduct various types of analysis. Although some encouraging relationships were developed for horizontal curvature, vertical grade, and shoulder width, using the Poisson regression models, the uncertainties associated with these models are still quite large, especially for the models for urban Interstate and freeway and rural two-lane undivided arterials. The authors of the study stress that these models are considered preliminary and need further refinements.

A 1989 study by Goodell-Grivas Inc. (Bowman, et al.,) concentrated on truck accidents on urban freeways. Although this study is not specifically focused on the question of large truck safety at interchanges it offers useful insights into the question of exposure and data accuracy which are in many ways applicable to the interchange environment. It also provided relevant statistics in classifying truck accidents by freeway area, which was subdivided into 5 (five) different categories:

Freeway Proper-76.9%
Ramps-5.7%
Right Hand Merge-9.2%
Right Hand Exit-5.5%
Left Hand Merge/Exit-2.7%

This break down of truck accidents by the freeway area shows that 23.9% of all truck accidents take place around interchanges. This data corresponds well with other studies which isolated truck accidents at interchanges.

2.2 TRUCK ACCIDENT STUDIES AT INTERCHANGES

A recent study by Garber et al., 1992 examined large truck accidents on ramps in Virginia. This study concentrated on identifying variables that are of statistical significance to occurrence of large truck accidents on ramps. A major deficiency in the data compiled, according to the authors, was the unavailability of the Average Annual Daily Traffic (AADT) and truck volumes on ramps. The difficulty with ascertaining truck exposure on ramps is not unique to the State of Virginia or the latest study by Garber et al., as this kind of information is not systematically collected by the Departments of Transportation and is generally not readily available. The question posed by Garber et al., was-what is a representative measure of truck exposure at interchanges in the absence of truck volumes on ramps, and what information should be collected in order to diagnose safety problems for trucks?

In order to identify problem areas Garber conducted detailed investigation of 16 interstate routes and 21 primary routes. As a result of this investigation a route was identified with the highest number of truck-related accidents on ramps. It is of interest to note that the selected route had neither more interchanges nor truck exposure as measured in truck Vehicles Miles of Travel (VMT) than some of the other routes in Virginia. Garber concluded that this overrepresentation might be attributed to restrictive geometrics coupled with the design speed differential between the main line and the ramp; however this inference was not conclusively proven in the study. It is also difficult to find a reasonable explanation as to why the entire route rather than isolated locations display unusually high number of truck accidents. This study offers an innovative measure of assessing truck safety on ramps by introducing the involvement ratio of truck accidents on a ramp to total number of accidents in the same section where the ramp is located. Garber et al., showed that the involvement ratio of trucks on ramps increases with the speed differences between the average speed of trucks approaching the ramps and the posted speed limits. Some of the other significant findings of this study are as follows:

- A higher percentage of truck accidents on the interstate highways occur at exit ramps. On primary highways, a greater percentage occur on entry ramps.
- Trucks at interchanges are not significantly involved in non-collision accidents, such as jacknifing, rollovers and run-off-the-roads accidents.

- Sideswipe-same direction collisions were predominant at entry ramps on the interstate system.
- At the exit ramps on the interstate system, rear-end and sideswipe same direction collisions were predominant.

Probably the most interesting finding of this study was the fact that a high occurrence of ramp accidents on the selected route was not due to either the truck VMT or the number of interchanges located on the highway. This finding presents some unique possibilities for further and more detailed study of this route in the future.

A major work examining the relationship between specific geometric features of interchanges and loss-of-control accidents involving large trucks was done at UMTRI in 1986. (Ervin et al.,). This thorough and innovative study of the relationship between geometrics and large truck accidents integrated statistical analysis with computer simulation of the interaction between the roadway and the vehicle. It is relevant to note however that this research effort concentrated on single vehicle rollovers, jackknifing and run-off-the-road accidents which constitute less than 6% of all large truck accidents at interchanges.

In the absence of the reliable truck exposure data on ramps, the UMTRI team used the files from the FHWA Office of Motor Carriers as a convenient data set for comparing States. The proportion of truck accidents which occurred on ramps was used as a measure of overrepresentation or ramp-related truck accidents. However, this did not account for the proportion of travel which was on ramps or the relative number of interchanges per mile of highway. A number of regressions were used to examine measures of overrepresentation of ramp accidents among the States using the highway mileage and population. Ten candidate States were selected as a result of this analysis. The DOT in each State was asked to identify approximately six ramps which have had a substantial involvement of large trucks in ramp accidents. The selection was to be based on overinvolvement relative to average daily traffic, or on large number of accidents if the truck ADT were not available. The responses of the States were positive but varied in details and led to the selection of 15 ramps at 11 interchanges in 5 States.

Ervin et al., used a simulation model developed by UMTRI to represent the dynamic response of the trucks along each of the selected ramps. The UMTRI model, which is capable of representing the behavior of commercial vehicles ranging from straight trucks to triple combinations, was used to diagnose specific problems which led to the loss-of-control of the vehicle. Dynamic simulation of commercial vehicle responses to ramps with a history of accidents showed that the leading vehicle-related causes of loss-of-control are as follows:

- Low roll stability
- High speed offtracking
- Limitations in braking control
- Difficulties in controlling speed on short downgrades
- Limited acceleration ability for effective merging and weaving

Geometric design features of the ramps identified in the UMTRI study which precipitated conditions leading to a loss-of-control are as follows:

- Poor superelevation transition on curves creates high levels of side friction demand that increase the threat of rollover.
- Abrupt changes of curvature in compound curves which often places excessive demands on the driver leading to rollovers.
- Short deceleration lane leading to tight-radius exit also places excessive demands on the driver and increases the possibility of jackknifing because of excessive braking or rollovers due to loss of control.
- Curbs placed on the outside of a ramp curve found to serve as a tripping agent in rollover accidents.
- Downgrade leading to a tight curve may lead to rollovers due to inability to decelerate adequately prior to negotiating a curvature.

- Reduced pavement friction on high-speed curves in wet weather leads to hydroplaning of lightly loaded trucks and subsequent loss-of-control problems.

A 1993 study *Ramp Signing for Trucks* by Knoblauch and Nitzburg addressed methods for identification and treatment of ramps with geometric characteristics that can cause trucks to overturn. The emphasis of this study is on ramp signing design which would alert the drivers of rollover potential. The study showed that although many States have developed specific treatments for locations with truck rollover problems, there are no specific procedures to identify those locations except waiting for truck rollover accidents to occur. The authors make an assertion that this approach is not as irresponsible as it may first appear because serious truck rollover problems are relatively rare. Unlike other studies this effort directly involved truck drivers in the process to obtain their perception of the problem and identify solutions. The authors conducted the "design-a-sign" experiment with 61 professional drivers to identify most effective sign design features which convey warning of potentially dangerous ramps. This experiment suggests that signs which perform best include the following elements:

- Rear silhouette of a tipping truck
- Diagrammatic curve arrow
- Advisory speed limit
- Word legend - "ROLLOVER HAZARD"
- Word legend - "TRUCK CAUTION"

The laboratory studies also clearly indicate the desirability of using advance signing located well before the ramp and the desirability of using flashing light in combination with these signs.

2.3 STUDIES EXAMINING THE RELATIONSHIP BETWEEN DESIGN STANDARDS AND TRUCK CHARACTERISTICS

A 1990 study by Harwood et al., presented the most thorough examination to date of *Truck Characteristics for Use in Highway Design and Operation.* The objectives of this study were as follows:

- Identify those highway design and operational criteria that are sensitive to truck performance characteristics.
- Determine the adequacy of those criteria for trucks.
- Develop and assess new criteria for those situations where the current criteria do not adequately address the current or future truck population.

The study was primarily analytical in nature with only occasional measuring or testing of the vehicles. Harwood et al., identified 16 highway design criteria based on vehicle characteristics. Each criterion was then evaluated to assess its adequacy for the fleet of large trucks. In the process of evaluation, the authors presented a sensitivity analysis for each criterion to the changes in truck characteristics associated with vehicle evolution.

Some of the selected findings from this study related to the criteria used in interchange design are presented below:

> Current AASHTO criteria are not adequate to accommodate trucks with conventional braking systems and poor performance drivers. Many drivers have little experience with the proper procedures for controlled braking in emergency situations.
>
> Trucks may require 100 to 400 ft more decision sight distance than passenger cars at a design speed of 70 mph, and lesser amounts of additional decision sight distance at lower design speeds.

The higher driver eye height for trucks offsets the increased decision sight distance requirements in most cases at vertical sight restrictions, but not at horizontal sight restrictions.

A change in decision sight distance criteria to accommodate trucks by using longer vertical curves on the approach to major decision points would be cost effective only in unusual situations with extremely high accident rates.

Based on the Gillespie (1986) model for intersection clearance times, the larger trucks currently on the road require up to 17.5 percent more sight distance for an intersection crossing maneuver than the current AASHTO criterion based on a WB-50 truck.

Trucks with conventional brake systems may require sag vertical curves up to 670 ft longer than current AASHTO criteria.

Current AASHTO criteria for horizontal curve radius and superelevation at particular design speeds are adequate to accommodate trucks. The existing criteria provide margins of safety against skidding off the road and against rollover that are substantially lower for trucks than for passenger cars.

Current superelevation transition methods appear adequate to accommodate trucks. Use of spiral transitions is preferable to the traditional 2/3-1/3 rule.

Increased emphasis is needed on the realistic selection of design speeds for horizontal curves, particularly on freeway ramps. It is critical that design speeds selected for off-ramps are consistent with the design speed of the main line highways. It is recommended that the lower range values of ramp design speeds presented in the AASHTO Green Book not be used for roadways that carry substantial volumes of truck traffic.

Revised criteria for pavement widening on horizontal curves are needed to accommodate STAA single 48-ft semitrailer trucks.

Advance warning sign criteria for trucks with conventional brake systems should be longer than the current criteria which are based on consideration of passenger cars.

The highway design and operational criteria examined in the study included geometric design policies based on the 1984 AASHTO Green Book and the 1988 edition of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD). Since the publication time of the Harwood et al., study there were 2 new editions of the Green Book, in 1990 and in 1994. While the 1994 edition primarily addressed the question of metrification, the 1990 Green Book introduced additional design vehicles for incorporation into the geometric design criteria. These design vehicles have longer wheel bases and greater minimum turning radii. They include tractor-trailer combinations listed below:

- *Interstate Semitrailer WB-62*, Design vehicle with 48' trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).
- *Interstate Semitrailer WB-67*, Design vehicle with 53' trailer as grandfathered in 1982 (STAA).
- *Triple Semitrailer WB-96*
- *Turnpike Double Semitrailer WB-114*

The Green Book states that the facility must be designed to accommodate the largest vehicle likely to use it with considerable frequency, but it leaves a great deal to the discretion of the individual design engineer by not defining what a considerable frequency is. Although turnpike doubles and triple trailers are not permitted on many highways, their occurrence warranted inclusion of these vehicles in the Green Book. Inclusion of these vehicles into the 1990 edition of Policy on Geometric Design of Highways and Street does not automatically spell out the retrofit of older interchanges which present most of the problems for larger trucks.

According to a survey jointly conducted by AASHTO and DOT (The Feasibility of a Nationwide Network of LCV's, FHWA 1986) "...a majority of interchange ramps had inadequate geometry to accommodate the off-tracking of some larger combinations. State DOTs estimated that approximately 43 percent of the Interstate interchanges could safely accommodate triples, 34 percent could accommodate Rocky Mountain doubles and only 25 percent could accommodate turnpike doubles. State DOTs also estimate that only one half of all Interstate Interchanges can safely accommodate WB-62 Interstate Semitrailer with 48 ft trailer."

Another significant development which influences the relationship between vehicle performance and highway design standards is recently passed legislation proposed by NHTSA on the antilock braking system and maximum stopping distance requirements for heavy trucks. 49 CFR Part 571 requires medium and heavy vehicles to be equipped with an antilock brake system to improve directional stability control of these vehicles while braking. By improving directional stability and control, these requirements will significantly reduce deaths and injuries caused by jackknifing and other losses of directional stability and control during braking. It also specifies distances in which different types of medium and heavy vehicle configurations must come to a complete stop from 60 mph on a surface with peak friction coefficient (PFC) of 0.9. These requirements are designed to reduce the number and severity of crashes involving trucks and buses.

The requirements set forth in the 49 CFR Part 571 pertaining to ABS and maximum braking distances apply only to new trucks and buses and will not require retrofit of the existing vehicle fleet. While these changes will go a long way in improving truck safety it is important to realize that this change will take place gradually and over time.

Chapter Three

STUDY DESIGN AND ANALYSIS APPROACH

3.1 OVERVIEW OF ANALYSIS APPROACH

Taking into account data availability and previous research, the primary objectives we sought to achieve in the data gathering and statistical analysis steps of this project were to:

1. Identify requirements of a comprehensive truck accident database to be used for highway improvement studies as part of a state's safety management system.

2. Statistically compare truck accident experiences of many different ramp designs in three states (Colorado, California, and Washington) so as to examine the effects of their design on interchange safety and recommend possible design improvements.

3. Develop a procedure to identify "high risk" locations for remedial action to improve safety using this truck accident database.

4. Include the experiences and observations of truck drivers and fleet managers to identify and assess problem locations, and to develop candidate safety improvements and risk mitigation strategies.

We tackled several research issues during the study such as (i) how to best estimate missing data from available information, and (ii) how to best use the available and estimated data to validly compare and contrast the accident experiences of different ramp geometric designs and traffic characteristics. We later explain the methods used in this study to address these issues.

We identified the following data as the minimum requirements of a truck accident database needed to make statistical comparisons of ramp accident experiences and to recommend potential improvements. We then obtained these data (to the extent possible) for truck accidents at interchanges in each state.

1. General Location Identifiers
   - interchange type (e.g., diamond, directional, etc.).
   - ramp type (e.g., diamond, loop, directional, etc.).
   - ramp connection type (freeway-to-freeway, freeway-to-arterial, etc.).
   - conflict area (e.g., merge, diverge, upstream, downstream, etc.).
   - accident location (route mile post) and direction of travel.
   - main and secondary route identifiers (perhaps both freeways).
   - highway lane or ramp section in which accident occurred.

2. Traffic, Road, and Accident Characteristics
   - numbers and types of vehicles involved.
   - fatalities, injuries, and property damage.
   - date, time-of-day, road and weather conditions.
   - accident type (e.g., sideswipe, rearend, rollover, etc.).
   - length of merge/diverge area from taper to gore (or vice-versa).
   - length of ramp from secondary connection to merge/diverge area.
   - distance of accident upstream from center of merge/diverge area.
   - distance of accident downstream from center of merge/diverge area.
   - average daily traffic and truck percentage on the main line (MADT).
   - average daily traffic and truck percentage on the ramp (RADT).

We needed "ramp truck ADT" (RTADT) as a measure of truck exposure at each ramp in order to compare truck accident rates by ramp design. Although ramp truck ADT's are not generally available, WSDOT was able to provide ramp truck ADT's that coincided with the study period for over 250 ramps. This sample allowed us to estimate ramp truck ADT's where missing based on the ramp ADT's of all vehicles. We explain our estimation of ramp truck ADT's further in Chapter 4.

3.2 ACCIDENT COMPARISONS OF INTEREST

Below are listed the key questions that we investigated on truck accidents at interchanges for Colorado, California, and Washington.

1. Do numbers of truck accidents or truck accident rates per truck trip or truck VMT (vehicle miles of travel) differ by ramp type, conflict area, or the combination of these two classifications?

2. Do these findings differ significantly by accident type?

3. Do these findings differ significantly by high, medium, or low ADT of trucks or all vehicles on the ramps or in the main freeway lanes due to greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes?

4. Do these findings differ significantly both upstream and downstream of the merge/diverge area?

5. Do these findings differ significantly for different lengths of the accel/decel lanes plus tapers?

We'll discuss data availability from each state in explaining our data collection procedures in Chapter 4. Because some required data elements were unavailable from both Colorado and California, we were only able to investigate all the above questions for Washington, and still needed to estimate some data elements such as ramp truck ADT's. In Chapter 7, we recommend future data collection by state DOT's for safety management systems.

In our analyses, we were careful to distinguish between accidents either (1) on the ramps, or (2) on the main freeway lanes near the ramps. In preparing our truck accident database, we distinguished all accidents at intersections connecting ramps to arterials, and excluded all intersection accidents from our accident comparisons.

We compare accident frequencies and rates by (i) numbers of ramp locations, (ii) truck trips on these ramps, and (iii) truck travel distances at these locations by (a) ramp type, (b) conflict area, and (c) accident type. These multiple comparisons allow us to examine the separate effects of location, truck use, and travel distance. Comparing truck accidents per ramp truck trip (RTT) is similar to comparing intersection accidents per "vehicle entered" where types and numbers of conflict points are more important than travel distances. Although ramps involve greater travel distances than intersections, most accidents occur near conflict points, where numbers of vehicles passing may be more critical than vehicle miles of travel. To examine travel distance effects, we compare accident rates per ramp truck trip and per ramp truck VMT. We discuss this point further in Chapter 4.

3.3 TRUCK DRIVERS' SURVEY AND FOCUS GROUP

High percentage of truck accidents concentrating in and around relatively small areas of interchange influence identified a need for additional information relating to difficulties of navigating a large truck through an interchange. In the opinion of the study team, important insight into this phenomenon can be gained from discussing this issue with truck drivers and safety managers themselves. In order to develop greater understanding of the relationship between truck accidents and the geometric design of interchanges the study team has developed and administered a series of surveys targeting truck drivers and safety managers operating in Colorado.

The first survey was administered at the annual Truck Rodeo in Denver and provided input from 84 truck drivers. The drivers filled out a survey form asking them to identify five interchanges most difficult to travel, and indicate reasons why using a rating scale of 1 through 5.

The second survey was administered at the monthly safety managers meeting of the Colorado Motor Carrier Association (CMCA). The second survey form itself was somewhat modified to better reflect the specifics of the group and to incorporate the knowledge gained in the survey administration at the Truck Rodeo. Only 13 safety managers filled out the second survey. Survey forms, a statistical summary of responses and focus group results are available in the appendix.

The results of both surveys identified a very broad spectrum of factors contributing to truck accidents as well as a long list of "difficult" interchanges as perceived by the drivers and safety managers. It is apparent from the statistical summaries of both surveys that opinions expressed by the participants were highly divergent and did not identify well pronounced trends in truck accident causality, nor did they exhibit locational consistency. The study team attributes this diversity of opinions to the heavy route-specific bias of survey participants. In other words, there is a natural tendency to have the best recollection of the most recent accident event or most recently traveled route. This phenomenon is known as *availability bias.* Furthermore little correlation was found between the "worst" interchange locations identified in the surveys and "worst" accident locations identified through statistical analysis of the accident history by the study team. In order to overcome the availability bias the study team used a Focus Group approach to gathering information from truck drivers and safety managers.

A group of 10 individuals representing a cross section of truck drivers and safety managers was presented with the layouts of 14 "worst" interchanges identified through statistical analysis of large truck accident history at interchanges in Colorado over the last 3 years. The focus group was then asked to point out the difficulties of driving a large truck through each interchange and identify possible strategies for improvement. The focus group's input and design drawings of problem interchanges are included in the appendix with the summary list of the improvements recommended by the focus group participants provided below:

- Improve maintenance of striping in high volume areas
- Provide more advanced signing
- Provide recommended speed signs on ramps directed at truck traffic
- Improve clarity of overhead signs
- Provide brighter sign panels with flashing lights

- Include schematic diagrams of interchange configurations on signs
- Redirect trucks to easier ramps if possible
- Provide additional education to truck drivers with respect to interchanges and ramps
- Install rumble strips in gore areas to alert drivers
- Improve overall visibility and communication through signing

As is evident from the above summary list, the most frequently expressed concem during the focus groups' session pointed to the inadequacy of waming and guidance provided to the truck drivers in problem areas. This observation can be interpreted as such: accidents often are not attributed to some specific geometric design features or feature which when present are sure to cause a crash involving a large truck at an interchange, but rather to a discrepancy between what the driver expects and what he actually encounters on the road. This phenomenon is known as the *driver expectancy violation.* Expectancy relates to driver's readiness to respond to situations, events, and information in predictable and successful ways. Aspects of the highway situation that match prevalent expectancies aid the driving task, while expectancies that are violated lead to longer reaction times, confusion and driving error. Violations of driver expectancies effect trucks even more adversely than passenger cars because of their dimensions and operating characteristics.

The case history at a rural interchange in northem Colorado illustrates this point rather well. At this location restrictive geometrics not expected in the open rural environment led to a series of single truck rollovers. Having identified this problem using statistical analysis and following the discussion with the focus group, the CDOT designed and installed waming signs to alert the truck drivers. In order to evaluate the effectiveness of the countermeasures applied at this location an observational before-and-after study was conducted. The results of the study are available in the appendix.

Another example of the driver expectancy violation can be observed at an interchange in an urban area of Colorado where the truck drivers are presented with a left-hand merge onto the freeway. Although a continuous lane is provided the truckers are anxious to change lanes in anticipation of a lane drop, which leads to an unusually high number of sideswipes.

Another problem identified by the focus group participants was signing and striping at interchanges. In response to this concern the study team initiated review of signing at selected interchanges with the CDOT Staff Traffic Branch. Following the review we observed that inadequate interchange spacing at the selected interchange sites complicates signing and often leads to accidents. As a result, interchange spacing was introduced into the data-set of geometric characteristics for further analysis.

In the process of review of selected interchange locations by the CDOT Staff Traffic Branch, it has been discovered that a substantial number of accidents were influenced by the on-going construction in the areas adjacent to interchanges as well as temporary phase-construction conditions. The presence of these factors affected the degree of significance we can attribute to these observations.

The focus group session combined with statistical analysis of accidents involving large trucks made it more apparent that the effects of specific geometric design features are better understood within the context of an interchange environment. In order to capture driver expectancy violations future research efforts should focus on interchanges with similar configurations operating in similar environments. This comparative analysis represents an important area of future research and may explain why one location is safer than the other by concentrating on specific features, which may include geometric characteristics as well as signing.

Chapter Four

DATA ACQUISITION AND PREPARATION

4.1 TRUCK ACCIDENT DATA SOURCES

The primary source of truck accident data in most any state is the state DOT, although it may be necessary to supplement the DOT data with data from police accident reports. Of the states we contacted, Washington State DOT (WSDOT) had compiled the most complete accident database, with location codes to cross-reference their computer files for traffic and geometric data. The accident recording systems in Colorado and California were not as advanced or complete at the time.

It's important to know an accident's location so as to identify its roadway and traffic characteristics. However, it's often difficult or impossible to determine exactly where an accident occurred from some accident databases. Accidents in interchange areas can occur:

1. On a ramp away from a merge/diverge area or intersection.
2. On a secondary road to which the interchange connects.
3. On a ramp, but at the junction of multiple ramps.
4. At an intersection of the ramp with a secondary road.
5. In the accel/decel lane of a merge/diverge area.
6. In the freeway through-lane adjacent to the accel/decel lane.
7. In the other freeway through-lanes of a merge/diverge area.
8. In the freeway lanes upstream of a merge/diverge area.
9. In the freeway lanes downstream of a merge/diverge area.

Once an accident's location has been identified, then other roadway data must be obtained for the same location. Invariably, the route mile post of an accident (to whatever accuracy it is known) must be used to "match" traffic and geometric data (if available) with the accident's location. It can require much time to match and compile data for each accident, even if data are in electronic form. Until state DOT's have more automated safety management systems, linking data in existing files is quite often difficult because of how the data is indexed and recorded.

4.2 DISCUSSION OF DATA DEFICIENCIES

The current situation in most state DOT's is that much data either doesn't exist or is not in computer files. Using (i) interchange drawings with route mile points, (ii) a concurrent file of highway geometrics, and (iii) police accident reports, it may be possible to identify the basic highway geometrics of each accident location such as lane widths, shoulder widths, ramp lengths, and taper lengths. We were able to identify these basic geometrics for most truck accident locations in Washington, but only for select locations in Colorado and California. We were not able to obtain several other important highway geometrics such as grades, curvatures, and sight distances for any state.

Due to data deficiencies, the issue of defining and obtaining the appropriate truck exposure measure was quite difficult to resolve. Ideally, we would like to know truck and car volumes passing the accident location at the time of the accident. Hourly volumes are generally not available, but WSDOT did provide us with ADT's for most roads and ramps where truck accidents occurred. Thus, we used ADT's to estimate exposure, assuming that time-of-day traffic volume and mix variations do not significantly effect accident rates. We have limited evidence from another FHWA truck accident database that time-of-day traffic variations have some, but less-than-significant effects on accident rates per vehicle passing.

Collecting a comprehensive truck accident database for Colorado and California comparable to the WSDOT data was far beyond the resources of this study. Without performing our own on-site surveys, the data available from those states is much less complete regarding accident locations, traffic volumes on the main lanes or ramps, and geometric characteristics of the ramp area. Our efforts to identify and obtain the data we needed from Colorado and California helped us to design and assemble our dataset for Washington more efficiently.

We decided to emphasize the use of Washington State data because it contained (i) ADT's on the main lanes and ramps at each interchange, (ii) truck ADT's for some ramps, and (iii) computerized drawings with route mile points, accident locations, and the general geometry of each interchange. Other accident characteristics such as number of vehicles, actions of drivers, weather conditions, and extent of injuries were linked by accident ID number to another data file.

A paramount concern was to obtain ramp truck ADT's for a sufficient number and variety of ramps where truck accidents did not occur so as not to underestimate the truck exposure of any ramp type. It was beyond the scope of this study to obtain ramp truck ADT's for all Washington ramps via a special collection effort. However, the ramp truck ADT's that we did obtain or estimated to satisfy our study design automatically included a sufficient coverage of conflict areas at ramp locations where accidents did not occur to control for this potential bias.

The next section describes our compilation of a truck accident database for Washington. We summarize our preparation of datasets for Colorado and California at the end of this chapter, emphasizing what we did differently because of data availability. We were not able to obtain any ramp truck ADT's for Colorado or California with which to compare truck accident rates per ramp truck trip or VMT, and instead compare truck accidents per ramp location in these states. Since ramp truck ADT's are not generally available from most states, we explain in Chapter 6 how accident frequencies per location can be used to identify high-risk locations.

4.3 PREPARATION OF THE WASHINGTON DATABASE

This section describes the truck accident database that we compiled from information sent to us by WSDOT. Section 3.2 listed the key questions regarding truck accidents that we sought to answer with this data. This database includes data for all truck accidents at *all* interchanges in Washington over the 27 months from January 1, 1993 to March 31, 1995.

WSDOT maintains very comprehensive accident and traffic data for their state highways. Except for ramp truck ADT's, very few data elements pertinent to this study were missing for any truck accidents near interchanges. The route mile point of each accident is provided to within ten feet accuracy. Using interchange drawings with route mile points and a corresponding file of highway geometrics, we were able to identify the basic highway geometrics of each truck accident location such as lane and shoulder widths, ramp and taper lengths, and lengths of accel/decel lanes. As mentioned earlier, we were not able to obtain other highway geometrics such as grades, curvatures, or sight distances.

We assembled our dataset from five basic data files provided by WSDOT. These were:

1. A computer listing of truck accident characteristics at interchanges containing the data elements listed in Table 4.1 (approximately half of the data elements in WSDOT's database listed here).

2. A computer listing of freeway ADT's by route mile post (see Table 4.2 for an example page of this listing).

3. A computer listing of ramp ADT's by route mile post (see Table 4.3 for an example page of this listing).

4. A computer listing of geometric design characteristics by route mile post (see Table 4.4 for an example page of this listing).

5. Computer drawings of each interchange with truck accident locations indicated by route mile post (see Figure 4.1 for an example of these drawings).

Using each accident's route mile post as its common identifier in each computer file, we were able to combine the data in the above files into one database. We excluded all accidents on secondary roads or ramps at intersections, but included all freeway-to-freeway accidents. If the route mile posts of two or more accidents were very close, then their traffic characteristics and highway geometrics were similar. However, based only on route mile posts, it was often difficult to determine whether an accident specifically occurred in the freeway lane or the accel/decel lane of a ramp connection area. Although the WSDOT dataset did include a lane identifier for each accident, we decided for this study to group all accidents into four separate conflict areas as defined in Chapter 5. Hence, we grouped all accidents in or adjacent to accel/decel lanes as being in ramp connection areas as defined in Chapter 5.

Merging data from the above five files into one file is more easily done if available in electronic form. We re-entered the data from hardcopy listings due to some format difficulties. Although this effort was labor intensive, we were able to verify and cross-check the data as we entered it. In select cases where a piece of data (such as an ADT value) was missing, the process often allowed us to obtain the missing value from another accident record previously entered for the same location.

In summary, the accident data that we directly extracted from the WSDOT computer files and coded into our database for each accident were:

1. Accident location (route mile post) and direction of travel.

2. Main and secondary route identifiers (perhaps both freeways).

3. Accident type (e.g., sideswipe, rearend, rollover, etc.).

4. Freeway lane number or place on ramp where accident occurred.

Accident data that were not directly available from the WSDOT computer files, but which we added to our database based on our interpretation of the WSDOT data and drawings of interchanges, were:

1. Interchange type (e.g., diamond, directional, etc.).

2. Ramp type (e.g., diamond, loop, directional, etc.).

3. Ramp connection type (freeway-to-freeway, freeway-to-arterial, etc.).

4. Conflict area (e.g., merge, diverge, upstream, downstream, etc.).

We started with detailed differences in interchange and ramp design, and then condensed our classification into fewer categories so as to disregard small differences and not have too few observations in any one crossclassification. Our accident comparisons in Chapter 5 are mainly made between different ramp types and conflict areas. Figure 4.2 shows the four basic ramp types by which we classified all truck accidents, and we define the conflict areas of each ramp by which we also classified these accidents in Chapter 5.

Lastly, using a printout of traffic counts and geometric drawings by route mile post, and a supplemental list of 250 ramp counts with truck percentages, we added to our database the additional accident characteristics listed below.

1. Length of merge/diverge area from taper to gore (or vice-versa).

2. Length of ramp from secondary connection to merge/diverge area.

3. Distance of accident upstream from center of merge/diverge area.

4. Distance of accident downstream from center of merge/diverge area.

5. Main road average daily traffic (MADT) and truck percentage.

6. Ramp average daily traffic (RADT) and truck percentage.

Field #	Accident Data Elenents
1	Year
2	Month
3	Day of Month
4	Day of Week
5	Hour
6	Minute
7	County Number
8	City Number
9	State Route Number
10	State Route Milepost
11	WSDOT District Number
12	Urban/Rural Location
13	Functional Class of Road
14	Accident Severity
15	Number of Injuries
16	Number of Fatalities
17	Most Severe Injury of Accident
18	Number of Vehicles in Accident
19	Amount of Propery Damage ($)
20	Character of Roadway
21	Location of Roadway
22	Roadway Surface Conditions
23	Weather Conditions
24	Light Conditions
25	Ramp Location
26	Vehicle 1's Movement
27	Diagram Accident Type
28	Vehicle 2's Movement
29	Impact Location
30	Collision Type
31	Object Struck
32	Accident Occurred On or Off Road
33	Driver 1's 1st Contributing Cause
34	Driver 1's 2nd Contributing Cause
35	Driver 2's 1st Contributing Cause
36	Driver 2's 2nd Contributing Cause
37	Driver 3's 1st Contributing Cause
38	Driver 3's 2nd Contributing Cause
39	Driver 1's Vehicle Actions
40	Driver 2's Vehicle Actions
41	Driver 3's Vehicle Actions
42	Vehicle 1's Type
43	Vehicle 2's Type
44	Vehicle 3's Type
45	Most Alcohol Impaired Driver
46	Driver 1's Age
47	Driver 2's Age
48	Driver 3's Age
49	Hazardous Materials Being Transported
50	Fuel Spillage Due to Collision
51	Pedestrian/Pedalcyclist 1's Injury
52	Pedestrian/Pedalcyclist 1's Age
53	Pedestrian/Pedalcyclist 1's Actions

Table 4.1: Listing of Washington State Accident Data elements

STATE OF WASHINOTON - OEPARTMENT OF TRANSPORTATION
T R I P S S Y S T E M
ANNUAL TRAFFIC REPORT

STATE ROUTE	STATE ROUTE MILEPOST	LOCATION	COUPLET	FUNCT CLASS	TRUCK PERCENTAGES SNGL	DBL	TRIPLE	TOTAL	AVERAGE DAILY TRAFFIC VOLUME 1991 UNITS	1992 UNITS	1993 UNITS	1994 UNITS
090	016.31	AFTER RAMP SR 900		5					47000	49000*	50000	57000*
090	017.69	AFTER RAMP 228TH AVE SE		5					28000	33000*	33000	35000*
090	018.38	AFTER RAMP E SUNSET WAY		5					32000	35000*	36000	37000*
090	020.75	AFTER RAMP HIGH POINT RD		5					33000	34000*	35000	38000*
090	023.54	AT ADC LOCATION S828		5					29000*	31000*	31000*	33000*
090	026.21	AFTER RAMP SR 18		5					40000	44000*	46000	45000*
090	030.23	BEFORE RAMP SR 202		5					37000*	33000*	34000	35000*
090	031.00	AFTER RAMP SR 202		5					27000*	32000*	33000	31000*
090	033.56	AT ADC LOCATION R039		5					24000*	25000*	26000*	27000*
090	035.00	AFTER RAMP EDGEWICK RD		5					20000*	26000*	24000*	26000*
090	041.75	BEFORE RAMP TINKHAM RD		5								28000*
090	047.98	AFTER RAMP TINKHAM RD		5					23000	20000*	21000	25000*
090	051.98	BEFORE RAMP SR 906		5					20000*	21000	22000	22000
090	051.98	AFTER RAMP SR 906		5					19000*	20000	20000	23000*
090	052.61	BEFORE RAMP E SUMMIT RD		5					22000	24000	24000	23000*
090	061.34	BEFORE PRICE CREEK REST AREA		5	04	13	04	21		22000+	23000	25000
090	064.23	AFTER RAMP CABIN CREEK RD		5					18000*	19000	20000	21000
090	070.60	AFTER RAMP WEST EASTON RD		5					17000*	18000	21000*	23000
090	073.84	BEFORE RAMP W NELSON RD		5	04	14	04	22	16000	19000+	20000	22000
090	078.88	AT YAKIMA RIVER BRIDGE		5	05	12	04	21	21000+	22000	22000	24000
090	082.70	AT ADC LOCATION 604		5						20000*	21000*	22000*
090	084.20	AT OAKES AVE		5							20000*	21000
090	088.06	AT ADC LOCATION R006		5					17000*	18000*	18000*	19000*
090	086.18	AFTER RAMP SR 970		5	05	14	05	24	13000	17000*	21000*	20000+
090	094.02	AFTER RAMP ELK HEIGHTS		5	05	16	05	26	16000	16000+	16000	17000
090	101.48	AFTER RAMP THORP RD		5	04	14	05	23	18000	18000+	18000	19000
090	106.33	AFTER RAMP SR 97		5	04	13	05	21	16000	18000	19000+	20000
090	109.89	AFTER RAMP S MAIN ST		5					18000	20000*	20000	21000

* BASED ON ACTUAL COUNT
+ SOURCE OF TRUCK PERCENTAGES

Table 4.2: Sample Listing of Freeway ADT by Route Mile Post

```
ND635A                          STATE OF WASHINGTON - DEPART.   OF TRANSPORTATION                 DATE   /27/95
                                        T R I P S   S Y     E M                                    TIME   11:10
                                        TRAFFIC COUNT HISTORY REPORT                               PAGE    1457

                                                                                        (D=DISCONTINUITY).
 0  S1 RAMP              07767   E NELSON RD TO SR 90 WB                                (C=COUPLET)......:
                                                                               (*=BASED ON ACTUAL COUNT).::
   ..DISTRICT     (* = ATR DESCRIPTION)..L D:        :          :   :M:D: TRUCK PERCENTAGES : PEAK HOUR % :       :      :ATR:::
     :                                   :E I:COUNT  : COUNT    :CNT:A:A:               TOTL:              :  AWD  :      :   :::
    :D: FEATURE  : DESCRIPTION           :G R: ID    : DATE     :TYP:N:Y:SNGL  DBL  TRN  TRCK: K     D    T :(* AWEO): AADT : YR:::
------------------------------------------------------------------------------------------------------------------------------------
 0  5 BEG RAMP   07767                   2 W HISTV6 08-03-93  YR   8                       13.7               226     180   94
                 E NELSON RD TO SR 90 WB 2 W HISTV6 08-03-93  YR   8                       13.7               226     170   93
      CTLSEC     CONTROL SECTION 1902
      INTRSECTN  CX07806-E NELSON RD

 8    MISC FEATR GORE (SR 90 WB)

 1    INTRSECTN  SR 90 WB
      END RAMP   07767
```

Table 4.3: Sample Listing of Ramp ADT by Route Mile Post

Table 4.4: Sample Listing of Geometric Design Characteristics by Route Mile Post

.N01A0J　　STATE OF WASHINGTON - DEPART　　OF TRANSPORTATION　　DATE 06/　5

T R I P S　S Y　T E M　　TIME 17:　5

STATE HIGHWAY LOG　　PAGE　1441

0　S1 RAMP 07767　　INTERSTATE - ISSH　　COUNTY KITTITAS　　DOT DISTRICT 5

0	ARM	FEATURE	DIRECTION TO INVENTORY 0	LEFT/RIGHT INDICATOR LR	DESCRIPTION	BRIDGE-UXING-XROAD DN	TC	L	NBR LNS D	I	WIDTH AND SURFACE INFORMATION: DECREAS/DIV LFT SHO W/S	RDY W/S	RHT SHO W/S	MEDIAN WD/S	DR	INCRES/UNDI LFT SHO W/S	RDY W/S	RHT SHO W/S	SPC USE LNS WID	TOT RDY WID	CLASSIFICATIONS: MTCE A	SE	CITY NBR	ST FC	LEGAL SPEED D	ID	T R	P K	S T
0	0.00	BEG RAMP			07767					1						4A	15A	0A		15	1	03		R5					
					E NELSON RD TO SR 90 WB																								
		CTLSEC			CONTROL SECTION 1902																								
		INTRSECTN		8	LX07006-E NELSON RD	CD		Y																					
.8	0.10	MISC FEATR		L	GORE (SR 90 WB)					1						$$$	15A	8A		15	1	03		R5					
.1	0.41	INTRSECTN		L	SR 90 WB	ST		Y																					
		END RAMP			07767																								

40

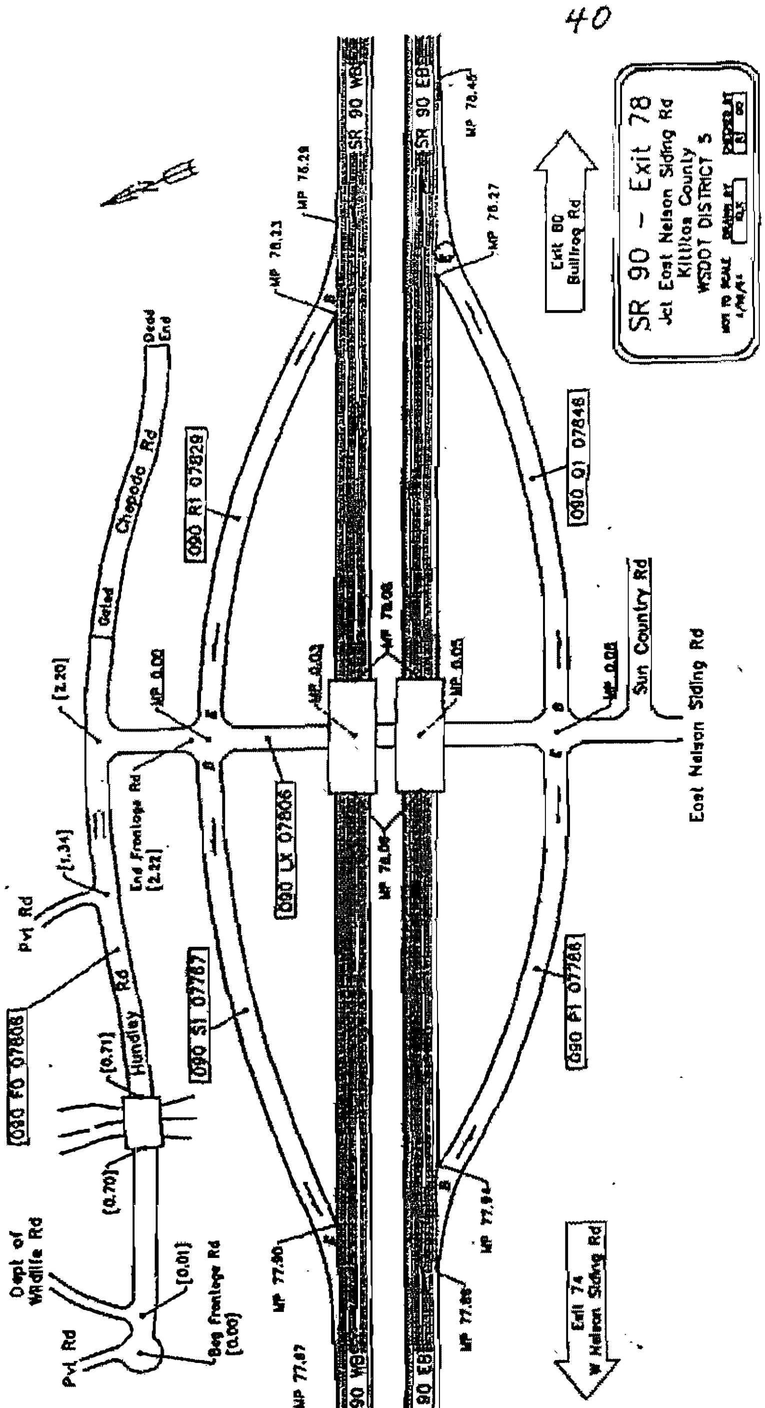
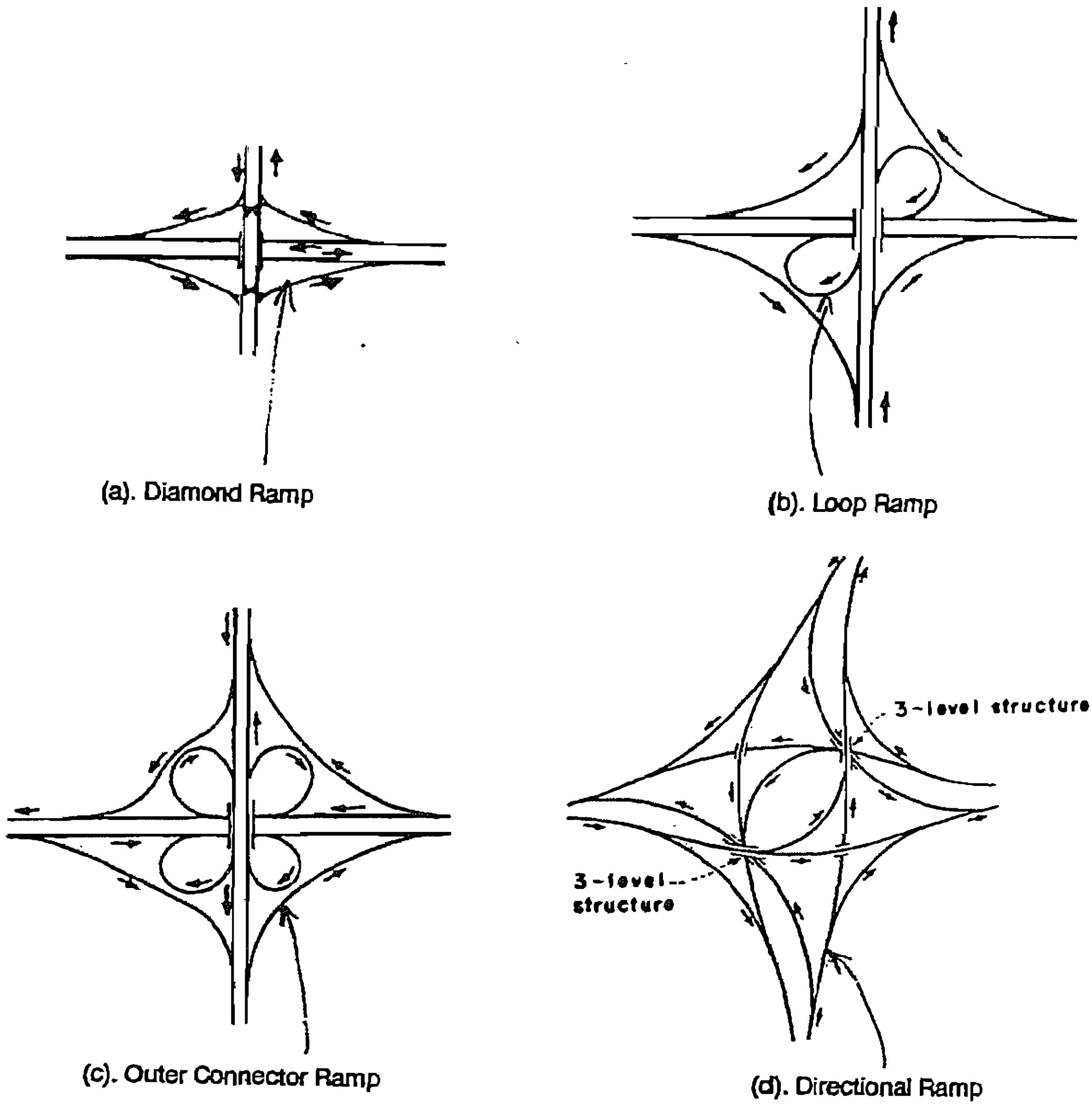


Figure 4.1: Sample Interchange Drawing with Truck Accident Locations by Mile Post



(a). Diamond Ramp

(b). Loop Ramp

(c). Outer Connector Ramp

(d). Directional Ramp

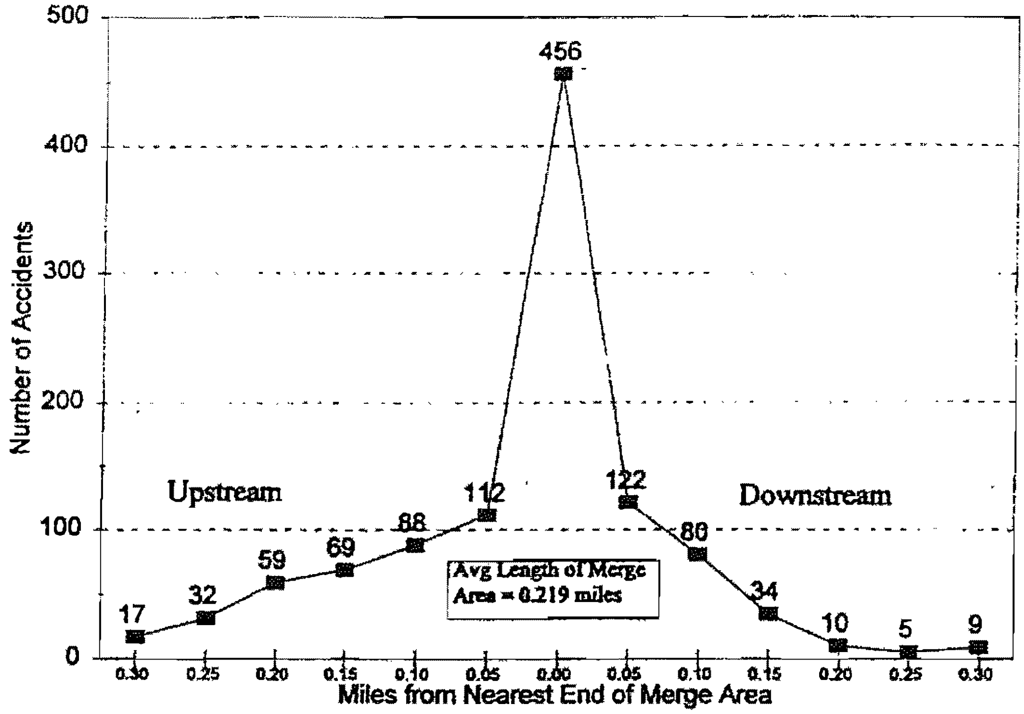
Figure 4.2: Four Basic Ramp Types

4.4 DEFINING THE RAMP INFLUENCE ZONE

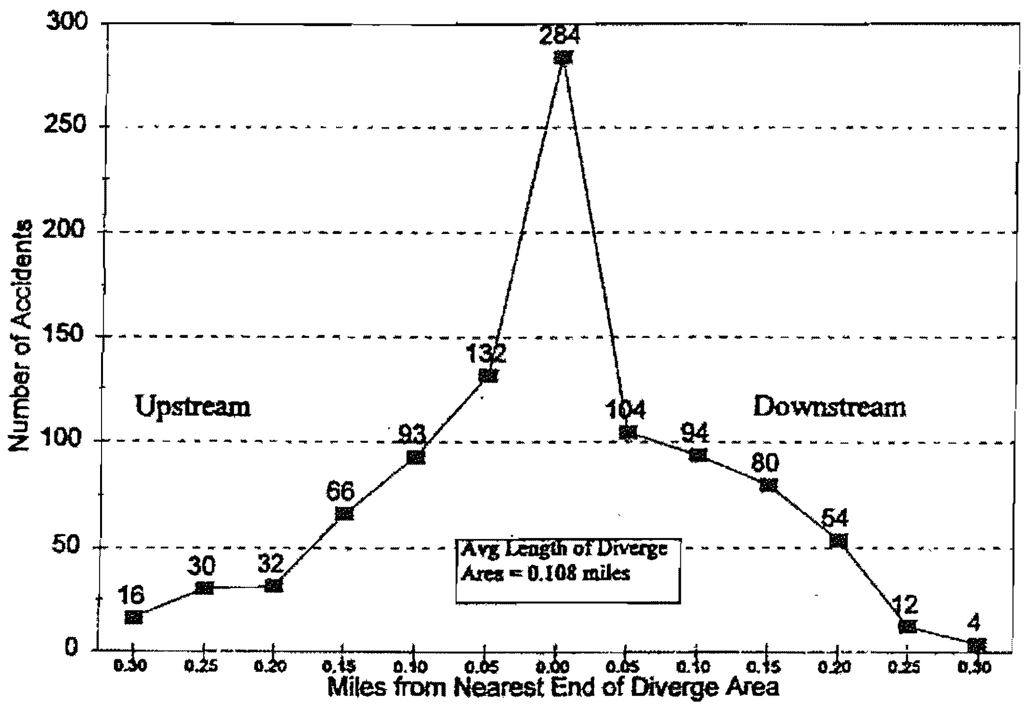
An important issue concerning accidents that were possibly affected by facility design characteristics is to define the area boundaries within which such effects are thought to be significant. To study ramp design effects, we defined this influence zone to (i) exclude intersections with arterials, (ii) be mainly confined to accidents either on the ramp, in the accel/decel lane of the ramp, or in the highway lane adjacent to the accel/decel lane of the ramp, and (iii) be within a certain upstream or downstream distance from the ramp that we next define.

One question posed in Section 3.2 concerned the effects on truck accident frequencies of upstream and downstream distances from a ramp. Figure 4.3 shows truck accident frequencies upstream and downstream from merge and diverge ramps in Washington. Upstream distances are measured in 0.05 mile increments from the tip of the merge gore or the beginning of the diverge taper. Downstream distances are also measured in 0.05 mile increments from the end of the merge taper or from the tip of the diverge gore. In the center of each figure is the frequency of accidents in the ramp connection area, which is the accel/decel lane plus adjacent freeway lanes. Note that the average length of the ramp connection area for merge ramps was 0.219 miles, but only 0.107 miles for diverge ramps.

We performed a simple test of frequency differences in successive sections of 0.05 miles either upstream or downstream from the ramp connection area for all truck accidents in our database, which were only accidents that occurred on the ramp itself, in the accel/decel lane, or in lane 1 nearest the ramp. We found that truck accident frequencies stopped changing significantly (i.e., leveled off to a similar number per 0.05 mile section) beyond 0.25 miles upstream for both merge and diverge ramps, beyond 0.2 miles downstream for diverge ramps, and beyond 0.15 miles downstream for merge ramps. The shorter downstream distance for merge ramps seems counterintuitive, but when added to the 0.219 mile average length of a merge area, the total length of 0.369 miles exceeds the combined downstream distance of 0.307 miles for diverge ramps (0.107 mile average length of a diverge area plus 0.2 miles).



a) Number of Accidents at Merge Area



b) Number of Accidents at Diverge Area

Figure 4.3: Washington Truck Accidents by Distance from Ramp Area

Figure 4.4 separates the accidents in Figure 4.3 by ramp type for lane 1 (lane adjacent to accel/decel lane) and shoulder accidents only. In comparison to other ramp types, truck accidents occur most frequently both upstream and downstream of diamond ramps relative to the frequency of accidents in the ramp connection area for both merge and diverge ramps. However, since differences in the frequencies of accidents by ramp type were found to be significant (see Chapter 5), we defined the influence zone to be the same for all ramp types as follows in order that later comparisons be consistent:

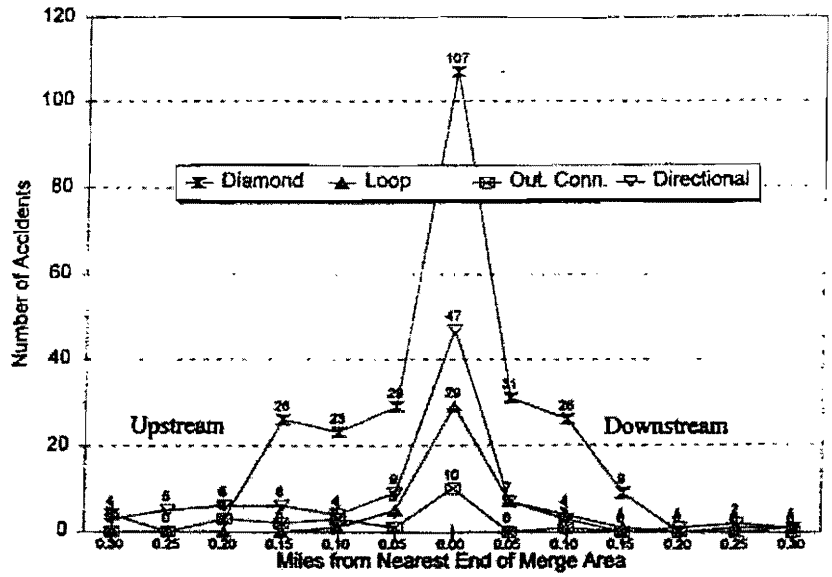
0.25 miles upstream of the tip of a merge ramp gore
0.25 miles upstream of the start of a diverge ramp taper
0.15 miles downstream of the end of a merge ramp taper
0.20 miles downstream of the tip of a diverge ramp gore

Figure 4.5 shows these influence zone distances for both merge and diverge ramps. The length of each ramp's merge/diverge connection area from the tip of its gore to the start or end of its taper was recorded and kept in our database for each ramp as indicated by its geometric drawing.

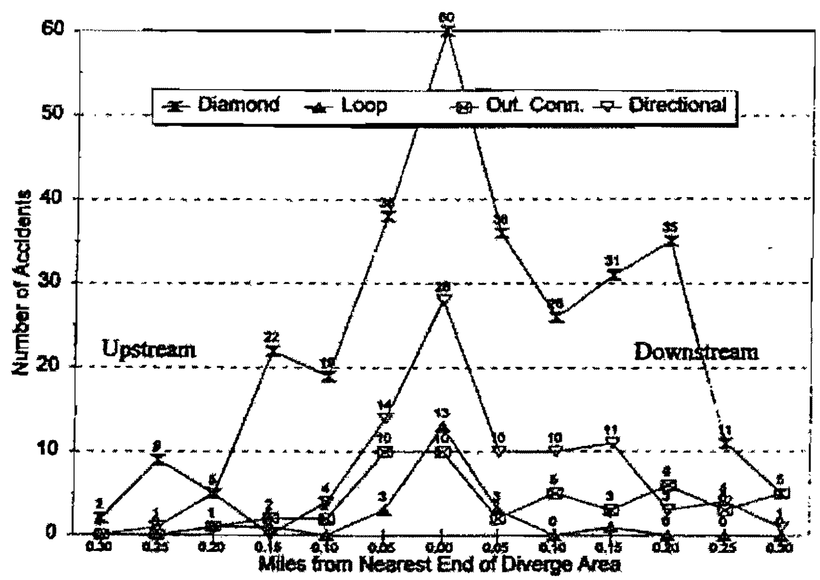
4.5 ESTIMATING TRUCK EXPOSURE MEASURES

In the next chapter, we compare accident frequencies and rates by ramp type, conflict area, and accident type in three ways so as to reveal the location, volume, and travel distance effects. We first compare average accidents per ramp location without accounting for truck volumes or travel distances. We then compare accidents per ramp truck trip (RTT) to account for the number of trucks passing.

A required data element that we estimated for locations where it was not recorded was ramp truck ADT, which we convert to ramp truck trips for the study period. Ramp truck ADT is not generally available, but WSDOT provided us with a sufficient number of ramp truck ADT's with which to estimate missing values based on the ramp ADT's of all vehicles. Figures 4.6 and 4.7 show estimated versus observed ramp truck ADT's for on and off ramps respectively, where the estimation equations are:



a) Number of Accidents at Merge Ramps



b) Number of Accidents at Diverge Ramps

Figure 4.4

Washington Truck Accidents by Distance from Ramp Area by Ramp Type

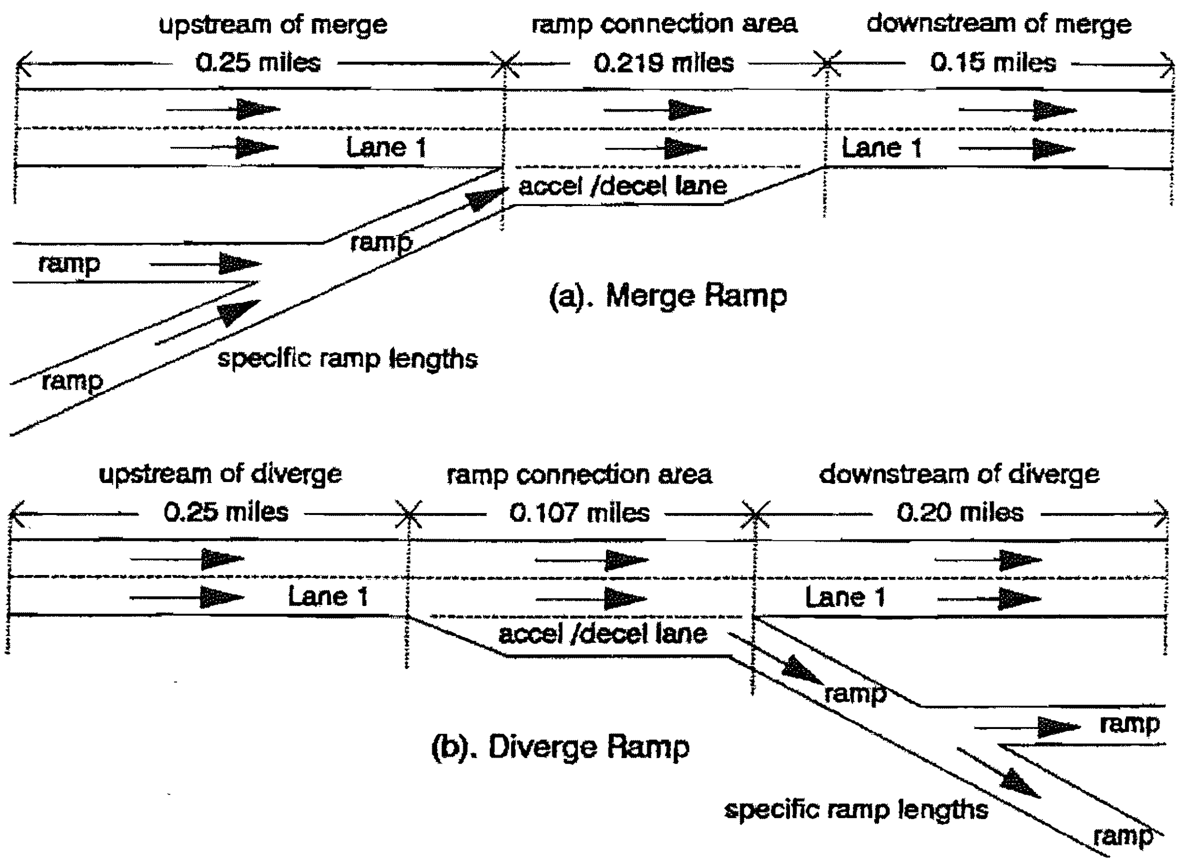


Figure 4.5: Influence Zone Distances

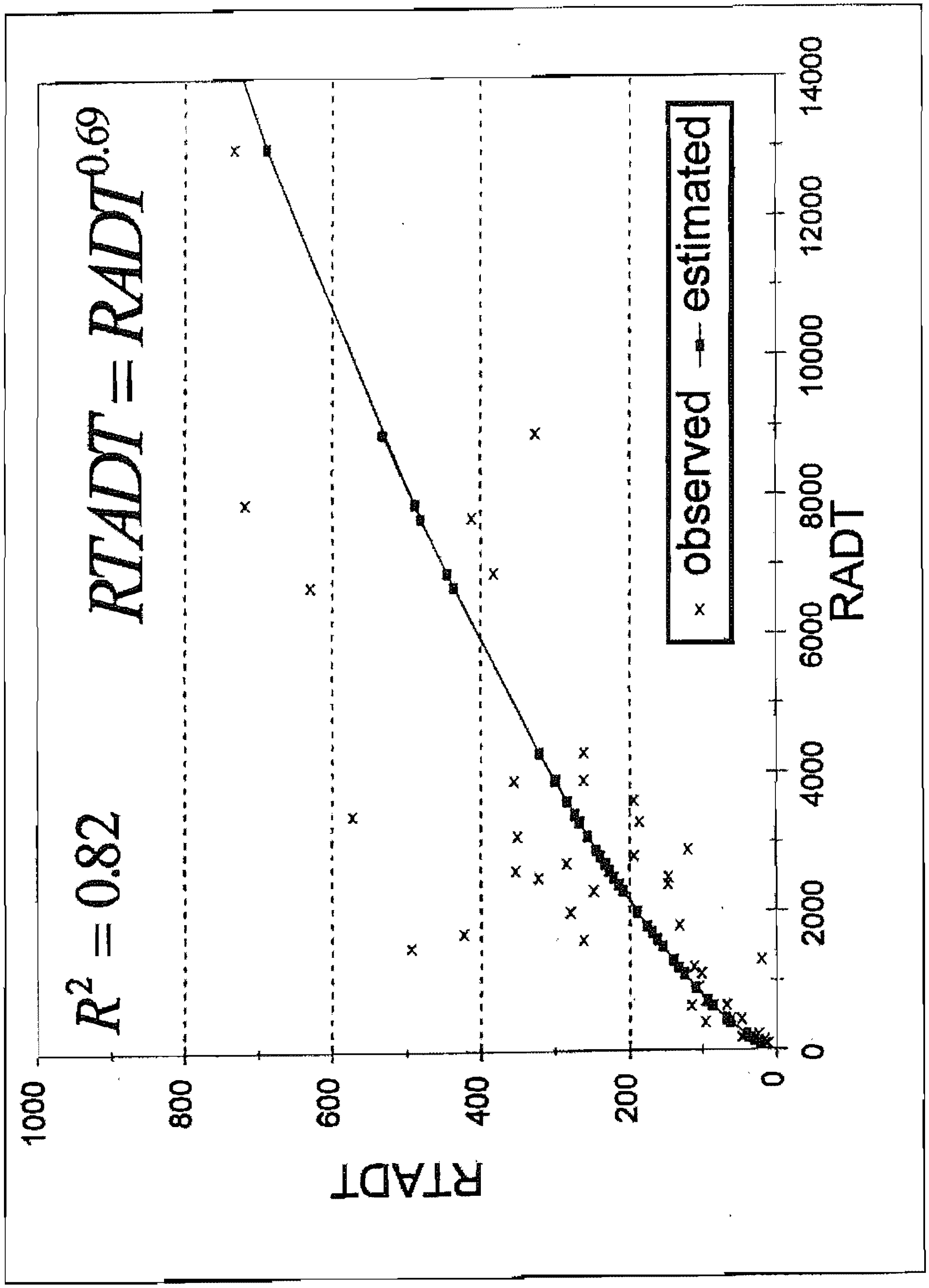


Figure 4.6

Washington On-Ramp Truck Volumes versus Total On-Ramp Volumes

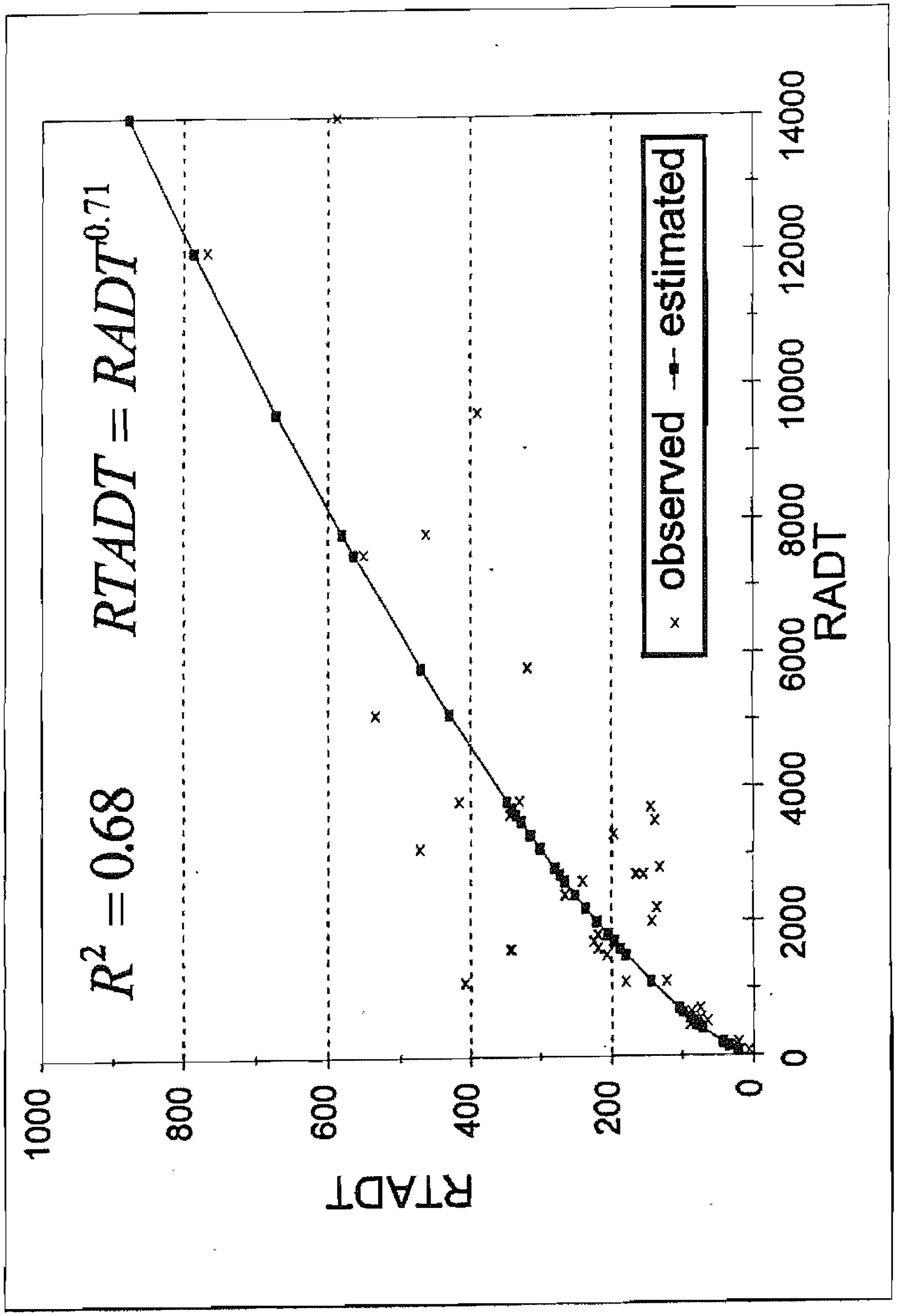


Figure 4.7

Washington Off-Ramp Truck Volumes versus Total Off-Ramp Volumes

$$RTADT = RADT^{0.69} \text{ for on ramps}$$

R-squared = 0.826, parameter's t-statistic = 131.2

$$RTADT = RADT^{0.71} \text{ for off ramps}$$

R-squared = 0.683, parameter's t-statistic = 106.2

where,

RTADT = ramp truck average daily traffic

RADT = ramp (all vehicle) average daily traffic

The above equations indicate that ramp truck ADT is a decreasing fraction of total ramp ADT as total ramp ADT increases. We fit several other equations to estimate ramp truck ADT including (i) a constant, (ii) main road ADT of all vehicles, (iii) truck ADT on the main road, and (iv) secondary road ADT of all vehicles. We also tried linear models rather than exponential models. However, the t-statistics of the other variables were not significant at the 95% confidence level for any of the other models, and the R-squared values were not much improved. Note that two independent datasets (on-ramps versus off-ramps) produced nearly the identical equation (0.69 versus 0.71) as the fitted parameter. Hence, RADT raised to the 0.7 power seems to be a fairly robust predictor for all ramps.

We believe an important predictor of ramp truck ADT would be truck ADT on the secondary road, but this data was not available for any interchange location. Certain facilities near an interchange, such as industrial plants, trucking terminals, truck stops, warehouses, and distribution centers will tend to increase ramp truck ADT as a proportion of total ADT. Absence of any such facilities, such as an interchange serving mainly residential areas, will tend to decrease ramp truck ADT as a proportion of total ADT. Examination of these specific interchange activities would require substantial surveying.

Despite their simplicity and lack of accuracy for some specific ramp locations, these equations do provide usable estimates of ramp truck ADT given the lack of better data. Ideally, state DOT's will sample ADT's and truck ADT's for a greater proportion of their ramps in the future. Only then will more accurate ramp truck ADT's be available to studies like ours without the need for estimation.

In order to not underestimate truck exposure for any ramp type, we needed to have truck ADT's for a sufficient number and variety of ramps where accidents did not occur. The ramp truck ADT's that we obtained or estimated automatically included a sufficient coverage of ramp locations and conflict areas where accidents did not occur. Hence, we were able to control for this potential bias.

4.6 PREPARATION OF COLORADO AND CALIFORNIA DATASETS

We compiled data on truck accidents at interchanges in both Colorado and California for the years 1991-1993. Since the required data was not available in electronic form from either state (including police report data, route mile points, highway geometrics, and drawings), we could not include all truck accidents at all interchanges within the analysis period as we had for Washington. Hence, we were only able to compile accident data on several hundred accidents in each state (more in California than in Colorado).

In both Colorado and California, we used three sequential criteria to identify relatively hazardous interchanges for trucks among all interchanges in each state. We first selected all interchanges with an accident severity index of 30 or greater. The severity index weighs the number of accidents over three years involving at least one truck according to the following formula:

Severity index (SI) = (12 * number of fatal accidents) + (5 * number of injury accidents) + (1 * number of property damage only accidents)

The above formula does not distinguish accidents by the number of vehicles involved, the number of injured persons or fatalities, or the extent of damage. Although such considerations could be made, the objective was to select a cross-section of interchanges, so a more specific index was not needed.

In addition to interchanges that surpassed the severity index, we also included interchanges with more than 15 accidents of any type involving trucks over three years. The first criterion considered both frequency and severity, whereas this criterion considers only frequency.

Finally, we used freeway truck ADT as an approximate measure of truck exposure through the entire interchange in order to identify interchanges that had high truck accident frequencies relative to exposure. If the interchange connected two freeways, we used the average truck ADT of the two freeways. Thus, our third criterion was whether the number of truck accidents over three years divided by freeway truck ADT exceeded 0.003. This value of the criterion was used because it identified a reasonable variety of additional interchanges beyond the first two criteria.

In summary, our interchange selection criteria for Colorado and California were:

1. Severity index of all truck accidents over three years ≥ 30

2. Number of truck accidents of all types over three years ≥ 15

3. Number of truck accidents of all types over three years divided by

   freeway truck ADT ≥ 0.003

Tables 4.5 and 4.6 list the interchanges we identified in Colorado and California for further analysis. Also shown is the interchange type, freeway ADT, truck percentage, and numbers of accidents by severity (fatal, injury, property damage only) for each location.

The data that we were able to assemble for Colorado and California directly from police reports and design drawings included:

1. Accident location (route mile post) and direction of travel.

2. Main and secondary route identifiers (perhaps both freeways).

3. Accident type (e.g., sideswipe, rearend, rollover, etc.).

4. Lane in which accident occurred.

5. Interchange type (e.g., diamond, directional, etc.).

6. Ramp type (e.g., diamond, loop, directional, etc.).

7. Ramp connection type (freeway-to-freeway, freeway-to-arterial, etc.).

8. Conflict area (e.g., merge, diverge, upstream, downstream, etc.).

Our datasets for Colorado and California are not comparable to our database for Washington in a number of ways. First, we could not obtain ramp truck ADT's or total ramp ADT's with which to estimate ramp truck ADT's. Second, we could not obtain reliable geometric measurements for each interchange during the study period. Hence, our between-state comparisons in Chapter 5 are limited to accident frequencies per ramp type, not accidents per ramp truck trip or VMT.

Table 4.5: Selected Colorado Interchanges for Accident Analysis

County	Description	Interch. Type	AVG AADT	AVG TRUCK %	# ACC. (FREQ.)	F/EXPO	P D O	I N J	F A T	INDEX
4	I - 25 & Bijou St.	Diamond	69900	3.7	8	0.0031	5	2	1	27
4	I - 25 & Fillmore St.	Diamond	74400	3.3	8	0.0033	4	4	0	24
1	I - 25 & Santa Fe	Directional	150400	2.5	11	0.0029	8	2	1	30
1	I - 25 & Speer Blvd.	Full Cloverleaf	167190	2.8	12	0.0025	9	2	1	31
1	I - 25 & Fox/38th Ave.	Partial Cloverleaf	180500	2.9	23	0.0043	19	4	0	39
1	I - 25 & I - 70	Directional T	139855	3.7	76	0.0148	60	16	0	140
12	I - 25 & SH 36	Directional	147600	3.6	11	0.0021	5	6	0	35
6	I - 25 & SH 34	Full Cloverleaf	33100	9.7	11	0.0034	6	5	0	31
11	I - 70 & Ward St.	Partial Cloverleaf	82000	3.9	14	0.0044	12	1	1	29
1	I - 70 & Pecos St.	Diamond	110300	3.8	19	0.0046	16	3	0	31
1	I - 70 & Steele St.	Diamond	94900	4.6	14	0.0032	9	5	0	34
1	I - 70 & Quebec St.	Diamond	93300	4.6	15	0.0035	13	2	0	23
1	I - 70 & I - 225	Directional	74000	7.2	16	0.0030	12	4	0	32
12	I - 70 & Chambers Rd	Diamond	30000	11.1	11	0.0033	7	4	0	27

District #	County	Description	Interch. Type	AVG AADT	AVG TRUCK	AADT TRUCK	#ACC. (FREQ.)	F/EXPO	PDO	INJ	FAT	INDEX
7	LA	JCT RTE 110&10	Semi-direct w/2 loops	289000	3.8	10880	46	0.004	38	10	0	[illegible]
7	LA	JCT RTE 605&60	Semi-direct w/2 loops	209500	11.7	24507	33	0.001	23	9	1	[illegible]
7	LA	JCT RTE 91&605	Semi-direct w/2 loops	240000	7.3	17633	55	0.003	41	13	1	[illegible]
7	LA	JCT RTE105&605	Semi-direct w/2 loops	197750	7.3	14507	39	0.003	35	4	0	[illegible]
7	LA	JCT RTE 91&710	Directional w/1 loop	220000	11.6	25461	48	0.002	32	15	1	[illegible]
7	LA	JCT RTE 5 & 10	Directional T	231000	7.6	17515	39	0.002	25	13	1	[illegible]
4	ALA	JCT RTE 24, 580 & 980	Fully Directional	200000	4.1	8239	38	0.005	35	3	0	[illegible]
7	LA	JCT RTE 60 &710	Fully Directional	173000	8.1	14044	42	0.003	35	7	0	[illegible]
7	LA	RTE 605 & TELEGRAPH RD	2-Quadrant Cloverleaf	197000	11.4	22554	19	0.001	16	3	0	[illegible]
12	ORA	JCT RTE 57 & 91	Semi-direct w/2 loops	215500	6.9	14765	29	0.002	27	2	0	[illegible]
3	SAC	JCT RTE 5 & 50	Fully Directional	113000	9.6	10848	20	0.002	12	8	0	[illegible]
7	LA	JCT RTE 101 & 110	Fully Directional (4-level	231250	2.9	6631	27	0.004	23	4	0	[illegible]
7	LA	JCT RTE 5 & 710	Semi-directional	254500	8.1	20504	24	0.001	21	3	0	[illegible]
4	SF	JCT RTE 80 & 4TH/5TH STREETS	Semi-directional	199500	5.4	10804	16	0.001	14	2	0	[illegible]
4	SF	JCT RTE 101 & ARMY ST.	Diamond	273000	4.0	10988	16	0.001	15	1	0	[illegible]
4	SCL	JCT RTE 101 & STORY RD	Directional w/1 loop	219000	6.9	15002	17	0.001	11	6	0	[illegible]
12	ORA	JCT RTE 5/22 & 57	Semi-directional	190833	6.3	11933	48	0.004	43	5	0	[illegible]
8	SBD	JCT RTE 15 & LENWOOD RD	Diamond	40250	16.2	6510	15	0.002	10	5	0	[illegible]
7	LA	JCT RTE 405 & 710	3-Quadrant Cloverleaf	208000	8.9	18590	27	0.001	18	9	0	[illegible]
12	ORA	JCT RTE 5 & 91	Semi-directional	182250	7.3	13284	22	0.002	21	1	0	[illegible]
8	SBD	JCT RTE 10 & MILLIKEN AVE	2-Quadrant Cloverleaf	206000	12.1	24928	20	0.001	12	8	0	[illegible]
8	SBD	JCT RTE 10 & ETIWANDA AVE	4-Quadrant Cloverleaf	156500	13.4	20919	22	0.001	11	11	0	[illegible]
7	LA	JCT RTE 710 & FLORENCE AVE	4-Quadrant Cloverleaf	197000	11.3	22261	18	0.001	16	2	0	[illegible]
7	LA	JCT RTE 5 & 605	Semi-direct w/2 loops	203000	9.9	19806	26	0.001	22	4	0	[illegible]
7	LA	JCT RTE 5 & 60	Semi-directional	266500	9.7	25888	95	0.004	80	14	1	[illegible]
7	LA	JCT RTE 710 & ATLANTIC BLVD	2-Quadrant Cloverleaf	197000	11.3	22261	44	0.002	44	0	0	[illegible]
7	LA	JCT RTE 710 & WASHINGTON BLVD	2-Quadrant Cloverleaf	216000	9.1	19655	17	0.001	12	5	0	[illegible]
7	LA	JCT RTE 10 & NORMANDIE AVE	Diamond	363000	3.8	13863	15	0.001	14	1	0	[illegible]
7	LA	JCT RTE 10 & 710	Semi-direct w/2 loops	141250	5.6	7904	18	0.002	14	4	0	[illegible]
8	RIV	JCT RTE 15 & 60	Directional w/1 loop	139000	24.4	33916	22	0.001	9	13	0	[illegible]
7	LA	JCT RTE 10 & 57/71/210	Fully Directional	212500	7.3	15530	44	0.003	33	10	1	[illegible]
12	ORA	JCT RTE 5 & 55	3-Quadrant Cloverleaf	227500	6.4	14673	24	0.002	24	0	0	[illegible]
7	LA	JCT RTE 405 & 110	Semi-direct w/2 loops	229500	5.8	13314	28	0.002	20	8	0	[illegible]
7	LA	JCT RTE 605 & VALLEY BLVD	2-Quadrant Cloverleaf	177000	10.0	17612	16	0.001	12	4	0	[illegible]
3	SAC	JCT RTE 50,51 & 99	Directional	162333	6.5	10625	26	0.002	14	12	0	[illegible]
4	ALA	JCT RTE 238 & 880	Directional T	136000	9.4	12753	28	0.002	22	6	0	[illegible]
4	ALA	JCT RTE 580 & 680	4-Quadrant Cloverleaf	128250	7.9	10035	18	0.002	16	2	0	[illegible]
7	LA	JCT RTE 101 & 405	Semi-direct w/2 loops	267000	4.1	10908	25	0.002	17	8	0	[illegible]
7	LA	JCT RTE 10 & 405	Fully Directional	273500	3.3	8921	22	0.002	19	3	0	[illegible]
7	LA	JCT RTE 710 & IMPERIAL HWY	4-Quadrant Cloverleaf	191000	12.1	23016	18	0.001	14	2	0	[illegible]

Table 4.6: Selected California Interchanges for Accident Analysis

Chapter Five

STATISTICAL ANALYSES OF ACCIDENT DATA

5.1 ACCIDENTS PER RAMP IN WASHINGTON

Chapter 4 explained the key attributes by which we classified all truck accidents at interchanges in Washington during the 27 months from January 1, 1993 to March 31, 1995. Table 5.1 shows numbers of ramps and accidents per ramp type for merge and diverge ramps. The term "ramp" in Table 5.1 refers to the entire ramp area including both ramp and adjacent freeway lanes. Parts (a-c) of Table 5.1 show separate tabulations by whether accidents occurred (a) on the ramps, (b) on the main lanes upstream, downstream, or adjacent to the ramps, or (c) on the main lanes or the ramps (all accidents). Each ramp is counted only once regardless of how many accidents occurred there. Since many ramps had multiple accidents, numbers of accidents by ramp type differ from the numbers of ramps where these accidents occurred. For all ramp types combined, 63% had only one accident, 22% had 2 accidents, and the other 15% had 3 or more accidents.

In Table 5.1, accidents shown in parts (a) and (b) add up to part (c) because every accident was coded by WSDOT to have occurred either on a ramp or on the main line. However, the numbers of ramps in parts (a) and (b) do not add up to part (c) because many ramp locations had accidents both on the ramp and main line. As noted in Chapter 4, we did not record any data for ramp locations where no accidents occurred. However, these ramps do have many conflict areas (i.e., the ramps themselves, ramp connection areas, upstream areas, and downstream areas) where no accidents occurred. Ramps in part (c) minus ramps in part (a) equal ramps where no accidents occurred specifically on the ramps. Ramps in part (c) minus ramps in part (b) equal ramps where no accidents occurred on the main lanes nearby the ramps. All accidents at intersections of ramps with arterial roads are excluded throughout this analysis.

RAMP TYPE	# of ON Ramps	# of OFF Ramps	% of ON Ramps	% of OFF Ramps	# of On-Ramp Acc	# of Off-Ramp Acc	% of On-Ramp Acc	% of Off-Ramp Acc	# of Acc per On-Ramp	# of Acc per Off-Ramp
Diamond	45	21	37.2	23.1	56	23	33.1	19.0	1.24	1.10
Loop	27	20	22.3	22.0	38	30	22.5	24.8	1.41	1.50
OuterConn	9	10	7.4	11.0	17	12	10.1	9.9	1.89	1.20
Directional	36	34	29.8	37.4	53	48	31.4	39.7	1.47	1.41
Other	4	6	3.3	6.6	5	8	3.0	6.6	1.25	1.33
Total %	121 57.1	91 42.9	100.0	100.0	169 58.3	121 41.7	100.0	100.0	1.40	1.33

Table 5.1.a Ramp Accidents

RAMP TYPE	# of ON Ramps	# of OFF Ramps	% of ON Ramps	% of OFF Ramps	# of On-Ramp Acc	# of Off-Ramp Acc	% of On-Ramp Acc	% of Off-Ramp Acc	# of Acc per On-Ramp	# of Acc per Off-Ramp
Diamond	140	127	57.1	59.3	216	195	54.3	57.0	1.54	1.54
Loop	32	10	13.1	4.7	51	15	12.8	4.4	1.59	1.50
OuterConn	21	22	8.6	10.3	35	36	8.8	10.5	1.67	1.64
Directional	41	49	16.7	22.9	79	89	19.8	26.0	1.93	1.82
Other	11	6	4.5	2.8	17	7	4.3	2.0	1.55	1.17
Total %	245 53.4	214 46.6	100.0	100.0	398 53.8	342 46.2	100.0	100.0	1.62	1.60

Table 5.1.b Main Line Accidents (Lane 1)

RAMP TYPE	# of ON Ramps	# of OFF Ramps	% of ON Ramps	% of OFF Ramps	# of On-Ramp Acc	# of Off-Ramp Acc	% of On-Ramp Acc	% of Off-Ramp Acc	# of Acc per On-Ramp	# of Acc per Off-Ramp
Diamond	168	142	49.6	46.6	272	218	48.0	47.1	1.62	1.54
Loop	53	28	15.6	9.2	89	45	15.7	9.7	1.68	1.61
OuterConn	28	31	8.3	10.2	52	48	9.2	10.4	1.86	1.55
Directional	69	83	20.4	27.2	132	137	23.3	29.6	1.91	1.65
Other	21	21	6.2	6.9	22	15	3.9	3.2	1.05	0.71
Total %	339 52.6	305 47.4	100.0	100.0	567 55.0	463 45.0	100.0	100.0	1.67	1.52

Table 5.1.c All Accidents

Table 5.1: Washington State Truck Accidents by Ramp type

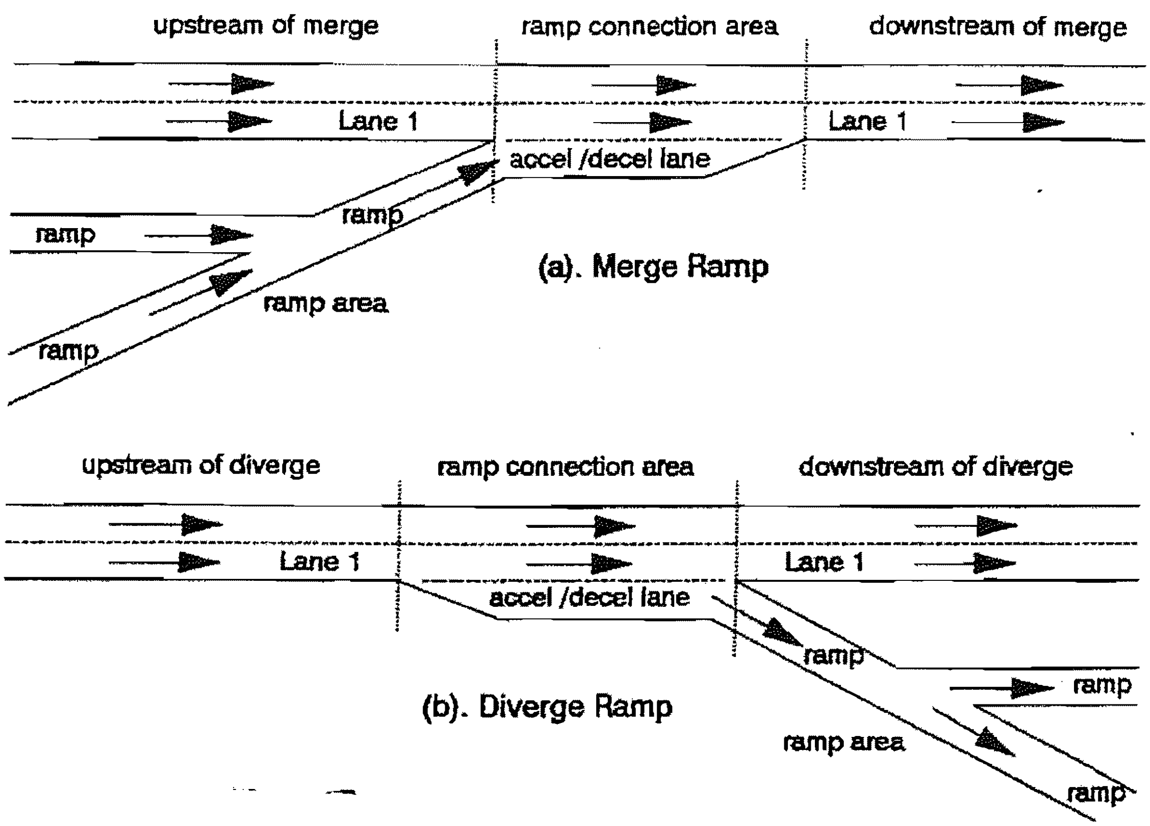


Figure 5.1: Four Ramp Conflict Areas

As noted in Chapter 4, we only compiled data for truck accidents on the freeway that occurred in the shoulder or in the adjacent lane 1 on the ramp connection side of the freeway as coded by WSDOT, since these are the majority of freeway truck accidents related to ramp conflicts. In Table 5.1, part (a) shows the freeway truck accidents, part (b) shows accidents that occurred in the accel/decel lane or on the ramp itself. In order study the effects of ramp geometrics on truck accidents, we decided it was better to separate accidents into the four conflict areas depicted in Figure 5.1. These four areas are (i) the ramp area away from the main lanes, (ii) the ramp connection including the accel/decel lane and the adjacent lane 1, (iii) lane 1 upstream of the ramp connection, and (iv) lane 1 downstream of the ramp connection. Of the 339 on-ramps and 305 off-ramps listed in Table 5.1c, only a few merged or diverged on the left side of the freeway. Roughly 60% of the ramps had one accident, 20% had two accidents, and 20% had three or more accidents in the study period.

Average accidents per ramp in Table 5.1 do not account for the volumes and distances of truck travel, but we later examine accident rates per ramp truck trip and per ramp truck VMT. These initial comparisons of average accidents per ramp help to separate out these volume and distance effects. As also discussed in Chapter 4, there is no "one best" truck exposure measure to use (e.g., ramp truck ADT, mainline truck ADT, total vehicle ADT, etc.). This section shows accident frequencies before introducing an exposure measure. In addition, since truck ADT's (both reported and estimated) are not precise, and accident frequencies may be so random or dependent on other factors that no significant relationship to truck ADT is found, an initial inspection of the data without truck ADT's is warranted.

Table 5.2 shows numbers of ramps, accidents, and average accidents per ramp in the four conflict areas just explained. Since numbers of ramps by conflict area include all places where accidents may have occurred even if none did, they generally equal the numbers of merge or diverge ramps. There are slightly more specific "on ramps" and "off ramps" due to ramps connecting collector/distributor lanes for which we did not count upstream and downstream areas. Hence, the average frequencies shown are per all conflict area regardless of whether any accidents occurred there.

Table 5.2 shows significant differences in frequencies of accidents per conflict area, which we later examine by ramp and accident type. Accidents occur at significantly lower average frequency on ramp sections away from freeway lanes (Table 5.2a) than in the upstream, downstream, or ramp connection areas of the freeway (Table 5.2b). Accidents that do occur on ramps away from freeway lanes occur more frequently on off-ramps than on on-ramps. We'll see later that loop off-ramps are a main source of this difference.

Accidents specifically on ramps can occur at junctions of multiple ramps (excluding intersections with arterial roads). Ramp junctions occur most often in directional ramps, and clearly contribute to the frequency of ramp accidents. Among 328 on-ramps containing 94 ramp junctions, 45 truck accidents occurred at junctions (0.644 accidents per junction). Only 40 other truck accidents occurred on the 328 on-ramps (0.122 accidents per ramp). Among 292 off-ramps containing 86 ramp junctions, 25 truck accidents occurred at junctions (0.402 accidents per junction). The 70 other truck accidents on off-ramps occurred away from the junctions (0.240 accidents per ramp). Beyond these comparisons, we did not separately investigate the effects of ramp junctions in this study, and grouped all accidents that occurred on ramps together, but still separate by merge or diverge ramp.

Table 5.3 shows a two-way frequency table of accidents by ramp and conflict area for both merge and diverge ramps. The third line of each cell shows the accident frequency per conflict area, where we see that accidents occur most frequently in ramp connection areas (merge and diverge areas). However, the average frequencies for all on-ramps, all off-ramps, and all ramps combined are not greatly different. Excluding ramp type "other", a two-way analysis of variance showed these average accident frequencies to be significantly different by conflict area at the 95% confidence level, but not by ramp type. This finding suggests the importance of examining accident histories by conflict area rather than differences by ramp type.

Conflict Area	Accidents	Percent	Conflict Areas	Accidents per Conflict Area
Upstream of Merge	151	26.6	331	0.46
Merge Ramp	267	47.1	331	0.81
Downstream of Merge	74	13.1	331	0.22
On Ramp	75	13.2	339	0.22
	567	100.0	1332	0.43

(a) On - Ramp Accidents

Conflict Area	Accidents	Percent	Conflict Areas	Accidents per Conflict Area
Upstream of Diverge	119	25.7	294	0.40
Diverge Ramp	131	28.3	294	0.45
Downstream of Diverge	122	26.3	294	0.41
Off Ramp	91	19.7	305	0.30
	463	100.0	1187	0.39

(b) Off - Ramp Accidents

Table 5.2: Washington State Truck Accidents by Conflict Area

Table 5.3: Washington State Truck Accidents by Ramp Type, Conflict Area

	CONFLICT AREA		RAMP TYPE					Total Accidents	Total Conflict Areas	Accidents per Conflict Area
			Diamond	Loop	OuterConn	Directional	Other			
On Ramps	Merge Upstream	# Accidents	91	7	15	31	7	151		
		# Conflict areas	167	50	25	69	20		331	
		Acc / Conf area	0.54	0.14	0.60	0.45	0.35			0.46
	Merge Area	# Accidents	116	50	27	63	11	267		
		# Conflict areas	167	50	25	69	20		331	
		Acc / Conf area	0.69	1.00	1.08	0.91	0.55			0.81
	On Ramp	# Accidents	21	17	8	28	1	75		
		# Conflict areas	168	53	28	69	21		339	
		Acc / Conf area	0.13	0.32	0.29	0.41	0.05			0.22
	Merge Downstream	# Accidents	44	15	2	10	3	74		
		# Conflict areas	167	50	25	69	20		331	
		Acc / Conf area	0.26	0.30	0.08	0.14	0.15			0.22
On Ramps Totals		# Accidents	272	89	52	132	22	567		
		# Conflict areas	869	203	103	278	81		1332	
		Acc / Conf area	0.41	0.44	0.50	0.48	0.27			0.43
Off Ramps	Diverge Upstream	# Accidents	67	4	12	32	4	119		
		# Conflict areas	142	24	28	80	20		294	
		Acc / Conf area	0.47	0.17	0.43	0.40	0.20			0.40
	Diverge Area	# Accidents	54	16	13	42	6	131		
		# Conflict areas	142	24	28	80	20		294	
		Acc / Conf area	0.38	0.67	0.46	0.53	0.30			0.45
	Off Ramp	# Accidents	17	23	10	38	3	91		
		# Conflict areas	142	28	31	83	21		305	
		Acc / Conf area	0.12	0.82	0.32	0.46	0.14			0.30
	Diverge Downstream	# Accidents	80	2	13	25	2	122		
		# Conflict areas	142	24	28	80	20		294	
		Acc / Conf area	0.56	0.08	0.46	0.31	0.10			0.41
Off Ramps Totals		# Accidents	218	45	48	137	15	463		
		# Conflict areas	568	100	115	323	81		1187	
		Acc / Conf area	0.38	0.45	0.42	0.42	0.19			0.39
All Ramps Totals		# Accidents	490	134	100	269	37	1030		
		# Conflict areas	1237	303	218	599	162		2519	
		Acc / Conf area	0.40	0.44	0.46	0.45	0.23			0.41

Table 5.4 shows a three-way frequency table of accidents by ramp type, accident type, and conflict area. Two observations here are that (i) rollover accidents are prevalent on loop off-ramps, but otherwise (ii) sideswipe accidents are most prevalent for all ramp types, especially in ramp connection areas. Table 5.5 shows a two-way frequency table of accidents by conflict area and accident type by aggregating all ramp types together. Here, numbers of conflict areas where accidents may have occurred always equal the numbers of merge and diverge ramps, allowing for a few ramps without freeway connections.

Values shown in the righthand portion of Table 5.5 show the accident frequencies per conflict area. A two-way analysis of variance showed these average accident frequencies to be significantly different by accident type at the 95% confidence level, but not by conflict area, due to these values varying highly within conflict areas. One reason why accident frequencies do not vary significantly by conflict area when grouped by accident type is that some accident types are so easily affected by driver actions (e.g., a sideswipe may result from the driver attempting to avoid a rearend collision on a short ramp). However, two important observations are that sideswipes are most frequent in merge areas, and rollovers are most frequent on ramps themselves, which occur mostly on loop ramps (see Table 5.4).

We next investigate whether stratifying ramps by high, medium, or low ADT of trucks or all vehicles on the ramp shows greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes. In Table 5.6, we grouped conflict areas together by whether ramp truck ADT was low, medium, or high. In Table 5.7, we grouped conflict areas by whether ramp ADT of all vehicles was low, medium, or high. These stratified results, especially in low to middle ADT levels, show accident frequencies on the ramps and in ramp connection areas to increase more consistently with higher ADT's compared to accident frequency in the upstream or downstream areas. This illustrates the effects of traffic volumes on truck accident frequencies on the ramps and in ramp connection areas where most weaving occurs.

5.2 ACCIDENTS PER RAMP TRUCK TRIP IN WASHINGTON

This section compares the same truck accident locations examined in the previous section taking ramp truck ADT (RTADT) into account. Table 5.8 shows numbers of ramps, accidents, cumulative ramp truck ADT's, ramp truck trips in millions (RTT), and accidents per RTT for the four conflict areas discussed earlier. To calculate RTT, each ramp truck ADT was divided by one million and multiplied by 820 days in the study period (January 1, 1993 to March 31, 1995).

Ramp truck ADT for each ramp is added just once to its sum for each conflict area regardless of whether none or many accidents occurred there. As explained in Chapter 4, we included ramp truck ADT's for conflict areas without accidents so as to most fully represent truck exposure. Note that RTT is identical for each merge ramp conflict area and for each diverge ramp conflict area, except for RTT of ramps themselves, which are slightly higher because of a few ramp-to-ramp connectors. Thus, accidents per RTT and accidents per conflict area in Table 5.2 compare similarly between conflict areas. Accidents per RTT are less meaningful for upstream areas of on-ramps and downstream areas of off-ramps, since trucks using the ramps do not travel those areas. Although we knew freeway truck percentages, we did not know truck percentages in each freeway lane, and thus could not calculate truck trips through each conflict area involving only lane 1 plus or minus ramp truck trips. By coincidence, there was an average of 1.0 truck accidents per million ramp truck trips through these conflict areas of both merge and diverge ramps. Since each ramp truck trip is counted four times in the total accident rate (once for each conflict area), this total accident rate equals an average of 4.0 accidents per ramp truck trip if the ramp is not subdivided into four parts.

Again, there is no "one best" truck exposure measure to use (e.g., ramp truck trips, mainline truck trips, total vehicles, etc.). We make all comparisons per ramp truck trip because this rate indicates the likelihood of a merging or diverging truck to be in an accident within each conflict area. Obviously, accidents upstream of merge ramps

Table 5.4: Washington State Truck Accidents by Ramp type, Conflict Area & Accident type

	CONFLICT AREA		Diamond Ramp				Loop Ramp				Outer Conn Ramp				Directional Ramp				Other Ramp				Total # of Accidents
			Accident Type				Accident Type				Accident Type				Accident Type				Accident Type				
			Sswp	Rend	Rovr	Other	Sswp	Rend	Rovr	Other	Sswp	Rend	Rovr	Other	Sswp	Rend	Rovr	Other	Sswp	Rend	Rovr	Other	
On Ramp	Mer_ups	# Acc	44	27	2	18	4	2	0	1	8	5	1	1	20	7	1	3	3	2	0	2	151
	Merge	# Acc	72	33	2	9	30	16	0	5	17	8	1	1	43	16	0	4	8	3	0	0	267
	On-Ramp	# Acc	11	1	5	4	4	1	8	4	2	1	3	2	18	4	2	4	1	0	0	0	75
	Mer_dwnst	# Acc	23	8	1	12	6	5	0	4	1	0	0	1	7	3	0	0	1	0	0	2	74
	Total	# Acc	150	69	10	43	44	23	8	14	28	14	5	6	68	30	3	11	13	5	0	4	567
Off Ramp	Div_ups	# Acc	29	24	1	13	3	1	0	0	5	6	0	1	20	8	0	4	1	1	0	2	119
	Diverge	# Acc	33	11	1	9	6	4	0	6	8	5	0	0	22	17	2	1	3	2	0	1	131
	Off_Ramp	# Acc	5	4	3	6	5	4	11	3	4	2	2	2	18	6	3	11	1	0	1	1	91
	Div_dwnst	# Acc	47	19	0	14	2	0	0	0	7	3	0	3	13	8	0	4	1	1	0	0	122
	Total	# Acc	114	58	5	41	16	9	11	9	24	16	2	6	73	39	5	20	6	4	1	4	463
	Totals		264	127	15	84	60	32	19	23	52	30	7	11	161	69	8	31	19	9	1	8	
						490				134				100				269				37	1030

Key: Sswp = Sideswipe
Rend = Rear-end
Rovr = Rollover
Mer_ups = Upstream of the Merge Area
Mer_dwnst = Downstream of the Merge Area
Div_ups = Upstream of the Diverge Area
Div_dwnst = Downstream of the Diverge Area

Table 5.5: Washington State Truck Accidents by Conflict Area & Accident type

	CONFLICT AREA	# of Conflict Area	ACCIDENT TYPE				Total # of Acc	Accidents per Conflict Area			
			Sideswipe	Rear-end	Rollover	Other		Sideswipe	Rear-end	Rollover	Other
On Ramps	Mer_ups	331	79	43	4	25	151	0.24	0.13	0.012	0.08
	Merge	331	170	75	3	19	267	0.51	0.23	0.009	0.06
	On-Ramp	339	36	7	18	14	75	0.11	0.02	0.053	0.04
	Mer_dwnst	331	38	16	1	19	74	0.11	0.05	0.003	0.06
	Total	1332	323	141	26	77	567	0.24	0.11	0.020	0.06
Off Ramps	Div_ups	294	58	40	1	20	119	0.20	0.14	0.003	0.07
	Diverge	294	72	39	3	17	131	0.24	0.13	0.010	0.06
	Off_Ramp	305	33	16	20	22	91	0.11	0.05	0.066	0.07
	Div_dwnst	294	70	31	0	21	122	0.24	0.11	0.000	0.07
	Total	1187	233	126	24	80	463	0.20	0.11	0.020	0.07
	Totals	2519	556	267	50	157	1030	0.22	0.11	0.020	0.06

Key:
- Sswp = Sideswipe
- Rend = Rear-end
- Rovr = Rollover
- Mer_ups = Upstream of the Merge Area
- Mer_dwnst = Downstream of the Merge Area
- Div_ups = Upstream of the Diverge Area
- Div_dwnst = Downstream of the Diverge Area

Table 5.6: Washington State Truck Accidents by Conflict Area and Accident Type Stratified by Ramp Truck ADT

	CONFLICT AREA		Ramp Truck ADT < 300 # of Loc	ACCIDENT TYPE Sswp	Rend	Rovr	Other	300>=Ramp Truck ADT<800 # of Loc	ACCIDENT TYPE Sswp	Rend	Rovr	Other	Ramp Truck ADT >= 800 # of Loc	ACCIDENT TYPE Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	114	22	7	2	12	148	39	25	0	8	69	18	11	2	5
		Acc / Loc		0.19	0.06	0.02	0.11		0.26	0.17	0.00	0.05		0.26	0.16	0.03	0.07
	Merge Area	# of Acc	114	39	13	2	5	148	87	40	1	10	69	44	22	0	4
		Acc / Loc		0.34	0.11	0.02	0.04		0.59	0.27	0.01	0.07		0.64	0.32	0.00	0.06
	On-Ramp	# of Acc	114	2	1	3	3	156	25	3	10	3	69	9	3	5	8
		Acc / Loc		0.02	0.01	0.03	0.03		0.16	0.02	0.06	0.02		0.13	0.04	0.07	0.12
	Merge downstream	# of Acc	114	15	5	1	9	148	16	10	0	5	69	7	1	0	5
		Acc / Loc		0.13	0.04	0.01	0.08		0.11	0.07	0.00	0.03		0.10	0.01	0.00	0.07
	On-Ramp	Totals	456	78	28	8	29	600	167	78	11	26	276	78	37	7	22
		Acc / Loc		0.17	0.06	0.02	0.06		0.28	0.13	0.02	0.04		0.28	0.13	0.03	0.08
Off Ramps	Diverge upstream	# of Acc	80	17	11	1	9	172	36	28	0	9	42	5	1	0	2
		Acc / Loc		0.21	0.14	0.01	0.11		0.21	0.16	0.00	0.05		0.12	0.02	0.00	0.05
	Diverge Area	# of Acc	80	12	7	1	8	172	49	26	2	8	42	11	7	0	1
		Acc / Loc		0.15	0.09	0.01	0.10		0.28	0.15	0.01	0.05		0.26	0.17	0.00	0.02
	Off-Ramp	# of Acc	83	3	2	5	7	180	21	13	14	12	42	9	1	1	3
		Acc / Loc		0.04	0.02	0.06	0.08		0.12	0.07	0.08	0.07		0.21	0.02	0.02	0.07
	Diverge downstream	# of Acc	80	15	7	0	12	172	50	21	0	8	42	5	3	0	1
		Acc / Loc		0.19	0.09	0.00	0.15		0.29	0.12	0.00	0.05		0.12	0.07	0.00	0.02
	Off-Ramp	Totals	323	47	27	7	36	696	156	87	16	37	168	30	12	1	7
		Acc / Loc		0.15	0.08	0.02	0.11		0.22	0.13	0.02	0.05		0.18	0.07	0.01	0.04
	All Ramps	Totals	779	125	53	15	65	1298	323	165	27	63	444	108	49	8	29
		Acc / Loc		0.16	0.07	0.02	0.08		0.25	0.13	0.02	0.05		0.24	0.11	0.02	0.07
							258					578					194

Key: Sswp = Sideswipe
Rend = Rear-end
Rovr = Rollover
Loc = Location (Conflict Area)

Table 5.7: Washington State Truck Accidents by Conflict Area and Accident Type Stratified by Total Ramp ADT

	CONFLICT AREA		Total Ramp ADT<4000 # of Loc	Total Ramp ADT<4000 ACCIDENT TYPE Sswp	Rend	Rovr	Other	4000>=Total Ramp ADT<10000 # of Loc	4000>=Total Ramp ADT<10000 ACCIDENT TYPE Sswp	Rend	Rovr	Other	Total Ramp ADT >=10000 # of Loc	Total Ramp ADT >=10000 ACCIDENT TYPE Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	114	26	7	2	12	119	30	21	1	7	98	23	15	1	6
		Acc / Loc		0.23	0.06	0.02	0.11		0.25	0.18	0.01	0.06		0.23	0.15	0.01	0.06
	Merge Area	# of Acc	114	40	10	2	3	119	68	35	0	10	98	62	30	1	6
		Acc / Loc		0.35	0.09	0.02	0.03		0.57	0.29	0.00	0.08		0.63	0.31	0.01	0.06
	On-Ramp	# of Acc	114	7	1	5	4	126	15	1	4	4	99	14	5	9	6
		Acc / Loc		0.06	0.01	0.04	0.04		0.12	0.01	0.03	0.03		0.14	0.05	0.09	0.06
	Merge downstream	# of Acc	114	13	5	1	10	119	16	8	0	4	98	9	3	0	5
		Acc / Loc		0.11	0.04	0.01	0.09		0.13	0.07	0.00	0.03		0.09	0.03	0.00	0.05
	On-Ramp	Totals	456	86	23	10	29	483	129	65	5	25	393	108	53	11	23
		Acc / Loc		0.189	0.05	0.022	0.064		0.267	0.135	0.01	0.052		0.275	0.135	0.028	0.059
Off Ramps	Diverge upstream	# of Acc	94	19	13	1	9	110	24	17	0	8	90	15	10	0	3
		Acc / Loc		0.20	0.14	0.01	0.10		0.22	0.15	0.00	0.07		0.17	0.11	0.00	0.03
	Diverge Area	# of Acc	94	13	7	1	10	110	32	16	1	5	90	27	16	1	2
		Acc / Loc		0.14	0.07	0.01	0.11		0.29	0.15	0.01	0.05		0.30	0.18	0.01	0.02
	Off-Ramp	# of Acc	97	3	3	6	8	116	10	5	10	8	92	20	8	4	6
		Acc / Loc		0.03	0.03	0.06	0.08		0.09	0.04	0.09	0.07		0.22	0.09	0.04	0.07
	Diverge downstream	# of Acc	94	16	10	0	14	110	36	15	0	4	90	18	6	0	3
		Acc / Loc		0.17	0.11	0.00	0.15		0.33	0.14	0.00	0.04		0.20	0.07	0.00	0.03
	Off-Ramp	Totals	379	51	33	8	41	446	102	53	11	25	362	80	40	5	14
		Acc / Loc		0.13	0.09	0.02	0.11		0.23	0.12	0.02	0.06		0.22	0.11	0.01	0.04
	All Ramps	Totals	836	137	56	18	70	929	231	118	16	60	755	188	93	16	37
		Acc / Loc		0.16	0.07	0.02	0.08		0.25	0.13	0.02	0.05		0.25	0.12	0.02	0.05
							281					415					334

Key: Sswp = Sideswipe
Rend = Rear-end
Rovr = Rollover
Loc = Location (Conflict Area)

Table 5.8: Washington State Truck Accidents per Ramp Truck ADT by Conflict Area

Conflict Area	Accidents	Conflict Areas	Total RTADT	Total RTT (millions)	Accidents per RTT
Upstream of Merge	151	331	175114	144	1.1
Merge Ramp	267	331	175114	144	1.9
Downstream of Merge	74	331	175114	144	0.5
On Ramp	75	339	179280	147	0.5
	567	1332	704622	578	1.0

(a) On - Ramps

Conflict Area	Accidents	Conflict Areas	Total RTADT	Total RTT (millions)	Accidents per RTT
Upstream of Diverge	119	294	145088	119	1.0
Diverge Ramp	131	294	145088	119	1.1
Downstream of Diverge	122	294	145088	119	1.0
Off Ramp	91	305	149500	123	0.7
	463	1187	584764	480	1.0

(b) Off - Ramps

RTT (Ramp Truck Trips) in millions for the study period = RTADT * 820 days / 1,000,000
Accident rates are per million RTT.

cannot involve merging trucks, and accidents downstream of diverge ramps cannot involve diverging trucks. Another complication is that accidents on the main lanes may involve trucks other than merging or diverging trucks. We do not compare accidents per other combinations of ramp and freeway ADT's of trucks and all vehicles, partly because we found a strong correlation between each of these ADT exposure measures. Instead, we report accidents per ramp truck trip for all conflict areas including upstream and downstream areas so as to use a consistent denominator for all rates.

Lengths of the upstream, downstream, and ramp connection areas will affect the number of accidents found to occur there. As explained in Chapter 4, the truck accident frequency per 0.05 mile section became very low and did not change significantly beyond 0.25 miles upstream of the diverge taper or merge gore. In the downstream direction, the accident frequency per 0.05 mile section became very low and did not change significantly beyond 0.15 miles downstream of the merge taper, and 0.20 miles downstream of the diverge gore. However, the average length of a merge connection area was 0.219 miles, versus 0.107 miles for a diverge connection area. Hence, it's partly a distance effect as to whether accidents occurred in the ramp connection areas versus downstream, but the sum of these two areas are very comparable. We later compare truck accidents per ramp truck VMT, which compensates for differences in these conflict area lengths.

Table 5.9 shows a two-way frequency table of accidents by ramp and conflict area. Table 5.9 also lists ramp truck trips in millions (RTT) for all conflict areas in the database of a given type where accidents may have occurred, including areas with no accidents. The third line listed for each conflict area shows accidents per RTT by ramp type, which shows that accidents occur most frequently in ramp connection areas (merge and diverge areas).

Table 5.9: Washington State Truck Accidents per Ramp Truck ADT by Ramp Type & Conflict Area

	CONFLICT AREA		RAMP TYPE Diamond	Loop	OuterConn	Directional	Other	Total Accidents	Total RTT	Total Accident Rate
On Ramps	Merge Upstream	# Accidents	91	7	15	31	7	151	144	1.1
		RTT(millions)	55	18	12	44	16			
		Accident Rate	1.66	0.38	1.30	0.71	0.45			
	Merge Area	# Accidents	116	50	27	63	11	267	144	1.9
		RTT(millions)	55	18	12	44	16			
		Accident Rate	2.12	2.75	2.34	1.45	0.70			
	On Ramp	# Accidents	21	17	8	28	1	75	147	0.5
		RTT(millions)	56	19	13	44	16			
		Accident Rate	0.38	0.87	0.61	0.64	0.06			
	Merge Downstream	# Accidents	44	15	2	10	3	74	144	0.5
		RTT(millions)	55	18	12	44	16			
		Accident Rate	0.80	0.82	0.17	0.23	0.19			
	On Ramps Totals	# Accidents	272	89	52	132	22	567	578	1.0
		RTT(millions)	219	74	48	174	63			
		Accident Rate	1.24	1.20	1.09	0.76	0.35			
Off Ramps	Diverge Upstream	# Accidents	67	4	12	32	4	119	119	1.0
		RTT(millions)	43	8	10	42	15			
		Accident Rate	1.57	0.50	1.16	0.75	0.26			
	Diverge Area	# Accidents	54	16	13	42	6	131	119	1.1
		RTT(millions)	43	8	10	42	15			
		Accident Rate	1.27	1.99	1.25	0.99	0.39			
	Off Ramp	# Accidents	17	23	10	38	3	91	123	0.7
		RTT(millions)	43	10	11	43	16			
		Accident Rate	0.40	2.36	0.89	0.88	0.19			
	Diverge Downstream	# Accidents	80	2	13	25	2	122	119	1.0
		RTT(millions)	43	8	10	42	15			
		Accident Rate	1.87	0.25	1.25	0.59	0.13			
	Off Ramps Totals	# Accidents	218	45	48	137	15	463	480	1.0
		RTT(millions)	171	34	42	171	62			
		Accident Rate	1.28	1.33	1.13	0.80	0.24			
	All Ramps Totals	# Accidents	490	134	100	269	37	1030	1057	1.0
		RTT(millions)	390	108	90	345	125			
		Accident Rate	1.26	1.24	1.11	0.78	0.30			

Key: RTT (Ramp Truck Trips) in millions for the study period = RTADT *820 days / 1,000,000
Accident rates are per million RTT.

In comparison to Table 5.3, which ignored differences in truck volumes by ramp type, the accident rate for all directional ramps is now significantly lower (0.78 per RTT) than for diamond, loop, or outer connector ramps. Diamond ramps, which had the lowest accident frequency per location in Table 5.3, now have the highest accident rate per ramp truck trip (1.26 per RTT) because they serve fewer trucks on average than other ramps. Also note the high rate of accidents on loop off-ramps (2.36 per RTT), which is mainly due to rollovers.

Excluding ramp type "other", a two-way analysis of variance showed these average accident rates to be significantly different by conflict area at the 95% confidence level, but not by ramp type. The average accident rates for diamond, loop, and outer connectors are not very different, and the rates within each ramp type vary a great deal by conflict area. Hence, despite the lower rate for directional ramps, the four average rates again did not vary significantly by ramp type, which is the same test outcome reported for the accident frequencies per conflict area, not taking ramp truck ADT into account. Otherwise, these rates differ by conflict area less than the accident frequencies (i.e., have a lower test power). Hence, some of the variation noted earlier was due to truck volume differences.

Table 5.10 shows accidents rates by accident type and conflict area, and ramp truck trips for all accident types and conflict areas where such accidents may have occurred. A two-way analysis of variance shows these average accident rates to be significantly different by accident type at the 95% level of confidence, but not by conflict area, which was the same result found for accident frequencies per conflict area, not taking ramp truck ADT into account.

We next investigate whether stratifying ramps by high, medium, or low ADT of trucks or all vehicles on the ramp shows greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes. In Table 5.11, we grouped conflict areas together by whether ramp truck ADT was low, medium, or high. In Table 5.12, we grouped conflict areas together by whether ramp ADT of all vehicles was low, medium, or high. These stratified results show truck accidents per RTT in all conflict areas to generally decrease with higher ADT's.. While truck accidents per location do increase with greater truck ADT (as indicated by Tables 5.6 and 5.7), the increase is relatively less than the increases in either truck ADT or the ADT of all vehicles.

This finding suggests that greater traffic volumes or truck volumes affect accident rates to only a limited extent. Two reasons may be that (i) lower traffic volumes allow greater speeds, which may lead to more accidents, and (ii) accidents are very random events, with many erroneous driver actions not resulting in accidents because of evasive avoidance maneuvers by that driver and others. One implication of finding that truck accidents and truck ADT's are not directly related is that sites with low accident rates per RTT may not compare so well if their low accident rates are simply due to high truck volumes. In our procedure to identify high-risk sites described in Chapter 6, we use accident frequencies per location to initially "flag" potential problem sites, and use accident rates per RTT and ramp truck VMT to warrant the need for additional investigation, site inspection, data gathering, and possible remedial action.

5.3 ACCIDENTS PER RAMP TRUCK VMT IN WASHINGTON

This section compares the same truck accident locations examined in the previous section taking ramp truck VMT into account. Table 5.13 shows numbers of ramps, accidents, cumulative ramp truck ADT's, ramp truck vehicle miles of travel in millions (RTVMT), and accidents per RTVMT for the four conflict areas discussed earlier. To calculate RTVMT, each ramp truck ADT was multiplied by its conflict area length, divided by one million, and multiplied by 820 days in the study period (January 1, 1993 to March 31, 1995). The upstream and downstream conflict area lengths were explained in Chapter 4. We calculated a specific length for each ramp and ramp connection area based on the route mile post data and geometric drawings provided by WSDOT.

Table 5.10: Washington State Truck Accidents per Ramp Truck ADT by Conflict Area & Accident type

	CONFLICT AREA	RTADT	RTT (millions)	ACCIDENT TYPE				Total # of Acc	Accidents per million RTT			
				Sideswipe	Rear-end	Rollover	Other		Sideswipe	Rear-end	Rollover	Other
On Ramps	Mer_ups	175114	144	79	43	4	25	151	0.56	0.30	0.03	0.17
	Merge	175114	144	170	75	3	19	267	1.18	0.52	0.02	0.13
	On-Ramp	179280	147	36	7	18	14	75	0.24	0.05	0.12	0.10
	Mer_dwnst	175114	144	38	16	1	19	74	0.26	0.11	0.01	0.13
	Total	704622	578	323	141	26	77	667	0.56	0.24	0.04	0.13
				13	1	5	6	25				
Off Ramps	Div_ups	145088	119	58	40	1	20	119	0.49	0.34	0.01	0.17
	Diverge	145088	119	72	39	3	17	131	0.61	0.33	0.03	0.14
	Off_Ramp	149600	123	33	16	20	22	91	0.27	0.13	0.16	0.18
	Div_dwnst	145088	119	70	31	0	21	122	0.59	0.26	0.00	0.18
	Total	584864	480	233	126	24	80	463	0.49	0.26	0.05	0.17
	Totals	1289486	1057	556	267	50	157	1030	0.53	0.25	0.05	0.15

Key:

Mer_ups = Upstream of the Merge Area
Mer_dwnst = Downstream of the Merge Area
Divr_ups = Upstream of the Diverge Area
Div_dwnst = Downstream of the Diverge Area
RTT (Ramp Truck Trips) in millions for the study period = RTADT *820 days / 1,000,000

Table 5.11: Washington State Truck Accidents per Ramp Truck Trips (RTT) by Conflict Area & Accident Type Stratified by Ramp Truck ADT

	CONFLICT AREA		Ramp Truck ADT < 300 RTT (millions)	ACCIDENT TYPE Sswp	Rend	Rovr	Other	300 >=Ramp Truck ADT< 800 RTT (millions)	ACCIDENT TYPE Sswp	Rend	Rovr	Other	Ramp Truck ADT >= 800 RTT (millions)	ACCIDENT TYPE Sswp	Rend	Rovr	Other	Total RTT (millions)	Total # of Acc	Total Accident Rate
On Ramps	Merge upstream	# of Acc		22	7	2	12		39	25	0	8		18	11	2	5	144	151	
		Acc / RTT	15	1.43	0.45	0.13	0.78	66	0.60	0.39	0.00	0.12	63	0.28	0.17	0.03	0.08			1.1
	Merge Area	# of Acc		39	13	2	5		87	40	1	10		44	22	0	4	144	267	
		Acc / RTT	15	2.53	0.84	0.13	0.32	65	1.34	0.62	0.02	0.15	63	0.69	0.35	0.00	0.06			1.9
	On-Ramp	# of Acc		2	1	3	3		25	3	10	3		9	3	5	8	147	75	
		Acc / RTT	16	0.13	0.06	0.19	0.19	68	0.37	0.04	0.15	0.04	63	0.14	0.05	0.08	0.13			0.5
	Merge downstream	# of Acc		15	5	1	9		16	10	0	5		7	1	0	5	144	74	
		Acc / RTT	16	0.97	0.32	0.06	0.58	65	0.25	0.15	0.00	0.08	63	0.11	0.02	0.00	0.08			0.5
	On Ramps	Totals		78	26	8	29		167	78	11	26		78	37	7	22	578	587	
		Acc / RTT	62	1.27	0.42	0.13	0.47	262	0.64	0.30	0.04	0.10	254	0.31	0.15	0.03	0.09			1.0
Off Ramps	Diverge upstream	# of Acc		17	11	1	9		36	28	0	9		5	1	0	2	119	118	
		Acc / RTT	12	1.42	0.92	0.08	0.75	69	0.52	0.41	0.00	0.13	38	0.13	0.03	0.00	0.05			1.0
	Diverge Area	# of Acc		12	7	1	8		49	25	2	8		11	7	0	1	119	131	
		Acc / RTT	12	1.00	0.58	0.08	0.67	69	0.71	0.36	0.03	0.12	38	0.29	0.18	0.00	0.03			1.1
	Off-Ramp	# of Acc		3	2	5	7		21	13	14	12		9	1	1	3	123	91	
		Acc / RTT	13	0.24	0.16	0.40	0.56	72	0.29	0.18	0.19	0.17	38	0.24	0.03	0.03	0.08			0.7
	Diverge downstream	# of Acc		15	7	0	12		50	21	0	8		5	3	0	1	119	122	
		Acc / RTT	12	1.25	0.58	0.00	1.00	69	0.73	0.30	0.00	0.12	38	0.13	0.08	0.00	0.03			1.0
	Off Ramps	Totals		47	27	7	38		156	87	16	37		30	12	1	7	480	463	
		Acc / RTT	48	0.97	0.56	0.14	0.74	279	0.56	0.31	0.06	0.13	152	0.20	0.08	0.01	0.05			1.0
	All Ramps	Totals		125	53	15	65		323	165	27	63		108	49	8	29	1057	1030	
		Acc / RTT	110	1.14	0.48	0.14	0.59	541	0.60	0.30	0.05	0.12	406	0.27	0.12	0.02	0.07			1.0
							258					578					194		1030	

Key: Swp = Sideswipe
Rend = Rear-end
Rovr = Rollover
RTT (Ramp Truck Trips) in millions for the study period = RTADT *820 days / 1,000,000
Accident rates are per million RTT.

Table 5.12: Washington State Truck Accidents per Ramp Truck ADT by Conflict Area & Accident Type Stratified by Total Ramp ADT

	CONFLICT AREA		Ramp ADT<4000 RTT (millions)	ACCIDENT TYPE Sawp	Rend	Rovr	Other	4000>= Ramp ADT<10000 RTT (millions)	ACCIDENT TYPE Sawp	Rend	Rovr	Other	Ramp ADT >=10000 RTT (millions)	ACCIDENT TYPE Sawp	Rend	Rovr	Other	Total RTT (millions)	Total # of Acc	Total Accident Rate
	Merge	# of Acc	17	28	7	2	12	51	30	21	1	7	76	23	15	1	6	144	151	
R	upstream	Acc / RTT		1.64	0.42	0.12	0.71		0.59	0.41	0.02	0.14		0.30	0.20	0.01	0.08			1.1
	Merge Area	# of Acc	17	40	10	2	3	51	68	35	0	10	76	62	30	1	6	144	267	
a		Acc / RTT		2.37	0.59	0.12	0.18		1.34	0.69	0.00	0.20		0.82	0.40	0.01	0.08			1.9
	On-Ramp	# of Acc	17	7	1	5	4	54	15	1	4	4	76	14	5	9	6	147	75	
O m		Acc / RTT		0.42	0.06	0.30	0.24		0.28	0.02	0.07	0.07		0.18	0.07	0.12	0.08			0.5
	Merge	# of Acc	17	13	5	1	10	51	16	8	0	4	76	9	3	0	5	144	74	
n p	downstream	Acc / RTT		0.77	0.30	0.06	0.59		0.31	0.16	0.00	0.08		0.12	0.04	0.00	0.07			0.5
s	On	Totals	67	86	23	10	29	206	129	65	6	25	304	108	53	11	23	578	567	
	Ramps	Acc / RTT		1.28	0.34	0.15	0.43		0.63	0.32	0.02	0.12		0.36	0.17	0.04	0.08			1.0
	Diverge	# of Acc	16	19	13	1	9	41	24	17	0	8	62	15	10	0	3	119	119	
R	upstream	Acc / RTT		1.16	0.79	0.06	0.55		0.59	0.42	0.00	0.20		0.24	0.16	0.00	0.05			1.0
	Diverge Area	# of Acc	16	13	7	1	10	41	32	16	1	5	62	27	16	1	2	119	131	
O a		Acc / RTT		0.79	0.42	0.06	0.61		0.78	0.39	0.02	0.12		0.44	0.26	0.02	0.03			1.1
	Off-Ramp	# of Acc	17	3	3	6	8	43	10	5	10	8	63	20	8	4	6	123	91	
f m		Acc / RTT		0.18	0.18	0.35	0.47		0.23	0.12	0.23	0.19		0.32	0.13	0.06	0.10			0.7
	Diverge	# of Acc	16	16	10	0	14	41	36	15	0	4	62	18	6	0	3	119	122	
f p	downstream	Acc / RTT		0.97	0.61	0.00	0.85		0.88	0.37	0.00	0.10		0.29	0.10	0.00	0.05			1.0
s	Off	Totals	67	51	33	8	41	166	102	53	11	25	247	80	40	5	14	480	463	
	Ramps	Acc / RTT		0.77	0.50	0.12	0.62		0.62	0.32	0.07	0.15		0.32	0.16	0.02	0.06			1.0
	All	Totals	134	137	56	18	70	372	231	118	16	50	552	188	93	16	37	1057	1030	
	Ramps	Acc / RTT		1.02	0.42	0.13	0.52		0.62	0.32	0.04	0.13		0.34	0.17	0.03	0.07			1.0
							281					415					334		1030	

Key: Sawp = Sideswipe
Rend = Rear-end
Rovr = Rollover
RTT(Ramp Truck Trips) in millions for the study period = RTADT *820 days / 1,000,000
Accident rates are accidents per million RTT.

Hence, the truck VMT of each upstream conflict area equals its ramp truck ADT multiplied by 0.25 miles. The truck VMT in each downstream conflict area equals its ramp truck ADT multiplied by 0.15 miles for merge ramps, and by 0.20 miles for diverge ramps. Since ramp lengths and ramp connection lengths (i.e., the accel/decel lane plus taper) vary between ramps, the ramp truck VMT of a ramp or ramp connection area equals its length multiplied by the ramp truck ADT. The length of a ramp is from where it intersects another road to where it joins the ramp connection area. We also calculated the length of each ramp-to-ramp connection, and added its VMT to the corresponding accident group or ramp type. While drawings from WSDOT fully showed each ramp connection area, they did not always fully show the length of every ramp. Hence, the lengths we calculated for some ramps were more approximate than lengths of the ramp connection areas.

Ramp truck VMT for each ramp is added just once to its sum for each conflict area regardless of whether none or many accidents occurred there. As explained in Chapter 4, we included ramp truck VMT's for conflict areas without accidents so as to most fully represent truck exposure. Since the lengths of these areas vary, RTVMT is different for each merge or diverge conflict area which leads to comparatively different accidents per RTVMT or RTT. In comparison to Table 5.8 where the average rate was 1.0 truck accidents per million RTT, the average rate of 4.0 truck accidents per million RTVMT means that the average conflict area length was 0.25 miles.

Table 5.14 shows a two-way frequency table of accidents by ramp and conflict area. Table 5.14 also shows the cumulative ramp truck VMT (RTVMT) for all ramp types and conflict areas in the database where such accidents may have occurred. Comparing these accident rates for on-ramps and off-ramps, we see the highest rates in the merge/diverge connection areas of these ramps. Again note the total accident rate for directional ramps is significantly lower than for the other type ramps, and the high accident rate on loop off-ramps.

Table 5.13: Washington State Truck Accidents per ramp Truck VMT by Conflict Area

Conflict Area	Accidents	Conflict Areas	Conflict Area Length	Total RTADT	Total RTVMT (millions)	Accidents per RTVMT
Upstream of Merge	151	331	0.25	175114	36	4.2
Merge Ramp	267	331	Varies	175114	27	9.9
Downstream of Merge	74	331	0.15	175114	22	3.4
On Ramp	75	339	Varies	179280	55	1.4
	567	1332		704622	140	4.1

(a) On - Ramps

Conflict Area	Accidents	Conflict Areas	Conflict Area Length	Total RTADT	Total RTVMT (millions)	Accidents per RTVMT
Upstream of Diverge	119	294	0.25	145088	30	4.0
Diverge Ramp	131	294	Varies	145088	15	9.0
Downstream of Diverge	122	294	0.20	145088	24	5.1
Off Ramp	91	305	Varies	149500	52	1.7
	463	1187		584764	120	3.8

(b) Off - Ramps

RTVMT (Ramp Truck VMT) in millions for the study period = RTADT * Conflict Area Length * 820 days / 1,000,000
Accident rates are per million RTVMT

Table 5.14: Washington State Truck Accidents per Ramp Truck VMT by Ramp Type & Conflict Area

	CONFLICT AREA		Diamond	Loop	OuterConn	Directional	Other	Total Accidents	Total RTVMT (millions)	Accidents per RTVMT
			RAMP TYPE							
On Ramps	Merge Upstream	# Accidents	91	7	15	31	7	151		
		RTVMT (millions)	13.66	4.55	2.89	10.88	3.91		35.9	
		Acc / RTVMT	6.66	1.54	5.19	2.85	1.79			4.2
	Merge Area	# Accidents	116	50	27	63	11	267		
		RTVMT (millions)	11.05	3.17	2.84	6.19	3.79		27.0	
		Acc / RTVMT	10.50	15.76	9.49	10.18	2.91			9.9
	On Ramp	# Accidents	21	17	8	28	1	75		
		RTVMT (millions)	19.81	6.52	4.37	16.02	8.36		55.1	
		Acc / RTVMT	1.06	2.61	1.83	1.75	0.12			1.4
	Merge Downstream	# Accidents	44	15	2	10	3	74		
		RTVMT (millions)	8.20	2.73	1.73	6.57	2.35		21.6	
		Acc / RTVMT	5.37	5.49	1.15	1.52	1.28			3.4
	On Ramps Totals	# Accidents	272	89	52	132	22	567		
		RTVMT (millions)	52.72	16.97	11.84	39.66	18.41		139.6	
		Acc / RTVMT	5.16	5.24	4.39	3.33	1.20			4.1
Off Ramps	Diverge Upstream	# Accidents	67	4	12	32	4	119		
		RTVMT (millions)	10.67	2.01	2.59	10.60	3.87		29.7	
		Acc / RTVMT	6.28	1.99	4.63	3.02	1.03			4.0
	Diverge Area	# Accidents	54	16	13	42	6	131		
		RTVMT (millions)	4.67	0.79	1.24	5.49	2.41		14.6	
		Acc / RTVMT	11.57	20.16	10.49	7.65	2.49			9.0
	Off Ramp	# Accidents	17	23	10	38	3	91		
		RTVMT (millions)	22.89	2.13	2.92	15.80	8.40		52.1	
		Acc / RTVMT	0.74	10.79	3.43	2.40	0.36			1.7
	Diverge Downstream	# Accidents	80	2	13	25	2	122		
		RTVMT (millions)	8.54	1.61	2.07	8.48	3.09		23.8	
		Acc / RTVMT	9.37	1.24	6.27	2.95	0.65			5.1
	Off Ramps Totals	# Accidents	218	45	48	137	15	463		
		RTVMT	46.76	6.55	8.82	40.38	17.77		120.3	
		Acc / RTVMT	4.66	6.87	5.44	3.39	0.84			3.8
	All Ramps Totals	# Accidents	490	134	100	269	37	1030		
		RTVMT (millions)	99.49	23.52	20.66	80.04	36.17		259.9	
		Acc / RTVMT	4.93	5.70	4.84	3.36	1.02			4.0

Key: RTVMT (Ramp Truck VMT) In millions for the study period =RTADT * conflict area length * 820 / 1,000,000
Accident rates are per million RTVMT

The accident rates shown in Table 5.14 can now be compared by both conflict and ramp type to address the first question of interest listed in Section 3.2. A two-way analysis of variance showed these accident rates per ramp truck VMT to be significantly different by conflict area at the 95% confidence level, but not by ramp type, which is the same test outcome reported for Tables 5.3 and 5.9, not taking ramp truck VMT into account. However, these rates differ by conflict area more than for Tables 5.3 and 5.9 (i.e., have a higher test power). Hence, when both ramp truck volumes and travel distances are properly accounted for, accident rates per ramp truck VMT most significantly differ by conflict area, with rates in ramp connection areas (merge and diverge areas) being the highest by a significant margin. While this may be an expected outcome, the finding reinforces the need to focus ramp related safety concerns on merge and diverge areas.

Table 5.15 shows a two-way table accidents rates by accident type and conflict area, and cumulative ramp truck VMT for all accident types and conflict areas where such accidents may have occurred. A two-way analysis of variance shows these accident rates to be significantly different by accident type at the 95% level of confidence, but not by conflict area, which is the same test outcome reported for Tables 5.5 and 5.10, not taking ramp truck VMT into account. The degree to which accident rates differ by accident type is not significantly affected by whether ramp truck ADT or VMT or neither was taken into account. This small variation in accident rates by accident type indicates that differences are not strongly related to truck travel volumes or distances. Although one may expect more rearend accidents in heavy congestion, accident types are often affected by driver actions (e.g., a sideswipe can result from the driver attempting to avoid a rearend collision on a short ramp).

We next investigate whether stratifying ramps by high, medium, or low VMT of trucks or all vehicles on the ramp shows greater lane-changing difficulties at higher volumes or the risks of greater speeds at lower volumes. In Table 5.16, we grouped conflict areas together by whether ramp truck VMT was low, medium, or high. In Table 5.17, we grouped conflict areas together by whether ramp VMT of all vehicles was low, medium, or high. These stratified results show truck accidents per RTVMT to consistently decrease in all conflict areas with higher RTVMT's. While truck accidents per location do increase with greater truck exposure (as indicated by Tables 5.6 and 5.7), the increase is much less than the increases in either truck VMT or the VMT of all vehicles. Hence, greater overall VMT or truck VMT affect accident rates to a very limited extent.

Table 5.18 is a summary of Washington truck accident frequencies and rates by conflict area per ramp truck trip and ramp truck VMT. Note that the average accident rates are all nearly equal for merge and diverge ramps when not divided by conflict area, but very different when separated by conflict area. This finding shows the importance of examining the accident history of a ramp by conflict area rather than of the whole ramp in order to identify possible problem spots.

5.4 COMPARISON OF ACCIDENTS PER RAMP IN THREE STATES

Since we were not able to obtain ramp truck ADT's for Colorado or Califomia, we limit our comparisons in this section to accident frequencies per ramp type. We did have freeway ADT's and truck percentages for most Califomia interchanges, and for some Colorado interchanges. Thus, we tried with Washington data to estimate both ramp ADT's and ramp truck ADT's from freeway ADT's and freeway truck percentages. The results were far too uncertain to use this approach to estimate ramp truck ADT's in Colorado or Califomia with which to make valid comparisons of accidents per ramp truck ADT between these states.

Tables 5.19 lists numbers of ramps and accidents per ramp type for Colorado, California, and Washington. The accident frequencies for Washington State are the weighted means of the frequencies shown in the last two columns of Table 5.1(c). Since our Washington data was for 27 months but our Colorado and California data was for 36 months, Table 5.20 converts the data in Table 5.19 to a yearly basis.

Table 5.15: Washington State Truck Accidents per Ramp Truck VMT by Conflict Area & Accident Type

	CONFLICT AREA	RTVMT (millions)	ACCIDENT TYPE: Sideswipe	ACCIDENT TYPE: Rear-end	ACCIDENT TYPE: Rollover	ACCIDENT TYPE: Other	Total # of Acc	Accidents per million RTVMT: Sideswipe	Accidents per million RTVMT: Rear-end	Accidents per million RTVMT: Rollover	Accidents per million RTVMT: Other
On Ramps	Mer_ups	36	79	43	4	25	151	2.20	1.20	0.11	0.70
	Merge	27	170	75	3	19	267	6.29	2.77	0.11	0.70
	On-Ramp	55	36	7	18	14	75	0.65	0.13	0.33	0.25
	Mer_dwnst	22	38	16	1	19	74	1.76	0.74	0.05	0.88
	Total	140	323	141	26	77	567	2.31	1.01	0.19	0.55
Off Ramps	Div_ups	30	58	40	1	20	119	1.95	1.34	0.03	0.67
	Diverge	15	72	39	3	17	131	4.93	2.67	0.21	1.16
	Off_Ramp	52	33	18	20	22	91	0.63	0.31	0.38	0.42
	Div_dwnst	24	70	31	0	21	122	2.94	1.30	0.00	0.88
	Total	120	233	126	24	80	463	1.94	1.05	0.20	0.67
	Totals	260	556	267	50	157	1030	2.14	1.03	0.19	0.60

Key: Mer_ups = Upstream of the Merge Area
Mer_dwnst = Downstream of the Merge Area
Div_ups = Upstream of the Diverge Area
Div_dwnst = Downstream of the Diverge Area
RTVMT (Ramp Truck VMT) in millions for the study period =RTADT * conflict area length * 820 / 1,000,000

Table 5.16: Washington State Truck Accidents per Ramp Truck VMT by Conflict Area & Accident type Stratified by Ramp Truck ADT

			Ramp Truck ADT < 300					300>=Ramp Truck ADT<800					Ramp Truck ADT >= 800				
	CONFLICT AREA		RTVMT (millions)	ACCIDENT TYPE				RTVMT (millions)	ACCIDENT TYPE				RTVMT (millions)	ACCIDENT TYPE			
				Sswp	Rend	Rovr	Other		Sswp	Rend	Rovr	Other		Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	3.8	22	8	2	12	16.2	39	25	0	8	15.9	18	10	2	5
		Acc / RTVMT		5.72	2.08	0.52	3.12		2.41	1.55	0.00	0.49		1.13	0.63	0.13	0.32
	Merge Area	# of Acc	3.2	39	13	2	5	12.5	87	40	1	10	11.3	44	22	0	4
		Acc / RTVMT		12.30	4.10	0.63	1.58		6.95	3.20	0.08	0.80		3.88	1.94	0.00	0.35
	On-Ramp	# of Acc	5.9	3	1	3	3	24.3	25	3	10	3	24.9	8	3	5	8
		Acc / RTVMT		0.51	0.17	0.51	0.51		1.03	0.12	0.41	0.12		0.32	0.12	0.20	0.32
	Merge downstream	# of Acc	2.3	15	5	1	9	9.7	16	10	0	5	9.6	7	1	0	5
		Acc / RTVMT		6.47	2.16	0.43	3.88		1.65	1.03	0.00	0.52		0.73	0.10	0.00	0.52
	On-Ramp	Totals	15.2	79	27	8	29	62.7	167	78	11	26	61.7	77	36	7	22
		Acc / RTVMT		5.19	1.77	0.53	1.90		2.66	1.24	0.18	0.41		1.25	0.58	0.11	0.36
Off Ramps	Diverge upstream	# of Acc	3.0	17	11	1	9	17.2	36	28	0	9	9.5	5	1	0	2
		Acc / RTVMT		5.68	3.67	0.33	3.01		2.09	1.63	0.00	0.52		0.52	0.10	0.00	0.21
	Diverge Area	# of Acc	1.3	12	7	1	8	7.6	49	25	2	8	5.7	11	7	0	1
		Acc / RTVMT		9.23	5.39	0.77	6.16		6.46	3.29	0.26	1.05		1.93	1.23	0.00	0.18
	Off-Ramp	# of Acc	3.4	3	2	5	7	33.2	21	13	14	12	15.6	9	1	1	3
		Acc / RTVMT		0.88	0.58	1.46	2.04		0.63	0.39	0.42	0.36		0.58	0.06	0.06	0.19
	Diverge downstream	# of Acc	2.4	15	7	0	12	13.8	50	21	0	8	7.6	5	3	0	1
		Acc / RTVMT		6.26	2.92	0.00	5.01		3.63	1.52	0.00	0.58		0.66	0.39	0.00	0.13
	Off-Ramp	Totals	10.1	47	27	7	36	71.8	156	87	16	37	38.4	30	12	1	7
		Acc / RTVMT		4.65	2.67	0.69	3.56		2.17	1.21	0.22	0.52		0.78	0.31	0.03	0.18
	All Ramps	Totals	25.3	126	54	15	65	134.5	323	165	27	63	100.1	107	48	8	29
		Acc / RTVMT		4.97	2.13	0.59	2.56		2.40	1.23	0.20	0.47		1.07	0.48	0.08	0.29
							260					578					192

Key: Sswp = Sideswipe
Rend = Rear-end
Rovr = Rollover
RTVMT (Ramp Truck VMT) in millions for the study period =RTADT * conflict area length * 820 / 1,000,000
Accident rates are per million RTVMT

Table 5.17: Washington State Truck Accidents per Ramp Truck VMT by Conflict Area & Accident Type Stratified by Total Ramp ADT

Ramp ADT < 4000

	CONFLICT AREA		RTVMT (millions)	Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	4.2	28	7	2	12
		Acc / RTVMT		6.17	1.66	0.47	2.85
	Merge Area	# of Acc	3.7	41	10	2	3
		Acc / RTVMT		11.16	2.72	0.54	0.82
	On-Ramp	# of Acc	6.6	7	1	5	4
		Acc / RTVMT		1.06	0.15	0.76	0.61
	Merge downstream	# of Acc	2.5	14	5	1	10
		Acc / RTVMT		5.51	1.97	0.39	3.94
	On-Ramp	Totals	17.0	88	23	10	29
		Acc / RTVMT		5.18	1.35	0.59	1.71
Off Ramps	Diverge upstream	# of Acc	4.1	19	13	1	9
		Acc / RTVMT		4.61	3.15	0.24	2.18
	Diverge Area	# of Acc	1.7	13	8	1	10
		Acc / RTVMT		7.51	4.62	0.58	5.77
	Off-Ramp	# of Acc	4.8	3	3	6	8
		Acc / RTVMT		0.63	0.63	1.26	1.68
	Diverge downstream	# of Acc	3.3	16	10	0	14
		Acc / RTVMT		4.85	3.03	0.00	4.25
	Off-Ramp	Totals	13.9	51	34	8	41
		Acc / RTVMT		3.67	2.44	0.58	2.95
	All Ramps	Totals	30.9	139	57	18	70
		Acc / RTVMT		4.50	1.84	0.58	2.26
							284

4000 >= Ramp ADT< 10000

	CONFLICT AREA		RTVMT (millions)	Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	12.7	33	22	1	8
		Acc / RTVMT		2.60	1.73	0.08	0.63
	Merge Area	# of Acc	10.3	71	37	0	11
		Acc / RTVMT		6.88	3.59	0.00	1.07
	On-Ramp	# of Acc	19.4	15	3	5	4
		Acc / RTVMT		0.77	0.15	0.26	0.21
	Merge downstream	# of Acc	7.6	16	8	0	4
		Acc / RTVMT		2.10	1.05	0.00	0.52
	On-Ramp	Totals	50.1	135	70	6	27
		Acc / RTVMT		2.70	1.40	0.12	0.54
Off Ramps	Diverge upstream	# of Acc	10.2	26	18	0	8
		Acc / RTVMT		2.54	1.76	0.00	0.78
	Diverge Area	# of Acc	4.4	35	15	1	5
		Acc / RTVMT		7.94	3.40	0.23	1.13
	Off-Ramp	# of Acc	23.1	10	5	11	8
		Acc / RTVMT		0.43	0.22	0.48	0.35
	Diverge downstream	# of Acc	8.2	39	16	0	5
		Acc / RTVMT		4.77	1.96	0.00	0.61
	Off-Ramp	Totals	45.9	110	54	12	26
		Acc / RTVMT		2.39	1.18	0.26	0.57
	All Ramps	Totals	96.0	245	124	18	53
		Acc / RTVMT		2.55	1.29	0.19	0.55
							440

Ramp ADT >= 10000

	CONFLICT AREA		RTVMT (millions)	Sswp	Rend	Rovr	Other
On Ramps	Merge upstream	# of Acc	19.0	20	14	1	5
		Acc / RTVMT		1.05	0.74	0.05	0.26
	Merge Area	# of Acc	13.0	58	28	1	5
		Acc / RTVMT		4.44	2.15	0.08	0.38
	On-Ramp	# of Acc	29.1	14	3	8	6
		Acc / RTVMT		0.48	0.10	0.27	0.21
	Merge downstream	# of Acc	11.4	8	3	0	5
		Acc / RTVMT		0.70	0.26	0.00	0.44
	On-Ramp	Totals	72.6	100	48	10	21
		Acc / RTVMT		1.38	0.66	0.14	0.29
Off Ramps	Diverge upstream	# of Acc	15.4	13	9	0	3
		Acc / RTVMT		0.84	0.58	0.00	0.19
	Diverge Area	# of Acc	8.5	24	16	1	2
		Acc / RTVMT		2.84	1.89	0.12	0.24
	Off-Ramp	# of Acc	24.2	20	8	3	6
		Acc / RTVMT		0.83	0.33	0.12	0.25
	Diverge downstream	# of Acc	12.3	15	5	0	2
		Acc / RTVMT		1.22	0.41	0.00	0.16
	Off-Ramp	Totals	60.4	72	38	4	13
		Acc / RTVMT		1.19	0.63	0.07	0.22
	All Ramps	Totals	133.0	172	86	14	34
		Acc / RTVMT		1.29	0.65	0.11	0.26
							306

Key: Sswp = Sideswipe
Rend = Rear-end
Rovr = Rollover
RTVMT (Ramp Truck VMT) in millions for the study period =RTADT * conflict area length * 620 / 1,000,000
Accident rates are per million RTVMT

Table 5.18: Summary of Washington State Truck Accident Rates by Conflict Area

	CONFLICT AREA	# of Acc	# of Conflict Area	RTT	RTVMT	Accident per Conf Area	Accidents per RTT	Accidents per RTVMT
On Ramps	Mer_ups	151	331	143.6	35.9	0.5	1.1	4.2
	Merge	267	331	143.6	27.0	0.8	1.9	9.9
	On-Ramp	75	339	147.0	55.1	0.2	0.5	1.4
	Mer_dwnst	74	331	143.6	21.6	0.2	0.5	3.4
	Total	567	1332	577.8	139.6	0.4	1.0	4.1
Off Ramps	Div_ups	119	294	119.0	29.7	0.4	1.0	4.0
	Diverge	131	294	119.0	14.6	0.4	1.1	9.0
	Off-Ramp	91	305	122.7	52.1	0.3	0.7	1.7
	Div_dwnst	122	294	119.0	23.8	0.4	1.0	5.1
	Total	463	1187	479.6	120.3	0.4	1.0	3.8
	Totals	1030	2519	1057.4	259.9	0.4	1.0	4.0

Key: Mer_ups = Upstream of the Merge Area
Mer_dwnst = Downstream of the Merge Area
Divr_ups = Upstream of the Diverge Area
Div_dwnst = Downstream of the Diverge Area
Accident rates are per million RTT and million RTVMT.

RAMP TYPE	# of Ramps	Percent	# of Accidents	Percent	Average Accident Frequency
Diamond	27	30.3	49	25.9	1.81
Loop	12	13.5	28	14.8	2.33
OuterConn	11	12.4	17	9.0	1.55
Directional	39	43.8	95	50.3	2.44
Other	0	0.0	0	0.0	0.00
Total	89	100.0	189	100.0	2.12

Colorado Accidents

RAMP TYPE	# of Ramps	Percent	# of Accidents	Percent	Average Accident Frequency
Diamond	19	3.9	59	5.6	3.11
Loop	25	5.1	57	5.4	2.28
OuterConn	23	4.7	33	3.1	1.43
Directional	324	65.9	797	75.8	2.46
Other	101	20.5	106	10.1	1.05
Total	492	100.0	1052	100.0	2.14

California Accidents

RAMP TYPE	# of Ramps	Percent	# of Accidents	Percent	Average Accident Frequency
Diamond	310	48.1	490	47.6	1.58
Loop	81	12.6	134	13.0	1.65
OuterConn	59	9.2	100	9.7	1.69
Directional	152	23.6	269	26.1	1.77
Other	42	6.5	37	3.6	0.88
Total	644	100.0	1030	100.0	1.60

Washington Accidents

Table 5.19: Comparison of Truck Accidents in Three States by Ramp Type

RAMP TYPE	# of Ramps	Percent	# of Accidents per year	Percent	Average Accident Frequency
Diamond	27	30.3	16	25.9	0.60
Loop	12	13.5	9	14.8	0.78
OuterConn	11	12.4	6	9.0	0.52
Directional	39	43.8	32	50.3	0.81
Other	0	0.0	0	0.0	0.00
Total	89	100.0	63	100.0	0.71

Colorado Accidents

RAMP TYPE	# of Ramps	Percent	# of Accidents per year	Percent	Average Accident Frequency
Diamond	19	3.9	20	5.6	1.04
Loop	25	5.1	19	5.4	0.76
OuterConn	23	4.7	11	3.1	0.48
Directional	324	65.9	266	75.8	0.82
Other	101	20.5	35	10.1	0.35
Total	492	100.0	351	100.0	0.71

California Accidents

RAMP TYPE	# of Ramps	Percent	# of Accidents per year	Percent	Average Accident Frequency
Diamond	310	48.1	218	47.5	0.70
Loop	81	12.6	60	13.0	0.74
OuterConn	59	9.2	44	9.7	0.75
Directional	152	23.6	120	26.1	0.79
Other	42	6.5	16	3.6	0.39
Total	644	100.0	458	100.0	0.71

Washington Accidents

Table 5.20: Comparison of Truck Accidents per Year in Three States by Ramp Type

5.5 CONCLUSIONS AND IDENTIFICATION OF HIGH–RISK SITES

It is mostly coincidental that the mean truck accident frequency per ramp for all ramp types was 0.71 per year in each of these states. The data in Colorado and California was for 1991-1993, while the data for Washington was for 1993-early 1995. The ramp types of the analysis interchanges were distributed differently in each state, and although we did not have ramp truck volumes for Colorado and California, these would also be distributed differently from those in Washington.

Yearly accident frequencies per directional ramp were very similar for all three states, and only slightly higher than for loop ramps. Yearly accident frequencies per loop ramp were also very similar for all three states. As shown by the last line of Table 5.14, the accident rate per ramp truck VMT for loop ramps in Washington (5.70) is much greater than for directional ramps (3.36). Relative rates per ramp truck VMT differ from relative frequencies per ramp, since directional ramps are generally longer and more heavily traveled. Because the accident frequencies per directional ramp and loop ramp are so consistent in all three states, we expect loop ramps to have higher accident rates per ramp truck VMT than directional ramps in both Colorado and California as they do in Washington.

The yearly accident frequencies per diamond ramp are less similar between states. If we combine Colorado and California, the average yearly accident frequency is 0.78 per diamond ramp compared to 0.76 per loop ramp. These frequencies are not statistically different from each other or from the comparable frequencies for Washington. As shown by the last line of Table 5.14, the accident rate per ramp truck VMT for diamond ramps in Washington (4.93) is lower than for loop ramps (5.70) but much greater than for directional ramps (3.36). Our sampling of Colorado and California interchanges does not allow us to confidently state how these rates may compare for these states, but we expect that they will compare similarly to Washington if a wider sample were collected.

The yearly accident frequency per outer connector is lowest among ramps in Colorado and California, but is roughly equal to the yearly frequencies for diamond, loop, and directional ramps in Washington. Outer connectors are similar to directional ramps in design and operational characteristics. Hence, it is somewhat surprising that the accident rate per ramp truck VMT in Washington as shown in Table 5.14 is similar for outer connectors (4.84) and diamond ramps (4.93). Since the accident frequency per outer connector is lowest among ramps in Colorado and California, the accident rate per ramp truck VMT for outer connectors is probably similar to directional ramps in these two states if the data to make that calculation were known.

In conclusion, truck accidents per ramp truck VMT are likely to be highest for loop ramps in all three states if the data to make that calculation were known. In Washington where the accident sample is least biased, Table 5.14 shows that accidents per ramp truck VMT are highest for loop ramps by a significant margin. One implication of this finding is that a given loop ramp may have a high accident frequency compared to all ramp types, but not compared to loop ramps. Short of reconstruction, lower cost measures to reduce the accident rate at a loop ramp to be comparable with other non-loop ramps may be limited. Thus, to evaluate the effectiveness of an accident mitigation measure, before and after accident experiences ought to be examined within ramp types.

We have compared truck accident frequencies and rates for different ramp types, accident types, and conflict areas. Although the average accident statistics did not differ significantly by ramp type, there was a great deal of variation by conflict area within each ramp type. As we added more specific information related to ramp truck volumes and travel distances, the differences did become greater by ramp type and conflict area. These findings led us to recommend an incremental stepwise procedure for using accident data to identify hazardous ramps. The procedure is a simple comparison of the accident history for a given ramp to comparable averages for other ramp types, conflict areas, and accident types. We designed the procedure to be straightforward in its simplest application so that it would be easy to implement and use within emerging safety management systems.

Seven comparisons can be made of the accident frequency at a given ramp by one or more of three attributes (accident type, ramp type, and conflict area) to the accident distribution of other ramps in a state. These comparisons can be made:

1. By accident type for all ramp types and conflict areas.

2. By ramp type for all accident types and conflict areas.

3. By conflict area for all ramp types and accident types.

4. By accident type and ramp type for all conflict areas.

5. By accident type and conflict area for all ramp types.

6. By ramp type and conflict area for all accident types.

7. By accident type, ramp type, and conflict area.

Each additional attribute by which accidents are grouped reduces the sample size of accidents and ramps to which a given ramp is compared. Moreover, the likelihood (or ease) of obtaining data to classify accidents by these attributes is greatest for accident type, less for ramp type, and least for conflict area. With those considerations, we recommend performing comparisons 1, 2, 4, 6, and 7 (in that order) as numbered above. Comparisons 1, 2, and 4 do not require identifying the conflict area, the least obtainable data. Comparisons 6 and 7 do require identifying the conflict area, but these comparisons are not necessary to warrant a site inspection and design evaluation. If a ramp is found to have a high frequency of accidents (1) overall, (2) by accident type, and (4) by accident and ramp type, then it probably warrants closer examination. Accident reports for that ramp would be studied, and accidents classified by conflict area and several other attributes such as vehicle type, weather, lighting, road condition, and driver actions. This information would then be used to determine whether improvements to geometric design, signage, or traffic controls are warranted considering various alternatives and their costs.

Thus, the high-risk site identification procedure is as follows:

1. First, for a given ramp (all conflict areas combined), compare its frequency of all accident types over a multiyear analysis period to the frequency distribution of all accident types in all conflict areas at all other ramps of a state. If a given ramp lies above the 75th percentile of this distribution, an initial flag is raised. The 75th percentile is suggested by Basha & Ramsey (1993) as an "initial check" to identify locations that may warrant further investigation. A higher or lower percentile might be considered after experience shows whether this percentile "flags" too many or too few locations that do or do not warrant further attention.

2. Second, for a given ramp (all conflict areas combined), compare its frequency of each accident type over a multiyear analysis period to the frequency distribution of each accident type in all conflict areas at all other ramps of a state. If any accident type of a given ramp lies above the 75th percentile of its distribution, a second flag is raised. Again, a higher or lower percentile might be considered.

3. Third, for a given ramp (all conflict areas combined), compare its frequency of each accident type over a multiyear analysis period to the frequency distribution of each accident type in all conflict areas at all similar type ramps of a state. If any accident type of a given ramp lies above the 75th percentile of its distribution, a third flag is raised.

This first comparison indicates whether the ramp has an unusual overall accident history in comparison to all other statewide ramps, and requires minimal information. This second comparison indicates whether the ramp has an unusual accident history for any particular accident type, knowing that data on conflict area and ramp type may not be available. The third comparison (number 4 in the prior list) indicates whether the ramp has an unusual accident history for any particular accident type in comparison to similar ramps, knowing that data on conflict area may still not be available. If all comparisons indicate a potential problem, then further evaluation is recommended, leading to comparisons 6 and 7 if conflict area data is available for many other ramps of similar design in the state. If only one or two comparisons indicate a potential problem, then further evaluation may be considered depending on available resources.

The following is an example of applying the above procedure to the interchange of Interstate 25 and State Highway 34 in Colorado, which serves the cities of Greeley and Loveland. As shown by Figure 5.2, this interchange is a full cloverleaf, with four loop ramps and four outer connectors. The entire interchange had experienced 11 truck accidents in the years 1991-1993, of which 6 were overturns, and 4 were overturns on the loop ramp leading from westbound SH-34 to southbound I-25.

Four truck accidents on one ramp in a three year period suggested a problem simply according to the first overall test. Four overturns on one ramp in a three year period more strongly indicated a problem according to the second test. Finally, even compared to other loop ramps, four truck accidents of any type in a three year period gave justification for a site inspection and design evaluation. Actions were taken to improve the lane markings and speed warning signs at this interchange, and the interchange continues to be monitored.

Since we were unable to obtain ramp truck trips or ramp truck VMT in Colorado, we were unable to make comparisons of ramps based on truck accident rates per those denominators. Moreover, since we found that truck accidents in Washington State were not directly proportional to truck trips or truck VMT, we caution the use of those accident rates to identify high-risk locations. We suggest that these rates be used at the next stage of evaluation if a location is found to have a high accident frequency according to tests 1, 2, and 4, above. One reason may be higher truck volumes, but the extent of that effect at a given site must be further assessed.

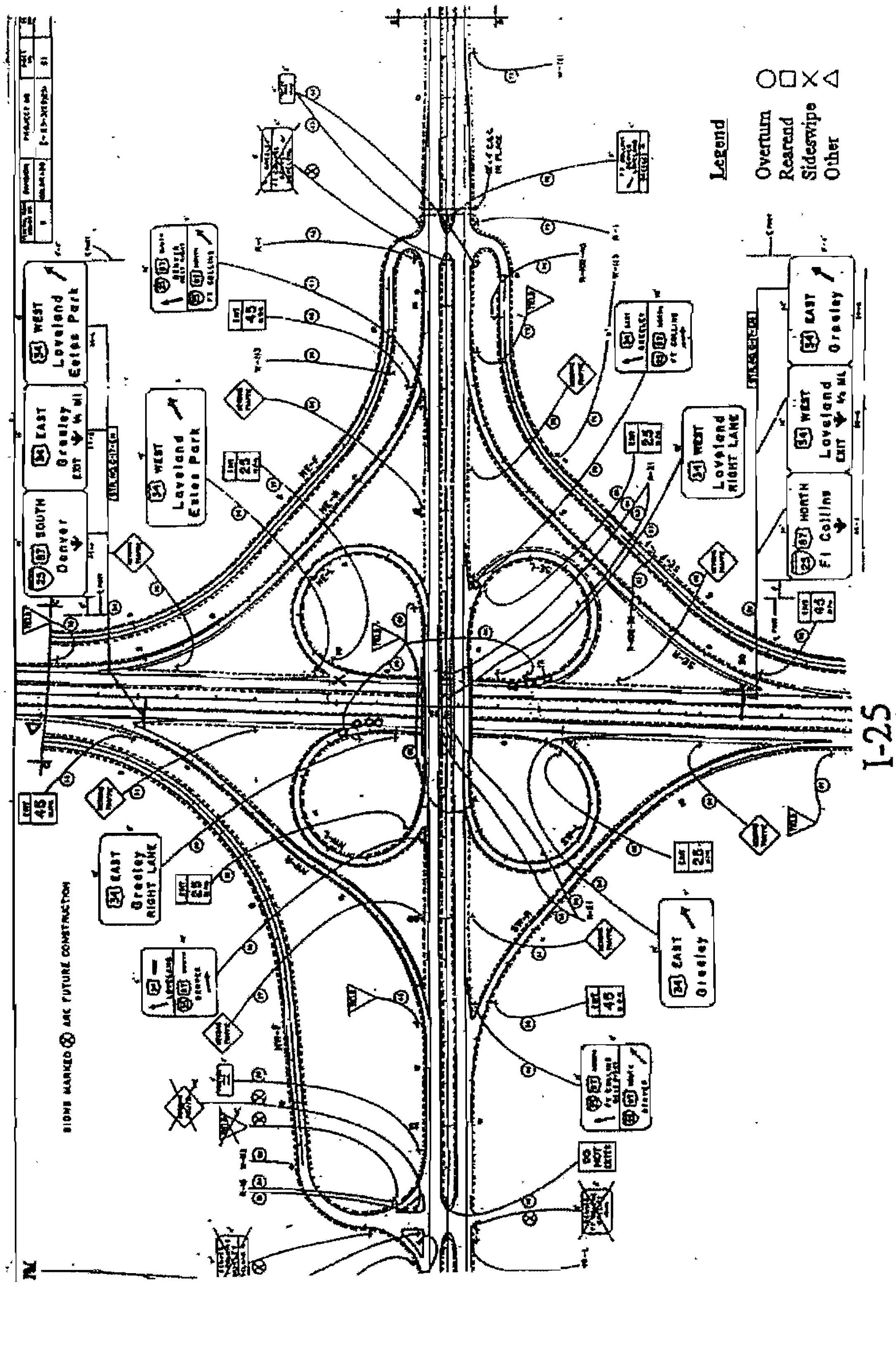


Figure 5.2 Interchange Accidents at I-25 and SH-34 in Colorado

Chapter Six

CRITICAL EXAMINATION OF AASHTO STANDARDS FROM THE STANDPOINT OF TRUCK OPERATIONS AT INTERCHANGES

6.1 OVERVIEW

Development of the highway infrastructure and development of the motor carrier industry are interrelated. Construction of the Interstate System in particular offered unprecedented economic opportunities for the development of trucking. The need to increase the cargo transporting efficiency of trucks in turn led to the development of larger vehicles capable of carrying heavier loads. Critical dimensions and operational characteristics of these vehicles have a direct effect on highway design criteria. This portion of the report will identify the basic operational characteristics and dimensions of modern large trucks and examine their impact on highway design criteria through literature review and direct contacts with trucking organizations and vehicle manufacturers around the country.

The design philosophy formulated throughout various editions of the AASHTO Policy on Geometric Design always aimed at accommodating the largest design vehicle likely to use the highway facility with considerable frequency or a design vehicle with special characteristics. A "design vehicle" was defined as a selected motor vehicle the weight , dimensions and operating characteristics of which are used to establish highway design controls to accommodate a vehicle of a designated type. Accommodation of the design vehicle is achieved through geometric design standards, which provide a safe and efficient environment for traffic operations. Trucks generally impose greater demands on the highway facilities than passenger cars because they are wider, longer, heavier, less maneuverable, less stable, slower and more difficult to stop. Yet, over the years vehicle designers and manufacturers have made significant improvements to various truck components resulting in a safer and more efficient vehicle fleet. The connections between truck characteristics and related highway design criteria are illustrated in Fig. 6.1. This self-explanatory drawing illustrates the numerous implications of truck dimensions and operating characteristics on highway design standards. These relationships as well as the trends in vehicle development will be discussed further in the report.

6.2 EFFECT OF VEHICLE DIMENSIONS ON ELEMENTS OF GEOMETRIC DESIGN

Over the years the evolution of commercial vehicles driven by the economic stimulus to lower the cost of cargo transport exerted greater and greater demands on the highway infrastructure. The largest design vehicle in the 1965 AASHTO Policy on Geometric Design of Rural Highways was the WB-50 semitrailer combination. The 1973 edition of the Geometric Design Policy introduced two additional design vehicles, one reflecting the dimensions of many buses at the time and another reflecting dimensions of the semitrailer-full trailer combination WB-60. In order to reflect the latest trends in motor vehicle manufacture and represent a composite of the vehicles currently in operation the 1990 edition of the Green Book added four more design vehicles to the design criteria. These vehicles are: WB-62, a design vehicle representative of a larger tractor-semitrailer combination allowed on selected highways by the Surface Transportation Assistance Act of 1982, WB-67 a design vehicle representative of a larger tractor-semitrailer grandfathered on selected highways by the Surface Transportation Assistance Act of 1982, WB-96 a design vehicle representative of tractor-semitrailer full trailer-full trailer combinations (triples) selectively in use, and WB-114 a design vehicle representative of larger tractor-semitrailer-full trailer (turnpike doubles) selectively in use (1990 Green Book). Although turnpike doubles and triple trailers are not permitted on many highways, their manufacture and use warranted inclusion of these vehicles in the 1990 Green Book. Every successive publication of the AASHTO Policy on Geometric Design incorporated all previous design vehicles and introduced new ones in an effort to capture present and future trends in vehicle manufacture and design. As a result, the 1990 edition has 15 different design vehicles,

CONNECTIONS BETWEEN TRUCK CHARACTERISTICS AND GEOMETRIC DESIGN CRITERIA

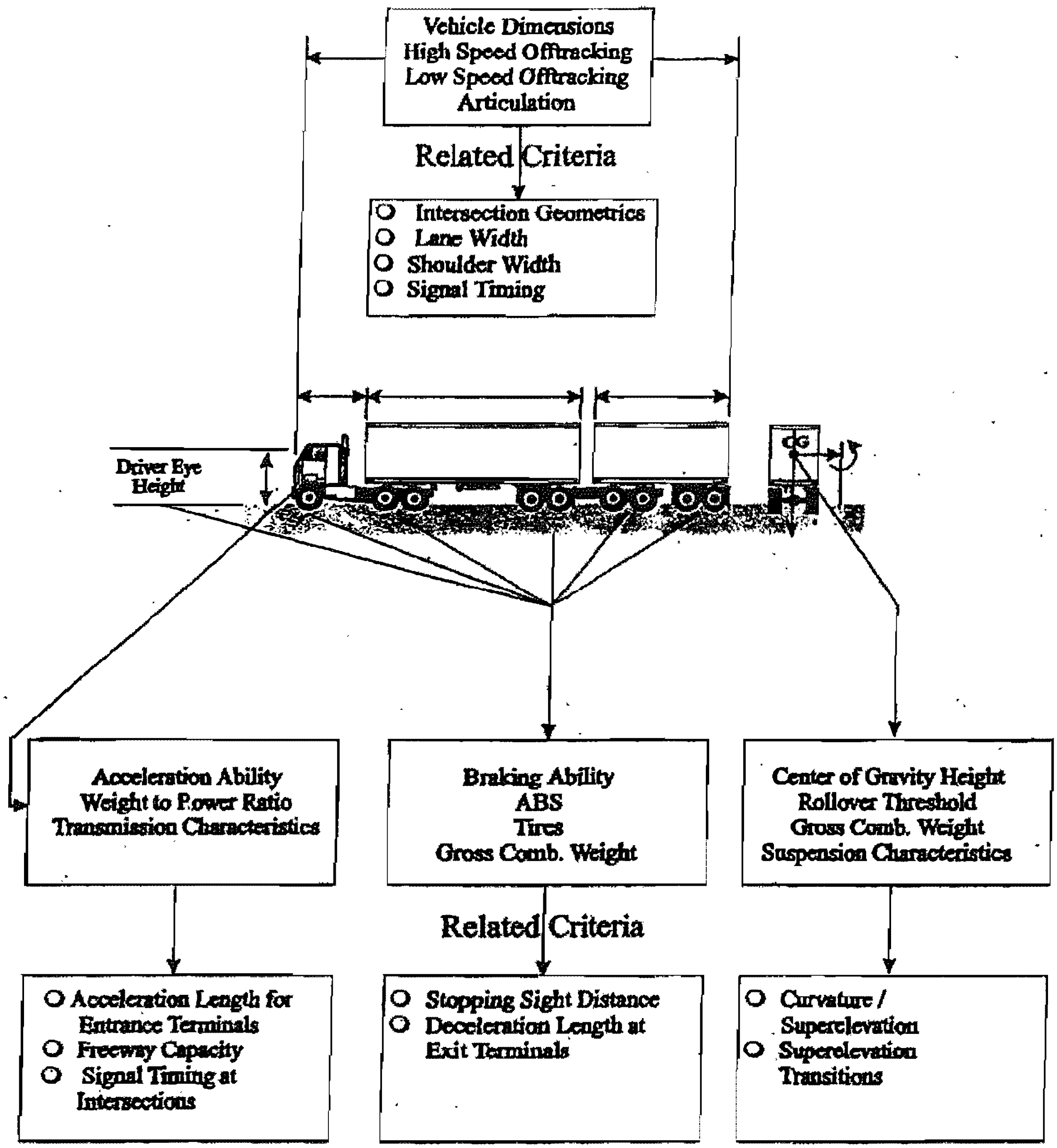


Figure 6.1

eight of which are trucks. Table 6.1 shows design vehicle dimensions and table 6.2 shows minimum turning radii of design vehicles included in the 1990 Green Book. Vehicle length, width, number of axles, distance between axles, number of articulation points and offtracking are design controls which define geometric design requirements of intersections and horizontal curves.

		Dimension (ft)										
		Overall			Overhang							
Design Vehicle Type	Symbol	Height	Width	Length	Front	REAR	WB_1	WB_2	S	T	WB_3	WB_4
Passenger car	P	4.25	7	19	3	5	11					
Single unit truck	SU	13.5	8.5	30	4	6	20					
Single unit bus	BUS	13.5	8.5	40	7	8	25					
Articulated bus	A-BUS	10.5	8.5	60	8.5	9.5	18		4^a	20^a		
Combination trucks												
Intermediate semitrailer	WB-40	13.5	8.5	50	4	6	13	27				
Large semitrailer	WB-50	13.5	8.5	55	3	2	20	30				
"Double Bottom" semi-trailer—full-trailer	WB-60	13.5	8.5	65	2	3	9.7	20	4^b	5.4^b	20.9	
Interstate Semitrailer	WB-62*	13.5	8.5	69	3	3	20	40–42				
Interstate Semitrailer	WB-67**	13.5	8.5	74	3	3	20	45–47				
Triple Semitrailer	WB-96	13.5	8.5	102	2.5	3.3	13.5	20.7	3.3^d	6^d	21.7	21.7
Turnpike Double Semitrailer	WB-114	13.5	8.5	118	2	2	22	40	2^c	6^c	44	
Recreation vehicle												
Motor home	MH		8	30	4	6	20					
Car and camper trailer	P/T		8	49	3	10	11	18	5			
Car and boat trailer	P/B		8	42	3	8	11	15	5			
Motor Home and Boat Trailer	MH/B		8	53	4	8	20	21	6			

* = Design vehicle with 48' trailer as adopted in 19872 STAA (Surface Transportation Assistance Act)
** = Design vehicle with 53' trailer as grandfathered in 1982 STAA (Surface Transportation Assistance Act)
a = Combined dimension 24, split is estimated.
b = Combined dimension 9.4, split is estimated.
c = Combined dimension 8, split is estimated.
d = Combined dimension 9.3, split is estimated.
WB_1, WB_2, WB_3, WB_4 are effective vehicle wheelbases.
S is the distance from the rear effective axle to the hitch point.
T is the distance from the hitch point to the lead effective axle of the following unit.

Table 6.1: Design Vehicle Dimensions

Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Bus	Articulated Bus	Semi-trailer Intermediate	Semi-trailer Combination Large	Semi-trailer Full Trailer Combination	Inter-State Semi-Trailer	Inter-State Semi-Trailer	Triple Semi-Trailer	Turnpike Double Semi-Trailer	Motor Home	Passenger Car with Travel Trailer	Passenger Car with Boat and Trailer	Motor Home and Boat Trailer
Symbol	P	SU	BUS	A-BUS	WB-40	WB-50	WB-60	WB-62*	WB-67**	WB-96	WB-114	MH	P/T	P/B	MH/B
Minimum design turning radius (ft)	24	42	42	38	40	45	45	45	45	50	60	40	24	24	50
Minimum inside radius (ft)	13.8	27.8	24.4	14.0	18.9	19.2	22.2	9.1	00	20.7	17	26.0	2.0	6.5	35

* Design vehicle with 48' trailer as adopted in 1982 STAA (Surface Transportation Assistance Act)
** Design vehicle with 53' trailer as grandfathered in 1982 STAA (Surface Transportation Assistance Act)

Table 6.2: Minimum Turning Radii of Design Vehicles

The Society of Automotive Engineers (F. Jindra, Scale Models of Offtracking...) defines offtracking as "The difference in the path of the first inside front wheel and the last inside rear wheel as a vehicle negotiates a curve. Figures 6.2 and 6.3 (Heald. Use of WHI Offtracking Formula) illustrate this phenomenon for single and double combinations traveling on a highway ramp where offtracking is fully contained within the roadway width.

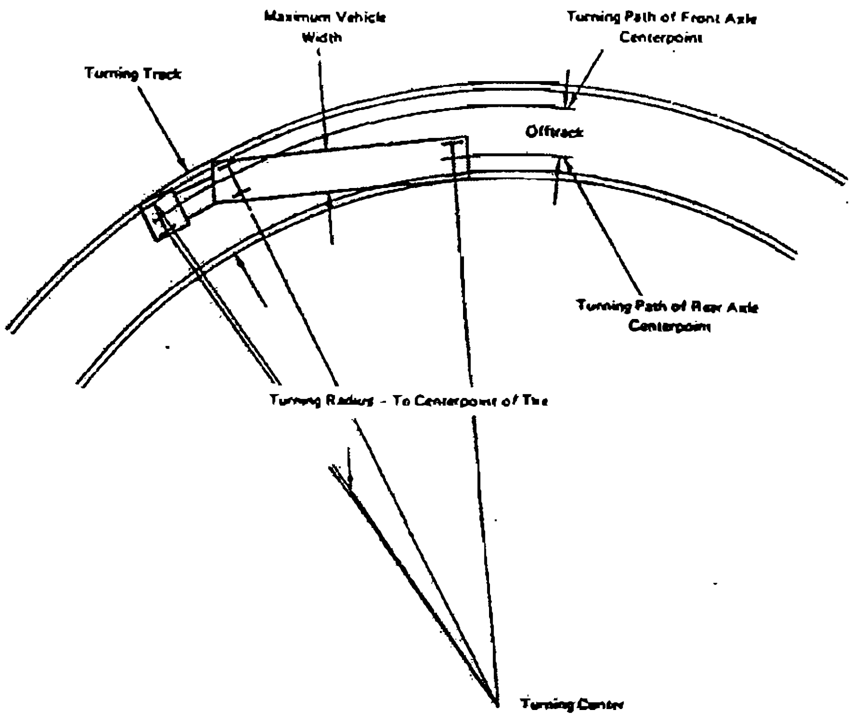


Figure 6.2: Schematic of Turning Track Components and Terms

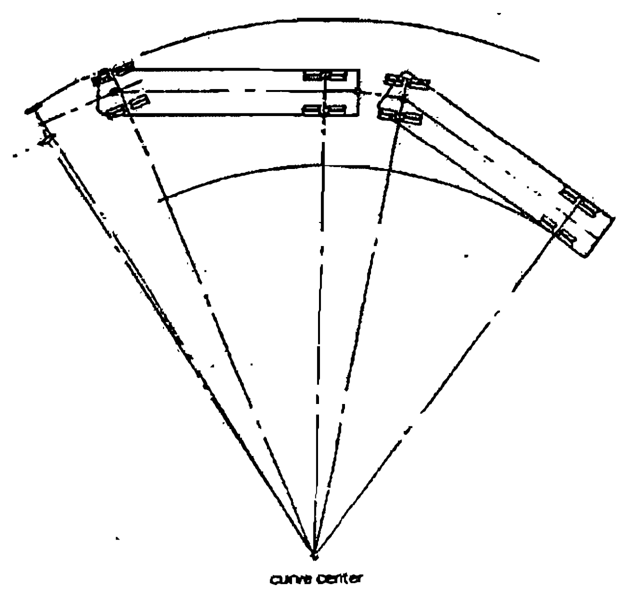


Figure 6.3: Graphic Representation of Steady-State Offtracking

The most important design parameter related to offtracking is the swept path width which is the controlling factor in computing the minimum required pavement width for turning roadways and intersections. Fig. 6.4 (AASHTO GB) shows the swept path width for low speed offtracking in a 90-degree turn. Offtracking and corresponding swept path width can be determined for various design vehicles using several of the accepted methods. These methods include: a computer simulation program developed by CALTRANS (Fong and Chenu), and the Western Highway Institute (WHI) offtracking formula (Offtracking Characteristics of Trucks). It is important to understand that WHI formulae provide theoretical steady-state maximum values of offtracking, while the computer simulation model determines the maximum amount of offtracking for a specific degree of turn. The amount of offtracking predicted by the WHI and simulation model match only if the degree of turn is sufficient to allow the vehicle to reach its steady state turning condition. For smaller angle and shorter radius turns, the differences between the WHI and CALTRANS methods can be substantial. The field tests conducted by CALTRANS (Fong and Chenu) support offtracking values generated by the CALTRANS simulation model. The important advantage of the CALTRANS simulation model is that it can keep track of where the truck is as it negotiates the turn. The amount of offtracking is reported along the turn to and from the point of maximum offtracking.

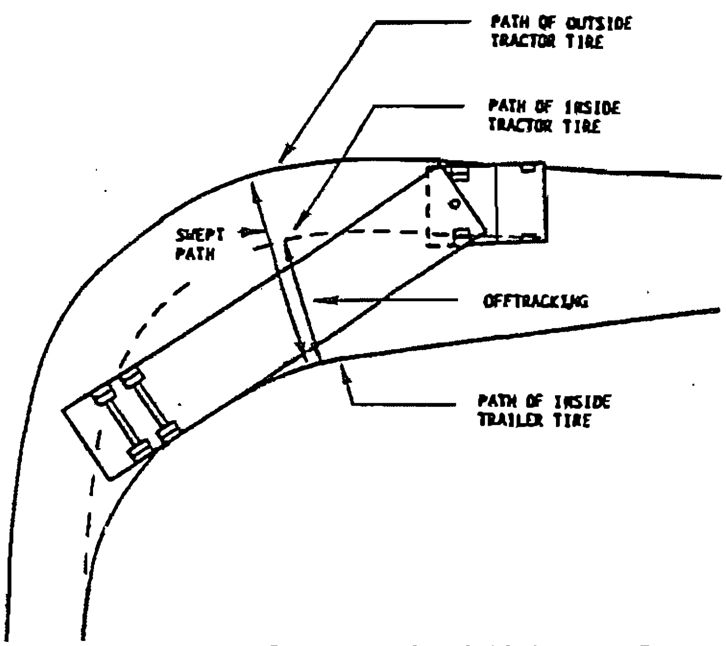


Figure 6.4: Swept Path Width in a 90 Degree Turn

6.3 EFFECT OF OFFTRACKING ON DESIGN OF RAMPS AND INTERSECTIONS

The study by Harwood et al., which evaluated offtracking and swept width requirements for the design vehicles included in the 1984 Green Book stressed the need to include the STAA vehicles. The 1990 edition of the Green Book added WB-62, WB-67, WB-96 and WB-114. While the 1990 Green Book included these new design vehicles it did not address the costly and sensitive issue of accommodating them on the highways through extensive retrofitting of interchanges and intersections. Harwood et al., presented estimates of the construction costs associated with widening required to accommodate vehicles larger than WB-50 at intersections (Table 6.3).

Turning radius (ft)	Additional paved area per quadrant (ft^2)			Additional construction cost[a] per quadrant		
	45-ft semitrailer	48-ft semitrailer	53-ft semitrailer	45-ft semitrailer	48-ft semitrailer	53-ft semitrailer
50	900.8	1,225.1	1,849.6	$ 2,620	$ 3,570	$ 5,380
60	1,095.6	1,423.0	2,283.0	3,190	4,140	6,640
80	1,243.4	1,673.0	2,939.0	3,620	4,870	8,550
100	1,498.1	2,085.6	3,319.3	4,360	6,070	9,660
150	1,601.8	2,242.5	3,752.8	4,660	6,530	10,920
200	1,631.6	2,249.6	3,732.8	4,750	6,550	10,860
250	1,554.3	2,331.5	3,730.3	4,520	6,790	10,860
300	1,403.1	2,245.0	3,648.1	4,020	6,533	10,620

Table 6.3: Cost Estimates for Widening at Intersections

This cost data shows that intersections alone will require very substantial investments. According to a survey of 46 States conducted by the DOT and AASHTO (The Feasibility of a Nationwide Network of LCV's, USDOT, FHWA-1986) "a majority of interchange ramps had inadequate geometry to accommodate the offtracking of some larger combinations. States estimated that approximately 43 percent of the Interstate interchanges could safely accommodate triples, 34 percent could accommodate Rocky Mountain doubles and 25 percent could accommodate turnpike doubles. The States estimated, however, that only about half of all

Interstate interchanges can safely accommodate the tractor-48-foot semitrailer combinations mandated by the 1982 STAA". There is little disagreement as to what the steady state offtracking/swept width requirements are regardless of the method employed. The larger question, which remains unaddressed, is who will pay for the infrastructure improvements associated with accommodating these vehicles. Presently, there is no national consensus on this issue.

6.4 BRAKING ABILITY OF TRUCKS vs. AASHTO STOPPING SIGHT DISTANCE AND DECELERATION REQUIREMENTS

Stopping sight distance requirements in the 1990 edition of the Green Book are based on the operating characteristics and dimensions of passenger cars as opposed to heavy commercial vehicles. In fact AASHTO does not recommend these standards for truck operations. At the same time however, there is no separate stopping sight distance for trucks, partially because of the elevated seat position which allows the truck driver to see further ahead and partially because of economic considerations. It is relevant to note that truck drivers can only see further if the controlling sight distance is associated with vertical obstructions such as crest vertical curves and not horizontal sight restriction. To circumvent this limitation the Green Book recommends exceeding minimum recommended values and providing a facility with a desirable range of design values. This approach allows flexibility for individual engineers to accommodate trucks based on information on the composition of present and anticipated traffic streams. Table 6.4 shows stopping site distances for various ranges of design values. (AASHTO Green Book, 1990).

Design Speed (mph)	Assumed Speed for Condition (mph)	Brake Reaction		Coefficient of Friction f	Braking Distance on Level (ft)	Stopping Sight Distance	
		Time (sec)	Distance (ft)			Computed (ft)	Rounded for Design (ft)
20	20-20	2.5	73.3-73.3	0.40	33.3-33.3	106.7-106.7	125-125
25	24-25	2.5	88.0-91.7	0.38	50.5-54.8	138.5-146.5	150-150
30	28-30	2.5	102-7-110.0	0.35	74.7-85.7	177.3-195.7	200-200
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0.31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650
65	55-65	2.5	201.7-238.3	0.29	347.7-485.6	549.4-724.0	550-725
70	58-70	2.5	212.7-256.7	0.28	400.5-583.3	613.1-840.0	625-850

Table 6.4: Stopping Sight Distance (Wet Pavement)

Fancher (*Site Distance Problems Related to Large Trucks)* has developed a model used to predict the braking distances for trucks under controlled and locked wheel deceleration with new and worn tires. Figure 6.5 (*Site Distance Problems Related to Large Trucks)* shows that braking distances predicted by Fancher are substantially longer than distances recommended in AASHTO policy. According to Fancher, "The notion of attempting to design for trucks passing over crest vertical curves at 60 mph or faster may not be economically reasonable. At 60 mph the braking distances for controlled braking exceed the AASHTO policy for 80 mph. At 55 mph, controlled stops of trucks require braking distances that are approximately equal to the AASHTO policy for 80 mph".

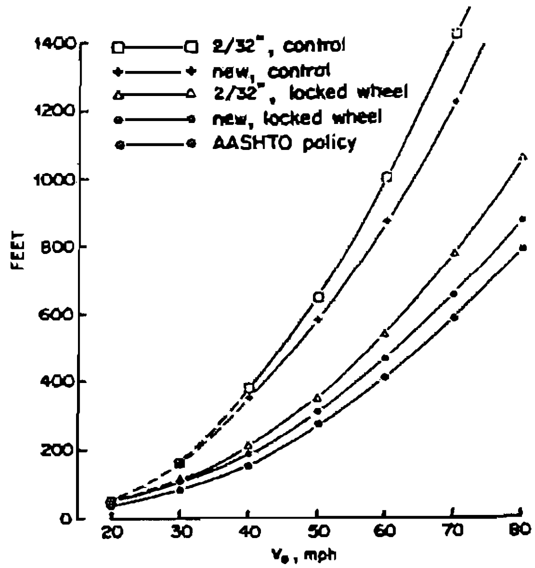


Figure 6.5: Truck Braking Distance

The discrepancy between the heavy vehicle's ability to come to a controlled stop and AASHTO design standards may be related to accidents involving commercial vehicles. Based on the analysis of national and state accident data, NHTSA (National Highway Traffic Safety Administration) estimates that between 10 percent and 15 percent of the crashes involving heavy combination vehicles involved braking induced instability or loss of control. In order to improve the directional stability, control characteristics and stopping distances of commercial vehicles NHTSA has issued a set of four regulations designed to address this important safety issue. The first one, *Stability and Control of Medium and Heavy Vehicles During Braking* mandated that new commercial vehicles be equipped with an antilock brake system (ABS) by March 1, 1997. The second one, *Stopping*

Distance requirements for Vehicles Equipped With Air Brake Systems specified distances in which different types of medium and heavy vehicles equipped with air brakes must come to a controlled stop from 60 mph on a high coefficient of friction surface. The third regulation *Stopping Distance Requirements for Vehicles Equipped With Hydraulic Brake Systems* is similar to the second but targets vehicles equipped with hydraulic brakes. The proposed braking distances for both air and hydraulic braking systems are presented below (49 CFR Part 571).

Vehicle Type	Speed	Surface PFC	Stopping Distance
Loaded and Unloaded Buses	60 mph	0.9	280 ft
Loaded Truck Tractors with Braked Control Trailer	60 mph	0.9	280 ft
Loaded Truck Tractors with Unbraked Control Trailer	60 mph	0.9	355 ft
Loaded Single-Unit Trucks	60 mph	0.9	310 ft
Unloaded Single-Unit Trucks and Truck Tractors (Bobtail)	60 mph	0.9	335 ft

Table 6.5: Stopping Distances from 49 CFR Part 571

Stopping distance is comprised of the distance traveled while the driver recognizes and reacts to a hazard by applying brakes and the actual braking distance required to bring the vehicle to a complete stop. The reaction time t assumed in the AASHTO stopping site distance (Table 6.4) is 2.5 seconds which at 60 mph corresponds to 220 ft. The approximate braking distance of a vehicle on a level roadway is determined by the use of the following formula (1990 GB):

$d=V^2/30f$ *(1)*

d= braking distance

V= initial speed, mph

f= coefficient of friction between tires and roadway

Assuming that during the tests which resulted in these regulations the test drivers were expecting to stop and their reaction and brake activation time can be reduced to 2.0 seconds which at 60 mph corresponds to a traveled distance of 176 feet. Let's now convert the stopping distances on dry pavement during the tests to stopping distances of the same vehicles on wet pavement and compare with AASHTO criteria. This can be accomplished by multiplying the braking distance on dry pavement by the ratio of f(d) / f(w) and adding it to the distance traveled during the reaction and brake activation period. Where f (d) = 0.9 represents dry pavement conditions and f(w) = 0.29 represents wet pavements. Table 6.5 presents the results of this comparison.

	New Regulations dry pavement stopping distance	f(d)/f(w)= 0.9/.29	New Regulations wet pavement stopping distance	AASHTO wet pavement stopping sight distance
Loaded/unl. buses	280 ft	3.1	498.4 ft	525-650 ft
Loaded trucks with braked control trailers	280 ft	3.1	498.4 ft	525-650 ft
Loaded trucks with unbraked control trailers	355 ft	3.1	730.9 ft	525-650 ft
Loaded single unit trucks	310 ft	3.1	591 ft	525-650 ft
Unloaded single unit & Bobtail	335 ft	3.1	668.9 ft	525-650 ft

Table 6.6: Comparison of AASHTO Criteria and New ABS/Stopping Distance Requirements

This exercise shows that these new stopping distances will bring the braking ability of new commercial vehicles in line with AASHTO standards.

The minimum deceleration requirements for exit terminals required by AASHTO for flat grades of 2% or less are also well within capabilities of most trucks equipped with ABS.

Highway Design Speed, V (mph)	Average Running Speed, V_a (mph)	Deceleration Length, L (ft) For Design Speed of Exit Curve, V' (mph): Stop Condition	15	20	25	30	35	40	45	50
		For Average Running Speed on Exit Curve, V'_a (mph): 0	14	18	22	26	30	36	40	44
30	28	235	185	160	140	—	—	—	—	—
40	36	315	295	265	235	185	155	—	—	—
50	44	435	405	385	355	315	285	225	175	—
60	52	530	500	490	460	430	410	340	300	240
65	55	570	540	530	490	480	430	380	330	280
70	58	615	590	570	550	510	490	430	390	340

V = Design speed of highway
V_a = Average running speed on highway
V' = Design speed of exit curve
V'_a = Average running speed on exit curve

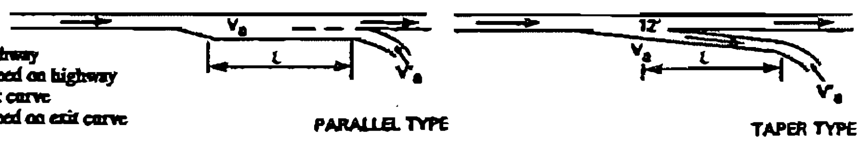
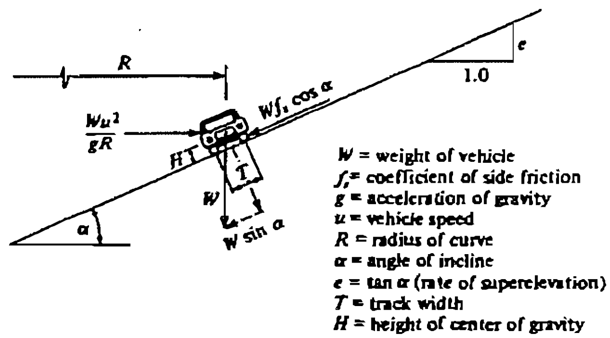


Table 6.7: Minimum Deceleration Lengths for Exit Terminals – All Main Highways Flat Grades – 2 Percent or Less

The last NHTSA Regulation on this issue, *Parts and Accessories Necessary for Safe Operation; Antilock Brake Systems,* addresses maintenance requirements related to ABS. While these requirements will go a long way in improving traffic safety it is important to realize that they apply only to new trucks and buses and will not require retrofitting of the existing fleet, which means that safety improvement is expected to take place gradually and over time.

6.5 RELATIONSHIP BETWEEN SUPERELEVATION / CURVATURE AND ROLLOVER THRESHOLD

The maximum degree of curvature for a given speed is determined from the maximum rate of superelevation and the maximum allowable friction factor. This relationship is based on the laws of Newtonian physics and is developed on the assumption that the vehicle is in equilibrium with respect to the superelevated plane of the roadway surface as it travels around the curve. Figure 6.6 shows the forces acting on a vehicle on a horizontal curve section.



Source: Redrawn from Donald R. Drew, *Traffic Flow Theory and Control*, copyright © 1968, McGraw-Hill Book Company.

where

a_c = acceleration for curvilinear motion = u^2/R
R = radius of the curve
W = weight of the vehicle
g = acceleration of gravity

Figure 6.6: Forces Acting on a Vehicle Traveling on a Horizontal Curve Section

When the vehicle is in a state of equilibrium the sum of all forces projected on the roadway plane is equal to zero. In other words the vehicle is not sliding up and down with respect to the roadway surface as it travels around the curve. As a result, the relationship between speed, curvature, superelevation and side friction can be expressed as follows:

$$R = V^2/15(e + f)$$

The AASHTO standard developed on the basis of this relationship has not changed in over 30 years and is presented in Table 6.8 (GB 1990).

Design Speed (mph)	Maximum e	Maximum f	Total (e+f)	Maximum Degree of Curve	Rounded Maximum Degree of Curve	Maximum[a] Radius (ft)
20	.04	.17	.21	44.97	45.0	127
30	.04	.16	.20	19.04	19.0	302
40	.04	.15	.19	10.17	10.0	573
50	.04	.14	.18	6.17	6.0	955
55	.04	.13	.17	4.83	4.75	1,186
60	.04	.12	.16	3.81	3.75	1,528
20	.06	.17	.23	49.25	49.25	116
30	.06	.16	.22	20.94	21.0	273
40	.06	.15	.21	11.24	11.25	509
50	.06	.14	.20	6.85	6.75	849
55	.06	.13	.19	5.40	5.5	1,061
60	.06	.12	.18	4.28	4.25	1,348
65	.06	.11	.17	3.45	3.5	1,637
70	.06	.10	.16	2.80	2.75	2,083
20	.08	.17	.25	53.54	53.5	107
30	.08	.16	.24	22.84	22.75	252
40	.08	.15	.23	12.31	12.25	468
50	.08	.14	.22	7.54	7.5	764
55	.08	.13	.21	5.97	6.0	960
60	.08	.12	.20	4.76	4.75	1,206
65	.08	.11	.19	3.85	3.75	1,528
70	.08	.10	.18	3.15	3.0	1,910
20	.10	.17	.27	57.82	58.0	99
30	.10	.16	.26	24.75	24.75	231
40	.10	.15	.25	13.38	13.25	432
50	.10	.14	.24	8.22	8.25	694
55	.10	.13	.23	6.53	6.5	877
60	.10	.12	.22	5.23	5.25	1,091
65	.10	.11	.21	4.26	4.25	1,348
70	.10	.10	.20	3.50	3.5	1,637
20	.12	.17	.29	62.10	62.0	92
30	.12	.16	.28	26.65	26.75	214
40	.12	.15	.27	14.46	14.5	395
50	.12	.14	.26	8.91	9.0	637
55	.12	.13	.25	7.10	7.0	807
60	.12	.12	.24	5.71	5.75	996
65	.12	.11	.23	4.66	4.75	1206
70	.12	.10	.22	3.85	3.75	1528

NOTE: In recognition of safety considerations, use of e_{max} = 0.04 should be limited to urban conditions.
[a]Calculated using rounded maximum degree of curve.

Table 6.8: Maximum Degree of Curve and Minimum Radius Determined for Limiting Values of e and f, Rural Highways and High-Speed Urban Streets.

The only reference to trucks in relationship to curve/superelevation standards in the 1990 Policy on Geometric Design is on page 142. "*Also some trucks have high centers of gravity and some cars are loosely suspended on the axles. When these vehicles travel slowly on steep cross slopes, a high percentage of the weight* *is carried by the inner tires."* In other words truck characteristics are not explicitly considered in the curvature /superelevation design criteria which is based solely on the vehicle characteristics of passenger cars. Given its low center of gravity the passenger car will slide off the road before a rollover occurs. Because the center of gravity of a loaded truck is located much higher the opposite is often true. Truck rollover occurs when the lateral component of the acceleration exceeds a certain level. This level is called the rollover threshold.

> *Rollover threshold is usually determined by performing a test under static conditions - a "tilt table" test. The schematic layout of the tilt table experiment is shown in figure 6.7. The vehicle is positioned on a tilt table platform and is subjected to a gradually increase roll angle. The roll rate of the tilt table is very slow to avoid dynamic effects. As the test progresses, axles start to lift off until a point is reached when the vehicle goes unstable and keeps rolling without an increase in the angle of the tilt table. This point is registered as the rollover threshold with a simulated lateral acceleration that is the appropriate component of the earth gravity. (Hugh McGee et al., USDOT 1993)*

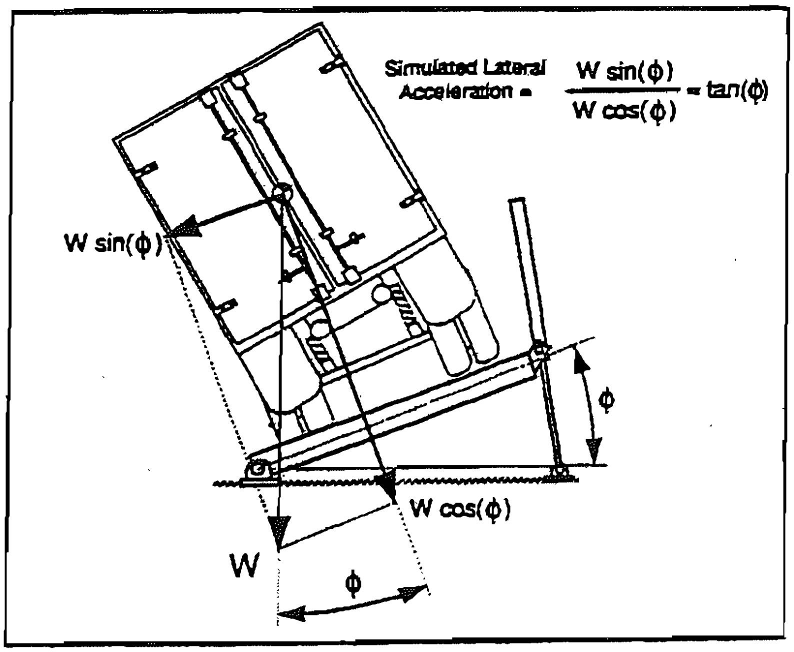


Figure 6.7: Schematic Layout of a Tilt Table Experiment (from Hugh McGhee et al.)

The rollover threshold for a typical passenger car is 1.2 (H. W. McGee, "Synthesis of Large Tuck Safety Research"), which is substantially higher than rollover thresholds for loaded truck configurations (Ervin et al.,) Figure 6.8.

CASE	CONFIGURATION	WEIGHT (lbs) GVW	PAYLOAD CG HEIGHT (in)	ROLLOVER THRESHOLD (g's)
A.	Full Gross, Medium-Density Freight (34 lb/ft³)	80,000	83.5	.34
B.	"Typical" LTL Freight Load	73,000	95.0	.28
C.	Full Gross, Full Cube, Homogeneous Freight (16.7 lb/ft³)	80,000	105.0	.24
D.	Full Gross Gasoline Tanker	80,000	68.6	.32
E.	Cryogenic Tanker (H_e and H_2)	80,000	100.	.26

Figure 6.8: Rollover Threshold Values for Various Example Vehicles

Ervin, Nisonger, MacAdam and Fancher (Influence of Size and Weight Variables on Stability and Control Properties of Heavy Trucks) have shown that

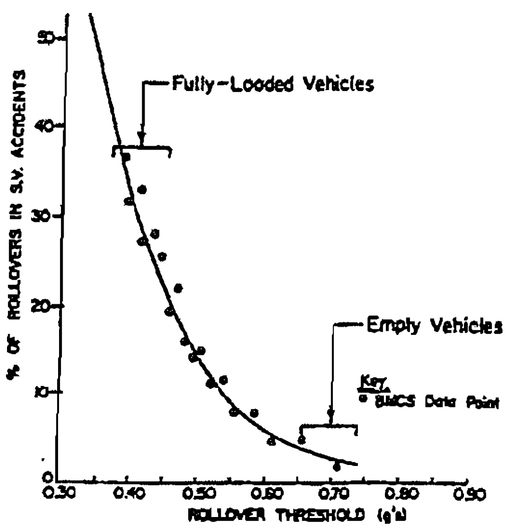


Figure 6.9: Rollover Accident Data vs. Calculated Rollover Threshold Value

vehicles with low rollover thresholds are much more likely to be involved in rollover accidents. Figure 6.9 (above) shows a graph of this relationship.

Harwood and Mason (Ramp/Mainline Speed Relationships and Design Considerations) concluded that truck rollovers and run-off-the-road accidents are attributed to vehicles traveling faster than design speed rather than to a flaw in the AASHTO design Policy. Harwood et al. evaluated AASHTO horizontal curve design criteria and found that although it is adequate for passenger cars and trucks it provides a very narrow margin of safety to trucks as compared with that provided to passenger cars. Harwood and Mason developed a table which summarizes vehicle speeds at impending skid and rollover based on the following conditions:

- A minimum-radius curve with a maximum superelevation rate of .08 ft/ft as per AASHTO criteria.
- Wet pavement friction levels equivalent to AASHTO stopping sight distance policy.
- A passenger car rollover threshold of 1.2.
- A truck rollover threshold of 0.3 (represents worst-case currently on the road).

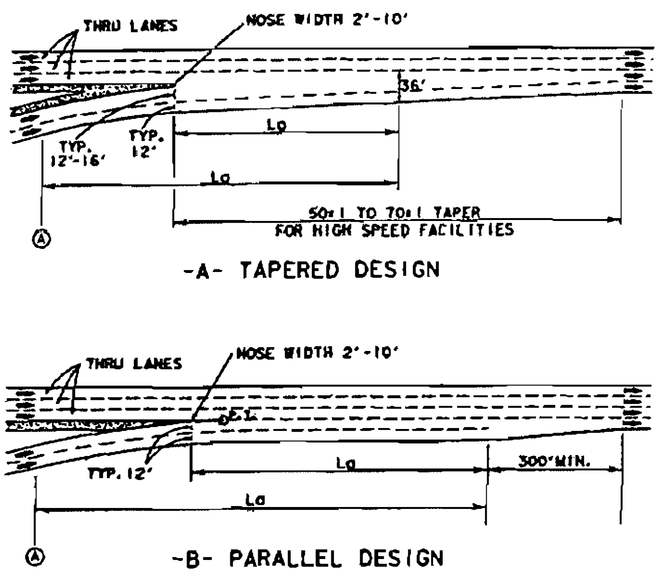
		Passenger car speed (mph)		Truck speed (mph)	
Design speed (mph)	Maximum e	At impending skid (wet)	At impending rollover	At impending skid (wet)	At impending rollover
20	0.08	32.5	45.3	26.8	24.7
30	0.08	47.1	69.6	39.0	37.9
40	0.08	61.8	94.8	51.3	51.6
50	0.08	76.8	121.1	63.9	66.0
60	0.08	95.2	152.2	79.3	82.9
70	0.08	118.0	191.5	98.5	104.3

Table 6.9: Vehicle Speed at Impending Skid and Rollover

The fact that trucks are traveling faster than is safe can often be attributed to the violation of the driver expectancy expressed in inadequate warning to the drivers as is discussed earlier in the report.

6.6 ACCELERATION ABILITY OF TRUCKS vs. AASHTO DESIGN CRITERIA FOR ENTRANCE TERMINALS

According to the AASHTO design criteria, the geometrics of the ramp proper should be such that motorists may attain a speed approximately equal to the average running speed of the freeway less 5 mph by the time they reach the point where the left edge of the ramp joins the traveled way of the freeway. The distance required for acceleration in advance of this point is governed by the speed differential between the average running speed on the entrance curve on the ramp and the running speed of the freeway. Figure 6.10 (1990 GB) shows the minimum lengths for gap acceptance and Figure 6.11 (1990 GB) shows the minimum length of acceleration distances for entrance terminals.

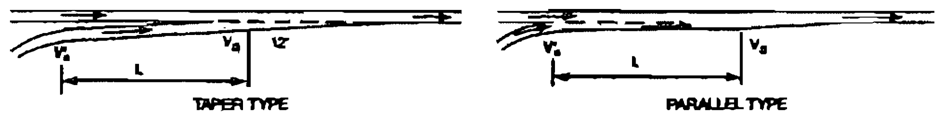


NOTES:

1. La IS THE REQUIRED ACCELERATION LENGTH AS SHOWN IN TABLE X-4 OR X-5.
2. POINT (A) CONTROLS SAFE SPEED ON THE RAMP. La SHOULD NOT START BACK ON THE CURVATURE OF THE RAMP UNLESS THE RADIUS EQUALS 1000' OR MORE.
3. Lg IS REQUIRED GAP ACCEPTANCE LENGTH. Lg SHOULD BE A MINIMUM OF 300' TO 500' DEPENDING ON THE NOSE WIDTH.
4. THE VALUE OF La OR Lg, WHICHEVER PRODUCES THE GREATEST DISTANCE DOWNSTREAM FROM WHERE THE NOSE WIDTH EQUALS TWO FEET, IS SUGGESTED FOR USE IN THE DESIGN OF THE RAMP ENTRANCE.

Figure 6.10: Minimum Length for Gap Acceptance

Highway		Acceleration Length, L (ft) For Entrance Curve Design Speed (mph)								
		Stop Condition	15	20	25	30	35	40	45	50
Design Speed (mph)	Speed Reached, V_a (mph)	and Initial Speed, V_a' (mph)								
		0	14	18	22	26	30	36	40	44
30	23	190	—	—	—	—	—	—	—	—
40	31	380	320	250	220	140	—	—	—	—
50	39	760	700	630	580	500	380	160	—	—
60	47	1,170	1,120	1,070	1,000	910	800	590	400	170
70	53	1,590	1,540	1,500	1,410	1,330	1,230	1,010	830	580



Note: Uniform 50:1 to 70:1 tapers are recommended where lengths of acceleration lanes exceed 1,300 feet.

Figure 6.11: Minimum Acceleration Lengths for Entrance Terminals

This standard has not changed in 30 years. Although the gross combination weight of commercial vehicles has been going up steadily over the same period of time, there is a consistent trend toward a decrease in weight-to-power ratios attributed to the design and manufacturing of yet more powerful engines. Figure 6.12 (1990 GB) shows the trend in weight-power ratios from 1949 to 1985 based on average data for all types of vehicles.

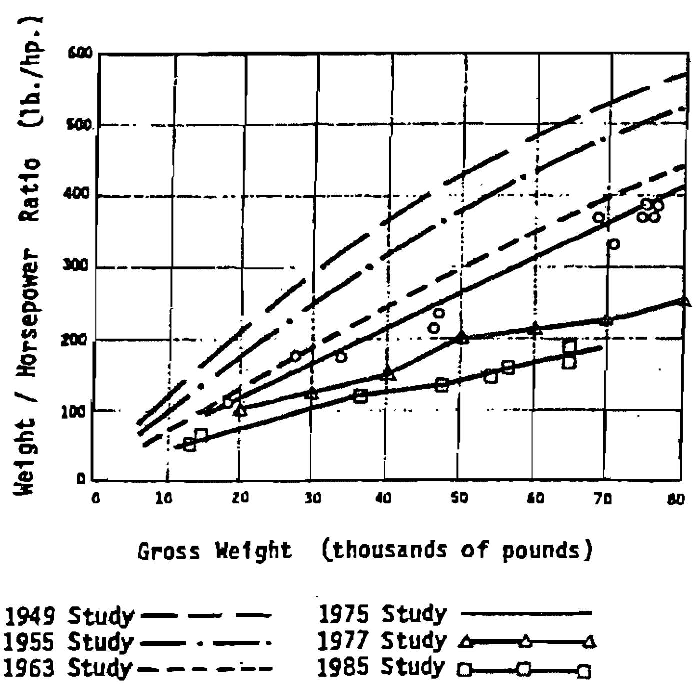


Figure 6.12: Trend in Weight-Power Ratios 1949 – 1985 (Average All Vehicles)

Slower acceleration of trucks as compared with passenger cars and the need for longer space during the gap acceptance process makes merging and lane changing for trucks more difficult. Accident statistics presented earlier in this report show that a large portion of truck accidents at interchanges take place in the merge turbulence zone which can be related to a trucks' inability to gain speed on the acceleration lanes designed to meet AASHTO criteria. A representative truck of the modern commercial vehicle fleet will a have a weight-power ratio of 200 LB/hp. A performance curve for such a vehicle is shown in Figure 6.13 (1985 Highway Capacity Manual). In order to reach a running speed of 53 mph, which is needed to merge with through traffic on freeways with 70 mph design speed and 1% grade, approximately 2 miles of acceleration length is required. Clearly, constructing such a facility may not be economically feasible. The question then becomes - what can be done to address this important safety issue? We should probably concentrate on providing a desirable range of design values when trucks are present along with better signing and a more predictable roadway environment.

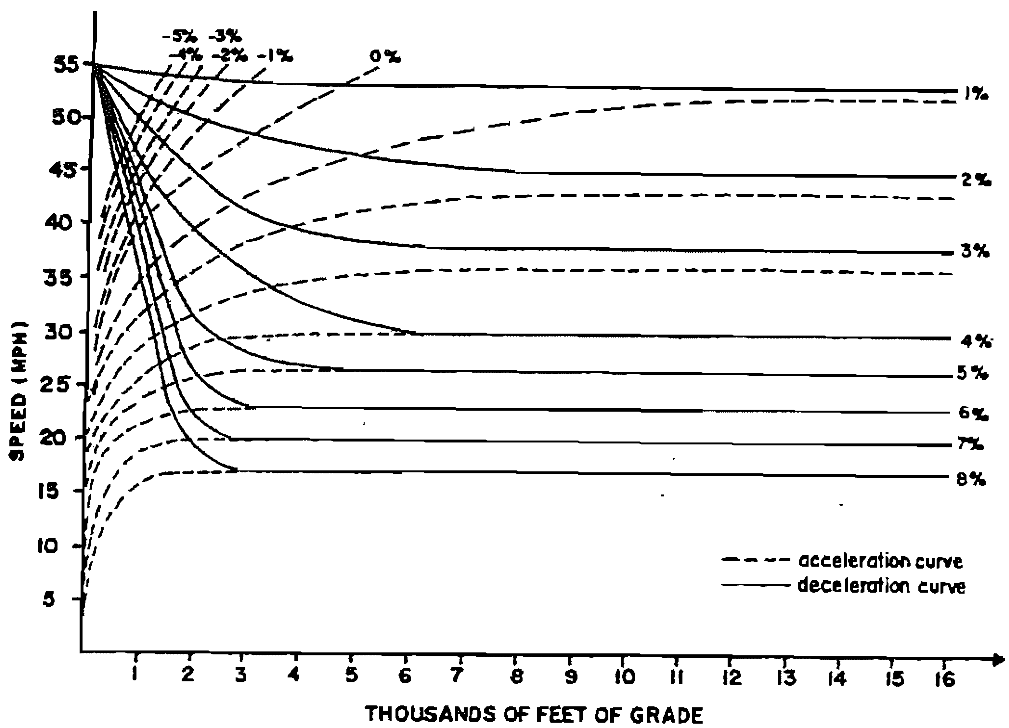


Figure 6.13: Performance Curves for a Standard Truck (200 lbs / hp)

6.7 CONCLUSIONS OF CRITICAL EXAMINATION OF AASHTO STANDARDS FROM THE STANDPOINT OF TRUCK OPERATIONS AT INTERCHANGES

- There is a definite trend toward longer and heavier trucks, yet it is important to realize that innovations in engine design, brakes, suspension, hitches and truck aerodynamic characteristics made trucks safer and more efficient to operate.

- The development of longer combination vehicles provide increased productivity while reducing exposure. At the same time these vehicles impose greater and greater demands on the roadway infrastructure. Comprehensive truck size and weight study currently in progress provides a forum for this important question at the national level.

- Dimensions of the design vehicles larger than WB-50 and their offtracking/swept width requirements are well defined in the latest edition of the AASHTO Geometric Design Policy. What is not well defined however is who will carry the financial burden of accommodating these vehicles on the roads.

- The new NHTSA regulations mandated maximum braking distances and ABS for all new heavy and medium trucks and buses beginning in March of 1997. These regulations will bring braking ability of commercial vehicles in line with AASHTO standards. While these requirements will go a long way in improving traffic safety it is important to realize that they apply only to the new trucks and buses and will not require retrofitting of the existing fleet, which means that safety improvement is expected to take place gradually and over time.

- AASHTO policy on the design of horizontal curves provides a very narrow margin of safety for the operation of commercial vehicles. It is especially true for the lower range of design speeds. To improve truck safety on curves, highway designers should become more sensitive to truck presence and provide "desirable" range of design values. This approach will increase the margin of safety available for the operation of commercial vehicles and reduce the probability of rollovers.

- Current AASHTO standards for acceleration at entrance terminals are well beyond the capabilities of loaded commercial vehicles. This disparity between vehicle capability and AASHTO standards is reflected in the high number of accidents in the merge turbulence zone. Yet, constructing facilities to accommodate acceleration abilities of trucks may not be economically feasible. The strategies to address this important issue include: providing desirable range of design values, better signing and predictable roadway environment and driver education.

- It would be highly beneficial for highway engineers to have certain basic knowledge of vehicle design and truck operation to gain greater appreciation of the problem.

APPENDIX

1. TRUCK DRIVER SURVEY INFORMATION
2. IMPLEMENTATION OF STUDY FINDINGS IN COLORADO

STATISTICAL SUMMARY

Interchange Number -- >	68	76	80	89	91	92	93	97	98	100	101	196	196a	197	199	202
# of Responses	5	12	2	26	4	4	4	4	25	29	16	3	4	14	2	2
Poorly Designed Ramp	4	2.2	1	1.5	2.7	1	1.7	2	2.3	1.4	1.6	2.7	1.5	1.4	1	3
Grade too Steep	4	4.5	5	4.3	3.7	3	3	2	3.4	3.2	3	5	5	3.9	2	5
Curve too Severe	3.5	3	5	2.3	3.7	1	2.3	3	2.6	1.8	2.3	5	1	2.4	5	3
Length too Short	4	2	1	2.6	2	1	1.7	3	3	2.4	1.8	1	5	1.9	1	1
Confusing Configuration	4	2.6	1	1.6	1.7	1	1	1.3	1.3	1.4	1.9	2.7	2	1.7	1	5
Short Sight Distance	4	3.4	1	2.5	2.3	1	1	1.3	2.1	1.7	1.3	3.5	3.5	2	1	3
Poor Markings/Signs	3	3.4	1	3.3	3.7	1	1	2	2.1	1.8	2.3	2	2	2.7	1	3
Traffic Speed	2	2.2	1	1.6	2.7	1	1	2.3	2.3	2.5	2.4	2	2.6	1.4	2	2
Lane Changing	2	1.3	1	1.3	2.3	1	1	2.7	1.3	1.6	1.4	1	1.5	1.4	1	3
Traffic Congestion	2	1.3	1	1.3	1.7	1	1	2	1.3	1.7	1	1	1	1.7	2	2
Poor Road Maintenance	2	3.5	5	2.6	1.7	1	1	4.3	3.7	3.1	3	5	2	3.3	1	3
Score Average	3.1	2.7	2.1	2.3	2.8	1.2	1.4	2.4	2.3	2.1	2.0	2.8	2.5	2.2	1.6	3.0
Score Std. Dev.	1.0	1.0	1.9	0.9	0.6	0.6	0.7	0.9	0.6	0.6	0.7	1.6	1.4	0.8	1.2	1.2

Interchange Number -- >	205	206	208	209	211	238a	241	246	248	252a	253	295	307	323	328	8th	avgs.	S.D.'s
# of Responses	6	4	3	9	3	3	8	4	7	4	7	6	4	7	17	6		
Poorly Designed Ramp	2	2.5	3	2.4	2.5	3	3	4.3	2.3	1	3	1	3	1	1.2	3	2.16	0.91
Grade too Steep	3	3	5	4.6	4.5	5	4	5	4.3	1	3.3	5	3	5	5	5	3.93	1.06
Curve too Severe	1.7	1.7	5	2.3	4.5	5	4.5	4.3	2	3	3	5	1	3	3.7	5	3.18	1.33
Length too Short	4.3	1.7	1	3.6	2.5	1	3.5	3.7	3	3	2.7	3	2	1	1	5	2.39	1.21
Confusing Configuration	1.5	1	5	3	2	3	4	4	1.8	3	3	1	3	1.2	1.8	3	2.28	1.16
Short Sight Distance	1.7	2	5	3	2	5	4	5	1.8	3	2	1.7	3	1.2	1.3	5	2.54	1.29
Poor Markings/Signs	2.3	3	5	2.6	1.5	5	4.5	5	1.3	3	2.3	3	2	2	3.8	3	2.65	1.16
Traffic Speed	1.3	2	5	1.9	1.5	5	2.5	3	1.3	3	1.6	2	3	2	1.7	3	2.22	0.93
Lane Changing	1	1	3	2.4	1.5	1	2.6	3	2	5	1.3	2	2.5	1.8	1.3	1	1.78	0.89
Traffic Congestion	1.3	1	1	1.6	1.5	1	1	3	1.7	5	1.3	2.5	1.5	2	1.9	1	1.61	0.80
Poor Road Maintenance	2.3	2	5	3	3.5	5	4	5	2.7	5	1	5	3	3.3	3.3	5	3.24	1.34
Score Average	2.0	1.9	3.9	2.8	2.6	3.6	3.4	4.1	2.2	3.2	2.2	2.8	2.5	2.1	2.4	3.5	2.54	0.68
Score Std. Dev.	0.9	0.7	1.6	0.8	1.2	1.8	1.1	0.6	0.9	1.4	0.6	1.6	0.7	1.2	1.3	1.8	0.68	0.36

Trucker's Survey Results, 1 = Bad 5 = Good

Table A.1 Summary of Trucker's Survey

TRUCK DRIVER SURVEY

The Western Highway Institute is currently working with the Colorado Department of Transportation to gather information on which ramps and interchanges create problems for the professional truck driver. The information gathered will be used to: 1) identify trouble areas in Colorado; 2) develop strategies to assist truck drivers in these high accident areas; and 3) enable highway engineers to design ramps and interchanges to more safely address the needs of commercial vehicle operators and the traveling public.

Please complete the following information. **All information will remain confidential. The goal of this project is to enhance the safety of commercial vehicle operators and their equipment.**

1. Check the type of trip you typically run.
   a.____30______ Interstate -- Long-haul (over 500 miles)
   b.____27______ Intrastate
   c.____41______ Local Pick Up and Delivery
   d.____1______ Small Package (under 50 pounds)
   e.____3______ Other; please specify___Peddle; Pedal; Shuttle________
   1 No Response
   103 Total

(note: more than 84 responses because some drivers indicated more than 1 type of trip)

2. Indicate percentage of loads that are:
   a.__________ Truckload
   b.__________ Less-than-truckload
   ____100%__ Total

% Truckload:	# of Responses	% Truckload	# of Responses
0	9	80	3
1	1	85	1
5	2	90	3
10	1	95	4
20	4	98	1
25	1	100	26
30	1	No Response	1
35	1	Total	84
45	1		
50	9		
60	2		
65	1		
70	6		
75	6		

(note: if the driver only checked the blank it was considered 100%)

3. Mark the type of commodities primarily hauled:

a.___34______ General Freight

b ___113______ Specialized Freight

____15______ Agricultural products

____2______ Heavy machinery

____39______ Refrigerated products

____4______ Liquid/Tank

____7______ Building materials

____12______ Household materials

____0______ Motor vehicles

____20______ Hazardous materials (please specify type)

Bleach
Not Specified
General Hazardous
Corrosive
Flammable
Not Specified
Matches, Antifreeze
Not Specified
Gas & Diesel
Not Specified
Not Specified
All except explosive
All types
Bread
Not Specified
Cleaners
Paint/Corrosives
Soap, Cleaners
Not Specified
Corrosive,
Flammable
Dish Chemicals

____9______ Other; (please specify)__Food/Candy
Groceries
Bakery Products
Groceries
Frozen, Fresh, Dry
US Mail
US Mail
US Mail
Restaurant Supplies

____5______ Not Specified

____0______ No Response

147 Total

4. Check the category below which most appropriately describes your professional status:

a.____84______ Company driver

b.__________ Owner - operator

c.__________ Leased employee

84 Total

5. a. Check years of driving experience:

a.____0______ Less than 1	d.___21______ 10 to 14
b.____4______ 1 to 4	e.___14______ 15 to 19
c.____14______ 5 to 9	f.___31______ 20 or more
	84 Total

6. Indicate sex and age:

Male

a.____1______	25 or less	d.____25______	40 to 49
b.____8______	26 to 29	e.____10______	50 to 59
c.____36______	30 to 39	f.____0______	60 or older

Female

1	30-39
3	40-49

(note: if no response to sex but response to age, assumed male)

7. Indicate the **type of vehicle(s)** you typically drive and **approximate weight hauled** (e.g., five-axle tractor trailer at 80,000 pounds, Rocky Mountain doubles at 94,000 pounds, triples at 110,000 pounds, etc.).

28' Tractor Trailer	1
5 Axle Reefer Van 80,000	4
3 Axle tractor-trailer 40,000	4
5 Axle Tractor Trailer	2
5 Axle Tractor Trailer 80,000	20
Doubles @ 80,000/Triples @ 110,000	3
Twin Trailers 70,000-80,000	1
5 Axle Tractor Trailer 65,000	2
80,000	1
Doubles	1
3 Axle 30,000	1
3 Axle 15,000	2
3 Axle	1
Doubles 80,000	1
5 Axle 35,000-43,000	1
5 Axle Van 65,000	1
Twin Trailers 75,000	2
Twin Trailers 40,000	1
3 Axle Tractor Trailer 14,000	1
Tandem axle straight truck 15,000	1
80,000-94,000	1
4 Axle 65,000	3
6 to 10 Axle to 200,000	1
5 Axle 70,000	2
5 Axle tractor trailer 60-70,000	2
Doubles 70,000	2
Triples and Doubles	2
3 Axle 20,000	1
5 Axle	2
Tandem Bobtail 40,000	1

5 axle tt 80,000/R.M. doubles 94,000/triples 110,000	2
5 axle van	1
5 axle van 70,000-75,000	1
5 axle 80,000/3 axle 54,000/2 axle 30,000	1
5 axle 79,000	2
5 axle van 50,000	3
3 axle straight 35,000/3 axle trailer 35,000	1
Doubles and Triples 60,000-110,000	1
4 axle TT 45,000	1
3 axle 10-18,000	1
27'-52' Vans-Straight Trucks 5,000-40,000	1
No Response	1

8. Rank up to FIVE numbered interchanges shown on the Colorado or Denver area map with 1 being the most difficult to travel.

Indicate interchanges in order of difficulty to travel safely

Interchange Number (list up to five inter-changes)	1	2	3	4	5
Please circle if difficult to:	ENTER EXIT	ENTER EXIT	ENTER EXIT	ENTER EXIT	ENTER EXIT

I/C #	No. of Resp.	I/C #	No. of Resp	I/C #	No. of Resp.	I/C #	# Resp.
68	5	99	1	205	5	295	6
70	1	100	28	206	4	307	4
72	1	101	16	208	3	308	1
76	12	112	1	209	9	316	1
80	2	180	1	211	3	323	7
81	1	182	1	238A	3	327	1
85	1	190	1	241	3	328	17
89	26	192	1	242	1	6th & I-25	6
90	2	196	3	245A	1	No Resp.	12
91	4	196A	4	245B	2		
92	4	197	14	246	4		
93	4	198	1	247	2		
95	1	199	2	248	7		
96	1	202	2	252A	4		
97	4	203	1	253	7		
98	25	204	1	293	1		

Attendance - Focus Group Meeting
October 26, 1994

Name	Organization
Howard Adams	King Soopers
James Blair	Westway Express
Lia Duda	Westway Express
Val Eagal	Colorado Petroleum
Chuck Finan	Westway Express
Ray Gassaway	USDOT/FHWA/OMC
James L. Harris	Colorado Petroleum
Norm Kaus	United Parcel Service
Don Pfertsh	United Parcel Service
John Pitzer	Colorado State Patrol
Al Ream	King Soopers
Steve Reeves	Klein Trucking

Project team:

Wael Awad	University of Colorado at Denver
Melissa Coleman	Western Highway Institute
Lynne Dearasaugh	University of Colorado at Denver
Greg Fulton	Colorado Department of Transportation
Bruce Janson	University of Colorado at Denver
Debb Johnson	Western Highway Institute
Donalee Kolva	Colorado Motor Carriers Association
Jake Kononov	Colorado Department of Transportation

Comments from Focus Group Meeting
October 26, 1994

Comments on specific interchanges:

I-25 & SH 34

Acceleration distance not adequate for trucks in weave area. **Yes (60 ft < mean=169 ft)**
Short weave area. **Yes (500 ft < mean=1117 ft)**
Avoidance maneuvers
Speeds too fast
Poor sight distance in weave areas.
Tight radius loop ramps. **Yes (R = 151 ft < mean=157 ft)**
Downward grade
Truck posted speeds need to be about 10 mph lower on loop ramps
Carrier base (familiar with interchange)
Fewer trucks headed north than south
Poor signage southbound
Loading conditions may be a problem
High truck exposure. **No (Truck Vol. = 3214 < mean=4005)**
Superelevation transition

I-70 & Quebec

Too much traffic. **No (AADT = 93300 < Mean=100540)**
End of NE ramp, accel. & decel. lane too short
End of NE ramp, lane configuration confusing
Insufficient advance warning & direction
Largest Denver truck stop & terminal. **Not largest (Truck Vol. = 4329 > mean=4005)**
Closeness of NB signal on Quebec & Sand Creek Yes
Familiarity with interchange
Visibility at end of NE ramp is poor
Major truck stop. **Yes (Truck Vol. = 4329 > mean=4005)**

I-70 & I-225

Now wider merge areas
Confusing signing
Congestion. **No (AADT = 74000 < mean=100540)**
No advance signing
Difficult road surface - on I-70 EB between SW1 & SE1
Construction has improved interchange
Many major streets in short proximity to each other
Visibility is a problem - SE1 to EB I-70

I-70 & Pecos

EB I-70 steep off-ramp - short - downgrade
I-70 too low below I-70 rising crest
Bridge blocking rear view sight distance -approaching SE1
Poor sight distance from SE1
Signs also in way
Mousetrap backup
Accidents in AM Peak
Exit to 48th - drivers don't expect stop light
Poor curvature on ramp to 48th. **Yes (107 Degree or R=54 ft < mean=157 ft)**

I-25 & Santa Fe

Merging too early - NB Santa Fe to NB I-25. Yes
Sudden grade change
Superelevation transition
Poor rear visibility
Possibly redirect trucks to other on-ramp & not mix with HOV vehicle
Drivers don't realize SE-1 continues as a continuous lane on I-25 SB

I-25 & Bijou

Strong curves for high speeds. **No (8 Degree or R=716 ft > mean=157 ft)**
Lane drop in NB direction on I-25. **Yes**
High traffic volumes. **No (AADT = 69900 < mean = 100540)**
Short ramps. **Yes (Ramp Length=450 ft < mean=733 ft)**
Need to relocate exit ramps past curve

I-70 & Ward

Truck stop. **No (Truck Vol. = 3190 < mean=4005)**
Sharp transition at merge point at ramp D. **No (Ramp Length=750 ft > mean=733 ft, and R=286 ft > mean=157 ft)**
Curvature of C is deceptively sharp. **Yes (Ramp Length=600 ft, R=130 ft)**
Steep grade on ramp D
Short decel lane for ramp C. **No (1680 ft > mean = 1117 ft)**

Others

I-70 & Glenwood Springs **Index = 7**
I-76 & SH 85 (reverse superelevation - 76 WB onto 85)
I-76 & I-270 **Index = 22, Frequency = 6, Exp. = 0.002**
I-25 & I-76 **Index = 10**
I-25 & 1st Ave (in Pueblo) **Index = 1**

Summary

Stripe maintenance in high volume areas
Lack of advanced signage
Separate signs for truck speeds on ramps - Truck speed signs
Lengthen acceleration lanes
Clear overhead signs
Brighter/Flashing signs
Picture signs (configuration of interchange)
Redirecting trucks to easier ramps
Educate car driver (newspaper/TV spot)
Warnings for high volume truck areas (signs)
Examine good interchanges
Grooving road & gore areas to alert drivers
Rumble stripes for slowing
Curve transitions
Visibility & Communication - big factors

UCK ACCIDENTS AT COLORADO INTERCHANGES (1991 – 1993)

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
Route-> I-25											
1	Starkville Interchange	1			1			1			1
2	Country Club Dr., Trinidad	1			1	1			1		5
3	SH 160, Trinidad	1	1		2			2			2
4	SH 12, Trinidad				0						0
5	Commercial St., Trinidad				0						0
6	SH 239, Goddard St., Trinidad				0						0
7	Hoehne Rd.			1	1			1			1
8	Ludlow				0						0
9	SH 25 Aguilar Spur				0						0
10	Rouse Rd.				0						0
11	SH 25 Walsenburg Bus. Rt S.		1		1			1			1
12	SH 10 and SH 160, e/o Walsenburg	1			1			1			1
13	SH 25 Walsenburg Bus. Rt N.				0						0
14	Butte Rd.			1	1			1			1
15	Huerfano Interchange, Rd E. (CO Rd. 104)				0						0
16	Apache Interchange				0						0
17	Granerso Rd.				0						0
18	SH 165				0						0
19	Burnt Mill Rd.				0						0
20	Stem Beach				0						0
21	SH 45				0						0
22	Access Rd. W. (Illinois Ave.)				0						0
23	Indiana Ave.		1		1			1			1
24	Central Ave.				0						0
25	Eldorado St.				0						0
26	Ilex St.	1	1	1	3	4		2	1		7
27	1st St.	1			1			1			1
28	5th St.	1			1			1			1
29	13th St.	1	1		2	2		1	1		6
30	SH 50, 20th St.	1	1		2	1		1	1		6
31	29th St.		1		1						0
32	SH 47 and SH 50	1	5	2	8	3		6	2		16
33	Eagleridge Blvd.	1			1			1			1
34	Eden Interchange				0						0
35	Bragdon				0						0
36	SH 85, Fountain				0						0
37	SH 16				0						0
38	SH 83			1	1			1			1
39	SH 29	2	3	1	6	2		5	1		10
40	SH 24 Bypass				0						0
41	SH 25 and SH 85, Nevada Ave.	2	1		3	1		2	1		7
42	Tejon St.				0						0
43	SH 24, Cimarron St.	3			3	1		2	1		7
44	Bijou St.	3	5	1	9	3		7	2		17
45	Uintah St.	1	1		2			2			2
46	Fontanero St.	2	1		3	2		1	2		11
47	SH 38, Fillmore St.	5	4	1	10	4		7	3		22

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
48	S. Ramps, Garden of Gods Rd.		3	2	5	1		4	1		9
49	N. Ramps, Garden of Gods Rd.				0						0
50	Rockrimmom Interchange		1	2	3	2		1	2		11
51	SH 25 Colo Spgs Bus. Rt., Nevada Ave.	2			2	1		1	1		6
52	Woodmen Rd.	2		3	5	1		4	1		9
53	SH 83 Spur and South Gate Rd.	2	1	4	7	5		3	4		23
54	Briargate				0						0
55	North Gate Rd.	1			1			1			1
56	Baptist Rd.		1	1	2	3			2		10
57	SH 105, Monument				0						0
58	Palmer Divide Rd.		1		1			1			1
59	SH 18				0						0
60	Lark Spur				0						0
61	South Castle Rock	1	1	1	3	2		2	1		7
62	North Castle Rock	2	1	1	4			4			4
63	SH 85, n/o Castle Rock				0						0
64	Meadows Pwky				0						0
65	Happy Canyon Rd (CO Rd. HC1)		2	1	3	2		2	1		7
66	Castle Pines (CO Rd. BH1)	1		1	2	2		1	1		6
67	Lincoln Ave. (CO Rd. 8)	1	1		2			2			2
68	SH 470			1	1			1			1
69	County Line Rd.			1	1	1			1		5
70	S. Ramp Dry Creek Rd. (ramp off)				0						0
71	N. Ramp Dry Creek Rd. (ramp on)			1	1			1			1
72	SH 88, Arapahoe Rd.	4	1	1	6	1		5	1		10
73	S. Ramps Orchard Rd. (ramp off)				0						0
74	N. Ramps, Orchard Rd. (ramp off)		1	1	2	1		1	1		6
75	SH 88, Belleview Ave.	1	3	2	6	1		5	1		10
76	I-225 Interchange	3	2	4	9	4		6	3		21
77	S. Ramp SH 30/SH 285, Hampden Ave. (ramp off	2	3	2	7	4		5	2		15
78	N. Ramp SH 30/SH 285, Hampden Ave. (ramp on)				0						0
79	Yale Ave.	8	1		9	2		7	2		17
80	Evans Ave.	4		2	6	2		4	2		14
81	SH 2, Colorado Blvd.	3	1	5	9	1		8	1		13
82	University Blvd.		2	3	5			5			5
83	Downing St.				0						0
84	Emerson St.				0						0
85	Washington St.	2	1	3	6			6			6
86	Broadway	3	3		6	1		5	1		10
87	SH 85, Santa Fe Dr.	1	5	4	10	2	1	8	1	1	25
88	SH 26, Alemeda Ave.	1	5	3	9	3		6	3		21
89	SH 6, 6th Ave.	5	1		6	1		5	1		10
90	8th Ave.		3	5	8	4		5	3		20
91	SH 40, Colfax Ave.	1	2	5	8	1		7	1		12
92	Auraria Pkwy.				0						0
93	17th Ave and 19th Ave. Ramps				0						0
94	23rd St.	8	4	2	14	3		11	3		26
95	Speer Blvd.	4	6	3	13	4	1	10	2	1	32
96	20th St.	4	2	5	11	3		8	3		23
97	Fox/38th Ave.	11	9	9	29	8		25	4		45
98	I-70 Interchange	9	5	11	25	10		18	7		53
99	SH 53, 58th Ave.	7	7	1	15	7		9	6		39

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
100	I-76 Interchange	5	1		6	2		5	1		10
101	SH 36	2	5	3	10	6		5	5		30
102	84th Ave.			1	1			1			1
103	Thornton Pkwy.		1	3	4	5		2	2		12
104	104th Ave.	5	3	1	9	2		7	2		17
105	SH 128, 120th Ave	1	3	2	6	3		5	1		10
106	SH 7		1	3	4	1		3	1		8
107	Rd. E. and W. (CO Rd. 8) (Erie)	1		1	2	6		1	1		6
108	SH 52		2	1	3	3		1	2		11
109	SH 119	1	2		3	3		1	2		11
110	SH 66		2		2			2			2
111	Mead Interchange				0						0
112	SH 56	1			1			1			1
113	SH 60				0						0
114	SH 402	1			1			1			1
115	SH 34	4	3	4	11	8		6	5		31
116	Rd. E and W (CO Rd. 26) (Airport Dr.)				0						0
117	SH 392	1			1			1			1
118	SH 68	1	1	1	3			3			3
119	Prospect Interchange	1			1			1			1
120	SH 14	3	3	2	8	1		7	1		12
121	CO Rd. 50				0						0
122	SH 1		1		1			1			1
123	Owl Canyon				0						0
124	Carr Interchange			1	1	2			1		5
Route->	I-70										
125	SH 6, to Mack	1			1	1			1		5
126	SH 139, to Loma			1	1			1			1
127	SH 340, Fruita				0						0
128	SH 6 and W SH 70 Grand Jct Bus. Rt.				0						0
129	Rd. N. and S. (CO Rd. 24)				0						0
130	Horizon Dr.		1		1			1			1
131	E. SH 70 Grand Jct Bus. Rt.	3			3	3			3		15
132	Palisade Interchange				0						0
133	SH 6, e/o Palisade				0						0
134	Cameo Interchange				0						0
135	SH 65 Interchange				0						0
136	Debeque Interchange				0						0
137	Parachute Interchange				0						0
138	Rulison Interchange				0						0
139	SH 6, w/o Rifle				0						0
140	SH 13	1	1		2			2			2
141	SH 70 Silt Spur				0						0
142	Rd. N.-S. (CO Rd. 240), to New Castle				0						0
143	SH 6, Canyon Creek				0						0
144	West Glenwood			1	1	1			1		5
145	SH 82	1		2	3	1		2	1		7
146	No Name				0						0
147	Deadhorse Creek, Hanging Lake Park				0						0
148	W. Dotsero				0						0
149	E. Dotsero				0						0
150	SH 6, Gypsum				0						0

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
151	SH 70, Eagle Spur	-	1	1	2	3		1	1		6
152	SH 131, se/o Wolcott				0						0
153	SH 70 Edwards Spur		1		1			1			1
154	SH 70 Avon Spur				0						0
155	SH 6 and SH 24, Dowd				0						0
156	West Vail		1		1			1			1
157	Main Vail	2			2			2			2
158	East Vail			1	1			1			1
159	SH 91, Copper Mtn			1	1			1			1
160	W. Frisco		1		1			1			1
161	SH 9, E. Frisco				0						0
162	SH 6 and SH 9, Silverthorne	3		2	5	2		3	2		13
163	SH 6, e/o Loveland Pass				0						0
164	Silver Plume				0						0
165	Georgetown			1	1			1			1
166	SH 40, Empire Jct				0						0
167	Downieville Interchange	2	1		3	1		2	1		7
168	Dumont Interchange				0						0
169	Fall River Rd.				0						0
170	SH 70 Idaho Spgs Bus. Rt. (W.)				0						0
171	SH 103	1			1			1			1
172	SH 70 Idaho Spgs Bus. Rt. (E.)		1		1			1			1
173	SH 6, Clear Creek Canyon		1		1			1			1
174	Hyland Hills Interchange				0						0
175	CO Rd. 65, Beaver Brook				0						0
176	SH 40 W. Evergreen				0						0
177	SH 74 E. Evergreen				0						0
178	Chief Hosa Rd.		1		1			1			1
179	SH 40, Genesee				0						0
180	Paradise Hills				0						0
181	SH 26	1	1		2	1		1	1		6
182	SH 470		1		1			1			1
183	SH 6, 6th Ave.			2	2	1		1	1		6
184	SH 40, Colfax Ave.	1		1	2	1		1	1		6
185	Denver West Blvd.	2			2	1		1	1		6
186	32nd Ave.	4	4	2	10	2		8	2		18
187	SH 58				0						0
188	SH 72, Ward Rd.	5	10	9	24	6	1	18	5	1	55
189	SH 391, Kipling St.	4	5	3	12	2		11	1		16
190	SH 121, Wadsworth Blvd.	5	1	3	9	3		7	2		17
191	SH 76		2	1	3	2		1	2		11
192	Harlan Interchange		1	1	2			2			2
193	SH 95, Sheridan Blvd.	2	2	1	5	4		3	2		13
194	Lowell Blvd.	2	2	1	5	1		4	1		9
195	SH 287, Federal Blvd.	3	2	2	7	4		5	2		15
196	Pecos St.	8	7	8	23	6		17	6		47
196A	I-25	13	11	13	37	11		28	9		73
197	Washington St.	3	8	6	17	10		10	7		45
198	Ramps on and off, Humboldt St.		3	1	4	1		3	1		8
199	SH 265, Brighton Blvd	5	1	5	11	1		10	1		15
200	Ramp off, assumed York St.	4	2	3	9	5		6	3		21
201	SH 6 N. (Steele St.) Rd. S. (Steele St.)	6	4	7	17	4		13	4		33

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
202	SH 2, Colorado Blvd.	5	6	2	13	3	1	9	3	1	36
203	Dahlia St.	2	1	1	4	1		3	1		8
204	Monaco St.	1		1	2			2			2
205	SH 35, Quebec St.	12	9	3	24	5		21	3		36
206	SH 270	3	5		8	1		7	1		12
207	Havana St.	9	4	3	16	14		11	5		36
208	Peoria St.	7	7	7	21	5		18	3		33
209	I-225 Interchange	3	8	2	13	7		9	4		29
210	Chambers Rd.	4	3	2	9	4		6	3		21
211	Pena Dr./N. Buckley Rd.				0						0
212	SH 32, Tower Rd.	2	3	3	8	4		4	4		24
213	SH 40, Colfax Ave.		1		1			1			1
214	Gun Club Rd., Rd. N. (CO Rd. 18N)	1			1	1			1		5
215	SH 36, w/o Watkins		1	1	2			1	1		6
216	SH 70 Watkins Spur				0						0
217	Manila Rd.				0						0
218	SH 79, Bennett	1			1	1			1		5
219	Ramp to US 36 and Bennett Rest Area				0						0
220	SH 70 Strasburg Spur				0						0
221	SH 36, Byers				0						0
222	Peoria, Frontage Rd. conn. to SH 40				0						0
223	SH 70 Deer Trail Spur				0						0
224	SH 70 Agate Spur				0						0
225	SH 86			1	1	1			1		5
226	SH 24 Limon Spur	2	1		3	2		1	2		11
227	SH 24, e/o Limon				0						0
228	SH 24 and SH 40	1		2	3	1		2	1		7
229	Genoa Interchange				0						0
230	Bovina Interchange			1	1			1			1
231	Arriba Interchange			1	1	3			1		5
232	Flagler Interchange				0						0
233	SH 59, sw/o Seibert	1			1	1			1		5
234	SH 70, Vona Spur			1	1			1			1
235	SH 57, Stratton			1	1			1			1
236	Bethune Interchange				0						0
237	SH 385, Burlington				0						0
238	Burlington Spur	1			1			1			1
Route->	I-225										
238A	I-25 Interchange	2	2	3	7			7			7
239	Tamarac	3		1	4			4			4
240	Yosemite St.			3	3	1		2	1		7
241	SH 83, Parker Rd.	2		1	3	5		1	2		11
242	Iliff Ave.	2	1		3	3		2	1		7
243	Mississippi Ave.	5		3	8	1		7	1		12
244	SH 30, 6th Ave.	1			1			1			1
245	SH 40, Colfax Ave.	6	2	4	12	9	1	7	4	1	39
245A	I-70 Interchange	4	4		8	6		5	3		20
Route->	I-270										
245B	I-76 Interchange	1	1	1	3	2		1	2		11
246	York St.	2		2	4			4			4
247	SH 6, Vasquez Blvd.	4	1	2	7	1		6	1		11
248	NB on ramp from SH 35 (Quebec St.)	1		1	2	1		1	1		6

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
249	SH 35, Quebec St.	1	2	1	4	1		3	1		8
Route->	I-76										
249A	I-70 and SH 121 Interchange			2	2	2			2		10
250	SH 95 (Sheridan Blvd.)			1	1			1			1
251	SH 287 (Federal Blvd.)		1		1			1			1
252	Assumed Pecos St.	1			1			1			1
252A	I-25	3	2	3	8			8			8
253	I-270 Interchange	2			2	3			2		10
254	SH 224		1		1			1			1
255	SH 6				0						0
256	88th Ave.	2		1	3	3		1	2		11
257	96th Ave.	3			3			3			3
258	SH 85	1		3	4	2		2	2		12
259	SH 2				0						0
260	SH 51	1		1	2	3			2		10
261	Rd. E. and W. (136th Ave.)				0						0
262	Rd. N. and S. (Burlington Blvd) (Barr Lake)				0						0
263	Rd. E. and W. (Bromley Ln.)				0						0
264	Rd. E. and W. (CO Rd. 2), Lockbuie	1		1	2	2		1	1		6
265	SH 52	1			1			1			1
266	Kersey Interchange	1		1	2	1		1	1		6
267	SH 76 Keenesburg Spur				0						0
268	Roggen Interchange, CO Rd. 73				0						0
269	Rainter Rd., (EB off only)				0						0
270	W. SH 6, w/o Wiggins				0						0
271	SH 39				0						0
272	E. SH 6 and SH 34, e/o Wiggins		1		1			1			1
273	Long Bridge				0						0
274	SH 34 w/o Fort Morgan	3			3	2		1	2		11
275	SH 144				0						0
276	SH 52		1		1			1			1
277	Barlow Rd	2		1	3			3			3
278	Dodd Bridge				0						0
279	Hospital Rd.				0						0
280	SH 71	1		1	2			2			2
281	SH 6 and SH 34 Spur, ne/o Brush				0						0
282	Hillrose Interchange				0						0
283	Merino Interchange				0						0
284	SH 63, Atwood			1	1			1			1
285	SH 6, Sterling			1	1			1			1
286	Iliff Interchange				0						0
287	Proctor Interchange				0						0
288	SH 55, Crook				0						0
289	Red Lion Rd.				0						0
290	SH 59, Sedgwick				0						0
291	Ovid Interchange				0						0
292	SH 385, Julesburg				0						0
Route->	US 36 (Denver-Boulder Tpk)										
293	SH 121				0						0
294	104th Ave				0						0
295	SH 95, Sheridan Blvd.				0						0
296	SH 287, Federal Blvd.				0						0

Intrchg Num	Cross Road	Accidents 1993	1992	1991	Total	Total Inj.	Total Fatal	# Acc. w/PDO	# Acc. w/Inj.	# Acc. w/Fatal	Index
297	Zuni St.				0						0
298	Pecos St.				0						0
299	Broadway				0						0
Route->	US 285										
300	SH 8				0						0
301	SH 470				0						0
302	SH 391 (Kipling Pwky.)				0						0
303	SH 121 (Wadsworth Blvd.)				0						0
304	SH 95 (Sheridan Blvd.)				0						0
305	Rd. N. (S. Knox Ct.) Rd. SW (S. Lowell Blvd.)				0						0
306	SH 88 (Federal Blvd.)				0						0
307	SH 85 (Santa Fe Dr.)				0						0
308	SH 75 (Broadway)				0						0
Route->	SH 470										
309	SH 8				0						0
310	Quincy Ave.				0						0
311	Bowles Ave.				0						0
312	Ken Caryl				0						0
313	Kipling				0						0
314	SH 121				0						0
315	SH 75 (Platte Canyon Rd.)				0						0
316	SH 85 (Santa Fe Dr.)				0						0
317	Broadway				0						0
318	SH 177 (University Blvd.)				0						0
319	Quebec				0						0
Route->	US 6										
320	Indiana St.				0						0
321	Simms St.				0						0
322	SH 391, Kipling St.				0						0
323	Garrison St.				0						0
324	Carr St.				0						0
325	SH 121, Wadsworth Blvd.				0						0
326	Knox Ct.				0						0
327	SH 88, Federal Blvd.				0						0
328	Bryant St.				0						0

I/C #	Interchange	Route	Index
97	Fox/38th Ave.	I-25	45
98	I-70 Interchange	I-25	53
99	SH 53, 58th Ave.	I-25	39
188	SH 72, Ward Rd.	I-70	55
196	Pecos St.	I-70	47
196A	I-25	I-70	73
197	Washington St.	I-70	45
202	SH 2, Colorado Blvd.	I-70	36
205	SH 35, Quebec St.	I-70	36
207	Havana St.	I-70	36
245	SH 40, Colfax Ave.	I-225	39

IMPLEMENTATION OF STUDY FINDINGS IN COLORADO

Following statistical analysis of truck accidents at interchanges a cloverleaf interchange in northern Colorado was identified as having higher than expected frequency of truck rollovers. The interchange of I-25 and SH 34 is depicted in Figure A.1 below. To address the issue, larger warning signs were installed at the entrances to the ramps. Following installation of the warning signs an observational before and after study was conducted to evaluate the effectiveness of the counter measures. The results of the study are presented in Table A.2.

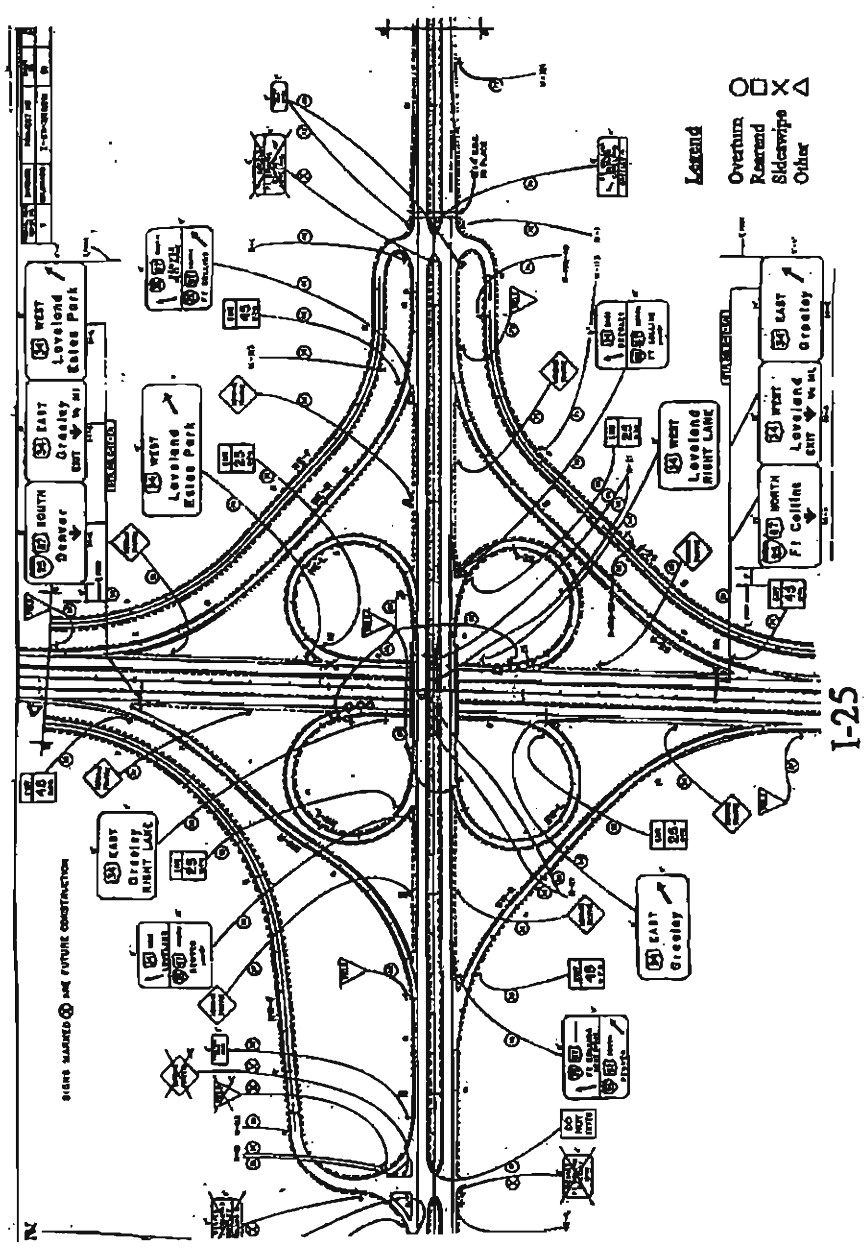


Figure A.1 I-25 and SH 34 interchange

Table A.2

Observational Before and After Study at the I-25 & SH 34 Interchange

BEFORE COUNTERMEASURE APPLICATION

Period	ADT I-25	ADT SH 34	% Trucks on I-25	% Trucks on SH 34	Number of Truck Overturn Accidents	Truck Overturning Accident Rate	Total Number of Truck Accidents	Total Truck Accident Rate	Total Number of Accidents	Total Accident Rate
1986	23,959	12,102	*NA*	*NA*	(0)	0.0	(2)	0.152	(12)	0.91
1987	23,959	12,102	15.5	9.0	(0)	0.0	(0)	0.0	(11)	0.84
1988	25,905	13,050	12.5	5.0	(0)	0.0	(3)	0.211	(6)	0.42
1989	27,908	13,500	11.0	6.5	(1)	0.066	(3)	0.198	(8)	0.53
1990	29,357	13,350	11.0	6.5	(0)	0.0	(2)	0.128	(14)	0.90
1991	32,182	15,550	11.0	7.0	(2)	0.115	(4)	0.230	(16)	0.92
1992	35,431	16,829	*NA*	*NA*	(3)	0.158	(4)	0.211	(16)	0.84
1993	35,796	16,700	16.5	5.5	(2)	0.104	(4)	0.209	(15)	0.78
1994	39,247	20,150	12.0	5.5	(0)	0.0	(1)	0.046	(19)	0.88
1/1/95 - 9/1/95	41,014	25,050	11.5	5.5	(0)	0.0	(1)	0.063	(9)	0.56
									126	

AFTER COUNTERMEASURE APPLICATION

Period	ADT I-25	ADT SH 34	% Trucks on I-25	% Trucks on SH 34	Number of Truck Overturn Accidents	OTR Truck Rate	Total Number of Truck Accidents	Truck Accident Rate	Total Number of Accidents	Total Accident Rate
10/1/95 - 10/1/96	41,288	20,509	12.33	4.20	(1)	0.044	(5)	0.222	(26)	1.15
10/1/96 - 10/1/97	42,806	25,642	11.75	5.75	(0)	0.0	(4)	0.160	(42)	1.68
10/1/97 - 6/1/98	42,806	25,642	*NA*	*NA*	(2)	0.121	(4)	0.242	(20)	1.21
									88	

The observational before and after study did not indicate a significant impact on safety as a result of warning sign installation. A recommendation was made to the Regional Office to consider this site for potential improvement under the Hazard Elimination Program.

BIBLIOGRAPHY

Alassar L. (1988). Analysis of Heavy Truck Accident Severity. Journal of Advanced Transportation 22:77-95.

Basha P.E. & Ramsey S.L. (1993). A Methodology for Comparing Accident Rates. ITE Journal, May 1993, pp. 30-35.

Campbell K.L. & Wolfe A.C. (1988). Fatal Accident Involvement Rates by Driver Age for Large Trucks. Technical Report. University of Michigan Transportation Research Institute (UMTRI). Ann Arbor, MI.

Campbell K.L., Blower D.F., Gattis R.G. & Wolfe A.C. (1988). Analysis of Accident Rates of Heavy-Duty Vehicles. Technical Report. University of Michigan Transportation Research Institute (UMTRI). Ann Arbor, MI.

Carsten O. & Pettis L.C. (1987). Trucks Involved in Fatal Accidents, 1980-84. Technical Report. University of Michigan Transportation Research Institute (UMTRI). Ann Arbor, MI.

Ceder A. (1982). Relationships Between Road Accidents and Hourly Traffic Flow - I: Analysis and Interpretation. Accident Analysis and Prevention 14(1):19-34.

Ceder A. & Livneh M. (1982). Relationships Between Road Accidents and Hourly Traffic Flow - II: Probabilistic Approach. Accident Analysis and Prevention 14(1):35-44.

Chang G.L. & Paniati J.F. (1990). Effects of 65 MPH Speed Limit on Traffic Safety. Journal of Transportation Engineering/ASCE 116(2):213-226.

Chang M.S. (1982). Conceptual Development of Exposure Measures for Evaluating Highway Safety. Transportation Research Record 847:37-42.

Chatterjee A. et al. (1994). Driver-Related Factors Involved with Truck Accidents. Technical Report. Institute for Transportation Research and Education (ITRE), University of North Carolina. Chapel Hill, NC.

Chirachavala T.; Cleveland D.E. & Kostyniuk L.P. (1984). Severity of Large Truck and Combination Vehicle Accidents in Over-the-road Service: A Discrete Multivariate Analysis. Transportation Research Record 975:23-36.

Ervin R., Barnes M., MacAdam C. & Scott R. (1986). Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges: Volume 1. Technical Report. University of Michigan Transportation Research Institute (UMTRI). Ann Arbor, MI.

Federal Highway Administration (1980). Accident Research Manual.
U.S. Department of Transportation. Washington, D.C.

Fancher P.S. (1986). Sight Distance Problems Related to Large Trucks Transportation Research Record 1052: 23-29.

Fancher P.S. & Mathew A. (1990). Safety Implications of Various Truck Configurations. Final Report to the Federal Highway Administration (FHWAMC-89-018) Volume 1: Technical Report. U.S. Department of Transportation. Washington, D.C.

Federal Highway Administration (1986). The Feasibility of a Nationwide Network of LCV's. U.S. Department of Transportation. Washington, D.C.

Fleischer G.A. (1977). Significance of Benefit/Cost and Cost/Effectiveness Ratios in Analyses of Traffic Safety Programs and Projects. Transportation Research Record 635:32-41.

Fleischer G.A. (1981). Review of FHWA's Evaluation of Highway Safety Projects. Transportation Research Record 808:16-24.

Fluery D., Fline C. & Peytain J. (1988). Road Accidents Involving Heavy Goods Vehicles. Recherche Transports Securite. English Issue No. 3. Institut National de Recherche sur les Transports, Paris, France.

Fong T. and Chenu C. (1986). Simulation of Truck Turns with a Computer Model. CALTRANS.

Garber N.J. & Gadiraju R. (1988). Speed Variance and Its Influence on Accidents. AAA Foundation for Traffic Safety. Washington, D.C.

Garber N.J. et al. (1992). Accident Characteristics of Large Trucks on Highway Ramps. Technical Report. Department of Civil Engineering, University of Virginia. Charlottesville, VA.

Garber N.J. & Gadiraju R. (1993). Impact of Differential Speed Limits on the Speed of Traffic and the Rate of Accidents. Transportation Research Record 1375:44-52.

Goodell-Grivas, Inc. (1989). Examination of Truck Accidents on Urban Freeways. Final Report. FHWA-RD-89-201. Federal Highway Administration, U.S. Department of Transportation. Washington, D.C.

Graham J.L. (1988). Design Considerations for Trucks in Work Zones. In Accommodation of Trucks on the Highway: Safety in Design, Smith B.L. & Mason J.M. (editors). American Society of Civil Engineers, New York, N.Y.

Gillespie T.D, "Start up Accelerations for Heavy Trucks on Grades," Transportation Research Record 1052 (Washington, D.C.: Transportation Research Board, 1986)

Giuliano G. (1989). Incident Characteristics, Frequency, and Duration on a High Volume Urban Freeway. Transportation Research 23A(5):387-396.

Harwood D., Mason J., Glauz D., Kulakowski B and Fitzpatrick K. (1990). Development of Truck Characteristics for Use in Highway Design and Operation. U.S. DOT, FHWA.

Hauer E. & Persaud B.N. (1984). Problem of Identifying Hazardous Locations Using Accident Data. Transportation Research Record 975:36-43.

Hauer E & Persaud B.N.. (1984). Comparison of Two Methods for De-Biasing Before and After Accident Studies. Transportation Research Record 975:43-49.

Heald K.L. (1986) Use of the WHI Offtracking Formula. Transportation Research Record 1052: 23-29.

Higle J.L. & Hecht M.B. (1989). A Comparison of Techniques for the Identification of Hazardous Locations. Transportation Research Record 1238:10-19.

Higle J.L. & Witkowski J.M. (1988). Bayesian Identification of Hazardous Locations. Transportation Research Record 1185:24-36.

Hutchinson B. (1990). Large-Truck Properties and Highway Design Criteria. Journal of Transportation Engineering/ASCE 116(1):1-22.

Janson B.N. & Rathi A. (1990). Feasibility of Exclusive Facilities for Cars and Trucks. Final Report. Federal Highway Administration, U.S. Department of Transportation. Washington, D.C.

Jindra F. (1962). Scale Model Investigations of Off-tracking of Trailer Trains. SAE Report 607A, Society of Automotive Engineers, Warrendale, P.A.

Jovanis P.P. & Delleur J. (1983). Exposure-Based Analysis of Motor Vehicle Accidents. Transportation Research Record 910:1-7.

Khasnabis S. & Al-Assar R. (1989). Analysis of Heavy Truck Accident DataExposure Based Approach. Journal of Transportation Engineering/ASCE 115(3):298-315.

Koepke F.J. (1993). Ramp Exit/Entrance Design - Taper versus Parallel and Critical Dimensions. Transportation Research Record 1385:126-132.

Kuroda K., Maleck T.L. & Taylor W.C. (1985). The Impact of Vehicle Size on Highway Safety. Presented at the 64th Annual Meeting of the Transportation Research Board. Washington, D.C.

Leonard J. & Recker W. (1992). Analysis of Large Truck Crashes on Freewayto-Freeway Connectors. Technical Report. Institute of Transportation Studies, University of California. Irvine, CA.

Mason J.M., Middleton D.R. & Peterson H.C. (1986). Operational and Geometric Evaluation of Exclusive Truck Lanes. Report No. 331-3F. Texas Transportation Institute. College Station, Texas.

McCasland W.R. & Stokes R.W. (1984). Truck Operations and Regulations on Urban Freeways. Report No. 338-1F. Texas Transportation Institute. College Station, Texas.

Meyers W.S. (1981). Comparison of Truck and Passenger-Car Accident Rates on Limited-Access Facilities. Transportation Research Record 808:48-55.

Miaou S. & Lum H. (1993). Modeling Vehicle Accidents and Highway Geometric Design Relationships. Accident Analysis & Prevention 25(6):689-709.

Miaou S-P., Hu P.S., Wright T., Davis S.C. & Rathi A.K. (1993a). Development of Relationship Between Truck Accidents and Geometric Design: Phase I. Technical Report. Center of Transportation Analysis, Oak Ridge National Laboratory. Oak Ridge, TN.

Miaou S-P., Hu P.S., Wright T., Rathi A.K. & Davis S.C. (1993b). Relationship Between Truck Accidents and Highway Geometric Design: A Poisson Regression Approach. Transportation Research Record 1376:10-18.

Middleton D. et al. (1994). Truck Accident Countermeasures on Urban Freeways. Technical Report. Texas Transportation Institute, The Texas A&M University System. Houston, TX.

National Highway Traffic Safety Administration (1988a). Fatal Accident Reporting System 1986. U.S. Department of Transportation (DOTHS-807-245). Washington, D.C.

National Highway Traffic Safety Administration (1988b). National Accident Sampling System 1986: A Report on Traffic Crashes and Injuries in the United States. U.S. Department of Transportation (DOT-HS-807-296). Washington, D.C.

Pigman J.G., Agent K.R. & Zeeger C.V. (1981). Interstate Safety Improvement Program. Transportation Research Record 808:9-16.

Poch M. & Mannering F. (1996). Negative Binomial Analysis of IntersectionAccident Frequencies. Journal of Transportation Engineering/ASCE 122(2):105-113.

Sayed T., Abdelwahab W. & Navin F. (1995). Identifying Accident-Prone Locations Using Fuzzy Pattern Recognition. Journal of Transportation Engineering/ASCE 121(4):352-358.

Sayed T. & Abdelwahab W. (1997). Using Accident Correctability to Identify Accident-Prone Locations. Journal of Transportation Engineering/ASCE 123(2):107-113.

Shankar V., Mannering F. & Barfield W. (1995). Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies. Accident Analysis & Prevention 27(3):371-389.

Western Highway Institute (WHI), (1970). Offtracking Characteristics of Trucks and Truck Combinations. WHI Research Committee Report 3. San Bruno. California.

Roy Jorgensen Associates (1975). Methods for Evaluating Highway Safety Improvements. Report No. 162. National Cooperative Highway Research Program, Transportation Research Board. Washington, D.C.

Sanford J.L., Meyer E.D. & Dameron H.A. (1986). A Cost-Safety Comparison of Illinois Rehabilitation Design Policies. Transportation Research Record 1060:70-74.

Sullivan E.C. (1990). Estimating Accident Benefits of Reduced Freeway Congestion. Journal of Transportation Engineering/ASCE 116(2):167-180.

Teal R.F. (1988). Estimating the Full Economic Costs of Truck Incidents on Urban Freeways. AAA Foundation for Traffic Safety. Falls Church, Virginia.

Twomey J.M., Heckman M.L., Hayward J.C. & Zuk R.J. (1993). Accidents and Safety Associated with Interchanges. Transportation Research Record 1385:100-108.

Transportation Research Board (1990). Safety Research for a Changing Highway Environment. Special Report 229. Transportation Research Board, National Research Council. Washington, D.C.

Wright P.H. & Paquette R.J. (1987). Highway Engineering. Fifth Edition. John Wiley & Sons, Inc. New York, New York.