2011

Modeling Truck Speed in the Upstream of One-lane Two-way Highway Work Zones: Implications on Reducing Truck-Related Crashes in Work Zones

Yeu Li
University of Kansas

Yong Bai Ph.D., P.E.
University of Kansas

Steven D. Schrock
University of Kansas, schrock@ku.edu

Thomas E. Mulinazzi
University of Kansas

MID-AMERICA TRANSPORTATION CENTER

Report # MATC-KU: 362

Final Report

University of Nebraska-Lincoln

K-State Kansas State University

KU The University of Kansas

Missouri S&T University of Science & Technology

The University of Iowa

Lincoln University

Prairie View A&M University 1876

Modeling Truck Speed in the Upstream of One-lane Two-way Highway Work Zones: Implications on Reducing Truck-Related Crashes in Work Zones

Yue Li, Ph.D.
Graduate Research Assistant
Department of Civil, Environmental and Architectural Engineering

Yong Bai, Ph.D., P.E.
Steven D. Schrock, Ph.D., P.E.
Thomas E. Mulinazzi, Ph.D., P.E., L.S.

KU The University of Kansas

2011

A Cooperative Research Project sponsored by the U.S. Department of Transportation Research and Innovative Technology Administration

MATC

Modeling Truck Speed in the Upstream of One-lane Two-way Highway Work Zones: Implications on Reducing Truck-Related Crashes in Work Zones

Yue Li, Ph.D.
Graduate Research Assistant
Department of Civil, Environmental and Architectural Engineering
University of Kansas

Yong Bai, Ph.D., P.E.
Associate Professor
Department of Civil, Environmental and Architectural Engineering
University of Kansas

Steven D. Schrock, Ph.D., P.E.
Assistant Professor
Department of Civil, Environmental and Architectural Engineering
University of Kansas

Thomas E. Mulinazzi, Ph.D., P.E., L.S.
Professor
Department of Civil, Environmental and Architectural Engineering
University of Kansas

A Report on Research Sponsored By

United States Department of Transportation

Research and Innovative Technology Administration

July 2011

Technical Report Documentation Page

1. Report No. 25-1121-0001-362	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Modeling Truck Speed in the Upstream of One-lane Two-way Highway Work Zones: Implications on Reducing Truck-Related Crashes in Work Zones		5. Report Date July 2011 6. Performing Organization Code
7. Author(s) Yue Li, Yong Bai, Steven D. Schrock, and Thomas E. Mulinazzi.		8. Performing Organization Report No. **25-1121-0001-362**
9. Performing Organization Name and Address Mid-America Transportation Center 2200 Vine St. Lincoln, NE 68583-0851		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Research and Innovative Technology Administration 1200 New Jersey Ave. SE Washington, DC 20590		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code MATC TRB RiP No. 24486
15. Supplementary Notes		

16. Abstract

Truck-related crashes constitute a major safety concern for government agencies, the construction industry, and the traveling public. Due to the rising needs in highway maintenance and construction, the number of work zones is increasing throughout the United States, while at the same time freight movement using trucks is also increasing nationwide. Developing effective safety countermeasures to reduce the truck-related crashes is a major challenge in front of the government agencies and the construction industry. The main objectives of this research project are to discover truck-related crash characteristics and to model the truck speeds in the upstream of one-lane two-way rural highway work zones. Work zones on two-lane highway are particularly hazardous for trucks due to the disruption of regular traffic flow and restrictive geometry. The developed models can be utilized to discover possible associations between work zone design variables and truck speeds with the purpose of reducing truck-related crash risks. As a result, government agencies and the construction industry can apply the findings of this project to improve work zone design and mitigate the crash risks in work zones.

17. Key Words Truck, Crash, Highway, Work Zone, Speed, Model		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 75	22. Price

Table of Contents

List of Figures

List of Tables

Abstract

Truck-related crashes constitute a major safety concern for government agencies, the construction industry, and the traveling public. Due to the rising needs in highway maintenance and construction, the number of work zones is increasing throughout the United States, while at the same time freight movement using trucks is also increasing nationwide. Developing effective safety countermeasures to reduce the truck-related crashes is a major challenge in front of the government agencies and the construction industry. The main objectives of this research project are to discover truck-related crash characteristics and to model the truck speeds in the upstream of one-lane two-way rural highway work zones. Work zones on two-lane highways are particularly hazardous for trucks due to the disruption of regular traffic flow and restrictive geometry. The developed models can be utilized to discover possible associations between work zone design variables and truck speeds with the purpose of reducing truck-related crash risks. As a result, government agencies and the construction industry can apply the findings of this project to improve work zone design and mitigate the crash risks in the work zones.

Chapter 1 Introduction

1.1 Background

Work zone safety has become more challenging because of increasing travel demand and the aging roadway system. Nationwide, there are more maintenance and rehabilitation projects on the highway system than ever. At the same time, the system is needed in order to continuously transport people and goods safely. Many efforts have been devoted to improve work zone traffic safety and mobility over the years.

At the national level, emphasis on work zone safety has increased through legislation. The Intermodal Surface Transportation Efficiency Act (ISTEA) emphasizes work zone safety in Sections 1051 and 2002 (FHWA 1991). The National Transportation Safety Board (NTSB) issued a report on June 3, 1992, which included two recommendations concerning the reporting of work zone crashes (NTSB 1992). The recent Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) included a number of provisions emphasizing highway work zone safety and other work zone-related issues (FHWA 2005). The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have played leading roles on this subject and have developed practical highway work zone safety guides and programs. In addition to the legislative emphasis on work zone safety, a myriad of studies have been published to reveal the safety problems in work zones and to propose measurements for improvements.

Truck related crashes contribute to a significant percentage of motor vehicle crashes in the United States and often result in fatalities and injuries. Results of several studies have pointed out that truck-related work zone crashes had a higher crash rate and were more severe than other crashes in work zones. It is important to understand the factors that affect the severity of truck-related crashes in work zones, so that potential countermeasures can be developed. Investigating the characteristics of truck-related crashes in work zones and modeling the truck speeds in the upstream of work zones may lead to the discovery of factors that might cause the crashes and could lead to the development of countermeasures to reduce instances of high-severity crashes.

1.2 Research Objectives and Scope

The primary objectives of this research were: 1) to investigate the characteristics of fatal, injury and Property Damage Only (PDO) truck-related crashes in work zones, 2) to determine if there are differences between fatal and injury crashes, fatal and PDO crashes, and injury and PDO crashes through characteristics comparison, and 3) to model the truck speeds in the upstream of a one-lane two-way work zone in a rural highway. The vehicles with lengths longer than 19 ft were defined as trucks.

The scope of the crash study was limited to truck-related crashes between 2000 and 2008 in Kansas highway work zones. The crash reports were provided by Kansas Department of Transportation (KDOT) which documented descriptive data on date, drivers, vehicle, roadway, environmental conditions, and crash type. Field experiments to determine the truck speed models were conducted in a one-lane two-way work zone in Kansas. When construction and maintenance operations are under way, the two-lane highway will be reduced to a one-lane two-way work zone that requires temporary traffic control signs, flaggers, and a pilot car to coordinate vehicles entering and leaving the work zone.

1.3 Research Methodology

The objectives of this research were achieved using a four-step approach. These steps were 1) literature review, 2) crash data collection and analysis, 3) field experiment and data analysis, and 4) conclusions and recommendations.

1.3.1 Literature Review

The literature review was conducted to establish the background for this research. The topics of review included work zone crash studies and characteristics of truck-related crashes.

1.3.2 Truck-related Data Collection and Analysis

The reports of truck-related crashes between 2000 and 2008 in Kansas highway work zones were collected. The crash reports were provided by KDOT which documented descriptive data on date, drivers, vehicle, roadway, environmental conditions, and crash type. In this study, the truck-related crashes in highway work zones were first analyzed separately based on severity levels, which include fatal injury and PDO. Then, the authors compared the characteristics among these levels.

1.3.3 Field Experiment and Data Analysis

Field experiments to determine the truck speed models were conducted in a one-lane two-way work zone in Kansas. In the field experiment, seven speed sensors (TRAX Apollyon) were used so that enough speed data points could be collected to develop truck speed models in the upstream of a work zone. The optimal model was developed based on the collected speed data. In addition, the comparison of speed models between passenger cars and trucks was performed.

1.3.4 Conclusions and Recommendations

Conclusions were made based on the results of data analyses. Recommendations on the improvements of truck safety in the one-lane two-way work zones were presented in the end as well as the needs for future research.

Chapter 2 Literature Review

In this chapter, the results of a comprehensive literature review on work zone safety and truck-related crashes are presented. The findings are organized in two categories including 1) previous analyses of vehicle crashes in work zones, and 2) truck-related crashes characteristics.

2.1 Characteristics of Work Zone Crashes

The review of the literature on the characteristics of work zone crashes shows that most of these studies were conducted statewide, and a few used nationwide work zone crash data. The diverse data scopes produced inconsistent findings even in the same area. The studies reviewed are categorized into the following areas: crash rate; crash severity; crash location; crash type; fatal crash, and other crash characteristics.

2.1.1 Crash Rate

Work zones on highways undoubtedly disturb the traffic flow, result in a decrease of capacity, and create hazardous environments for motorists and construction workers. **Table 2.1** lists the studies of work zone crash rates after the late 1970s. It can be concluded that work zone traffic safety is a nationwide problem because it exists in every state in the United States.

Table 2.1 Previous Crash Rate Studies

No.	Year	Study Data	Location	Researchers	Crash Rate
1	1978	151 accidents	Ohio	Nemeth and Migletz	Increase
2	1978	79 projects	Multi States	Graham et al.	6.9 percent increase
3	1988	Crashes in Chicago Area Expressway System	Illinois	Rouphail et al.	Increase
4	1989	Total 499 crashes occurred in 114 projects	New Mexico	Hall and Lorenz	26 percent increase
5	1990	7 projects	Virginia	Garber and Woo	57 percent 168 percent increase
6	1990	2,013 accidents From 1983-1986	Kentucky	Pigman and Agent	Increase
7	1996	25 projects	Indiana	Pal and Sinha	Increase
8	2002	36 projects	California	Khattak	21.5 percent increase

Nemeth and Migletz studied 151 accidents in Ohio; the researchers compared the accident rate per million vehicle kilometers or per million vehicle miles before, during, and after construction and maintenance operations. The results showed that crash rates during construction increased significantly (Nemeth and Migletz 1978). Graham et al. analyzed 79 projects in seven states: as a whole, crash rates increased 6.9 percent during construction. The change in the crash rate was found to vary substantially among individual projects (Graham et al. 1978). Rouphail et al. selected 46 sites in the Chicago Area Expressway System and collected the crash data from 1980 to 1985. The researchers found that the crash frequency increased by 88% during the existence of the work zone site (Rouphail et al. 1988). Hall and Lorenz in New Mexico found that the crash rate during construction increased 26% compared with thr crash rate in the previous years when no construction occurred (Hall and Lorenz 1989). In 1990, Garber and Woo selected seven project sites in Virginia; the researchers found that "accident rates at work zones on multilane highways in Virginia increase on the average by about 57%" and "by about 168% on two-lane urban highways when compared with accident rates just prior to the installation of the work zones" (Garber and Woo 1990). Pigman and Agent examined the accident reports from 1983 to 1986, which contained 2,013 accidents in Kentucky. The researchers discovered that "at 14 of the 19 locations where accident rates were calculated, rate during construction exceeded those in the before period" (Pigman and Agent 1990). Pal and Sinha found that there was a significant change of accident rates between before and during construction in Indiana (Pal and Sinha 1996). Khattak et al. pointed out the rate of total work zone crashes was 21.5% higher than the pre-work zone crash rate and indicated that "work zone projects on limited-access roadways can be more hazardous than those same segments in the pre-work zone period" (Khattak et al. 2002). These studies demonstrated that the increase in crash rates as a result of construction and maintenance "was highly variable and likely dependent upon specific factors related to traffic conditions, geometrics, and environment" (Wang et al. 1996).

2.1.2 Crash Severity

Table 2.2 lists the previous studies on the crash severity in work zones. Inconsistent conclusions had been reached about whether more severe crashes occur in work zones.

Table 2.2 Previous Crash Severity Studies

No.	Year	Study Data	Location	Researchers	Crash Severity
1	1978	151 accidents	Ohio	Nemeth and Migletz	Increase
2	1981	WZ accidents in 1977	Texas	Richards and Faulkner	Truck-related crash severity increase
3	1981	2127 accidents	Virginia	Hargroves	Less severe
4	1987	FARS & National Survey	Multistate	AASHTO	Increase
5	1988	Crashes in Chicago	Illinois	Rouphail et al.	Less severe
6	1989	Total 499 crashes occurred in these 114 projects	New Mexico	Hall and Lorenz	No significant difference
7	1990	2,013 accidents From 1983-1986	Kentucky	Pigman and Agent	Increase
8	1990	7 projects	Virginia	Garber and Woo	No significant difference
9	1995	1982-1986 accidents	Ohio	Ha and Nemeth	Less severe Truck-related crash severity increase
10	1995	Crashes in three states	Multistate	Wang et al.	Less severe
11	2000	181 crashes	Georgia	Daniel et al.	Truck-related crash severity increase
12	2002	1484 crashes	Virginia	Garber and Zhao	Increase
13	2004	77 fatal crashes	Texas	Schrock et al.	Truck-related crash severity increase
14	2006	157 fatal crashes	Kansas	Li and Bai	Truck-related crash severity increase

Nemeth and Migletz showed that the severity of work zone crashes increased, especially for injury crashes (Nemeth and Migletz 1978). A national study discovered that the fatal accident frequency and the fatalities per accident on average were higher in work zones nationwide (AASHTO 1987). Pigman and Agent (1990) concluded that work zone crashes were more severe than other crashes. Garber and Zhao collected 1,484 crashes from 1996 to 1999 in Virginia and pointed out that more severe crashes happened in work zones (Garber and Zhao 2002). However, Hall and Lorenz (1989) and Garber and Woo (1990) concluded the severity was not significantly different between work zone crashes and non-work zone crashes. Hargroves (1981), and Ha and Nemeth (1995) found that work zone crashes were less or slightly more severe than other crashes. Work zone crashes involving large trucks were more severe than other crashes. Richards and Faulkner (1981), Pigman and Agent (1990), Ha and Nemeth (1995), Daniel et al. (2000), Schrock et al. (2004), and Li and Bai (2006) pointed out the disproportionate number of large trucks involved in severe crashes (fatal and injury).

2.1.3 Crash Location

Many researchers agreed that there is an unbalanced crash distribution along a work zone. When considering the different locations in the work zone, Pigman and Agent (1990) pointed out that the most severe crashes occurred in the advance warning area. Nemeth and Migletz (1978) and Hargroves (1981) indicated that the activity area was the area which could be more susceptible to work zone crashes. Rural highways account for more work zone crashes compared with urban highways; a national study found that about 68% of all fatal crashes occurred on rural highways (AASHTO 1987). Pigman and Agent (1990) discovered that the percentage of work zone crashes occurring in rural areas was much higher than in business and residential areas. Daniel et al. (2000) concluded that the fatal crash rate increased about 13% in rural work zones. A study conducted by Li and Bai found that, in Kansas, 63% of fatal crashes happened on two-lane highways (2006).

2.1.4 Crash Type

The prevailing type of work zone crashes varies with times and locations in the work zones (Li and Bai 2006). However, results of most of the previous studies indicated that the rear-end collision was one of the most frequent work zone crash types (Nemeth and Migletz 1978; Hargroves 1981; Rouphail et al. 1988; Hall and Lorenz 1989; Pigman and Agent 1990; Garber and Woo 1990; Wang et al. 1995; Ha and Nemeth 1995; Sorock et al. 1996; Daniel et al. 2000; Mohan and Gautam 2002; Garber and Zhao 2002; Chambless et al. 2002; Bai and Li 2006; Bai and Li 2007; and Li and Bai 2008). Other major types of work zone crashes include same-direction sideswipe collision (Nemeth and Migletz 1978; Pigman and Agent 1990; Garber and Woo 1990; and Li and Bai 2008), angle collision (Pigman and Agent 1990), and hit-fixed-object crashes (Nemeth and Migletz 1978; Hargroves 1981; Mohan and Gautam 2002; and Garber and Zhao 2002).

2.1.5 Fatal Crash Characteristics

The study of fatal crashes allowed for an evaluation of the most severe type of crashes and indicated where safety improvements should be focused. Janice Daniel and other researchers studied fatal crashes in Georgia, including 181 crashes from 1995 to 1997. Daniel et al. (2000) pointed out fatal crashes in work zones were more likely to involve another vehicle than non work-zone fatal crashes, and trucks were involved in a higher proportion (20%) of fatal crashes compared with 13% for non-work-zone fatal crashes. Rear-end crashes represented a high proportion (12.1 percent) of fatal crashes in work zones compared with those in non work-zone locations (5.0 percent) (Daniel et al. 2000). In addition, 28 percent of fatal crashes in work zones occurred on rural principal roadways compared with 15 percent of fatal crashes in non-work-zone locations.

Schrock et al. (2004) collected data from 77 fatal crashes in work zones in Texas from February 2003 to April 2004. The researchers found that 29 percent of all fatal crashes involved a large truck, typically with a truck striking another vehicle or vehicles. In addition, the researchers pointed out one trend in the data that large truck-involved crashes were more likely to involve more than two vehicles. This seems reasonable because the energy that a large truck had would make it more likely to hit multiple vehicles before it stopped. Researchers concluded that 8 percent of investigated fatal crashes had a direct influence from the work zone, and 39 percent of the investigated crashes had an indirect influence from the work zone (Schrock et al. 2004).

After analyzing 157 fatal crashes in Kansas, Li and Bai (2006) found that head-on collision was the dominant type in fatal crashes; a large percentage of fatal crashes involved trucks (40 percent); and almost all of these crashes were multi-vehicle crashes. Their study results implied that truck involvement could increase the severity of work-zone crashes. In addition, 63 percent of fatal crashes in Kansas work zones occurred on two-lane highways (Li and Bai 2006).

2.1.6 Other Crash Characteristics

Most studies concluded that human errors, such as excess speeds, following too close, misjudging, and inattention, were the most common causes for work-zone crashes (Nemeth and Migletz 1978; Hargroves 1981; Hall and Lorenz 1989; Pigman and Agent 1990; Garber and Woo 1990; Ha and Nemeth 1995; Chambless et al. 2002; and Li and Bai 2008). Two studies (Hall and Lorenz 1989; and Garber and Woo 1990) indicated that multi-vehicle crashes were overrepresented, whereas nine studies (Nemeth and Migletz 1978; Hargroves 1981; Richards and Faulkner 1981; Hall and Lorenz 1989; Pigman and Agent 1990; Ha and Nemeth 1995; Daniel et al. 2000; Schrock et al. 2004; and Li and Bai 2006) indicated that truck-related crashes were overrepresented.

Pigman and Agent (1990) found that "crashes during darkness were more severe." Nemeth and Migletz (1978) found that "the proportion of tractor-trailer and bus-caused accidents at night and dawn or dusk was greater than the proportion for other vehicles." Richards and Faulkner (1981) concluded that "nighttime crashes were especially concentrated at the transition area." Ha and Nemeth (1995) also found that "night crashes were more likely to be the fixed-object crashes and single-vehicle crashes were predominant at night."

2.2 Truck-Related Crashes in Work Zones

Truck-related crashes contribute to a significant percentage of motor vehicle crashes in the United States. The information from the Fatality Analysis Reporting System (FARS) shows that there were 50,430 fatal crashes in 2008; 8.1% (4,066) of them were large truck related, 37.8% (19,072) were light truck related. Here a light truck is referred to as a truck of 10,000 pounds gross vehicle weight or less; a large truck is over 10,000 pounds gross vehicle weight.

Some researchers have investigated and analyzed truck-related crashes in work zones using various sources and techniques. Benekohal et al. (1995) conducted a statewide opinion survey of 930 semitrailer drivers in Illinois in 1993. Researchers found that about 90 percent of truck drivers consider traveling through work zones to be more hazardous than non-work-zone areas. About half of the drivers wanted to see an advance warning sign 5 to 8 kilometers (3 to 5 mi) ahead of the work zones. The drivers did not have a clear preference between one-lane closure and median crossover configurations. About two-thirds of drivers considered the speed limit of 89 km/hr (55 mi/hr) about right, but one-fourth of them believed it was too fast. Nearly half of drivers would exceed a speed limit of 72 km/hr (45 mi/hr), and nearly one-fifth of them would drive at least 8 km/hr (5 mi/hr) faster than the speed limit. About one-fifth of the drivers said some signs should be added to the work zones. About one-third of the crashes were in the advance warning area, and about two-third of crashes were in the transition area. In another paper, Benekohal and Shim pointed out that, in terms of VMT (vehicle miles traveled), fatal crash rates for large trucks had been consistently higher than the rates for passenger cars;

semitrailer trucks were underrepresented in the PDO (Property Damage Only) and injury crashes but overrepresented in fatal crashes (Benekohal and Shim 1999).

Meyers (1981) compared truck and passenger-car crash rates from 1976 to 1978 at 34 limited-access facilities (21 toll expressways and turnpikes, and 13 bridges and tunnels). He found that fatal, injury, and overall expressway crash rates for heavy trucks exceeded that of passenger cars.

Garber and Joshua (1990) found 75% of all large-truck crashes and 91% of large-truck fatal crashes were attributed to driver-related errors. Hall and Lorenz (1989) found that in New Mexico the number and rate of truck-related crashes increased during the construction season. Work-zone crashes involve large trucks are more severe than other crashes, Daniel et al. (2000); Schrock et al. (2004); Li and Bai (2008); Ha and Nemeth (1995); Pigman and Agent (1990); Richard and Faulkner (1981) pointed out the disproportionate of large trucks involved in severe crashes (fatal and injury).

Bezwada and Dissanayake (2009) pointed out that truck drivers might face many challenges while traversing on interstate or state highways at high speeds, at intersections, or while taking turns to have control over the vehicle because the physical dimension of a truck creates blind spots.

In summary, several research projects have been conducted to reveal the characteristics of truck-related crashes in highway work zones since 1981. Most studies conveyed that the crash rate and severity of truck-related crashes were higher than other types of crashes in work zones. However, some issues are still being debated, such as whether the majority of accidents can be described as “truck striking” and “truck struck”; what kind of factors make a difference in impacting the crash severity level. Studying the characteristics of truck crashes is the most crucial step towards the identification of work-zone safety deficiencies.

Chapter 3 Truck-Related Crash Data Collection and Analysis

The scope of truck-related crash data analysis is limited to the crashes between 2000 and 2008 in Kansas highway work zones. The crash reports were provided by KDOT, which documented descriptive data on date, drivers, vehicle, roadway, environmental conditions, and crash type. Because some materials were recorded using text, the reports could not be directly utilized for analysis using statistical software. Thus, a necessary step was to compile the crash data into the excel spreadsheet with a single row per crash. During this process, the narrative text was translated into numbers to represent the text meanings.

3.1 Truck-Related Crash Data Collection

Kansas had 35 fatal, 374 injury and 1,541 PDO truck-related crashes in highway work zones between 2000 and 2008. It would be time-consuming yet not statistically meaningful to compile and analyze the entire PDO dataset. Therefore, a sample size was determined based on the method of Thompson (2002). Considering that the data would be used for frequency analysis of characteristics reflected through the proportions of the different crashes marked by different variable observations, the sample size, as determined through which these proportions can be estimated accurately. Based on normal approximation, to obtain a proportion estimator $\hat{p}$ with a probability of at least 1- α of being no farther than *d* (error) from the true population proportion *p*, one would choose a corresponding sample size such that

$$P(|\hat{p} - p| > d) < \alpha \qquad (3.1)$$

when $\hat{p}$ is an unbiased, normally distributed estimator of *p*, the variable

$$\frac{\hat{p} - p}{\sqrt{\text{var}(\hat{p})}}$$

has a standard normal distribution N(0, 1). For estimating a proportion, an unbiased estimator of the variance var($\hat{p}$) can be estimated by:

$$\text{var}(\hat{p}) = \left(\frac{N-n}{N}\right)\frac{\hat{p}(1-\hat{p})}{n-1} \tag{3.2}$$

where N is the population size.

Given the above theoretical basis, to obtain an estimator $\hat{p}$ of the true proportion *p* with *1- α* confidence of having an error less then *d*, the minimum sample size n_{min} required should be computed by the following equation:

$$n_{\min} = \frac{Np(1-p)}{(N-1)(d^2 / z_{\alpha/2}^2) + p(1-p)} \tag{3.3}$$

where $z_{\alpha/2}$ is the upper α/2 point of the standard normal distribution. When there is no estimate of *p* available and *N* is large, a worst-case value of $p = 0.5$ can be used in determining the minimum sample size:

$$n_{\min} = \frac{1}{(N-1)/Nn_0 + 1/N} \approx \frac{1}{1/n_0 + 1/N} \tag{3.4}$$

where:

$$n_0 = \frac{z_{\alpha/2}^2 p(1-p)}{d^2} = \frac{0.25 z_{\alpha/2}^2}{d^2} \tag{3.5}$$

Note that the minimum sample size determined using Equation 5 is theoretically appropriate to estimate the proportion of the accidents with only binary variables. In fact, variables frequently have several values and multiple proportions need to be estimated simultaneously. For example, the “age” variable is usually divided into several groups (i.e. 15-19, 20-24, 25-29…) and the crash proportions of all these groups need to be estimated simultaneously. In this situation, the sample size should be adjusted accordingly. Based on the same rationale, Thompson (2002) provided a table (table 3.1) of adjusted n_0 when the population size N is large.

Table 3.1 Sample Size n_0 for Simultaneously Estimating Several Proportions within Distance d of the True Values at Confidence Level (1- α)

α	d^2n_0	n_0 with d = 0.05	m
0.5	0.44129	177	4
0.4	0.50729	203	4
0.3	0.60123	241	3
0.2	0.74739	299	3
0.1	1.00635	403	3
0.05	1.27359	510	3
0.025	1.55963	624	2
0.02	1.65872	664	2
0.01	1.96986	788	2
0.005	2.28514	915	2
0.001	3.02892	1212	2
0.0005	3.33530	1342	2
0.0001	4.11209	1645	2
Note:	The worst-case minimum sample size occurs when some *m* of the proportions in the population are equal and the rest are zero.		

Based on equation 5 and table 3.1, given 1,541 PDO crashes, the minimum sample size for PDO crashes needed for frequency analysis at confidence level 95% with an error d less than 5% was determined as:

$$n_{\min-PDO} \approx \frac{1}{1/n_0 + 1/N} = \frac{1}{1/510 + 1/1{,}541} \approx 380$$

Therefore, the total sample sizes for fatal, injury, and PDO are shown as in table 3.2.

Table 3.2 Sample Size for Different Crash Classes

Crash Classes	Sample Size
Fatal	35
Injury	374
PDO	380

After the determination of the sample size for each crash class, crash data were classified into six categories with a total of 25 crash-related variables as shown in table 3.3. Values of each variable are shown in Appendix I except three variables, Number of Vehicles, Number of Lanes, and Speed Limit. Their values were defined as the same numbers indicated in the crash reports. A portion of the data collection sheet used for data analysis is shown in Appendix II.

Table 3.3 Crash Data Categories and Variables

No.	Category	Variable	Observations
1	Information of Truck Driver	Gender	See Table 1 in Appendix I
		Age	See Table 2 in Appendix I
		Driver Factor	See Table 3 in Appendix I
2	Crash Time Information	Time	See Table 4 in Appendix I
		Day	See Table 5 in Appendix I
		Month	See Table 6 in Appendix I
3	Climatic Environment Information	Light Condition	See Table 7 in Appendix I
		Weather Condition	See Table 8 in Appendix I
		Road Surface Condition	See Table 9 in Appendix I
4	Crash Information	Truck Maneuver	See Table 10 in Appendix I
		Crash Type	See Table 11 in Appendix I
		Vehicle Type	See Table 12 in Appendix I
		No. of Vehicles	Using the number in report
5	Road Conditions	Road Class	See Table 13 in Appendix I
		Road Character	See Table 14 in Appendix I
		Number of Lanes	Using the number in report
		Speed Limit (mph)	Using the number in report
		Crash Location	See Table 15 in Appendix I
		Surface Type	See Table 16 in Appendix I
		Road Special Feature	See Table 17 in Appendix I
		Area Information	See Table 18 in Appendix I
		Traffic Control	See Table 19 in Appendix I
6	Contributing Factors	Pedestrian Factor	See Table 20 in Appendix I
		Environment Factor	See Table 21 in Appendix I
		Vehicle Factor	See Table 22 in Appendix I

3.2 Truck-Related Crash Data Analysis

The truck-related crashes in highway work zones were first analyzed separately based on severity level. Then, the authors compared the characteristics among fatal, injury and PDO crashes. For three types of crashes, frequency analysis was utilized to discover the basic characteristics based on single-variable frequencies. **Table 3.4** lists the most frequent observations for these three severity level crashes.

Table 3.4 Frequent Observations for Fatal, Injury and PDO Crash Variables

Variable	Most Frequent Observations		
	Fatal Crashes	Injury Crashes	PDO Crashes
Information of Truck Drivers			
Gender	Male (100%)	Male (96%)	Male (97%)
Age	35-44 (43%)	45-54 (26%)	35-44 (25%)
Driver Factor	No human error (43%)	No human error (37%)	No human error (37%)
Crash Time Information			
Time	10:00am-4:00pm (46%)	10:00am-4:00pm (46%)	10:00am-4:00pm (50%)
Day	Monday (26%)	Tuesday (20%)	Monday (22%)
Month	June (20%)	September (15%)	July (14%)
Climatic Environment Information			
Light Condition	Daylight (69%)	Daylight (77%)	Daylight (82%)
Weather Condition	Good (94%)	Good (90%)	Good (91%)
Road Surface Condition	Dry (94%)	Dry (86%)	Dry (88%)
Crash Information			
Truck Maneuver	Straight/following road (74%)	Straight/following road (64%)	Straight/following road (54%)
Crash Type	Rear-end (31%)	Rear-end (37%)	Rear-end (22%)
Vehicle Type	Truck-vehicle (74)	Truck-vehicle (64%)	Truck-vehicle (63%)
No. of Vehicles	Two (60%)	Two (60%)	Two (68%)
Road Conditions			
Road Class	Other freeways & expressways (80%)	Interstate highway (43%)	Interstate highway (35%)
Road Character	Straight and level (54%)	Straight and level (58%)	Straight and level (66%)
Number of Lanes	Two-lane (63%)	Four-lane (51%)	Two-lane (46%)
Speed Limit (mph)	65 (57%)	65 (25%)	55 (20%)
Crash Location	Non-intersection (74%)	Non-intersection (63%)	Non-intersection (60%)
Surface Type	Blacktop (71%)	Blacktop (59%)	Blacktop (58%)
Road Special Feature	None (83%)	None (82%)	None (79%)
Area Information	Rural (86%)	Rural (52%)	Urban (59%)
Traffic Control	Center/edge lines (43%)	Center/edge lines (54%)	Center/edge lines (45%)
Contributing Factor			
Pedestrian Factor	No	Inattention (0.5%)	No
Environment Factor	No	Rain, mist, or drizzle (2.4%)	Animal (3.7%)
Vehicle Factor	No	Brakes (1.6%)	Cargo (2.9%)

3.2.1 Information of Truck Drivers

Male drivers were the majority of the drivers of these three different crashes in highway work zones. As shown in **Table 3.4**, all truck drivers in fatal crashes were male; there were 96% and 97% male drivers in injury and PDO crashes, respectively. However, these data could not be used to interpret whether male truck drivers were more susceptible to the crashes in work zones. The largely male composition of truck drivers in U.S. may be the reason for this phenomenon.

Drivers between 35-44 years old were in 43% of the fatal work-zone crashes; the same age group was involved in 25% of PDO crashes. Drivers between 45-54 years old were involved in 26% of injury crashes. It was also necessary to find the age distribution for the truck drivers who were at fault. When the fatal crashes occurred in work zones, 57% of truck drivers were at fault; 63% of them were at fault when injury and PDO crashes happened in work zones. **Figure 3.1** illustrates the overall distribution of three crash severity levels over driver age and **Figure 3.2** presents the age distribution of truck drivers who were at fault in three crash severity levels.

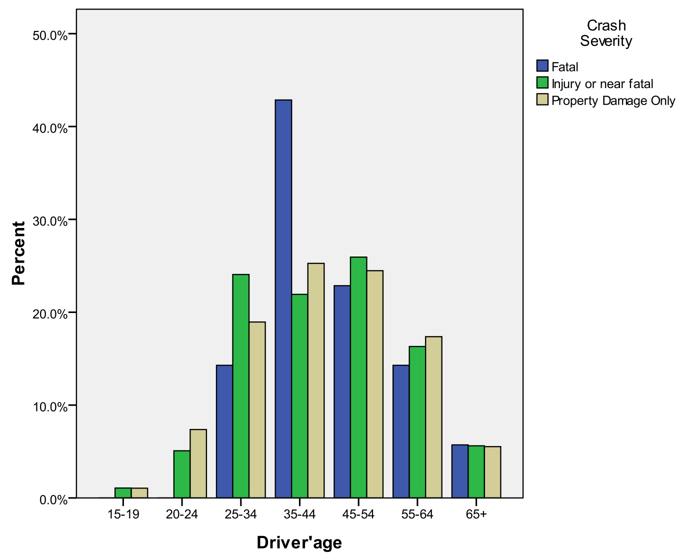

Figure 3.1. Overall age distribution of truck drivers in three severity level crashes

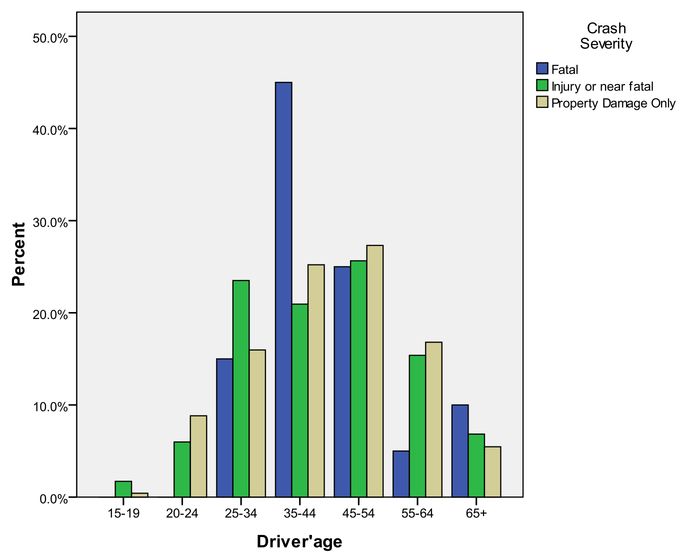

Figure 3.2 Age distribution of at-fault truck drivers

3.2.2 Time Information

As indicated in **Figure 3.3**, daytime hours (10:00 a.m.-4:00 p.m.) had the highest frequency for all three types of crashes (46%, 46% and 50% for fatal, injury and PDO crashes, respectively). When comparing the dates of crashes, Monday was the day on which the fatal and PDO crashes took place most frequently; Tuesday was observed as the day on which injury crashes occurred most often. The majority of both fatal and injury crashes occurred between June and September, which accounts for 54.3% and 50.3% of yearly total fatal and injury crashes respectively. The monthly distribution of PDO crashes showed that the PDO crashes were most common from April until October. The curves of three crash types are presented in **Figure 3.4**, which clearly indicates that the busy construction season in the summer causes the increase of truck-related crashes in work zones.

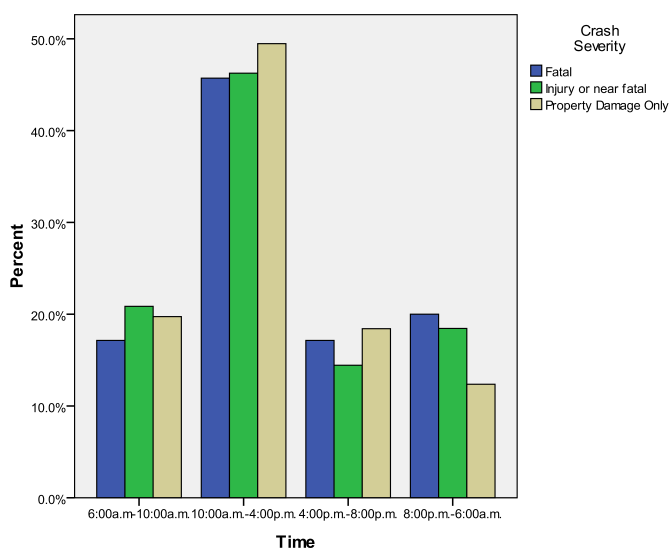

Figure 3.3. Crash distribution by crash time

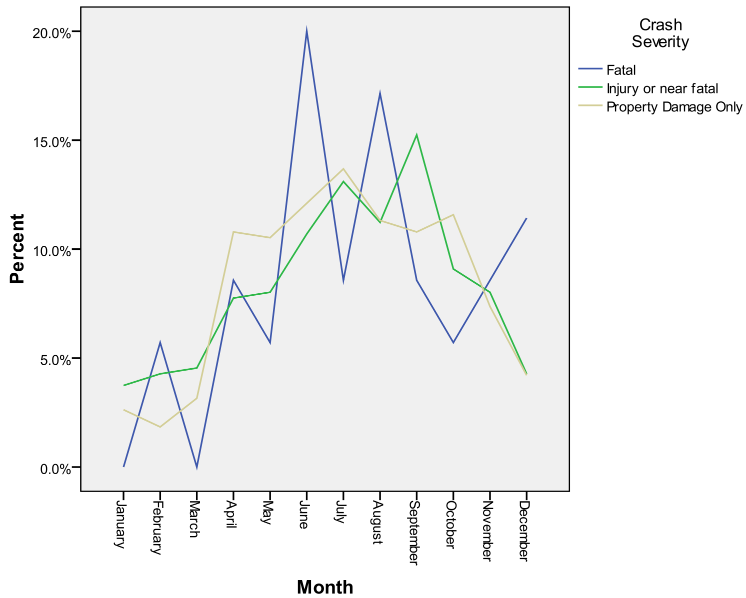

Figure 3.4. Monthly crash distribution

3.2.3 Climatic and Environment Information

Most of the truck-related crashes occurred when the weather and road surface conditions were actually favorable, as indicated in **Table 3.4**. About 31% of fatal crashes occurred when there were poor light conditions such as dawn, dark with or without street lights. The poor light conditions affected the injury and PDO crashes less compared with fatal crashes, while 23% of injury crashes occurred with poor light conditions and 18% of PDO crashes happened under poor light conditions. Dark without street lights was the most frequent factor among poor light conditions for fatal and injury crashes. The frequencies of crashes by light conditions are illustrated in **Figure 3.5**.

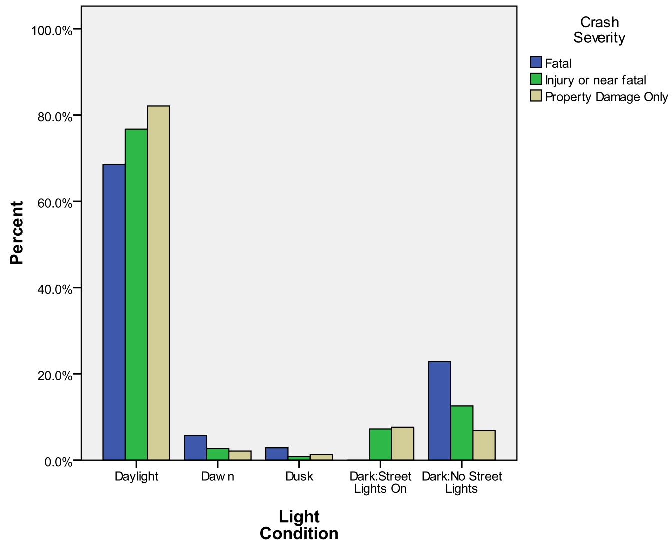

Figure 3.5. Crash distribution by light conditions

3.2.4 Crash Information

Crash information indicated that straight following was the maneuver most truck drivers took before the crash happened. Rear-end was dominant for fatal, injury and PDO crashes. About 31% of fatal crashes were rear-end, followed by angle side (23%) and head-on (17%) crashes. When comparing fatal crashes with injury and PDO crashes, there was a significant percent difference of head-on crashes, which accounts for only 2% for injury crashes and 0.5% for PDO crashes as shown in **Figure 3.6**. Rear-end, angle side and head-on account for 71% of fatal crashes; this indicated that the impact point of crashes was critical in the truck-related work-zone crashes. Because the rear-end was dominant among all crashes, it was necessary to reduce the speed variance in work zones. In addition, to reduce the severity of the crashes, more space for trucks was needed when traversing in work zones which could prevent head-on and angle side crashes.

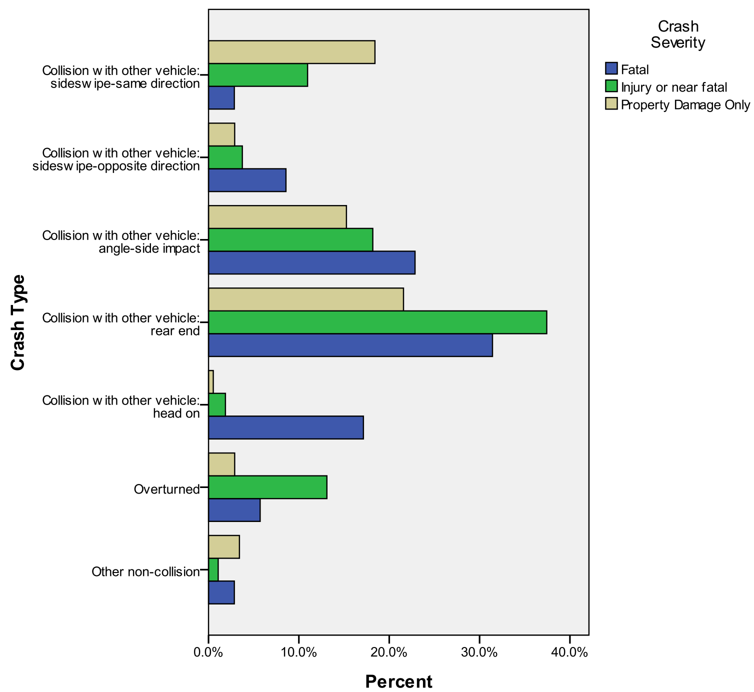

Figure 3.6. Crash distribution by crash types

3.2.5 Road Condition

A dominant proportion of fatal crashes occurred on two lane highways as shown in **Figure 3.7**. This result showed that, in Kansas, the rural highway was still the most susceptible area for fatal truck-related crashes. For injury crashes, highways with multiple lanes accounted for 63% of crashes, and 54% of PDO crashes happened on multiple lane highways as well. For injury crashes, since most of them happened on multiple lanes, it was reasonable to associate the high traffic volume with the injury crashes. The high traffic volume may also increase the speed variance, which could lead to rear-end crashes.

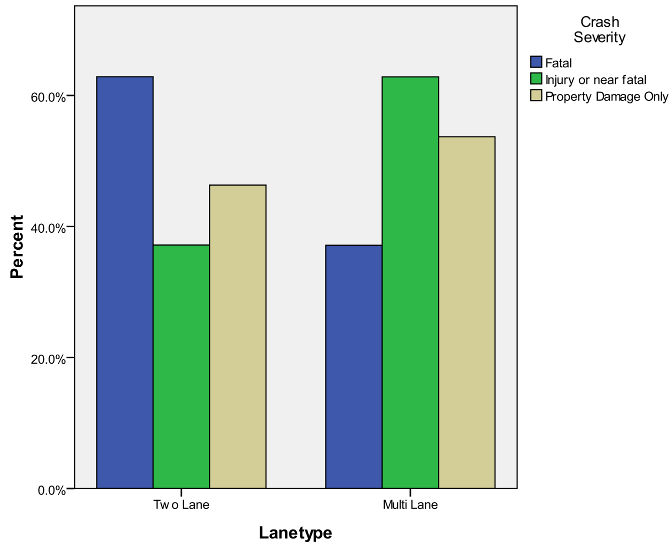

Figure 3.7. Crash distribution by number of lanes

The speed limit varied from fatal to PDO crashes as shown in **Figure 3.8**. Highways with 65 mph speed limits had the highest proportion of fatal crashes (57%), and accounted for 25% and 16% of injury and PDO crashes, respectively. The fatal crashes happened only when the speed limit was above 40 mph as shown in **Figure 3.8**. It confirmed that high speed was the main cause of fatal crashes.

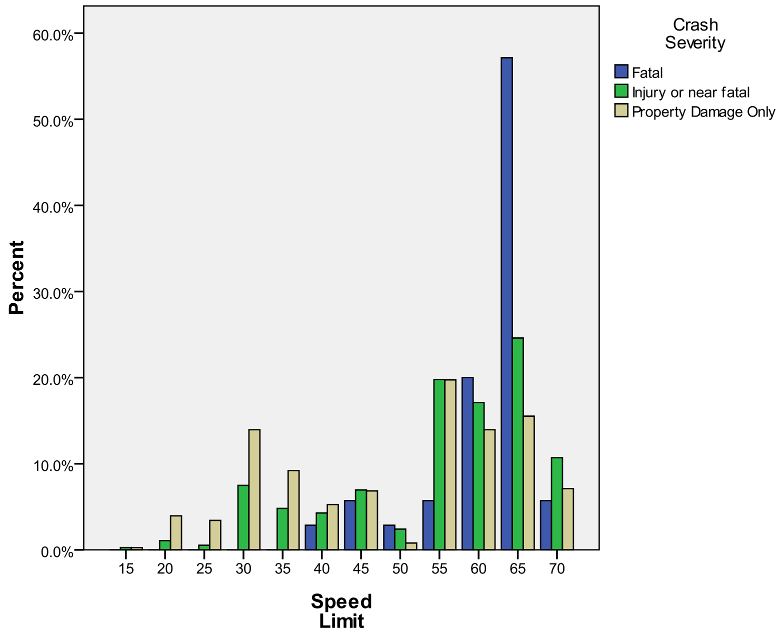

Figure 3.8. Crash distribution by speed limits

As shown in **Table 3.4**, most fatal crashes (86%) took place in rural highways. This result could be used to explain the fatal crash rate associated with number of lanes and speed limits discussed before. The rural highways usually had narrow space for trucks and high speed limits for all vehicles. All these factors might contribute to the high fatal crash rate compared with the urban highways.

In terms of road characteristics, 54% of the fatal crashes occurred on straight and level highway work zones and 31% happened on straight on grade highway work zones as shown in **Figure 3.9**. In addition, half of truck-related work-zone crashes happened on straight and level highway sections followed by straight and grade. The curve alignments resulted in more injury crashes than fatal and PDO crashes.

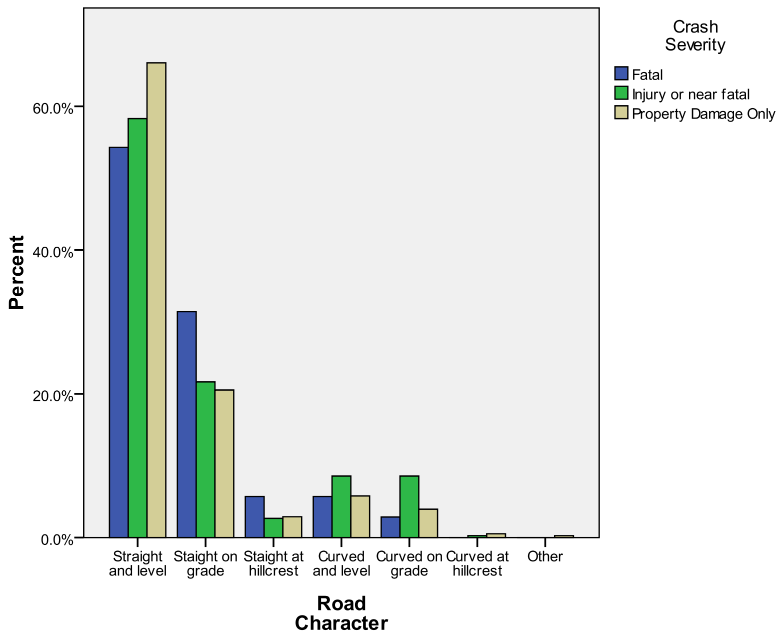

Figure 3.9. Crash distribution by road character

3.2.6 Driver fault

When identifying the truck drivers' fault in the crashes, about 43% of truck drivers were passive, which meant they were struck by other vehicles in fatal crashes as shown in **Figure 3.10** as "No human error." Inattention driving and "disregarded traffic signs, signals, or markings" each contributed to 17% of fatal crashes. Among trucks, 37% were struck by other vehicles in injury crashes (indicated as "No human error" in figure 3.10). For injury crashes, inattentive driving was the major fault of truck drivers, which accounted for 21% and was followed by "too fast for conditions" (10%). In addition, inattentive driving contributed to 29% of PDO crashes.

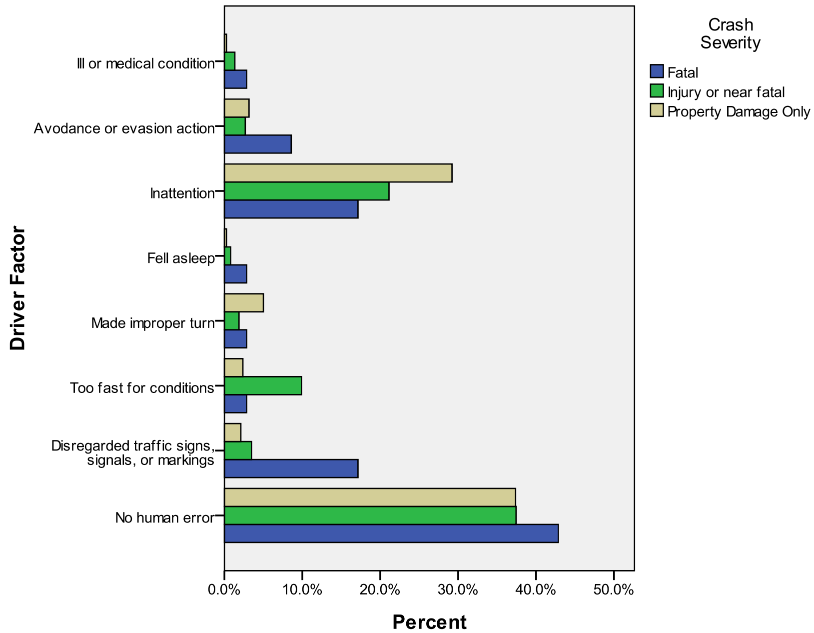

Figure 3.10. Crash distribution by driver fault

3.2.7 Independence analysis

During the data compiling process, some data are sorted as ordinal variables including severity level and age; some are sorted as nominal variables including gender of driver, time of crashes, and light condition; others are kept in the original format, such as speed limit and number of vehicles in crashes. For categorical variables, the Pearson Chi-square test and Likelihood-ratio test were used to test the dependent variable (Severity) and potential independent variables.

The Pearson chi-square statistic used for testing is

$$X^2 = \sum \frac{(n_{ij} - \mu_{ij})^2}{\mu_{ij}} \tag{3.6}$$

This statistic takes its minimum value of zero when all $n_{ij} = \mu_{ij}$. For a fixed sample size, greater differences {$n_{ij} - \mu_{ij}$} produce larger X^2 values. Here, n_{ij} and μ_{ij} mean the observed frequency and expect frequency for each cell of contingency table.

Each explanatory variable was paired with a dependent variable (Severity Level) and the Pearson Chi-square test and Likelihood Ratio test were used for testing the independence of each pair. **Table 3.5** shows the results of the independence test. The variables: Light Condition, Vehicle Maneuver, Crash Type, Number of Vehicles, Speed Limit, Area Information, and Traffic Control were the variables which correlated with severity of crashes at 95% confidence level, meaning the changes of these variables affected the crash severity.

Table 3.5 Independence Test of Variables

Variable	Statistic	Value	df	Asymp. Sig. (2-
Light Condition	Pearson Chi-	18.589	8	0.017
	Likelihood Ratio	19.546		0.012
Vehicle Maneuver	Pearson Chi-	92.241	30	0.000
	Likelihood Ratio	84.469		0.000
Crash Type	Pearson Chi-	181.841	28	0.000
	Likelihood Ratio	173.353		0.000
Number of Vehicles	Pearson Chi-	92.575	12	0.000
	Likelihood Ratio	63.394		0.000
Speed Limit	Pearson Chi-	76.423	22	0.000
	Likelihood Ratio	80.114		0.000
Area Information	Pearson Chi-	30.130	2	0.000
	Likelihood Ratio	32.121		0.000
Traffic Control	Pearson Chi-	81.980	20	0.000
	Likelihood Ratio	80.942		0.000

3.3 Summary of Truck-Related Crash Characteristics

The characteristics of truck-related fatal, injury and PDO crashes in Kansas work zones were investigated systematically in this research project. The frequency analysis and tests of independence were utilized for identifying the factors affecting crash severity level.

The study discovered that 38% of truck drivers were not responsible for the crashes in work zones. For the fatal crashes, 53% of truck drivers were at fault and responsible for the crashes. The truck drivers with ages between 35-44 were the most susceptible group because they accounted for 43% of fatal crashes, and there were no younger truck drivers (age<25) involved in fatal crashes. Daytime hours (10:00 a.m.-4:00 p.m.) had the highest frequency for three types of crashes. Monday was the day on which the fatal and PDO crashes happened most frequently, Tuesday was observed as the day for most injury crashes. The authors found that the truck-related crashes occurred when the weather and road surface conditions were favorable; Truck related crashes did not occur more often during adverse weather. Straight following was the maneuver most truck drivers took before the crash happened. Rear-end was dominant for fatal, injury and PDO crashes. The rural highways in Kansas were the most susceptible area for fatal truck-related crashes. Highways with a 65 mph speed limit had the highest proportion for fatal crashes. More than half of the fatal crashes occurred on straight and level highway work zones.

Based on the results of the independence test, the factors such as Light Condition, Vehicle Maneuver, Crash Type, Number of Vehicles, Speed Limit, Area Information, and Traffic Control, could affect the severity level of a crash. Therefore, these factors should be further studied and countermeasures should be developed to mitigate the severity levels of truck-related crashes in highway work zones.

Chapter 4 Truck Speed Profile Model in the Upstream of Work Zones

In chapter 2, the literature review on truck safety pointed out that truck-related crashes contribute to a significant percentage of motor vehicle crashes in the United States, which often result in fatalities and injuries. With the growing rate of freight movement, the amount of truck miles traveled is dramatically increasing. Regarding truck safety in work zones, many studies indicated that there was a significant increase in crash severity when a truck crash occurred in the work zones. Therefore, government agencies and the transportation industry need to pay more attention to the safety of trucks in work zones.

To mitigate the prominent high crash rate and severity of crashes in work zones, many temporary traffic control (TTC) devices have been utilized in the work zones including the portable changeable message sign (PCMS). However, the effectiveness of a PCMS on reducing truck crash risk in the work zones is not clearly understood. One effective indicator of the effectiveness of PCMS is truck speed reduction. A slow speed is more likely to reduce the probability of having a vehicle-related crash or the severity of a vehicle-related crash in work zones, and thus provide a safer environment for the drivers and construction workers. Therefore, there is a need to study the truck speed changes in the upstream of work zones when a PCMS is deployed. The truck speed changes can be described using the speed profiles that are developed through field experiments.

4.1 Objectives of Field Experiments

The primary objectives of the field experiments were 1) to develop the truck and passenger car speed profile models when there was a PCMS deployed in the upstream of rural highway work zones, and 2) to determine if there were differences between the speed reductions of passenger cars and trucks when they were approaching the work zones. In the field experiments, a PCMS was used as the TTC device to warn drivers about the upcoming work zone. If the field experiments are successful, other TTC devices can be evaluated using the same procedure.

In September and October 2010, the field experiment was conducted in the upstream of a one-lane two-way rural highway work zone located on Highway US-36. Data of passenger cars and trucks were collected using seven speed sensors. Since there were seven sensors used in the experiments, the vehicle length was determined by the average of the seven length measurements. If the average length of a vehicle was larger than 19 feet, then the vehicle was classified as a truck.

4.2 Data Collection

4.2.1 Installation of Vehicle Speed Sensors

In the field experiment, the selected rural highway work zone might move several times every day. To accommodate the work-zone activity progress, an easy installing-and-disassembling traffic recorder, TRAX Apollyon Counter, was selected for field experiments. TRAX Apollyon Counter is an automatic traffic recorder manufactured by JAMAR Technologies, Inc. It is designed for ease use, but contains many options and features that could be used for comprehensive traffic data collection. Information on volume, speed, class, and gap can be collected using two pneumatic road tubes and then converted into traffic data. **Figure 4.1** shows one of the working counters in the field. A total of seven counters were used in field experiments. A detailed description of counter layout will be introduced in Section 4.2.2. These seven counters were named as Sensor 1, 2, 3, 4, 5, 6, and 7 in the field experiments.

Figure 4.1. TRAX Apollyon Counter in field experiment

As showed in **Figure 4.1**, two tubes are connected with the counter and are placed perpendicularly to the road; all tubes are fastened by mastic strips. A fixed distance (2 ft) between tubes is measured using a ruler. When vehicle tires press on the tubes, the counter detects the air pulse. Therefore, the vehicle speed and classification can be determined by calculating the time gap between vehicle axles. Proper road tube installation is very important for collecting accurate data. There are five steps to install road tubes:

1. Selecting an installation location. In the field experiment, all tubes were installed following the field experimental layout which will be described in the section 4.2.2. The counters were deployed every 250 ft between each other in the upstream of work zones. Sensor 7 was placed at the same location of the first

Temporary Traffic Control sign (W20-1: ROAD WORK AHEAD) in the work zones.

2. Determining a layout. A total of 14 tube layouts can be selected in every counter; each of them has its own working environment. The scope of this research was limited to one-lane two-way rural highway work zones, thus, layout L5 was chosen for field experiments to reduce tube installing time. In this layout, both tubes are extended across the traffic lane. **Figure 4.2** shows the L5 layout.
3. Preparing road tubes. After choosing L5 as the layout to be used in the field experiments, to encompass all types of vehicles and speeds, for a mini tube, a length of 40 to 60 ft is recommended by TRAX Apollyon user's manual. Fourteen 50 ft length mini tubes were used in the field experiments.
4. Preparing the installation tools. Once the layout and mini tubes were selected, having sufficient tools was the key step for a quick and efficient installation on the road. This step includes measuring distance between counters, and preparing mastic strips.
5. Installing the road tubes. Road tubes should be installed exactly perpendicular to the traffic flow. Each counter is connected to two tubes in the field.

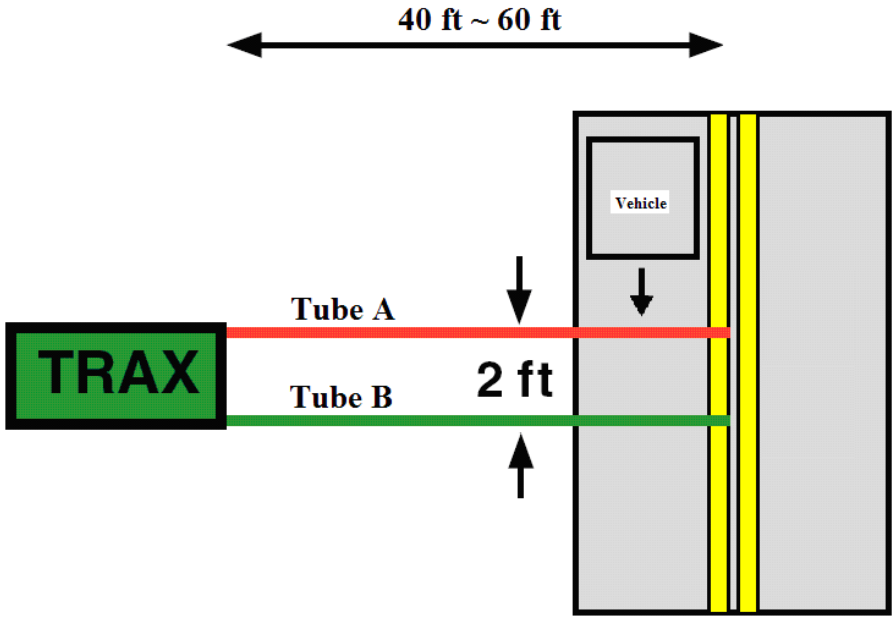

Figure 4.2. L5 Tubes layout

Safety is always the main priority when conducting experiments. Reducing working time on the road and keeping alert for upcoming traffics were critical when conducting field experiments. The total installation time needed for one single counter system was about 10 minutes. It included the time for measuring distance between counters, the time for sticking two tubes on the road, and the time for connecting tubes with counters and adjusting counters into working mode. When dissembling the counter system, a total of four minutes was needed. **Figure 4.3** shows the procedure of tube installation in the field.

1. Preparing mastic strips

2. Fastening tube ends on the road

3. Installing tubes with a tape measure

4. Completing the tube installation

Figure 4.3. TRAX Apollyon Counter installation

4.2.2 Layout of Field Experiments

One of the field experimental objectives was to develop the vehicle speed profile models in the upstream of rural highway work zones with a PCMS. Theoretically, a speed profile will be exactly accurate if the speed of a vehicle can be recorded every moment along the specific road section. However, it is not feasible to measure the vehicle speed at every second when it approaches a work zone. Thus, seven speed counters were installed at locations where speed changes could be observed in the upstream of the work zone.

To determine the distance between counters and record the vehicle speed changes, it is critical to realize that it takes time for drivers to process the traffic information displayed on the highways. When the driver brakes for a simple, unexpected action, some of them may take as long as 2.7 seconds to respond (FHWA 2009). Assuming a vehicle traveling at 65 mph, which is the speed limit of rural highways in Kansas, the total distance traveled during the reaction time will be 257 ft. Thus, the 250 ft interval between counters was utilized to record the speed changes in the upstream of the work zone. **Figure 4.4** shows the layout of field experiments. Sensor 7 was placed at the location of W20-1 sign (Road Work Ahead Sign). The location of Sensor 1 was defined as the starting point of field experiments for the purpose of data analyses.

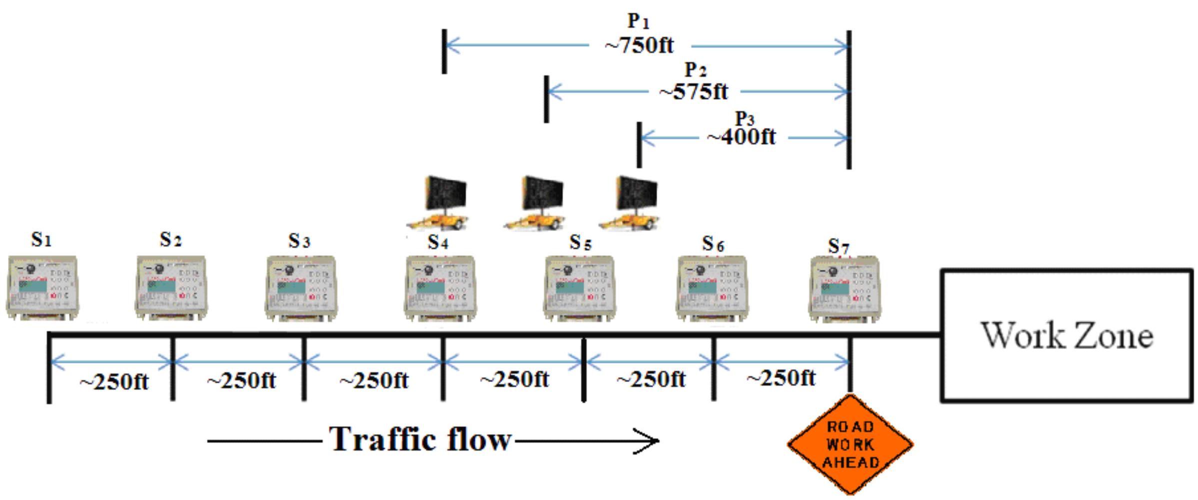

Figure 4.4. Field experiment layout

The PCMS was placed at three different locations from the start point of a work zone, which was the location of the W20-1 sign. These three different locations were: (1) 750 ft away from the W20-1, (2) 575 ft away from the W20-1, and 3) 400 ft away from the W20-1.

In September 2010, the experiments were conducted in the upstream of a one-lane two-way rural highway work zone located on US-36 as shown in **Figure 4.5**. The traffic volume on US-36 was 3,550 vehicles per day (vpd) with 590 being trucks. The US-36 had a statutory speed limit of 65 mph. The roadway surfaces were being paved during the construction operations. While construction operations were underway, the two-lane highway was reduced to a one-lane two-way work zone that required temporary traffic control signs, flaggers, and a pilot car specified by the MUTCD to coordinate vehicles entering and leaving the work zone. The PCMS used in the field experiments was installed in the upstream of the work zone, in addition to the required temporary traffic control signs, to warn the drivers when they approached the work zone.

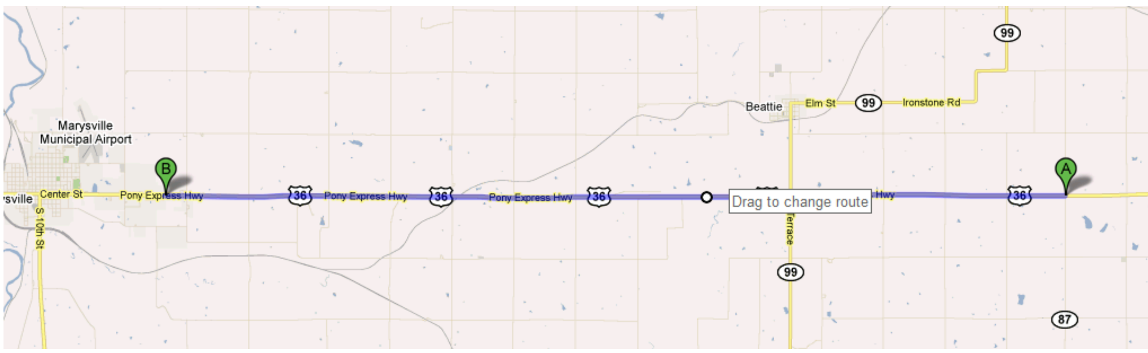

Figure 4.5. Work zone on US-36

The dimensions of the PCMS panel were 6.2 ft tall by 11.5 ft wide. **Figure 4.6** shows the PCMS used in the field experiments. The messages on the PCMS changed from “WORKZONE/AHEAD/SLOWDOWN” to “FLAGGER/AHD PREP/TO STOP” every three seconds during the experiments. The PCMS was placed on the shoulder of the highway about 9-10 ft away from the road. The inside edge of the panel was 3-4 ft away from the road.

Figure 4.6. Messages displayed on PCMS

4.2.3 Data Collection

The vehicle speed data were collected and stored by the TRAX Apollyon Traffic Counters in the field experiments. A speed datum was kept for further analysis if all seven speed measurements of a vehicle were collected. External factors, which occasionally interfered with passing vehicles and caused the data to be incorrectly recorded, included the interference of pedestrians, low-speed farm vehicles, and construction-related vehicles that either had very low speed or whose drivers had been well aware of the upcoming work zone conditions. These factors were taken into consideration and were screened in the data collection process. Incorrectly recorded data were removed from the data set before the data analysis by the research team.

The raw data (.DMP files) collected in the field experiment were exported, sorted into a datasheet, and put through a screening process. Any single vehicle datum that did not have corresponding speed measurements from all seven counters was discarded. In addition, a datum measurement was discarded from the data population if one of vehicle length measurement was significantly different from other measurements.

A total of 3,265 vehicle speed data was collected following the time-consuming experimental procedure. Of these, 1,144 vehicle speed data were collected when the PCMS was placed at P_1 location (750 ft); 1,125 were collected when the PCMS was placed at P_2 location (575 ft); 996 were collected when the PCMS was placed at P_3 location (400 ft). **Table 4.1** shows the list of data collected when the PCMS was placed at three different locations.

Table 4.1 Speed Data by Vehicle Types at Different PCMS Locations

PCMS Location	No. of Passenger Cars	No. of Trucks	Total
PCMS at 750ft	799	345	1,144
PCMS at 575ft	761	364	1,125
PCMS at 400ft	652	344	996

4.3 Data Analysis

The major tasks that needed to be accomplished in the data analysis were the development of the passenger car and truck speed profile models when the PCMS was placed at three different locations in the upstream of the work zone and the comparison between the passenger car speed profiles and the truck speed profiles. When the PCMS was placed at 750 ft away from the W20-1 sign, it was named Situation 1. In Situations 2 and 3, the PCMS was placed at 575 ft and 400 ft away from the W20-1 sign, respectively.

4.3.1 Truck Speed Profile Model for Situation 1

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 345 truck speed data were collected in the field experiments as shown in table 4.1. **Table 4.2** shows the descriptive statistics of truck speeds recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed.

Table 4.2 Descriptive Statistics of Truck Speeds with PCMS at 750 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	26	72	58.9	6.6
Speed at Sensor 2	26	71	57.9	6.3
Speed at Sensor 3	27	71	57.4	7.0
Speed at Sensor 4	28	71	57.0	7.7
Speed at Sensor 5	28	71	55.6	7.2
Speed at Sensor 6	28	68	53.9	6.9
Speed at Sensor 7	29	70	53.1	7.0

Note: STD-Standard Deviation

The truck speed profile model when the PCMS was at 750ft was developed using the truck speed measurements at the locations of seven sensors. Using the SPSS software program, regression analyses using the Curve Estimation were conducted to determine the model that could best represent the collected data. There are Linear, Quadratic, Compound, Growth, Logarithmic, Cubic, S, Exponential, Inverse, Power, and Logistic models which can be chosen in the Curve Estimation. To find the best fit model, the X coordinate of the Sensor 1 location was set as one foot to avoid zeros in the Inverse, S, Logarithmic and Power models. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 58.756 - 0.002x - 1.332e^{-6}x^2 + 9.49e^{-14}x^3 \quad (4.1)$$

X: Distance between a truck location and the Sensor 1 Location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 1 are presented in **Figure 4.7**.

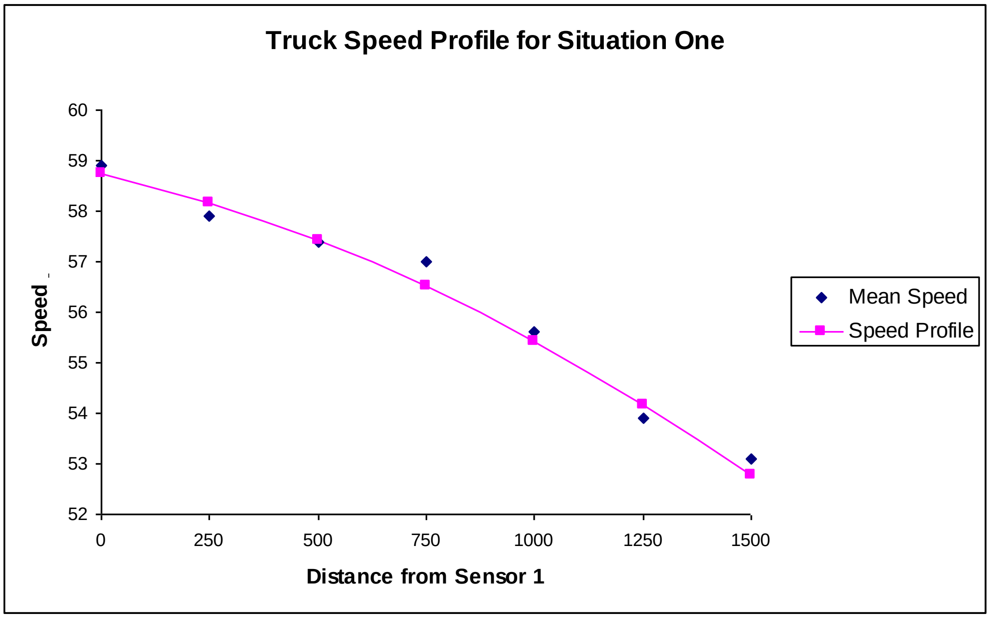

Figure 4.7. Truck speed profile curve for Situation One

When the PCMS was placed at 750 ft upstream of the W20-1 sign, 799 passenger car speed data were collected in the field experiments. The passenger car speed profile model was developed using the same procedure as the one used for trucks. **Figure 4.8** shows the two speed profile curves. As shown in **Figure 4.8**, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently in the upstream of the work zone.

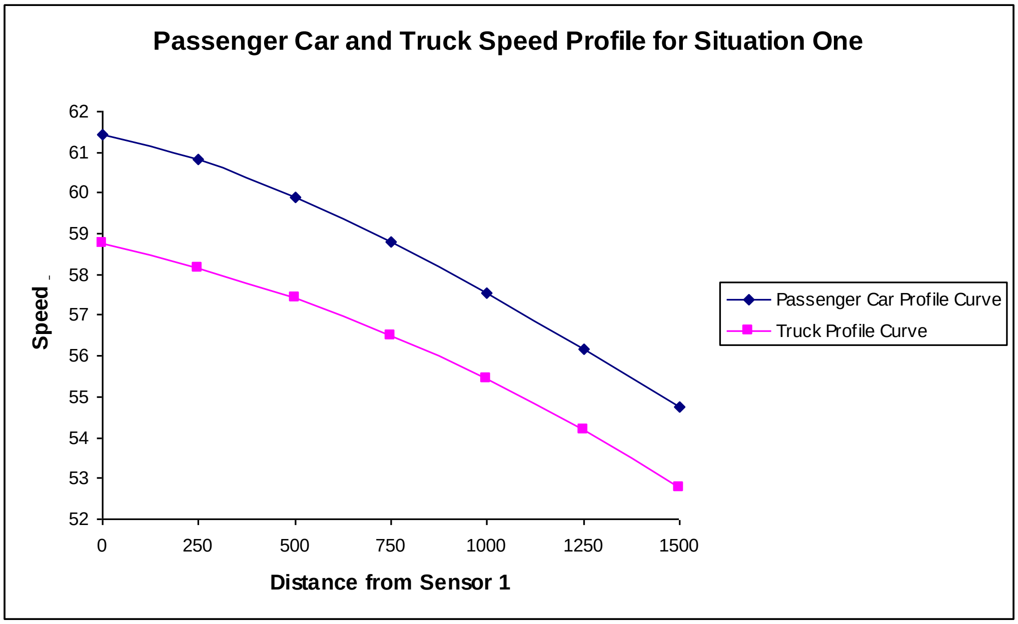

Figure 4.8. Passenger car and truck speed profile curves when PCMS at 750ft

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speed data at seven sensor locations. The t-test was used to compare the measured mean passenger car speed with the measured mean truck speed at seven sensor locations. For an example, at the location of Sensor 1, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 1)

$$H_0:\ \mu_P = \mu_T$$

$$H_1:\ \mu_P \neq \mu_T$$

where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 750 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed being equal to the measured mean truck speed. The alternative hypothesis was interpreted as the measured mean passenger car speed not being equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. Since the P-values of Levene's tests would indicate if the speed variance between the two populations was equal or not, accordingly, the t-tests with equal and unequal variances were used for analysis. **Table 4.3** shows the results of Levene's tests and t-tests for Situation One.

Table 4.3 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation One

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	3.85	.050	5.785	601.092	.000	2.637	.456	1.742	3.532
Speed at Sensor2	Equal variances not assumed	5.352	.021	5.938	583.634	.000	2.649	.446	1.773	3.525
Speed at Sensor3	Equal variances assumed	2.488	.115	5.377	1142	.000	2.486	.462	1.579	3.392
Speed at Sensor4	Equal variances assumed	.374	.541	4.196	1142	.000	2.085	.497	1.110	3.060
Speed at Sensor5	Equal variances assumed	1.372	.242	4.763	1142	.000	2.256	.474	1.327	3.185
Speed at Sensor6	Equal variances not assumed	4.366	.037	3.757	599.079	.000	1.789	.476	.854	2.724
Speed at Sensor7	Equal variances assumed	2.141	.144	4.131	1142	.000	1.930	.467	1.013	2.847

As shown in **Table 4.3**, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variances at the locations of Sensors 3, 4, 5, and 7. At all seven senor locations, the measured mean speeds of passenger cars were significantly larger than the measured mean speeds of trucks based on the results of t-tests. The difference of mean speeds ranged from 1.8 mph to 2.6 mph over 1,500 ft distance. Compared with the curves in **Figure 4.8**, the speed difference between passenger cars and trucks reduced when they were approaching the work zone. The results indicated that though both passenger cars and trucks slowed down when the PCMS was placed at 750 ft away from W20-1, the significant differences of mean speeds (speed variations) between them could spark the cause of vehicle crashes.

4.3.2 Truck Speed Profile Model for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 364 truck speed data were collected in the field experiments. **Table 4.4** shows the descriptive statistics of truck speed data recorded by each sensor. In the table, the minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor location are listed.

Table 4.4 Descriptive Statistics of Truck Speeds with PCMS at 575 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	37	78	62.0	5.8
Speed at Sensor 2	35	72	57.2	6.0
Speed at Sensor 3	36	76	58.6	6.6
Speed at Sensor 4	35	79	58.3	7.1
Speed at Sensor 5	34	77	56.1	7.2
Speed at Sensor 6	32	74	52.0	6.7
Speed at Sensor 7	31	71	51.5	6.7

Note: STD-Standard Deviation

The truck speed profile model when PCMS at 575 ft was developed using the truck speed measurements at the locations of seven sensors. The model development and selection process was the same as the one described in the last subsection. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 61.175 - 0.01x + 9.333e^{-6}x^2 - 4.975e^{-9}x^3 \quad (4.2)$$

X: Distance between a truck location and the Sensor 1 Location ($1 \le x \le 1{,}500$ ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 2 were presented in **Figure 4.9**.

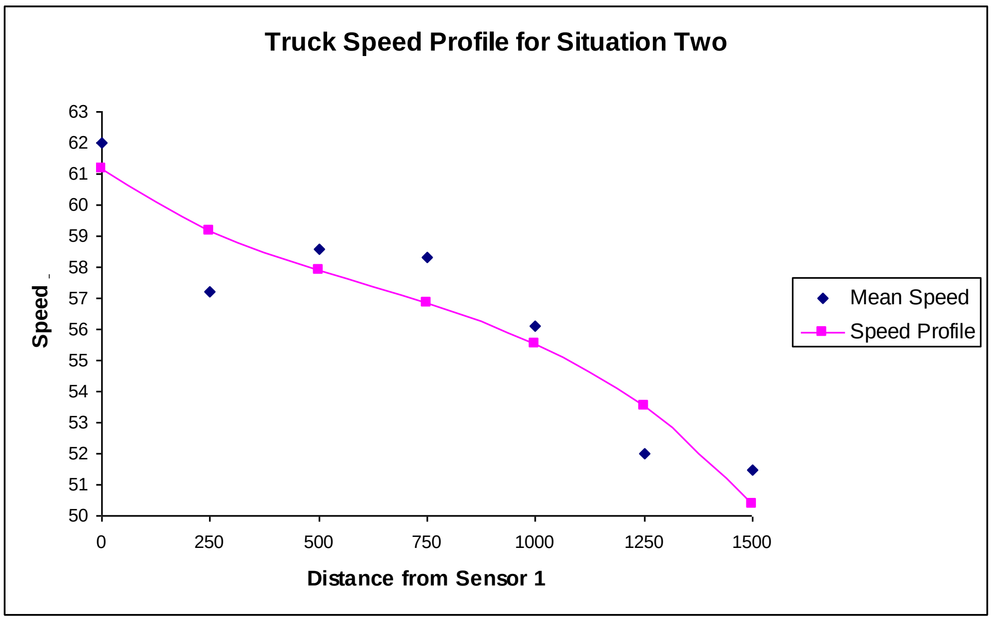

Figure 4.9. Truck speed profile curve for Situation Two

When the PCMS was placed at 575 ft upstream of the W20-1 sign, 761 passenger car speed data were collected in the field experiments. The passenger car speed profile model was developed using the same procedure as the one used for trucks. **Figure 4.10** shows the two curves when PCMS at 575 ft. As shown in **Figure 4.10**, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently.

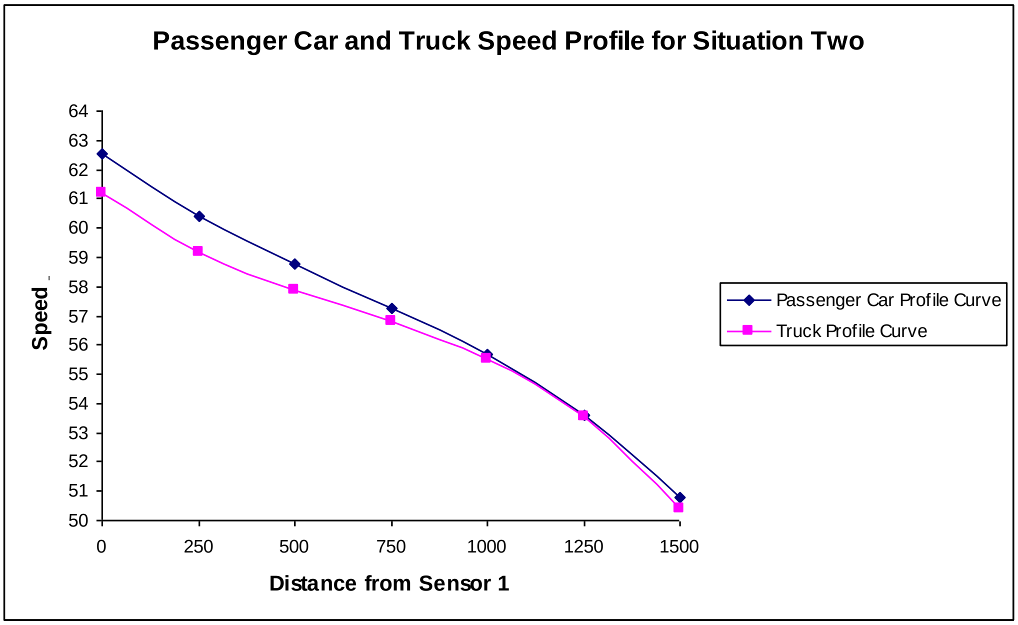

Figure 4.10. Passenger car and truck speed profile curves when PCMS at 575 ft

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speed data at seven sensor locations. For an example, at the location of Sensor 1, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 2)

$$H_0: \mu_P = \mu_T$$

$$H_1: \mu_P \neq \mu_T$$

where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 575 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed being equal to the measured mean truck speed at the Sensor 1 location. The alternative hypothesis was interpreted as the measured mean passenger car speed not being equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. **Table 4.5** shows the results of Levene's tests and t-tests at all seven sensor locations for Situation 2. As shown in **Table 4.5**, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variance only at the Sensor 7 location. At the first two sensor locations (Sensors 1 and 2), the measured mean speeds of passenger cars were significantly higher than those of trucks based on the results of t-tests. When measuring speed starting from the Sensor 3 location, there was no significant difference between the mean speeds of passenger cars and trucks. The difference in mean speeds changed from 1.0 mph to 2.0 mph from the Sensor 1 location to the Sensor 2 location. Compared with the curves in **Figure 4.10**, the speed difference between passenger cars and trucks reduced when vehicles were approaching the work zone. The results indicated that both passenger cars and trucks slowed down and reached an equivalent speed at the Sensor 3 location when the PCMS was placed at 575 ft away from W20-1. Compared with the Situation 1, the Situation 2 was safer for vehicles in the upstream of a work zone because the traveling distance with significant speed difference between passenger cars and trucks was reduced.

Table 4.5 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation Two

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances not assumed	9.907	.002	2.783	824.126	.006	1.095	.393	.323	1.867
Speed at Sensor2	Equal variances not assumed	11.576	.001	4.803	828.586	.000	1.951	.406	1.154	2.748
Speed at Sensor3	Equal variances not assumed	9.497	.002	1.329	805.048	.184	.582	.438	-.278	1.441
Speed at Sensor4	Equal variances not assumed	8.766	.003	.799	806.124	.425	.379	.474	-.552	1.310
Speed at Sensor5	Equal variances not assumed	10.237	.001	1.002	808.998	.317	.483	.482	-.463	1.428
Speed at Sensor6	Equal variances not assumed	3.925	.048	1.568	773.546	.117	.692	.441	-.174	1.559
Speed at Sensor7	Equal variances assumed	1.352	.245	1.368	761.200	.172	.594	.434	-.258	1.445

4.3.3 Truck Speed Profile Model for Situation Three

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 344 truck speed data were collected in the field experiments. **Table 4.6** shows the descriptive statistics of truck speed data recorded by each sensor. The minimum speed, the maximum speed, the mean vehicle speed, and the standard deviation of speeds at each sensor are listed in the table,.

Table 4.6 Descriptive Statistics of Truck Speeds with PCMS at 400 ft

Speed Measurement Location	Min (mph)	Max (mph)	Mean (mph)	STD
Speed at Sensor 1	34	71	58.9	6.2
Speed at Sensor 2	32	71	57.7	6.5
Speed at Sensor 3	23	72	57.5	7.1
Speed at Sensor 4	30	73	57.7	7.6
Speed at Sensor 5	25	73	56.9	7.7
Speed at Sensor 6	22	67	53.9	7.2
Speed at Sensor 7	24	66	52.6	7.0

Note: STD-Standard Deviation

The truck speed profile model when the PCMS placed at 400 ft was developed using the truck speed measurements at the locations of seven sensors. The model development process was the same as the one described in the last section. According to the R square value of each model, the Cubic model was the best fit. The Cubic model is:

$$Y = 58.698 - 0.003x + 4.462e^{-6}x^2 - 3.379e^{-9}x^3 \quad (4.3)$$

X: Distance between a passenger car location and the Sensor 1 Location ($1 \leq x \leq 1{,}500$ ft)

Y: Vehicle speed

The truck speed profile curve and mean speeds at the locations of seven sensors for Situation 3 are presented in **Figure 4.11**.

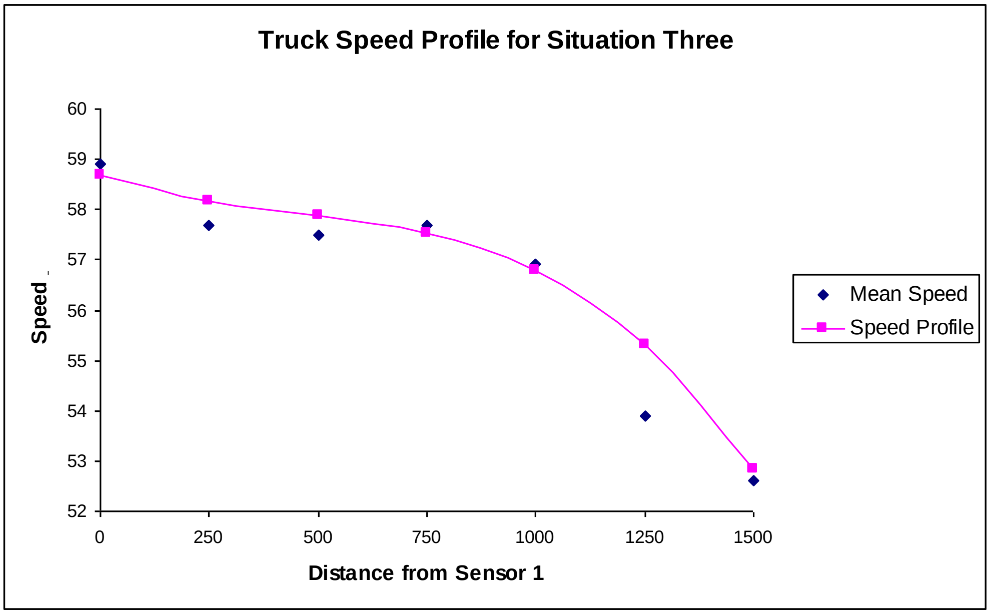

Figure 4.11. Truck speed profile curve when PCMS at 400 ft

When the PCMS was placed at 400 ft upstream of the W20-1 sign, 652 passenger car speed data were collected in the field experiments. The passenger car speed profile model was developed using the same procedure as the one used for trucks. As shown in **Figure 4.12**, the speed profile curves indicated that both passenger cars and trucks slowed down smoothly and consistently.

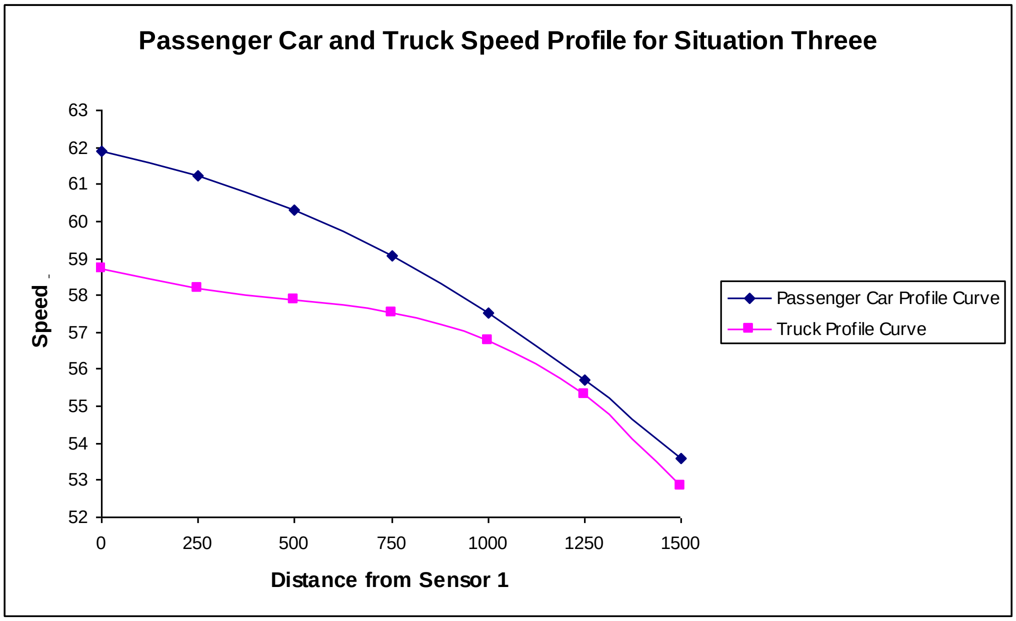

Figure 4.12. Passenger car and truck speed profile curves for Situation Three

To determine the difference of speed reductions between passenger cars and trucks, the Levene's test and t-test were conducted using the measured speeds at seven sensor locations. For an example, at the location of Sensor 1, a null hypothesis (H_0) and an alternative hypothesis (H_1) were defined as follows:

(Case 3)

$$H_0: \mu_P = \mu_T$$

$$H_1: \mu_P \neq \mu_T$$

where μ_P and μ_T = measured mean passenger car speed and measured mean truck speed at the Sensor 1 location, respectively, when the PCMS was placed 400 ft away from the W20-1 sign. The null hypothesis was interpreted as the measured mean passenger car speed being equal to the measured mean truck speed at the Sensor 1 location. The alternative hypothesis was interpreted as the measured mean passenger car speed not being equal to the measured mean truck speed at the Sensor 1 location. A 5% (0.05) level of confidence was used in the t-test. Table 4.7 shows the results of Levene's tests and t-tests at all seven sensor locations for Situation 3.

Table 4.7 Levene's Test and t-test of Measured Passenger Car and Truck Speeds for Situation 3

Independent Samples Test										
		Levene's Test		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Speed at Sensor1	Equal variances assumed	.633	.427	7.571	994	.000	3.213	.424	2.38	4.046
Speed at Sensor2	Equal variances assumed	2.161	.142	6.789	994	.000	3.076	.453	2.187	3.965
Speed at Sensor3	Equal variances assumed	2.438	.119	5.269	994	.000	2.588	.491	1.624	3.552
Speed at Sensor4	Equal variances not assumed	5.178	.023	3.065	784.217	.002	1.605	.542	.577	2.633
Speed at Sensor5	Equal variances not assumed	9.116	.003	1.998	784.217	.046	1.084	.542	.019	2.148
Speed at Sensor6	Equal variances not assumed	5.136	.024	1.074	741.183	.283	.532	.495	-.440	1.503
Speed at Sensor7	Equal variances assumed	3.147	.076	2.199	994	.028	1.069	.486	.115	2.024

As shown in **Table 4.7**, the results of Levene's tests indicated that the passenger cars and trucks had equal speed variances at the locations of Sensors 1, 2, 3, and 7. Only at the Sensor 6 location was the measured mean speed of passenger cars equal to the one of trucks based on the results of t-tests. The mean speed differences changed from 3.2 mph to 1.1 mph from the Sensor 1 location to Sensor 5 location. Compared with the curves in **Figure 4.12**, the measured mean speed difference between passenger cars and trucks reduced when vehicles were approaching the work zone until reaching the Sensor 6 location where they reached an equal speed. However, the measured mean speed difference became significantly different at the Sensor 7 location. Compared with Situation 2, Situation 3 was not safer for vehicles in the upstream of a work zone because the traveling distance with significant speed difference between passenger cars and trucks was increased.

4.4 Summary

In this chapter, the truck and passenger car speed profile models were developed separately for three situations: 1) PCMS at 750 ft away from the W20-1 sign; 2) PCMS at 575 ft away from the W20-1 sign; and 3) PCMS at 400 ft away from the W20-1 sign. When the PCMS was placed at 750 ft away from the W20-1 sign in the upstream of the work zone, at all seven sensor locations, the measured mean speeds of passenger cars were larger than the measured mean speeds of trucks. The results indicated that though both passenger cars and trucks slowed down, the significant differences of mean speeds between them could lead to vehicle crashes.

When the PCMS was placed at 400 ft away from the W20-1 sign in the upstream of the work zone, both passenger cars and trucks slowed down and reached equal speed at the Sensor 6 location. However, the significant mean speed differences existed at the other six locations.

When the PCMS was placed at 575 ft away from the W20-1 sign in the upstream of the work zone, both passenger cars and trucks slowed down and reached equal speed at the Sensor 3 location and thereafter. Compared with Situations 1 and 3, Situation 2 was the safest for vehicles in the upstream of a work zone because the traveling distance with significant speed differences was reduced. Therefore, it indicated that the optimal deployment range of a PCMS in the upstream of a work zone should be near 575 ft away from the W20-1 sign for the trucks and passenger cars.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Truck-related crashes constitute a major safety concern for government agencies, the construction industry, and the traveling public. Due to the rising needs in highway maintenance and construction, the number of work zones is increasing throughout the United States, while at the same time freight movement using trucks is also increasing nationwide. Previous research results indicated that there was a significant increase in crash severity when a truck-related crash occurred in the work zones. To mitigate truck-related crash risks and develop effective countermeasures, the characteristics of truck-related fatal, injury and PDO crashes in Kansas work zones were first investigated systematically. The frequency analysis and tests of independence were utilized for identifying the factors on affecting crash severity level. Then, the truck and passenger car speed profile models in the upstream of the work zone were developed when a PCMS was deployed. The speed reduction differences between passenger cars and trucks were determined using the speed profile models. The results provided insights for the development of best practices for utilizing the PCMS to reduce the risk of truck-related crashes in the work zones.

The authors discovered that 38% of truck drivers were not responsible for the crashes in the work zones. For the fatal crashes, 53% of truck drivers were at fault and were responsible for the crashes. The truck drivers whose ages were between 35 and 44 were the most susceptible group since they accounted for 43% of fatal crashes. There were no younger truck drivers (age<25) involved in fatal crashes. Daytime hours (10:00 a.m.-4:00 p.m.) had the highest frequency for all three types of crashes. Monday was the day on which the fatal and PDO crashes happened most frequently; Tuesday was observed as the day when most of the injury crashes occured. The truck-related crashes occurred when the weather and road surface conditions were favorable; the truck-related crashes did not occur more often in adverse weather. Straight following was the maneuver most truck drivers took before the crash happened. Rear-end crashes were dominant for fatal, injury and PDO crashes. The rural highways in Kansas were the most susceptible area for fatal truck-related crashes. Highways with the 65 mph speed limit had the highest proportion of fatal crashes. More than half of the fatal crashes occurred on straight and level highway work zones. Using the independence test, it was determined that factors such as Light Condition, Vehicle Maneuver, Crash Type, Number of Vehicles, Speed Limit, Area Information, and Traffic Control could affect the crash severity level.

Using the field experiments, it was found that the PCMS was effective in reducing passenger car and truck speeds in the upstream of a one-lane two-way rural highway work zone. The passenger car and truck speed profiles in the upstream of the work zones could be best described using the cubic models. When the PCMS was placed 575 ft away from the first TTC sign (W20-1 sign), the significant speed difference between trucks and passenger cars in the upstream of the work zone was reduced most, which helped reduce the probability of truck-related crash risk. The speed profile models were keys to understand vehicle (both passenger cars and trucks) speed changes and they were used to determine the optimal deployment range of a PCMS in the upstream of work zones. For this research project, the optimal deployment of a PCMS was 575 ft away from the first TTC sign in the upstream of a work zone. The success of this research project provided a roadmap for evaluating the effectiveness of other TTC devices in the work zones.

5.2 Recommendations

The following recommendations are suggested for implementing the results of this research project and for future research.

1. The PCMS was effective on reducing vehicle speeds in the upstream of work zones when it was used properly. The results of field experiments indicated that if the PCMS was not properly placed, the vehicle speeds would fluctuate, thus increasing the probability of vehicle crashes. To maximize the benefits of utilization of a PCMS in the work zones, it is recommended that the PCMS should be placed 575 ft away from the first TTC sign in the upstream of work zones.

2. The optimal deployment of a PCMS in the upstream of a work zone was determined using two specific text messages in the field experiments. Future research is needed to determine whether the optimal deployment range will be different if using other text messages.

3. In the field experiments, the PCMS was utilized to convey text messages to motorists. However, the differences in physical condition among drivers make it difficult to expect the same effect on all drivers. For instance, older drivers might take a longer time to capture text messages displayed on the PCMS. Thus, there is a need to investigate the possibility of using graphics to convey information.

4. In this research project, the PCMS was placed in the upstream of the work zones. Future research is needed to determine the optimal deployment range for a PCMS installed in the other areas of a work zone. These areas included the advance warning area, the transition area, the activity area, and the termination area.

References

AASHTO (1987). *Summary Report on Work Zone Crashes.* Standing Committee on Highway Traffic Safety, American Association of State Highway and Transportation Officials, Washington, D.C.

Bai, Y. and Li, Y. (2006). "Determining Major Causes of Highway Work Zone Accidents in Kansas." Final Report, Kansas Department of Transportation Research Project *KAN37040*, June 2006.

Bai, Y. and Li, Y. (2007). "Determining Major Causes of Highway Work Zone Accidents in Kansas - Phase II." Final Report on Research Sponsored by Kansas Department of Transportation, October 2007.

Benekohal, R. F., Shim, E., and Resende, P. (1995). "Truck Drivers' Concerns in Work Zones: Travel Characteristics and Accident Experiences". *Transportation Research Record. 1509*, Transportation Research Board, Washington, D.C., 55-64.

Benekohal, R. F. and Shim, E. (1999). "Multivariate Analysis of Truck Drivers' Assessment of Work Zone Safety." *Journal of Transportation Engineering*, 398-406.

Bezwada, N. and Dissanayake, S. (2009). "Characteristics of Fatal Truck Crashes in the United States." *Proc., 2009 Mid-Continent Transportation Research Symposium,* Ames, IA.

Chambless, J., Ghadiali, A., Lindly, J. and McFadden, J. (2002). "Multistate Work Zone Crash Characteristics." *ITE Journal*, Institute of Transportation Engineers, 46-50.

Daniel, J., Dixon, K. and Jared, D. (2000). "Analysis of Fatal Crashes in Georgia Work Zones." *Transportation Research Record. 1715,* Transportation Research Board, Washington, D.C., 18-23.

FARS. (2008). “Vehicles Involved in Fatal Crashes by Vehicles Type – State: USA, Year: 2008”. Fatality Analysis Reporting System Encyclopedia. http://www-fars.nhtsa.dot.gov/Vehicles/VehiclesAllVehicles.aspx.

FHWA. (1991a). Section 1051. *Intermodal Surface Transportation Efficiency Act.* Federal Highway Administration, Washington, D.C..

FHWA. (1991b). Section 2002. *Intermodal Surface Transportation Efficiency Act*. Federal Highway Administration, Washington, D.C.

FHWA. (2005). “A Summary of Highway Provisions in SAFETEA-LU.” Program Analysis Team, Office of Legislation and Intergovernmental Affairs, Federal Highway Administration (FHWA). http://fhwa.dot.gov/safetealu/summary.htm.

FHWA. (2009). “Temporary Traffic Control”. *Manual on Uniform Traffic Control Devices for Streets and Highways.* 2009 edition, Federal Highway Administration (FHWA), Washington, D.C.

Garber, N. J. and Woo, T. H. (1990). “Accident Characteristics at Construction and Maintenance Zones in Urban Areas.” *Report No. VTRC 90-R12.* Virginia Transportation Research Council, Charlottesville, VA.

Garber, N. J. and Joshua, S. C. (1990). “Traffic and Geometric Characteristics Affecting the Involvement of Large Trucks in Accidents.” *Report No. VTRC 91-R17.* Virginia Transportation Research Council, Charlottesville, VA.

Garber, N.J. and Zhao, M. (2002). “Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia.” *Transportation Research Record. 1794*, Transportation Research Board, Washington, D.C., 19-25.

Graham, J., Paulsen, R. and Glennon, J. (1978). "Accident Analyses of Highway Construction Zones." *Transportation Research Record. 693*, Transportation Research Board, Washington, D.C., 25-32.

Ha, T. J. and Nemeth, Z. (1995). "Detailed Study of Accident Experience in Construction and Maintenance Zones." Transportation Research Record 1509, pp. 38-45.

Hall, J. W. and Lorenz, V. M. (1989). "Characteristics of Construction-Zone Accidents." *Transportation Research Record. 1230*, Transportation Research Board, Washington, D.C., 20-27.

Hargroves, B. T. (1981). "Vehicle Accidents in Highway Work Zone." *Journal of Transportation Engineering* 107 (TE5), ASCE, 525-539.

Khattak, A. and Council, F. M. (2002). "Effects of Work Zone Presence on Injury and Non-injury Crashes." *Accident Analysis and Prevention* 34, 19-29.

Li, Y. and Bai, Y. (2006). "Fatal and Injury Crash Characteristics in Highway Work Zones." *Proc., Transportation Research Board 87th Annual Meeting*, Washington, D.C.

Li, Y. and Bai, Y. (2008). "Comparison of Characteristics between Fatal and Injury Accidents in the Highway Construction Zones." *Safety Science*, 46(4), 646-660.

Meyers, W.S. (1981). "Comparison of Truck and Passenger-car Accident Rates on Limited-access Facilities." *Transportation Research Record. 808*, Washington, D.C., 48-53.

Mohan, S.B. and Gautam, P. (2002). "Cost of Highway Work Zone Injuries." *Practice Periodical on Structural Design and Construction*, 7(2), 68-73.

Nemeth, Z. A. and Migletz, D. (1978). "Accident Characteristics Before, During, and After Safety Upgrading Projects on Ohio's Rural Interstate System." *Transportation Research Record. 672*, Transportation Research Board, Washington, D.C., 19-23.

NTSB (1992). Safety Recommendation. *Report NTSB/SS-92-02.* National Highway Traffic Safety Administration, Washington, D.C..

Pal, R. and Sinha, K. (1996). "Analysis of Crash Rates at Interstate Work Zones in Indiana." *Transportation Research Record. 1529*, Transportation Research Board, Washington, D.C., 43-53.

Pigman, J. and Agent, K. (1990). "Highway Accidents in Construction and Maintenance Work Zones." *Transportation Research Record. 1270,* Transportation Research Board, Washington, D.C., 12-21.

Richards, S. H. and Faulkner, M. (1981). An Evaluation of Work Zone Traffic Accidents Occurring on Texas Highway in 1977. *Report No: FHWA/TX-81/44+263-3*. Texas Transportation Institute, College Station, TX

Rouphail, N. M., Zhao, S. Y., and Fazio, J. (1988). "Comparative Study of Short- and Long-Term Urban Freeway Work Zone." *Transportation Research Record. 1163*, Transportation Research Board, Washington, D.C., 4-14.

Schrock, D. S., Ullman, G. L., Cothron, A. S., Kraus, E., and Voigt, A. P. (2004). ''An Analysis of Fatal Work Zone Crashes in Texas''. *Report FHWA/TX-05/0-4028-1*, FHWA, U.S. Department of Transportation, Washington, D.C.

Sorock, G. S., Ranney, T. A., and Lehto, M. R. (1996). "Motor Vehicle Crashes in Roadway Construction Work Zones: An Analysis Using Narrative Text from Insurance Claims." *Accident Analysis & Prevention*, 28(1), 131-138.

Thompson, S. K. (2002). *Sampling.* 2nd ed. New York: John Wiley & Sons, Inc.

Wang, J., Hughes, W., Council, F., and Paniati, J. (1995). "Investigation of Highway Work Zone Crashes." Final Report *FHWA-RD-96-100.* Federal Highway Administration, Washington, D.C.

Wang, J., W. Hughes, F. Council and J. Paniati (1996). “Investigation of highway work zone crashes: What we know and what we don't know.” *Transportation Research Record. 1529*, Transportation Research Board, Washington, D.C. 54-62.

Appendix I

Index of the tables included in Appendix I

Table 1 Observations of Gender

Number	Name of Observation
0	Male
1	Female

Table 2 Observations of Age

Number	Name of Observation
1	15-19
2	20-24
3	25-34
4	35-44
5	45-54
6	55-64
7	65+

Table 3 Observation of Driver Factor

Number	Name of Observation
0	No Fault for Truck Driver
1	Under influence of drugs
2	Under influence of alcohol
3	Failed to yield right of way
4	Disregarded traffic signs, signals, or markings
5	Exceeded posted speed limit
6	Too fast for conditions
7	Made improper turn
8	Wrong side or wrong way
9	Followed too closely
10	Improper lane change
11	Improper backing
12	Improper passing
13	Improper or no signal
14	Improper parking
15	Fell asleep
16	Inattention
17	Did not comply-license restrictions
18	Other distraction in or on vehicle
19	Avoidance or evasion action
20	Impeding or too slow for traffic
21	Ill or medical condition
22	Distraction-cell phone
23	Distraction-other electronic devices
24	Aggressive/Antagonistic driving
25	Reckless/Careless driving
26	Other/unknown

Table 4 Observations of Crash Time

Number	Name of Observation
1	6:00 a.m.-10:00 a.m.
2	10:00 a.m.-4:00 p.m.
3	4:00 p.m.-8:00 p.m.
4	8:00 p.m.-6:00 a.m.

Table 5 Observations of Day of Week

Number	Name of Observation
1	Monday
2	Tuesday
3	Wednesday
4	Thursday
5	Friday
6	Saturday
7	Sunday

Table 6 Observations of Month

Number	Name of Observation
1	January
2	February
3	March
4	April
5	May
6	June
7	July
8	August
9	September
10	October
11	November
12	December

Table 7 Observations of Light Condition

Number	Name of Observation
1	Daylight
2	Dawn
3	Dusk
4	Dark: street lights on
5	Dark: no street lights

Table 8 Observations of Weather Condition

Number	Name of Observation
1	No adverse conditions
2	Rain, Mist, Drizzle
3	Sleet
4	Snow
5	Fog
6	Smoke
7	Strong winds
8	Blowing dust, sand
9	Freezing rain
10	Rain & fog
11	Rain & wind
12	Sleet & fog
13	Snow & winds
14	Other

Table 9 Observations of Road Surface Condition

Number	Name of Observation
1	Dry
2	Wet
3	Snow or slush
4	Ice or snowpacked
5	Mud, dirt or sand
6	Debris
7	Other

Table 10 Observations of Truck Maneuver before Crash

Number	Name of Observation
1	Straight/following road
2	Left turn
3	Right turn
4	U-turn
5	Overtaking (passing)
6	Changing lanes
7	Avoiding Maneuver
8	Merging
9	Parking
10	Backing
11	Stopped awaiting turn
12	Stopped in traffic
13	Illegal parked
14	Disabled in roadway
15	Slowing or stopping
16	Other

Table 11 Observations of Crash Type

Number	Name of Observation
1	Other non-collision
2	Overturned
3	Collision with pedestrian
4	Collision with parked motor vehicle
5	Collision with railway train
6	Collision with pedalcycle
7	Collision with animal
8	Collision with fixed object
9	Collision with other vehicle: head on
10	Collision with other vehicle: rear end
11	Collision with other vehicle: angle-side impact
12	Collision with other vehicle: sideswipe-opposite direction
13	Collision with other vehicle: sideswipe-same direction
14	Collision with other vehicle: backed into
15	Collision with other vehicle: other
16	Other object

Table 12 Observations of Vehicle Body Type

Number	Name of Observation
1	Commercial truck with commercial truck
2	Commercial truck with vehicle
3	Commercial truck with motorcycle
4	Commercial truck with pedestrian/worker/animal
5	Commercial truck with object
6	Vehicle with vehicle
7	Vehicle with motorcycle
8	Vehicle with pedestrian/worker/animal
9	Vehicle with object
10	other

Table 13 Observations of Road Class

Number	Name of Observation
1	Interstate highway
2	Other freeways & expressways
3	Other principal arterial
4	Minor arterial
5	Major collector
6	Minor collector
7	Local roads

Table 14 Observations of Road Character

Number	Name of Observation
1	Straight and level
2	Straight on grade
3	Straight at hillcrest
4	Curved and level
5	Curved on grade
6	Curved at hillcrest
7	Other

Table 15 Observations of Crash Location

Number	Name of Observation
1	Non-intersection
2	Intersection
3	Intersection-related
4	Interchange area
5	On crossover
6	Parking lot or driveway
7	Roadside (including shoulder)
8	Median
9	Parking lot, rest area traffic way
10	Other

Table 16 Observations of Surface Type

Number	Name of Observation
1	Concrete
2	Blacktop
3	Gravel
4	Dirt
5	Brick
6	Other

Table 17 Observations of Road Special Features

Number	Name of Observation
1	None
2	Bridge
3	Bridge overhead
4	Railroad bridge
5	Railroad crossing
6	Interchange
7	Ramp
8	Other

Table 18 Observations of Area Information

Number	Name of Observation
0	Urban
1	Rural

Table 19 Observations of Traffic Controls

Number	Name of Observation
1	None or inoperative
2	Officer or flagger
3	Traffic signal
4	Stop sign/signal
5	Flasher
6	Yield sign
7	RR gates or signal
8	RR crossing signal
9	No passing zone
10	Center/edge lines
11	Other control

Table 20 Observations of Pedestrian Factor

Number	Name of Observation
1	Under influence of illegal drugs
2	Under influence of alcohol
3	Failed to yield right of way
4	Disregarded traffic controls
5	Illegally in roadway
6	Pedalcycle violation
7	Clothing not visible
8	Inattention
9	Distraction-cell phone

Table 21 Observations of Environment Factor

Number	Name of Observation
1	Fog, smoke, or smog
2	Sleet, hail or freezing rain
3	Blowing sand, soil or dirt
4	Strong winds
5	Rain, mist, or drizzle
6	Animal
7	Vision obstruction: building, vehicles, objects made by humans
8	Vision obstruction: vegetation
9	Vision obstruction: glare from sun or headlights
10	Reduced visibility due to cloudy skies
11	Falling Snow
12	Malfunction of facility

Table 22 Observations of Vehicle Factor

Number	Name of Observation
1	Brakes
2	Tires
3	Exhaust
4	Headlights
5	Window or windshield
6	Wheels
7	Trailer coupling
8	Cargo
9	Unattended or driverless (in motion)
10	Unattended or driverless (not in motion)
11	Other lights

Appendix II

Data Collection Sheet (A Portion)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		Responsible Drvier		Time Information				Climatic Environment			Crash Information				
2	Crash No.	Age	Gender	Time	Day	Month	Year	Light Condition	Weather Condition	Road Sur. Condition	Vehicle Maneuver	Crash Severity	Crash Type	Vehicle Type	No. of Vehicles
3	200000901520	4	0	4	6	6	1	2	1	1	1	1	12	2	3
4	200000902310	3	0	2	5	7	1	1	1	1	1	1	9	2	2
5	200000902560	7	0	2	5	8	1	1	1	1	1	1	10	1	2
6	200000903040	4	0	1	2	10	1	5	2	2	1	1	11	2	3
7	200100900950	3	0	3	2	4	2	1	1	1	7	1	10	2	2
8	200100902710	4	0	4	7	8	2	5	1	1	1	1	2	10	1
9	200100903630	4	0	2	6	10	2	1	1	1	6	1	9	2	2
10	200100903750	4	0	3	7	11	2	5	1	1	1	1	11	2	2
11	200200793000	7	0	2	1	2	3	1	1	1	1	2	8	5	7
12	20020090190B	4	0	4	5	6	3	3	1	1	2	1	11	2	2
13	200200901920	4	0	1	3	7	3	1	1	1	1	1	1	10	1
14	200200904150	6	0	3	7	11	3	5	1	1	1	1	11	2	2
15	200200904360	5	0	2	1	12	3	1	1	1	1	1	11	2	2
16	200300901470	5	0	2	5	5	4	1	1	1	1	1	2	9	3
17	200300901750	4	0	2	1	4	4	1	1	1	1	1	13	2	3
18	200300902770	3	0	4	6	9	4	5	1	1	14	1	4	2	2
19	200300903580	5	0	2	4	11	4	1	1	1	1	1	10	1	2
20	200400900840	6	0	1	4	4	5	1	1	1	1	1	9	2	2
21	200400901090	6	0	2	1	5	5	1	1	1	1	1	10	2	3
22	200400901640	5	0	2	1	6	5	1	1	1	1	1	10	2	4
23	200400901740	3	0	3	2	6	5	1	1	1	1	1	10	2	6
24	20040090209B	4	0	2	1	6	5	1	1	1	1	1	10	2	3
25	200400902220	3	0	2	3	8	5	1	1	1	1	1	3	4	2
26	200400902450	4	0	2	1	9	5	1	1	1	16	1	12	2	2
27	200400902770	6	0	4	1	9	5	5	1	1	1	1	10	3	3
28	200400903900	4	0	1	5	12	5	2	1	1	1	1	10	2	2
29	200500900290	4	0	4	5	2	6	5	1	1	1	1	9	2	2
30	200500902250	5	0	2	1	8	6	1	1	1	5	1	11	2	2
31	200500902620	4	0	1	3	8	6	1	1	1	1	1	10	2	2
32	200600901970	4	0	3	3	6	7	1	1	1	12	1	10	2	3
33	200600902180	4	0	2	3	7	7	1	1	1	1	1	11	3	2
34	200600902290	6	0	3	6	8	7	1	1	1	1	1	12	2	3
35	20070090284C	5	0	2	4	12	8	1	1	2	7	1	11	2	2
36	200800950620	5	0	1	4	6	9	1	7	1	1	1	9	2	2
37	200800951740	5	0	4	4	12	9	5	1	1	7	1	9	2	2

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1	Road Information											Contribution Factor						
2	Road Class	Road Character	No. of Lanes	Speed Limit	Crash Location	Surface Type	Road Sp. Feature	Area info.	TC1	TC2	TC3	DF1	DF2	DF3	DF4	Pedes. Factor	Envir. Factor	Vehicle Factor
3	1	2	4	60	1	2	1	1	9	10	11	0						
4	2	1	2	65	1	1	1	1	10			0						
5	2	2	4	45	1	2	1	1	11			6	16					
6	2	2	4	70	1	2	2	4	10			0						
7	2	1	2	65	1	2	1	1	2	10		4	16	5				
8	1	2	4	60	4	1	6	1	4	10		4	6	15				
9	1	1	4	60	1	1	1	1	10	11		4	6	8	16			
10	2	1	2	65	2	2	1	1	4	9	10	0						
11	1	5	4	60	8	2	2	0	10			21						
12	2	1	2	60	3	2	1	1	10			7						
13	1	4	4	50	7	2	1	0	10			5						
14	2	3	2	65	1	2	1	1	9	10		0						
15	2	2	2	65	1	2	1	1	10			0						
16	2	1	4	60	1	2	7	1	9	10		0						
17	2	2	2	65	1	2	1	1	2	4	10	4	6	15	16			
18	1	1	4	70	1	2	1	1	10			0						
19	2	2	2	65	1	2	1	1	2	10		16						
20	2	1	2	65	4	2	6	1	9	10		0						
21	2	1	2	65	1	1	1	1	2	10		16						
22	2	1	2	65	1	1	1	1	10			16						
23	2	1	2	65	1	1	1	1	2	10		15	16					
24	2	1	2	65	1	2	1	1	2	10		4	6	16				
25	3	4	4	40	1	2	1	0	10			16						
26	2	3	2	65	1	2	1	1	10			19						
27	2	1	4	55	3	2	1	0	3	10		0						
28	2	2	4	60	1	1	2	1	10			16						
29	2	1	2	65	1	1	1	1	10			0						
30	2	2	2	55	1	2	1	1	5	9	10	4	5	6	16			
31	2	2	2	65	1	2	1	1	2	10		16						
32	2	1	2	65	1	2	1	1	2	9	10	0						
33	2	1	2	65	2	2	1	1	9	10		0						
34	2	1	2	65	1	2	1	1	10			0						
35	2	1	2	65	2	1	1	0	4			19						
36	2	1	2	65	1	2	1	1	9	10		0						
37	2	2	4	45	1	1	1	1	10			19						

TC: Traffic Control; DF: Driver's Factor