EXAMINING POTENTIAL FACTORS AFFECTING THE SAFETY PERFORMANCE AND DESIGN OF EXCLUSIVE TRUCK FACILITIES

A Thesis
by
VICHIKA IRAGAVARAPU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

December 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Dominique Lord
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	Tom Wehrly
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ABSTRACT

Examining Potential Factors Affecting the Safety Performance and Design of Exclusive Truck Facilities. (December 2007)

Vichika Iragavarapu, B.Tech., Acharya Nagarjuna University, India
Chair of Advisory Committee: Dr. Dominique Lord

Many state agencies consider exclusive truck facilities to be an alternative to handle the safety and operational issues due to the increasing truck volumes. No such facilities exist, and there are no standard tools or procedures for measuring safety performance of an exclusive truck facility. This thesis aims at identifying factors that affect truck crashes, whose results could be used for better designing exclusive truck facilities. To accomplish the objectives of this thesis, five years' roadway and crash data for Texas was collected to develop a comprehensive crash database. Negative binomial regression models were used to establish a relationship between truck crashes and various environmental, geometric and traffic variables. Separate models were developed for truck-related (involving at least one truck and another vehicle), truck-only (two trucks or more) and single-truck crashes. The results suggested that the percentage of trucks in Average Annual Daily Traffic (AADT), classification of the roadway (Rural/Urban), posted speed limit, surface condition, alignment and shoulder width are associated with truck crashes. It was observed that truck-related and truck-only crashes decreased as the percentage of trucks increased on freeway facilities. Based on conclusions derived from the literature review and statistical analyses, straight segments with wider shoulders and uniform grades are recommended for exclusive truck facilities. It is also recommended to provide ramps, horizontal and vertical curvature and signing based on truck size, driver eye height, braking ability and maneuverability. These models were developed using mixed-flow traffic data to understand the association of various factors with truck crashes. These models should not be used directly to estimate or predict truck crashes. Further analysis with more detailed data under different flow conditions might help in quantifying the safety performance of exclusive truck facilities.

DEDICATION

Dedicated to my family

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr.Lord, for his patience, guidance and support throughout the course of this research. I also extend my gratitude to Dr.Wehrly and Dr.Zhang for serving on my committee and providing me with valuable suggestions.

I would also like to acknowledge my friends and family here at College Station for their love and affection. Finally, thanks to my mother, father and brother for making my dream come true.

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CHAPTER I

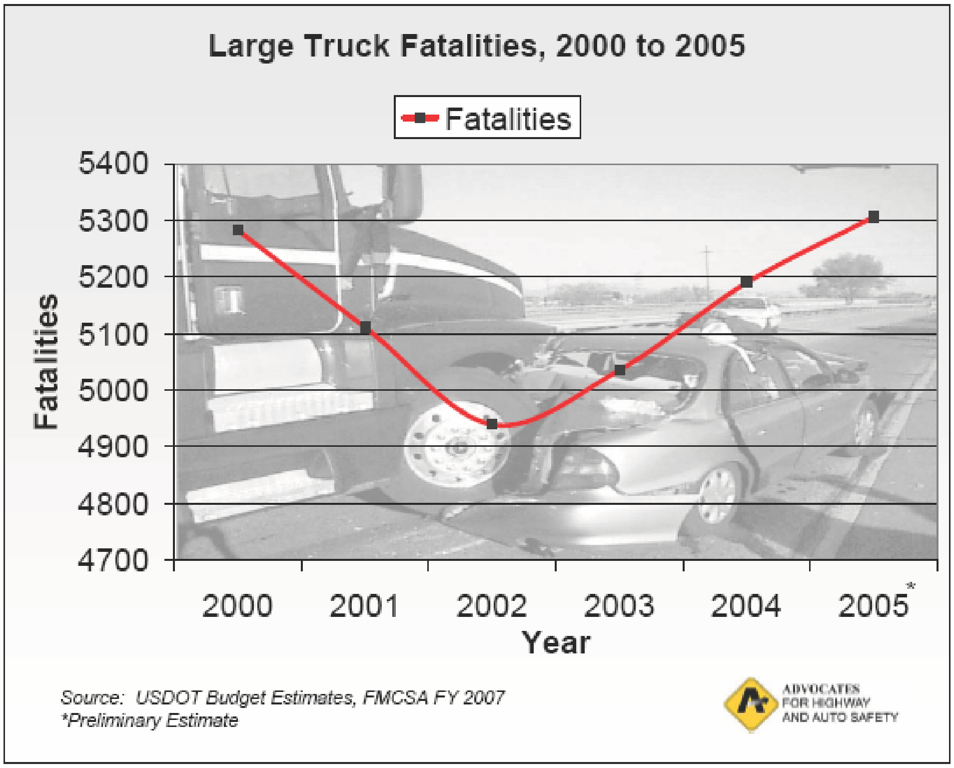
INTRODUCTION

1.1 Background

The U.S. highway system has seen an increase of 43.9% in the number of trucks over the last two decades (USDOT, 2002). Increasing truck volumes contribute to traffic congestion, pavement deterioration and crashes due to differences in the physical and operational characteristics of trucks and passenger cars (Peeta et al., 2005). In fact, the US DOT (USDOT, 2002) reported that the number of crashes involving commercial trucks have increased by 40.3% over the last two decades.

Figure 1 shows the trend related to large truck fatalities from 2000 to 2005. The graph shows that there was a decrease in large truck crash fatalities from 2000 to 2002 and that the fatalities increased from 2003 to 2005. Due to their greater weight, crashes involving large trucks are more likely to result in deaths and serious injuries. It is observed that in a two-vehicle crash involving a truck and a passenger vehicle, 98 percent of the fatalities involve occupants of the passenger vehicle (Insurance Institute for Highway Safety (IIHS), 2001-2006; NHTSA, 2001-2005).

This thesis follows the style of Accident Analysis and Prevention.


Large Truck Fatalities, 2000 to 2005

Source: USDOT Budget Estimates, FMCSA FY 2007
**Preliminary Estimate*

Figure 1: Large truck fatalities, 2000 to 2005 (USDOT, 2007)

It is observed that, trucks represent eleven to thirteen percent of all crash fatalities, while they make up only three percent of all registered vehicles (Insurance Institute for Highway Safety (IIHS), 2001-2006; NHTSA, 2001-2005). Truck crashes are associated with high costs. A study by Zaloshnja and Miller, (2004) estimated the cost per crash including injuries for large trucks (without any trailer) to be an average of US$164,730 in 2000.

Given the recent increase in truck-crash rates and the large cost involved, the Federal Motor Carrier Safety Administration (FMCSA) has proposed an objective of reducing these crashes by 50% by 2010 (Daniel, et al. 2004). Many state transportation agencies are currently looking at different strategies for making highways safer and more comfortable for truck and non-truck drivers (Cate, 2004). Three common treatments have been considered: lane restrictions, dedicated or exclusive truck lanes, and exclusive truck-lane facilities or travelway. Lane restriction consists of restricting trucks to and from using certain lanes along the same traveled way (Middleton, et al., 2006). These lanes can still be used by other vehicle types. Dedicated truck lanes are designed such that they will be used exclusively by trucks, without being physically separated from other lanes (Middleton et al., 2006). Exclusive truck-lane facilities are lanes designed exclusively for trucks and is physically separated from other lanes (Middleton et al., 2006).

Based on some preliminary studies, Poole et al. (2004) reported that truck-only facilities should have at least one travel lane in each direction with a passing lane every few miles. The pavement and structures for the designated truck lanes would be stronger and more durable than a typical pavement currently in used for mixed-traffic conditions. According to a study on constructing truck ways in Florida's freeways by Reich et al. (2003), construction costs are estimated to be $4 to $8 million per mile (Reich et al., 2003). Many believe that truck-only lanes would smoothen traffic flow, but the effects on safety are not well understood (Golob and Recker, 2004). In order to justify this huge investment, it is important to assess the safety benefits of any improvement or alternative solution.

There have been many research efforts to understand the relationship between risk factors related to truck traffic and crash frequencies, but most have produced contradicting results. This study aims at examining factors that may influence the safety performance of truck-only facilities and at providing recommendations for designing truck-only facilities.

1.2 Problem statement

Many state agencies are currently considering exclusive truck facilities as a treatment for increasing congestion and crashes on highways because of increasing truck volumes. These lanes are designed to physically separate truck traffic from passenger cars to enhance safety and stability of flow. As no such lanes currently exist in the United States, there are no safety evaluation tools and design guidelines. Examining factors that impact safety performance of exclusive truck lanes will help in the decision-making process of such projects. Various research efforts in this regard have aimed at finding the relationship between truck volumes and crashes, but have arrived at opposite conclusions.

1.3 Study objectives

The primary objective of this study is to determine factors that affect truck crashes on freeways under non-homogeneous conditions. A secondary objective consists of using these findings to help designing truck-only facilities based on safety. In order to accomplish the objectives of this study, regression models will be developed for this purpose. The proposed study will be accomplished in six tasks.

1.4 Thesis organization

This thesis is composed of five chapters. The second chapter provides a review of previous research and state-of-the art on truck-traffic safety studies and alternative design options to deal with the increasing truck volumes. The third chapter covers the data collection process and provides summary statistics of the collected data. The fourth chapter gives an overview of the methodology employed for this study and results obtained from the analyses. The fifth chapter quantifies the safety of an exclusive truck facility applying the regression models to a hypothetical network. The sixth chapter summarizes the results from the analyses and provides recommendations for future work.

CHAPTER II

LITERATURE REVIEW

This chapter contains an extensive review of literature on alternative design alternatives to accommodate trucks on freeways and important characteristics associated with truck safety. The first section describes different freeway design alternatives that have been proposed in available literature to handle increasing truck traffic. The second section provides a detailed description of various studies that documented truck crash data analyses.

2.1 Truck-related freeway design alternatives

This section provides literature review on various design alternatives suggested to deal with the increasing truck traffic. Lane restrictions, exclusive truck lanes and exclusive truck facilities are the treatments discussed in literature. Lane restrictions, limit trucks to certain lanes, but most of the times, other vehicles may also use the lane. Exclusive truck lanes are designated only for trucks and separate truck traffic from mainlanes physically. Exclusive truck facilities are generally separated from mainlanes by a barrier or median. Exclusive truck lanes or facilities have pavement and geometric features specific for a truck (Middleton et al., 2006).

Very few truck-only lanes currently exist in the U.S. Though, some states do practice lane restriction with trucks, they also allow other vehicles to use these lanes. Lane restrictions are a management strategy to limit certain types of vehicles to some lanes. Lane restrictions improve operations, reduce crashes and decrease pavement structure deterioration (Middleton et al. 2006). Major concern in having lane restriction is the weave area. Due to the speed differential and the difference in their physical and operational characteristics, trucks have limited visibility and maneuverability. This causes danger for passenger cars entering and exiting the roadway (Middleton et al., 2006). Some examples, cited in this study by Middleton (2006) showed decrease in truck crashes during the monitoring period, however it was not clear if this change was not influenced by the increased enforcement.

The first grade-separated and controlled access roads reserved for cars were made in 1920s and 1930s and were called parkways. A new way of separating truck and car traffic is with dual-dual roadways (Fischer et al., 2003). Many configurations were suggested for truck-only lanes. They ranged from adding lanes in the median space of an existing highway to the construction of a separate, parallel roadway to elevated structure built in the median. The study indicates that multilane configuration would provide for greater flexibility in traffic management during incidents. Providing access to these facilities needs to be decided based on cost and demand generating locations. Available right of way can be a major constraint in deciding the configuration of a truck-only lane facility.

A research conducted at the Texas Transportation Institute aimed at developing guidelines for implementation of truck lanes in Texas. The report recommended such restrictions only on access-controlled facilities with three or more lanes in each direction of travel (Jasek et al., 1997). The report also suggests that the facility be such that the trucks are able to cross other lanes to enter and exit the roadway. Authors of the report recommend that exclusive truck lanes would be reasonable only for congested highways where truck volumes contributed to more than 30 percent of the vehicle mix, peak hour volumes were more than 1,800 vehicles per lane-hour, and off-peak volumes were over 1,200 vehicles per lane-hour.

Another study at TTI established criteria for selecting the type of exclusive truck-treatment (Middleton et al., 2006). Using information from available literature, measurable and easily obtainable variables specific to state of Texas and researcher knowledge, the authors proposed a set of criteria for selecting truck treatments. Table 1 summarizes these criterions to be used as an initial evaluation framework. From the study it was observed that it is difficult to determine the criteria for lane restrictions as its benefits are hard to estimate.

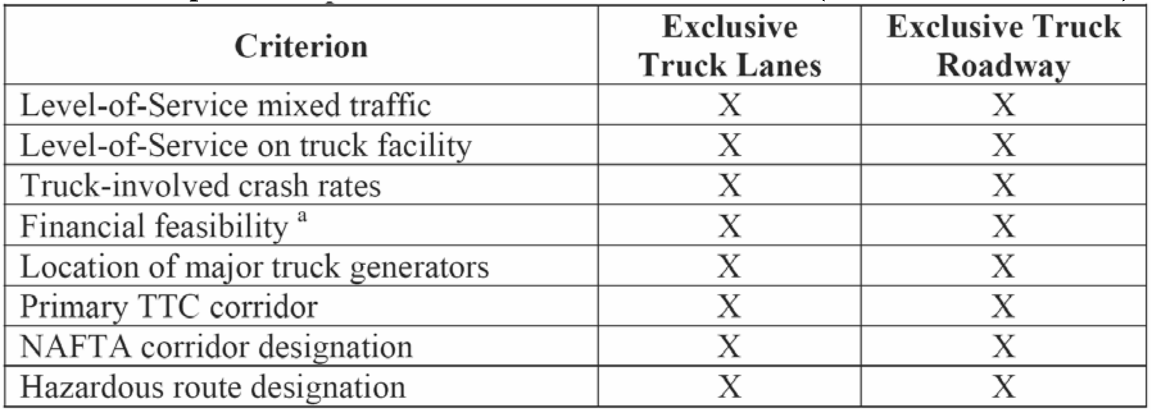


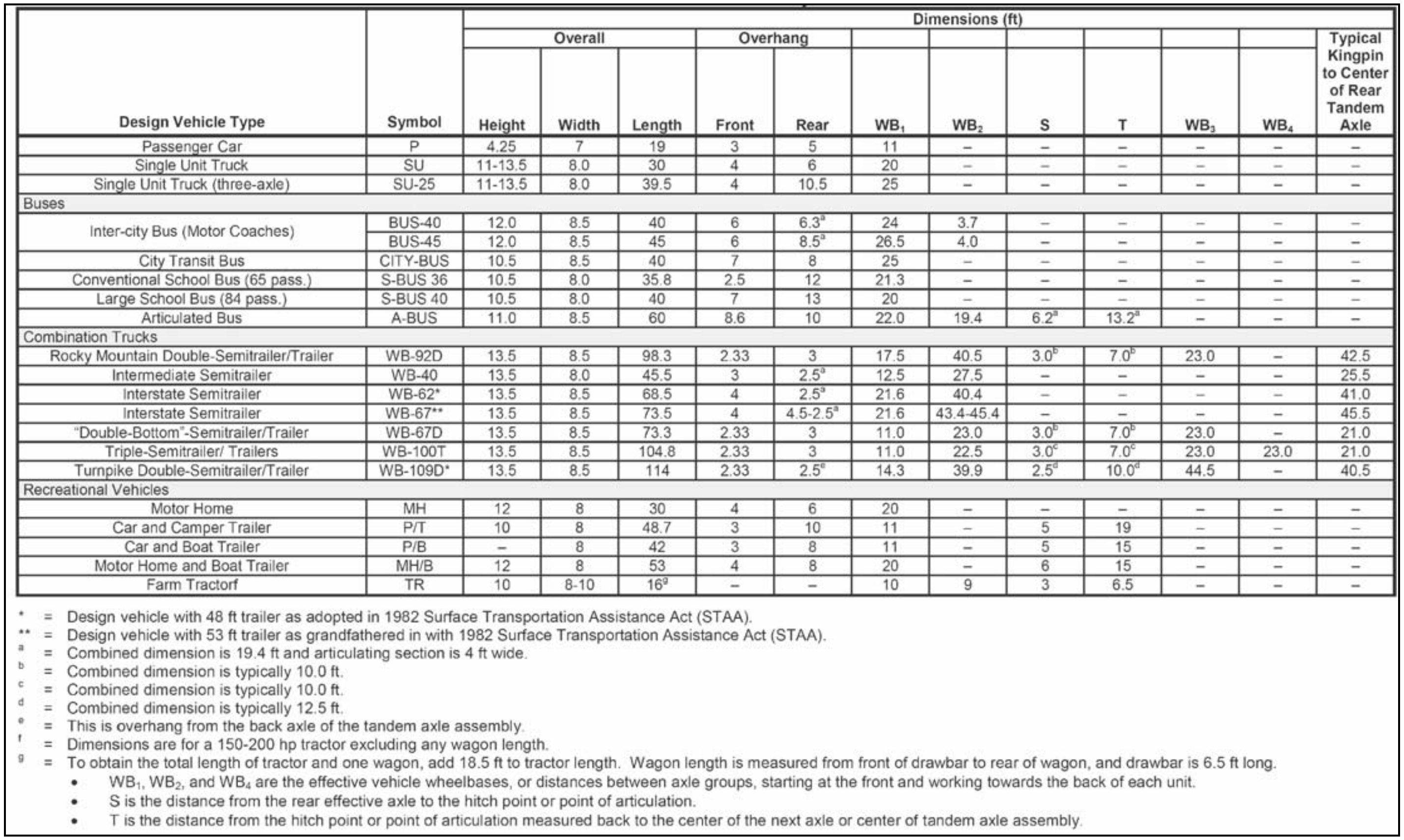
Table 1: Proposed selection criterion for truck treatments (Middleton et al., 2006)

Criterion	Exclusive Truck Lanes	Exclusive Truck Roadway
Level-of-Service mixed traffic	X	X
Level-of-Service on truck facility	X	X
Truck-involved crash rates	X	X
Financial feasibility [a]	X	X
Location of major truck generators	X	X
Primary TTC corridor	X	X
NAFTA corridor designation	X	X
Hazardous route designation	X	X

A study by Middleton (2003) suggested geometric design guidelines for accommodating trucks. The study used American Association of State Highway and Transportation Officials (AASHTO) green book and the TxDOT Roadway Design Manual (TRDM) (Middleton, 2003). For the recommendations, sight distance, horizontal alignment, vertical alignment, and cross section elements were studied for accommodating heavy trucks. The author recommended that in consideration for trucks, a word of caution regarding horizontal curves at the end of long downgrades be added to the existing TRDM. For exclusive truck facilities, it is recommended to increase the lane width from 12 ft to 13 ft. The authors also recommended the outside shoulder to be increased to 12ft and minimum vertical offset to be 2ft from the outer edge of the usable shoulder along truck roadways. Acceleration lane lengths at exits and entrances are recommended to be increased to reflect truck needs (Middleton, 2003).

In the NCHRP report 505, Harwood et al. (2003) reviewed truck characteristics as factors in roadway design (Harwood et al., 2003). The study illustrated the fact that trucks generally need more generous geometric designs than passenger cars because of their physical and operational features. Results from this study recommend some changes to the AASHTO policy on geometric design of highways and streets (AASHTO Green book) to accommodate trucks in roadway design. The study suggests that truck templates WB-20 [WB-67] should be used as the design vehicle for "*intersections of freeway ramp terminals with arterial crossroads and for other intersections on state highways and industrialized streets that carry high volumes of traffic and/or that provide local access for large trucks*" (Harwood et al., 2003). shows revised dimensions for design vehicles as suggested in the NCHRP report. The dimensions considered in this study were in line with recent trends in motor vehicle sizes manufactured in the Unites States. The revised list of design vehicles includes farm tractor with one wagon. Table 3 shows the revised minimum turning radii for the design vehicles. The minimum centerline turning radius, the out-to-out track width, the wheelbase, and the path of the inner rear tire were considered to be of significance for roadway design in this study.

Table 2: Revised design vehicle dimensions (US Customary) to accommodate trucks in roadway design (Harwood et al., 2003).



Design Vehicle Type	Symbol	Dimensions (ft)											
		Overall			Overhang								
		Height	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	WB_4	Typical Kingpin to Center of Rear Tandem Axle
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Single Unit Truck (three-axle)	SU-25	11-13.5	8.0	39.5	4	10.5	25	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-40	12.0	8.5	40	6	6.3[a]	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5[a]	26.5	4.0	–	–	–	–	–
City Transit Bus	CITY-BUS	10.5	8.5	40	7	8	25	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12	21.3	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40	7	13	20	–	–	–	–	–	–
Articulated Bus	A-BUS	11.0	8.5	60	8.6	10	22.0	19.4	6.2[a]	13.2[a]	–	–	–
Combination Trucks													
Rocky Mountain Double-Semitrailer/Trailer	WB-92D	13.5	8.5	98.3	2.33	3	17.5	40.5	3.0[b]	7.0[b]	23.0	–	42.5
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5[a]	12.5	27.5	–	–	–	–	25.5
Interstate Semitrailer	WB-62*	13.5	8.5	68.5	4	2.5[a]	21.6	40.4	–	–	–	–	41.0
Interstate Semitrailer	WB-67**	13.5	8.5	73.5	4	4.5-2.5[a]	21.6	43.4-45.4	–	–	–	–	45.5
"Double-Bottom"-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0[b]	7.0[b]	23.0	–	21.0
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0[c]	7.0[c]	23.0	23.0	21.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5[e]	14.3	39.9	2.5[d]	10.0[d]	44.5	–	40.5
Recreational Vehicles													
Motor Home	MH	12	8	30	4	6	20	–	–	–	–	–	–
Car and Camper Trailer	P/T	10	8	48.7	3	10	11	–	5	19	–	–	–
Car and Boat Trailer	P/B	–	8	42	3	8	11	–	5	15	–	–	–
Motor Home and Boat Trailer	MH/B	12	8	53	4	8	20	–	6	15	–	–	–
Farm Tractor[f]	TR	10	8-10	16[g]	–	–	10	9	3	6.5	–	–	–

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[a] = Combined dimension is 19.4 ft and articulating section is 4 ft wide.

[b] = Combined dimension is typically 10.0 ft.

[c] = Combined dimension is typically 10.0 ft.

[d] = Combined dimension is typically 12.5 ft.

[e] = This is overhang from the back axle of the tandem axle assembly.

[f] = Dimensions are for a 150-200 hp tractor excluding any wagon length.

[g] = To obtain the total length of tractor and one wagon, add 18.5 ft to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 6.5 ft long.

- WB_1, WB_2, and WB_4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

2.2 Truck traffic and safety

This section summarizes various studies performed on truck crash data. Many studies have been conducted to understand the relationship between crash frequency and various traffic, roadway and environmental factors. It is believed that the highway or the physical infrastructure is rarely the sole factor leading to a crash; it usually includes human and environmental factors (Ceder and Livneh, 1992). Many studies in the form of exploratory analysis of crash data, simulation or statistical methods have been conducted to address this problem. Most of these studies arrived at different conclusions. They are summarized below.

Lord and Middleton (2005a)· conducted an exploratory analysis to assess whether homogenous flows of traffic are safer than the mixed traffic. The study was conducted on crash data obtained from a selected freeway segment of the New Jersey turnpike for 2002. This facility functions as a dual-dual freeway system, with inner lanes dedicated to passenger cars only and the outer lanes open to mixed traffic. Crashes were categorized by location, collision type, severity, and lane designation. Sideswipe collisions were observed to be more frequent in mixed traffic condition. It was also seen that Property Damage Only (PDO) crashes were very high in the mixed traffic lanes, whereas crashes involving injury were observed to be same in both traffic conditions. This indicated that trucks may have a strong influence on safety of mixed traffic lanes. Lord and Middleton (Lord and Middleton, 2005a) proposed four hypotheses to explain this difference in type and severity of crashes. First being the significant blind spot of trucks leading to more sideswipe collisions. Second being the more probability of PDO crashes involving larger commercial vehicles being reported. Third being the location of ramps, that causes complex lane change maneuvers leading to crashes. Lastly, it is believed that higher variation in speed distribution of vehicle on a freeway section increases risk of collision. Though the analysis shows the effect on crashes of different traffic scenarios, it fails to explain the factors causing this difference.

A number of research efforts attempted to develop statistical models to identify specific factors that would help determine accident probability and rates for a specific highway section. Some studies focused on understanding the effect of traffic flow characteristics, geometrics of the road and environmental factors on crash frequencies.

While others focused on the precursors to car-truck crashes and the complex human behavior patterns associated with car-truck crashes.

In one of their studies, Ceder and Livneh (1982)· used quantitative models (power functions) to understand the effect of hourly flow on accident rate. A combination of time-sequence (for roadway section data) and cross sectional (for year based data) were used. It was observed that hourly flows provide better understanding of the interactions between accidents and traffic flow. Single and multi-vehicle accidents were separated to find effects of traffic flow on each type of accident. The regression results showed that for multi-vehicle accidents, weighted accident (ie. accident density per one hour of exposure) always increased with hourly flow, while accident rate either increases or slightly decreases with hourly flow. A further study by Ceder separated hourly flow into free flow and congested flow to better understand the accident-traffic flow relationship (Ceder, 1982)·. The study showed that in case of congested flow condition, accident rate sharply increases with hourly flow. This suggests that high traffic volumes should be avoided, which is against the general interest of moving as many cars as possible (Ceder, 1982).

Miaou and Lum (1993)· illustrated how Poisson regression model can be used to evaluate the effect of highway geometric elements on truck accident involvement. They studied statistical properties of four regression models – two conventional linear regression models and two Poisson regression models to understand their ability to model accidents and highway geometric design relationship. The study showed that the conventional linear regression models lack the distributional property to describe accident events which Poisson regression models were found to have. It was found that all of the estimated coefficients for the traffic and geometric variables were consistent among the models and had expected algebraic signs. The models indicated that truck involvement rate in crashes increased with increase in AADT/per lane, horizontal curvature length of horizontal curve, vertical grade and length of vertical grade. The model also suggested that the truck involvement in crashes decreased with increase in paved inside shoulder width per direction and percentage of trucks in a given vehicle density. On comparing the models it was found that Poisson regression models are not sensitive to section length. However, it was also seen that in case of significantly overdispersed data, Poisson regression models may overstate or understate the likelihood of vehicle accidents. It was suggested that in such a case, more general probability distributions, like the negative binomial or double Poisson distribution be used (Miaou and Lum, 1993).

Milton and Mannering (1998) studied the relationship among highway geometrics and traffic elements to motor vehicle accident frequencies using a negative binomial regression model. They found that accident frequency tends to increase with increase in section length, vertical grade, AADT per lane, peak hour percentages (percentage of AADT occurring during the peak hour), number of lanes, narrow right shoulder (right shoulders less than 1.5m), narrow left shoulders (left shoulders less than 1.5m), space between horizontal curves. A decrease in accident frequency was observed with an increase in the percentage of all trucks, horizontal curves with radii less than 868 m, larger horizontal curve radius, and smaller tangent length before a horizontal curve. Milton and Mannering (1998) concluded that the negative binomial regression is a powerful predictive tool in accident-analysis research.

Chang and Mannering (1999) conducted a study to understand the relationship between risk factors and accident severity in truck and non-truck accidents. This paper studied the effect of vehicle occupancy on injury severity and assessed the differences between injury severity in truck and non-truck crashes. A nested logit formulation using generalized extreme value distribution was used to develop separate models for truck and non-truck crashes. This model showed the effect of vehicle occupancy on the most severely injured vehicle occupant. A wide range of variables including driver characteristics and environmental factors were studied. It was concluded that many variables that increase severity in truck crashes did not have the same influence for non-truck crashes and vice-versa. Also, it was observed that significant variables between truck and non-truck crashes had more impact if a truck was involved in the crash. It was also seen that crashes involving trucks increased the probability for the crash to be classified as severe injury for a multi-occupant vehicle than for a single-occupant vehicle (Chang and Mannering, 1999).

Kostyniuk et al. (2002) studied the casual driver-behavioral factors leading to car-truck crashes. Probability analysis techniques were used to determine the likelihood of each of the 94 driver related factors being involved in a crash. It was found that all of the factors were about as likely in fatal car-truck crashes as in fatal car-car crashes. The study concluded that following improperly, driving with obscured vision, drowsy or fatigued driving and improper lane changing were the most likely crash causing factors. Thus, general safe driving practices also work in presence of trucks, but the severity is more when a truck is involved. A limitation of the study was that it did not address nonfatal crashes, single-vehicle crashes, or crashes involving more than two vehicles. This is important to keep in mind because fatal and injury crashes are not similar in their causes or in the numbers of people they affect.

Another study conducted by Hiselius (2004) estimated the relationship between accident frequencies and homogenous and inhomogeneous traffic flow, empirically. The main assumption in this study was that only traffic flow in terms of vehicle per hour effects number of accidents. The results from the regression analysis suggested a good fit for both Poisson and negative binomial regression models. The analysis found that the relationship mainly depended on whether different traffic modes were considered or not. “The study indicated that at a given number of cars per hour, the expected number of accidents will decrease with an increase in the number of lorries per hour” (Hiselius, 2004). This decrease is attributed to factors like speed reduction and uneasiness of non-truck driver in the presence of truck on the road.

Daniel and Chien (2004) used Poisson, Negative binomial and zero-inflated negative binomial prediction models to understand factors impacting truck accidents on urban arterials with signalized intersections. Two approaches were used: a unified model for accidents occurring on both intersections and nonintersection locations and a separate model for signalized intersections, roadway segments and a combination of both these types. The data was found to be overdispersed, hence Negative binomial and Zero-Inflated Negative binomial were used in the study. For the unified model, length of segment, number of lanes, pavement width, posted speed limit, degree of horizontal curve, and the rate of vertical curvature were found to be significant. Among the separate models, the signal segment model showed horizontal curvature variables to be significant, while the roadway segment model showed vertical curvature variables to be significant. On removing insignificant variables from the model, length of segment was found to have the most positive impact on truck crashes. On developing similar models for non-trucks, it was found that for unified model, percentage of trucks had the largest impact on non-truck crashes. For separate models, almost all variables were similar to that of truck crashes. The study concluded that horizontal and vertical curvature features were important factors to be considered to accommodate trucks in roadway design (Daniel, Chien, 2004).

A study by Golob and Recker, (2004) aimed at coming up with a safety measurement tool that can be used to measure the effects of changes in traffic flow patterns (sometimes referred to as traffic flow states) on traffic safety. The study used a disaggregated approach in which crashes themselves were the unit of analysis, instead of their aggregation over time and space. Characteristics of the crash, traffic flow at the time of crash and environmental conditions were the variables considered in the study. Multivariate statistical methods were employed to find the relation between crashes and these variables. Principal components analysis and cluster analysis were used to interpret the correlation structure among the variables and to group the data based on similar structure. Non-linear canonical correlation analysis (NLCCA) was used to find the strength of correlation between the clustering solutions and crash characteristics. Police-reported crash data was combined with traffic flow data for the analysis. Crash typology based on weather and lighting conditions were identified using an application of NLCCA. The results of this analysis indicated a strong relationship between the crash characteristics and prevailing traffic conditions. This approach was unique as it dealt with the problem as that of data analysis and relied on statistical techniques to understand the phenomenon rather than using traffic engineering principles. However, this analysis applies only to the case studied, during the given period of analysis.

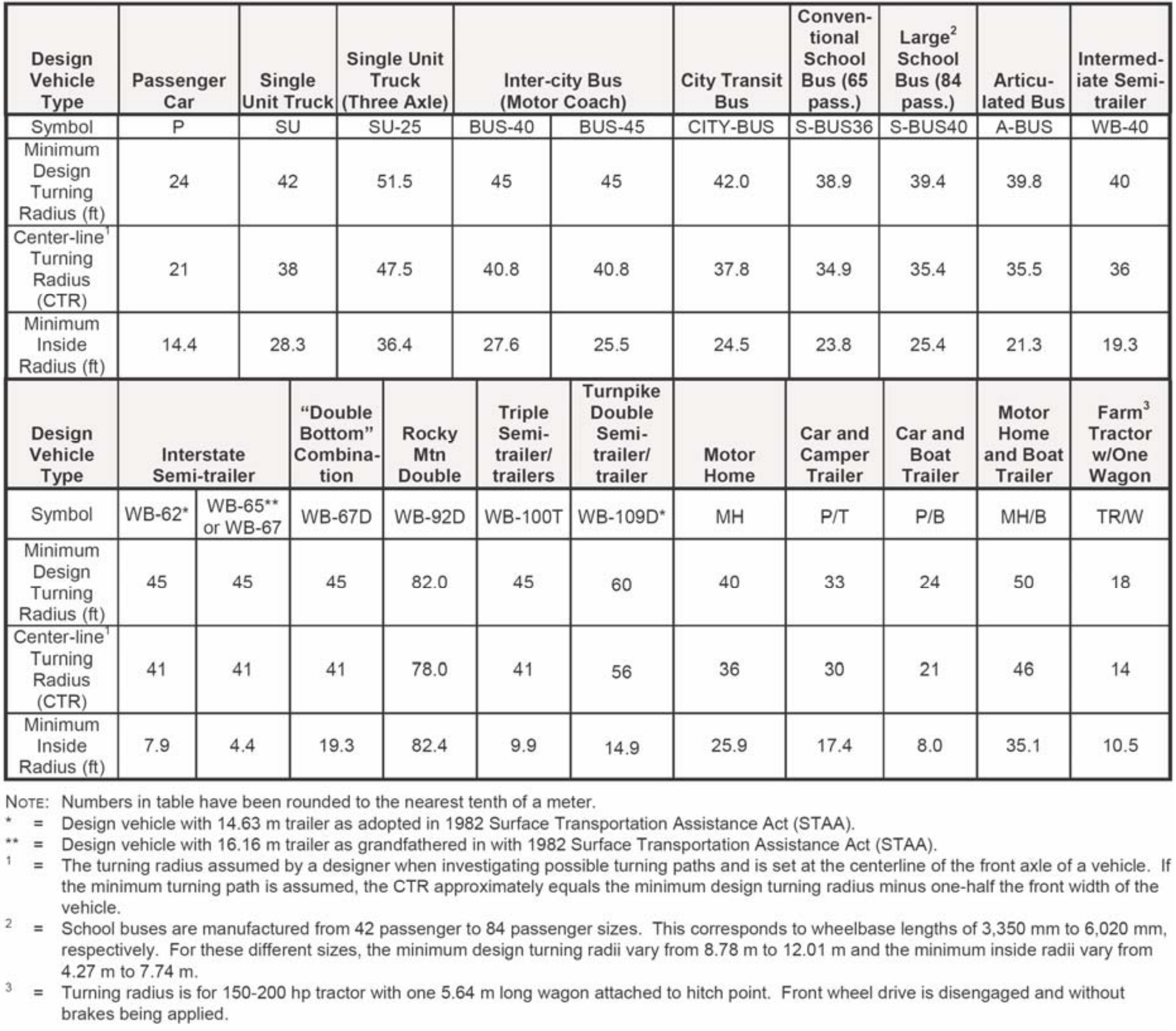
In another study, Golob and Regan, (2004) used a Multinomial Logit Model to determine how the difference in traffic and roadway conditions lead to various types of truck accidents: weaving, run-off road, and rear-end collisions. This model was expanded from a logistic regression model with a dichotomous dependent variable indicating whether a truck was involved or not. Average annual daily traffic (AADT) for the freeway section, truck traffic as a percentage of AADT on that section, percent of truck traffic that has 5-or-more axles, and nine dummy variables designating time periods were taken as independent variables for the model. Controlling for other factors, it was found that likelihood of truck involvement decreased as a function of AADT per lane. However, controlling the AADT per lane and trucks as a percentage of AADT, it was observed that likelihood of truck involvement in crashes increases as a function of proportion of trucks in traffic. The analysis also showed that run-off or overturn crashes were independent of the percentage of trucks in AADT, whereas, rear-end and weaving collisions were proportional to truck traffic. The logistic regression model was used to assess significance of parameters and was expanded to a Multinomial Logit model to pick up the relation between trucks and different crash types using the same fourteen variables. From the coefficients found from this analysis, it can be seen how likelihood of trucks involved in collision depends on various variables. One limitation of the dataset used by Golob and Regan (2004) was that trucks were suspected to be over represented. The dataset had truck AADT as a percentage of total AADT ranges from 2.1% to 10.6%, with a mean of 6.4%. And trucks were involved in more than 10% of accidents. They strongly suggested separation of truck-involved and non-truck involved accidents in data for better analysis.

In one of his studies, Hoel (1999) used FHWA simulation model FRESIM to simulate traffic flow elements on freeway segments under conditions of restricted and non - restricted truck lane conditions. Site plans and traffic counts were used in modeling the site to predict traffic behavior. Simulation results for various truck lane restriction scenarios, were analyzed for performance measures like density, speed differential and lane changes. Hoel (1999) used the paired t-test to determine if the difference in these measures was significantly different for scenarios with and without lane restriction (Hoel, 1999). The study concluded that restricting trucks from left lane decreases density and number of lane changes and increased speed differential in steep grades.

In a study Cate and Urbanik (2004) used VISSIM to study truck restrictions scenarios with varied traffic characteristics like volume, percentage of trucks etc. Many user-adjustable parameters such as lane usage, free-flow speeds, lane changing behavior, traffic composition among others were utilized in simulating the scenarios. Data used for this study included rate of compliance with lane restriction, lane distribution by vehicle classification, time gap between vehicles and vehicle speeds. To assess the impact of lane restriction, various combinations of factors were considered. For each scenario, two simulations run were performed – one with and one without lane restriction. The trucks were restricted to the right two lanes of travel. With the output performance statistics like vehicle density, level of service, average travel time of various types of vehicles and detailed description of every lane change maneuver were calculated, the two cases were compared. The results showed that effect of lane restriction on the above mentioned performance measures was not much on a level terrain, but was considerable on steep grades.

From various studies, it has been observed that lack of substantial data also hinders the development of statistical models. Availability of appropriate data to validate the models developed is very important. Most of the studies conducted above were based on aggregated data. Important information on contributing factors can be lost with such data. To get annual truck traffic data, trucks are counted at certain sections and intermediate sections are interpolated. When counting truck AADT, seasonal influence and weekly variations need to be considered. Also in various studies, the trucks are defined differently for different studies. Consistency in definition of trucks is important to infer about relationship between truck traffic and crash rates, from various studies. Moreover, data collection also becomes easier if trucks are well defined, helping find any factor influencing crash rates.

Table 3: Revised minimum turning radii (US Customary) to accommodate trucks in roadway design (Harwood et al., 2003).



Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Truck (Three Axle)	Inter-city Bus (Motor Coach)		City Transit Bus	Conventional School Bus (65 pass.)	Large[2] School Bus (84 pass.)	Articulated Bus	Intermediate Semi-trailer
Symbol	P	SU	SU-25	BUS-40	BUS-45	CITY-BUS	S-BUS36	S-BUS40	A-BUS	WB-40
Minimum Design Turning Radius (ft)	24	42	51.5	45	45	42.0	38.9	39.4	39.8	40
Center-line[1] Turning Radius (CTR)	21	38	47.5	40.8	40.8	37.8	34.9	35.4	35.5	36
Minimum Inside Radius (ft)	14.4	28.3	36.4	27.6	25.5	24.5	23.8	25.4	21.3	19.3

Design Vehicle Type	Interstate Semi-trailer		"Double Bottom" Combination	Rocky Mtn Double	Triple Semi-trailer/ trailers	Turnpike Double Semi-trailer/ trailer	Motor Home	Car and Camper Trailer	Car and Boat Trailer	Motor Home and Boat Trailer	Farm[3] Tractor w/One Wagon
Symbol	WB-62*	WB-65** or WB-67	WB-67D	WB-92D	WB-100T	WB-109D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (ft)	45	45	45	82.0	45	60	40	33	24	50	18
Center-line[1] Turning Radius (CTR)	41	41	41	78.0	41	56	36	30	21	46	14
Minimum Inside Radius (ft)	7.9	4.4	19.3	82.4	9.9	14.9	25.9	17.4	8.0	35.1	10.5

NOTE: Numbers in table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 3,350 mm to 6,020 mm, respectively. For these different sizes, the minimum design turning radii vary from 8.78 m to 12.01 m and the minimum inside radii vary from 4.27 m to 7.74 m.

[3] = Turning radius is for 150-200 hp tractor with one 5.64 m long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

In summary, studies reviewed in this section were found to have contradictory results. The exploratory analysis of New Jersey Turnpike data showed trucks to have a positive impact on crashes, while most of the statistical models, show that crash rates decrease with increase in percentage of trucks in AADT. One of the simulation study discussed in this section indicated that there was not much of an effect in level terrain, but was considerable in steep grades. The studies suggested that it is difficult to represent the physical and operational impacts of trucks in most traffic models as it involves driver behavior influenced by many dynamic factors like time of day, weather, etc.

2.3 Chapter summary

This chapter has documented the literature review conducted on design alternatives that have been recommended to accommodate trucks on freeways and studies on impact of trucks on safety.

Many studies were conducted to establish appropriate alternatives for managing the increasing truck traffic. Recommendations available for accommodating trucks in the design process include changes in design vehicle dimension and characteristics like minimum turning radii to reflect physical and operational characteristics of a truck. Incorporating these changes in the design process implies a higher construction cost. This makes it more important to understand the relationship between geometric characteristics and truck crashes and evaluate the safety impact of truck-only lanes to justify the investment.

Numerous studies that attempted to characterize the effect of truck traffic along with various other traffic, roadway and environmental factors on crash rates were conducted. Most of these studies used either exploratory analyses, statistical methods or simulation to establish the relationship between truck crashes and various environmental, mixed traffic flow conditions, and geometric design features. Most of these studies were observed to have produced contradictory results on affect of truck traffic on crash rates. Next chapter explains the data collection process and summarizes the data used for this study.

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CHAPTER III

DATA COLLECTION AND SUMMARY

This chapter describes the characteristics of data used for developing the regression models. The first section covers data collection process while the second section describes the summary statistics of the data.

3.1 Data collection

Road and crash data for this study were collected from a previous Texas Department of Transportation (TxDOT) project (Middleton et al., 2006). Each database is described in a separate section below.

3.1.1 TxDOT Reference marker (TRM) database

The TxDOT Reference Marker (TRM) database was used to extract the roadway data. Information about the traffic volume and geometric features of all control sections across Texas were included in this data. Table 4 summarizes the different variables included in this data that are used to create a roadway database for this analysis.

Table 4: Features of TRM data.

Category	**Variables**
Control Section Information	District, County number, City Number, start and end reference marker, Control Section Number, beginning milepoint, ending milepoint, Length of section.
Roadway Information	Highway System, Designated Highway number, Highway status, Highway design, Functional system, Restricted Load limit, Rural/Urban, Roadbed ID.
Roadway features	Right-of-way width, Roadbed width, Base type, Surface width, Surface type, Speed Limit - Maximum, Speed Limit – Minimum, Number of Lanes, shoulder type (left and right), Shoulder use (left and Right), Curb type (left and right), Median type, Median width.
Traffic information	Percentage of single trucks in Average Annual Daily Traffic (AADT), Percentage of combination trucks in AADT, Percentage of single trucks in Design Hourly Volume (DHV), Percentage of combination trucks in DHV, Average Annual Daily Traffic (AADT) for current and for 9 years before the current year, Percentage of trucks in AADT, Percentage of trucks in DHV, Direction of travel, design year, estimated AADT for design year.

3.1.2 Department of public safety (DPS) database

The Department of Public Safety (DPS) accident databases were used for assembling the crash data. Crash data from 1997 to 2001 for various control sections, across the Texas roadway network was collected. A control section represents a segment of road over which geometric design features are constant or do not change over the length of the segment. Two types of databases were used.

The first one contains information about the crash, such as severity, location, factors leading to the crash (as reported by the police officer), time and day when the crash occurred, environmental conditions, geometric and traffic features of the road segment on which the crash occurred. Table 5 describes the various variables and features of the crash database used in the analysis. In case of multi-vehicle crashes, an array was built with information on various types of vehicles involved. A maximum of three vehicles were considered involved in each multi-vehicle crash for the database extraction process.

Table 5: Features of DPS accident data.

Category	**Variables**
Crash Identification	Accident Number.
Crash Location	County, Control Section, Milepoint within each control section, District, Position of first vehicle before accident, Position of second vehicle before accident, Position of point of impact, Population group, Location of crash on part of roadway, Direction of milepoint numbers, Part of roadway involved, Direction of travel.
Time of crash occurrence	Accident year, Month, day of month, day of week, time of day.
Roadway features	Road Class, surface condition, Road condition, Alignment, Traffic Control, intersection road type, Degree of curve.
Environmental features	Light condition, Weather.
Factors leading to crash	Driver behavior leading to crash, first harmful event, vehicle movements/manner of collision.
Crash features	Accident severity, object stuck total number of vehicles involved, persons killed in the crash.

The second database includes information about the driver and the vehicle(s) involved. Driver information database incorporates information about the crash, such as alcohol consumption leading to the crash and details of the vehicle(s) involved. Table 6 summarizes the various variables explaining features of the driver database used in the analysis. The crash information database and driver information database were merged by the unique identification number for each crash to develop a crash database. This crash database includes details on the crash location, nature of crash, driver information and location details for crashes occurred between 1997 and 2001 on Texas freeways.

Table 6: Features of DPS driver data.

Category	**Variables**
Crash Identification	Accident Number.
Driver features	Driver alcohol/drug test, driver race and sex, Driver License status, Driver status, Driver defect, Driver age.
Vehicle features	Vehicle make and model, vehicle body style, vehicle type, vehicle defects, total in vehicle.
Crash features	Vehicle damage scale, injury level of vehicle, driver injury severity, Driver ejected from vehicle.
Factors leading to crash	Contributing factors due to driver’s behavior, Driver restraining device.
Post-crash services	Liability insurance, Driver Emergency service.

3.1.3 GIS data

Traffic data embedded in GIS was taken from a previous TxDOT project (Middleton et al., 2006). This data graphically represented distribution of various traffic features like AADT and DDHV over the entire highway network in Texas. Figure 2 shows the AADT distribution on various roadways across Texas, from the 2002 roadway data. From the map, border areas and roads connecting major cities are observed to have heavy volumes. From Figure 3, it can be seen that truck traffic is mainly concentrated on interstate highways. Heavy truck traffic is observed between major cities and on interstate highways connecting borders.

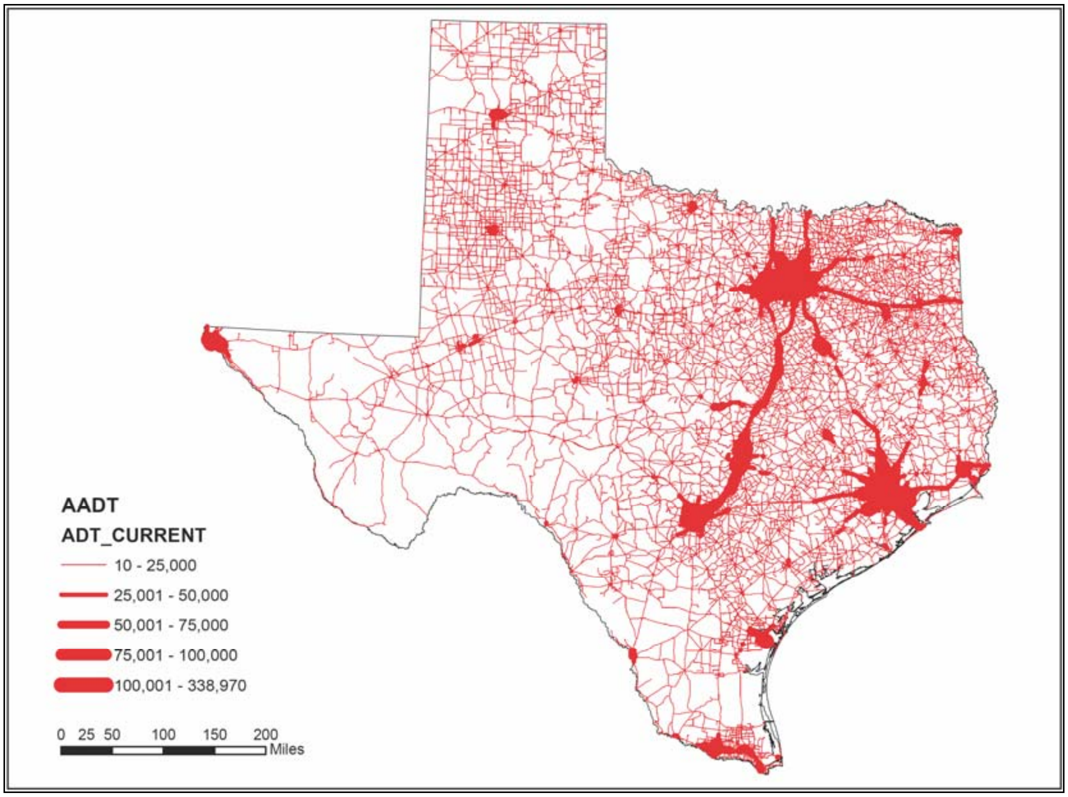


Figure 2: Texas average annual daily traffic for 2002 (Middleton, 2006).

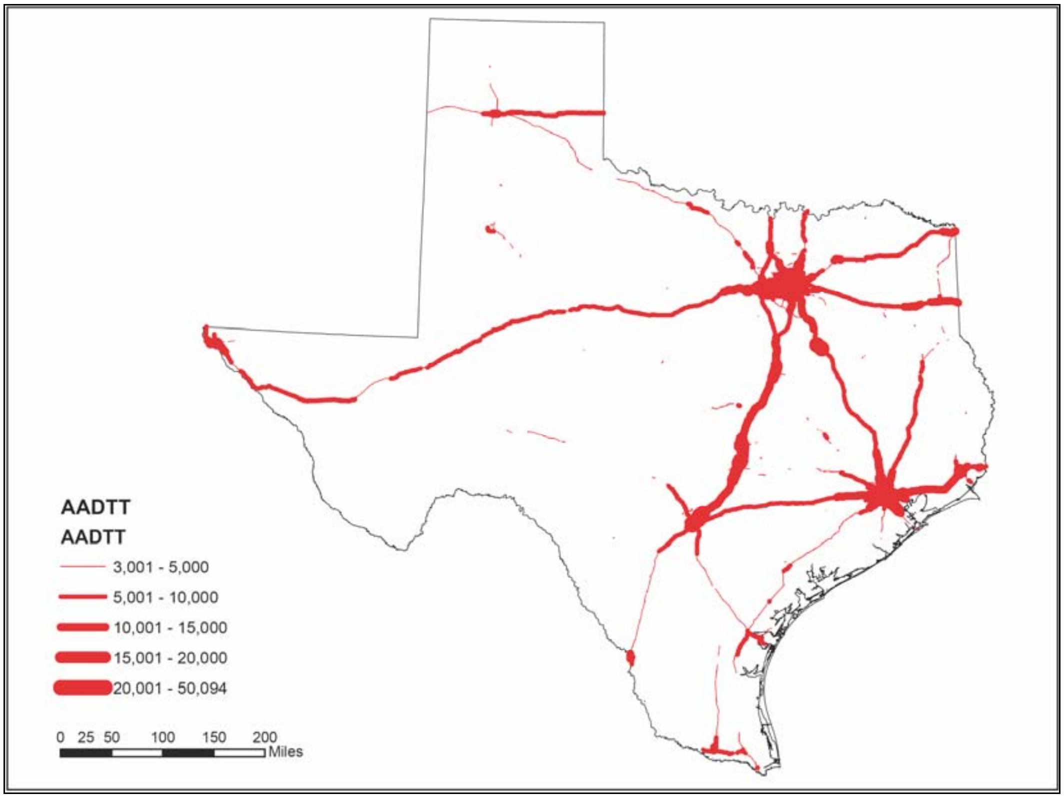


Figure 3: Texas average annual daily truck traffic in 2002 (Middleton, 2006).

3.1.4 Truck crashes database

The above mentioned databases were merged by control section to develop a database with geometric, environmental and traffic features associated with the crashes occurring on a control sections along the Texas roadway network. To build the crash database for this analysis, a new table was created from these databases using the "PROC SQL" procedure in SAS. The procedure matched the location of the crash to beginning and ending mile point of each control section and allocated crashes to each segment.

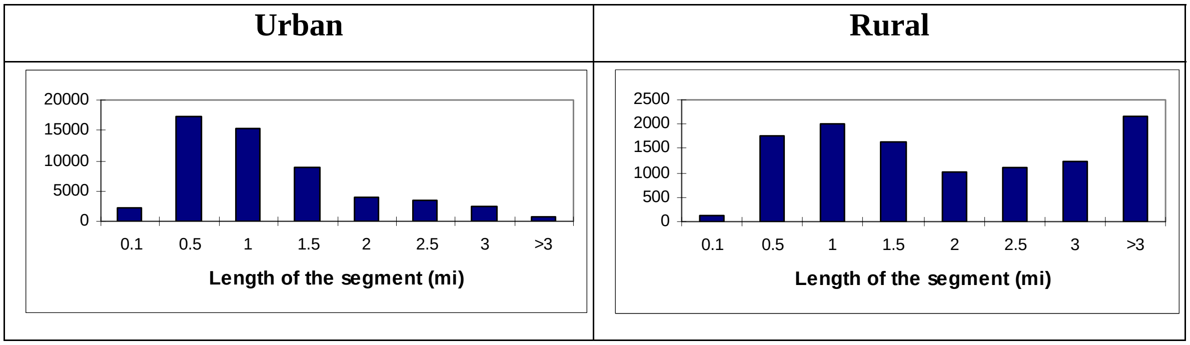
As described above, only crashes occurring on mainlanes of highways and interstates were considered in the analysis. Other classes of roadway were not included as exclusive truck facilities have been proposed to be built only on higher classes of roads (i.e., Controlled access highways, etc.). Also, only segments with truck-involved crashes were considered in this study. These models should not be used for directly estimating safety performance of a highway, as it does not consider segments with zero crashes. From the crash database, crashes on interstates or US highways or State highways were extracted. To include only mainlane crashes in the analysis, record type “1” (representing mainlane) and roadway part involved in the crash “1” (representing mainlane) were extracted. According to Hauer (2004) segments should not be shorter than the precision with which accident locations are recorded. Segment lengths less than 0.1 mile were subsequently removed from the database. Finally, the database was separated into three groups: truck-related crashes (two or more vehicles involving at least one truck), truck-only (two or more trucks only) and single-truck crashes, using SAS procedures.

3.2 Summary statistics

On collecting the data it was seen that out of the total 204,848 crashes recorded on mainlanes of Texas freeways over five years (1997-2001), 74,174 involved at-least one trucks. Of the truck-related crashes, 10,370 involved only trucks and 17,436 were single-truck crashes. The following sections summarize the characteristics of the data.

3.2.1 Roadway data

This section summarizes the geometric and traffic features of the freeway segments in the roadway data. Figure 4 shows the distribution of the segment length in urban and rural areas. From this figure, it can be seen that most urban segments are less than 1 mile long. The distribution also indicates that rural area has more number of long segments (greater than 3 miles) than the urban area.



Urban

Rural

Figure 4: Distribution of length of the segment

Figure 5 shows the distribution of the number of lanes across segments in urban and rural areas. The distribution shows that most urban and rural segments have either 4 or 6 lanes. Some urban segments on this highway network also have 8 to 12 lanes.

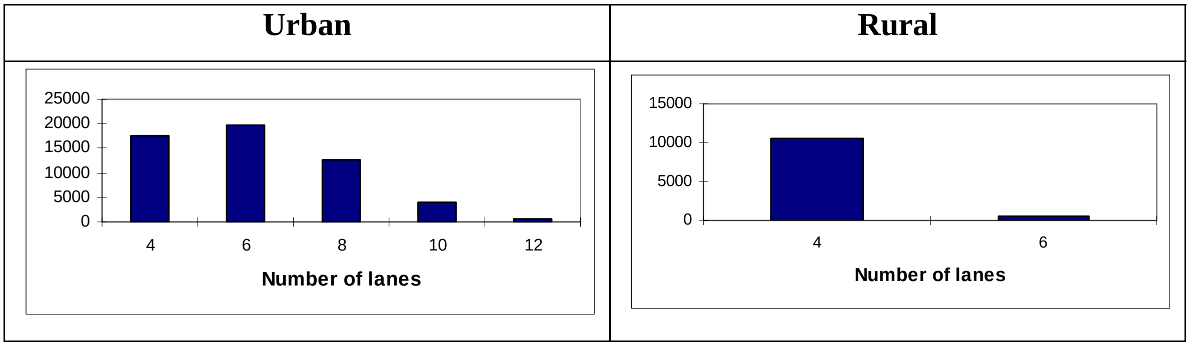

Urban
Rural

Figure 5: Distribution of number of lanes

Figure 6 shows the distribution of speed limit among urban and rural segments. From this figure, it can be seen that most urban segments have a lower speed limit compared to rural segments. Most urban segments were observed to have a speed limit of 55mph while most rural segments had a 70mph speed limit.

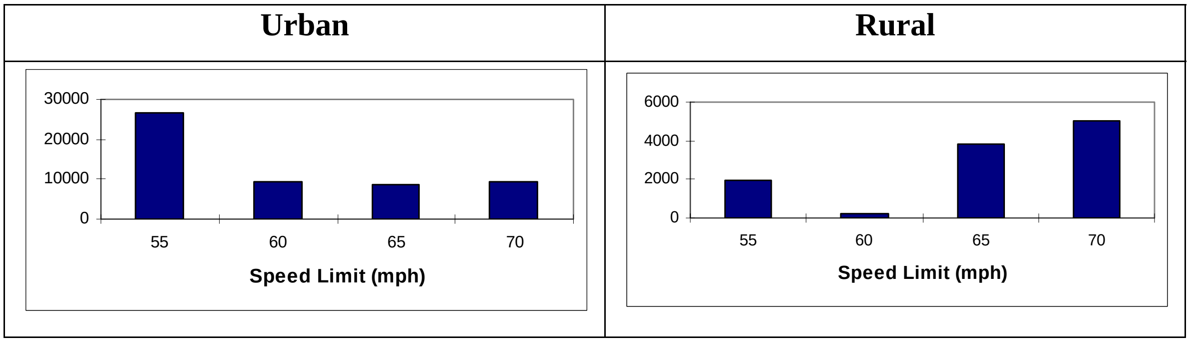

Urban
Rural

Figure 6: Distribution of speed limit (mph)

Figure 7 and Figure 8 show the distribution of left and right shoulder widths. The numbers shown in these figures represent the sum of left and right shoulder widths in each direction. The distribution shows that there are more urban no-shoulder segments than rural. Also, it was seen that most urban and rural segments seem to have combined shoulder width between 10 and 20 feet.

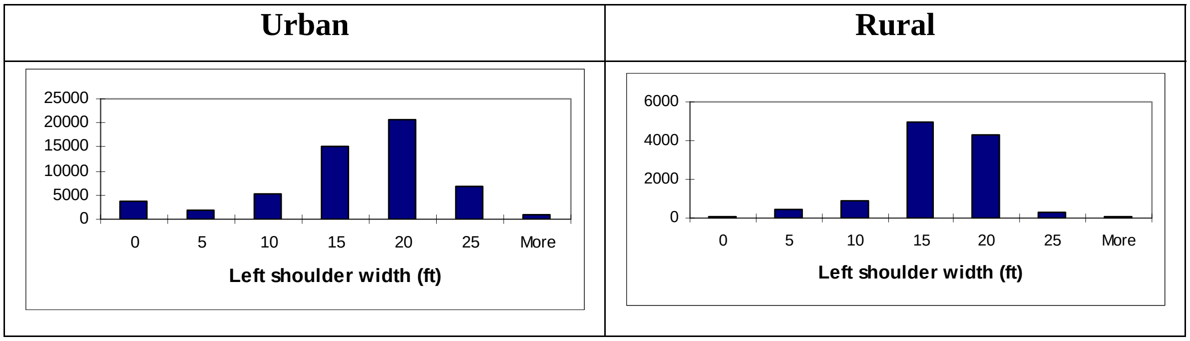


Figure 7: Distribution of left shoulder width (in feet)

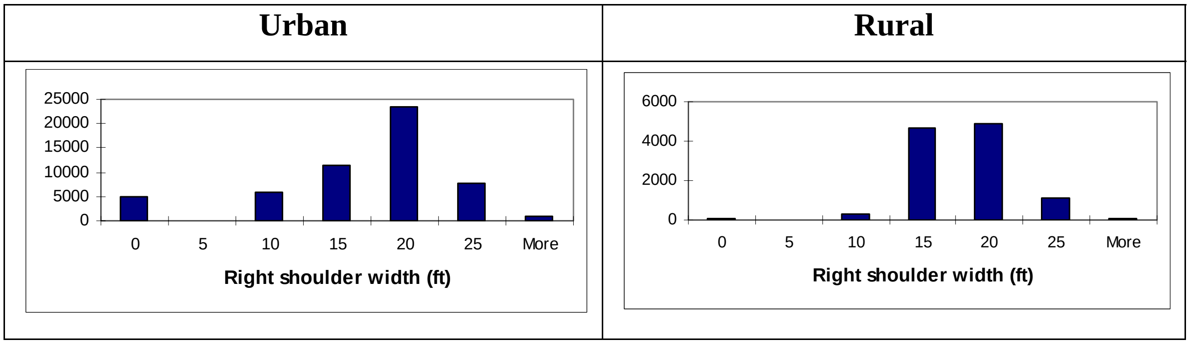
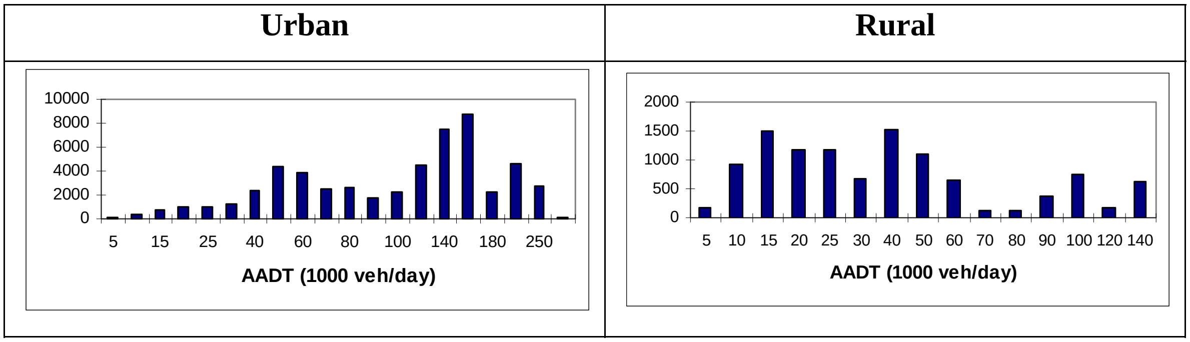


Figure 8: Distribution of right shoulder width (in feet)

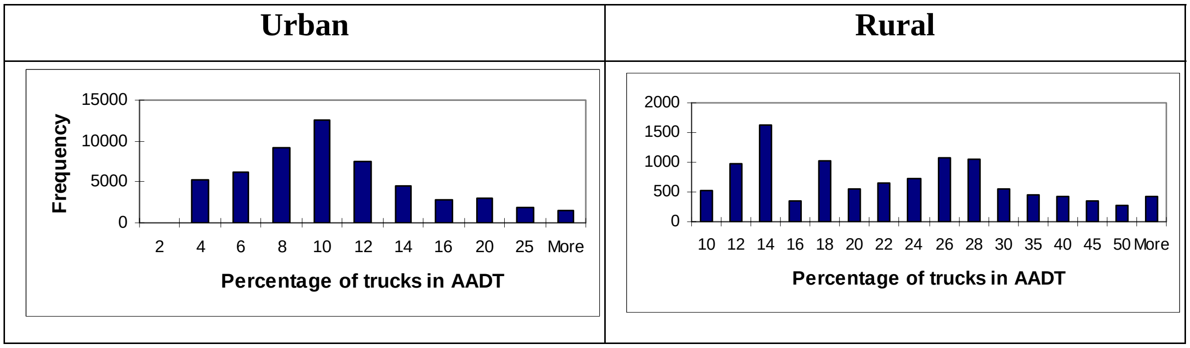
Figure 9 and Figure 10 show the distribution of AADT and percentage of trucks in AADT across various segments in urban and rural areas. From the distribution, it can be observed that urban segments have higher volumes and lower percentage of trucks, while rural segments have lower volumes and higher percentage of trucks. The higher percentage of trucks cannot be interpreted as an absolute larger number of trucks because of the difference in volumes. It was also observed that, for most urban segments, about ten percent of the AADT volume were trucks, while, for most of the rural segments, fifteen percent of the traffic were trucks. The segments with high percentage of trucks in AADT were found to be located on freeways connecting the three major cities in Texas.



Urban

Rural

Figure 9: Distribution of AADT (1000 veh/day)



Urban

Rural

Figure 10: Distribution of percentage of trucks in AADT

3.2.2 Crash data

From the crash database, accident rate and crashes per mile were calculated for each control section. Figure 11 shows the distribution of the number of crashes per mile per year for all parts of the highways including frontage, entrance and exit ramps. Table 7 summarizes crash rate and crashes per mile for crashes occurring on the mainlane on Texas freeways. From this crash database, three databases were extracted: truck-related crashes, truck-only crashes and single-truck crashes. Truck-related crashes are crashes involving at-least one truck.

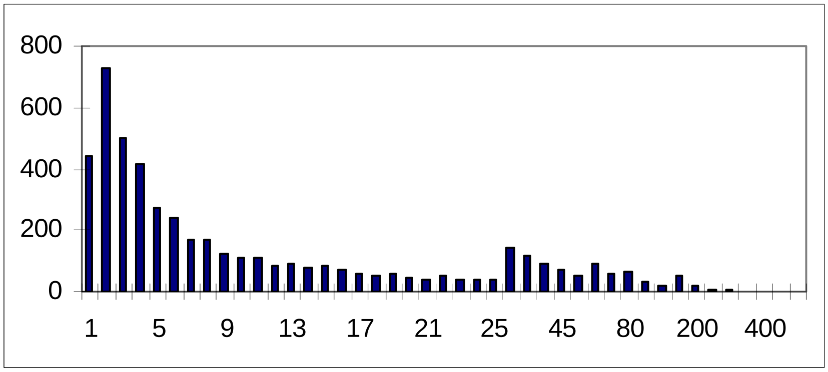


Figure 11: Distribution of freeway crashes per mile per year

Table 7: Freeway crash summary

	Crash per Mile	Crash per Mile per year	Crash rate	Length	AADT	No. of lanes
Maximum	2146.9	429.4	56.1	9.1	333858.0	12.0
Minimum	0.4	0.1	0.0	0.1	3160.0	4.0
Average	76.4	15.3	0.7	0.8	53740.8	-

3.2.2.1 Truck-related crashes

Frequency distribution of crashes by traffic, geometric and environmental factors were plotted to explore truck-related crashes. Figure 12 shows the frequency distribution of truck-related crashes per mile per year. From the figure, it can be seen that most segments have two or three crashes per mile per year.

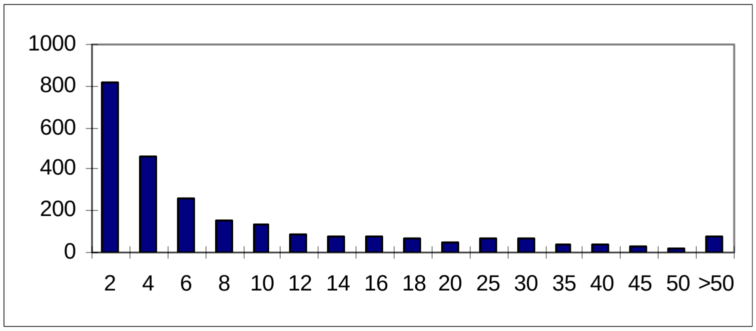
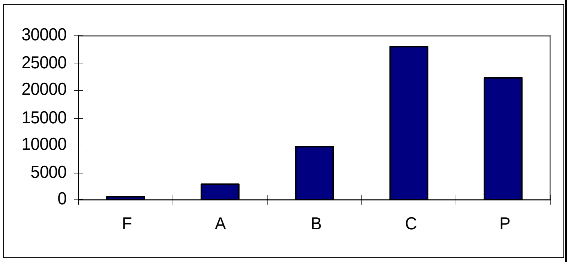
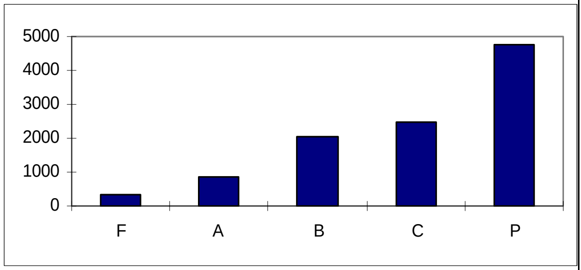


Figure 12: Distribution of crash per mile per year for truck-related crashes.

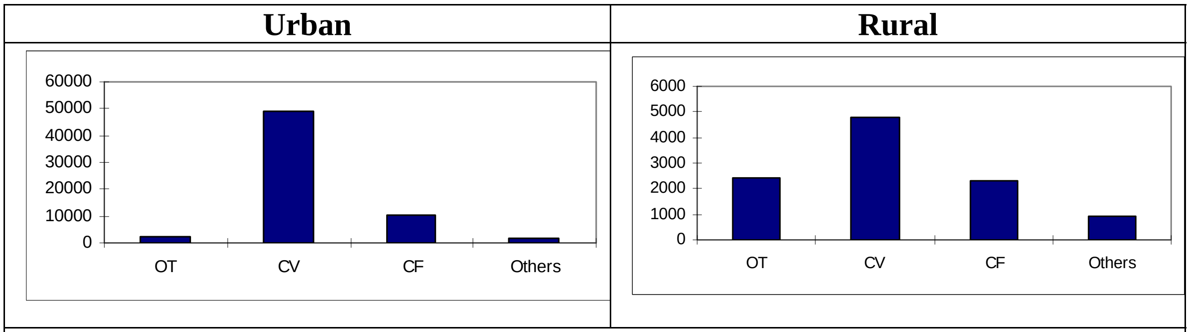
Figure 13 shows the distribution of truck-related crashes by severity level. From the figure, it can be seen that most crashes were classified as possible injury (C) or non-injury type of crashes (PDO). From the comparison between truck-related crash severity between urban and rural segments, it was observed that urban segments experience less severe crashes than rural segments. Most crashes in rural segments seem to be PDO type of crashes, while most urban segments experience possible injury type of crashes. It was also observed that rural segments experienced more number of fatal crashes when compared to urban segments.

Urban	**Rural**
	

Note:
F - Fatal
A - Incapacitating injury - not able to walk, drive, etc.
B - Nonincapacitating injury - bump on head, abrasions, minor lacerations
C - Possible injury - limping, complaint of pain
P – Property Damage Only (PDO)

Figure 13: Distribution of truck-related crash severity

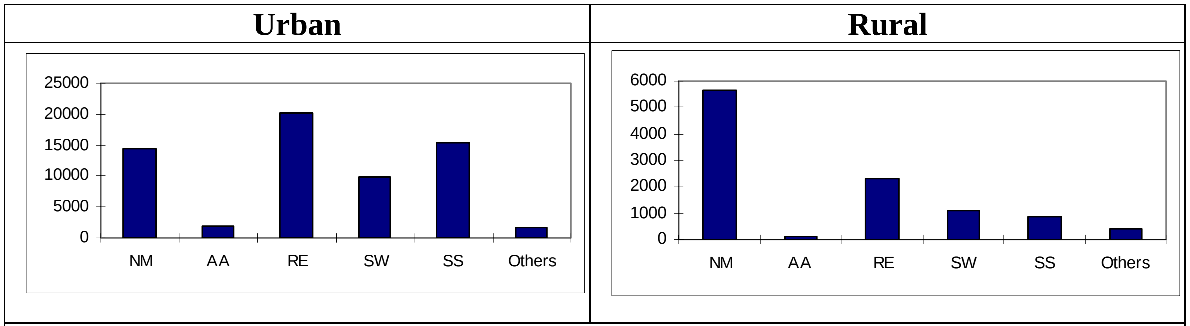
Figure 14 shows the distribution of first harmful event in truck-related crashes. From the figure, it was observed that most crashes resulted from collision with another vehicle in transport. On urban segments, 78% of truck-related crashes were collision with another vehicle, while that on rural segments was about 45%. It was also observed that there were more overturned vehicles in rural segments than on urban segments. Overturning may be attributed to higher speed limits.



Note: OT- Overturn, CV- Collision with another vehicle in transport, CF – Collision with fixed object.

Figure 14: Distribution of first harmful event in truck-related crashes

Figure 15 shows the distribution of collision types among truck-related crashes. From the figure, it is observed that one-third of truck-related crashes in urban segments were rear-end collisions. Another major part of truck-related crashes were either side-swipe or collision with a stopped vehicle. It was also observed that rural segments had more non-motor vehicle collisions than the urban segments.



Note:
NM – Collision with a Non-Motor Vehicle
AA - Vehicles approaching at an angle
RE- Vehicles going in same direction - Rear-end collision
SW- Vehicles going in same direction - Side-swipe collision
SS - Collision with a stopped vehicle.

Figure 15: Distribution of type of collision in truck-related crashes

The following figures show distribution of truck-related crashes by environmental characteristics of the segment at the time of crash. Figure 16 shows distribution of crashes by surface condition. From the plots, it can be seen that most truck-related crashes occurred in dry surface condition and only about 20% of the truck-related crashes on both urban and rural segments, occurred in wet surface condition. It was also observed that rural segments had more truck-related crashes in icy surface condition than urban segments.

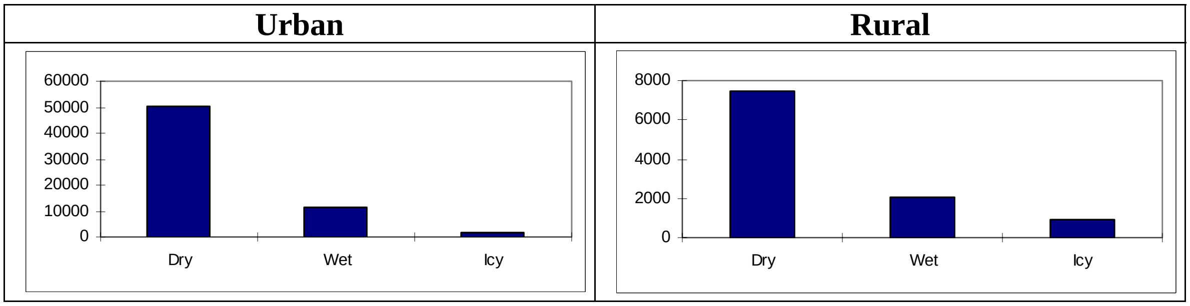


Figure 16: Distribution of truck-related crashes by surface condition

Figure 17 shows the distribution of truck-related crashes by lighting condition at the time of the crash. It was seen that most crashes occurred in daylight. About 30% of truck-related crashes occurred in darkness (not lighted) condition on rural segments, while only 7% of them occurred in the same lighting condition on urban segments.

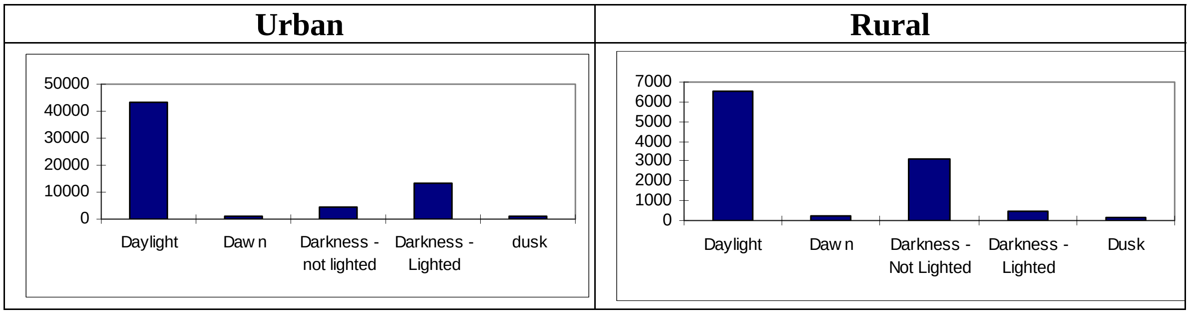


Figure 17: Distribution of truck-related crashes by light condition

Figure 18 shows the distribution of truck-related crashes by weather conditions at the time of the crash. It was observed that most crashes occurred in clear weather and that rural segments had more truck-related crashes in snowy weather. It was also observed that about 15% of truck-related crashes occurred in rainy weather condition on both urban and rural segments.

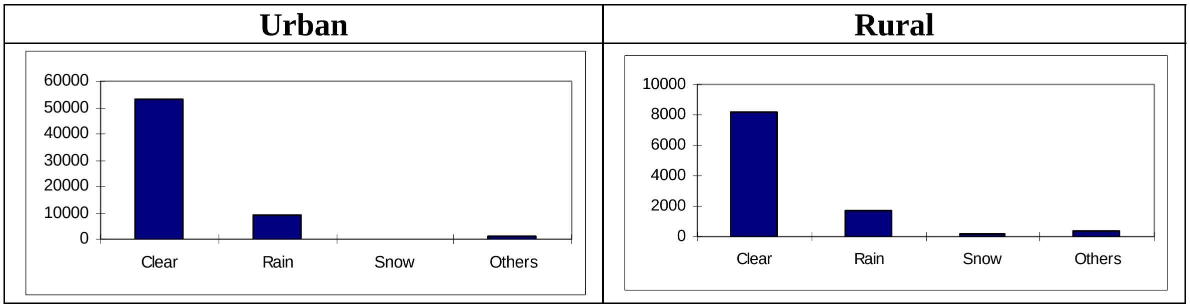


Figure 18: Distribution of truck-related crashes by weather condition

The following figures show the truck-related crash frequency distribution for various geometric design features. Figure 19 shows the distribution of crashes by alignment. From the figure, it was observed that most crashes occur in straight alignment in both urban and rural segments. The distribution also suggests that more truck-related crashes occurred on rural curved segments than on urban curved segments.

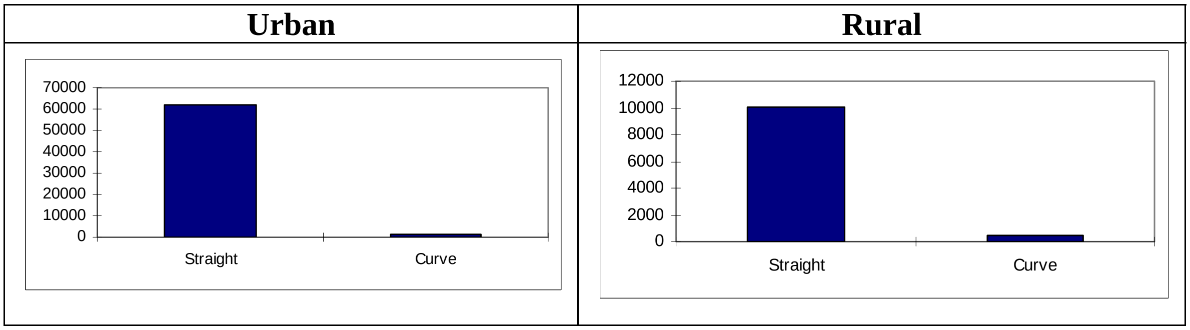


Figure 19: Distribution of truck-related crashes by alignment

Figure 20 shows the distribution of truck-related crashes by speed limit. It was observed that most crashes occurred in 55mph speed limit zones in urban segments and in 70mph zones in rural segments. A larger number of 55mph zones in urban areas and 70mph zones in rural areas could explain this difference.

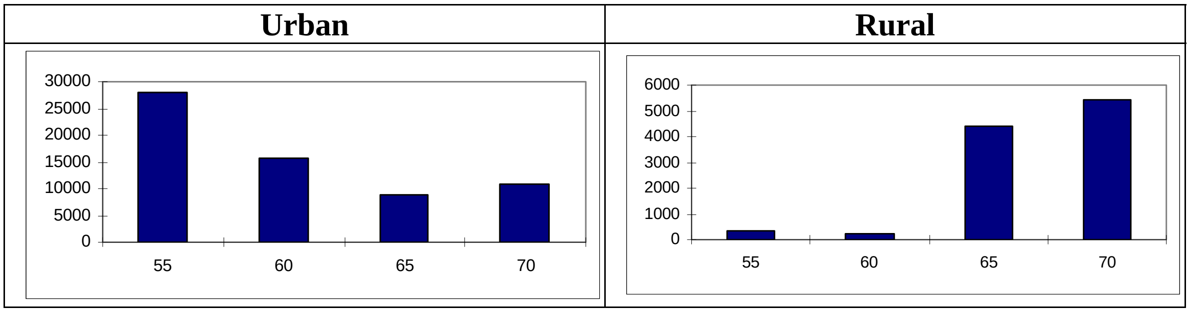


Figure 20: Distribution of truck-related crashes by speed limit (in mph)

Figure 21 shows the distribution of truck-related crashes by left shoulder widths (sum of both directions). It was observed that most crashes on urban segments occur at segments with left shoulder widths equal to 20 feet. A large number of crashes were observed on segments with no left-shoulder width in urban areas. More number of truck-related crashes seems to occur on rural segments with wider left shoulder widths (more than 20 feet).

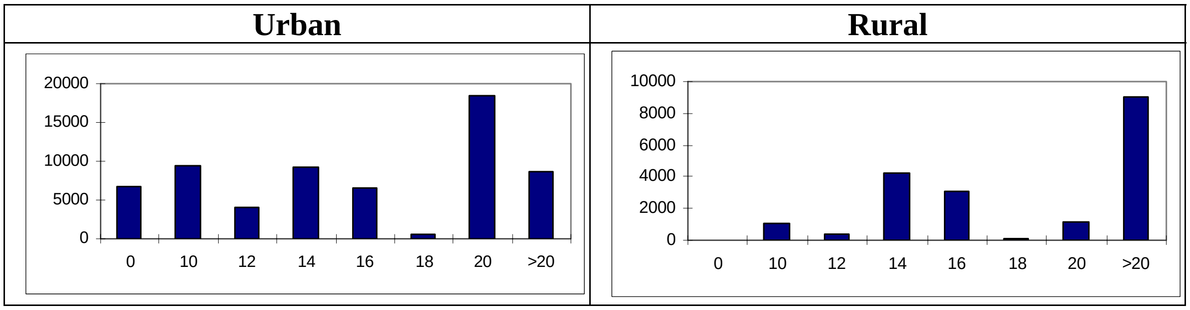


Figure 21: Distribution of truck-related crashes by left shoulder width

Figure 22 shows the distribution of truck-related crashes by right shoulder widths (both sides). The distribution is similar to that of truck-related crashes by left shoulder widths. It was observed that most crashes on urban segments occur on segments with right shoulder widths equal to 20 feet

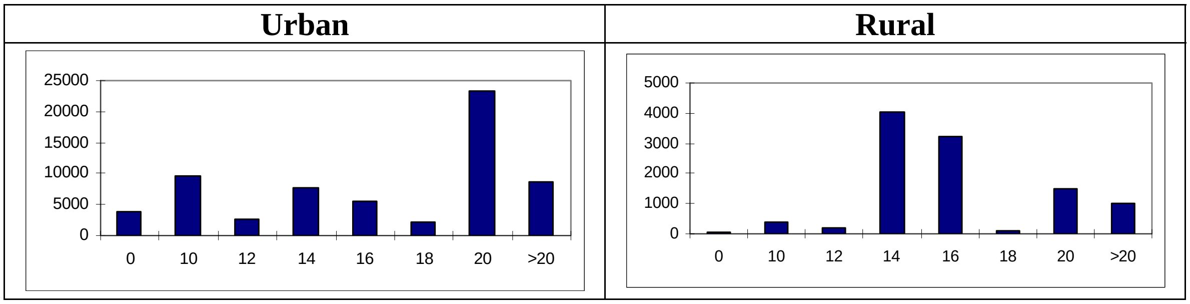


Figure 22: Distribution of truck-related crashes by right shoulder width

Figure 23 shows the distribution of truck-related crashes by AADT. The figure suggests that a higher number of truck-related crashes occur at high volumes on urban segments. It was also observed that most truck-related crashes on rural segment occurred at relatively lower volumes. The characteristic low volumes on rural segments might be a reason for this difference.

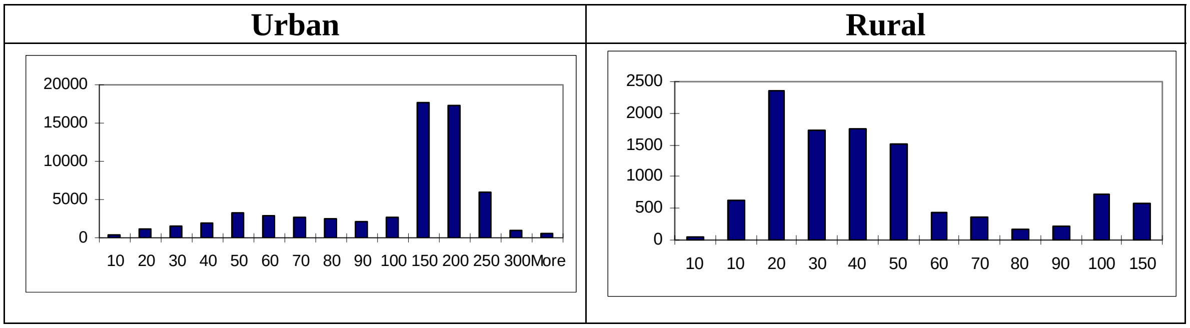


Figure 23: Distribution of truck-related crashes by AADT (1000 veh/day)

Figure 24 shows the distribution of truck-related crashes by percentage of trucks in AADT. From the figure, it was observed that most truck-related crashes occurred between 10 and 15 percent truck traffic on urban segments. The figure also suggests that there are considerable number of crashes on segments with more than 50% trucks.

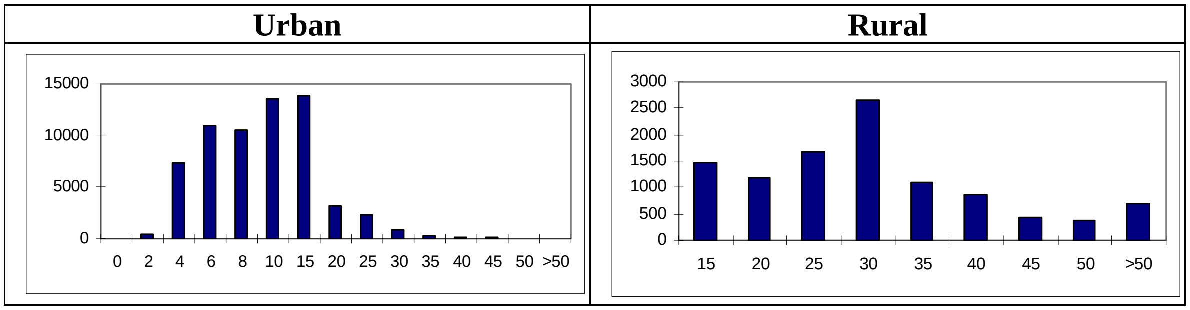


Figure 24: Distribution of truck-related crashes by percentage of trucks in AADT

3.2.2.2 Truck-only crashes

Frequency distribution of crashes by traffic, geometric and environmental factors were plotted to explore the truck-only crash data. Two or more trucks involved in the same crash were included in the database. Figure 25 shows the distribution of truck-only crashes per mile per year over the Texas roadway network. From the figure, it can be seen that most segments experience on an average two to three crashes per mile per year.

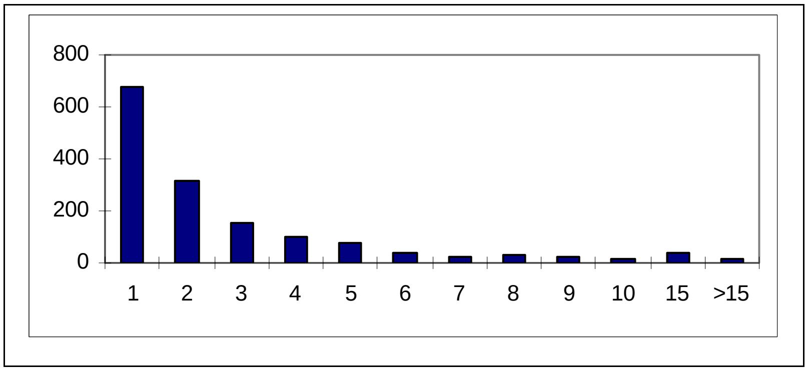


Figure 25: Distribution of crashes per mile per year for truck-only crashes

Figure 26 shows the distribution of truck-only crash by severity level. From the figure, it can be observed that most crashes on urban segments are possible injury type of crashes. Most of the rural segments were classified as PDO type of crashes. It was also observed that rural segments had more number of fatal truck-only crashes when compared to urban segments.

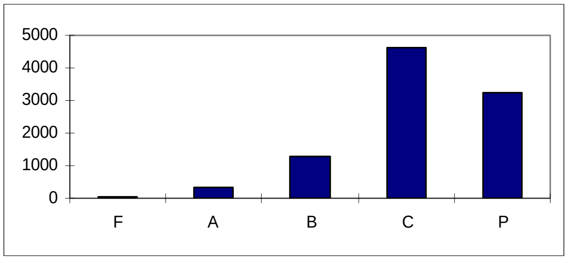
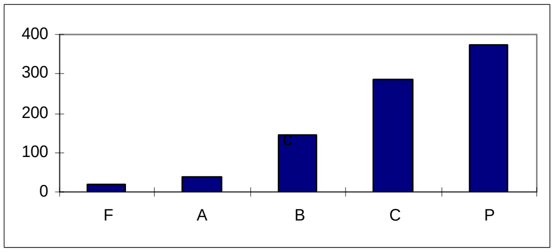
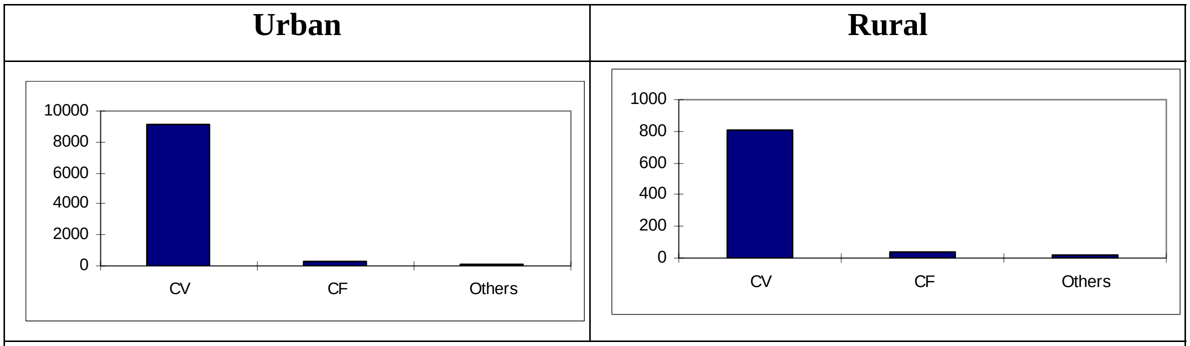
Urban	**Rural**
	
Note: F - Fatal A - Incapacitating injury - not able to walk, drive, etc. B - Nonincapacitating injury - bump on head, abrasions, minor lacerations C - Possible injury - limping, complaint of pain P - Non-injury or Property Damage Only (PDO)	

Figure 26: Distribution of crash severity of truck-only crashes

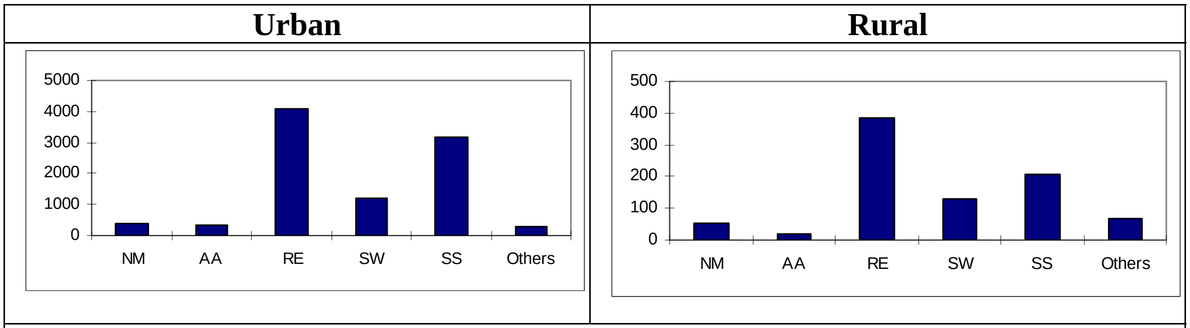
Figure 27 shows distribution of first harmful event for truck-only crashes. It was observed that most crashes were involved a collision with another vehicle in transport. Only 3% to 4% of truck-only crashes on urban and rural segments implicated a collision with a fixed object. The collision with a fixed object cannot be treated as an isolated event, as it may lead to another collision.



Note: CV- Collision with another vehicle in transport, CF – Collision with fixed object.

Figure 27: Distribution of first harmful event in truck-only crashes

Figure 28 shows the distribution of the types of collision for truck-only crashes. From the figure, it can be seen that for of the urban segments, most of the crashes were either rear-end or side-swipe collision or collision with a stopped vehicle. It was observed that 43 to 44% of truck-only crashes on both urban and rural segments were rear-end collisions. It can also be seen that there urban segments experienced more collisions of vehicles approaching at an angle than rural segments.



Note:
NM - Collision with a Non-Motor Vehicle
AA - Vehicles approaching at an angle
RE- Vehicles going in same direction - Rear-end collision
SW- Vehicles going in same direction - Side-swipe collision
SS - Collision with a stopped vehicle.

Figure 28: Distribution of collision type in truck-only crashes

The following figures show a comparison of urban and rural truck-only crash frequencies by environmental characteristics of the segment at the time of the crash. Figure 29 shows the distribution of truck-only crashes by surface condition of the segment at the time of the crash. From the figure, it can be seen that most truck-only crashes occurred on dry surface condition and that rural segments experienced more crashes on wet segments than urban segments.

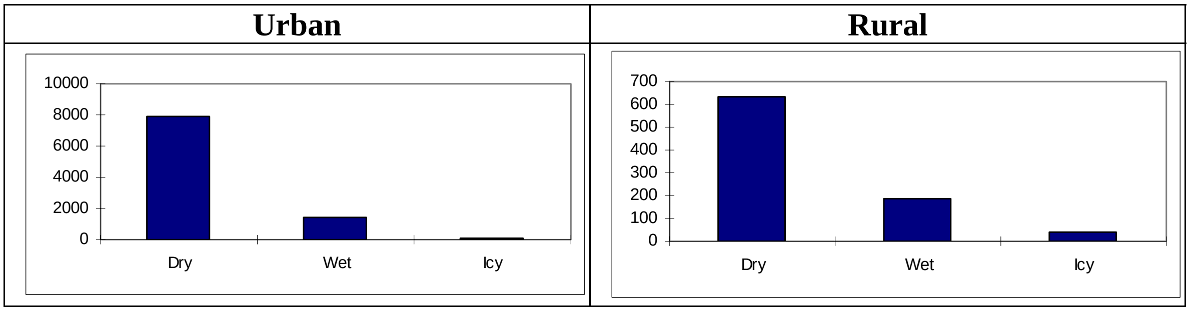


Figure 29: Distribution of truck-only crashes by surface condition

Figure 30 shows frequency distribution of the number of truck-only crashes by lighting conditions at the time of the crash. It was observed that more truck-only crashes occurred in daylight than in darkness. 7% of truck-only crashes on urban segments and 17% of truck-only crashes on rural segments were observed to have occurred in darkness (not lighted) condition.

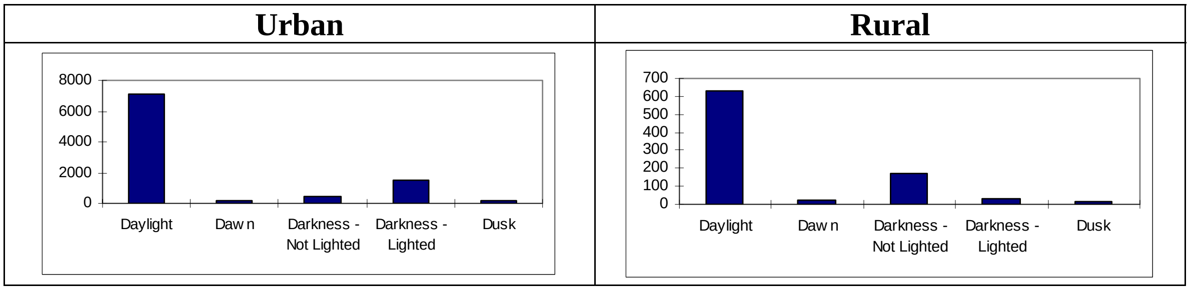
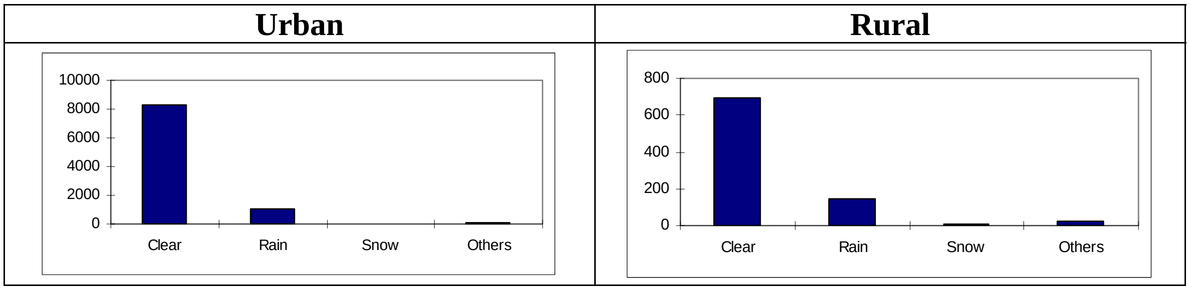


Figure 30: Distribution of truck-only crashes by light condition

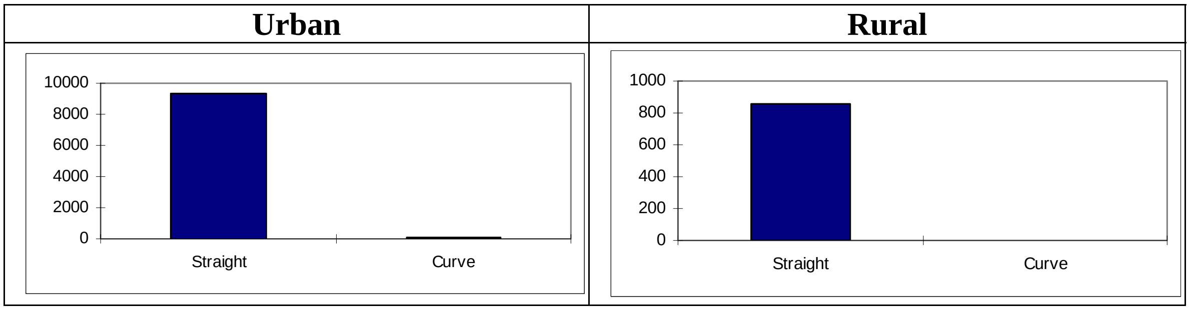
Figure 31 shows the distribution of truck-only crashes by weather conditions at the time of the crash. From the figure, it can be seen that most crashes occurred in clear weather condition. Only 12% of truck-only crashes on urban segments and 17% of truck-only crashes on rural segments occurred in rainy weather condition. Rural segments seem to experience more truck-only crashes in snowy weather condition.


Urban

Rural

Figure 31: Distribution of truck-only crashes by weather condition

Figure 32 shows the distribution of truck-only crashes by alignment. As observed for truck-related crashes, more number of truck-only crashes were observed on straight segments than curved segments. Curved rural segments seem to have fewer truck-only crashes than curved urban segments.


Urban

Rural

Figure 32: Distribution of truck-only crashes by alignment

Figure 33 shows the distribution of truck-only crashes by speed limit. It was observed that urban segments experienced more truck-only crashes in 55mph speed zones, while rural segments have more truck-only crashes in 65mph speed zones. About 15% of truck-only crashes on urban segments and about 38% of truck-only crashes on rural segments occurred on segments with 70mph speed limit.

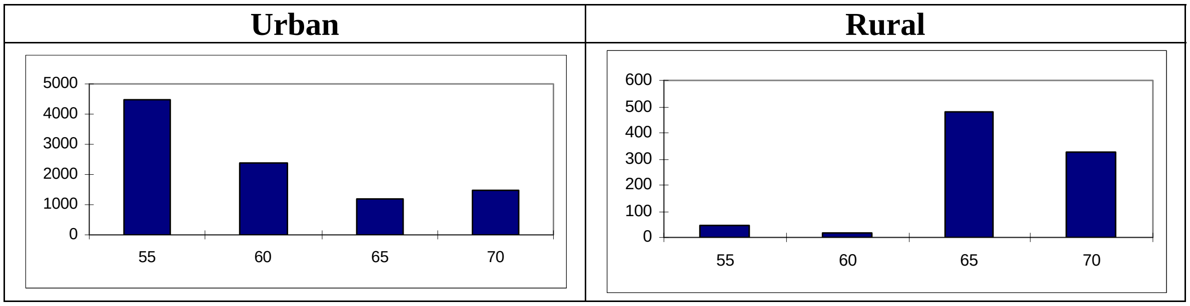


Figure 33: Distribution of truck-only crashes by speed limit (mph)

Figure 34 and Figure 35 show the distribution of truck-only crashes by left shoulder width and right shoulder width. Most truck-only crashes on urban segments were observed to be on segments with 20 feet shoulder widths. While, most truck-only crashes on rural segments were on 14 feet shoulder width segments. From the figure, it was seen that urban segments had more truck-only crashes on segments with more than 20 feet left shoulder widths than rural segments.

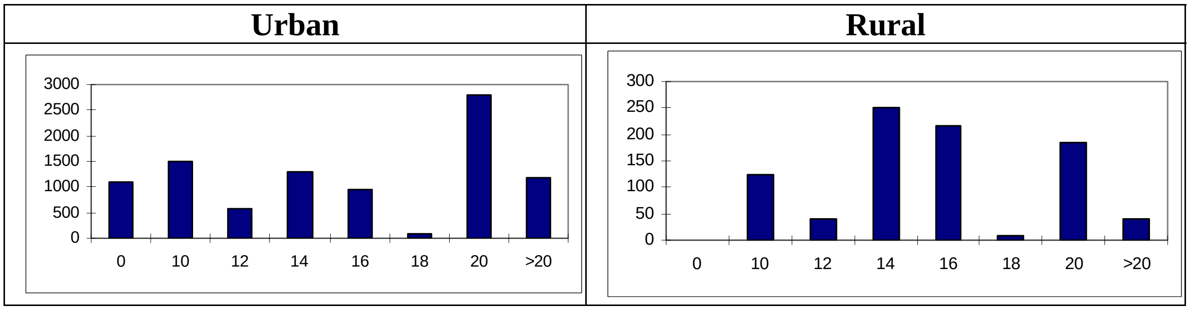


Figure 34: Distribution of truck-only crashes by left shoulder width in feet

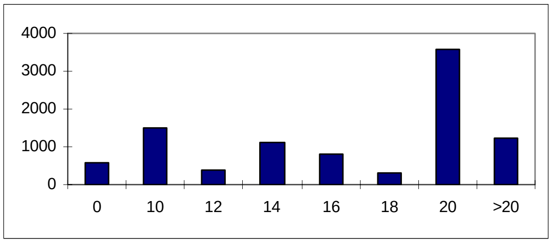
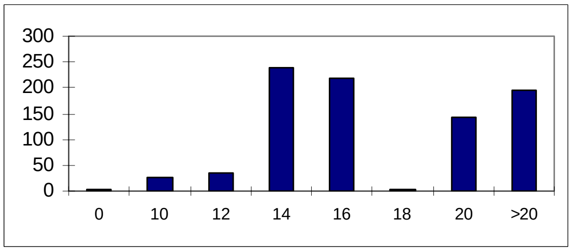
Urban	Rural
	

Figure 35: Distribution of truck-only crashes by right shoulder width in feet

Figure 36 shows the distribution of truck-only crashes by AADT. As observed for truck-related crashes, more truck-only crashes on urban segments were observed under high volumes, while those on rural segments were observed under relatively lower volumes.

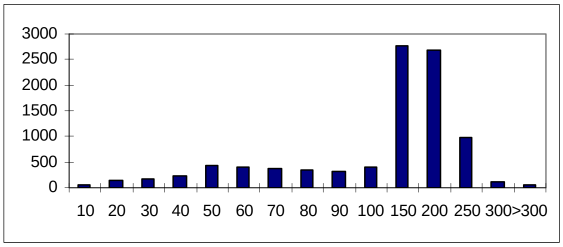
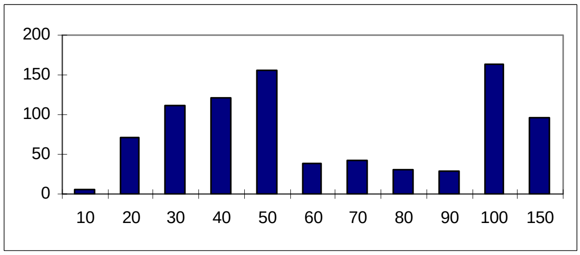
Urban	Rural
	

Figure 36: Distribution of truck-only crashes by AADT (1000 veh/day)

Figure 37 shows the distribution of truck-only crashes by percentage of trucks in AADT. From the figure, it can be seen that most truck-only crashes occur at 15 percent of trucks. It was also observed that rural segments have truck-only crashes at higher percentage of trucks when compared to urban segments.

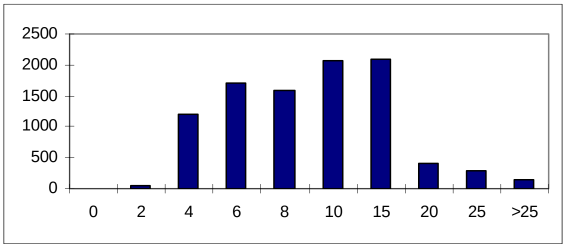
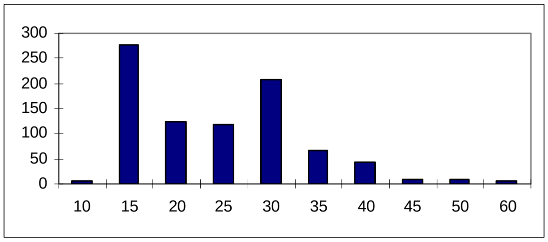
Urban	**Rural**
	

Figure 37: Distribution of truck-only crashes by percentage of trucks in AADT

3.2.2.3 Single-truck crashes

The frequency distribution of crashes by traffic, geometric and environmental factors were plotted to explore single-truck crashes. Figure 38 shows the distribution of single-truck crashes per mile per year across the Texas highway network. From the figure, it was observed that most segments had one or two crashes per mile per year.

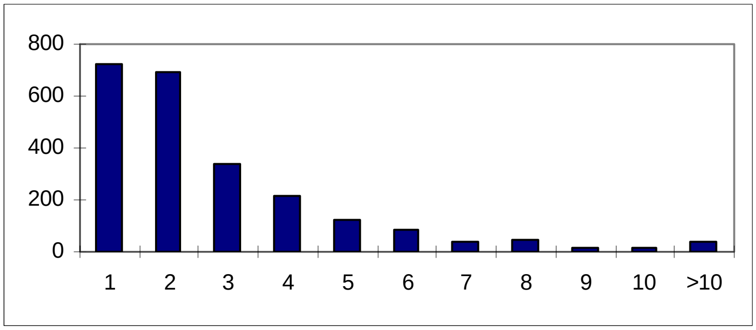
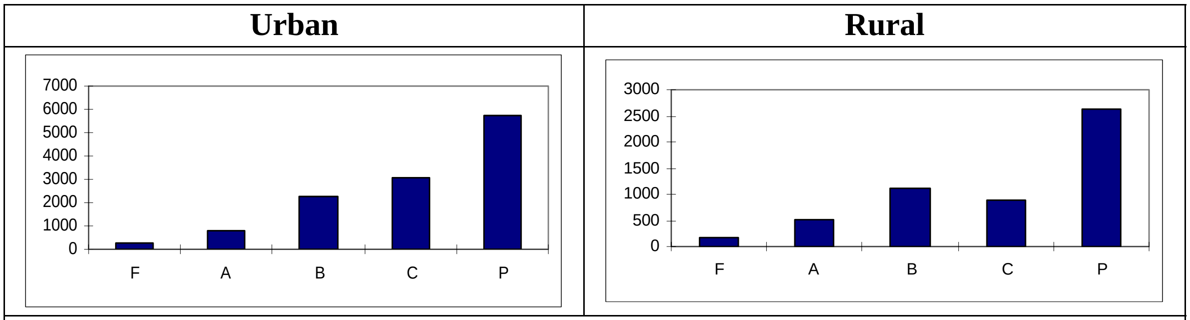


Figure 38: Distribution of single-truck crashes per mile per year

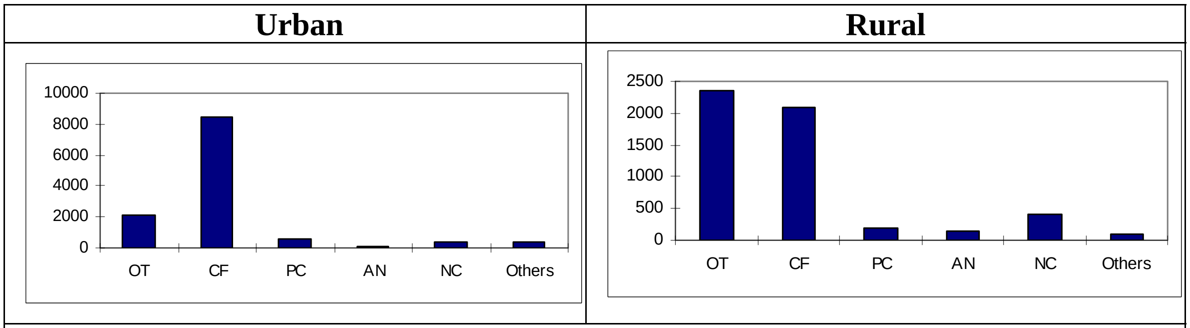
Figure 39 shows the distribution of single-truck crash severity over urban and rural segments. It was observed that most single-truck crashes were non-injury type of crashes. Only about 3% of single truck crashes were found to be fatal on both urban and rural segments.



Note:
F - Fatal
A - Incapacitating injury - not able to walk, drive, etc.
B - Nonincapacitating injury - bump on head, abrasions, minor lacerations
C - Possible injury - limping, complaint of pain
P - Non-injury or Property Damage Only (PDO)

Figure 39: Distribution of single-truck crash severity

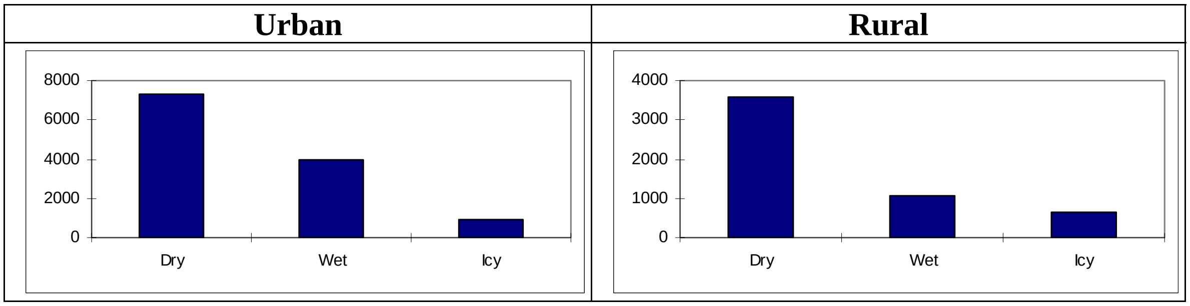
Figure 40 shows the distribution of first harmful event in single-truck crashes on urban and rural segments. It was observed that most single-truck crashes on urban segments involved collision with a fixed object. Most single-truck crashes on rural segments were either overturned vehicles or collision with a fixed object. From the figure, it was observed that there were more number of collisions with animals on rural segments than on urban segments.



Note: OT – Overturned, CF – Collision with fixed object, PC – Collision with parked car, AN – Collision with an animal, NC – Non-Collision.

Figure 40: Distribution of first harmful event in single-truck crashes

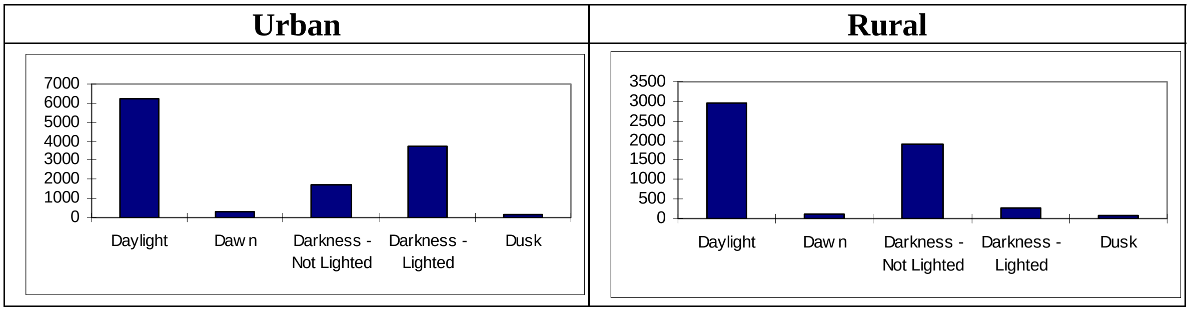
Following figures explore single-truck crashes under various environmental conditions at the time of the crash. Figure 41 shows the distribution single-truck crashes by surface condition of the segment at the time of the crash. As observed for truck-related and truck-only crashes, most single-truck crashes were observed to occur in dry surface condition. When compared to other truck crashes, single-truck crashes were observed to be more in number in icy surface condition.


Urban

Rural

Figure 41: Distribution of single-truck crashes by surface condition

Figure 42 shows the distribution of single-truck crashes by lighting conditions at the time of the crash. As observed for truck-related and truck-only crashes, most single-truck crashes were observed to occur during daylight. More single-truck crashes on rural segments were observed to occur in darkness not lighted condition than those on urban segments.


Urban

Rural

Figure 42: Distribution of single-truck crashes by light condition

Figure 43 shows the distribution of single-truck crashes by weather condition at the time of the crash. It was observed that most single-truck crashes occurred in clear weather condition. 18% of single-truck crashes on urban segments and 28% single-truck crashes on rural segments were observed to occur in rainy weather condition.

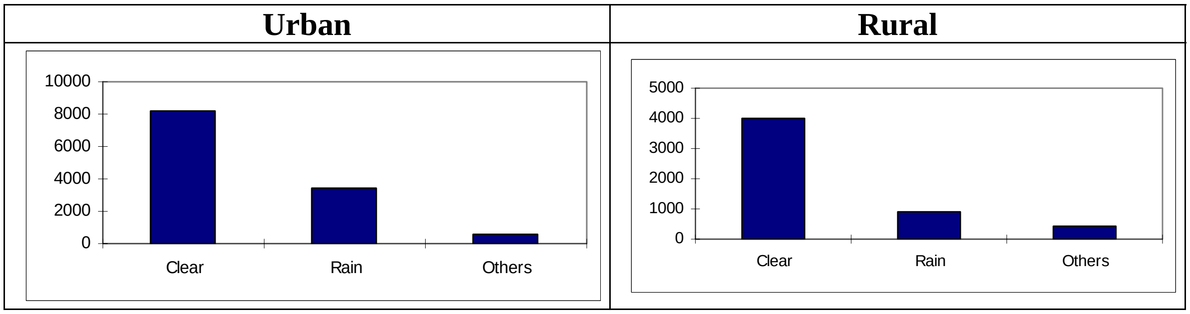


Figure 43: Distribution of single-truck crashes by weather condition

Figure 44 shows the distribution of single-truck crashes by alignment of the segment. As observed for truck-related and truck-only crashes, most single-truck crashes were observed to occur on straight segments. From the figure, it can be seen that only 6% of single-truck crashes on urban and rural segments seem to occur on curved segments.

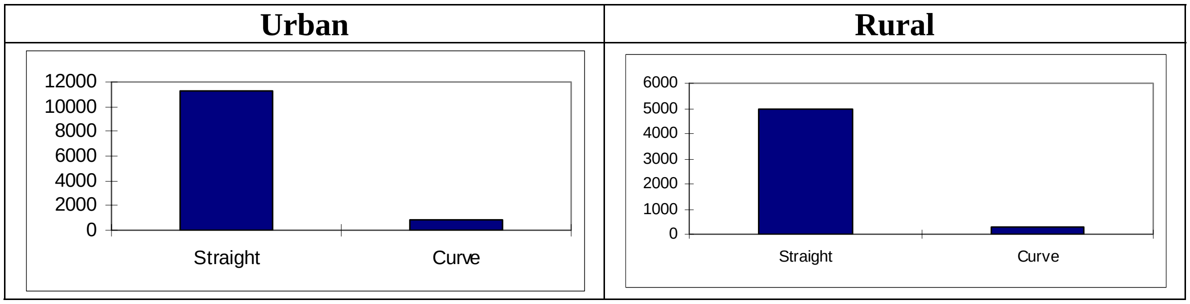


Figure 44: Distribution of single-truck crashes by alignment

Figure 45 shows the distribution of single-truck crashes by speed limit on the segment. As observed for truck-related and truck-only crashes, most single-truck crashes on urban segments were in 55mph speed limit zones and those on rural segments were in 70mph speed limit zones.

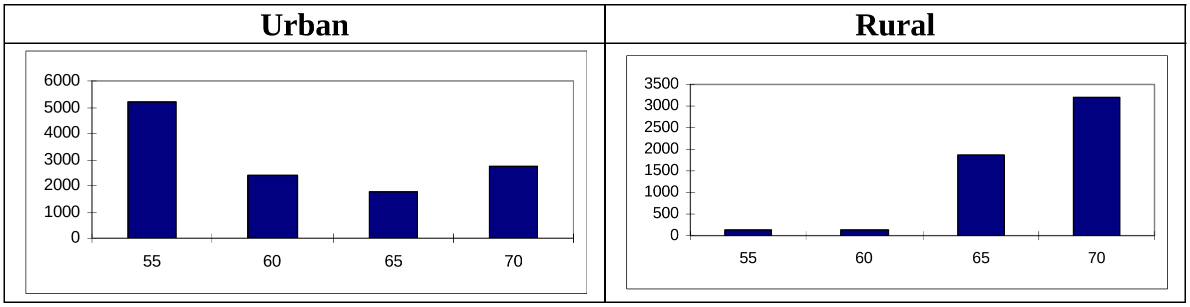


Figure 45: Distribution of single-truck crashes by speed limit

Figure 46 and Figure 47 show the distribution of single-truck crashes by left and right shoulder widths of the segment. It was observed that most single-truck crashes on urban segments occur on segments with 20 feet shoulder widths. Most single-truck crashes on rural segments occur on segments with 14 feet shoulder widths. From the figures, it was observed that there were more single-truck crashes on urban segments with more than 20 feet shoulders than on rural segments with more than 20 feet shoulders. Lesser number of rural segments with greater than 20 feet shoulders explains this difference.

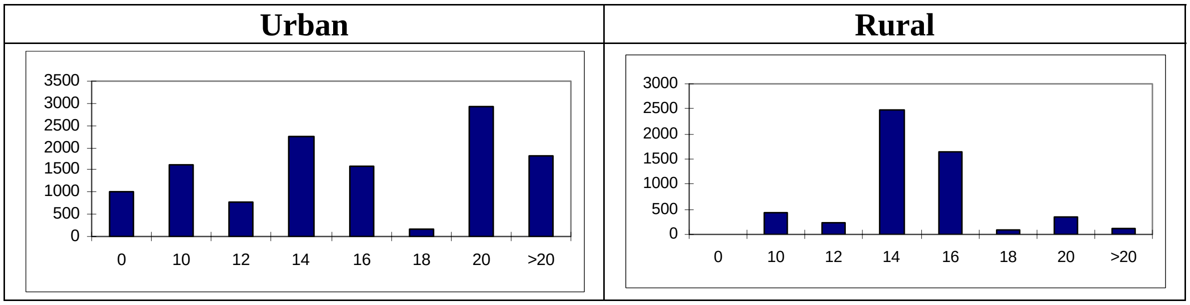


Figure 46: Distribution of single-truck crashes by left shoulder width (in feet)

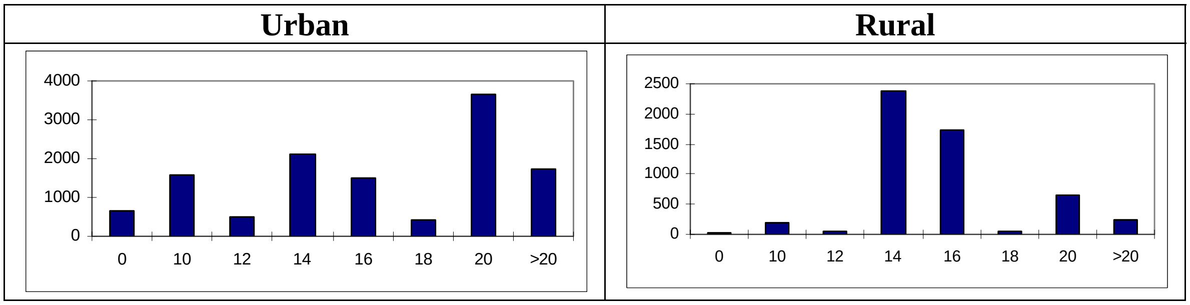


Figure 47: Distribution of single-truck crashes by right shoulder width (in feet)

Figure 48 shows the distribution of single-truck crashes by AADT. It was observed that more number of single-truck crashes occurred on urban segments with higher volumes and on rural segments with relatively lower volumes.

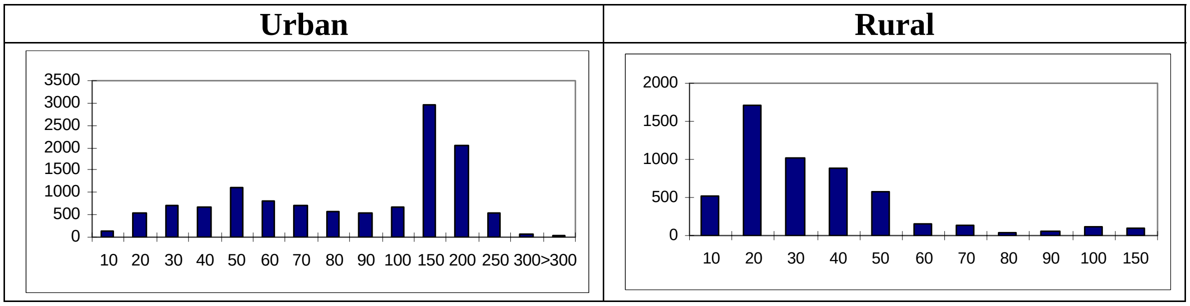


Figure 48: Distribution of single-truck crashes by AADT (1000 veh/day)

Figure 49 shows the distribution of single-truck crashes by percentage of trucks in AADT. It was observed that most single-truck crashes occur at 15 percentage of trucks in AADT on urban segments and at 30 percentage of trucks in AADT on rural segments. It was also observed that rural segments experienced more single-truck crashes at higher percentage of trucks in AADT, when compared to urban segments.

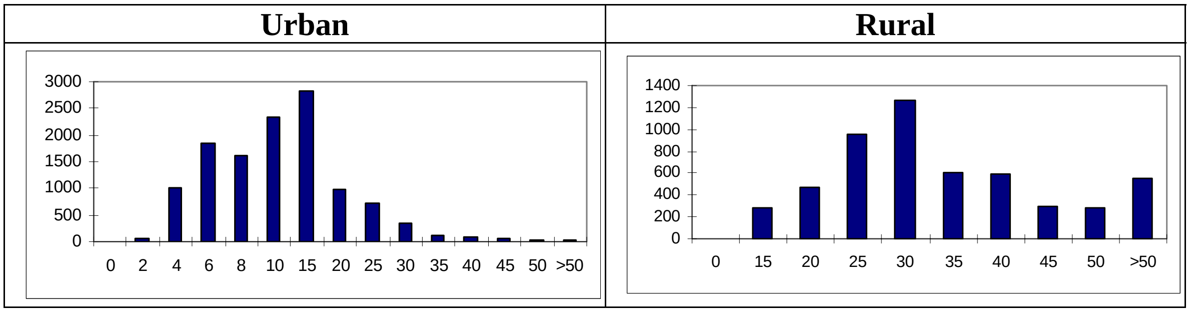


Figure 49: Distribution of single-truck crashes by percentage of trucks in AADT

3.3 Chapter summary

This chapter covered the data collection process and described various characteristics of the data. The TRM roadway database and DPS accident database were used as sources of data. These two databases were match-merged by the control-section and the beginning and ending mile point, to obtain the truck-crash database. From this database, segments with truck-related crashes, truck-only crashes and single-truck crashes were extracted for further analysis. From the exploration of the data, it was observed that most segments were three miles long and had four or six lanes with 15 to 20 feet of right and left combined shoulder widths. The speed limit is observed to vary between 55 to 70mph. Most urban segments had 55mph speed limit and most rural segments had 65mph or 70mph speed limit.

It was also observed that urban segments experienced more crashes than rural segments. Most truck crashes observed on the Texas highway network were either possible injury or PDO type of crashes. Urban segments seemed to have crashes with lower severity when compared to rural segments. Most crashes were either rear-end collision or side-swipe collision or collision with a stopped vehicle. Most crashes were observed to have occurred in dry surface conditions, in daylight and clear weather conditions.

Though this exploration of data provides clues about the characteristics of various truck crashes, it does not give any information about relationship between the crashes and various environmental, geometric and traffic variables. The next chapter documents the statistical analysis carried out to identify potential factors affecting truck crashes.

CHAPTER IV

STATISTICAL ANALYSIS

This chapter describes the results of the statistical analyses used for examining the relationship between truck crashes and geometric, traffic and environmental variables. Regression models are used to understand this relationship. The chapter is divided into two sections. The first section provides an overview on regression models and the second section deals with the development of the negative binomial regression models.

4.1 Regression models

Various statistical methods can be used to model crash frequencies on highway segments. As crashes are clearly non-negative discrete (and assumed independent) data, Poisson or negative binomial (NB) are usually the recommended model types. Past research has also indicated that crash data are characterized by overdispersion (the variance is greater than the mean), making negative binomial regression (NB) appropriate for modeling crash data (Milton and Mannering, 1998; Lord et al., 2005b).

In highway safety, NB models can be represented in the following way. The number of crashes on a segments i;Y_i, when conditional on its mean, μ_i can be assumed to be Poisson distributed and independent over all segments (Lord and Bonneson, 2007).

$$Y_{it} \mid \mu_{it} \sim Po(\mu_{\mathrm{it}}) \qquad \mathrm{i} = 1,2,\ldots\ldots, \mathrm{I} \text{ and } \mathrm{t} = 1,2\ldots,\mathrm{T} \tag{1}$$

The mean of the Poisson is structured as:

$$\mu_i = f(X;\beta)\exp(e_i) \tag{2}$$

Where, *f(.)* is the predictive model represented as a function of the variable (X);

β is a vector of unknown coefficients; and

e_i is the model error

It is assumed that exp (e_{it}) is independent and gamma distributed with a mean equal to 1 and a variance of $1/\phi$ (with $\phi>0$). With this characteristic, it can be shown that Y_i conditional on $f(.)$ and ϕ, is distributed as a negative binomial random variable with mean $f(.)$ and variance $f(.)(1+f(.)/\phi)$ respectively. $1/\phi$ is called the dispersion parameter for the NB distribution. If $\phi \rightarrow \infty$, the distribution converges to a Poisson distribution and a Poisson regression model should be used as the predictive model (Lord and Bonneson, 2007).

An important characteristic for developing statistical relationships is the choice of the functional form linking crashes with covariates. For this study, the following functional form was used –

$$\mu_i = \beta_0 L_i F_i e^{\Sigma X_i \beta_i} \tag{3}$$

Where, μ_i = the estimated number of crashes per year on segment *i*;

F_i = vehicle per day (both ways for two-way operations) (AADT) for segment *i*;

L_i = Length of segment *i* in miles;

X_i = a series of covariates; and,

$\beta_0, \beta_1, \beta_2 \ldots, \beta_n$ = regression coefficients.

For this study, the coefficients in the model were estimated using the GENMOD function in SAS. The following sections in this chapter describe the modeling results for estimating the relationship between number of truck crashes and various roadway features for the three different crash categories: truck-related crashes, truck-only crashes and single-truck crashes. During the model development phase, all variables initially considered to be important were added and based on the modeling results, inappropriate variables (i.e. non-significant at the 5% level or counterintuitive) were removed. Models that provided a combination of good statistical fit and a logical relationship between the number of crashes and the variables are discussed in the following sections.

4.1.1 Modeling results for truck-related crashes.

From the freeway mainlane crash database, truck-related crashes were extracted, as described in the previous chapter. Table 8 summarizes the negative binomial regression model output for these crashes. This table shows a comparison of model results when the AADT was used in an offset variable and when truck AADT was also used as an offset variable. Variables such as number of lanes, the functional classification of the roadway (Urban or Rural), percentage of trucks and left shoulder width were included.

From the results of model, it was observed that as the number of lanes within the segment increases, more crashes occurred on the segment. This result is in accordance with the conclusions drawn by Daniel and Chien (2004) in a recent study. Daniel and Chien, (2004) reported that the higher number of lanes provides more opportunities for sideswipe collisions caused by lane changing maneuvers. Nonetheless, since the variable was found to be not significant in both the models, it can be therefore removed from the model.

The output also suggests that urban roadway segments have more crashes compared to rural roadway segments. This result is intuitive as urban segments have higher AADT and thus have a greater likelihood of crashes. According to the output, dry surface condition is associated with lower crashes than for wet surface condition.

The modeling results (with truck AADT as offset variable) indicate a lower number of truck-related crashes at higher speeds of 70 mph and 65 mph than lower speeds of less than or equal to 60mph.This is a common observation in many similar studies (e.g., Daniel and Chien, 2004). It is also observed that fewer truck-related crashes are expected for 65mph than 70mph speed limit. The negative coefficient associated with the percentage of trucks indicates fewer crashes at higher percentage of trucks. This result should be carefully interpreted since on lower AADT segments, even a small number of trucks shows up as higher percentage of trucks. A higher percentage of trucks may bring in stability and uniformity in traffic flow, which might be the reason for lower number of crashes (Hiselius, 2004).

Table 8: Modeling result for truck-related crashes

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient Value	Standard error	P-value	Model Variables	Coefficient Value	Standard error	P-value
Intercept	0.3055	0.3383	0.3664	Intercept	-2.2639	0.4362	<.0001
Number of Lanes (β_1)				Number of Lanes (β_1)			
4 lanes	-0.6228	0.3280	0.0576	4 lanes	-0.3820	0.4249	0.3687
6 lanes	-0.5764	0.3273	0.0782	6 lanes	0.0204	0.4240	0.9616
8 lanes	-0.5011	0.3279	0.1265	8 lanes	0.1278	0.4258	0.7640
10 lanes	-0.4306	0.3365	0.2006	10 lanes	0.1816	0.4363	0.6772
12 lanes	0.0000	0.0000	.	12 lanes	0.0000	0.0000	.
Urban / Rural (β_2)				Urban / Rural (β_2)			
Rural	-0.2740	0.0448	<.0001	Rural	-1.1458	0.0495	<.0001
Urban	0.0000	0.0000	.	Urban	0.0000	0.0000	.
Surface Condition (β_3)				Surface Condition (β_3)			
Dry	-0.0648	0.0314	0.0391	Dry	-0.0143	0.0397	0.7176
Wet	0.0000	0.0000	.	Wet	0.0000	0.0000	.
Alignment (β_4)				Alignment (β_4)			
Curve	0.3136	0.0754	<.0001	Curve	0.2845	0.0947	0.0027
Straight	0.0000	0.0000	.	Straight	0.0000	0.0000	.
Speed limit (β_5)				Speed limit (β_5)			
70mph	-0.0881	0.0398	0.0268	70mph	-0.4432	0.0538	<.0001
65mph	-0.1591	0.0427	0.0002	65mph	-0.6442	0.0474	<.0001
<=60mph	0.0000	0.0000	.	<=60mph	0.0000	0.0000	.
Percentage of Trucks in AADT (β_6)	-0.0071	0.0015	<.0001	Percentage of Trucks in AADT (β_6)	-	-	-
Left Shoulder Width (β_7)	-0.0154	0.0037	<.0001	Left Shoulder Width (β_7)	-0.0214	0.0043	<.0001
Right Shoulder Width (β_8)	-0.0089	0.0041	0.0302	Right Shoulder Width (β_8)	-0.0022	0.0047	0.6440
Dispersion Parameter (α)	0.3935	0.0131		Dispersion Parameter (α)	0.6824	0.0201	
Deviance = 2624.3836 on 2515 degrees of freedom Log likelihood = 241062.7595				Deviance = 2744.1860 on 2516 degrees of freedom Log likelihood = 240398.4341			

Variables that were found not to be significant at 5% level and counterintuitive were removed to obtain the following revised models. Table 9 summarizes the modeling results for the revised models with number of lanes, surface condition and right shoulder width removed for the truck-related crashes. The table shows that all the variables are significant at 5% level. The modeling output indicates that there are more crashes in urban segments than on rural segments. The output also shows that more crashes occur on curves than on straight segments. It is also seen that fewer crashes can be expected at 70 mph and 65 mph when compared to speed limits less than or equal to 60 mph. As discussed above, this should not be interpreted as crashes would decrease when speed limit is increased. The negative coefficient of percentage of trucks indicates that there are fewer crashes at higher percentage levels. This could be a result of more uniform traffic flow at higher truck percentage, as discussed above. It is also seen that there were fewer crashes on segments with wider left shoulders.

Table 9: Revised modeling result for truck-related crashes.

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient Value	Standard error	P-value	Model Variables	Coefficient Value	Standard error	P-value
Intercept	-0.3966	0.0477	<.0001	Intercept	-2.4885	0.0553	<.0001
Urban / Rural (β_2) Rural Urban	-0.2927 0.0000	0.0444 0.0000	<.0001 .	Urban / Rural (β_2) Rural Urban	-1.3511 0.0000	0.0467 0.0000	<.0001 .
Alignment (β_4) Curve Straight	0.3025 0.0000	0.0754 0.0000	<.0001 .	Alignment (β_4) Curve Straight	0.1799 0.0000	0.0959 0.0000	0.0959 0.0000
Speed limit (β_5) 70mph 65mph <=60mph	-0.1089 -0.1821 0.0000	0.0392 0.0422 0.0000	0.0055 <.0001 .	Speed limit (β_5) 70mph 65mph <=60mph	-0.4678 -0.6950 0.0000	0.0538 0.0474 0.0000	<.0001 <.0001 .
Percentage of Trucks in AADT (β_6)	-0.0074	0.0015	<.0001	Percentage of Trucks in AADT (β_6)	-	-	-
Left Shoulder Width (β_7)	-0.0186	0.0027	<.0001	Left Shoulder Width (β_7)	-0.0164	0.0032	<.0001
Dispersion Parameter (α)	0.3973	0.0131		Dispersion Parameter (α)	0.7181	0.0208	
Deviance = 2623.0768 on 2521 degrees of freedom Log likelihood = 241053.3689				Deviance = 2732.7507 on 2522 degrees of freedom Log likelihood = 240344.0525			

From the above analysis, it is seen that there is a difference in rural and urban crashes. Table 10 shows modeling results for truck-related crashes on rural segments. The number of lanes, speed limit and shoulder widths (left and right) were removed from the initial model as they were not found to be significant at 5% level. From the model results for rural segments, fewer crashes are observed in dry surface condition and at higher percentage of trucks.

Table 10: Modeling result for truck-related crashes on rural segments

Model Variables	Coefficient Value	Standard error	P-value
Intercept	-1.1178	0.0677	<.0001
Surface Condition (β_3)			
Dry	-0.1689	0.0485	0.0005
Wet	0.0000	0.0000	.
Alignment(β_4)			
Curve	0.4929	0.1146	<.0001
Straight	0.0000	0.0000	.
Percentage of Trucks in AADT (β_6)	-0.0036	0.0017	0.0347
Dispersion Parameter (α)	0.2645	0.0182	
Deviance = 821.2554 on 839 degrees of freedom Log likelihood = 22417.0074			

4.1.2 Modeling results for truck-only crashes

From the truck-related crashes database, truck-only crashes (involving two or more trucks) were extracted. Table 11 summarizes the modeling results for truck-only crashes. The results show that the functional classification of the roadway (Urban/Rural) and the left shoulder width were the only significant variables. All the coefficients were found to have similar sign as those for truck-related crashes, except for the surface condition. It can be seen that in case of truck-only crashes, more crashes were observed in dry condition, which seems counterintuitive. This variable is not very significant and can be removed from further analysis. The number of lanes variables is also found to be not significant at 5% level and can therefore be removed from this model.

Table 11: Modeling result for truck-only crashes

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient Value	Std error	P-value	Model Variables	Coefficient Value	Std error	P-value
Intercept	-1.3126	0.4432	0.0031	Intercept	-3.9895	0.5428	<.0001
Number of Lanes (β_1)				Number of Lanes (β_1)			
4 lanes	-0.6511	0.4267	0.1271	4 lanes	-0.4279	0.5262	0.4161
6 lanes	-0.7252	0.4251	0.0880	6 lanes	-0.1854	0.5241	0.7235
8 lanes	-0.7559	0.4258	0.0759	8 lanes	-0.1200	0.5260	0.8196
10 lanes	-0.6755	0.4351	0.1205	10 lanes	-0.0746	0.5375	0.8896
12 lanes	0.0000	0.0000	.	12 lanes	0.0000	0.0000	.
Urban / Rural (β_2)				Urban / Rural (β_2)			
Urban	-0.3842	0.0819	<.0001	Urban	-1.2590	0.0862	<.0001
Rural	0.0000	0.0000	.	Rural	0.0000	0.0000	.
Surface Condition (β_3)				Surface Condition (β_3)			
Dry	0.1234	0.0555	0.0263	Dry	0.1796	0.0667	0.0071
Wet	0.0000	0.0000	.	Wet	0.0000	0.0000	.
Alignment (β_4)				Alignment (β_4)			
Curve	0.0881	0.1788	0.6220	Curve	0.3970	0.2098	0.0584
Straight	0.0000	0.0000	.	Straight	0.0000	0.0000	.
Speed limit (β_5)				Speed limit (β_5)			
70mph	-0.1782	0.0657	0.0067	70mph	-0.3983	0.0796	<.0001
65mph	-0.1334	0.0608	0.0281	65mph	-0.6678	0.0686	<.0001
<=60mph	0.0000	0.0000	.	<=60mph	0.0000	0.0000	.
Percentage of Trucks in AADT (β_6)	-0.0213	0.0036	<.0001	Percentage of Trucks in AADT (β_6)	-	-	-
Left Shoulder Width (β_7)	-0.0177	0.0048	0.0002	Left Shoulder Width (β_7)	-0.0206	0.0054	0.0001
Right Shoulder Width (β_8)	-0.0073	0.0054	0.1770	Right Shoulder Width (β_8)	-0.0048	0.0061	0.4375
Dispersion Parameter (α)	0.4138	0.0219		Dispersion Parameter (α)	0.7098	0.0310	
Deviance = 1487.4610 on 1501 degrees of freedom Log likelihood = 16313.6627				Deviance = 1569.9024 on 1502 degrees of freedom Log likelihood = 15996.2183			

Table 12 summarizes the revised modeling results for truck-only crashes. All variables not significant at 5% level, (except speed limit) were removed from the previous model. Speed limit was left in the model, because it is believed to be an important factor for truck-only crashes. The model suggests that rural roadways experience fewer crashes when compared to urban. Also, fewer single-truck crashes were observed on dry roadways when compared to wet surfaces, which seems logical. It is also seen that segments with curves experience more crashes than straight segments. The output also indicates that a smaller number of crashes was observed with higher percentage of trucks and wider left shoulder widths. Association of speed limit with number of crashes seems to change between using the two models.

Similar model was developed to understand rural crashes. Table 13 summarizes the model results for truck-only crashes on rural segments. From the model results, only percentage of trucks in AADT was found to be significant at 5% level of significance and fewer crashes were observed at higher truck percentage in AADT.

Table 12: Revised modeling results for truck-only crashes

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient value	Standard Error	P-value	Model Variables	Coefficient value	Standard Error	P-value
Intercept	-2.0742	0.085	<.0001	Intercept	-4.3253	0.0925	<.0001
Urban/Rural (β_2)				Urban/Rural			
Rural	-0.3714	0.0808	<.0001	Rural	-1.3964	0.0817	<.0001
Urban	0.0000	0.0000	.	Urban	0.0000	0.0000	.
Surface condition (β_3)				Surface condition			
Dry	0.1205	0.0557	0.0305	Dry	0.1917	0.0669	0.0042
Wet	0.0000	0.0000	.	Wet	0.0000	0.0000	.
Alignment(β_4)				Alignment			
Curve	0.0865	0.1794	0.6299	Curve	0.3815	0.2103	0.0696
Straight	0.0000	0.0000	.	Straight	0.0000	0.0000	.
Speed Limit(β_5)				Speed Limit			
70mph	-0.1344	0.0601	0.0254	70mph	-0.7063	0.0678	<.0001
65mph	-0.1868	0.0647	0.0039	65mph	-0.4245	0.0784	<.0001
<=60mph	0.0000	0.0000	.	<=60mph	0.0000	0.0000	.
Percentage of trucks in AADT (β_6)	-0.0193	0.0035	<.0001	Percentage of trucks in AADT	-	-	-
Left shoulder width(β_7)	-0.0224	0.0036	<.0001	Left shoulder width	-0.0197	0.0043	<.0001
Dispersion Parameter(α)	0.415	0.0219		Dispersion Parameter	0.73	0.0313	
Deviance = 1492.7713 on 1506 degrees of freedom Log likelihood = 16309.7149				Deviance = 1559.0848 on 1507 degrees of freedom Log likelihood = 15985.5178			

Table 13: Modeling results for truck-only crashes on rural segments

Model with AADT in offset variable			
Intercept	-3.1856	0.8062	<.0001
Number of lanes			
4	0.2614	0.716	0.715
6	-0.1307	0.7427	0.8603
10	0.0000	0.0000	.
P_TRKADT	-0.0257	0.0077	0.0008
Surface Condition			
Dry	-0.1365	0.1201	0.2559
Wet	0.0000	0.0000	.
Alignment			
Curve	1.5112	1.1433	0.1862
Straight	0.0000	0.0000	.
Speed Limit			
65mph	0.1243	0.2199	0.5719
70mph	0.0016	0.224	0.9945
<=60mph	0	0	.
Left shoulder width	-0.0316	0.0188	0.0932
Right shoulder width	0.0476	0.0201	0.018
Dispersion parameter	0.2989	0.0491	
Deviance = 250.8482 on 283 degrees of freedom Log likelihood = 546.8971			

4.1.3 Modeling results for single-truck crashes

Table 14 summarizes the modeling results for single truck crashes. From the model output, surface condition, alignment, percentage of trucks and right shoulder width seem to be the significant variables. It was also seen that the number of crashes was larger for segments with higher speed limit. This outcome is expected since, at higher speeds, single vehicles are at a greater risk of running off the road and this risk is bigger on wet surface and on curves (as shown in the model output in Table 14).

Table 14: Modeling results for single truck crashes

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient value	Standard Error	P-value	Model Variables	Coefficient value	Standard Error	P-value
Intercept	-2.1013	0.4315	<.0001	Intercept	-4.2009	0.5105	<.0001
Number of Lanes				Number of Lanes			
4 lanes	0.2184	0.4223	0.6051	4 lanes	0.1812	0.5012	0.7178
6 lanes	-0.0911	0.4215	0.8289	6 lanes	0.1858	0.5003	0.7103
8 lanes	-0.2513	0.4217	0.5512	8 lanes	0.0338	0.5009	0.9462
10 lanes	-0.2421	0.429	0.5726	10 lanes	0.0188	0.5091	0.9705
12 lanes	0.0000	0.0000	.	12 lanes	0.0000	0.0000	.
Urban/Rural				Urban/Rural			
Rural	-0.0311	0.0467	0.5048	Rural	-0.6179	0.0468	<.0001
Urban	0.0000	0.0000	.	Urban	0.0000	0.0000	.
Surface Condition				Surface Condition			
Dry	-0.2321	0.031	<.0001	Dry	-0.2304	0.0357	<.0001
Wet	0.0000	0.0000	.	Wet	0.0000	0.0000	.
Alignment				Alignment			
Curve	0.4227	0.0602	<.0001	Curve	0.4978	0.0696	<.0001
Straight	0.0000	0.0000	.	Straight	0.0000	0.0000	.
Speed Limit				Speed Limit			
70mph	0.1017	0.0424	0.0165	70mph	-0.2317	0.0466	<.0001
65mph	-0.0212	0.0451	0.6384	65mph	-0.2747	0.0516	<.0001
<=60mph	0.0000	0.0000	.	<=60mph	0.0000	0.0000	.
Percentage of trucks	0.0099	0.0016	<.0001	Percentage of trucks	-	-	-
Left shoulder width	0.0062	0.004	0.119	Left shoulder width	-0.0003	0.0044	0.9429
Right shoulder width	-0.017	0.0044	0.0001	Right shoulder width	-0.0148	0.0048	0.0022
Dispersion parameter	0.2866	0.0133		Dispersion	0.4284	0.0173	
Deviance = 2361.0900 on 2321 degrees of freedom Log likelihood = 23954.2121				Deviance = 2469.8176 on 2322 degrees of freedom Log likelihood = 23601.1090			

Table 15 summarizes modeling results for revised single-truck crash models. Most coefficients estimated in this model are similar to the previous models. From the modeling results, it is evident that presence of curves, higher number of trucks and greater speeds lead to more single-truck crashes.

Table 15: Revised modeling results for single-truck crashes

Model with AADT in offset variable				Model with truck AADT in offset variable			
Model Variables	Coefficient value	Standard Error	P-value	Model Variables	Coefficient value	Standard Error	P-value
Intercept	-1.9987	0.0633	<.0001	Intercept	-4.026	0.0657	<.0001
Urban/rural				Urban/rural			
Rural	0.0382	0.0466	0.4124	Rural	-0.6	0.044	<.0001
Urban	0.0000	0.0000	.	Urban	0.0000	0.0000	.
Surface condition				Surface condition			
Dry	-0.2202	0.0316	<.0001	Dry	-0.2336	0.0356	<.0001
Wet	0.0000	0.0000	.	Wet	0.0000	0.0000	.
Alignment				Alignment			
Curve	0.4514	0.0615	<.0001	Curve	0.5045	0.0695	<.0001
Straight	0.0000	0.0000	.	Straight	0.0000	0.0000	.
Speed Limit				Speed Limit			
70mph	0.0482	0.0454	0.288	70mph	-0.2125	0.0509	
65mph	0.165	0.0426	0.0001	65mph	-0.254	0.0455	<.0001
<=60mph	0.0000	0.0000	.	<=60mph	0.0000	0.0000	<.0001
Percentage of trucks in AADT	0.0131	0.0016	<.0001	Percentage of trucks in AADT	-	-	-
Right shoulder width	-0.0208	0.0033	<.0001	Right shoulder width	-0.017	0.0036	<.0001
Dispersion parameter	0.3013	0.0138		Dispersion parameter	0.4284	0.0173	
Deviance = 2393.4258 on 2326 degrees of freedom Log likelihood = 23903.3947				Deviance = 2478.1653 on 2327 degrees of freedom Log likelihood = 23596.9322			

Similar to the previous sections, a model was estimated for single-truck crashes on rural segments. Table 16 summarizes the model results for single truck crashes in rural segments. As can be seen from the results, only the right shoulder width is found to be significant.

Table 16: Modeling results for single-truck crashes on rural segments

Model with AADT in offset variable			
Model Variables	Coefficient value	Standard Error	P-value
Intercept	-2.6294	0.7362	0.0004
Number of lanes			
4 lanes	0.8454	0.7114	0.2347
6 lanes	0.5535	0.7216	0.443
10 lanes	0	0	.
Percentage of trucks	0.01	0.002	<.0001
Surface condition			
Dry	-0.2064	0.0536	0.0001
Wet	0	0	.
Alignment			
Curve	0.5677	0.1168	<.0001
Straight	0	0	.
Speed Limit			
65mph	-0.0193	0.1357	0.8867
70mph	0.0585	0.1348	0.6642
<=60mph	0	0	.
Left shoulder width	-0.0019	0.0109	0.8598
Right shoulder width	-0.0184	0.0102	0.0721
Dispersion parameter	0.239	0.0208	
Deviance = 772.9348 on 769 degrees of freedom Log likelihood = 6657.7069			

4.2 Chapter summary

From the statistical analyses performed on the collected data, it can be concluded that negative binomial modeling was helpful in finding relationships between crash frequencies and various geometric, traffic and environmental factors. From the regression modeling results, percentage of trucks, classification of the roadway (Rural/Urban), posted speed limit, surface condition, alignment, left and right shoulder widths seem to be the significant factors affecting crash rates. For truck-related and truck-only crashes, it was seen that crashes decrease with increase in percentage trucks, left shoulder width and at higher speed limits for some truck-related crash types.

CHAPTER V

SAFETY PERFORMANCE OF EXCLUSIVE TRUCK FACILITIES

This chapter describes how the results of this research could be used for estimating the safety performance of exclusive truck facilities. The first section in this chapter discusses the factors observed to influence truck crashes. The second section describes an attempt to quantify the safety performance of an exclusive truck facility by modifying the models developed in Chapter IV. The third section provides recommendations for designing exclusive truck facilities based on safety.

5.1 Factors affecting truck safety

The literature suggests that highway geometrics, environmental conditions and driver characteristics have a strong influence on the number of crashes on any roadway segment.

In a study on affect of traffic conditions on truck crashes, Golob and Regan (2004) concluded that most truck-involved crashes involve one of the first two vehicles changing lanes or merging. They also concluded that truck involvement in run-off the road or overturn crashes was independent of percentage of trucks in AADT (which is different than the results found in this thesis), while rear-end and weaving crashes were proportional to the percentage of trucks. Lord and Middleton (2005a) suggested that significant (truck) blind spot and highway geometric elements (such as steep grades) which negatively affect the vehicle performance of trucks may be the reason for larger number of truck-related crashes in a mixed traffic situation.

Miaou and Lum (1993) reported that truck crash rate increases with increase in AADT per lane, horizontal curvature, length of horizontal curve, vertical grade and length of vertical grade. The models produced by these authors also indicated that truck crash rate decreased with a wider inside shoulder width per direction and percentage of trucks for a given density. Results from the negative binomial models developed by Milton and Mannering (1998) also indicate the same relationship. These authors also concluded that higher posted speed limits, narrow lanes (less than 3.5m wide), smaller tangent length and higher peak hour percentages are associated with lower crash frequency. Whereas, more number of lanes, narrow left and right shoulder (less than

1.5m), smaller central horizontal curve angle were observed to be associated with a higher crash frequency.

Negative binomial models developed in this study indicated similar results. Various geometric, traffic and environmental features were found to have different influence on different truck crash type. Roadway class (Urban/Rural), presence of curves, speed limit, percentage of trucks, left shoulder width, right shoulder width and surface conditions were associated with truck crashes. Most of the coefficients estimated were consistent in all the models and were in agreement with results from similar studies in literature.

Most multi-vehicle crashes were observed to be rear-end or side-swipe collisions. It was also observed that curved segments, urban segments, narrow left shoulder width segments and segments with lower speed limits experience more truck-related crashes than others (below 60 mph).

In case of single-truck crashes, overturn vehicles were the most common first harmful events. From the modeling results, it was observed that right shoulder width had a greater impact on truck safety than left shoulder width. This is not surprising since truck drivers tends to use the right lane more often than the middle or left lanes on freeways. Single-truck crashes were observed to decrease with increase in right shoulder width. More single-truck crashes per year were observed for higher percentage of trucks in AADT (in contrast to multi-vehicle truck crashes), presence of curves and higher speed limit.

5.2 Quantifying safety of exclusive truck facilities

To illustrate how the models developed in this study could be used to estimate the number of truck-crashes per year, two hypothetical scenarios were considered. In the first scenario, truck-only and single-truck models (with truck AADT) were applied to the same segment, but for different speed limits. From the previous chapter, the number of crashes per year for different truck-crash situations was estimated as –

Truck-only crashes per year,

$$\mu_{to} = L_i F_i e^{\sum \beta 0 + \text{Class}\beta 2 + \text{surface condition } \beta 3 + \text{Alignment } \beta 4 + \text{ Speed limit}\beta 5 + \text{left shoulder}\beta 7}$$

Single-truck crashes per year,

$$\mu_{st} = L_i F_i e^{\sum \beta 0+\text{Class}\beta 2+\text{surface condition }\beta 3+\text{Alignment }\beta 4+\text{ Speed limit}\beta 5+\text{right shoulder}\beta 8}$$

Only segments with truck crashes were used to develop these models and hence, they should not be used to directly predict the safety performance of a highway facility.

Table 22: Summary of regression coefficients for scenarios 1 and 2.

	Truck-Only Crashes per year	Single-Truck Crashes per year
Model Variables	Coefficient value	Coefficient value
Intercept	-4.3253	-4.026
Urban/Rural (β_2)		
Rural (1)	-1.3964	-0.6
Urban (0)	0.0000	0.0000
Surface condition (β_3)		
Dry (1)	0.1917	-0.2336
Wet (0)	0.0000	0.0000
Alignment(β_4)		
Curve (1)	0.3815	0.5045
Straight (0)	0.0000	0.0000
Speed Limit(β_5)		
70mph (1)	-0.7063	-0.2125
65mph (1)	-0.4245	-0.254
<=60mph (0)	0.0000	0.0000
Left shoulder width(β_7)	-0.0197	-
Right shoulder width(β_8)	-	-0.017

5.2.1 Scenario 1

The segment considered is a straight, level 1.0 mile long 4-lane rural freeway with 10 feet left and 12 feet right shoulders and average annual daily truck traffic (AADTT) of 3000 with dry surface under normal conditions.

Using the functional form discussed above and the estimated coefficients in the previous chapter, truck-only and single-truck crashes per year for this scenario were estimated. About 1 truck-only crashes per year and 3 single-truck crashes per year were estimated for scenario 1 with 70 mph speed limit. For 65 mph speed limit, about 1 truck-only crashes per year and 3 single-truck crashes per year were estimated. For 60 mph speed limit, 2 truck-only and 4 single-truck crashes per year were estimated.

5.2.2 Scenario 2

A 1.0 mile long 4-lane rural segment with a curve and 3000 average annual daily truck traffic is considered. The segment has 10 feet left and 12 feet right shoulder and has wet surface under normal conditions.

Using the functional form discussed above and the estimated coefficients in the previous chapter, truck-only and single-truck crashes per year for this scenario were estimated. About a single truck-only crash per year and 7 single-truck crashes per year were estimated for scenario 2 with 70 mph speed limit. For 65 mph speed limit, about 2 truck-only crashes per year and 6 single-truck crashes per year were estimated. For 60 mph speed limit, about 3 truck-only and 8 single-truck crashes per year were estimated.

5.2.3 Discussion

Although the negative binomial models were found to have desirable distributional properties to represent the crash-geometric design relationship, these models also have some limitations (Miaou, 1994). The models developed in this study had proper algebraic signs and consistent estimated parameters. As zero crash segments were not considered in this study, the estimated crashes are multiplied by a factor to account for the difference In the scenarios discussed above, the estimated truck-only and single-truck crashes per year seem to follow intuition.

Table 23: Summary of estimated number of crashes per year for Scenarios 1 and 2

	Scenario 1		Scenario 2	
	Truck Only	Single Truck	Truck Only	Single Truck
70mph	0.25	1.30	0.30	2.73
65mph	0.33	1.25	0.39	2.62
60mph	0.50	1.61	0.60	3.37

Coefficients from Table 22 were used in the above mentioned equations to estimate the number of truck-only and single-truck crashes per year for these scenarios. Scenario 1 represents a straight segment with normal dry surface conditions. Scenario 2 represents a curved segment with wet surface under normal condition. Table 23 shows a summary of estimated truck crashes per year for both the scenarios.

Scenario 1 is estimated to have fewer truck-only crashes and single-truck crashes than scenario 2. The presence of curves and wet surface conditions in scenario 2 could explain this difference. At a higher speed of 70mph, the segments were estimated to have fewer truck-only crashes and more single-truck crashes than at a lower speed limits of 65 mph and less than or equal to 60 mph. The higher flow stability with higher speed might be the reason for lower truck-only crashes at higher speed limit. Trucks traveling at lower speeds on curves are less likely to run-off-the-road. Recall that most single-truck crashes were found to be either classified as overturned or as a collision with a fixed object.

The models developed in this study provided a good indication of how change in geometric design elements affects exclusive truck facilities' safety. However, they should not be used directly for estimating the safety performance of exclusive truck lanes, since they were estimated with data from collected for mixed-traffic conditions. The purpose of these comparisons is to give us a general idea about the magnitude of what may be expected in terms of truck crashes. The models might not give the exact and actual number of truck-crashes for given geometric conditions, but the relationship between geometric elements and crashes gives us general trends in truck crashes. To properly estimate the safety performance of exclusive truck-only facilities, one would have to estimate the models using data on such facilities. However, no facilities have been built yet.

5.3 Recommendations

Key controls in geometric design of highways are the physical characteristics of the design vehicles. In designing truck-only facilities, the appropriate truck type needs to be selected as the design vehicle to represent the weight, dimension and operational characteristics of the vehicles using the facility. Intuitively, trucks need more generous geometric design than passenger cars. As discussed by Harwood et al. (2003), exhibit 2-1 in the NCHRP report 505 should be used for the dimensions of the selected design vehicle.

From the literature and the regression analyses carried out in this thesis, most multi-vehicle crashes involved in rear-end or side-swipe collisions (often located at merging, weaving and speed change lanes). On the other hand, most single-vehicle crashes involved overturning vehicles or a vehicle hitting a fixed object, after the vehicle runs off the road. This indicates that most multi-vehicle crashes were either caused by lane changing maneuvers or speed differentials between vehicles. In designing the horizontal alignment and cross section, minimum centerline turning radius, the out-to-out track width, the wheelbase, and the path of the inner rear tire of the design vehicle are of high importance (Harwood et al., 2003). These characteristics vary drastically between passenger cars and trucks, trucks have longer wheelbases and greater minimum turning radii. The modifications suggested by Harwood et al. (2003) are reflected in exhibit 2-2 of NCHRP report 505 and can be used to determine the minimum turning radii for the selected design vehicle. Although, the minimum turning radii and transition lengths shown in these exhibits were for turns at less than 15 mph (10mph), longer transition curves and curve radii will be needed for roadways with higher speeds.

The model results also suggest exclusive truck facilities to have higher speeds, with higher level of design standards. Uniform and level grades help in achieving uniform truck traffic flow. The modeling results show that wider left shoulders result in fewer multi-vehicle crashes, while wider right shoulders result in fewer single truck crashes. Hence, it is suggested to provide wide shoulders for exclusive truck facilities to allow safe emergency stopping.

Trucks have different physical and operational features when compared to passenger cars; one of them being a large blind spot. Weaving areas need to be designed based on the size of the truck, braking ability and maneuverability. Most multi-vehicle collisions are side-swipe collisions attributed to unsafe lane change maneuvers. These characteristics also need to be applied while designing intersections for truck-only facilities. Also, due to the difference in their weight, trucks have a direct impact on the pavement design. Pavements for exclusive truck facilities should be designed according to the stresses developed due to the higher weight of trucks and the overlay should be designed to account for the greater wear-and-tear.

Ramp design plays a major part in designing exclusive truck facilities. It is not only important to design the main lanes of truck roadway for safety, but it is also important to have safe entry and exit points to and from the main lanes. Adequate acceleration and deceleration lanes based on speed, truck size and braking ability are to be provided for safe entry and exit into and out of the exclusive truck facility.

Proper signing, sight distance requirements and grades help in ensuring safety of the roadway. Sign post height, font size and lateral distance from the pavement also need to be evaluated for truck's physical characteristics that effect the driver's eye height, braking ability and sight distance.

5.4 Chapter summary

Observations from the literature and regression analyses indicate that various geometric, traffic and environmental features have different levels of association with truck crashes. Roadway location (Urban/Rural), presence of curves, speed limit, percentage of trucks, left shoulder width, right shoulder width and surface conditions seem to have strong influence on truck crashes. The coefficients estimated are consistent with previous models documented in the literature. Evaluating the models for hypothetical segments shows that they represent the truck crash-geometric element relationship, but not necessarily estimate the actual or real number of truck crashes. This difference is due the fact that the models were not developed using data collected at exclusive truck facilities (since none exist). However, the models give some information about the relative magnitude of one would expect in terms of truck crashes.

CHAPTER VI

SUMMARY AND FUTURE WORK

The main objective of this study was to examine potential factors affecting the safety performance and design of exclusive truck facilities. The literature review and the regression analyses have provided some insights about what may affect the safety performance of exclusive truck facilities.

Reich et al. (2003) associate a high construction cost to exclusive truck facilities, which translates to more effective evaluation measures before investing in these facilities. Poole et al. (2004) suggests at-least one lane in each direction with a passing lane every few miles. This lane could also help in traffic management at the time of a crash.

The first two sections of this chapter summarize the key observations from the literature review and the modeling results obtained from the statistical analyses. The third section discusses recommendations suggested for designing truck-only facilities based on the results of this thesis and the literature. The fourth section presents research ideas for future work.

6.1 Summary of the study

Many state agencies are currently considering exclusive truck lane facilities (or truck-traveled-ways) as a treatment for reducing congestion and truck crashes on existing highways. As no such facilities currently exist in the United States, there are no safety evaluation tools and design guidelines that could help designers building this kind of facilties. Examining factors that could impact the safety performance of exclusive truck facilities will help in the decision-making process of such projects.

From literature review (Chapter II) it can be concluded that there have been numerous studies that have tried to characterize the effects of truck traffic along with various other traffic operations, roadway and environmental factors on crash rates. Most studies used exploratory analyses, statistical methods or simulation to establish this relationship. From the available literature, it is seen that most studies produced contradictory results. Many studies have also been conducted to establish appropriate alternatives for increasing truck traffic. It can be concluded that each of these treatments needs to accommodate the physical and operational characteristics of trucks.

Recommendations available for including trucks in the design process include changes in design vehicle dimension and characteristics like minimum turning radii. Incorporating these changes in the design process implies a higher construction cost. This makes it more important to understand the relationship between geometric characteristics and truck crashes and evaluate the safety impact of truck-only lanes to justify the investment.

To examine the relationship between truck crashes and geometric, traffic and environmental factors, data were collected to perform statistical analyses. Chapter III covered the data collection process and described various characteristics of the data. The TRM roadway database and DPS accident database were used as data sources. These two databases were match-merged by control section and begin and end mile point, to obtain the truck-crash database. From this database, segments with at-least one truck involved a crash, truck-only crashes and single-truck crashes were extracted for further analysis. From the exploration of the data, it was observed that most segments were less than 1 mile long and had four lanes with 14 ft right and left shoulder width. The speed limit in these segments was observed to vary between 55 to 70mph. Most crashes observed on these segments were found to be either PDO or Injury Type C (possible injury) crashes, with most collisions being either rear-end or side-swipe or with a stopped vehicle. Most crashes were observed to occur in dry surface conditions in daylight and clear weather. It was also seen that urban segments had more crashes than rural segments. Urban crashes seemed to be more frequent and severe when compared to crashes in rural segments, since multi-vehicle crashes involving a truck are usually more severe (for the occupants of the passenger cars).

Chapter IV described the statistical analyses framework and results obtained in this thesis. Negative binomial regression models were used to establish a relationship between crashes and traffic, geometric and environmental variables. Models were developed with various traffic, geometric and environmental variables such as number of lanes, AADT, percentage of trucks, surface condition, weather, left shoulder width and speed limit were included in the initial analysis. Variables that were not found to be significant at the 5% confidence level were removed from the model for further analysis. Separate models were created for truck-related, truck-only and single-truck crashes. Results from the regression analysis suggest that the percentage of trucks, functional classification of the roadway (Rural/Urban), posted speed limit, surface condition, alignment and left shoulder width seem to influence truck crash rates. For truck-related and truck-only crashes, crashes seem to decrease with increase in percentage trucks, left shoulder width and higher speed limits. Single-truck crashes seem to increase with an increase in speed limit, percentage of trucks and presence of curves.

Chapter V documented the application of the models for quantifying the safety of an exclusive truck facility. Two hypothetical segments were considered with two speed limits. Truck-only and single-truck crashes were estimated to increase with presence of curves and wet surface conditions. It was also observed that truck-only crashes decreased with increase in speed limit and left shoulder width. Single-truck crashes were observed to increase with increase in speed limit and decrease in right shoulder widths.

6.2 Summary of statistical analyses

Highway geometric features interact with traffic and environmental factors that can contribute to a crash. Results obtained from the statistical modeling process indicated various geometric, traffic and environmental features influence truck crashes. The coefficients estimated are consistent in all the models and are in agreement with results from similar studies in literature. From the regression model results, it can be concluded that functional classification of the roadway, presence of curves, speed limit, percentage of trucks in AADT, left shoulder width and surface condition seem to have strong influence on truck crashes.

The results show that there is a decrease in truck crashes at higher percentage of trucks. The percentage of trucks was included in the model to characterize the effects of car-truck mix. It was observed that there is a decrease in crashes as the percentage of trucks increases for truck-related and truck-only crashes; this was also observed by (Hiselius, 2004). This may be attributed to the decrease in lane changes maneuvers by drivers of passenger cars when the number of trucks increases. The fact that more trucks are involved in truck-car crashes than truck-only crashes also explains this decrease. For single-truck crashes, the number of crashes was observed to increase with increase in percentage of trucks.

It was observed from the modeling results that segments with higher posted speed limit have fewer truck-related and truck-only crashes. This is in accordance with the general assumption that highways with greater posted speed limit have higher level of design features; a combination of elements that make them safer. However, this result cannot be interpreted as increasing the speed limit will decrease accident frequency. For single-truck crashes, more crashes were observed at higher speeds and on segments with horizontal curves. This is intuitive as trucks tend to have a greater likelihood to run-off-the-road on curves at higher speeds.

From the estimated coefficient for alignment, it is concluded that more crashes occur in a segment with a horizontal curve than a straight segment. Due to their physical characteristics, heavy weight vehicles may have difficulty negotiating horizontal curves that may not be properly designed for the conditions; this does not mean that the curve is designed below existing guidelines. From the regression modeling results, percentage of trucks, functional classification of the roadway (Rural/Urban), posted speed limit, surface condition, alignment and left shoulder width seem to be the significant factors effecting crash rates. For truck-related and truck-only crashes, it was observed that crashes decrease with increase in percentage trucks, shoulder widths and at higher speed limits..

6.3 Summary of recommendations for geometric design

Key controls in geometric design of highways are the physical characteristics of the design vehicles. In designing truck-only facilities, the appropriate truck type needs to be selected as the design vehicle to represent the weight, dimension and operational characteristics of the vehicles using the facility. Intuitively, trucks need more generous geometric design than passenger cars. As discussed by Harwood et al. (2003), exhibit 2-1 in the NCHRP report 505 should be used for the dimensions of the selected design vehicle.

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Proper signing, sight distance requirements and grades help in ensuring safety of the roadway. Sign post height, font size and lateral distance from the pavement also need to be evaluated for truck's physical characteristics that effect the driver's eye height, braking ability and sight distance.

6.4 Future work

To better understand the relationship between truck crashes and geometric, traffic and environmental features, it is recommended to have a more extensive and detailed database. Modeling crashes by type of truck could help for better estimating the effects of various variables on truck crashes. More extensive data with degree of curves, super elevation and vertical alignment details would be helpful in estimating coefficients for these models. Data from other states agencies could be used for a better comparison as suggested in TRB special report 228 (Harwood et al.,2003). Building a national monitoring system will help improve uniformity in the truck accident and travel data between states. This need is more prominent in the crash database used for rural segments. Simulation studies could also be used to support the factors identified in this research. All these new models with more detailed data would offer enhanced tools for estimating the safety performance of exclusive truck facilities.

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