TTI: 0-6860

Develop Metrics of Tire Debris on Texas Highways: Technical Report

Technical Report 0-6860-1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-6860-1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-16/0-6860-1		
4. Title and Subtitle DEVELOP METRICS OF TIRE DEBRIS ON TEXAS HIGHWAYS: TECHNICAL REPORT		5. Report Date Published: June 2017 6. Performing Organization Code
7. Author(s) Raul E. Avelar, Michael P. Pratt, Jeffrey D. Miles, Tomas Lindheimer, Nada Trout, and Jason Crawford		8. Performing Organization Report No. Report 0-6860-1
9. Performing Organization Name and Address Texas A&M Transportation Institute College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-6860
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483		13. Type of Report and Period Covered Technical Report: January 2015–June 2016 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Develop Metrics for Tire Debris on Texas Highways

URL: http://tti.tamu.edu/documents/0-6860-1.pdf

16. Abstract

This research effort estimated the amount, characteristics, costs, and safety implications of tire debris on Texas highways. The metrics developed by this research are based on several sources of data, including a statewide survey of debris removal practices, field data from a probability sample of Texas roads, Texas Department of Transportation crash databases, and publically available reports on economic and environmental impact of road debris.

A statewide survey found differences in road debris removal practices among districts. A cost analysis showed that the unit cost of debris removal activities increases with increasing proportion of contractor debris removal.

Data from a probability sample of Texas highways were obtained. This probability sample represented approximately 2289 lane-miles, or 443 centerline miles, of Texas highways. A total of 14,998 pieces of tire debris were identified from this sample, and their dimensions were estimated using an image-processing procedure.

A safety assessment of tire debris on Texas highways was performed. It was found that tire debris crashes are extremely rare, amounting to less than 0.1 percent of all crashes in Texas. However, this research found that the odds of this type of crash increase with increasing speed limits, truck percent, and number of lanes, as well as on rural rather than urban facilities.

A suit of statewide metrics of tire debris metrics was generated. It is estimated that between 1,389.2 and 7,226.1 metric tons of tire debris were left on Texas highways last year. Between 501.4 and 3,616.3 metric tons corresponded to pieces of tire debris 64 in.^{2} or bigger. The statewide generation rate of tire debris was estimated to be between 10.27 and 13.94 lb per mile of highway per week.

17. Key Words	18. Distribution Statement
Tire Debris, Road Debris, Maintenance, Maintenance Costs, Safety, Debris Removal	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	204	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Report 0-6860-1
Project 0-6860
Project Title: Develop Metrics for Tire Debris on Texas Highways

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published: June 2017

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors thank Sonya Badgley, the research project manager for the TxDOT Research and Technology Implementation Office. The research team especially thanks Brandye Munn for providing crucial data for this work and for her feedback throughout this research effort.

The authors thank all the members of the project monitoring committee:

- Brandye Munn, TxDOT Maintenance Division.
- Carolyn Dill, TxDOT Maintenance Division.
- Charlotte Aslin, TxDOT Atlanta District.
- Danny Magee, Laredo District.
- David Salazar, Laredo District.
- Larbi Hanni, TxDOT Traffic Operations Division.
- Jason Dupree, Atlanta District.
- Kellie Pierce, TxDOT Traffic Operations Division.
- Dennis Markwardt, Maintenance Division.
- Debra Vermillion, TxDOT Traffic Operations Division (retired).

The authors also thank the following Texas A&M Transportation Institute employees who provided assistance with data collection, data reduction, and data processing on this project:

- George Gillette, student intern.
- Dan Walker, assistant research specialist.
- Caitlin Sheehan, student assistant.
- Abigail Carine, student worker.
- Mehdi Mohades, graduate student worker.
- Ivan Lorenz, research specialist.
- Stacey Alejandro, office assistant.
- Jeremy Dai, graduate student worker.
- Ashesh Pant, assistant transportation researcher.
- Maria C. Rodriguez, student worker.
- Crystal Salazar, student technician.
- John Graber, assistant transportation researcher.
- Colby Arthur, research assistant.
- Nick Wood, associate transportation researcher.

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LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation or Acronym	Description
AAA	American Automobile Association
AADT	Annual Average Daily Traffic
AAH	Adopt-a-Highway Program
ADOT	Arizona Department of Transportation
ARDVAC	Automated Roadway Debris Vacuum
Caltrans	California Department of Transportation
CI	Confidence Interval
CRIS	Crash Records Information System
DOT	Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
FY	Fiscal Year
GPS	Global Positioning System
HT	Horvitz-Thomson
IRB	Institutional Review Board
KAB	Keep America Beautiful Inc.
MMS	Maintenance Management System
NASS-CDS	National Automotive Sampling System—Crashworthiness Data Set
RHINo	Road-Highway Inventory Network
SE	Standard Error
SRS	Simple Random Sample
STU	Scrap Tire Unit
TCEQ	Texas Commission on Environmental Quality
TTI	Texas A&M Transportation Institute
TD	Tire Debris
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation

UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department Of Transportation
VMT	Vehicle-Miles Traveled
VRRD	Vehicle-Related Road Debris
VSL	Value of Statistical Life
WO	Work Order

CHAPTER 1. INTRODUCTION

The overall objective of this research effort is to investigate the volume, characteristics, costs, and safety implications associated with tire debris (TD) on Texas highways since no metrics of TD currently exist for the state of Texas.

Chapter 2 includes a literature review of previous research conducted on the topic of TD and its implications. This chapter includes literature sources that identify and describe the volume of TD produced on U.S. highways, the costs of removing TD for various jurisdictions in the United States, TD disposal practices around the country, and the involvement of TD in crashes.

Chapter 3 summarizes a statewide survey of Texas Department of Transportation (TxDOT) districts concerning their TD removal practices. The chapter provides an overall view of the survey design and process followed to contact Texas districts and summarizes the responses received from the districts interviewed. In addition to the responses to the survey, this chapter also presents an analysis on the cost of road debris removal in fiscal year (FY) 2013 and 2014. This analysis uncovered key differences between districts regarding debris removal activities and contactors' pay in proportion to debris removal work.

Chapter 4 documents the methods and activities required to obtain data from a set of sites statistically representative of Texas highways. This chapter documents the design and development of a probability sample, the rationale of the sampling procedure, and the optimization of the sampling parameters prior to data collection. This chapter also outlines the work plan developed to collect the field data and general considerations adopted prior to begin data collection. This chapter also documents the development and fine-tuning of a high-capacity image acquisition system for collecting a massive photographic database from the district visits. This chapter provides a brief description of the analytical framework developed for processing the photographic database. This chapter also describes the collection and processing of samples of TD obtained from the field visits.

Chapter 5 documents a safety assessment of TD on Texas highways. The researchers present a description of the mining and analysis of the Texas crash database, including a revision of 2,247 crash narratives in search of direct evidence of TD crashes. This chapter next presents various exploratory analyses of the trends of TD crashes in Texas and a formal statistical assessment of the TD crashes identified.

Chapter 6 provides statewide estimates of TD for Texas. This chapter describes the methodology to obtain estimates for the following key metrics: amount of observable TD, frequency of debris removal activities, TD generation rates, and total amount of TD generated yearly on Texas highways. Additionally, this chapter presents a cost analysis of TD removal, disposal, and its safety outcomes. Finally, conclusions and recommendations are presented at the end of this chapter.

In addition to the six chapters described above, this report has a list of references and three appendices.

CHAPTER 2. LITERATURE REVIEW

This chapter comprises a comprehensive literature review on the topic of TD. The authors reviewed sources that identify and describe the volume of TD produced on U.S. highways, the costs to various jurisdictions for removing TD, the procedures for how TD is disposed of around the country, and previous research that investigated the involvement of TD in crashes. This literature review also identified knowledge gaps that the researchers remained mindful of during subsequent tasks.

VOLUME OF TD PRODUCED ON U.S. HIGHWAYS

The U.S. Environmental Protection Agency (EPA, n.d.) estimated that the United States in 2003 generated 290 million scrap tires. EPA reported that about 80 percent of this quantity was absorbed by various markets for scrap tires, including fuel generation and recycling for construction projects or rubber products. Another 5.7 percent of the scrap tires were retreaded. Approximately 27 million of these tires (or 9.3 percent) were disposed of in landfills or monofills. These percentages were a significant improvement from previous years. In another document, EPA (1999) reported that the total estimate of scrap tires in the United States for 1996 was 266 million (only 9 percent less than in 2003), but the number of tires that ended up in landfills and stockpiles (legal or illegal) was significantly higher—64 million for 1996.

Keep America Beautiful (KAB) is a large nonprofit organization that conducts significant volunteer-based campaigns to educate communities to take action to keep public spaces clean (Keep America Beautiful Inc., 2013). In its 2015 annual report (Keep America Beautiful Inc., 2015), the nonprofit reported that the Great American Cleanup—one of its largest programs—reached out to 20,000 communities across the United States (including activities in all 50 states, Puerto Rico, and parts of Canada). During that year, the report highlights picking up 148 million lb of litter and debris, among other achievements. Removal activities covered 95,000 mi of roads, streets, highways, and outdoors trails, recovering 918,000 tires for recycling, compared to 377,000 tires collected the previous year. The efforts from this program, however, include materials recovered from waterways and parks, not just roadways.

The 2009 National Litter Study

The 2009 National Litter Study (Mid Atlantic Solid Waste Consultants, 2009) was funded by KAB and conducted by Mid Atlantic Solid Waste Consultants. The final report stated that 51 billion pieces of litter were left on U.S. roads in 2009, and 4.6 billion pieces were larger than 4 in. These statistics were based on data obtained from 240 study sites selected from a national sampling of states that weighted each state by their number of road miles.

The final sample represented 45 states, with a sample stratified by four types of roads (national highways, state highways, county roads, and municipal roads) and by road character (urban and rural). In total, eight strata were represented in the sample. Site selection was not entirely at random but was based on proximity to select metropolitan areas that served as hubs of operations. All eight types of roads were randomly selected from a 10-mi radius around the centroids of each of the metropolitan areas using a geographic information systems database. The radius was extended to 40 mi for larger metropolitan areas.

Consultants from the 2009 national study (Mid Atlantic Solid Waste Consultants, 2009) calculated rates of litter per mile by type of road found in their sample of U.S. roads. These consultants estimated the amount of debris per mile is proportional to the hierarchy of functional class (i.e., more litter per mile at a higher functional class). This trend also implies that debris frequency should correlate with traffic volume. The same report asserted that TD originated at a rate of 99 pieces per mile, or 3.02 percent of all accumulated litter found. This document also made the distinction of fresh litter, of which tire pieces represented 3.00 percent, or 39 pieces per mile.

A nationwide survey of state departments of transportation (DOTs) conducted by Andres (1993) reported that rubber and leather constitute 2.7 percent of municipal solid waste by weight and 6.1 percent by volume.

Volume of TD in Various Places in the United States

One of the most relevant studies on this matter was conducted in 1999 by Carey and sponsored by the Arizona Department of Transportation (ADOT). In this study, the author reported an estimate of 3.3 tons of TD generated weekly in the Phoenix metropolitan area in 1998. In terms of the total amount of debris, the same report stated that the Phoenix Maintenance District estimated collecting 1,316 tons of debris weekly from state system highways in the

Phoenix metropolitan area (any type of debris). ADOT personnel at the Durango maintenance yard estimated processing about 364 tons of road debris per day coming from the state highways under their jurisdiction.

In the ADOT study (Carey, 1999), the author reported that debris volumes vary with traffic volumes by location and by season. Based on an interview with Arizona district managers in December 1998, the author reported that about 25.3 tons of TD were collected each week from seven out of nine ADOT maintenance districts. The yearly projection of that quantity amounts to 1,691 tons (1861 metric tons) of TD generated in Arizona highways in 1998.

The researcher from a 1991 TD study in Pennsylvania (TriLine Associates Inc., 1992) visited 138 randomly selected highway segments in that state. This study found that TD was the fifth most prominent type of debris in general, and the most frequent type of accidental debris found on Pennsylvania roads. In this study, tire shreds represented 6 percent of all litter (percentage by count of litter items). The author reported that most complaints about litter are in response to large pieces of debris, typically very prominent and visually unpleasant, such as tire shreds.

The Department of State Police in 2000 (Department of State Police, Virginia, 2000) conducted a similar study of TD in Virginia. The Virginia Department of Transportation collected data for an eight-week period (May 30 to July 30, 1999) at three locations. The resulting amount of TD was 42,997 lb collected from I-95; 42,475 lb from I-81; and 42,050 lb from I-81/I-77. In total, 127,522 lb of TD was found over a distance of 658 mi of interstate highway during that eight-week period. This finding implies a rate of about 24 lb per mile per week.

Lee et al. (2005) reported that California spent about 6 percent of its annual maintenance budget in 1993 (about $23 million) to remove 218,000 m^3 (7,698,597 ft^3) of litter from its highways and freeways. It is unclear from this statistic, however, what proportion of those quantities represent TD specifically.

Research by Page and Woodrooffe (2009) reported that a survey of Florida roads in 2006 found TD constituting 14 percent of all visible litter in that state. This same research reported that 4.4 million tons of solid waste in 1990 (or 2.7 percent) represented rubber and leather collected by municipalities. The volume-to-weight ratio of these materials, estimated at 2.2, was the highest among 11 types of debris identified.

Difference between Retread and New Tires

Several researchers have tried to quantify if there is any overrepresentation of retread tires in roadside TD. Although that question is not the purpose of this project, potential insights may assist the current research effort.

In the ADOT study (Carey, 1999), the researcher collected and examined TD from the Phoenix, Arizona, metropolitan area in order to assess its quantity and composition. This study hypothesized that TD, as well as other types of roadway debris, may represent an important concern to highway safety when present, but its occurrence is relatively rare. The author attempted to estimate the expected composition of TD by accounting for exposure (vehicle-miles traveled [VMTs]) and number of tires in the vehicle fleet. Among other analyses, the author made a comparison between the expected and observed compositions in the data he collected for that study. The author prepared a similar comparison between observed and expected proportions of debris from the data collected by two previous studies funded by the American Trucking Association. That supplemental comparison strongly suggested truck tires being overrepresented in the debris he found in Phoenix by a factor of 1.42 (light truck) or 1.43 (medium/heavy truck). This calculation was based on adjustment factors for federal estimates of vehicle travel and the average number of tires per vehicle type for 1995.

More recently, in 2007, the University of Michigan Transportation Research Institute (UMTRI) conducted a debris survey in Florida, California, Indiana, Arizona, and Virginia (Page and Woodrooffe, 2009). UMTRI collected 85,000 lb of rubber debris that provided approximately 1,500 truck tire samples for subsequent failure analysis. UMTRI collected 1,700 tire fragments and 300 casings and classified them as original equipment tread or retreaded tires. The protocol given to field collection crews specified that “only casings or shreds from large trucks are required. Tire shreds of a minimum 2 ft (0.6 m) in length and 4 in. (10.16 cm) in width” (p. 50).

Volume of TD in Texas

The most recent audit report by the Texas Commission on Environmental Quality (TCEQ, 2010) explains the role of this agency in overseeing the collection, processing, storage, and recycling or disposal of scrap tires in Texas. This document reported 26 million tires discarded in Texas in 2009. TCEQ requires of different stakeholders the documentation of scrap tire volumes, from generation to disposal. The most recent data of scrap tire final use or landfill disposal in this report correspond to 2009 and are reproduced in Table 1.

Table 1. Texas Scrap Tire Usage and Landfill Disposal in 2009: Table 1 from *Tracking the Fate of Scrap Tires in Texas: An Audit Report* (TCEQ, 2010).

Category	Pounds	Scrap Tire Units*	Percentage of Total
Land Reclamation	100,262,600	5,013,130	19%
Tire-Derived Fuel	166,195,200	8,309,760	32%
Crumb Rubber	29,743,080	1,487,154	6%
Septic/Leachate Drainage	58,413,660	2,920,683	11%
Other End Uses	26,706,060	1,335,303	5%
End Uses Subtotal	**381,320,600**	**19,066,030**	**73%**
Landfill Disposal	140,592,560	7,029,628	27%
Total	**521,913,160**	**26,095,658**	**100%**

*Scrap tire unit (STU). 1 STU = 20 lb of scrap tire material. This unit is used because scrap tire material can take many different forms.

Since 1986, Texas has had in place “Don’t Mess with Texas,” an outreach campaign to keep highways free of litter (Texas Department of Transportation, 2014). The campaign has financed and published a series of studies on roadway litter in Texas in order to support its different programs. One of these studies was conducted by NuStats, and published in 2010 (NuStats, 2010). This study collected and characterized litter from four types of roadways maintained by TxDOT (interstate highways, U.S. highways, state highways, and farm-to-market roads). The foundation of this study was a probability sample of 129 Texas sites, with each site constituting 1000 ft of roadway length. Using this sample, the consulting firm developed statewide projections for various types of litter. This study estimated that 1.1 billion pieces of litter were left on Texas roads during 2009. Although only a fraction of that grand total, tire parts represented about 5 percent (or 55 million pieces) of all roadway litter. However, it is not clear if this category includes tire rubber only, or if other items, such as tire rims, are included as well.

This study states that rubber/leather materials comprised the fourth most common type of litter left on Texas roads (after cigarette butts, paper pieces, and metals). Compared to results from a similar study (NuStats, 2005), the 2009 study found a 33 percent increase in the number of litter pieces since 2005, though the statistical analysis in the 2010 study did not have enough statistical power to find such an increase statistically significant.

In addition to its statewide characterization of litter, the NuStats study (2010) explored the correlation of litter frequency to various ancillary variables suspected as influential in the litter-generation process. This exploratory analysis found a modest but statistically significant correlation between litter density and average daily traffic counts ($r = +0.265$, $p\text{-value} = 0.01$ from the null hypothesis of this correlation equals zero).

TD Physical Properties

A set of physical properties of scrap tires is provided by the *User Guidelines for Waste and Byproduct Materials in Pavement Construction*, published by the Federal Highway Administration (FHWA) (2012). The research team deemed some of these properties useful for developing comparable volume estimates from the literature review, given the variety of metrics of TD volumes developed by different researchers.

According to this report, a typical scrapped automobile tire is a steel-belted radial tire (the most common type in the United States), and it weighs 20 lb. This number is consistent with the STU defined by TCEQ (2010). Only 12 to 13 lb of the typical tire consists of recoverable rubber, most likely composed of 35 percent natural rubber and 65 percent synthetic rubber. According to the same report, a typical truck tire weighs 40 lb. According to the Washington State Department of Ecology (2014), a light truck tire with a rim of 17 in. or less weighs about 35 lb. In contrast, a large truck tire (i.e., semi-truck tire) weighs between 100 and 110 lb.

Additionally, the FHWA (2012) guidelines state that the typical tire shred size (from both passenger cars and trucks) varies from 1 in. to 18 in. The most common particle size ranges from 4 in. to 8 in. These particles are flat pieces of rubber, irregularly shaped with jagged edges that sometimes contain sharp pieces of metal (which are parts of the steel belt or beads from the tire that generated the shred). The average loose density of tire shreds ranges from 24 lb/ft^3 to 33 lb/ft^3. Tire chips, in turn, are more uniformly sized pieces of rubber, ranging from 0.5 in. to 3 in. in size. Their loose density is slightly smaller because they do not include metal pieces; in this case, density ranges from 20 to 30 lb/ft^3. Pieces of tread coming from retread tires tend to be significantly larger, but they are found less frequently.

COSTS OF REMOVING TD

The 2009 National Litter Study estimated that it costs U.S. governments, businesses, educational institutions, and volunteer organizations around $11.5 million annually to clean road litter (Mid Atlantic Solid Waste Consultants, 2009). Page and Woodrooffe (2009) articulated that removing tires and TD often requires additional costs, such as sorting before disposal because casings and tire shreds are not universally accepted in landfills. The disposal of these materials, in general, represents a significant cost to jurisdictions. The alternative of leaving this debris on the roadway carries negative environmental impacts, such as zinc and lead runoff, as well as the potential for harboring harmful creatures, such as snakes. As mentioned earlier, Lee et al. (2015) reported that California removed 218,000 m^3 of litter from its highways and freeways in 1993, with an associated cost of $23 million. Andres (1993) estimated a cost of $500 million for litter removal at public areas and roads nationally in the United States.

Manual Removal Procedures

Currently, it is most common for personnel from the agency responsible for these activities to manually remove highway debris. Strong and Valdes-Vasques (2014) reported that agency workers are subject to safety risks when engaged in debris removal because these activities occur in proximity to active travel lanes. Manual collection typically involves leaving an agency vehicle in the vicinity of large debris and manually removing it (this includes tires, lumber, cargo loss, rocks, and other types of debris). If the debris was generated by a crash or erosion of lateral embankments, personnel typically sweep the travel lanes and shoulders before leaving the scene.

Paid Litter Removal

The ADOT study (Carey, 1999) reported that during 1993, most state DOTs spent between 3 and 4 percent of their budget on collection and disposal of highway litter. More specifically, this study investigated the removal procedures and frequency of TD removal in the Phoenix area. Private contractors picked up most debris in 1999 from the state highway system. At that time, ADOT had two contractors for sweeping and debris removal on a daily basis (Saturday through Thursday). One contractor used automated equipment to capture and remove large debris, such as whole tires and most tire shreds. The second contractor performed sweeping duties of the median and shoulder areas. Jointly, both contractors dealt with all aspects of collection and disposal and charged ADOT monthly for those services, including fees at local landfills. Despite the significant amounts of debris removed by contractors, it is estimated that ADOT personnel still had to collect about 30 percent of the debris in the Phoenix metropolitan area. The frequency of these activities varied by season and by the frequency of public requests, among other factors. It is estimated that the average frequency of removal duties for ADOT personnel was between once a week and twice a week.

More recently, Conroy-Ben and Christensen (2013) conducted a survey of various state DOTs about roadside litter collection and disposal. They reported that the Utah Department of Transportation (UDOT) ceased to use prison crews due to the costs associated with full-time salaried guards and vehicles required for such crews. Hargadon et al. (2006), reporting on the costs of various litter and debris removal activities in California in 2006, stated that litter and debris removal activities are often combined with other maintenance tasks such as landscaping. It is estimated, however, that labor costs for litter removal account for 25 percent of total labor costs. In addition to litter pickup, the California Department of Transportation (Caltrans) uses sweepers to clean the paved roadway. Most often, this equipment is driven in a moving lane closure with an attenuator attached either to the sweeper or to an additional vehicle. This equipment can operate between 10 and 14 mph and requires one operator. Typically, a sweeper can cover 5 to 6 lane-miles in a day. The authors of that study estimated an average hourly labor rate for Caltrans of $39.15 per worker, which includes a 15 percent overhead rate. Conroy-Ben and Christensen (2013) pointed out that paid litter removal was one of the most expensive methods of removal, with a cost of $1.29 per item removed.

Adopt-a-Highway

Conroy-Ben and Christensen (2013) calculated the cost of various methods of debris removal from their interviews of various DOT personnel. Adopt-a-Highway (AAH) programs were ranked as one of the most cost-effective methods when compared to other methods to pick up litter, averaging $0.18 per item removed. However, the authors estimated that the number of items collected by AAH programs comprise, at the most, only 35 percent of all litter removed.

In his National Cooperative Highway Research Program synthesis, Forbes (2009) cited an analysis of seven visible litter surveys commissioned by KAB. This analysis estimated the impact of AAH programs as creating a reduction in highway litter of 13 percent. This synthesis also reported that Hawaii and Pennsylvania have seen reductions of nearly 50 percent associated with AAH.

Cost of Roadside Litter for Various States

Conroy-Ben and Christensen (2013) reported that, on average, litter collection and disposal cost between $430 and $505 per centerline mile covered (including both sides of the road) in 2013. For UDOT, these costs amounted to between $1.5 and $1.8 million per year for 2005 through 2012, including litter control, contractual removal, and AAH (which represents only a small fraction).

Use of Specialized Equipment

Strong and Valdes-Vasques (2014) documented the use of specialized equipment in litter removal activities by various state DOTs. Caltrans uses the automated roadway debris vacuum (ARDVAC) system to collect litter and small debris from roadsides. The system consists of a large truck with a vacuum and an extendable arm (shown in Figure 1). This equipment, however, operates at low speeds and is incapable of handling larger pieces of debris. The authors report that the use of this piece of equipment translates into savings that average $122 per mile with a fixed lane closure, compared to manual pickup operations without lane closure. The authors also presented a sensitivity analysis of how the operation of the ARDVAC becomes more efficient than manual removal when operations with the equipment can cover more than 1 mph. The savings of $122 per mile were calculated under the assumption of operation at an average rate of 2.0 mph.

Figure 1. Automated Road Debris Vacuum (Left) and Liter Bag/Debris Vehicle (Right) (Strong and Valdes-Vasques, 2014).

Additionally, Strong and Valdes-Vasques (2014) described another piece of equipment used by Caltrans named the automated litter bag/debris collection vehicle, also shown in Figure 1.

This piece of equipment uses a contractible basket to scoop up debris. It has the capacity to handle larger debris such as tires, mufflers, litterbags, and more. Caltrans (2015) reports on its website that this system is able to pick up several tires at one time, or up to eight bags of debris. This equipment, however, cannot operate at high speeds, a limitation similar to that of the ARDVAC. The upfront investment for either of these two pieces of equipment, according to Strong and Valdes-Vasques (2014), is $381,000, with a nominal useful life of 10 years.

Strong and Valdes-Vasques (2014) also reported that Missouri and Ohio DOTs use the Gator Getter™, a piece of equipment developed and commercialized by Gator Industries, LLC, and shown in Figure 2. The product description (Work Safe USA Inc., 2015) states the ability to pick up debris at speeds of up to 60 mph. In their analysis, Strong and Valdes-Vasques concluded that this piece of equipment is most effective when operating at average speeds of 45 mph and above. They reported significant decreases in effectiveness at operating speeds below 45 mph and on rough surfaces. Effectiveness was also limited on mixed debris; these types of debris have the potential to undermine the safety of using the equipment, especially when visibility conditions are adverse.

Figure 2. Gator Getter Mounted on a Colorado DOT Truck (Strong and Valdes-Vasques, 2014).

Strong and Valdes-Vasques (2014) reported the cost of the Gator Getter at $16,000 per unit. Optionally, the system can be supplemented with a front camera for an additional $600.

TD DISPOSAL AROUND THE COUNTRY

On its website, EPA (n.d.) reports some statistics of landfill disposal around the country: 38 states have banned whole tires from landfills, 35 states allow shredded tires to be placed in landfills, 11 states have banned any form of tire from landfills, and 17 states allow processed tires to be placed in monofills. Only eight states have no restrictions on placing scrap tires in landfills.

TD Disposal in Arizona

An ADOT study (Carey, 1999) reported at the time of the study that it was common practice for ADOT to accumulate TD in its maintenance yards until the quantity warranted the expense of hauling it to the landfill. Most yards separate whole tires from tire shreds because of weight-based fees to dispose of tire shreds at landfills; in contrast, landfills do not charge fees for whole tires because of their potential for recycling.

TD Disposal in Oregon

Oregon, where recycling is most attractive, is among the states that do not allow disposal of tires in landfills (Washington County Oregon, 2015). Marion County in Oregon (Salem-Keizer Recycling and Transfer Station, 2016) stipulates a fee for disposal that ranged from $1.25 for a small tire (less than 20 in.) to $11.75 for a medium tire (a 20- to 26-in. rim) prior to April 2016. These rates were increased after April 2016 to $2.00 for a small tire (less than 20 in.) and to $20.00 for a medium tire (a 20- to 26-in. rim) respectively. A multi-state regional company collects and disposes of bigger tires in west Oregon (Tire Disposal and Recycling Inc., 2006). To dispose of such tires, this company participates in several markets identified previously (EPA, n.d.).

TD Disposal in Florida

A county in Florida (Miami Dade, 2016) lists its fee per ton of waste tires at $114.18 (or about $1.01 per tire, which are typically 20 lb each).

TD Disposal in Texas

TCEQ (2010) requires documentation of the life cycle of scrap tires from their genesis to their final use or disposal. Through its regulatory program, TCEQ follows the activities of seven types of stakeholders:

1. *Generators.* This group is comprised of any entity that generates scrap tires, such as junkyards and fleet operators. Generators are not required to register with TCEQ but must follow TCEQ rules on storage and record-keeping.
2. *Transporters.* Before being authorized to collect scrap tires from other businesses, entities must first register with TCEQ to operate as transporters.
3. *Processing or recycling facilities.* These facilities are where tires are reduced for recycling or use as fuel. These facilities must register with TCEQ.
4. *Storage sites.* Storage facilities must register with TCEQ in either of the following cases:
    - The equivalent of 500 scrap tires or more is stored in the open.
    - The equivalent of 2000 scrap tires is stored in an enclosed space.
    - The safety design of these facilities must be under the charge of a registered professional engineer.
5. *Transportation facilities.* Similar to storage facilities, any facility where the equivalent of more than 500 scrap tires is stored temporarily (during the transport process) must be registered with TCEQ. Typically, these types of facilities include marine terminals, rail yards, or trucking facilities.
6. *Land reclamation projects using tires*. These projects use tire scraps in order to stop erosion and restore original grades of the natural terrain. TCEQ must be notified of such projects, and the input of local governments and fire departments must also be part of the project.
7. *Landfills.* Landfills are sites to dispose of solid waste in general. TCEQ issues permits to these sites that regulate their operations. Scrap tires are stored or processed if the permit issued to a landfill allows these activities.

In its 2010 audit, TCEQ (2010) summarized the volumes of scrap tires tracked during the previous year. This report asserted that 27 percent of all scrap tires generated in Texas during 2009 ended up in landfills (about 7 million STUs, according to Table 1). This percentage is very comparable to the 30 percent reported for the period 2004 to 2014 in Washington (Washington State Department of Ecology, 2014).

The cost of disposing of the yearly amount of tires that end in landfills in Texas (7 million STUs) can be estimated preliminarily as follows: if the rates listed by Wise County Public Dumps on its website (Wise County TX, 2004) can be considered typical, and an average share of 50 percent truck tires is assumed, then landfill disposal of TD should cost Texas $495 per ton, or $31.5 million a year. However, the proportion of these costs that pertains to TD cannot be determined from this exercise.

RELATIONSHIP BETWEEN TD AND CRASHES

Forbes (2009) reported that between 650 and 800 crashes related to highway litter on Utah highways from 2008 to 2012. The author stated that there were three fatalities involved with these types of crashes in 2008 and no fatalities between 2009 and 2012. Woodrooffe et al. (2008) offered an interesting insight, arguing that crashes that involve road debris should be more common at night, given the limited visibility at that time.

Lindquist and Wendt (2009) identified in their synthesis of literature that crashes involving objects on the roadway are remarkably rare—only 0.16 percent of fatal crashes and 0.53 percent of all crashes. They reported these numbers from another author (University of Michigan Transportation Research Institute, 2009).

Forbes and Robinson (2014) combined data from two sources (Florida Center for Solid and Hazardous Waste Management, 1998; Florida Department of Highway Safety and Motor Vehicles, 1996) to estimate the proportion of crashes attributed to TD in Florida. That estimate corresponds to 0.4 percent yearly, representing the average of 1993 and 1996. The authors further estimated a rate of TD crashes per VMT using the data from the Florida Department of Highway Safety and Motor Vehicles (1996) and arrived at an estimate of 0.6 yearly crashes per 100 million VMT between 1993 and 1996.

Strong and Valdes-Vasques (2014) looked at vehicle/freight-debris crashes as a percentage of all crashes with fixed and other types of objects in Colorado. The authors found that metric to vary between 5.7 and 6.4 percent for 2007 through 2011.

Most research has pointed out that vehicle-related road debris (VRRD) crashes are extremely rare, which remains the case even when considering the relatively large proportion of VRRD crashes among crashes involving fixed or other objects.

Similarly, the ADOT study (Carey, 1999) reported an annual average of 79 crashes that were caused by debris of any kind on Arizona highways in the period from 1991 to 1998. That number represents 0.07 percent of all yearly Arizona crashes reported for the same period. In Maricopa County, that rate reduces to 0.02 percent of all accidents, with no fatalities or injuries reported that had road debris as a leading factor. During that period, only 0.6 percent of crashes in Maricopa County—or 0.8 percent statewide—were reported having a tire defect as a factor conducive to the crash.

In their comprehensive review of literature and analysis, Forbes and Robinson (2014) found that VRRD is involved in less than 1 percent of all crashes. Since TD is a fraction of VRRD, crashes involving this particular type of debris should represent an even smaller percentage. From the dataset those researchers assembled, they estimated that over 25,000 crashes per year in the United States and Canada had VRRD as a conductive factor, representing only 0.4 percent of all crashes for that year. They also estimate 80 to 90 fatalities in 2001 associated with VRRD, which represents only 0.2 percent of all fatal crashes.

Narrative-Based Studies

A study by Forbes and Robinson (2014) and sponsored by the American Automobile Association (AAA) Safety Foundation in 2004 is perhaps the most comprehensive piece of literature on road debris and crashes. The researchers obtained data from the National Automotive Sampling System—Crashworthiness Data Set (NASS-CDS) to investigate the involvement of VRRD in crashes. This dataset is assembled by field research teams across the United States. The data for this database are collected yearly, sampling 5,000 tow-away crashes from across the country. Crash investigators visit the sites of these crashes, locate and examine the vehicles, and interview persons involved, including reviewing their medical records. The result is a very detailed account, including comprehensive narratives, for the set of sampled crashes.

Crashes Involving Non-fixed Objects

Forbes and Robinson (2014) queried the NASS-CDS databases for 1997 through 2001 to identify crashes involving a vehicle that struck or was struck by a non-fixed object. Using appropriate sample weights, they estimated the percentage of tow-away crashes that VRRD crashes represent. The reported proportions are very steady from year to year before applying the sampling weights; the weighted estimates appear less stable. Regardless of the set of estimates used, in no case did the proportion of VRRD crashes exceed 1.0 percent of the total tow-away crashes. The yearly average estimate of such proportions is 0.31 percent from the unweighted sample or 0.46 percent from the weighted sample.

Based on the crash narratives and the sampling weights, Forbes and Robinson (2014) estimated that about 63 percent of the VRRD crashes involved stationary VRRD, and 35 percent of the crashes involved VRRD still in motion; in about 2 percent of the crashes, it was not possible to determine the kinematics of the VRRD involved. Of the crashes with VRRD still in motion, 95 percent involved a collision with the debris; in contrast, only 68 percent of the cases with static VRRD resulted in collision with the debris, which suggests that in 32 percent of those cases, the drivers most likely performed a maneuver to avoid the debris (but did not avoid crashing afterward).

When combining these conditional proportions with the marginal proportions of crashes by the motion state of VRRD, the authors of this report inferred from Forbes and Robinson (2014) that about 0.2 percent of all tow-away crashes represent cases with static VRRD that resulted in collision with the debris; similarly, 0.153 percent of all tow-away crashes should be VRRD crashes where the vehicle collided with moving debris. In total, 0.35 percent of all tow-away crashes resulted in collision with VRRD. This amount represents 76.1 percent of all VRRD crashes (i.e., 0.35 / 0.46 * 100 percent).

Most informative for this research, Forbes and Robinson (2014) reported that 21 out of the 66 VRRD crash narratives reviewed in their study had the following descriptive terms associated with the narratives: spare tire, tire, tire and rim, tire tread, or wheel. In other words, about 32 percent (unweighted sample) of VRRD crashes are TD crashes. In the scale of the sampling frame, this number represents just 0.14 percent of all tow-away crashes.

Finally, Forbes and Robinson (2014) presented a table with various proportions of VRRD crashes obtained from their literature review and from the datasets they analyzed. Although variability among studies was present, all estimates were in agreement with a proportion smaller than 1 percent (except for a study that focused on four bridge locations only).

Crashes Involving TD

Woodrooffe et al. (2008) also queried the NASS-CDS to identify a more specific type of crash: TD-related cases. For 2001 to 2005, they identified a set of 81 crashes potentially involving TD, a number moderately larger than the 66 identified by Forbes and Robinson (2014), who had studied the previous five years. Upon review of the narratives for these 81 crashes, Woodrooffe et al. verified the involvement of TD. However, they determined that only in 10 cases (or 12.3 percent of the 81 crashes) was TD a potential factor leading to the crash. In most other cases, the sequence of events shows the separation of tread material from a vehicle’s tire, which subsequently led to that vehicle losing control. These figures are about one-third of the estimate of Forbes and Robinson (32 percent of the 66 VRRD tow-away crashes identified).

Most of the 10 crashes identified by Woodrooffe et al. (2008) had narratives indicating avoidance maneuvers around TD leading to a loss of control and either crashing into another vehicle or departing the road. In four of the 10 TD crashes, a truck was identified as the origin of the debris. However, tire blowouts are rare among other types of truck crashes, according to Bareket et al. (2000). In general, the numbers by Woodrooffe et al. (2008) and Forbes and Robinson (2014) agree with each other and with earlier works, such as that carried by Carey (1999).

In their investigation of crashes related to stopping sight distance, Kahl and Fambro (1995) report that about 50 percent of drivers engage in evasive maneuvers when encountering an object of height of 6 in, and that most drivers elect to perform evasive maneuvers when facing an object higher than 8 in.

SUMMARY OF FINDINGS

This literature review contains the following findings:

- Traffic volume has been consistently documented in the literature as an important covariate of TD, particularly truck traffic. Even though there are different views in the literature about the share of truck TD (i.e., different views on what overrepresentation of this type of debris means), in absolute terms, research shows that a large proportion of TD comes from truck tires.

- Most studies found that TD represents a small proportion of all road debris. By count, that proportion varied from 2 percent to 14 percent. Specifically for Texas, this proportion was estimated at 5 percent in 2009 (NuStats, 2010). By weight, however, that proportion was higher by a factor ranging from two to three times the proportion identified by count.
- According to TCEQ (2010), 27 percent of all 26 million scrap tires in 2009 in Texas ended up in landfills. The recycling categories of land reclamation and tire-derived fuel accounted for 51 percent of all scrap tires that year.
- The cost to Texas of disposing of the 7 million tires that end up in landfills is estimated at $495 per ton, or $31.5 million a year. TxDOT's share of this fiscal burden is undetermined.
- Most evidence found in the literature about TD and crashes is based on crashes involving a collision with an object on the pavement. Two studies reviewed crash narratives specifically searching for vehicle-related debris. These studies found that less than 1 percent of crashes can be identified as triggered by TD (Forbes and Robinson, 2014; Woodrooffe et al., 2008).

Several elements that are key determinants of the costs of TD have been identified in this review of literature. Past research documents the economic and safety advantages of using specialized equipment to collect TD and other types of litter from highways. Because they require an initial capital investment and associated maintenance costs, there is an economic decision required prior to using such types of equipment.

CHAPTER 3. STATEWIDE SURVEY OF TIRE DEBRIS MANAGEMENT

TxDOT is responsible for maintaining numerous centerline miles (i.e., one-way miles without considering number of lanes) across the state of Texas. In 2013, TxDOT reported that it maintained 80,268 centerline miles, including FM roads (40,932 centerline miles), state highways (16,411 centerline miles), U.S. highways (12,062 centerline miles), and interstates (3,272 centerline miles), in both urban and rural areas. A total of 195,022 lane-miles (i.e., miles per lane of roadway) in the state of Texas correspond to the 80,268 centerline miles. Although these miles represent only one-quarter of all roadways in Texas, they carry about three-quarters of all vehicle travel in the state (measured as VMT) (TxDOT, 2013).

One of the key maintenance tasks TxDOT districts perform is to remove litter and clear debris, particularly debris that comes from failed tires on vehicles. Tires represent a significant source of roadway debris, and TD is often found on roadways with higher volumes and a higher proportion of trucks, per findings in the literature review of this project (Carey, 1999; Andres, 1993; Department of State Police, Virginia, 2000; Forbes, 2009; Lindquist and Wendt, 2009; Mid Atlantic Solid Waste Consultants, 2009; Page and Woodrooffe, 2009; TriLine Associates Inc, 1992; Woodrooffe et al., 2008; University of Michigan Transportation Research Institute, 2009).

Debris removal operations represent a significant expense to TxDOT and other agencies. TxDOT districts and their contractors drive a large number of miles on state-maintained highways to locate and remove TD and expend additional resources to process and dispose of the debris. Additionally, debris presence on roadways can present hazards to motorists, particularly if it is located within travel lanes. In urban areas, debris in travel lanes often causes disruption in traffic flow.

This chapter documents interviews conducted with TxDOT district practitioners in order to assess the impacts of TD presence and the state’s practices to remove debris. This chapter also presents the tabulated and synthesized insights gained from the interviewees’ responses.

Additionally, this chapter documents a preliminary analysis of cost data by district, which is provided by the TxDOT Maintenance Division.

INFORMATION NEEDS TO BE ADDRESSED BY SURVEY

In Chapter 2 of this report, the research team identified several key elements of the costs associated with TD. However, that chapter did not cover specific details about the cost to TxDOT of collection, storage, and pre-processing of such debris for disposal or reuse. Given those findings, the costs to different districts of handling TD will vary depending on the number and types of maintained miles, the stakeholders involved in the process, the type and scope of the share covered by contractors, and the equipment and other district resources available for direct removal and handling tasks. Questions specific to that information requirement were incorporated while designing the survey for this task.

Chapter 2 also identified specialized removal equipment that offers potential economic and safety advantages in handling TD. However, the associated initial capital investment of specialized equipment, as well as its operation and maintenance costs, restricts its use to areas where mileage and associated amount of TD are large enough to justify the investment. It is of interest to determine the economic feasibility of different removal strategies and equipment use as a function of the characteristics of a district. Consequently, the research team explicitly incorporated information about specialized equipment in the survey.

Finally, the investigation in Chapter 2 found that previous research suggests a weak link between TD and safety, in the sense that TD-related crashes amount to a small proportion of the total of crashes expected in highway networks: up to 1 percent of all crashes might be triggered by TD (Forbes and Robinson, 2014; Woodrooffe et al., 2008). However, these statistics do not necessarily reflect the case of Texas, so questions about safety were included in the survey.

SURVEY DESIGN

The research team designed a survey to be conducted in all 25 TxDOT districts. The research team underwent multiple revisions of the survey document in order to assure a natural flow of the questions intended. The main objective of the survey document was to capture insights about the following issues:

- Written policies and practices regarding debris removal.
- Cost of debris removal operations.
- Record-keeping practices.

- Debris volume and composition.
- Anecdotal evidence of crash involvement.

The process of designing the survey was rather iterative. An initial draft document was prepared covering mostly questions related to cost and operations for TD.

The survey document evolved to reflect identified research needs as findings from Chapter 2 emerged. Questions were gradually incorporated into the survey covering involvement with the scrap-tires program of TCEQ, anecdotal evidence of safety issues, and inquiries about the existence of written policies and safety practices.

Once the research team constructed a preliminary document, a copy was emailed to the TxDOT project team requesting their feedback. The TxDOT project manager replied with a compilation of comments from the project team. The following points summarize the feedback received:

- The survey language needed to be reviewed to be more conversational.
- The target respondents should include personnel closely involved with field work; maintenance engineers alone may not have all required information.
- Tire handling manifests from TxDOT may not offer enough detail to differentiate TD from the road and used tires discarded by the district.

The survey was modified to incorporate the feedback received from TxDOT. One particular enhancement at this stage was to adopt a format that could be sent by email to district engineers prior to the interview. This format was such that it would allow respondents to print the survey and break it in two parts: one with higher-level questions (e.g., average costs and written policies) and one with questions at the operations level (e.g., record-keeping, average volume of tire/rubber and other debris).

The modified draft was sent to the Institutional Review Board (IRB) at Texas A&M University for approval. After one round of revisions and edits, IRB approved the survey. The final approved survey is provided in its entirety in Appendix C at the end of this report.

PROCESS OF SURVEYING TXDOT DISTRICTS

In June 2015, the research team requested a list of district engineers from the TxDOT project manager. Upon receipt of the requested information, the research team contacted the persons from the list by email. These initial contacts were either the director of maintenance or the director of operations in most districts. Interviews were requested from the individuals who responded to this initial communication. In some cases, these contacts recommended others within their district. The interviews were scheduled and performed at times and dates that were convenient to the interviewees. Interviews were performed during the months of June and July 2015.

During the months of July and August, the research team made additional attempts to follow up by email with contacts who did not initially reply. Although a few additional representatives from districts responded to the follow-up email, the number of outstanding districts without a response was large. Finally, the research team contacted a few additional practitioners within the remaining districts. Ultimately, the research team was able to conduct interviews with representatives from the following 12 districts:

- Bryan.
- Brownwood.
- Childress.
- Corpus Christi.
- Dallas.
- El Paso.
- Fort Worth.
- Lubbock.
- Odessa.
- Pharr.
- San Angelo.
- Waco.

Although respondents only represent about half of the 25 districts, the represented districts exhibit a good distribution in terms of state geography and population density.

SYNTHESIS OF RESPONSES

The survey was organized into the following three topic areas: (a) policies and practices, (b) cost and record-keeping, and (c) debris volume. Appendix C shows the entire survey. This chapter provides discussion of the topic areas in the survey.

Debris Removal Policies, Practices, and Records

Four of the 12 interviewed practitioners stated that they had written policies for debris removal practices, and five acknowledged having written safety practices. Four of the districts shared their written policy documents with the research team. One of the policy documents is a 10-point best practice plan that applies to debris removal and third-party assistance operations (not published). The 10 points in that document are as follows:

1. Turn on overhead lights/light stick as you approach stop.
2. Park as far to the right on the shoulder as possible.
3. Turn wheels to the left (right if you are in median or inside shoulder).
4. Park before the debris if possible.
5. Use your vehicle as a shield.
6. Keep an eye on and face oncoming traffic. NEVER, NEVER, NEVER turn your back on traffic.
7. Wait for a clearing before exiting or entering vehicle.
8. Wait for a clearing before moving into roadway to clear debris.
9. Exercise extreme caution if more than one lane of traffic must be crossed.
10. Consider using a moving lane closure with truck-mounted attenuators to remove debris from the inside lanes of multilane facilities (expressways, freeways, etc.).

These 10 points cover the key safety points that are included in the other three policy documents that practitioners provided. One of the documents addressed debris and critter removal, which is removal of debris, including dead animals, from roadways. Another document addressed illegal dumpsite removal and disposal/litter. The third provided a list of considerations for personnel to use to determine if they could safely remove debris without assistance based on site conditions. All four documents addressed safety and injury avoidance practices during

TxDOT operations. None of the practitioners had written safety practices for debris removal operations that occur in partnership with other agencies.

The practitioners generally explained that their debris removal practice is straightforward and involves simply sending one or two people in a pickup truck to the location of the debris for its removal. Sometimes these activities are conducted as part of scheduled debris removal operations; sometimes they represent unscheduled operations in response to reports from the public or other agencies (e.g., law enforcement); last, sometimes these activities are performed in conjunction with other activities that provided the primary reason for the trip. If the debris to be removed is located in a travel lane on a high-volume roadway, personnel will often use a work convoy with a truck-mounted attenuator.

Two practitioners (Odessa and El Paso) mentioned that their respective districts have a Gator Getter™. As was documented in Chapter 2 (Strong and Valdes-Vasques, 2014), the Gator Getter™ is a device that allows TD to be retrieved while the vehicle is in motion.

Across the districts, practice varies in terms of the frequency of debris removal activities. The practitioners generally agreed that high-volume roads (especially urban freeways) need to be cleared of debris on a weekly basis, while lower-volume roads can be cleared biweekly, monthly, or even on an unscheduled, as-needed basis.

Ten districts provided responses when asked about average crew size for debris removal. The most common crew size is two people, though occasionally it can be as many as three. Six districts indicated that they sometimes send a single person to remove debris, provided traffic conditions and debris size do not pose safety concerns.

Five of the 12 practitioners stated that their districts have contractors who handle a portion of their debris removal activities. The most common practice is to assign urban highways to a contractor and handle the rural highways with state personnel. Practitioners from two large urban districts stated that their districts do not conduct any scheduled debris removal operations because they have hired contractors to conduct all scheduled debris removal activities on both the urban and the rural portions of their highway networks. However, these districts do conduct unscheduled debris removal operations with their own personnel when needed. A third practitioner stated that his district does not conduct any scheduled debris removal activities but handles all debris removal by state personnel on an unscheduled, as-needed basis.

When asked if there are certain types of debris that are not removed when found, eight of the 12 districts stated that their personnel do not remove hazardous materials (hazmat) that are spilled. In those cases, they call specialty contractors when needed who are trained to handle hazmat. One practitioner stated that his district does not remove granular material, such as dirt, when it is spilled on a highway.

When asked about record-keeping, the practitioners generally stated that their districts simply log the number of miles driven and the amount of time spent on debris removal. They do not archive detailed data to describe the type of debris found, so they could not determine what types of tires most frequently fail or what the causes for the failures were. Three of the practitioners acknowledged that their districts are registered as a tire handler with TCEQ scrap tire management program.

None of the practitioners were aware of recorded crashes that were attributed to TD, but one practitioner suggested querying the Crash Records Information System (CRIS) database to explore the influence of TD on crash frequency (an analysis of the CRIS database is the subject of a later chapter of this research project).

Debris Composition and Volume

The practitioners were asked to characterize the debris that is typically found on their districts' highways. Specifically, they were asked what percentage of the debris falls within the following categories: TD, vehicle parts (other than tires), garbage/litter, animal debris (i.e., dead animals), and other. Ten of the practitioners were able to provide answers to this question, and Figure 3 shows the average of their responses.

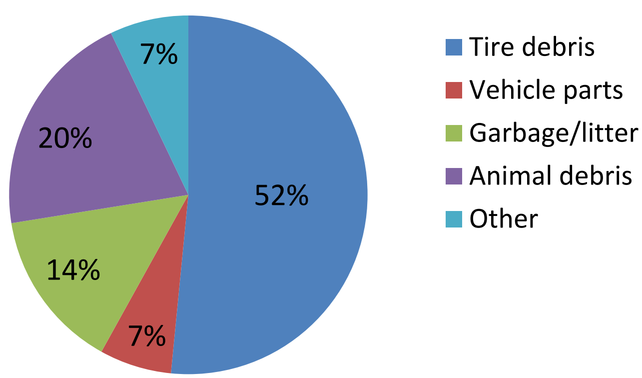


Figure 3. Debris Composition Distribution.

Roughly half of the debris was characterized as TD, and another 20 percent was characterized as animal debris. Debris categorized as “other” included discarded furniture and appliances, ladders, brush, hay bales, and miscellaneous metal objects or stone material.

When asked specifically how much TD they remove from their roadways in a typical year, four practitioners were able to provide answers in terms of weight. Their answers ranged from 103,100 lb (for a rural district that has a few small cities) to 792,000 lb (for a district that has several medium-sized urban areas and a significant amount of state-maintained highway mileage). One practitioner in a district with a medium-sized city stated that his district finds about 520 cubic yards of TD in a typical year. One practitioner explained that in some districts, all maintenance offices send their TD to the district office for processing, and those districts are the districts that should be able to provide estimates of TD quantity.

When asked if there are any noticeable seasonal trends in the TD generation rate, 11 of the 12 practitioners stated that they find more TD in the high temperature months. One of these practitioners also acknowledged an increase in debris during move-in or move-out time periods for students at a university in his district.

The research team asked which types of roadways tend to have the largest amount of TD present. Table 2 lists the answers provided by the interviewees to this question. The most common answers indicate that TD frequency tends to increase on interstates, U.S. highways, or high-volume roads in general (including interstates and U.S. highways). These answers reflect the trend that TD presence is correlated with traffic volume, as was found in Chapter 2 (NuStats, 2010; Carey, 1999).

Table 2. Roadway Types Having Large Amounts of TD.

Frequency	Response
6	Interstates
5	High-volume roads
4	U.S. highways
1	Urban routes
1	Freeways
1	Truck routes
1	Entire district, due to energy-sector development

Most of the answers listed in Table 2 correspond to roads that have large numbers of trucks because the road has generally high truck volume, the road is a truck route, or the road is near an energy-sector development area.

COST AND CONTRACT STRUCTURE DIFFERENCES AMONG DISTRICTS

Several interviewees stated that they log and report debris removal efforts in terms of miles driven, and the efforts are coded as Function Code 523 in TxDOT's internal records. Per the practitioners' suggestions, the research team obtained a statewide query of the number of miles driven for debris removal for FY 2014 from TxDOT's Maintenance Division. The research team then performed an exploratory analysis on the data obtained by TxDOT Maintenance Division, as described in this section.

Cost of Debris Removal Operations

Figure 4 shows the monthly distribution of debris removal efforts (in terms of miles driven) for all TxDOT districts.

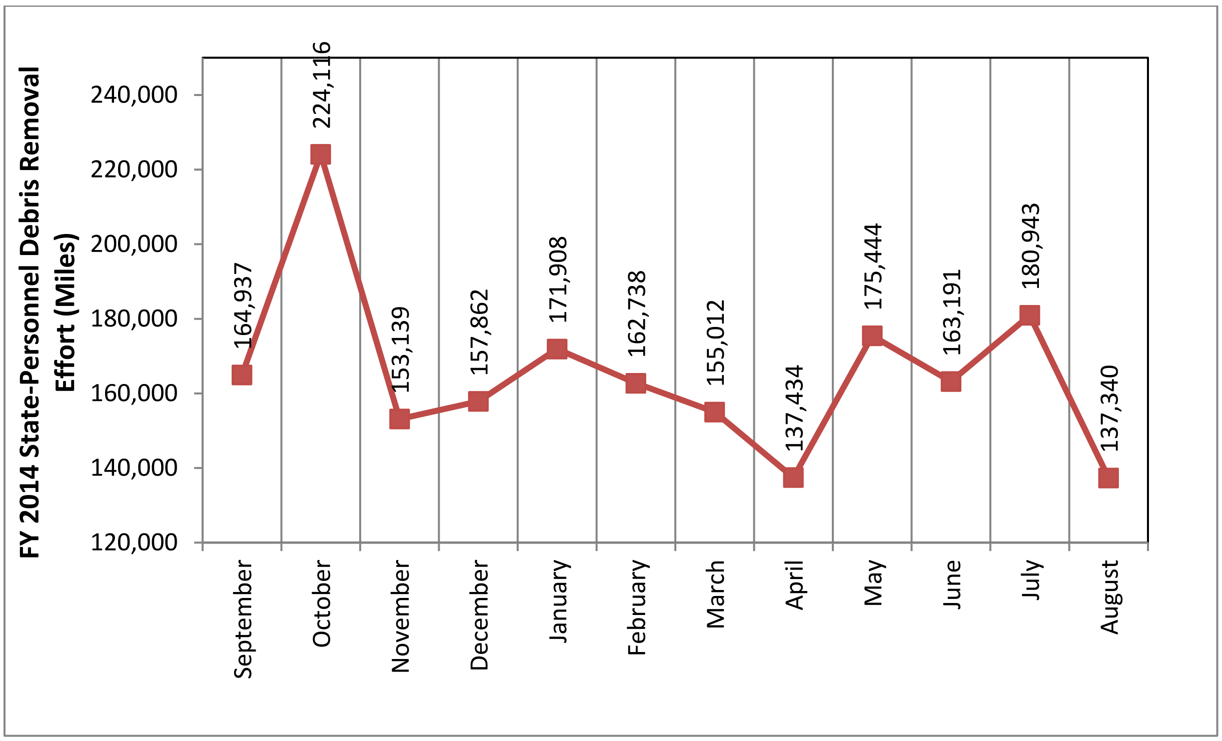


Figure 4. Debris Removal Efforts by Month, FY 2014.

Two points should be noted about the data in Figure 4: (a) they reflect only debris removal operations by TxDOT personnel, and (b) they include all debris removal efforts (not just TD). Additionally, this figure shows that the months of October and July were the busiest for debris removal efforts in 2014.

Miles driven by state force for debris removal only are shown by district in Figure 5. San Antonio, Austin, and Odessa logged the largest number of miles driven for debris removal operations in FY 2014. When totaled across the state, these data show that about 2,106,000 miles were driven that year by TxDOT employees for the purpose of removing debris from state-maintained highways. An interesting observation is that, in terms of miles driven, Houston and Dallas ranked 14th and 17th among all districts, despite these two districts being the largest in terms of miles they maintain.

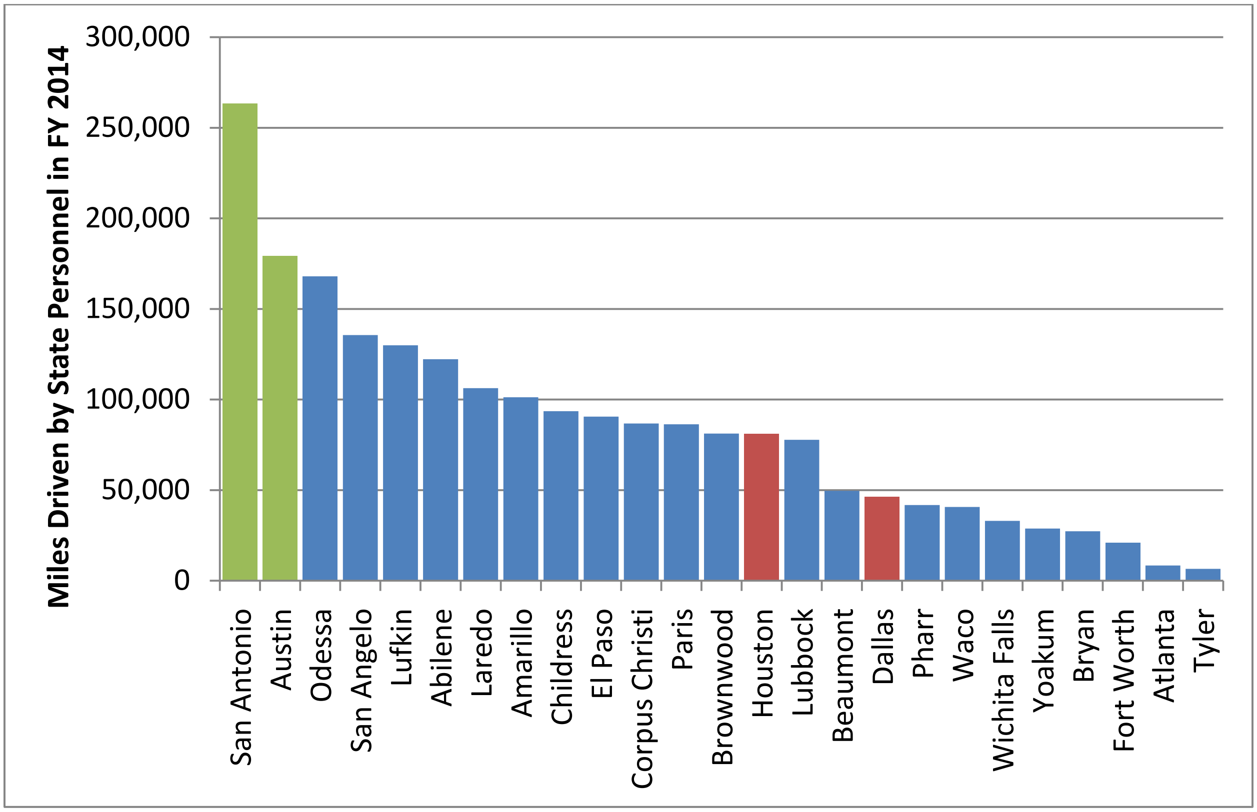


Figure 5. State-Force Work on Debris Removal by District, FY 2014.

For the four largest districts, this plot suggests differences in miles driven between San Antonio and Austin (shown in green) on one hand, and Houston and Dallas (shown in red) on the other (the pairs are color-coded for comparison with further figures). Another observation is that the relatively large district of Fort Worth ranked 23rd in terms of logged miles, despite its geographic extension and relatively dense roadway network. A more detailed exploration of these differences is offered later in this report.

The Maintenance Division also provided cost data corresponding to debris removal activities. Figure 6 includes both cost and effort data plotted by month. Figure 7 shows the dollar amount per district. When totaled across the state, about $18.9 million was spent in FY 2014 on removing debris from state-maintained highways.

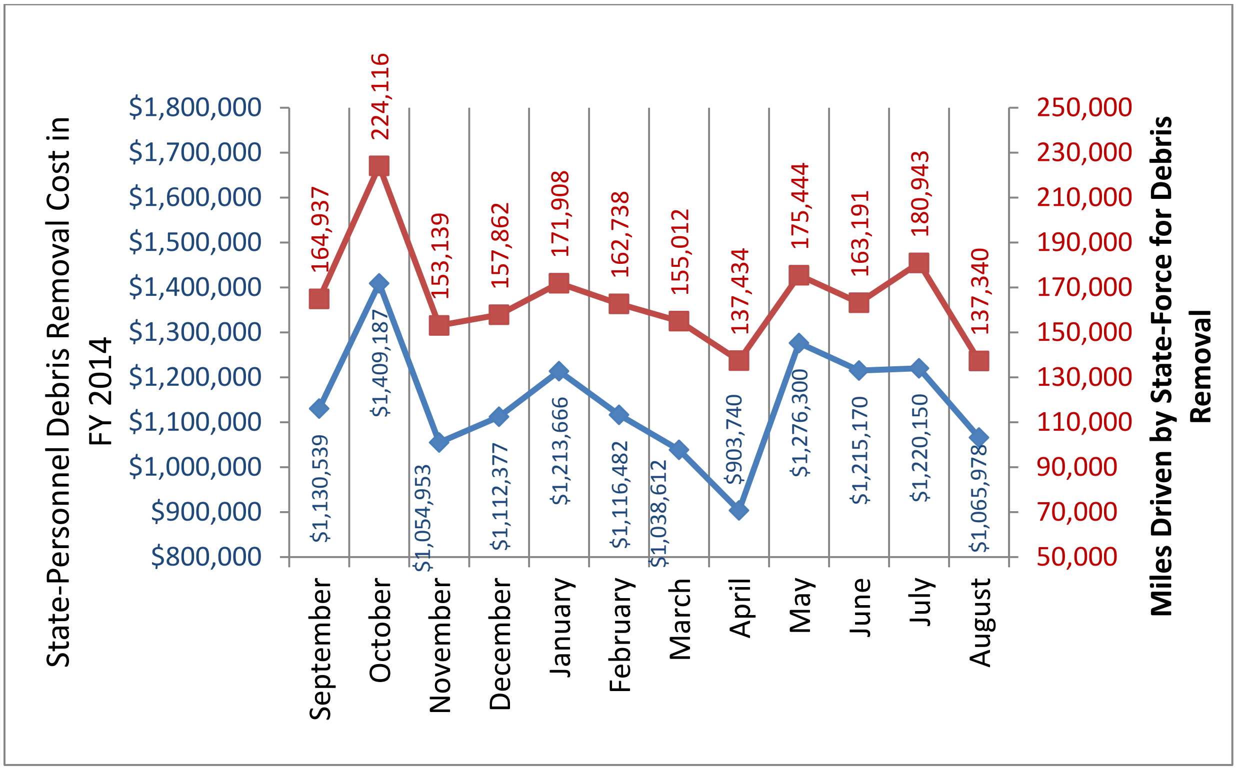


Figure 6. Work and Cost of State-Force Debris Removal by Month, FY 2014.

Figure 6 shows that the trends for work amount and cost of state-force debris removal track each other very well, but with a few mild differences. Debris removal costs are shown to be highest in the months of October, May, and July. Figure 7 shows that gross debris removal costs tend to be highest in districts with large urban areas—specifically, San Antonio, Austin, Houston, and Dallas. San Angelo, El Paso, and Odessa are also notable in this figure.

The contrast between Figure 5 and Figure 7 suggests that important differences exist between how the four largest districts manage debris removal alternatives. It is apparent from this contrast that Houston and Dallas remove a higher share of their debris using external contractors, compared to San Antonio and Austin. Nevertheless, quantity and cost of debris removal are bound to vary by district, primarily as functions of the extension of roadway network, traffic, and geography, among other factors.

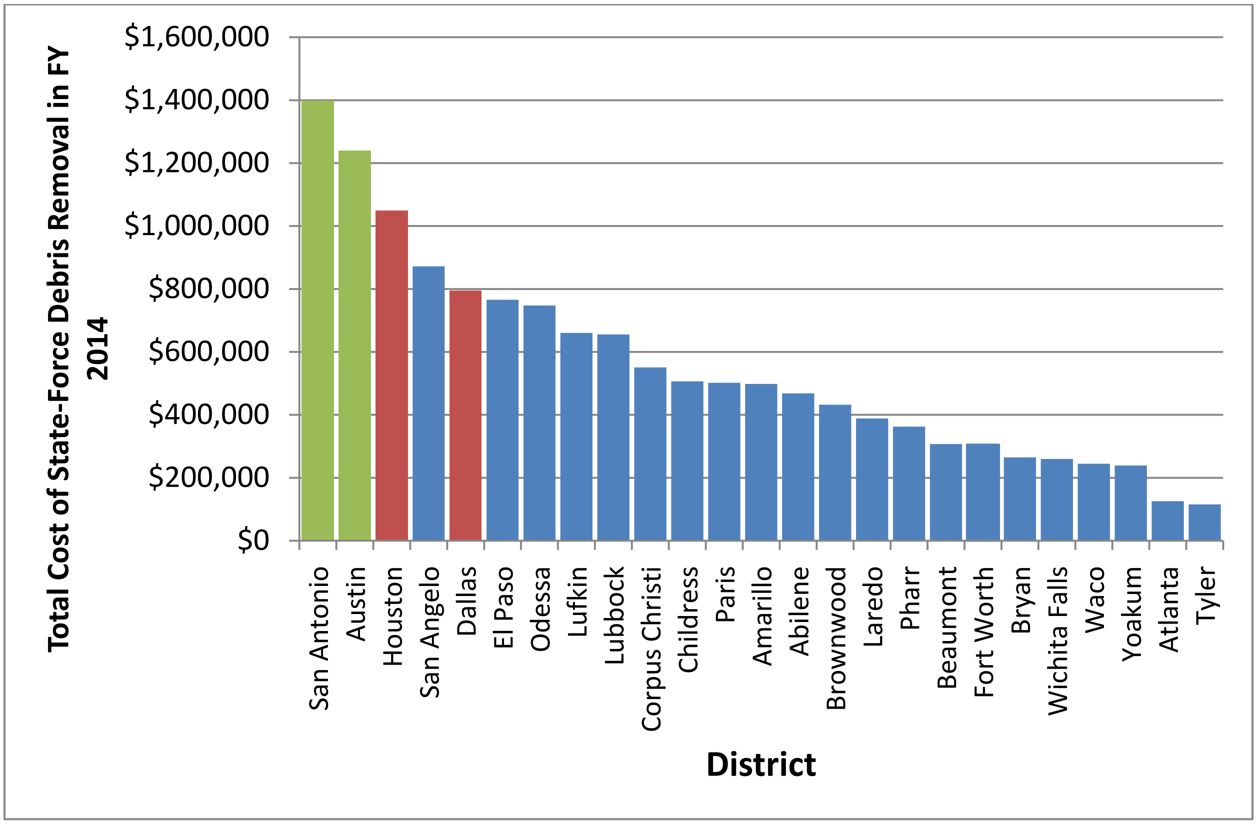


Figure 7. State-Force Debris Removal Cost by District, FY 2014.

Even after the considerations discussed above, important variations in total costs of debris removal may still reflect different strategies of balancing work performed by contactors and by state force.

Differences in Contract Structures

To investigate if the trends observed in Figure 7 also correlate with the number of external contracts and corresponding dollar amounts, the research team obtained summary statistics from a report on a recent recapitulation of TxDOT statewide contracts specifying maintenance as the type of work on the contract. Figure 8 shows the number of 2014 contracts per district.

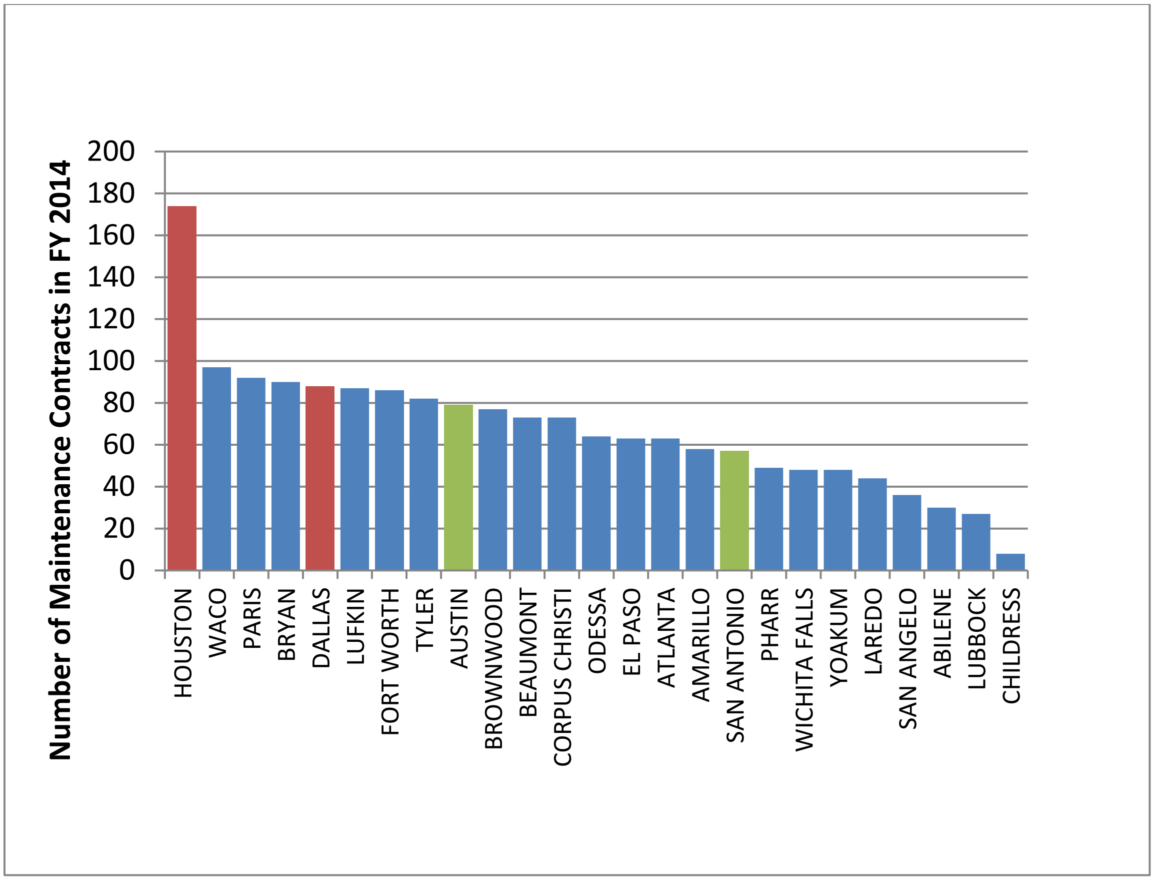


Figure 8. Number of Maintenance Contracts per District, FY 2014.

The Houston District, with 174 current contracts, almost doubles the number of contracts of the Waco District (97), the second largest according to this metric. Other large districts do not stand out much based on their number of active maintenance contracts: Dallas is ranked fifth with 88 contracts, Fort Worth seventh with 86 contracts, Austin ninth with 79 contracts, and San Antonio 17th with 57 contracts.

Figure 9 shows the dollar amounts that correspond to the contracts of Figure 8. The three largest districts in terms of joint amount of maintenance contracts are Houston, Dallas, and San Antonio. These districts also tend to incur high efforts and expenditures in state-force debris removal operations, per Figure 7. Additionally, Figure 9 shows that the total contracted amounts in Waco and Austin are very comparable.

Caution is advised when directly interpreting Figure 8 and Figure 9 in the context of this research. Only a fraction of all maintenance contracts should be specific to debris removal and road-cleaning activities. As such, because contracts tend not to target any specific types of debris, no known percentage of the contract amounts can be attributed to TD removal activities. Regardless, the value of these figures is to document differences between the four largest districts in terms of how they handle maintenance activities.

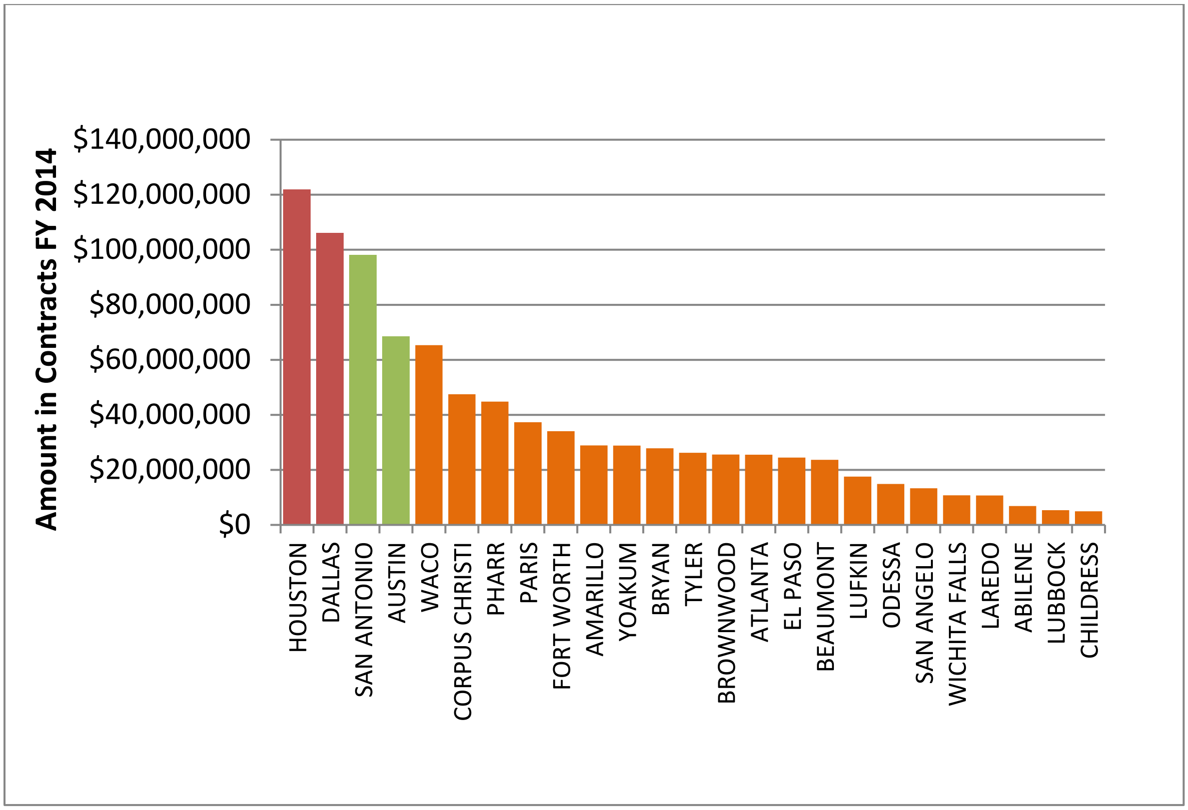


Figure 9. Total FY 2014 Maintenance Contract Amounts per District.

The four largest districts can be easily recognized by their total dollar amounts of awarded maintenance contracts (shown as different colored bars in Figure 9). However, Figure 8 suggests differences between the Houston, Dallas, Austin, and San Antonio Districts in terms of how they let maintenance contracts. Houston tends to award significantly more maintenance contracts than the other three districts. Although the dollar amounts represented by maintenance contracts in Houston are also the highest (Figure 9), it is clear from these two figures that Dallas, Austin, and San Antonio tend to award larger contract amounts to fewer contractors than Houston.

The research team requested additional cost data specific to debris removal from TxDOT Maintenance Division in order to look into contracted work specific to debris removal. This updated data request included work performed by contractors in the same format as state-personnel data received previously so that meaningful comparisons could be drawn. The next subsection documents an exploratory analysis of debris removal cost at all 25 districts.

Unit Cost of State-Force Debris Removal

Figure 5 shows that San Antonio and Austin Districts tend to cover more miles to remove debris with state personnel than Houston and Dallas. Since Figure 7 shows that cost and mileage track each other relatively well, comparisons in terms of unit costs (i.e., costs per mile) are potentially useful. Next, the research team explored the data for differences in unit costs among districts throughout FY 2014.

Figure 10 shows the trend lines for the five districts that contain the largest cities in the state. In this figure, Houston, Dallas, and Fort Worth show similar monthly costs per driven mile. These costs differ from the average costs per mile in San Antonio and Austin, whose trend lines are very comparable to each other.

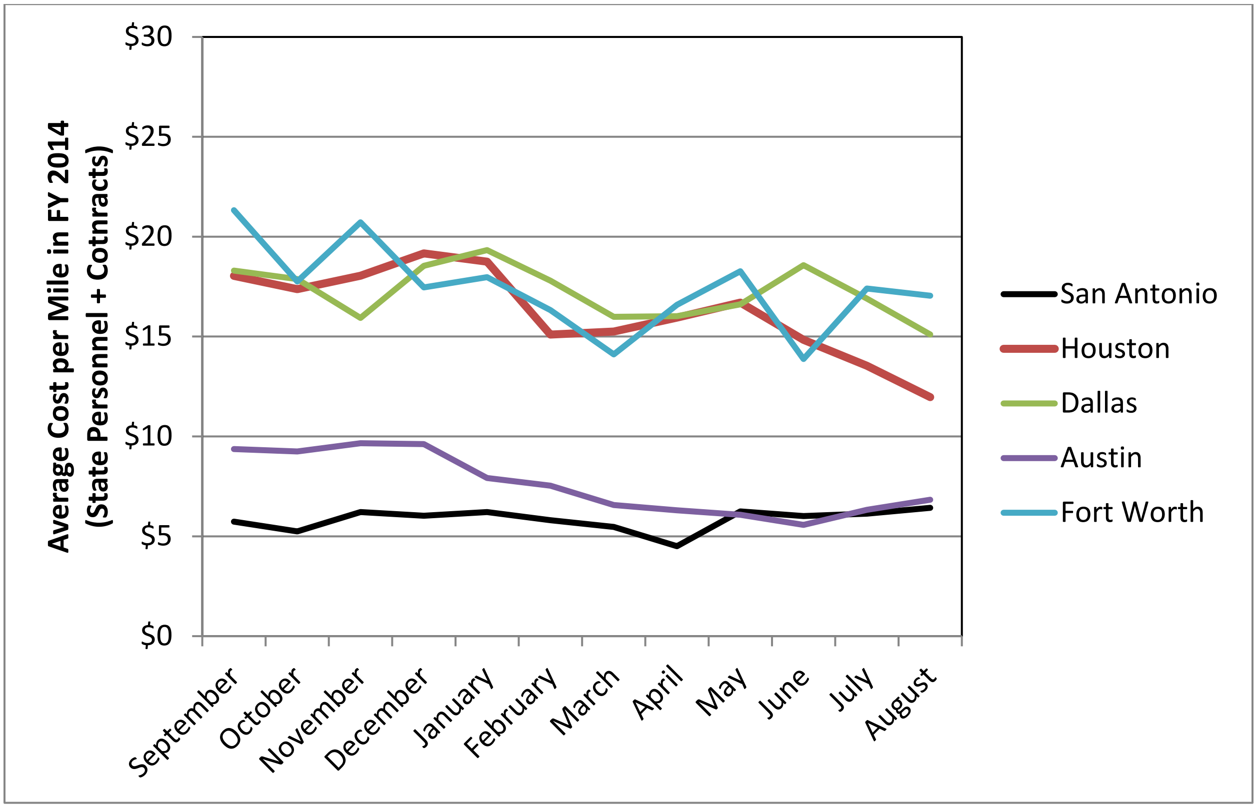


Figure 10. Monthly Unit Cost of Debris Removal (State Personnel and Contracts), FY 2014.

It is notable in Figure 10 that the cost per mile seems to vary steadily and smoothly for the large districts. When the same plot is generated to include data for state-force work only (Figure 11), the gap between the pair of San Antonio and Austin and the set of the other three districts in the plot tends to close. This behavior suggests that the proportions of contract work and state-force work may be an important factor in increasing the gap between unit costs of debris removal observed in Figure 10.

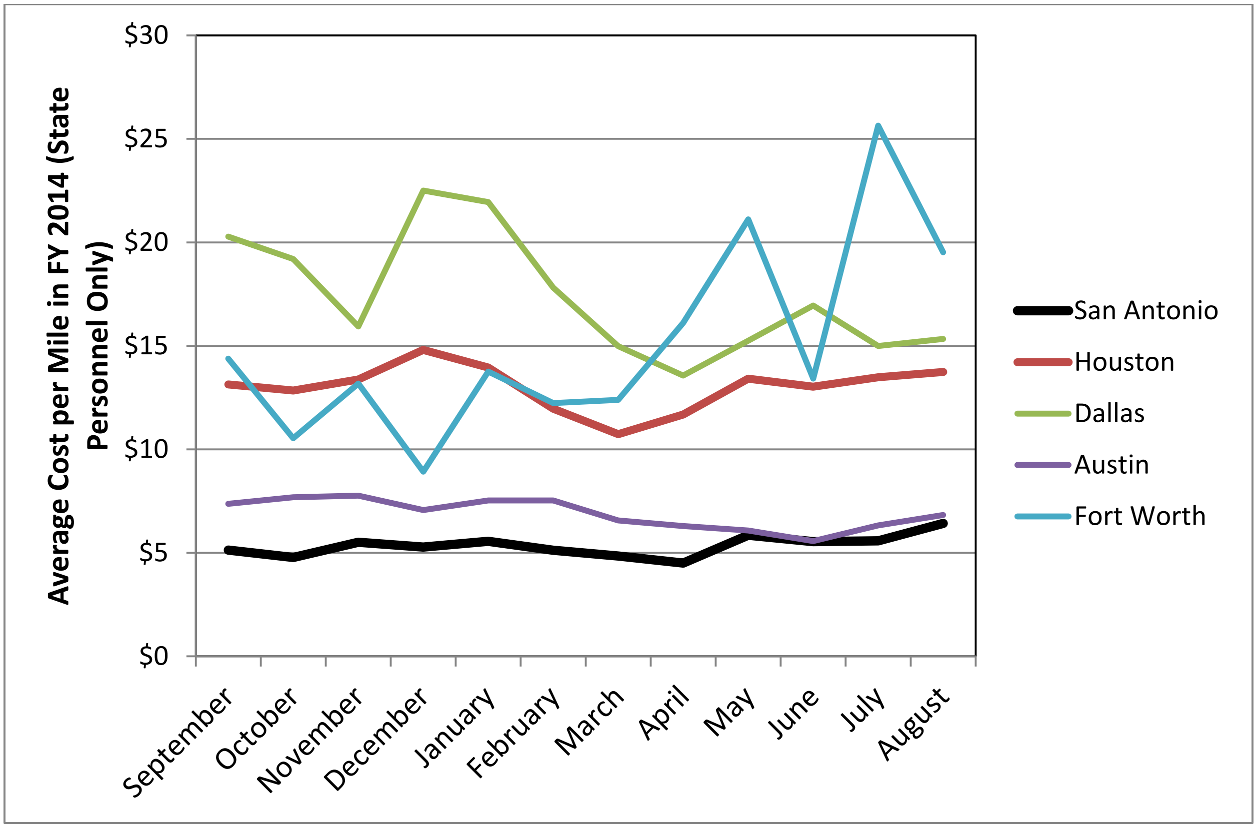


Figure 11. Monthly Cost per Mile of Debris Removal at Select Districts (State Personnel Only), FY 2014.

Additionally, Figure 11 shows that unit cost varies very mildly for San Antonio, Austin, and Houston, but more noticeably for Dallas and Fort Worth. Interestingly, the seasonal variation for the Dallas and Fort Worth Districts appears to mirror each other (i.e., when unit cost goes down in Dallas, it goes up in Fort Worth).

Figure 5 and Figure 7 suggest that Fort Worth is a small district in terms of total mileage and cost incurred by state-force debris removal. This fact is also suggested by Figure 11 since the unit cost of that district appears more volatile than the unit costs of San Antonio, Houston, and

Austin. Figure 10 suggests, in contrast, that the unit costs of debris removal for Fort Worth and Dallas are more similar to Houston when considering work performed by state force and contractors jointly.

Figure 12 shows a set of 10 districts whose monthly costs per mile resemble the trend observed for San Antonio in Figure 11. The trends of Houston and San Antonio are provided, in a heavier line weight and including point nodes for easy comparison. Except for a spike in March in the San Angelo District, in September in Laredo, in July in Waco, and a drop in July in Lufkin, all districts in Figure 12 exhibit rather flat lines ranging from \$4 to \$8 per mile. Interestingly, except for Waco, these districts tend to be the districts with more driven miles with state force, as seen in Figure 5 (after San Antonio, Austin, and Odessa).

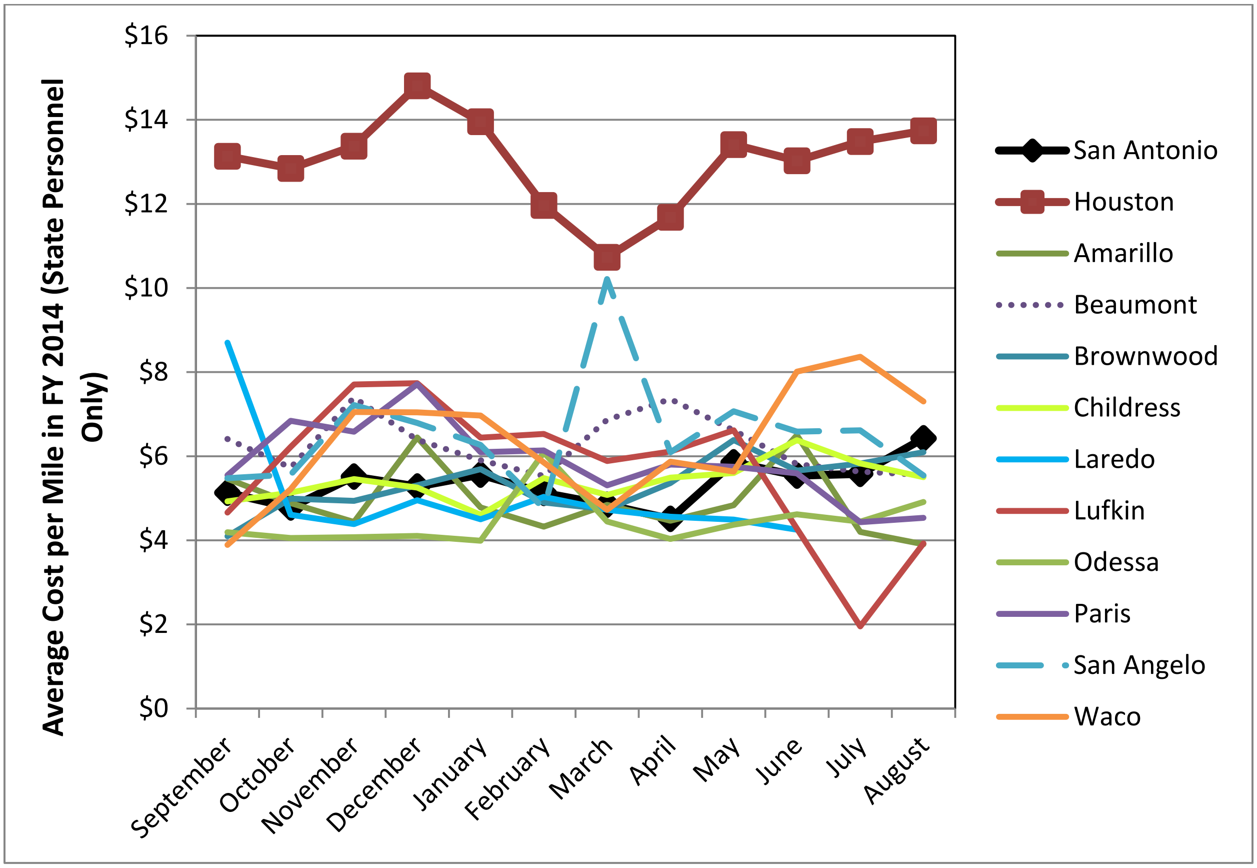


Figure 12. FY 2014 Monthly Debris Removal Costs at Districts with Lowest Cost per Mile.

In contrast to the set of districts shown in Figure 12, El Paso and Abilene experienced a climb in their cost rates during the summer months, as shown in Figure 13. Again, Houston and San Antonio are shown for reference. A notable feature in Figure 13 is that the monthly costs per mile in El Paso were similar to San Antonio until June, when a steady summer-time climb occurred in this district.

The trend is similar for Abilene, although this district's baseline cost rates were more comparable to Houston for most of the year before it experienced a significant spike during the months of July and August.

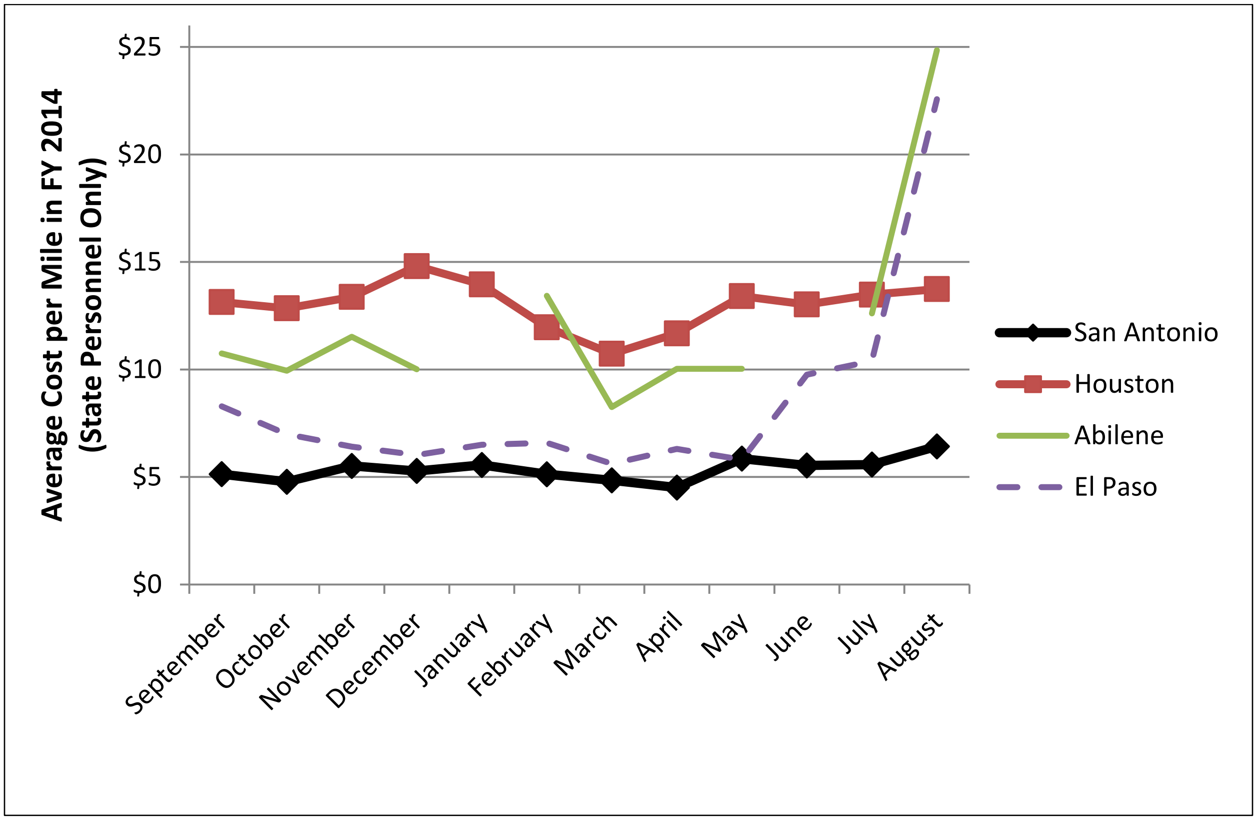


Figure 13. FY 2014 Monthly Debris Removal Costs at Districts with a Summer Cost Spike.

Figure 14 shows a set of six districts whose cost rates vary widely throughout the year. For the most part, these districts experience costs per mile that range between the two reference districts in the figure (Houston and San Antonio).

The districts in Figure 14 tend to be closer to the unit cost of San Antonio between September and January but they tend to be more similar to Houston between February and July. An interesting observation is that these districts tend to appear toward the right in Figure 5 (indicating fewer miles driven on debris removal activities). The exception to that observation is Corpus Christi, ranked 11 out of 25 districts in Figure 5. Only two districts exceed the unit costs of Houston at some point in the year: Bryan and Yoakum.

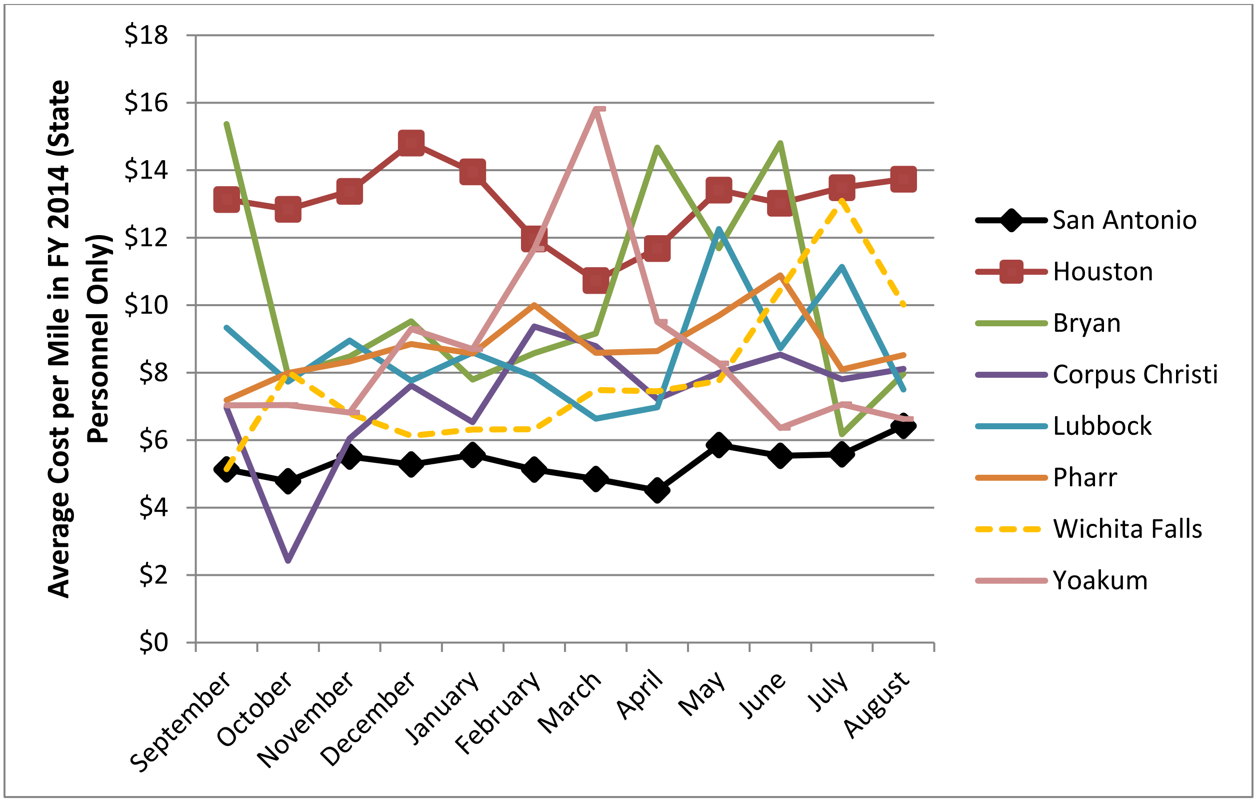


Figure 14. FY 2014 Monthly Debris Removal Costs at Districts with Large Variation.

Figure 15 shows the unit cost trends for Atlanta and Tyler, the two smallest districts in terms of miles driven by state personnel (per Figure 5).

The unit cost of Atlanta is very comparable to Houston during 6 months out of the 11 months of available data, but it significantly increases during September, December, May, June, and July.

The variability in the unit cost of Tyler is by far the largest among the districts, with unit costs ranging from about $10/mi to about $45/mi. However, this is the smallest district regarding the amount spent and miles driven by state personnel to remove debris in comparison to the other 24 districts.

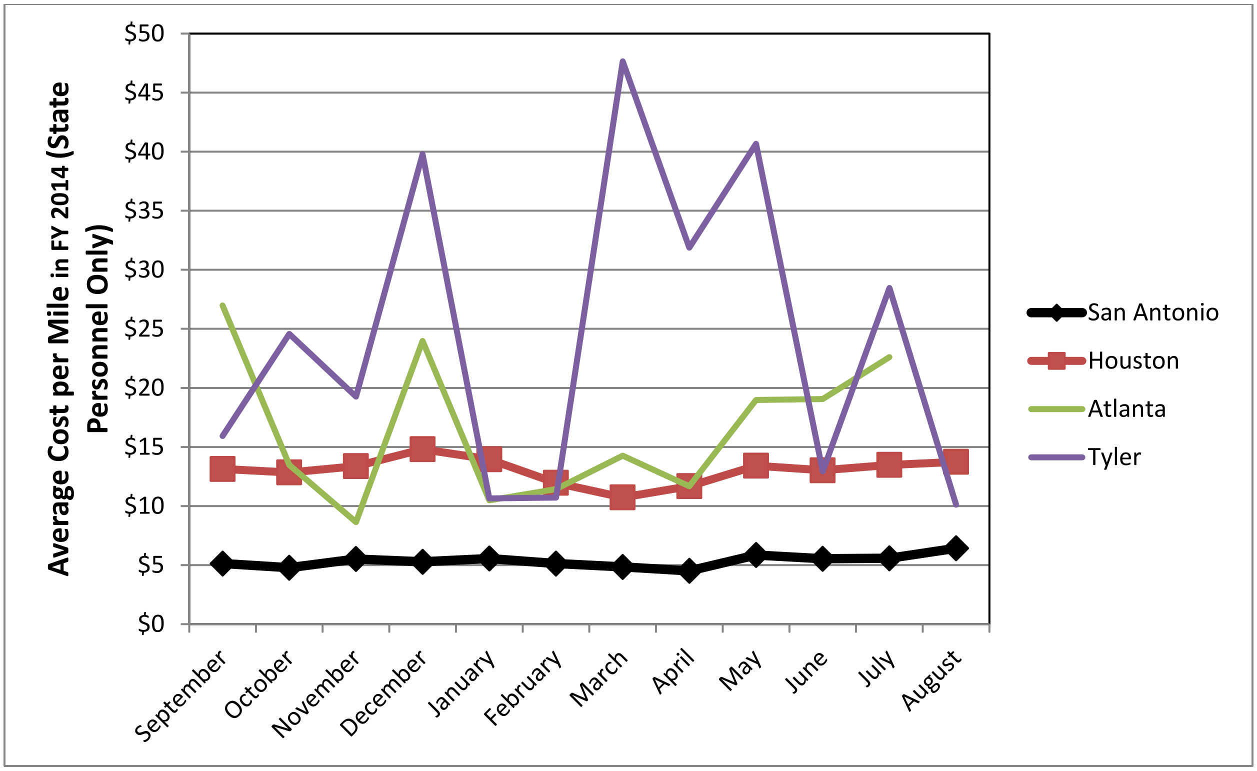


Figure 15. FY 2014 Monthly Trends at Districts with High Volatility in Debris Removal Unit Costs.

Given the trends observed in Figure 10 through Figure 15, it appears that districts can be classified into four distinct groups based on the behavior of their unit cost of removing debris using state-force work alone.

Cost by Percent of Debris Removal by Contractors

It is desirable to observe how the unit cost behaves when work that is performed by contractors is also considered. The research team constructed Figure 16 to investigate if the groups of districts appear to behave differently for varying amounts of work performed by contractors. This figure shows the average unit cost versus percent of debris removal work done by contractors for the five districts depicted in Figure 10 and the groups of districts depicted in Figure 12 through Figure 15.

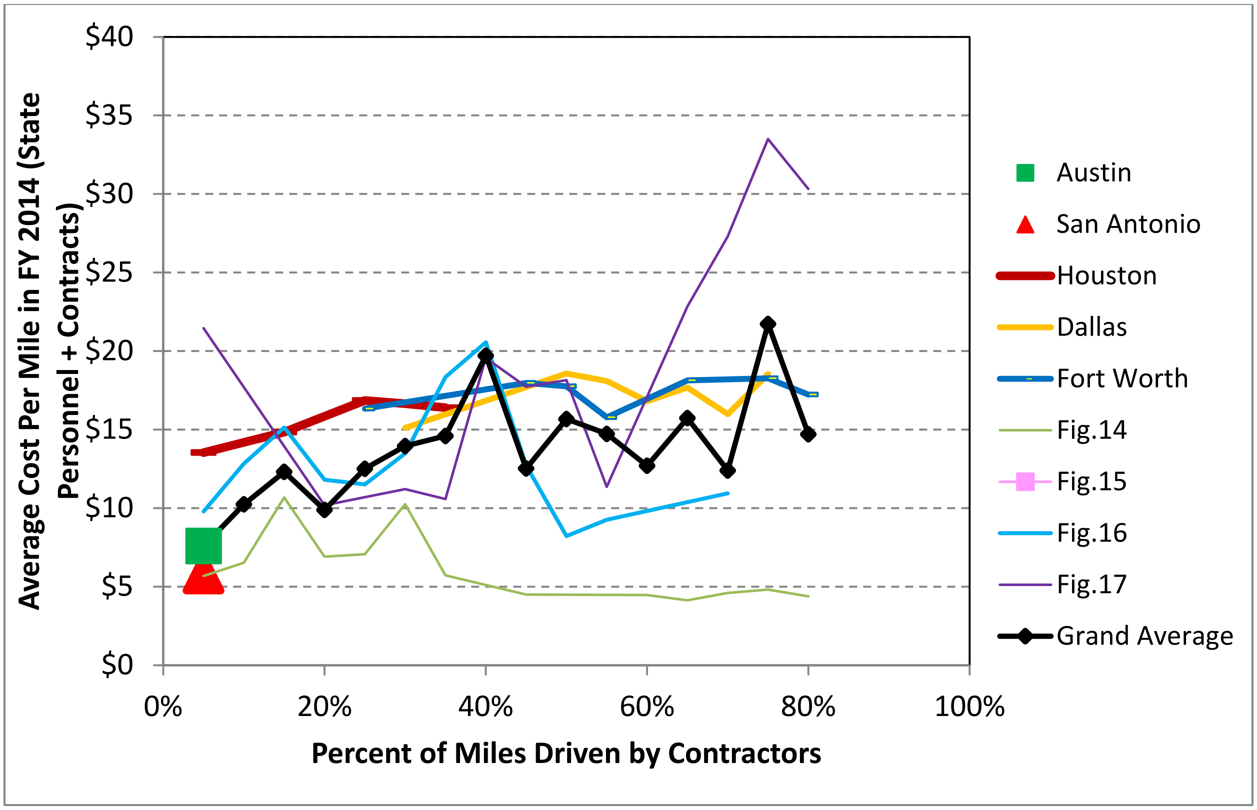


Figure 16. Average Unit Work vs. Percentage of Contracted Work, FY 2014.

The grand average trend in Figure 16 (shown in black and with point nodes) indicates that the unit cost of debris removal increases with increasing share of work done by contractors, from about $7.6/mi at 5 percent contractor work, up to about $18.0/mi for a share of 80 percent contractor work. Although this is a general trend, the figure depicts important differences among large districts and the groups of districts identified previously. San Antonio and Austin only have one point represented in Figure 16 since these districts let 5 percent or less of debris removal work to external contractors throughout the year. These are the two districts shown to have the most miles driven by state personnel in Figure 5, which corresponds to the lowest two average unit costs of state-force debris removal consistently throughout the year in Figure 11.

In contrast, Figure 16 shows that Houston, Dallas, and Fort Worth have very similar trends for unit costs versus contractor share of work. In fact, these three districts seem to have a common trend line, though they each cover a distinct range in the amount of contracted work they let: contracted debris removal in Houston varied between 5 percent and about 35 percent, with the corresponding unit cost range of $13.5/mi–$16.9/mi. In contrast, Dallas contracted between 30 percent and 75 percent of its debris removal, with a range of costs per mile of $15.1/mi– $18.6/mi. Fort Worth contracted between 25 percent and 80 percent of its debris removal, with costs per mile ranging from $16.3/mi to $18.3/mi.

Figure 16 also shows the trends of the groups of districts identified in Figure 12 through Figure 15. Interestingly, the average amount of contracted work in the 10 districts identified in Figure 12 does not seem to correlate with the corresponding average unit cost per month. This average cost remains steady at around $5.0/mi for contracted work ranging from 5 to 80 percent. In contrast, the two districts identified in Figure 13 only had 5 percent or less of their debris removal done by contractors, at an average unit cost of $10.12/mi. The districts identified in Figure 14 seem to have experienced a mild increase in unit cost for up to 40 percent of contracted debris removal; at that point, the trend drops and continues to increase mildly. The research team found that the reason for this drop is that all six districts in this group are represented in the range of 5 to 40 percent contracted work, but only Yoakum had monthly costs with contracted work larger than 40 percent.

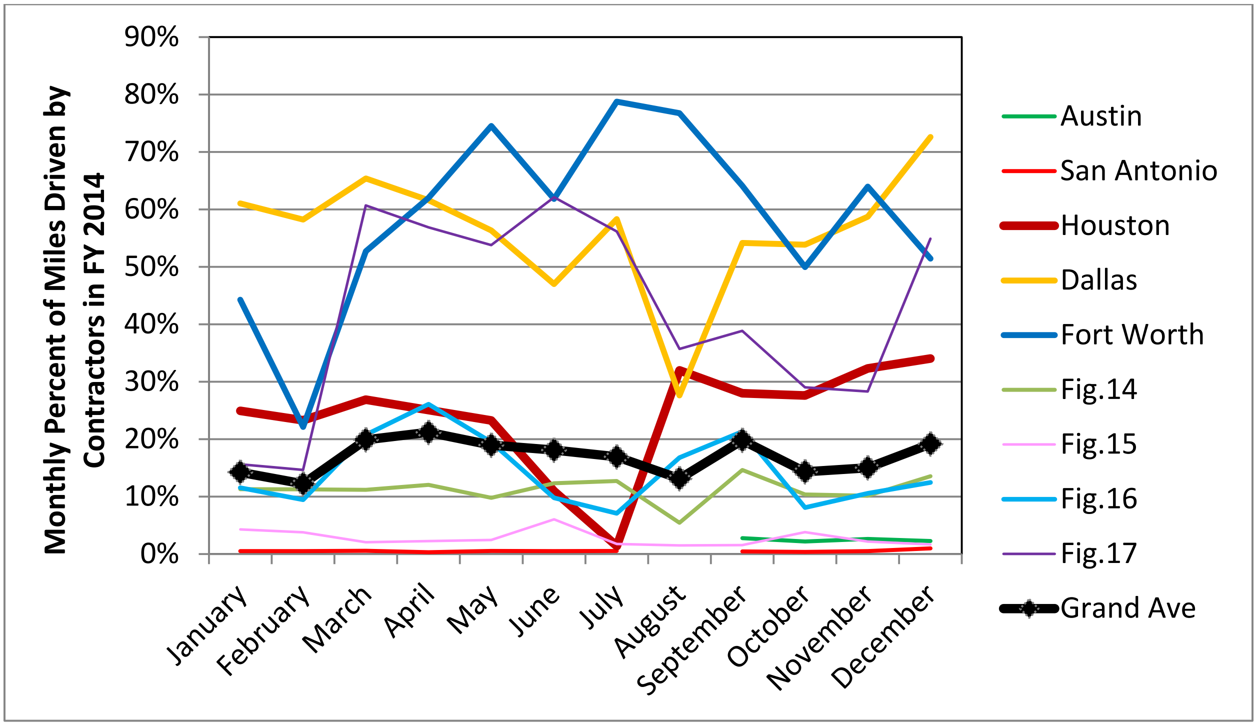


Figure 17. Monthly Percent of Contract Work, FY 2014.

Figure 16 also shows the trend for the two districts identified in Figure 15. The joint trend for the unit cost at these districts also increases with an increasing percent of work performed by contractors.

Figure 17 shows the trends by the districts identified in Figure 16. The amount of contracted work varied considerably throughout the year for Dallas, Fort Worth, and the two districts identified in Figure 15 (Tyler and Atlanta).

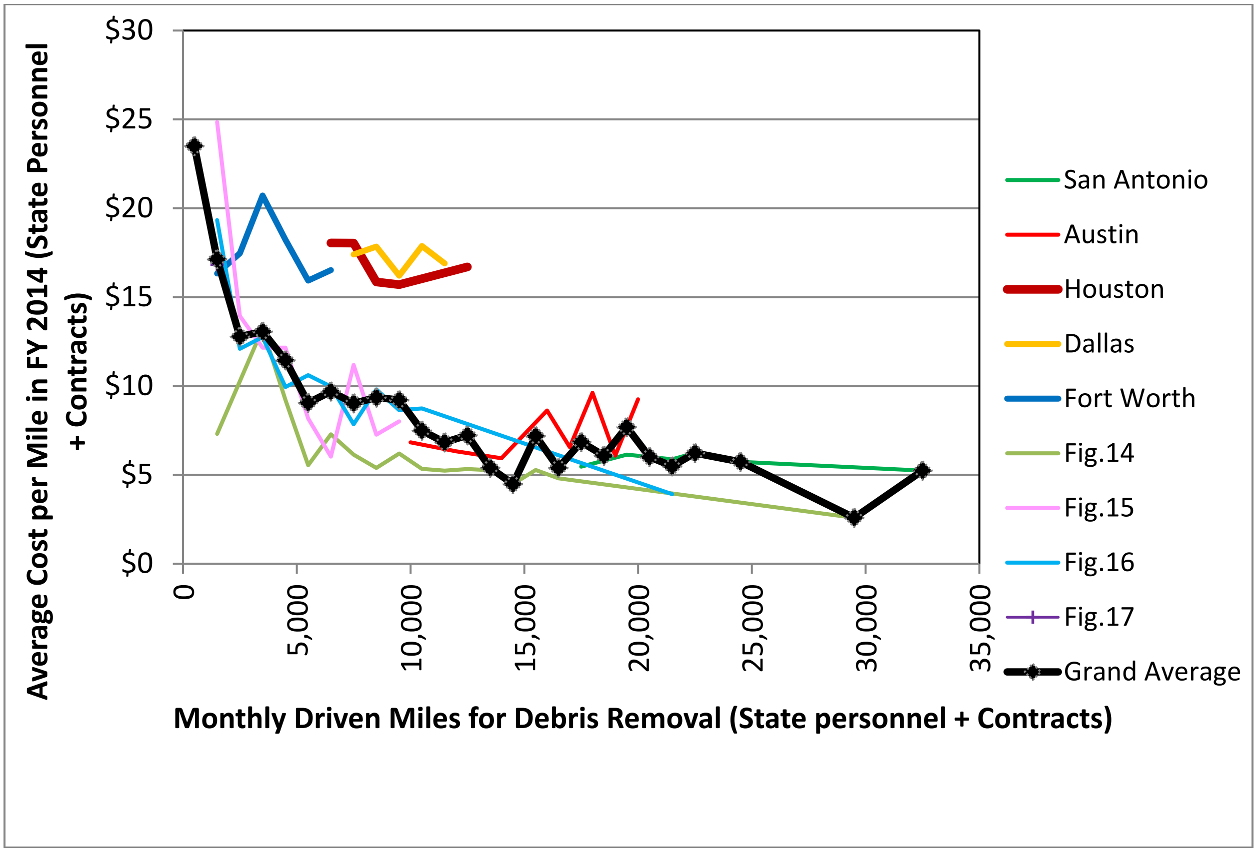


Figure 18. Average Cost per Mile vs. Number of Miles Driven for Debris Removal, FY 2014.

Except for a significant drop in July, the percent of work contracted in Houston was relatively steady, perhaps mildly increasing throughout the year. Both groups of districts named in Figure 12 and Figure 13 had relatively steady shares of contract debris removal work through the year. The districts in Figure 12 averaged from 10 to 15 percent contractor work for most of the year. In contrast, districts in Figure 13 maintained a minimal cost per mile, with a monthly average that never exceeded 7 percent. San Antonio, Austin, and the group of districts in Figure 13 contracted 5 percent or less of their debris removal work throughout the year.

Finally, Figure 18 shows a general trend of diminishing cost per mile as the number of driven miles increases, consistent with the concept of economies of scale. Only Dallas, Fort Worth, and Houston seem to deviate from the general trend just described. Rather, these three districts seem to have a relatively flat average cost per mile.

KEY FINDINGS

The research team surveyed TxDOT districts about their practices of handing TD. Responses were obtained from 12 out of 25 TxDOT districts. In general, TD handling varies significantly by district, as evidenced in the responses of the statewide survey of TxDOT district practitioners. The research team requested cost and quantity of work data from TxDOT Maintenance Division to search for further insights about TD handing. Most important, the requested data should allow the research team to estimate TD generation rates. Such estimation requires combining records of debris removal frequency and actual volumes of TD found on Texas roads. That estimation is described in Chapter 5 of this report. The following subsections summarize the findings of the efforts in this task.

Debris Generation and Removal

Unfortunately, the rate of TD generation cannot be determined directly from the responses of the statewide survey. The survey found that districts log debris removal in terms of miles driven rather than quantity of debris removed. A few practitioners did provide estimates of TD quantities that are removed from their districts' roadways in a typical year, but these numbers varied widely based on the types of roadways, volumes, and traffic composition (particularly truck volume) present in the districts. The practitioners provided more relevant insights into the composition of debris that their personnel find on state-maintained highways. They generally stated that TD represents about half of the debris that they remove from roadways (see Figure 3). They were also able to verify that debris generation is correlated with traffic volume, and their responses suggested a possible connection with truck volume.

Though the practitioners acknowledged some variability throughout the year, they generally stated that their personnel or a contractor removes debris from high-volume roadways on a weekly basis and from lower-volume roadways less frequently. The scheduling of past debris removal operations by TxDOT personnel is kept in records and logged in terms of miles driven. The required scheduling of debris removal operations by contractors is typically stated in the contract. Hence, it is more feasible to obtain archived data on debris removal than from the responses in the survey. In terms of total miles driven for debris removal by state personnel, San Antonio, Austin, and Odessa totaled more miles than the rest of the districts, as shown in Figure 5. San Antonio, Austin, and Houston are the districts with the highest total cost of state-force debris removal, per Figure 7.

Differences in Cost and Contract Structure among Districts

The research team performed an exploratory analysis of cost differences between districts. First, this analysis focused on the four largest districts in terms of debris removal expenditures and dollar amounts of maintenance contracts. This preliminary analysis found that Houston and Dallas notably differ from Austin and San Antonio:

- Houston and Dallas spend the largest dollar amounts in maintenance contracts, closely followed by San Antonio and Austin. Houston is the district with the largest total amount in maintenance contracts (Figure 9).
- The same rankings prevail among large districts on the number of maintenance contracts they have in place. However, Houston almost doubles the number of maintenance contracts of Dallas. Dallas ranked fifth in terms of number of maintenance contracts; Waco ranked second based on the metric used (Figure 8).
- Austin, San Antonio, and Odessa are the districts that logged the most miles to remove debris by the state personnel (Figure 5).
- The research team pursued a more detailed analysis of the cost of debris removal using additional data provided by TxDOT Maintenance Division.
- Austin and San Antonio have consistently lower costs per mile for state-force debris removal compared to Houston, Dallas, and Fort Worth (Figure 10). Perhaps this finding relates to the fact that Austin and San Antonio logged more miles driven by state personnel in debris removal activities.

Different sets of districts were identified based on how their monthly costs per mile of state-force debris removal compare with the reference cases of Houston and San Antonio. The following points summarize those comparisons:

- The Dallas and Fort Worth Districts are similar to Houston in terms of their cost rates of state-force debris removal, per Figure 10. When also considering debris removal work done by contractors, these three districts seem to have a common trend in how their cost per mile varies in response to the proportion of debris removal miles driven by contractors Figure 16. For these three districts, the cost per mile does not seem to vary much as a function of the number of monthly miles driven to remove debris, in contrast to the rest of districts (Figure 18).
- The four districts with more yearly variability in the amount of debris removal work let to contractors are Dallas, Fort Worth, Tyler, and Atlanta, per Figure 17.
- Tyler is the district with the largest variability in its cost per mile of removing debris using state force, per Figure 15. However, in absolute terms, this district appears to have the smallest debris problem since it logged the least miles driven on debris removal activities (Figure 5) and the smallest total cost of debris removal (Figure 7).
- The set of Amarillo, Beaumont, Brownwood, Childress, Laredo, Lufkin, Odessa, Paris, San Angelo, and Waco Districts experienced low cost rates of state-force debris removal, very comparable to San Antonio and Austin, per Figure 12. Although the amount of debris removal done by contractors varied widely among these districts, their costs per mile are relatively flat through the range of contract/state-force mix of debris removal work, per Figure 16.
- The El Paso District has similar costs per mile to San Antonio, except for a spike in cost during the summer months, as shown in Figure 13.
- The Abilene District has a spike in cost rate during the summer months similar to the El Paso District. However, Abilene has consistently larger monthly cost rates than El Paso, per Figure 13.
- The Bryan, Corpus Christi, Lubbock, Pharr, Wichita Falls, and Yoakum Districts experienced large variability throughout the year in their costs per mile when state

personnel removed road debris. Typically, their cost per mile tends to oscillate between the cost rates of San Antonio and Houston throughout the year (Figure 14).

- Figure 18 shows that, except for Houston, Dallas, and Fort Worth, the general trend for TxDOT districts is that monthly cost per mile relates inversely to the amount of monthly miles driven to remove debris from roads (including miles driven by both state personnel and contractors). In contrast, the cost per mile appears relatively flat in this figure for Houston, Dallas, and Fort Worth.

Answers from several interviewed practitioners suggest that annual average daily traffic (AADT) and truck percentage may correlate with TD occurrence. Finally, the exploratory analysis on cost/contract structure suggests considerable differences between districts, mostly in response to the size of the road networks they serve; however, differences exist between districts of comparable sizes.

CHAPTER 4. SAMPLE OF VOLUME AND CHARACTERISTICS OF TIRE DEBRIS ON TEXAS HIGHWAYS

The overall goal of this research effort is to investigate the volume, characteristics, costs, and safety implications associated with TD on Texas highways. Conducive to that goal, this chapter summarizes field visits at a random sample of Texas districts' sites. The contents of this chapter include sampling methodology, field data methodology, data collection, and data reduction.

This chapter describes the efforts of this research intended to characterize TD on highways in the state of Texas as a whole. A robust dataset of high quality and adequate quantity are required to produce statewide representative numbers. The research team developed an image acquisition system to produce a photographic record of the debris found at the visit sites. The research team developed a protocol, analytical procedures, and programming code to process the massive photographic record from the field visits.

In addition, this chapter summarizes an analysis of a subset of TD pieces retrieved from the field visits. These pieces were measured and weighted in order to calibrate and verify the results from the image analysis of the whole data.

Finally, the main purpose of estimating TD volume from district visits is to combine those estimates with the corresponding amount of work and frequency of debris removal data obtained from the maintenance division in order to estimate debris volume generation rates in Texas roads. These quantities, in turn, will allow for the estimation of statewide costs of TD on Texas roadways.

DESIGN OF TEXAS ROADS PROBABILITY SAMPLE

The research team developed a probability sample of the state roadways to obtain field data rather than selecting a sample of sites by convenience. A probability sample allows researchers to draw inferences about quantities of interest at the sampled population level. Because the sampled population in this case is all TxDOT-maintained roads in Texas, this procedure will allow drawing conclusions about debris on roads in the state as a whole, based on the conditions observed at a subset of roads.

The sample frame for probability sample design can be controlled effectively using the variables available from state databases, such as the Road-Highway Inventory Network

(RHINo). The research team initially proposed a stratified sample based on the following criteria:

- TxDOT regions (north, west, south, and east).
- Facility character (urban, rural).
- Functional classification (interstate highways, U.S. highways, state highways, farm-to-market roads).The procedures to determine an appropriate probability sample are described in more detail in the following sections.

The RHINo File as Sampling Frame for a Probability Sample Design

The research team used the RHINo database as a sampling frame for the sample design. The RHINo database contains records for all roadway segments maintained by TxDOT. Such records include various crucial variables for this sample design: the area character (urban versus rural), the geo-location of each segment, the length in miles of each segment, the functional classification, the historic AADT, and the percentage of trucks, among other variables.

Unequal Probabilities Sampling

The research team considered two premises throughout the sample in the design: (a) TD is found more often on heavily traveled roads, and (b) previous research has found that truck traffic is expected to correlate with TD frequency. The literature review in Chapter 2 found a study indicating that the proportion of TD produced by trucks is approximately 50 percent, a disproportionate representation compared to the proportion of miles traveled (Carey, 1999).

The research team chose to apply unequal probabilities of selection to different road segments as a function of their length, overall traffic volume, and the truck share of traffic in order to incorporate the two mentioned premises. The following sections offer more details about the implementation of this procedure.

Three-Stage Sample Design

The research team developed a multiple-stage strategy for the sample design. The three criteria for stratification mentioned earlier were incorporated within this multiple-stage sampling procedure. The first stage of the sample design included additional criteria for clustering the population by sub-regions so that miles of travel between data collection sites were minimized while miles traveled on direct data collection activities were maximized.

The first criterion originally proposed (stratification by Texas region) assured the sample representativeness of the geographic spread in the state of Texas. Therefore, stratification by region was determined as the first stage of the design.

Texas districts break down the state in 25 continuous sub-regions of relatively similar size. The research team used this partition to implement clustering in a second stage in the proposed design.

Finally, a third stage was implemented as an additional stratification based on the other two criteria originally proposed (facility character and functional classification). The expected effect of such stratification was to discount a significant amount of variability between roads of different functional classification within a district. Overall, the proposed sample design intended to balance considerations of efficiency, accuracy, and cost of data collection. Figure 19 shows a schematic of the sample design.

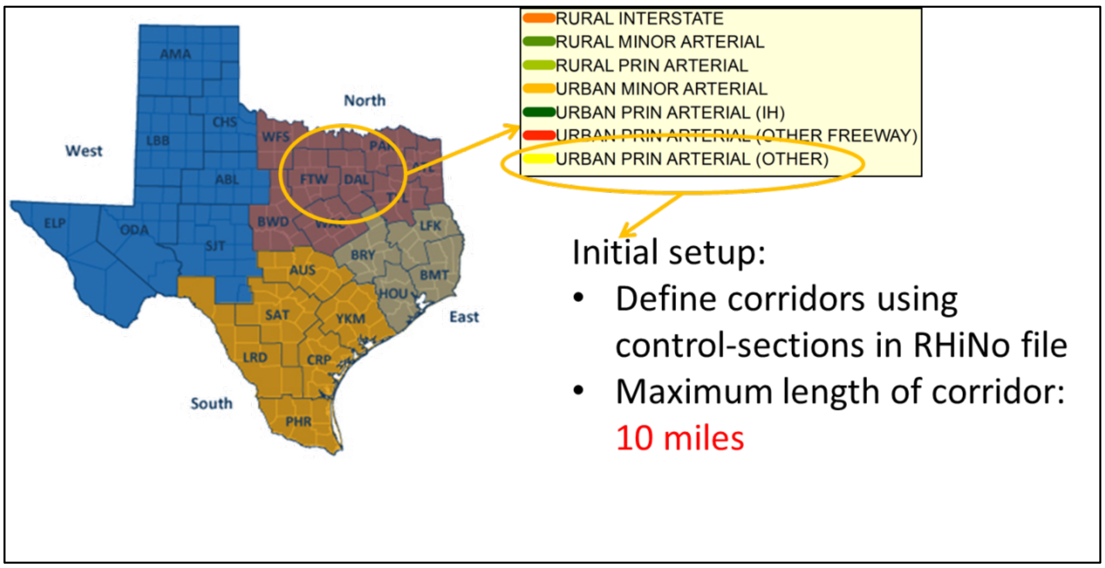


Figure 19. Three-Stage Sampling Scheme for the State of Texas.

The corresponding procedure can be summarized as follows:

- Determine a total amount of miles to be surveyed in the state of Texas.
- Assign a weight coefficient to districts based on the expected amount of TD, anticipated variability of TD occurrence, and the cost of collecting data within that district.

- Stage 1: stratification by Texas region. An appropriate number of districts were allocated to each Texas region.
- Stage 2: clustering by district. A predetermined number of Texas districts were randomly selected from each region, using the weights mentioned above.
- Stage 3: stratification by functional class and road character. For each selected district, a predetermined number of road segments were randomly selected from each functional class and road character of interest. This selection was based on the expected number of miles within functional class and road character, expected variability of TD for those miles, and the expected cost of data collection.

First Stage in the Sample Design: Stratification by Region

The first stage of the design stratified the Texas roadway network by Texas region. The simplest way to achieve this goal was to sample each stratum proportionally to the number of elements it contains. Such a procedure resulted in equal probability of selection for each sampling element in the population to be sampled. Generally, it made sense to sample more heavily at strata with more elements.

Second Stage in the Sample Design: Clustering by District

Clustering by district was incorporated in order to minimize travel miles between sites for data collection. Similar to the first stage, weights were assigned to each district in order to take advantage of the expected correlations between TD and traffic volumes.

The number of miles, the expected amount of TD, the expected variability of TD, and the relative cost of data collection at remote sites were all considerations incorporated into this stage of the sampling.

Third Stage of the Sample Design: Stratification by Functional Class

Similar to the first stage, the third stage of the design stratified the Texas roadway network by functional class and road character simultaneously. The research team reviewed the suitability of the variables proposed for defining strata. In the case of functional class, using the highway system designations was originally considered (i.e., interstate, U.S., state, and FM classes). However, the research team found that a single route might have sections of different functional classes within a single district. For example, FM 2818 in the Bryan District has

15.5 mi designated as urban principal arterial, 0.65 mi as urban minor arterial, and 0.92 mi as urban local road. Since it is known that the efficiency of a stratified sample design decreases in proportion to the heterogeneity of the strata (Lohr, 1999), the research team selected a variable that combines the two criteria for facility character and functional class instead. This variable is FUNC_SYS_ID (Roadway Function) in the RHINo file. Table 3 shows all the available levels. For the sample design, the following levels were selected as strata: 1, 2, 6, 11, 12, 14, and 16 (these levels are indicated in bold type).

Table 3. Levels of Roadway Function Variable in RHINo.

FUNC_SYS_ID	FUNC_SYS_DESC
1	**RURAL INTERSTATE**
2	**RURAL PRIN ARTERIAL**
6	**RURAL MINOR ARTERIAL**
7	RURAL MAJOR COLL
8	RURAL MINOR COLL
9	RURAL LOCAL
11	**URBAN PRIN ARTERIAL (IH)**
12	**URB PRIN ART (OTHER FRWY)**
14	**URBAN PRIN ART (OTHER)**
16	**URBAN MINOR ARTERIAL**
17	URBAN COLLECTOR
19	URBAN LOCAL

Additional Considerations for Sampling

It was expected that some percentage of collected data might not be useful for various reasons (e.g., equipment failure, unforeseen road features encountered). To compensate for this anticipated data loss, the research team designed a sample larger than what was expected to be an appropriate sample size. The research team originally proposed collecting data from 600 miles of Texas roads. However, important road characteristics such as number of lanes and number of roadbeds effectively double the chances of TD being generated and the effort required to collect data. Therefore, the research team initiated this sample design under the assumption of 600 lane-miles as a minimum for the sample size. The actual sample was designed to exceed that minimum when the schedule and budget allowed.

The actual number of miles selected varies from sample to sample when using the proposed three-stage scheme because of the randomness associated with the sampling mechanism and the sequential nature of the three stages of the proposed scheme. In order to better understand this uncertainty and account for it, the following subsections describe general considerations and mitigation strategies associated with the various elements in the probability sample.

Length of Segments

An important characteristic of the sampling units in the RHINo file is that the segments of road have varying lengths. These segments are such that a change in the cross-section of the road triggers the beginning of a different road segment. As a result, the length of segments ranges from a few feet to several miles. However, roadway cross-section was not expected to influence the occurrence of TD, at least as much as other critical variables (i.e., AADT and segment length itself), so the research team decided to merge adjacent segments whose control sections were the same. This procedure was such that the maximum length of a merged segment did not exceed 10 mi.

Speed Limit at Candidate Sites

Speed limit was expected to be among the factors that influence occurrence of TD. Because of the added stress at higher speeds, it was reasonable to expect that a potentially defective tire, or a worn out one, be more likely to blow up at higher rather than at lower speeds. Given this consideration, the sampling frame comprised RHINo segments with speed limits of at least 45 mph.

Size of Strata

With regard to the strata size in the population of roads, the research team used the exact number of segments available from the filtered set of merged RHINo segments for both the first and third stages. Because the variable of interest was TD frequency, each segment was given a weight in proportion to its length and amount of traffic volume. It was anticipated that these two characteristics should correlate with TD frequency.

Developing Weights for the Sampling Procedure

As mentioned earlier, the research team chose to implement unequal probabilities of selection in the random selection mechanism as a way to incorporate available knowledge about which roads experience the largest amounts of TD generation. Segment length was a natural choice to weight the relevance of a segment, so the weighting procedure incorporated the length of the segment explicitly. Similarly, roads with higher traffic volumes are expected to have higher frequency of TD and more variability in the occurrence of TD—similar to a Poisson random variable. Therefore, traffic intensity was incorporated into the individual weights for road segments along with the length of the segment.

Finally, cost considerations were incorporated into the weighting of road segments to maximize the amount of miles that could be visited within the time frame and budget of this research.

Optimal Allocation for Data Collection

Optimal allocation, as defined by Lohr (1999), incorporates stratum size, expected variance within the stratum, and an estimate of cost of data collection. This type of allocation should maximize the number of miles to be collected by balancing the necessary logistics and the need to reduce the uncertainty of the sample estimates.

In simple terms, the objective was to maximize the number of sampling units within a stratum or cluster while considering the following principles: (a) more data are acquired at strata/clusters that represent a larger proportion of the population of interest—Texas roads, in the case of this research; (b) more data are acquired from strata/clusters where the variance of the variable of interest (TD frequency) is expected to be larger. Sampling heavier at such strata/clusters offsets the uncertainty created by the increased variability; and (c) more data are acquired from strata/clusters where the cost of sampling is low, relative to other strata/clusters.

Relative Cost of Data Collection

In order to maximize the amount of miles that can be visited, the research team defined two qualitative variables designating a relative cost of data collecting. One of the variables assessed a relative cost for remoteness, and the other assessed the relative cost of collecting data at different facility types. These two costs guided the research team in weighting the optimal data allocation at each stage of the sampling. Regardless, the procedure was such that any road in any district had a measurable probability of being drawn into the final sample. The relative cost by remoteness was constructed such that it reflects the distance of a district to Texas A&M Transportation Institute (TTI) headquarters (within Bryan District). Table 4 shows the relative cost values assigned to each district. Similarly, Table 5 shows the relative cost values assigned by facility type and the total number of miles of each facility type by district.

Table 4. Relative Cost of Data Collecting per District.

District	1	2	3	4	5
Abilene			X		
Amarillo					X
Atlanta			X		
Austin	X				
Beaumont		X			
Brownwood		X			
Bryan	X				
Childress				X	
Corpus Christi		X			
Dallas		X			
El Paso					X
Fort Worth		X			
Houston	X				
Laredo			X		
Lubbock				X	
Lufkin	X				
Odessa				X	
Paris			X		
Pharr			X		
San Angelo			X		
San Antonio		X			
Tyler		X			
Waco	X				
Wichita Falls			X		
Yoakum	X				

Note: The rankings in this table are qualitative assessments of the expected costs of data collection, given the location of the research team's headquarters (1 means least expensive and 5 means most expensive).

Table 5. Strata Sizes and Relative Costs.

Region	FUNC_SYS	Weighted Average Cost	Total Miles
East	RURAL INTERSTATE	1.27	177.6
	RURAL MINOR ARTERIAL	1.22	1589.4
	RURAL PRIN ARTERIAL	1.21	1171.9
	URBAN MINOR ARTERIAL	1.12	2451.0
	URBAN PRIN ARTERIAL (IH)	1.14	261.8
	URBAN PRIN ARTERIAL (OTHER FREEWAY)	1.09	412.9
	URBAN PRIN ARTERIAL (OTHER)	1.13	1361.2
North	RURAL INTERSTATE	2.19	519.8
	RURAL MINOR ARTERIAL	2.23	3138.6
	RURAL PRIN ARTERIAL	2.32	2059.7
	URBAN MINOR ARTERIAL	2.02	2995.8
	URBAN PRIN ARTERIAL (IH)	2.01	487.8
	URBAN PRIN ARTERIAL (OTHER FREEWAY)	2.04	506.8
	URBAN PRIN ARTERIAL (OTHER)	2.06	2045.6
South	RURAL INTERSTATE	1.91	432.4
	RURAL MINOR ARTERIAL	1.81	2046.1
	RURAL PRIN ARTERIAL	2.03	2042.0
	URBAN MINOR ARTERIAL	1.96	1965.0
	URBAN PRIN ARTERIAL (IH)	1.78	290.1
	URBAN PRIN ARTERIAL (OTHER FREEWAY)	1.86	417.2
	URBAN PRIN ARTERIAL (OTHER)	2.02	1557.1
West	RURAL INTERSTATE	4.01	926.7
	RURAL MINOR ARTERIAL	3.84	3312.8
	RURAL PRIN ARTERIAL	4.08	2406.7
	URBAN MINOR ARTERIAL	4.11	896.1
	URBAN PRIN ARTERIAL (IH)	4.25	176.1
	URBAN PRIN ARTERIAL (OTHER FREEWAY)	4.17	181.1
	URBAN PRIN ARTERIAL (OTHER)	4.33	830.5
TOTAL			**36,659.6**

Developing a Surrogate Measure of TD Frequency for Sample Design

Since the variable of interest was the frequency (and quantity) of TD, the research team constructed a surrogate estimate of TD frequency as a function of quantities known from the RHINo database.

The surrogate function relied mostly on the relationship with AADT documented in the literature. Researchers constructed Equation 1 by considering that truck traffic was given almost twice the weight of non-truck volume. The surrogate was proportional to both AADT counts at different rates and to the length of the segment.

The calculation of this surrogate for a segment of known AADT and truck AADT was defined as follows:

$$\boldsymbol{td^{*} = Segment\_Length \times \sqrt{0.65 \cdot (AADT_{Trucks})^{2} + 0.35 \cdot (AADT_{Cars})^{2}}}$$

Equation 1

Where:

td^*	=	Surrogate measure of TD, the sampling design variable.
$AADT_{Trucks}$	=	The AADT for trucks given in the RHINo file.
$AADT_{Cars}$	=	The AADT for non-truck vehicles given in the RHINo file.
Segment_Length	=	The length of the segment in miles.

By using this surrogate measure, the research team was able to evaluate how the sampling procedure was expected to perform. Additionally, this surrogate measure allowed the optimization of the parameters involved in the data collection scheme.

Sensitivity Analysis, Parameter Optimization, and Expected Performance

There was always uncertainty about the performance of a sample design, especially complex designs that incorporate both stratification and clustering, such as the design proposed in this research. Certainty could be achieved only if the actual distribution of the variable of interest were known; however, in that case a sampling procedure would not be necessary.

In any case, the expected performance can be assessed based on reasonable assumptions about the behavior of the variable of interest. The research team performed such an assessment prior to beginning data collection. An additional motivation for this exercise was that the same framework to assess the sample design performance offers the opportunity to perform a sensitivity analysis and to optimize the sampling parameters.

Sample Segments Selection

The research team developed computer code in R language to implement the sampling procedure described in this chapter. The procedure was a sequential implementation of the following steps:

- Randomly select a predetermined number of districts from each Texas region, given the weights assigned to each district resulting from the optimal allocation definition discussed earlier.
- Extract the prior probability of each selected district, per the selected sampling mechanism: systematic sampling with unequal probabilities and without replacement.
- Within each selected district, randomly select a predetermined number of segments of the functional classes previously mentioned according to the weights assigned to each functional class, per the discussion of optimal allocation earlier in this chapter.
- Extract the prior probability of each selected segment using systematic sampling with unequal probabilities and without replacement.

Optimization of Sampling Scheme

The objective of optimizing the sampling scheme was to obtain an estimate for total amount of TD in Texas that has maximum precision, given all the considerations previously described in this chapter. Utilizing the R code that implements the three-staged sampling (The R Development Core Team, 2013; Tillé and Matei, 2015), the research team generated multiple realizations of the sample. By observing the change in precision from multiple realizations of the probability sample, it is possible to find optimal values for the initial setup variables such that the expected performance of the sampling scheme was maximized. This optimization procedure sought to answer the following three questions, given the available budget: (a) what is the optimal number of districts to allocate per region? (b) what is the optimal number of segments (or miles) to allocate per each selected district? and (c) what is the optimal number of segments (or miles) to be allocated per each functional class in each district?

In terms of comparative performance, it was important to contrast how the proposed design procedure compares to a simple random sample (SRS; SRS is a common benchmark when comparing efficiency of sampling designs). Depending on the appropriateness of the criteria used for stratification and cluster in the design, the relative precision could be comparable to or even better than the precision of a SRS design. Poor criteria, however, could compromise the precision of the estimates obtained from the proposed sampling scheme. The careful selection of criteria defining the stages for the proposed scheme should yield an improved precision given a total sample size. These criteria were justified and supported by previous knowledge about TD, truck volume, passenger-vehicle volume, and facility type.

Optimal Number of Districts

The first parameter for optimization in the sampling scheme corresponds to the number of districts to be visited. The research team generated sets of 500 realizations (replications) from the sampling scheme, allowing the number of districts to vary from six to nine. For each set of 500 realizations, a fixed set of values was defined for the rest of parameters in the sampling scheme. Since the objective was to determine the total amount of debris in Texas roads, the total of the surrogate variable td* was calculated from each available sample realization. In the case of variable td*, the actual total can be directly evaluated from Equation 1 for each RHINo segment. Figure 20 shows box plots for the total estimates obtained from each set of 500 sample realizations and how they compare to the actual total for variable td*, denoted as a green horizontal line.

The coding of each boxplot in Figure 20 is as follows: the initial four characters read “Syst,” indicating that the random mechanism is systematic sampling (without replacement); the next four digits represent the number of districts per region under that sampling scheme. For example, for the first boxplot in Figure 20, the four digits 3321 indicate a set of realizations that sampled three districts from the east region, three from the north region, two from the south region, and one from the west region. Finally, the number in parentheses indicates the total number of districts selected. From this figure, the best performing sets can be recognized as those with narrower boxes, indicating that more precision was achieved by those parameters. The three boxes to the right in the figure are the ones that would result in less precise estimates; similarly, the four boxes to the left in the figure are those expected to result in higher precision.

The expected performance of the leftmost option—which requires collecting data in nine districts—is comparable to the expected performance of option Syst.2221(7) that requires only seven districts. Because of its expected performance, the research team adopted Syst.2221(7) for the sampling scheme.

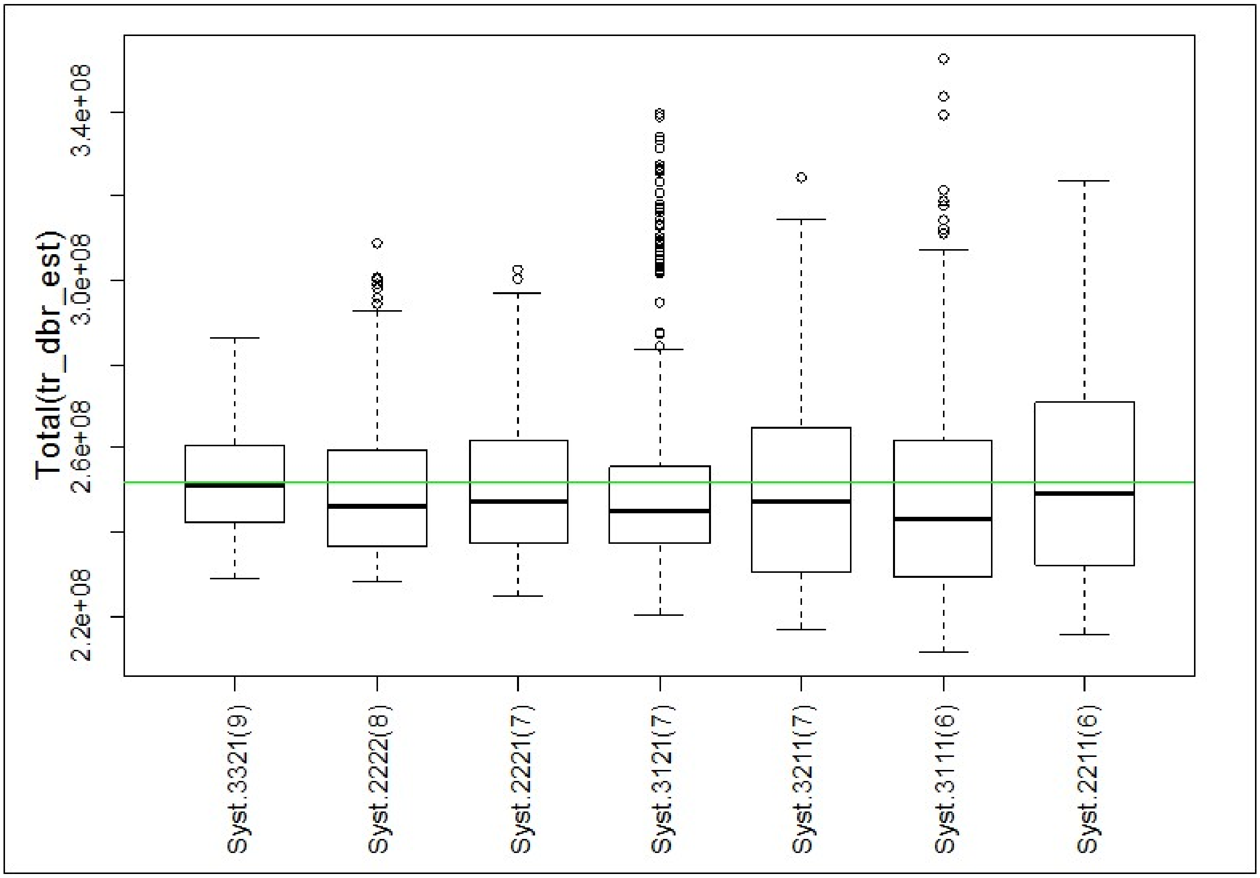


Figure 20. Expected Performance by Number of Districts.

Optimal Number of Miles

Using the parameterization of Syst.2221(7), the research team compared performance of the sampling scheme for varying number of miles to be collected. Figure 21 shows the results of this comparison. The coding of the groups in this figure include the characters "grn###," which indicate how many aggregated RHINo segments are selected. Figure 21 also shows the average number of miles corresponding to two of the boxplots. It is evident from this figure that once the number of districts was fixed, increasing the number of miles does not have a significant impact in the precision of the sample. For the purposes of this research, the research team proposed adopting the Syst.2221.grn100 option for the sampling scheme. This option would yield about 400 miles in the final sample. The research team sought advice from TxDOT about adopting this option, and TxDOT agreed with this proposed scheme.

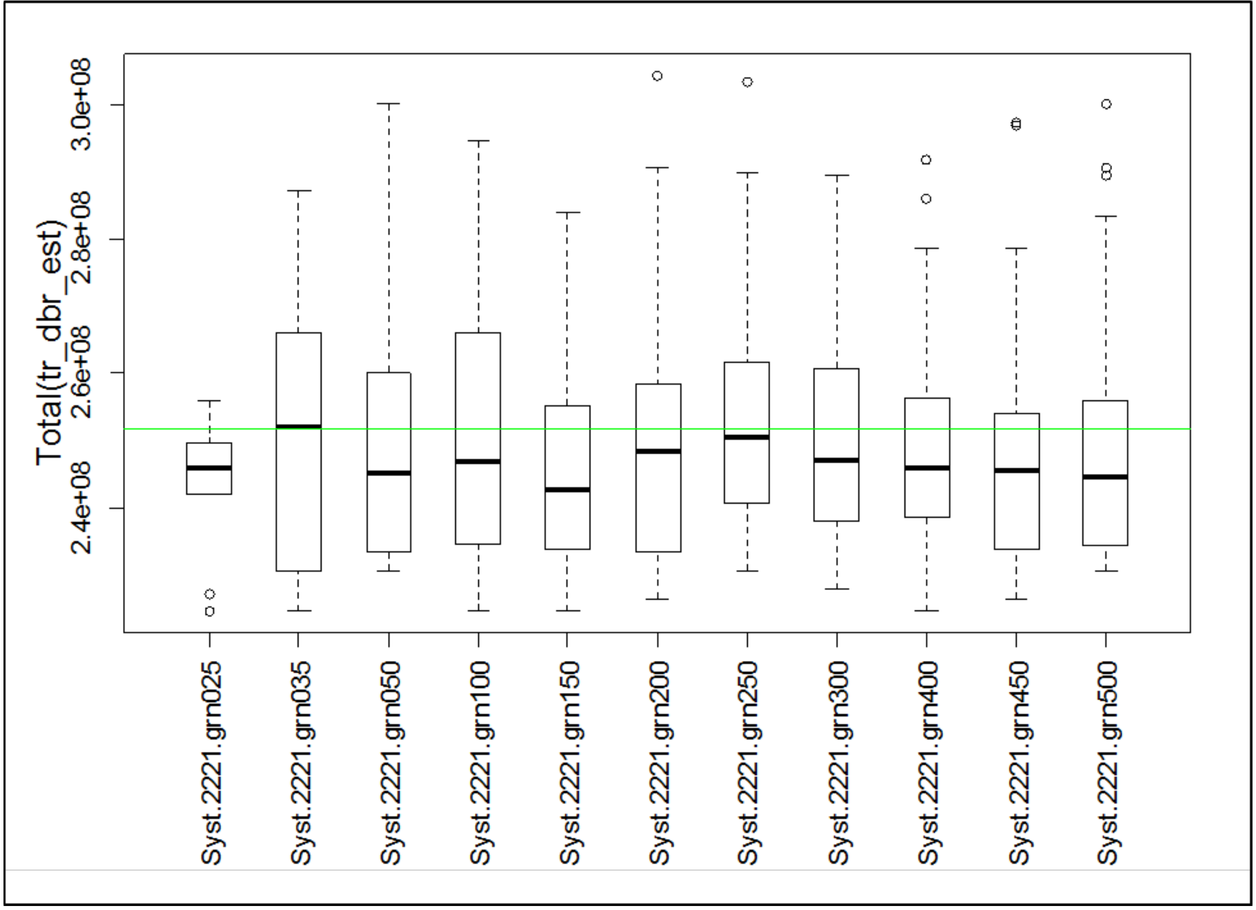


Figure 21. Expected Performance by Total Number of Miles.

Additionally, given that fewer miles than anticipated are expected to provide accurate results, there was an opportunity to revisit a subset of the selected sites for additional data. Such additional data could be used to explore for the presence of seasonal variability, as was suggested in the survey documented in Chapter 3. For this purpose, it was determined that the sites from the Bryan District would be visited during summer and fall 2015.

Expected Performance of the Optimized Sampling Scheme

After adopting the optimized parameters as described in the previous subsections, the research team generated estimates for the total of td* (the design variable) from a set of 500 samples using the optimized parameters of the sampling scheme. The distribution of these estimates was then compared to the distribution of 500 SRS estimates from the RHINo file. Figure 22 shows this comparison graphically.

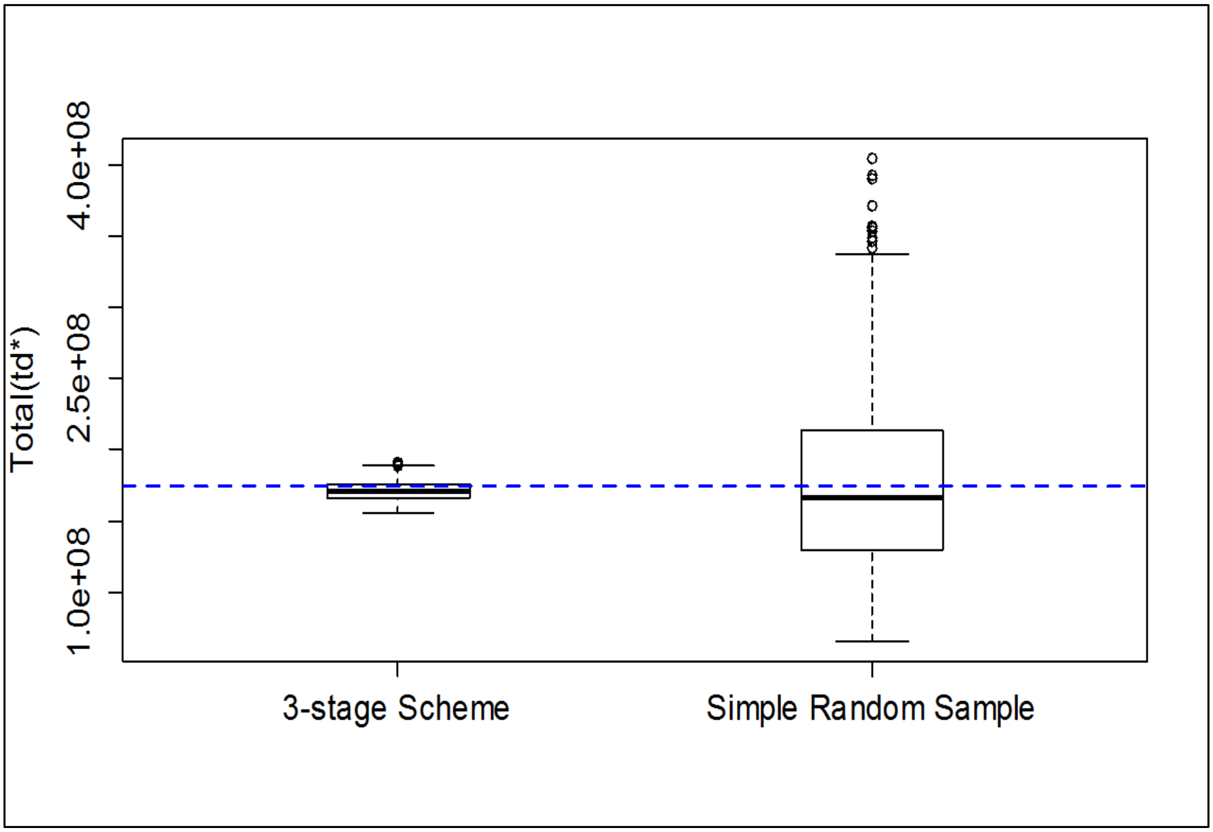


Figure 22. Comparative Performance of Optimized Three-Stage Sampling Scheme and Simple Random Sampling.

The dashed horizontal line in this figure indicates the real value of the parameter of interest (i.e., the total for the TD surrogate variable, td*). As can be seen, both sampling procedures are expected to perform accurately in estimating the parameter of interest. However, the precision that was expected from the three-stage scheme was clearly superior to the precision that a simplistic SRS was expected to yield.

Selection of a Sample for Data Collection

Using the optimized sampling scheme, the research team generated various candidate sample realizations for consideration for the data collection effort. Figure 23 shows four of those candidate sample realizations.

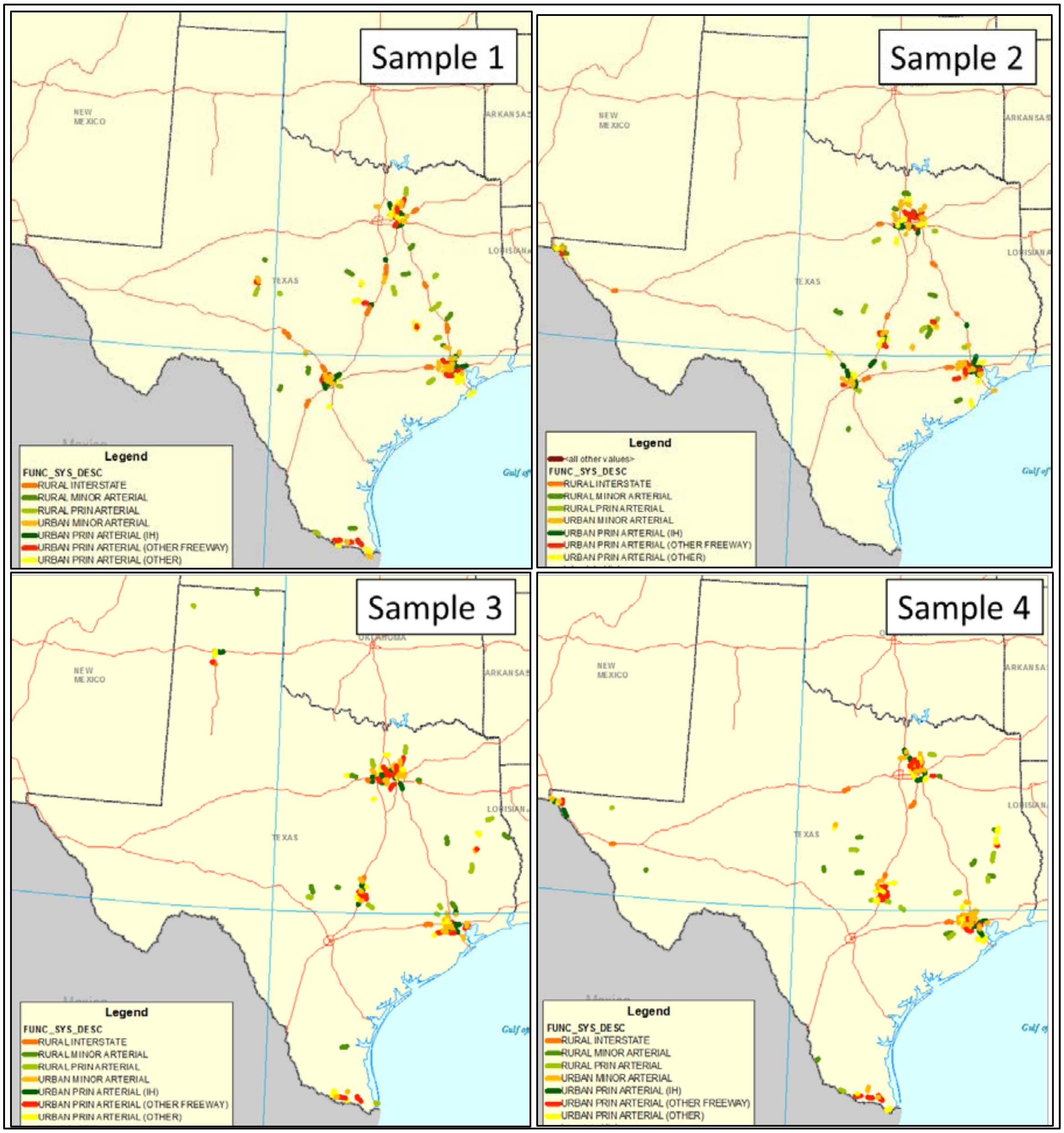


Figure 23. Sample Realizations from the Optimized Three-Stage Sampling Scheme.

Each of the samples in this figure represents one output of running the sampling code with the optimized parameters. They are different from one another because of the randomness in selecting a different set of segments each time. Since final probabilities of selection for each segment are known for all these realizations, any of them can be used for data collection.

The research team selected Sample 2 because this option seemed to minimize required travel. Other than the El Paso District, the majority of the sites at districts in this alternative are within driving distance of each other. The selected sample consists of 443.3 centerline miles distributed between functional classes and districts, as shown in Table 6.

Table 6. Number of Centerline Miles in Selected Sample per District and Functional Class.

	SAT	AUS	BRY	DAL	ELP	FTW	HOU	Grand Total
RURAL INTERSTATE	5.4	3.8	8.3	6.0	9.2	2.3	6.6	**41.6**
RURAL MINOR ARTERIAL	6.4	2.8	9.1	9.0	3.7	9.1	7.0	**47.0**
RURAL PRIN ARTERIAL	0.5	7.9	11.6	2.4	4.8	6.7	8.4	**42.4**
URBAN MINOR ARTERIAL	2.1	8.1	1.9	1.6	7.2	1.3	5.2	**27.4**
URBAN PRIN ARTERIAL (IH)	24.0	19.6	5.0	20.7	5.9	21.1	36.5	**132.8**
URBAN PRIN ARTERIAL (OTHER FREEWAY)	14.3	20.6	5.7	22.8	8.7	4.5	32.3	**108.7**
URBAN PRIN ARTERIAL (OTHER)	5.0	12.6	4.3	3.4	5.9	0.9	11.3	**43.4**
Grand Total	**57.7**	**75.2**	**45.9**	**66.0**	**45.3**	**45.9**	**107.4**	**443.3**

Similarly, Table 7 shows the number of lane-miles in the sample selected. In total, the sample consists of 2289.2 lane-miles. This table should be more representative of the effort necessary to collect the required data. The research team used this table to plan data collection activities.

Table 7. Number of Lane-Miles in Selected Sample per District and Functional Class.

Row Labels	SAT	AUS	BRY	DAL	ELP	FTW	HOU	Grand Total
RURAL INTERSTATE	21.6	22.7	33.3	23.8	36.9	9.3	26.5	**174.1**
RURAL MINOR ARTERIAL	16.4	11.0	18.2	18.1	13.0	27.3	14.0	**118.0**
RURAL PRIN ARTERIAL	2.1	31.5	29.0	9.8	19.0	26.8	33.8	**151.9**
URBAN MINOR ARTERIAL	4.2	20.6	3.7	9.4	27.1	2.6	11.6	**79.3**
URBAN PRIN ARTERIAL (IH)	172.6	117.5	19.8	142.0	42.0	149.7	294.7	**938.3**
URBAN PRIN ARTERIAL (OTHER FREEWAY)	82.5	122.6	22.6	109.7	42.7	23.0	229.0	**632.1**
URBAN PRIN ARTERIAL (OTHER)	19.9	50.3	17.3	17.3	23.4	3.8	63.2	**195.3**
Grand Total	**319.3**	**376.3**	**144.1**	**330.1**	**204.2**	**242.5**	**672.8**	**2289.2**

The next section describes the logistics and preparation the research team underwent prior to beginning data collection.

DATA COLLECTION PLAN

Once a sample of roads was selected, the research team briefed the TxDOT project team about the procedure followed to obtain a representative sample of Texas roads for data collection. The next subsection summarizes the details of the data collection activities as they were incorporated into the data collection plan.

Specific Considerations for Data Collection

The smallest piece of TD of interest for this research was determined to be between 3 and 4 in. wide. One reason for electing that minimal size was because of the expected difficulty of detecting pieces smaller than 3 in. wide using photographic data, considering the potential range of distances between the instrumented vehicle and the road debris. Another important consideration is the unlikely scenario that a smaller piece would be the cause of an unscheduled trip for debris removal. Assuming the resolution of human vision at 1 arc minute, a 3 in. wide piece with a thickness of 0.5 in. can be detected at around 75 to 100 ft in front of the vehicle. In contrast, a person traveling at 60 mph whose perception-reaction time between 0.5 and 1.0 s would travel 44 to 88 ft while assessing and recognizing such a small piece of debris in front of the vehicle.

The research team determined to collect data for 443 mi because the precision of the probability sample was not expected to improve significantly after a sample size of 400 mi (per Figure 21). A subset of these sites was scheduled for two visits. The data obtained during the second visit for a subset of sites were intended to investigate seasonal variability of TD (since seasonality was suggested by many interviewees during the statewide survey).

The research team developed a data collection system using machine vision cameras at highway speeds to assess the amount of roadway debris. This system was based on an iterative process of design-trial-redesign. The next section discusses the development process; later in this document, details are given about the testing procedure on the accuracy of the data acquisition system, and a section describes the final field data collection procedure.

Development of an Image Acquisition System

Initially, the researchers evaluated various alternatives for a mobile data collection system. For example, the research team considered adapting a system developed for a previous study (shown in Figure 24) that uses an instrumented vehicle to capture images of vehicles in front, the distance to that vehicle, and the current speed of the instrumented vehicle.

Figure 24. Setup for System Developed in Previous Study to Estimate Distance to a Leading Vehicle.

In the previous study, distance was measured by a researcher manually tracking the lead vehicle using light detection and ranging (LiDAR). However, the manual tracking of debris downstream of the instrumented vehicle, as required for the study, could be extremely difficult depending on the quantity and size of the TD. Due to this limitation, the researchers explored variations of the image acquisition system, as well as other potentially feasible alternatives.

Another method initially considered uses a pair of machine vision cameras to generate stereoscopic vision. In general terms, the shift between the images from the pair cameras can be used to estimate distance. Although the appeal of utilizing a stereoscopic system was that it combines the information of two simultaneous images, the research team discarded the idea of using such a system because it doubles the data storage needs and it potentially increases the needed efforts to reduce the data.

A final image acquisition system was developed stemming from the first system described in this section (see Figure 25). Since the objective was estimating the size of various debris pieces, the new variant of the acquisition system focused on assessing the dimensions of objects of interest based on the apparent distance recorded in a photograph. Using spatial information derived from a calibration image and camera optical specifications, the distance to the object of interest can be derived. A critical spatial parameter for this procedure is the pitch angle of the camera with respect to the horizontal plane. A range of pitch angles was tested in an attempt to strike a balance between depth (maximal at zero pitch) and detail (maximum at 90° pitch).

Figure 25. Final Imaging System Setup.

Calculations are performed under the assumption that the longitudinal roadway geometry is relatively flat (at least for a short distance in front of the camera).

Development of an Analytical Framework for Data Processing

To derive transformation formulas from the two-dimensional image to the three-dimensional space it represents, the research team started from the abstract case of locating a piece of debris in the image and then estimating its area. More sophisticated calculations were developed as field information made evident that additional assumptions were necessary. Figure 26 shows the basic schematic of the data collection system.

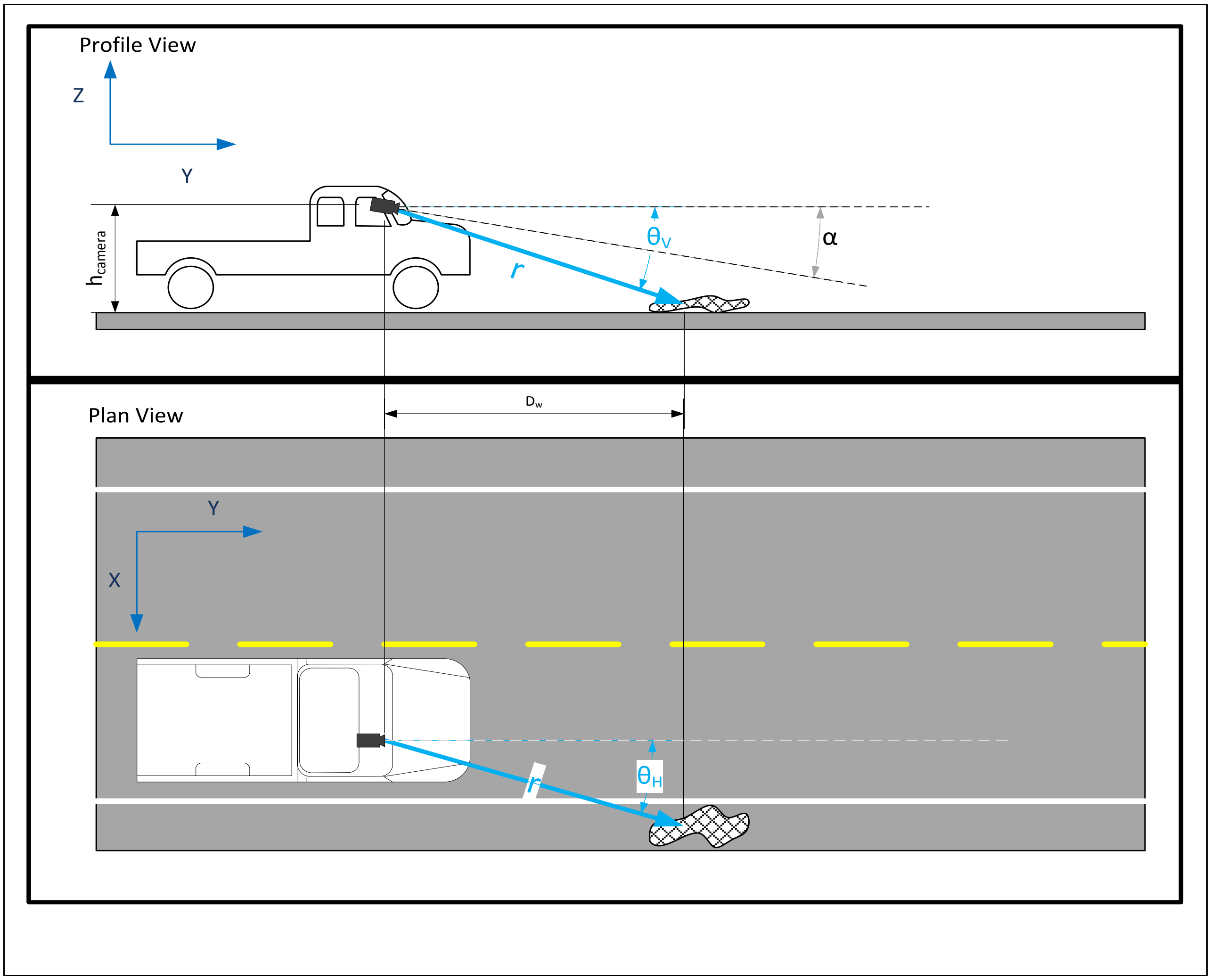


Figure 26. Spatial Location of a Particle in a Flat Piece of Debris.

For the Cartesian coordinate system located at the focal point in the camera, the following is the definition of **r** in the three-dimensional space, once the height of the camera and both the horizontal and vertical angles can be determined:

$$\boldsymbol{r} = h_{camera} \cdot \left[\cot\theta_V \cdot \tan\theta_H \cdot \hat{\imath} + \cot\theta_V \cdot \hat{\jmath} - \hat{k}\right]$$

Equation 2

Where,

r	=	Vector in space that locates the debris particle from camera.
h_{camera}	=	Height of camera relative to the pavement (i.e., z distance to the pavement).
θ_V	=	Vertical angle, or angle between y-axis and the projection of **r** in plane y–z.
θ_H	=	Horizontal angle, or angle between y-axis and the projection of **r** in plane x–y.

During the calibration process, the height of the camera was measured directly, as were at least one of two additional pieces of information: (a) the pitch angle or (b) the location of objects at different (known) distances in front of the camera.

Estimating Distances to an Object Given Its Apparent Position in a Photograph

In order to perform this estimation, it is important to determine how the angular distances in the grid of pixels in a photograph relate to angular distances in the space of an area photographed.

As suggested in Figure 26, the camera was generally tilted with respect to the plane of the road. Therefore, the coordinate system shown in Figure 26 differs from an internal coordinate system of the camera chip X'Y'Z' that corresponds to the grid of pixels in the resulting photograph. Figure 27 shows the relationship between these coordinate systems.

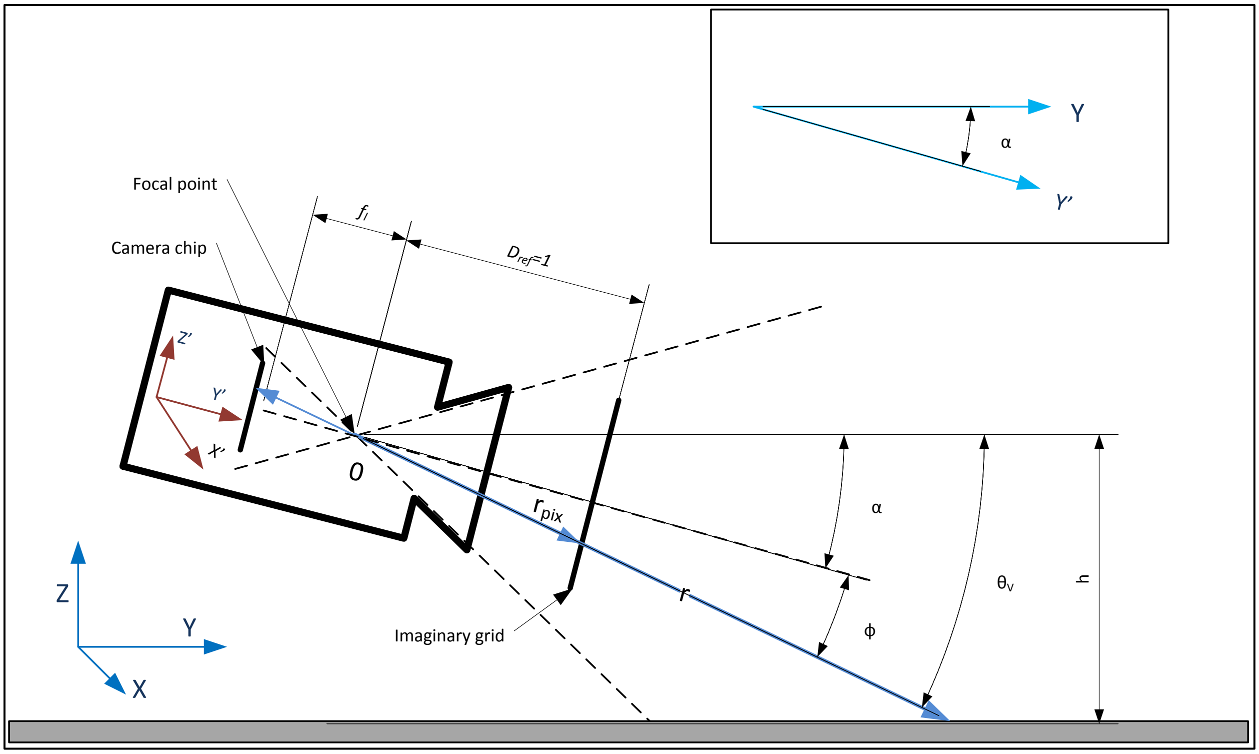


Figure 27. Detail of Position in Reference Grid and on Measurement Space with a Tilted Camera.

Where,

r	=	Vector in space locating a point on the pavement in front of the camera.
$\mathbf{r_{pix}}$	=	Vector in space that locates the apparent location in the photograph, in coordinates X'Y'Z'.
h	=	Height of camera relative to the pavement (i.e., z distance from the pavement).
D_{ref}	=	Reference distance, or y distance, between the camera and the imaginary grid.
α	=	Pitch angle of the camera.
θ_V	=	Vertical angle, or angle between y-axis and the projection of **r,** in plane y–z.
ϕ	=	Angle between y' axis and the component of $\mathbf{r_{pix}}$ in plane y'–z'.

The imaginary grid in Figure 27 rests over a plane perpendicular to the Y' axis such that each square in that grid maps to one pixel in the camera chip. This relationship exists because of similar triangles; one formed from the focal point and any pixel on the camera chip and another formed between the focal point and the corresponding cells in the imaginary grid. Figure 27 also shows that a point on the pavement behind the imaginary grid has an apparent location on the imaginary grid in front of the camera, $\mathbf{r_{pix}}$. It can be shown that angular changes in space should correspond between the two vectors **r** and $\mathbf{r}_{pix}$ regardless of them being measured on the XYZ coordinate system or on the X'Y'Z' coordinate system.

The function of correspondence between pixel position and local angular increment can be derived from the relations above. Figure 28 shows the local $\Delta\phi$ increment as a function of ϕ in its complete range of values.

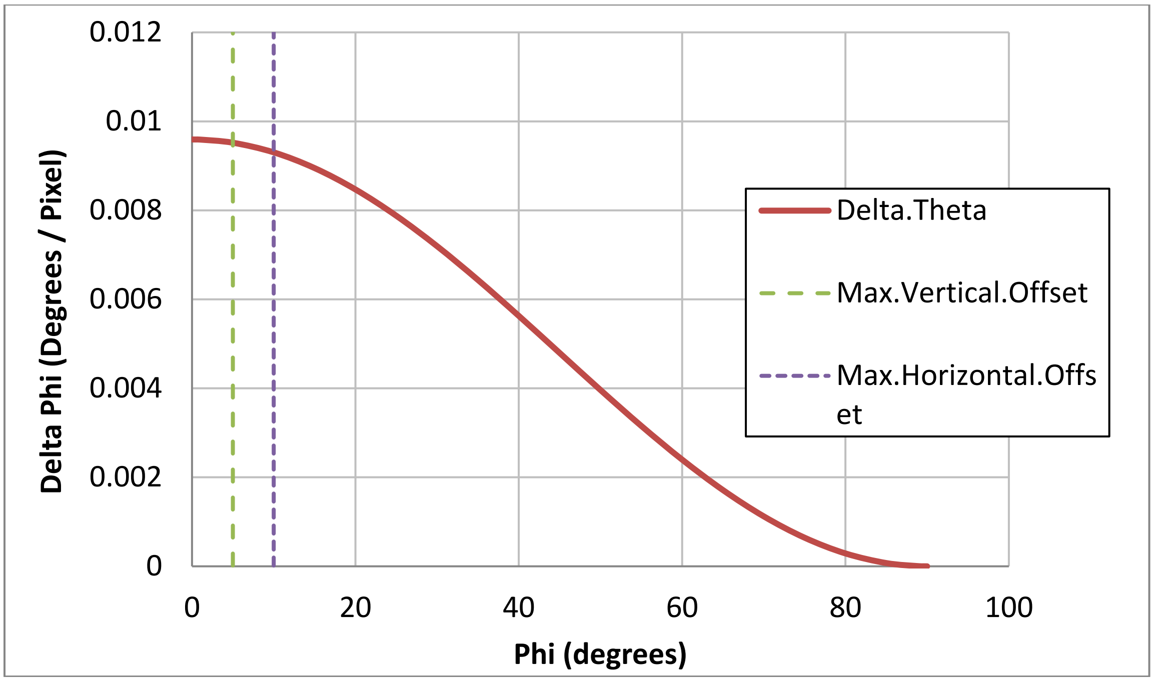


Figure 28. Incremental Angle vs. Offset Angle per Pixel.

This figure also shows the maximum offset visible angle for both X' and Z' as vertical lines.

Developing Discrete Analytical Methods

Depending on an object's orientation in space, different analytical discrete methods were developed to calculate the dimensions of a photographed piece of debris. Developing discrete methods was necessary because the objects of interest were not expected to be regularly shaped. Therefore, the image analysis was developed at the pixel level. The next example summarizes one such analytical method.

When considering the squared pixel on the left side of Figure 29, that pixel *abcd* corresponds to a flat area of pavement, then the squared-shape is apparent, and it emerges as the projection of a quadrangle *abcd*, shown in the right side of Figure 29, laying on a plane perpendicular to the camera line of sight. Dually, the projection of an arbitrary pixel *abcd* over the plane of the road is an irregular quadrangle because each incremental pixel in either the horizontal or the vertical direction corresponds to different incremental angles and heights that are a function of the angular measures at that point, as shown earlier.

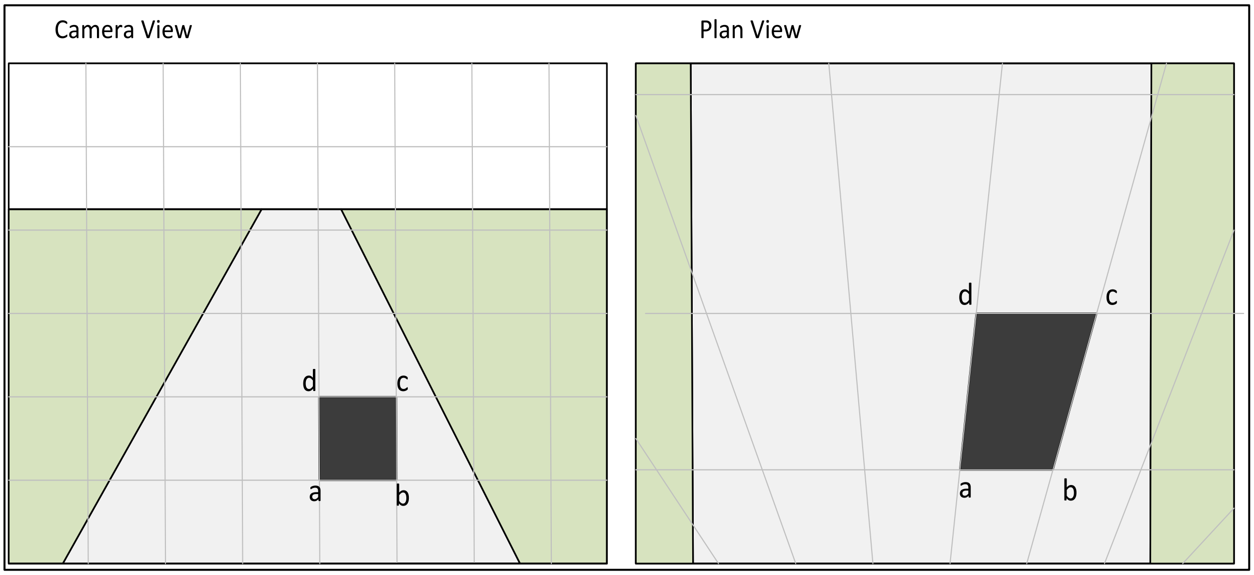


Figure 29. Area of Road Represented by a Pixel.

In order to calculate the area of *abcd*, it is necessary to break the quadrangle down into two triangles *abd* and *bcd* and add the areas, as can be seen in Figure 30.

Vector algebra can be used to compute the areas of interest. The area of a region of interest on the pavement surface (i.e., an identified piece of debris) can be estimated from a photograph by adding the calculated areas of each pixel corresponding to the region of interest (i.e., representing TD). Additionally, similar methods can be developed to estimate width and depth of debris objects as they appear in a photograph.

The data collection protocol dictates that the camera pitch angle and camera height be recorded every time data collection takes place. Since these pieces of information are known, each pixel in the photograph is associated with a known incremental $\Delta\phi$.

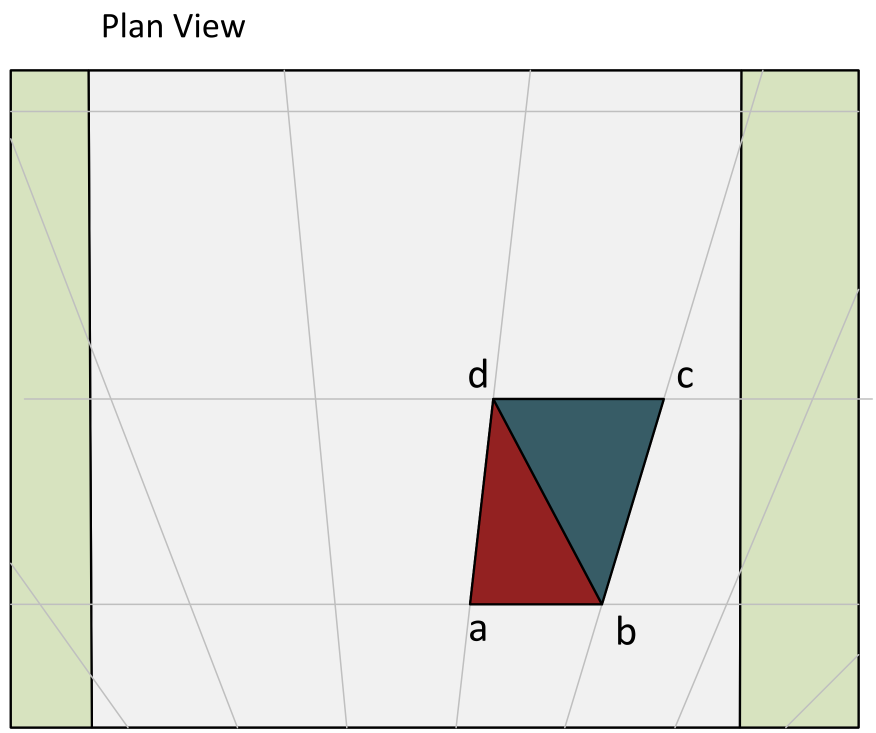


Figure 30. Area *abcd* Shown as the Sum of the Areas of Triangles abd and bcd.

Analytical methods derived from trigonometry and vector algebra were developed to process the acquired data. Calibration images were collected and stored during data collection in order to verify calculations per this theoretical framework. The next section summarizes the general setup developed for object-size calculations from the data acquired with the imaging system.

Testing of Discrete Analytical Methods

Data were initially collected under static and dynamic conditions at the Texas A&M University Riverside Campus. This facility is a closed-course testing facility that allows for greater control over testing conditions to ensure accurate measurements under safe field conditions. The following are the characteristics of this initial testing:

- Four sizes of debris.
- Speed range: 45, 60, 75 mph.
- Lateral offset from lane range: 0, 12, 24 ft.

Figure 31 and Figure 32 show sample images acquired using the test runs. Initial analysis suggested the need for methods to account for lateral offset. These tests also suggested that accuracy was adequate when the object was 100 ft away or closer.

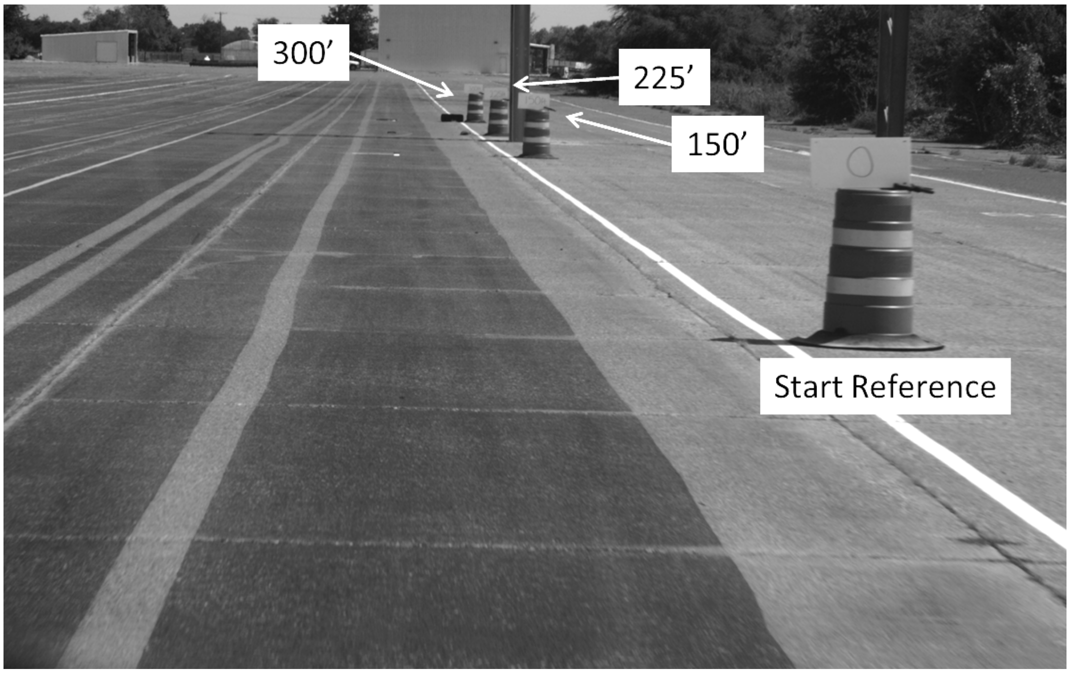


Figure 31. Testing Setup at Riverside Campus.

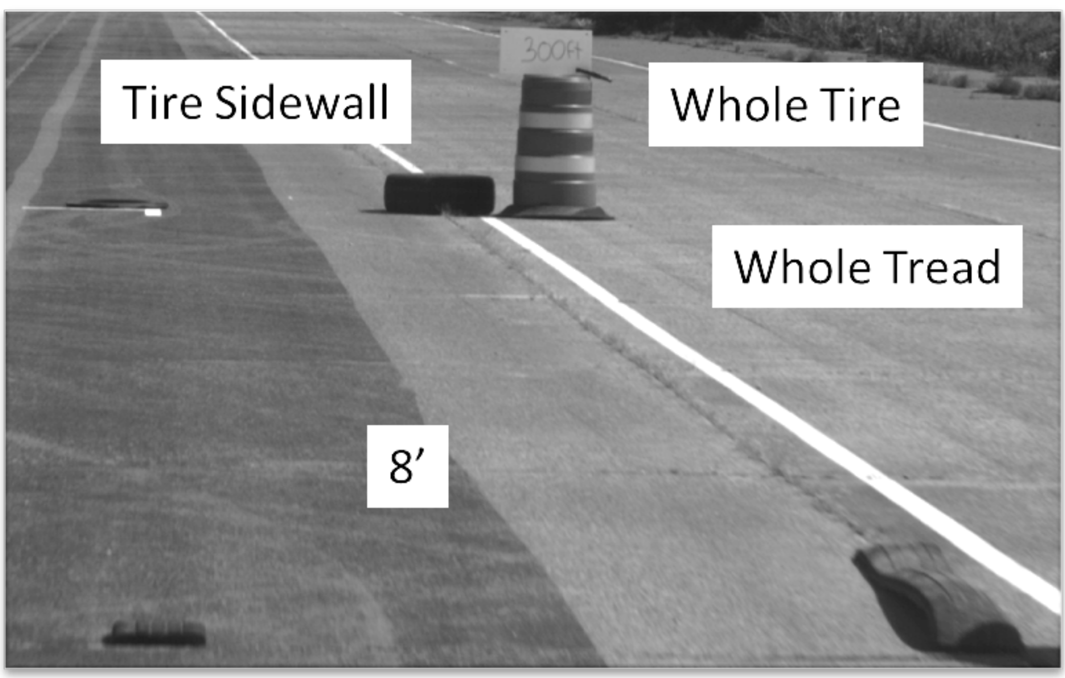


Figure 32. Detail of Testing Setup at Riverside Campus.

The findings of the initial tests were incorporated into updated analytic methods. The formulas derived initially were adjusted to account for lateral offset of an object. This and other necessary modifications were tested—and the methods updated—using actual debris pieces collected from the field and their corresponding field photographs, as described in the following sections.

Testing with Calibration Images

In the data collection protocols, the research team included the requirement that one calibration image be acquired for any data collection trip. The purpose for this calibration image was to verify the post-processing calculations, if such verification seemed necessary at any point during data reduction and analysis. Figure 33 shows a sample calibration image taken at a parking lot near TTI's headquarters. Because the image includes an object at known distance, the sizes of other objects in the image can be calculated using trigonometry.

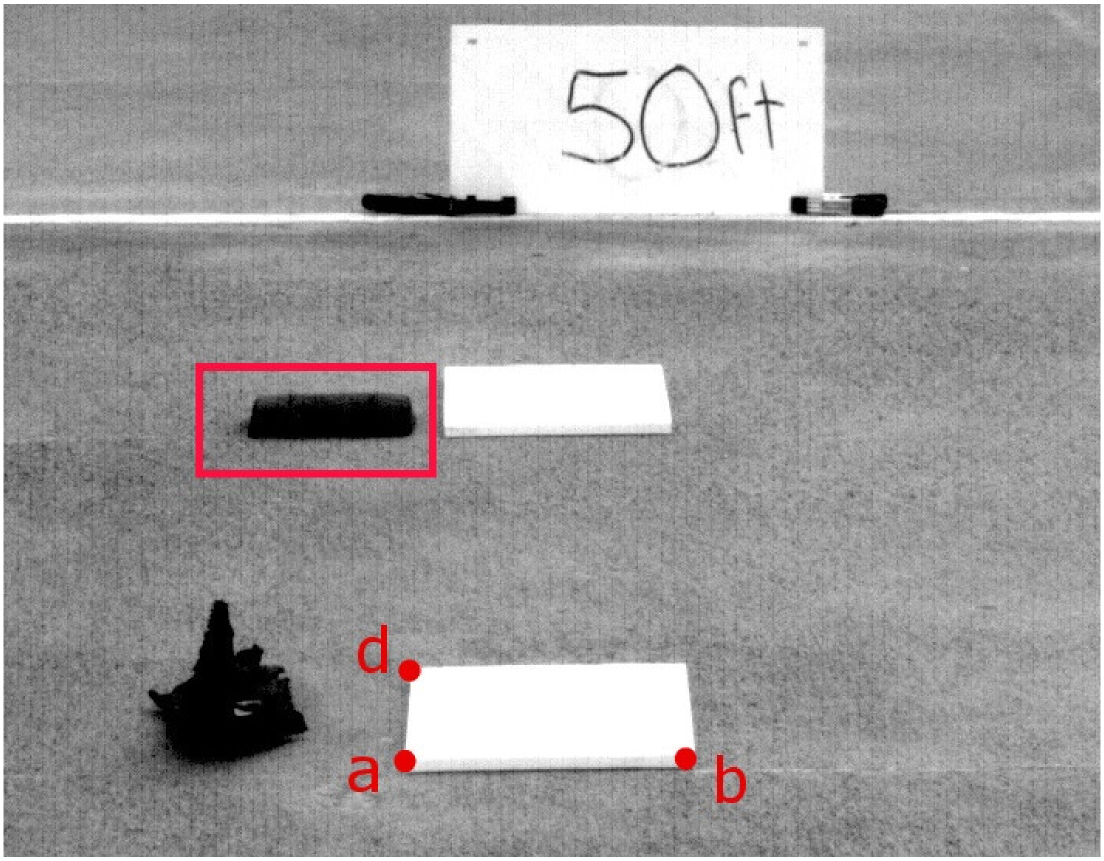


Figure 33. Sample Calibration Image.

The accuracy of the method for flat pieces can be assessed by estimating the area of a flat object of known area, such as the white board closest to the camera in Figure 33. Using the pixel coordinates of points a, b, and d—and the camera parameters and system calibration setup—it was possible to estimate the area inscribed between these points from the photograph. Table 8 shows the intermediate calculations necessary to estimate the area in this example.

Table 8. Sample Area Calculation from Calibration Image.

Point	x_{px}	y_{px}	$theta_h$	$theta_v$
a	743	940	−2.0808	9.1577
b	930	940	−0.2878	9.1577
d	743	882	−2.0808	8.6028
Calculated Area:	313.66	**Real Area:**	288.0	**Error: 9%**

Using additional tests as the one just described, the accuracy of analytic methods and their assumptions were tested and adjusted, as field data became available.

Estimation of the Area of an Arbitrarily Oriented Piece of Debris

Considering the piece closest to the camera in Figure 33, the assumption that this piece lays completely on the pavement is clearly violated. In this and similar instances, an additional complication in the estimation procedures emerges: trying to estimate a range of objects containing three-dimensional protuberances from a two-dimensional image. To mitigate for this issue, the research team performed an analysis of the geometry of a finite element with arbitrary orientation in space. This analysis focused on obtaining a closed functional form relating two projections of the particle (i.e., an area differential of TD), one on the horizontal plane, and one on the vertical plane. A brief description of the procedure is given next.

Let A be the plane of the particle S_R arbitrarily oriented in space. Figure 34 shows a profile view of the particle and its projections, S_V and S_H.

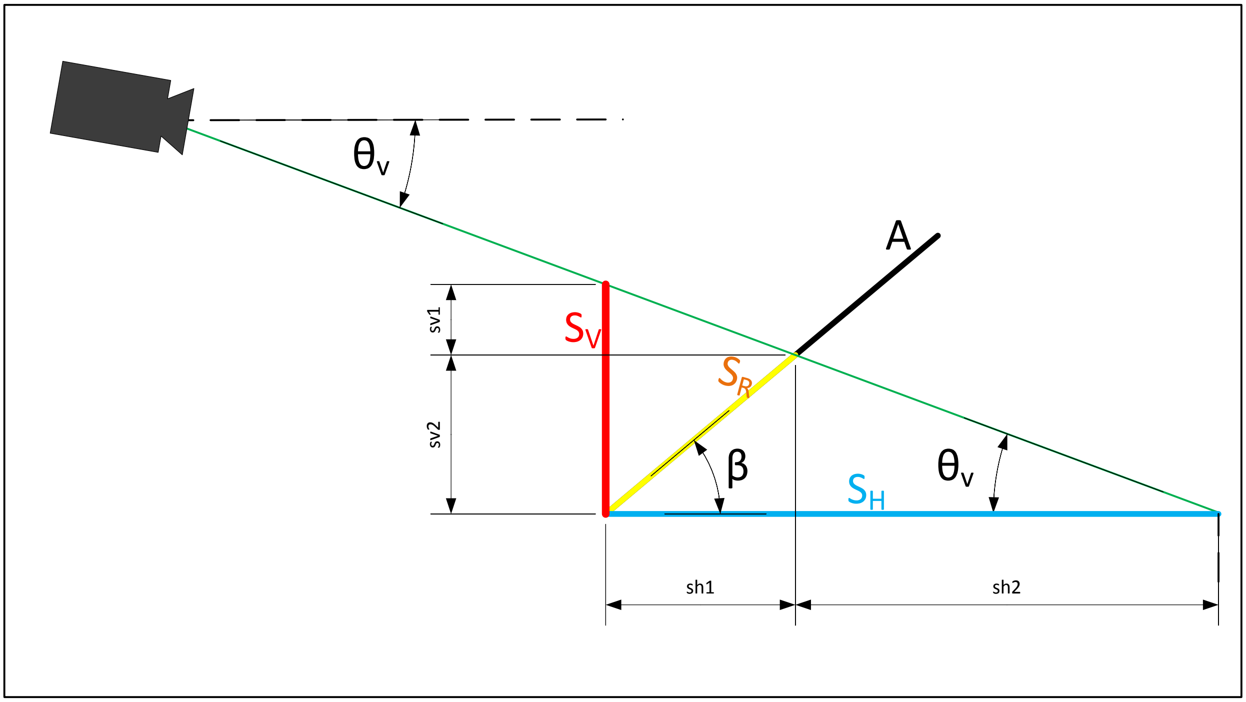


Figure 34. Spatial Relations for Angled Strip and Its Horizontal and Vertical Projections.

Where,

S_R	=	Discrete particle arbitrarily oriented in space.
S_V	=	Vertical projection of S_R.
S_H	=	Horizontal projection of S_R.
β	=	True angle of orientation of S_R in space.
sv1, sv2, sh1, and sh2	=	Sub-areas of S_V and S_H (for intermediate calculations).

Previous works in mathematics have shown that the relation between the projection area to the real area of an object in the three-dimensional space is bound (Slepian, 2012).

More specifically to the problem at hand, it is clear that S_V and S_H covariate negatively as the pitch angle θ_V changes, per their definitions. Equation 3 shows the following relationship holds independently of the value of θ_V:

$$S_R = \frac{1}{\frac{\cos\beta}{S_H} + \frac{\sin\beta}{S_V}}$$

Equation 3

Although the projections S_V and S_H can be reasonably estimated under the assumption of a locally flat road (making the position of each pixel of debris a function of the distance to the camera and a fixed height), the only unknown quantity in Equation 3 is β.

The true area of a piece of debris can be found by integration, over a region where the differentials of the photograph projection of the piece of debris are defined.

In Figure 35, the real area R_i can be calculated if the variation of β is known over the domain of integration, that is $\beta = f_i(x, y)$, as shown in Equation 4.

$$R_i = \iiint_{P_i} S_R(x, y) \cdot dA_i$$

Equation 4

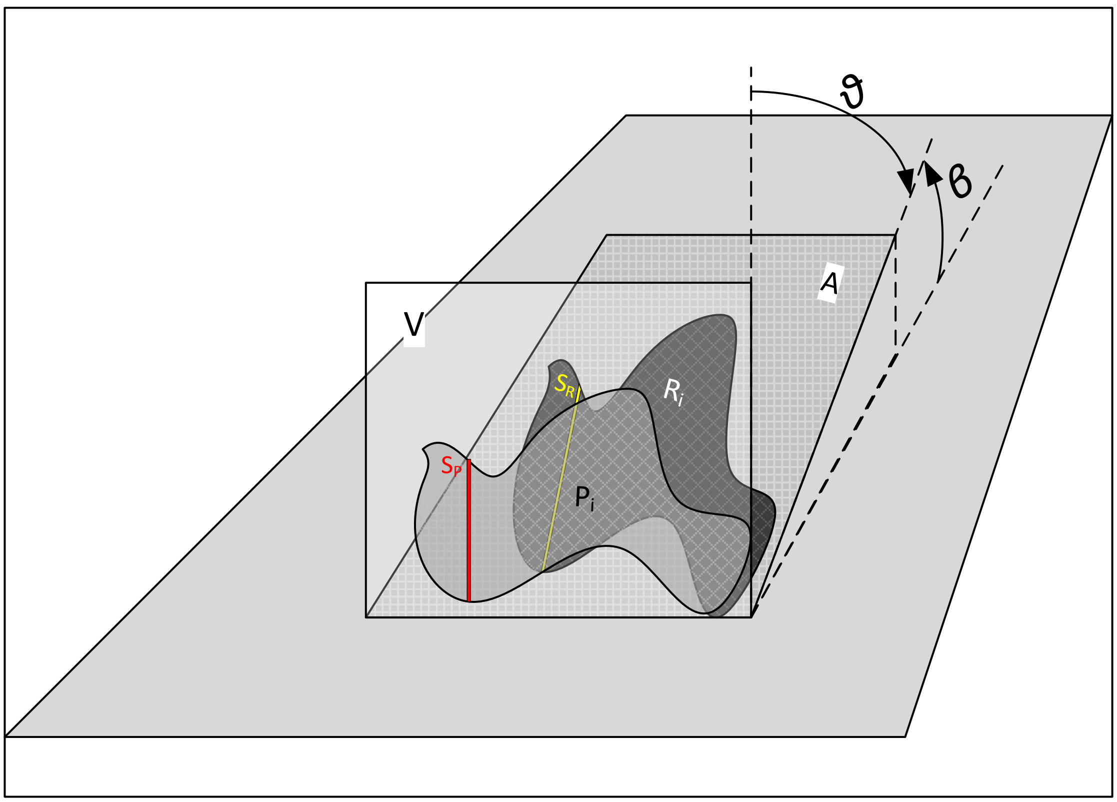


Figure 35. Sample Debris with Arbitrary Orientation in Space.

In general, β would vary with each piece of debris and with each pixel making out that piece; thus, more specifically:

$$\iiint_{P_i} S_R(x,y)\cdot dA_i = \int_{x_1}^{x_2}\int_{y_1}^{y_2}\int_{\beta_1}^{\beta_1} \frac{1}{\frac{\cos\beta}{S_H}+\frac{\sin\beta}{S_V}}\, d\beta\cdot dy\cdot dx$$

Equation 5

Applying the Mean-Value Theorem to the innermost integral, a value β^* exists such that:

$$\int_{x_1}^{x_2}\int_{y_1}^{y_2}\int_{\beta_1}^{\beta_1} \frac{1}{\frac{\cos\beta}{S_H}+\frac{\sin\beta}{S_V}}\, d\beta\cdot dy\cdot dx = \int_{x_1}^{x_2}\int_{y_1}^{y_2} \frac{\beta_2-\beta_1}{\frac{\cos\beta^*}{S_H}+\frac{\sin\beta^*}{S_V}}\cdot dy\cdot dx$$

Equation 6

Because the integration over the unknown domain of β can be avoided, the result above implies that the double integral remaining must be proportional to the real area R_i. The equality is achieved if the unknown but constant values β_1, β_2, and β^* can be determined.

Also, since the domain of β has not been defined yet, it was convenient to do so in a way such that $\beta_2 - \beta_1 = 1$. This definition leaves β^* as the only unknown quantity needed to estimate R_i. The research team developed an empirical formulation for β^*, as briefly explained in the next subsection.

Calibration of Analytic Procedures with Field Data

The research team performed a regression analysis on field images obtained for the samples of TD retrieved from the field. For that subset of samples, all quantities of interest are known—namely, S_R, S_H, and S_V. Unfortunately, complete datasets were successfully identified for only 17 of the pieces that were collected from the field. A value of β^* was computed for each piece such that Equation 3 relates the true area S_R as measured in the laboratory and the estimates for S_H and S_V (from analyzing images from the field).

To select a model for β^* using a relatively independent performance metric, a reduced functional form selected from a set of potential predictors was implemented based on leave-one-out cross-validation. The final model included three variables: distance to object, width of the object, and the flag variable indicating that the object is either angled or vertical to the pavement. The first two variables were estimated automatically from the procedures described in this section. The third variable was manually coded as "Standing, Angled?" by inspection during the data reduction (details in the next section, see Table 10). The average percent error of the regression estimator to the computed value of β^* was found to be −1.16 percent with a standard error (SE) of ±7.45. The research team deemed such expected precision for $\hat{\beta}^*$, the regression estimate from this procedure, adequate. Given the range for the average percent error, it also appears that the regression estimate is an unbiased estimator of the true quantity β^*. Therefore, the regression estimate was incorporated as a last step of the image-processing algorithm to be used in analyzing the reduced photographic database. The following section describes the data collection activities and summarizes the data reduction and processing procedures.

DATA COLLECTION

Members of the research team collected field data in seven TxDOT districts, randomly selected through the process described earlier in this document. The distribution of data collection segment sites is provided in Table 6 and Table 9 and illustrated in Figure 36. The sites were selected to represent the geographic distribution of the state and a range of roadway types.

Table 9. Distribution of Data Collection Segment Sites by Speed Limit (Miles).

Speed Limit (mph)	Austin	Bryan	Dallas	El Paso	Fort Worth	Houston	San Antonio	All Districts
45	0	0	0	0	3	0	0	3
50	8.1	0	10.3	0	0	0	0	18.3
55	10.5	17	0.3	10.3	17.8	31.7	4.7	92.3
60	8.2	1.9	35.9	13.4	35.6	48.4	16.1	159.4
65	19.7	0	20.9	8.4	2.3	32.3	11.8	95.5
70	17.5	9.1	0	0.5	7	0	20.2	54.3
75	11.1	19	4.1	9.2	0	0	5.1	48.7
All Roadways	75.1	47.0	71.7	41.8	65.7	112.4	57.9	443.3

All field data were collected in the months of July–November 2015. Some of the sites in the Bryan and Houston Districts were sampled twice (i.e., in July and again in November) to determine if seasonal variations in debris presence could be observed. The data collection procedure was implemented by two-person teams and involved collecting high-resolution photographs of the pavement surface along the selected segments and creating global positioning system (GPS) logs that contained user-generated codes to flag locations where debris was present. At the beginning of each day of data collection efforts, the team would mount the camera and GPS receiver in the vehicle, aim the camera so it would capture the vehicle's lane and the lanes or shoulders to either side of the lane, and calibrate the view by capturing a photograph of pavement while two boards of known size were placed at distance of 50 ft and 100 ft ahead of the vehicle.

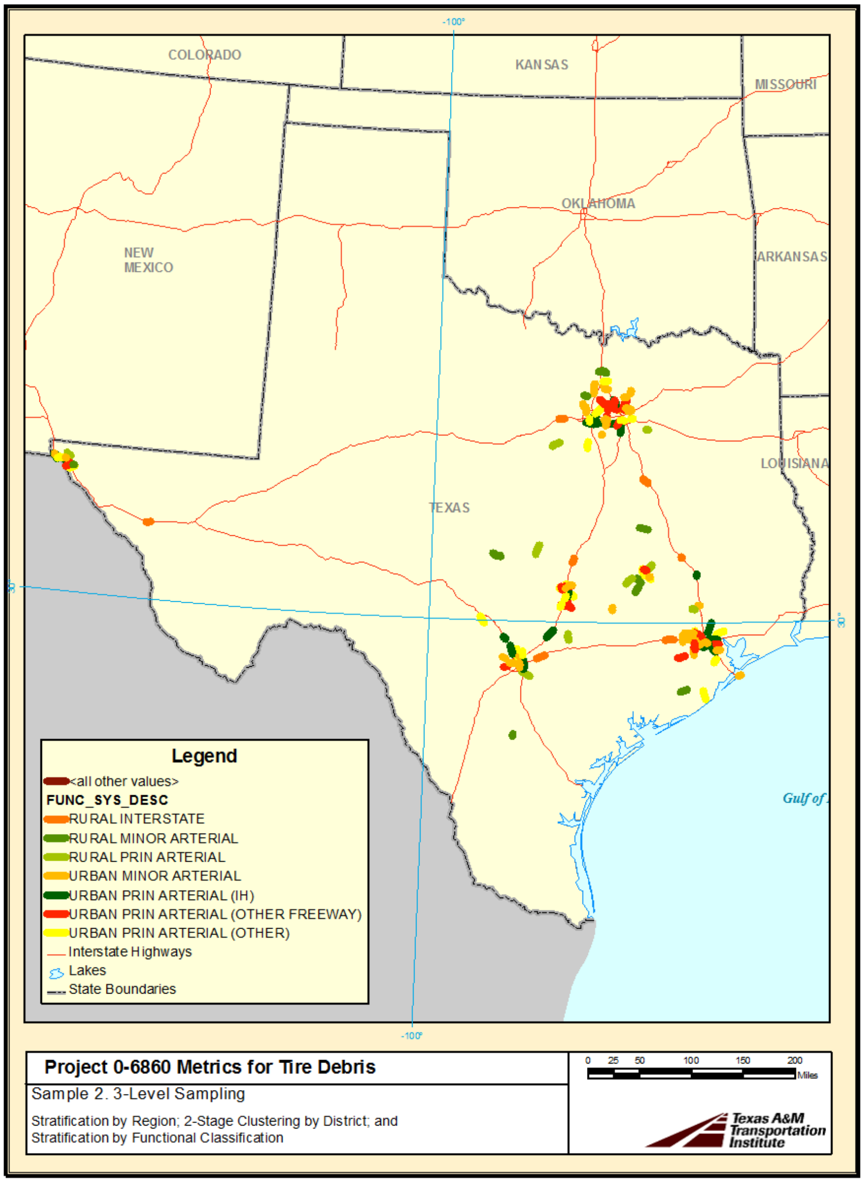


Figure 36. Segment Site Locations.

Detailed maps were developed for each district prior to data collection in order to provide the data collection crews with reference points in the field. Figure 37 shows a reduced image of an example of such a map.

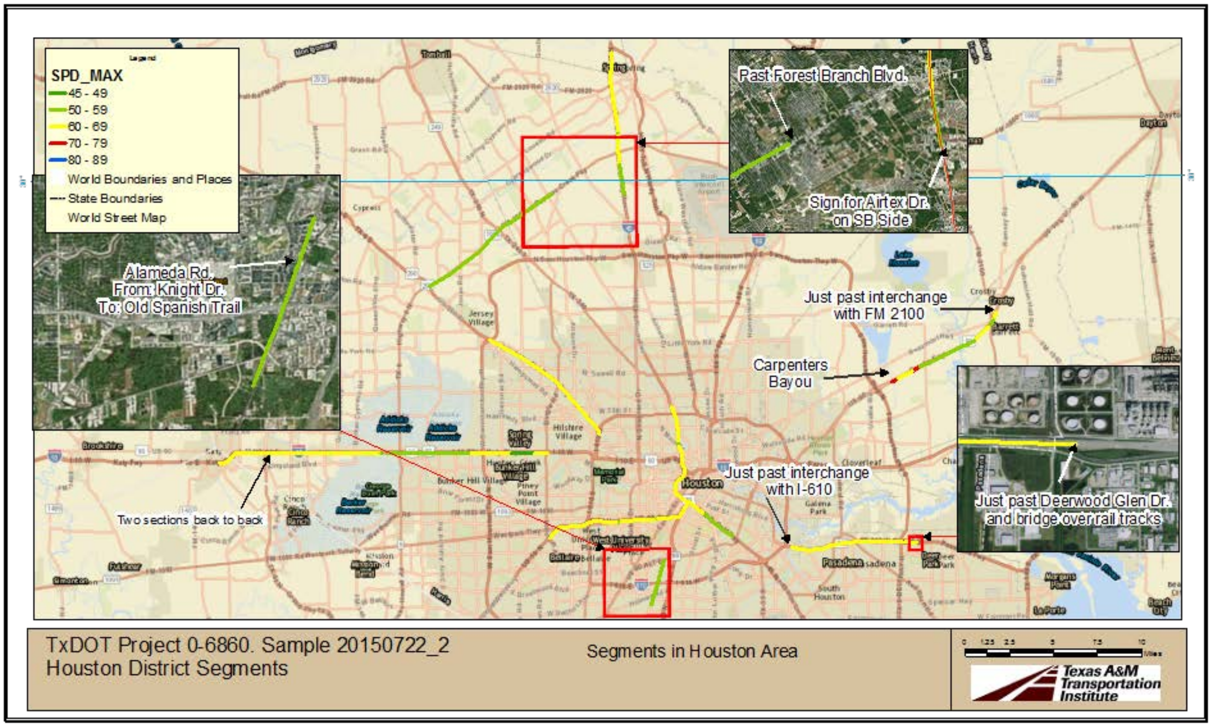


Figure 37. Detail Map for Urban Sites in Houston District.

Data collection runs were conducted on all segments that were identified in the previously described site selection process. Multiple runs at each segment were conducted because of the limited view width of the camera. Runs were always conducted in the rightmost and leftmost lanes to ensure documentation of debris on each shoulder (right and left shoulders), and runs were also conducted on interior lanes of urban freeways with more than four lanes if debris was observed in the interior lanes. On undivided two-lane roadways, runs were conducted once in both directions unless the team observed that no debris was present during the first data collection run.

The data collection team conducted their efforts during daytime, dry-weather conditions. Congested traffic was avoided as much as possible since it was necessary to obtain photographs of the pavement surface while the pavement was not occupied by queued vehicles.

The team used real-time traffic condition maps to facilitate their route planning and sequencing and also used aerial photographs to identify appropriate travel paths (i.e., entry, exit, and turnaround locations) on some of the more complex urban freeway facilities. The data collection runs were conducted at the posted speed limit (or the free-flow traffic speed, if lower) to minimize disruption to traffic flow.

Photographs were saved at a rate of five images per second to ensure that all debris pieces present would be pictured even at highway speeds. Figure 38 shows an example image that depicts a TD piece in a travel lane.

Figure 38. Photograph with In-Lane TD Piece.

To facilitate data reduction efforts, GPS data log files were recorded during all data collection runs using a program that allows the user to document locations of interest by pressing a key. The research team used the letter "T" when encountering a TD piece and the letter "O" when encountering other types of debris.

After concluding their data collection runs at each site, teams collected a few sample debris pieces from the roadway surface for further analysis. These debris pieces were labeled for identification. Each collected piece was brought back to College Station for further analysis. Figure 39 shows one such piece being measured over a grid of known dimensions.

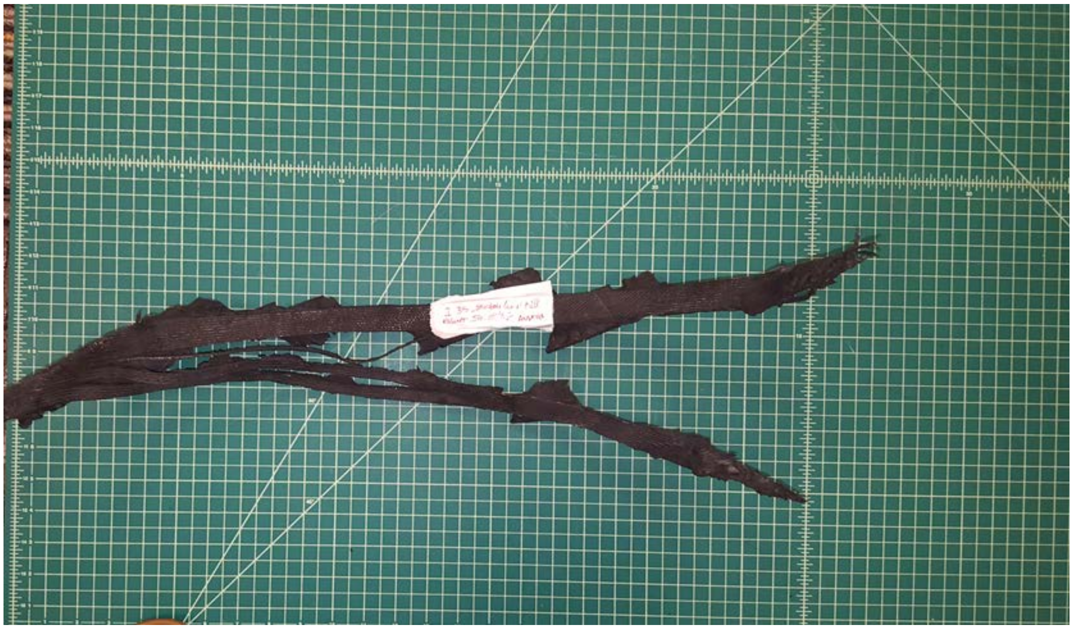


Figure 39. Sample TD Piece Retrieved from Field Visits.

Debris pieces were retrieved only if they were located on a sufficiently wide shoulder and the team could identify a safe location to stop. The photographs of the debris pieces were identified and flagged, such that the size of the debris piece could be both measured in the office and computed by analyzing the photograph. Hence, the research team was able to verify the camera calibration and assess the error range in the size computations.

DATA PROCESSING

Data reduction and processing included the following activities: (a) measuring the samples of debris collected from the field visits in order to estimate density, volume, and thickness of typical TD; and (b) reducing the database with a photographic record of the visits to a set of images usable to estimate size of individual pieces of TD.

The following sections summarize the procedures followed during these activities. Chapter 6 summarizes the results of these procedures, other summaries, and metrics of interest derived from the field data.

Measuring Density, Volume, and Average Thickness from Field Samples

The volume and density of the debris samples from the field visits were measured using water displacement. The results of these measurements were incorporated into the estimation of the amount of debris in terms of their weight so that they could be included in the cost analysis. The measurement process involved a container of sufficient volume to completely submerge the debris sample and a container to collect displaced water. Figure 40 illustrates this setup.

Figure 40. Water Displacement Measurement Setup.

The main container was then filled to a level slightly above the drain tap and allowed to drain to the level of the tap. A separate container was placed under the tap to collect the water displaced by a submerged debris sample. This water was weighed, and the volume of the debris sample computed by dividing the weight of the displaced water by the density of water. The density of the debris piece was computed by dividing the dry weight of the piece by the volume of water that it displaced while submerged. The method to measure the TD was modified depending on the size of the TD. In the case of measuring smaller pieces, they raised the water level very little when placed in a container large enough to submerge the largest TD pieces. This limitation was due to the small ratio of the piece’s volume to the surface area of the water in the container. To increase the accuracy of measurements, two different container sizes were used: one for larger pieces and one for smaller. To further reduce the surface area, a second smaller container was placed in the large container and filled with water to anchor it. The large debris pieces could then be placed in the reduced space between the two containers. A surfactant was added to the water to reduce the surface tension and promote consistent drainage of the displaced water. Figure 41 shows the equipment to perform the weighing operations.

Figure 41. Weight of Displaced Water and TD.

After all of the collected debris pieces were measured, approximately 10 percent of the larger pieces had a small section of uniform thickness removed and measured as an additional degree of consistency and for use in determining the average thickness of the larger samples. Figure 42 shows cut-out pieces.

Figure 42. Cutouts from Debris for Further Measurement.

The density and thickness values obtained from these procedures were used later in combination with the processed field images to perform calculations of size and weight of the TD. More details are provided in the following section and in Chapter 6.

Reduction of Photographic Database

The raw database of photographs amounted to approximately 1.6 terabytes, including data from the second visits to some sites in the Bryan and Houston Districts. Figure 43 shows a map of TD data collected from July to November 2015.

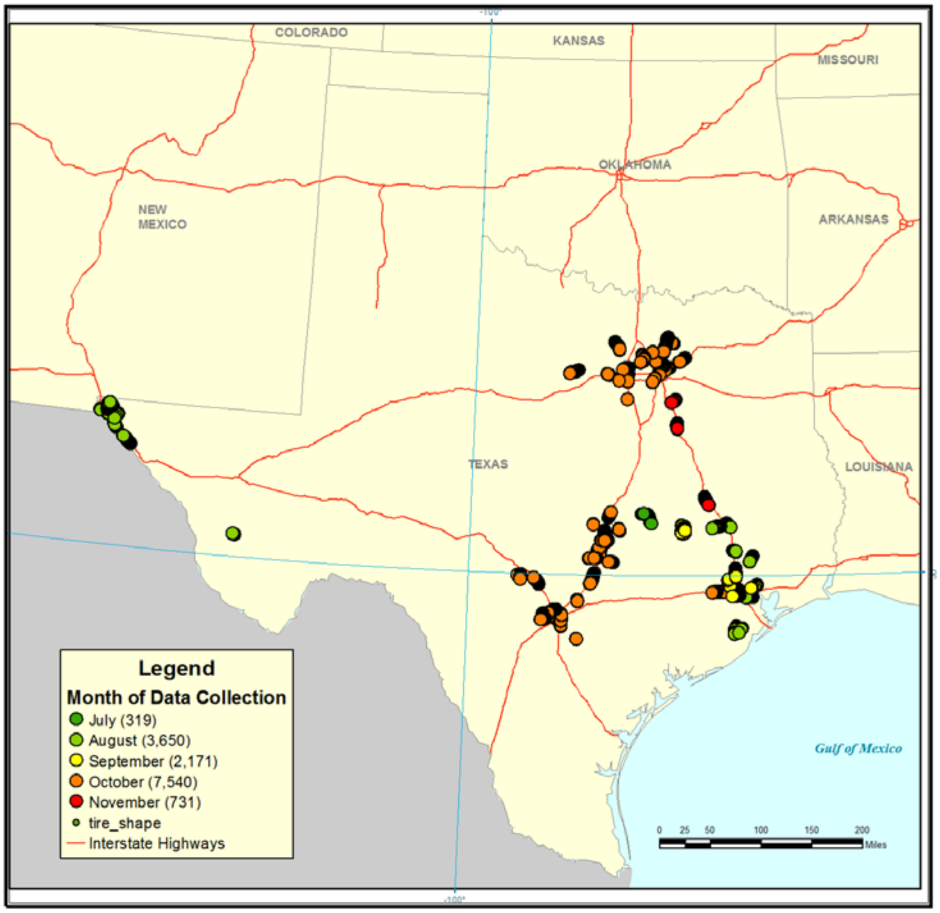


Figure 43. TD Data Collected by Month.

In the legend of Figure 43, quantities in parentheses represent the number of GPS tags in the data. Since those tags were typed by the field data collection team to indicate presence of TD, this set of GPS tags represents a first rough estimate of the number of pieces identified. However, this estimate deviated with the actual number of pieces as a function of the site characteristics and the field data collection team. At sites with small amounts of TD, a GPS tag typically corresponded with a single piece of debris. However, at sites with high frequency of TD, a GPS tag would sometimes indicate a single piece or many pieces clustered at a single location. Multiple runs were conducted at each site, depending on the number of lanes and quantity of TD observed. In total, 303 runs were conducted. Each of those runs corresponded to one GPS data file and a folder of photographs taken at a rate of 5 Hz.

A team of student workers reviewed the GPS data stream for each run of the field visits. From each of these runs, the data reduction team reviewed all photographs within one second of the time recorded on the GPS tag. Each piece of TD discovered in these photographs was enclosed in a red square, and a copy of that photograph was saved for later analysis. For each photograph with TD identified, members of the data reduction team generated codes in an Excel file containing the variables shown in Table 10.

Table 10. Variables Coded While Reducing the Photographic Database.

Variable	Description
# of objects	Number of objects identified.
# of TD	Number of TD pieces identified.
Tire on lane	Is the tire on the travel lanes?
Is it FLAT?	Is the TD piece flat?
Is it large?	Does the TD piece appear large? (i.e., larger than 8 in × 8 in)
Shaded, Obscured, Background?	Are there shadows or contrast issues in the photo?
Visible Edge?	Is the edge of the piece visible?
Standing, Angled?	Is the piece at an angle with the plane of the road?
Manual	Are there issues that warrant that the size of this piece be computed manually?
Comments about shape	Any relevant comments about the shape, size, or position of the TD?

The reduction of the photographic database took place from July 2015 to April 2016. A grand total of 14,998 images identifying individual TD pieces were identified for analysis.

SUMMARY

The research team developed a probability sampling of roads in the state of Texas in order to collect data about frequency and characteristics of TD in Texas highways.

Next, the research team implemented the developed methodology in R, a statistical computer language, and optimized the corresponding parameters in order to obtain maximum precision estimates of debris frequency on Texas roads. Further, the research team drew a probability sample of Texas roads representing 472 centerline miles and prepared to collect field data at those sites.

In addition, the research team developed an imaging system to acquire data from field visits and developed an appropriate data collection protocol. Then, the research team developed analytical methods to process the data from the field visits. The research team visited every site selected in the probability sample and acquired the image data as planned. Later, the research team visited a subset of the sites in the sample for a second time in order to assess for the presence of seasonality in TD occurrence. In addition to image data from the field, the research team collected actual samples of TD to be measured. These samples provided reliable estimates of density and volume of typical debris in Texas roads.

CHAPTER 5. SAFETY ANALYSIS OF TIRE DEBRIS ON TEXAS HIGHWAYS

This chapter summarizes a safety investigation on TD performed as part of this research project. Crash records were reviewed and crashes involving TD identified for the period 2012–2014. This chapter summarizes the data collection, general trends, a formal statistical analysis, and the interpretation of results.

DATA COLLECTION

In Texas, statewide crashes are coded into CRIS. The records in CRIS provide a level of detail and flexibility that make it possible to perform most types of safety analyses. However, since this research intends to investigate the safety implications of a relatively narrow risk factor (i.e., TD), it was not possible to identify a field (or combination of fields) in the CRIS database that clearly codes TD involvement, despite an otherwise substantial level of detail available in the CRIS database.

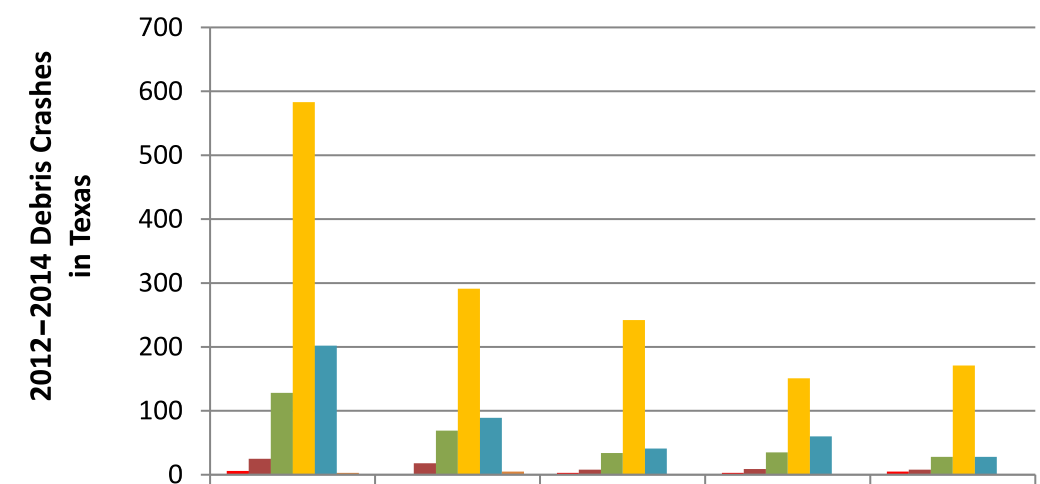
However, two fields, OB_STRUC_ID and OTHER_FACTR_ID, were found to be of particular interest since they allow identifying crashes involving foreign objects in the pavement. Specifically, these fields contain codes that indicate debris on road involvement and whether or not there were any avoidance maneuvers due to such objects in the road.

In order to identify crashes with particular involvement of TD, the TxDOT project team recommended reviewing crash narratives of crashes suspected to relate to TD. Reviewing crash narratives was also essential because it allowed an additional level of filtering: separating crashes that involved previously existing TD from blowout crashes. Generally, crashes of the latter type are such that debris generated from one vehicle causes another vehicle to have a crash. Such crashes are not of interest to this research and can only be identified by reviewing crash narratives.

As a first step, the research team queried the CRIS databases for crashes with potential involvement of TD during the three most recent years (2012–2014). Because the process to retrieve and review the corresponding crash narratives was a relatively slow, time consuming process, the research team narrowed this query to the types of facilities most likely to have TD involvement: interstate freeways, non-interstate freeways, and principal arterial highways, each in both rural and urban environments. These facility types correspond to functional class codes 01, 02, 11, 12, and 14 in field FUN_CLS_ID (see Table 3).

Characteristics of Crashes with Road Debris Involvement

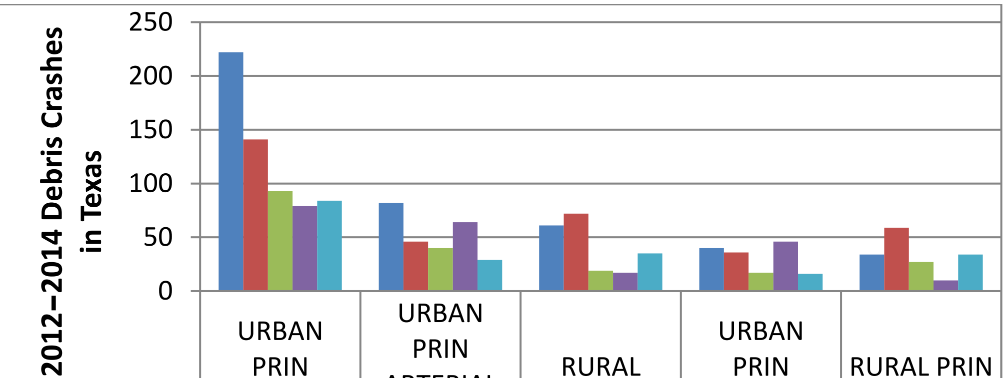
An initial set of 2,247 crashes with potential involvement of road debris was identified for the period of analysis (2012–2014). Figure 44 shows the distribution by severity and facility type of this initial set of crashes (this figure shows the levels of the variable FUN_SYS_DESC in the RHiNo and CRIS databases, as shown in Table 3). It is noticeable that non-injury crashes are most prominent, followed by possible injury. Together, these two severity levels account for 83 percent of all the crashes identified.



	URBAN PRIN ARTERIAL (IH)	URBAN PRIN ARTERIAL (OTHER FREEWAY)	RURAL INTERSTATE	URBAN PRIN ARTERIAL (OTHER)	RURAL PRIN ARTERIAL
FATAL	6		3	3	5
INCAPACITATING INJURY	25	18	8	9	8
NON-INCAPACITATING	128	69	34	35	28
NOT INJURED	583	291	242	151	171
POSSIBLE INJURY	202	89	41	60	28
UNKNOWN	3	5		1	1

Figure 44. Crashes with Potential Involvement of TD by Severity and Facility Type.

Figure 45 shows the distribution of the five contributing factors most commonly listed in the subset of crashes involving road debris. In total, this subset contains 1,403 out of the 2,247 crashes initially identified. The most common contributing factor among crashes involving road debris was FAULTY EVASIVE ACTION. The second most common contributing factor (shown in Figure 45) shows that a contributing factor was not identified. It appears that few crashes could be classified under the three remaining categories of contributing factors.



	URBAN PRIN ARTERIAL (IH)	URBAN PRIN ARTERIAL (OTHER FREEWAY)	RURAL INTERSTATE	URBAN PRIN ARTERIAL (OTHER)	RURAL PRIN ARTERIAL
FAULTY EVASIVE ACTION	222	82	61	40	34
OTHER FACTOR (WRITE ON LINE ABOVE)	141	46	72	36	59
LOAD NOT SECURED	93	40	19	17	27
FAILED TO CONTROL SPEED	79	64	17	46	10
NONE	84	29	35	16	34

Figure 45. Most Common Contributing Factors for Crashes with Debris Involvement by Facility Type.

The next subsection summarizes a thorough examination of the 2,247 crash narratives by the research team in an effort to identify crashes specifically indicating TD involvement.

Review of Crash Narratives

From the beginning of the project, a clear distinction between two classes of crashes was established: (a) crashes that occurred as a result of a tire blowout involving the vehicle with the tire problem or any other vehicles in the vicinity; and (b) crashes that occurred because some debris was present in the pavement previously, so that generation of the TD was effectively unrelated to the crash. This research project focuses on the second of these classes.

The research team investigated if further clearance was necessary from the Texas A&M IRB to access and examine crash narratives of interest. It was determined that no further IRB paperwork was necessary since the extraction and preliminary filtering of the narratives would be performed by TTI personnel already trained and with adequate clearance. After initial extraction and filtering, the research team received crash narratives stripped of any sensitive data (e.g., personal information of individuals, vehicle registration, officer on scene).

Crash narratives include a description of the events by the crash investigator and a diagram of the crash in some cases. Figure 46 shows a sample of the type of information available from the crash narratives.

Investigator's Narrative Opinion of What Happened (Attach Additional Sheets If Necessary)
Unit 1 was traveling S/B on IH-35 in the inside lane when it ran over a large piece of rubber that was in the roadway. The vehicle in front of Unit 1 ran over the rubber object, causing it to lift into the air. Unit 1 struck the rubber with its FR. Unit 1 came to rest facing S/B on the inside shoulder. Unit 1 was unable to avoid striking the rubber as there were other vehicles in the lane beside it.

Figure 46. Sample Narrative of a Crash Involving TD.

Personnel from the safety center in TTI extracted and reviewed all narratives corresponding to the 2,247 crashes that had potential involvement of TD. In the case shown in Figure 46, involvement of TD in the crash is clear. However, this figure also illustrates the degree of ambiguity that was found in some of the narratives. Figure 47 shows the narrative corresponding to a crash similar to that shown in Figure 46 that was not considered TD related, per direction given by the TxDOT project team.

UNIT 1, 2 AND 3 WERE TRAVELING EB ON IH-20. UNIT 2 HAD A BLOWOUT, THE TIRE TRED CAME OFF. UNIT 3 RAN OVER THE TIRE CAUSING DAMAGE TO THE FRONT END OF THE VEHICLE. NO ONE WAS INJURED.

Figure 47. Sample Narrative of Crash Not Involving TD.

Although both crashes in the previous examples involved TD on the pavement, only the example in Figure 46 was considered TD related for the purposes of this project. In that case, the piece of rubber involved was at the scene prior to the arrival of any of the involved vehicles. In contrast, the example in Figure 47 was not considered TD related because the tire tread came from a blowout that affected an adjacent vehicle.

Summary Statistics of Crashes Involving Road Debris

After finalizing the review of all 2,247 crash narratives, the research team determined that only 471 crashes clearly identified the object involved in the crash as a tire, TD, or other tire-like object.

For the next step in this exploratory analysis, the research team prepared summary statistics of the crashes whose narratives were reviewed, as indicated earlier in this chapter. Figure 48 shows the distribution of the 471 crashes involving tires, TD, or other objects that appear related (i.e., rubber-like, tire-like unknown objects).

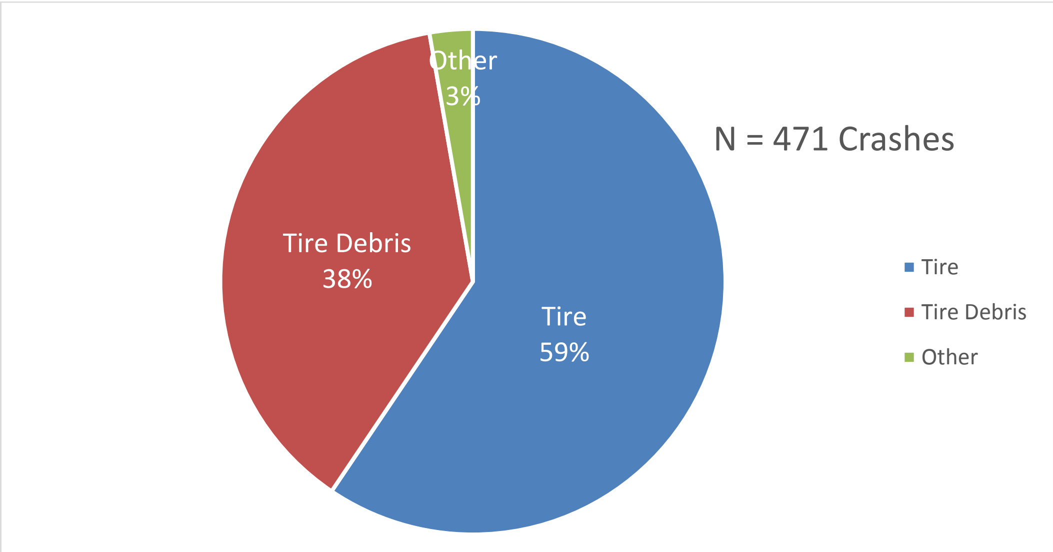


Figure 48. Distribution of 471 Crashes Involving Tires or TD by Type of Object.

From the narratives, it was possible to determine when crashes resulted from situations such as Figure 47 and thus were not of interest to this research. Narratives were reviewed to determine the origin of the TD. Three categories were identified: (a) TD was present before the crash; (b) TD was generated during the crash; and (c) undetermined origin. Figure 49 shows the relative frequencies of these cases.

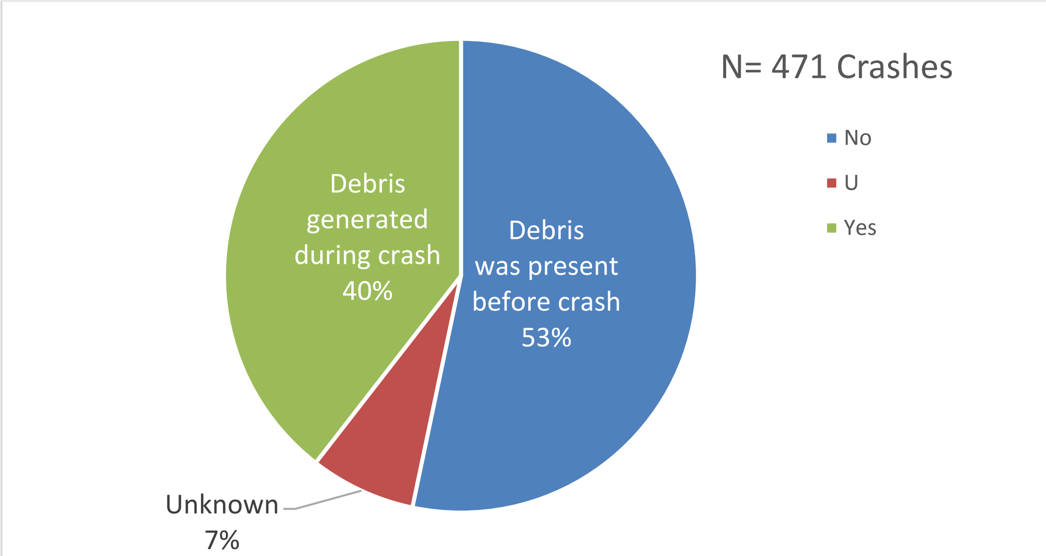


Figure 49. Distribution of 471 Crashes Involving TD on Roadway.

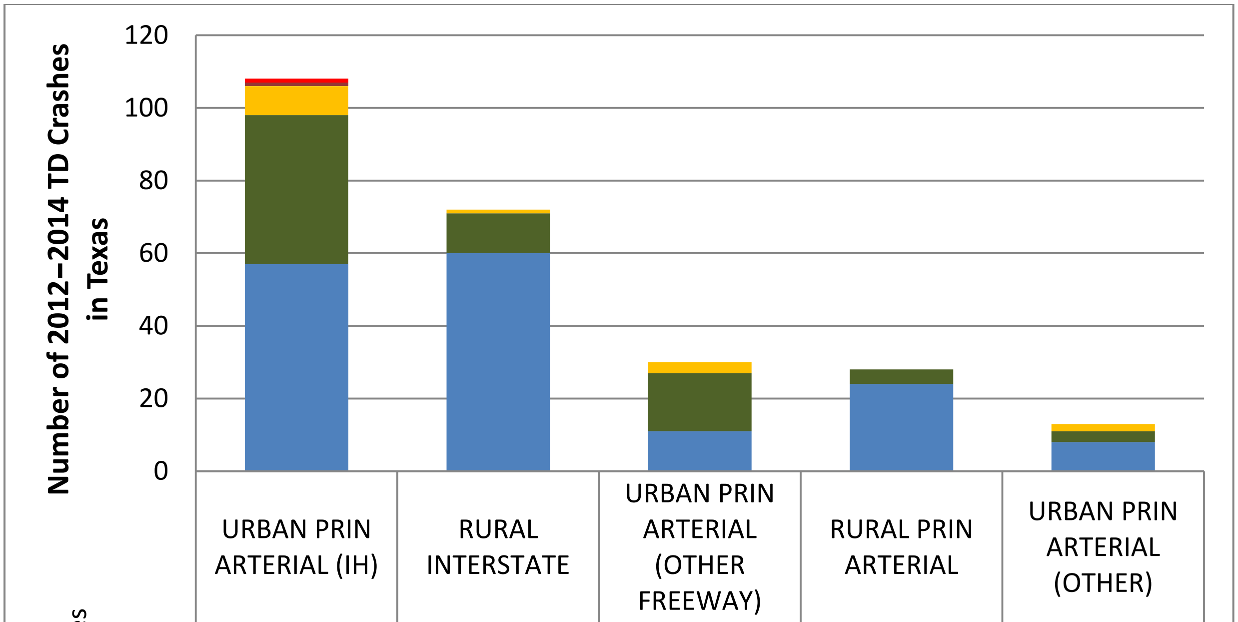
Only 53 percent of the 471 identified crash narratives clearly indicated that tire or tire-like objects were present at the crash site before the crash occurred. This percentage corresponds to 251 crashes. Of these 251 crashes, 160 involved a single vehicle, 75 involved two vehicles, and 16 crashes involved three or more vehicles.

EXPLORATORY ANALYSIS

This section reviews the data collected in order to gain insights into crash risk of road debris, and TD specifically, at different facility types and districts.

Crashes Triggered by TD

The subset of 251 crashes was the set of interest to this research, referred to as TD crashes from this point forward. The narratives corresponding to TD crashes indicate that TD or tire-like objects were present before the involved vehicle or vehicles arrived at the crash scene and were the catalyst of the crash. Figure 50 shows the distribution of TD crashes by facility type and number of vehicles involved.



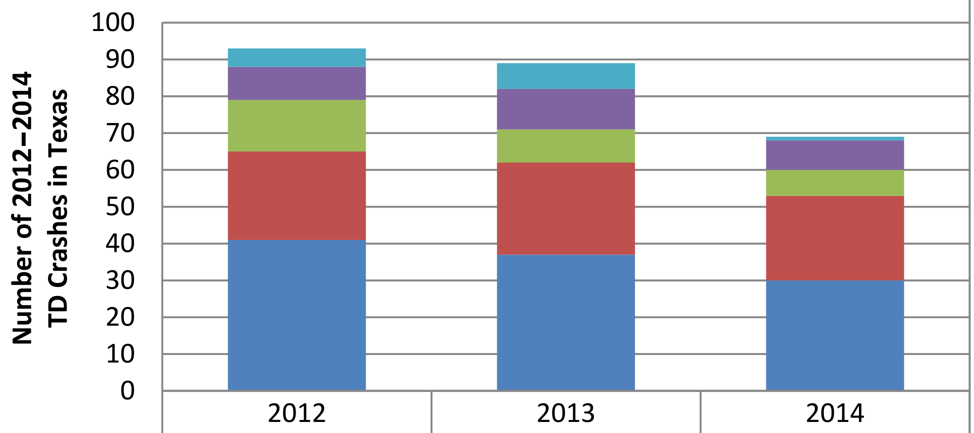
Number of Vehicles	URBAN PRIN ARTERIAL (IH)	RURAL INTERSTATE	URBAN PRIN ARTERIAL (OTHER FREEWAY)	RURAL PRIN ARTERIAL	URBAN PRIN ARTERIAL (OTHER)
7	1				
6	1				
3	8	1	3		2
2	41	11	16	4	3
1	57	60	11	24	8

Figure 50. Distribution of 251 Crashes Triggered by TD on Roadway.

The majority of these crashes, 178 out of the 251 crashes, occurred on urban or rural interstates and represent 71 percent of all TD crashes in the three-year period. These frequencies contrast with the frequencies observed for crashes involving any type of debris. As indicated by Figure 45, crashes involving any type of debris tend to occur more frequently at urban freeways (interstate or otherwise).

An interesting feature was the noticeable difference between urban and rural facilities in Figure 50 regarding their TD crash distribution; urban facilities tend to have a larger proportion of multivehicle crashes than rural facilities.

For temporal trends, Figure 51 shows a steady decline of TD crashes from 2012 to 2014, particularly on urban freeways. Without other critical variables, the reasons for that trend remain unclear. Several factors may potentially contribute to an explanation, including increases in the frequency of debris collection activities and statewide decreases in the total number of crashes at these facility types, perhaps due to a reduction in miles traveled. To investigate the second possibility, the research team queried the total number of crashes at the facilities of interest for years 2012–2014.

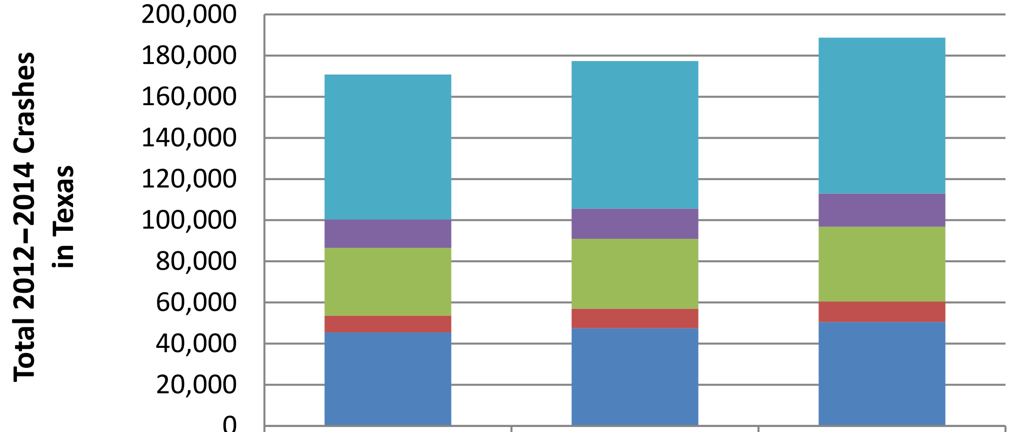


	2012	2013	2014
URBAN PRIN ARTERIAL (OTHER)	5	7	1
RURAL PRIN ARTERIAL	9	11	8
URBAN PRIN ARTERIAL (OTHER FREEWAY)	14	9	7
RURAL INTERSTATE	24	25	23
URBAN PRIN ARTERIAL (IH)	41	37	30

Figure 51. Yearly Trend for 251 Crashes Triggered by TD on Roadway.

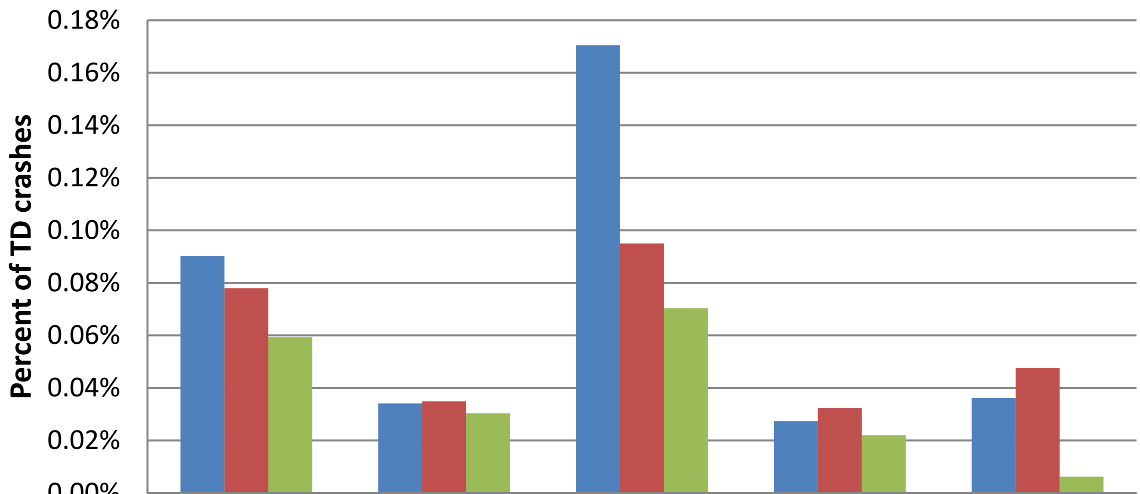
Figure 52 summarizes the total number of crashes at the facilities of interest for years 2012–2014. As this figure shows, the trend was opposite to that observed in Figure 51. This contrast suggests that there was a systematic reason for the drop of TD crashes at urban facilities.

When comparing the sheer numbers in Figure 51 and Figure 52, perspective can be gained on the relatively small magnitude of impact on safety of TD on Texas highways. Namely, TD crashes represent less than 1 percent of all crashes at the facilities investigated by this research, as shown in Figure 53.



	2012	2013	2014
URBAN PRIN ART (OTHER)	70,459	71,747	75,751
RURAL PRIN ARTERIAL	13,801	14,698	16,127
URB PRIN ART (OTHER FRWY)	32,868	33,960	36,323
RURAL INTERSTATE	8,210	9,475	9,960
URBAN PRIN ARTERIAL (IH)	45,449	47,486	50,554

Figure 52. Yearly Trend for 536,868 Texas Crashes on Roadway Classes of Interest.



	URBAN PRIN ARTERIAL (IH)	URBAN PRIN ART (OTHER)	RURAL INTERSTATE	URB PRIN ART (OTHER FRWY)	RURAL PRIN ARTERIAL
2012	0.09%	0.03%	0.17%	0.03%	0.04%
2013	0.08%	0.03%	0.09%	0.03%	0.05%
2014	0.06%	0.03%	0.07%	0.02%	0.01%

Figure 53. Yearly Percent of TD Crashes by Facility Type.

Whereas Figure 50 shows that TD crashes tend to occur more often on urban freeways, Figure 53 shows that the proportion of these types of crashes was larger on rural freeways. The yearly decline in TD crashes appears most accentuated on both urban and rural interstate freeways.

When considering that the numbers in Figure 49 through Figure 51 represent statewide totals that occurred in the last three years, the small number of TD crashes was noteworthy. The very small percentages of TD crashes found suggest that this type of crash was uncommon and that roadway safety can be better improved by focusing resources on reducing other types of crashes. In any case, the set of TD crashes established by this research are sufficient to perform an analysis on the risk factors underlying TD crashes, as presented in the next section.

Frequency and Proportion of Crashes Specific to TD

In general, crashes are relatively rare events. The previous section established that TD crashes are even rarer than other types of crashes. This section explores trends in the TD crash data for both their frequency and relative proportions. Looking at proportions was important because appropriate statistical methods of analysis exist. More details on the statistical methods will be provided later in this chapter.

In general, more crashes are expected with increasing levels of exposure variables such as VMT. Since large, urbanized districts tend to record more VMTs, it was expected that the frequency of crashes in general—and TD crashes specifically— would be higher at such districts.

Figure 54 shows debris crash frequencies by district. The three districts with higher frequencies of debris-related crashes are large, urbanized districts, as expected. However, a high crash frequency by itself does not necessarily indicate an increased risk since higher exposure to traffic will typically result in more crashes, all other factors being equal.

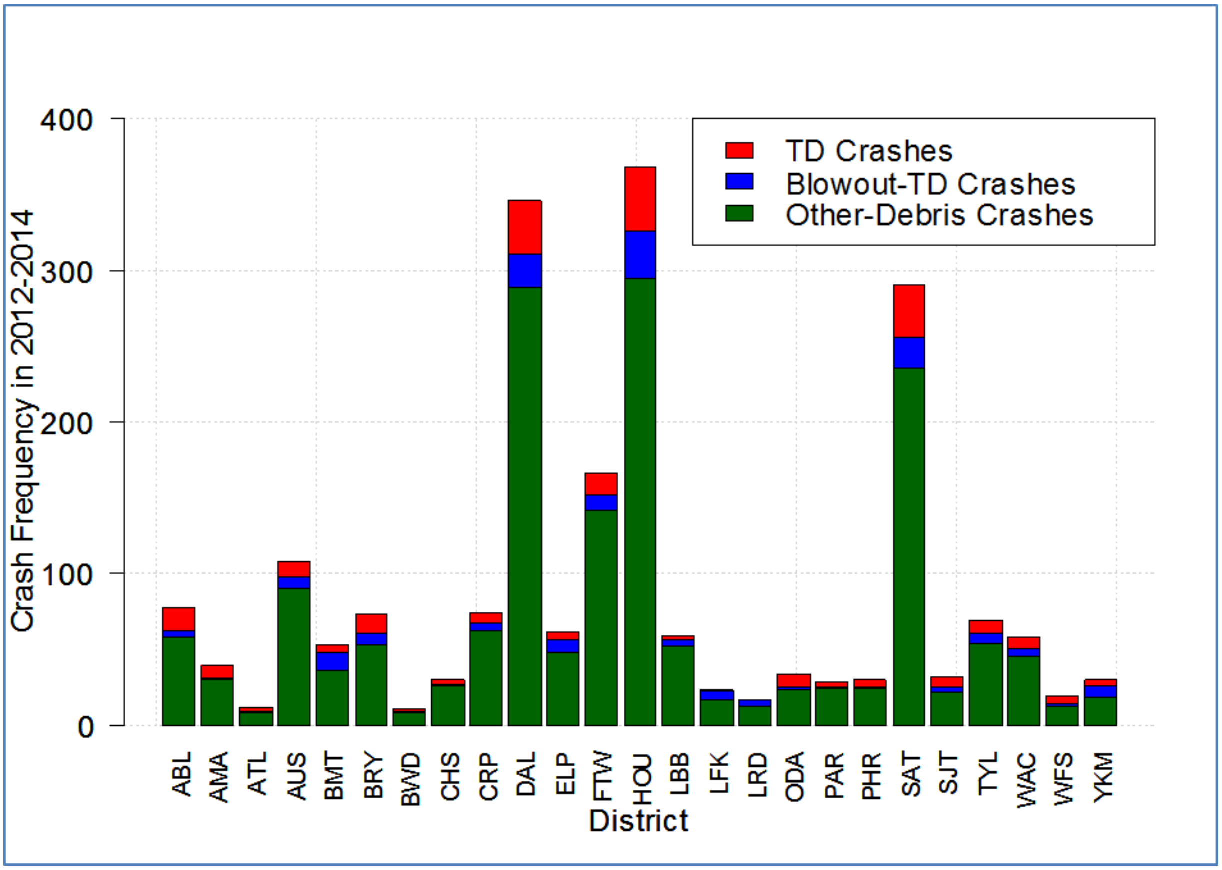


Figure 54. Tire-Debris, Tire-Blowout, and Other-Debris Crash Frequencies by District.

The relative frequency of TD crashes compared to all other debris-related crashes was of interest, as mentioned above. The mosaic plot in Figure 55 shows the proportion of TD crashes per district. The height of the bars was drawn to represent proportions of TD and other type of debris. The width of the bars was drawn proportional to the number of crashes in each district. Opposite to the absolute frequencies in Figure 54, TD crashes are less likely at the larger urban districts in relative terms, as shown in Figure 55. These contrasts were also suggested in Figure 53 when comparing urban and rural interstate freeways.

Figure 55 shows that the set of districts with the higher absolute frequency of debris crashes (i.e., districts with wider bars) has a very comparable proportion of TD crashes among them. In contrast, districts with fewer debris-related crashes tend to have larger proportions of TD crashes.

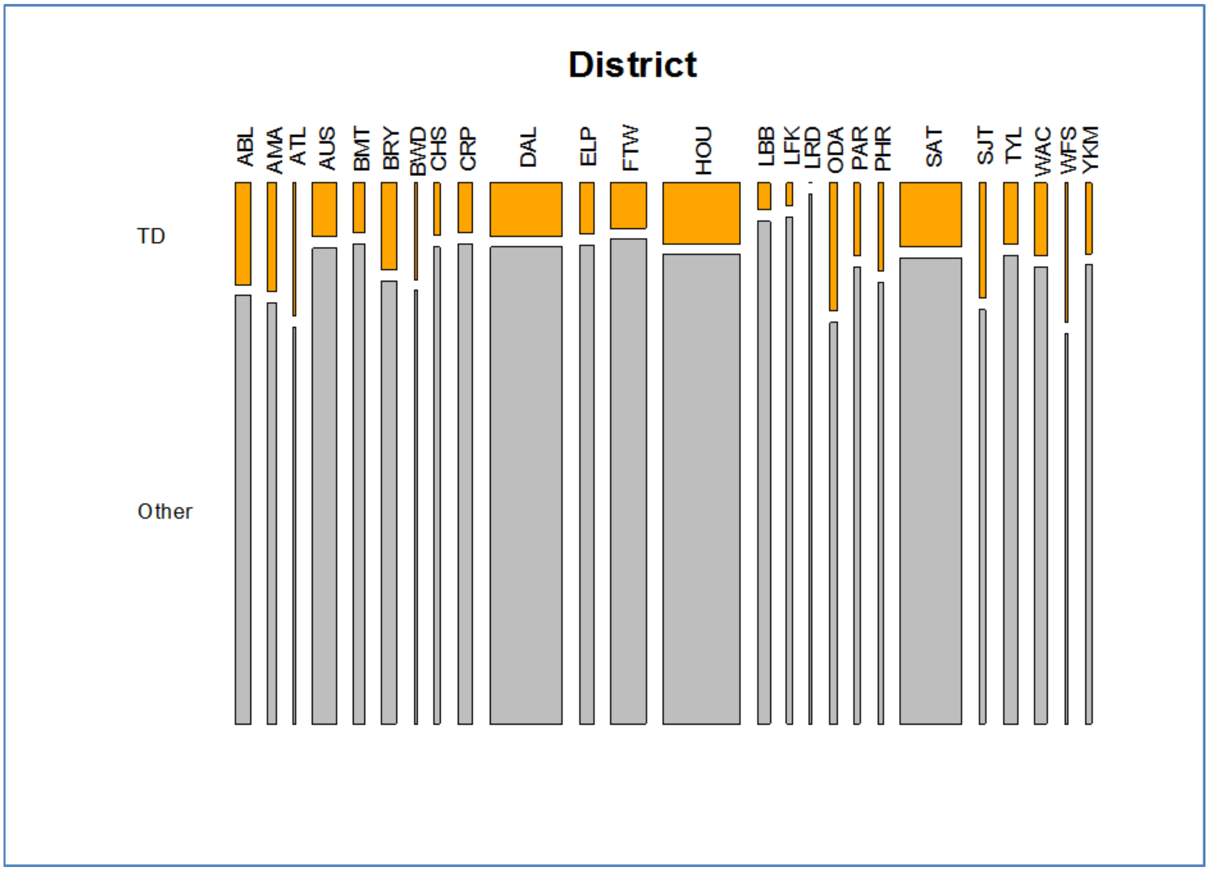


Figure 55. Proportion of Tire-Debris Crashes among Debris-Related Crashes by District.

Figure 56 shows the frequencies of TD, blowout, and other debris crashes by month in a similar format to Figure 55. Except for the notably low crash frequencies in February, the general trend of this plot shows relatively low crash frequencies during the fall months (September through December) and higher crash frequencies during the rest of the year.

Another notable trend in this plot was that the width of the blue band narrows sensibly during the fall months. The decrease of blowout crashes during the fall contrasts with the increase of this type of crash during spring (March through May).

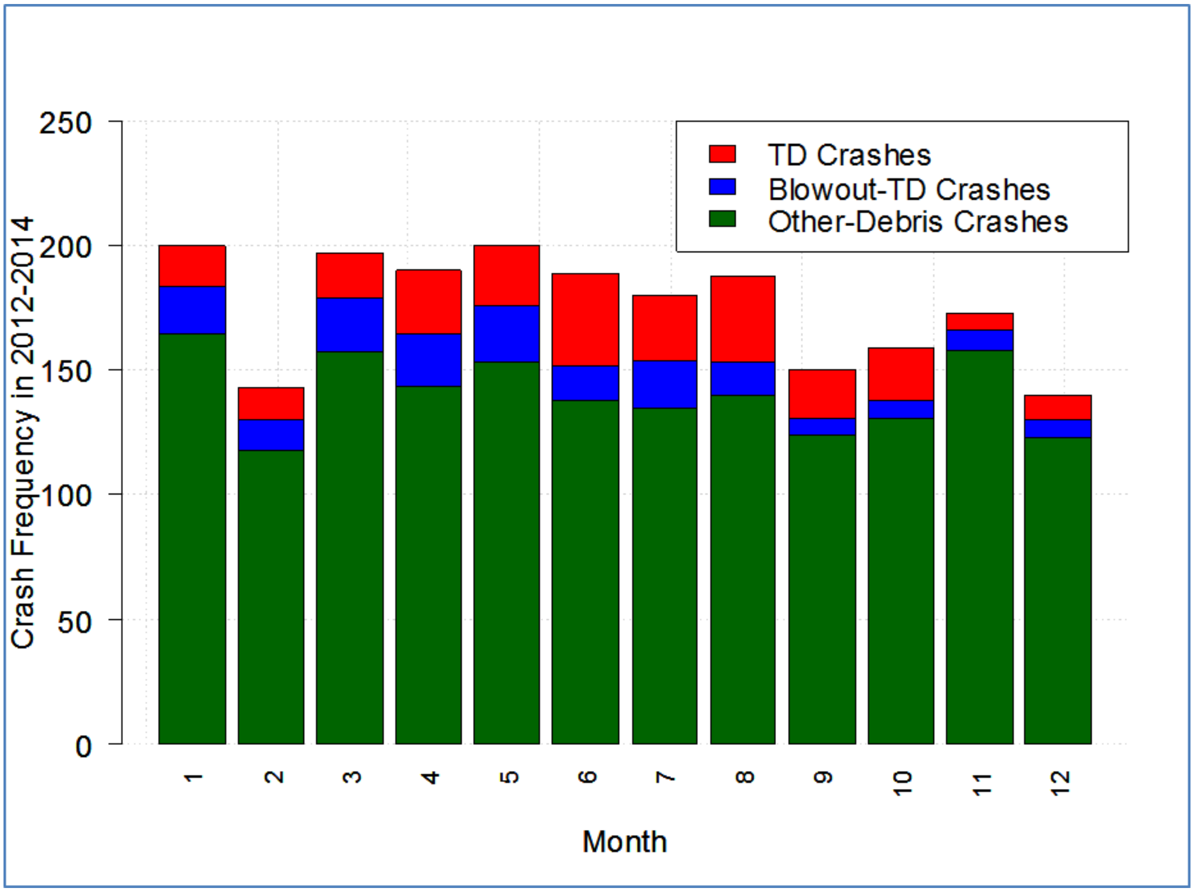


Figure 56. TD, Tire-Blowout, and Other-Debris Crash Frequencies by Month.

A more relevant trend in Figure 56 was a notable swell of the red strip during the summer months (June through August). This feature indicates that TD crashes tend to increase during the summer months in relation to other types of crashes. The summer spike in TD crashes and the relatively flatter distribution of blowout crashes can be better observed in Figure 57.

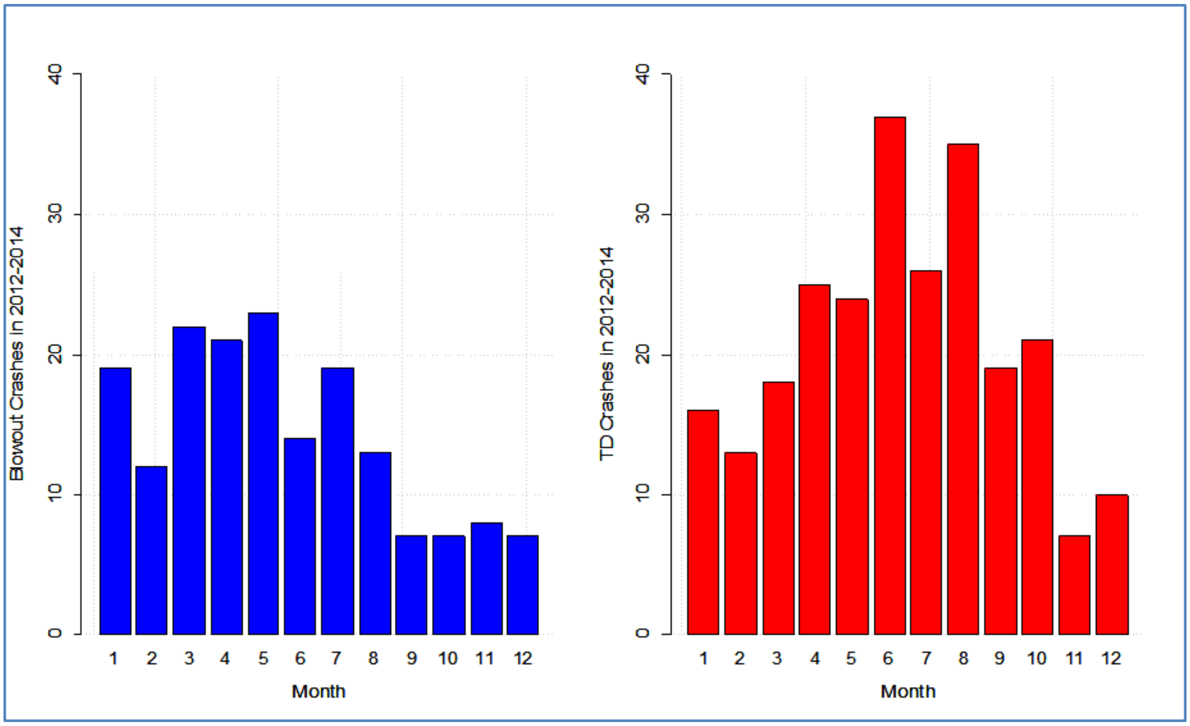


Figure 57. Blowout and TD Crash Frequencies by Month.

This figure shows the frequencies for TD crashes on the right, with blowout crashes on the left, for comparison.

Figure 58 shows the monthly trend in terms of proportions (similar to Figure 55). It clearly reflects the trend observed in Figure 57 in terms of proportion of debris crashes. This figure shows a higher proportion of TD crashes between May and August compared to the rest of the months.

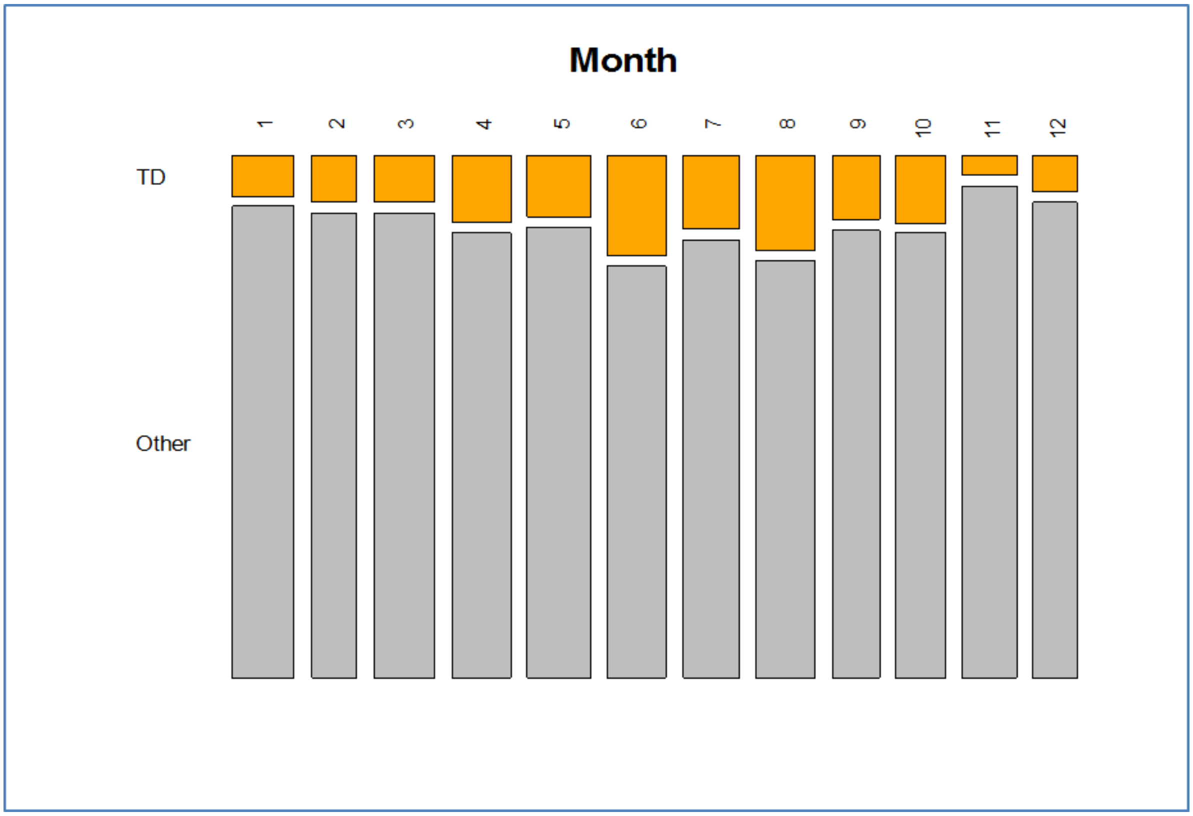


Figure 58. Proportion of TD Crashes among Debris-Related Crashes by Month.

Interestingly, the spike in TD crashes during the summer corresponds with the months with an increase in TD, per the district responses in the statewide survey. Survey respondents indicated that TD and debris collection activities intensify during the summer months. This clearly suggests that an increase in the quantity of TD on the roads increases the risk of crashes caused by TD.

The next section expands the exploratory analysis to variables expected to relate to TD crashes.

Risk Factors Associated with Crashes Specific to TD

This section explores the relationship between TD crashes and potential risk factors. The proportion of TD crashes was the focus of this stage of the analysis rather than frequencies, since statistical methods exist for analyzing proportions in data that were collected retrospectively, that is, data that were collected based on the outcome (debris-related crash) and not on the explanatory factors.

An appropriate statistical analysis of proportions in a retrospective sample allows inferences about potential risk factors (i.e., explanatory variables) associated with the outcome (TD crashes). In contrast, a frequency analysis on a retrospective sample was expected to yield biased results. Such a sample does not represent the typical conditions at locations where TD crashes have not been observed (Ramsey and Schafer, 2002). Figure 59 shows how the proportion of TD crashes varies with increasing AADT. No clear trend appears to be present. This plot also shows that about half of all TD crashes occurred at AADTs lower than 100,000 vpd. This was indicated by the fact that bars of AADT smaller than 100,000 vpd constitute about half of the total width of the plot.

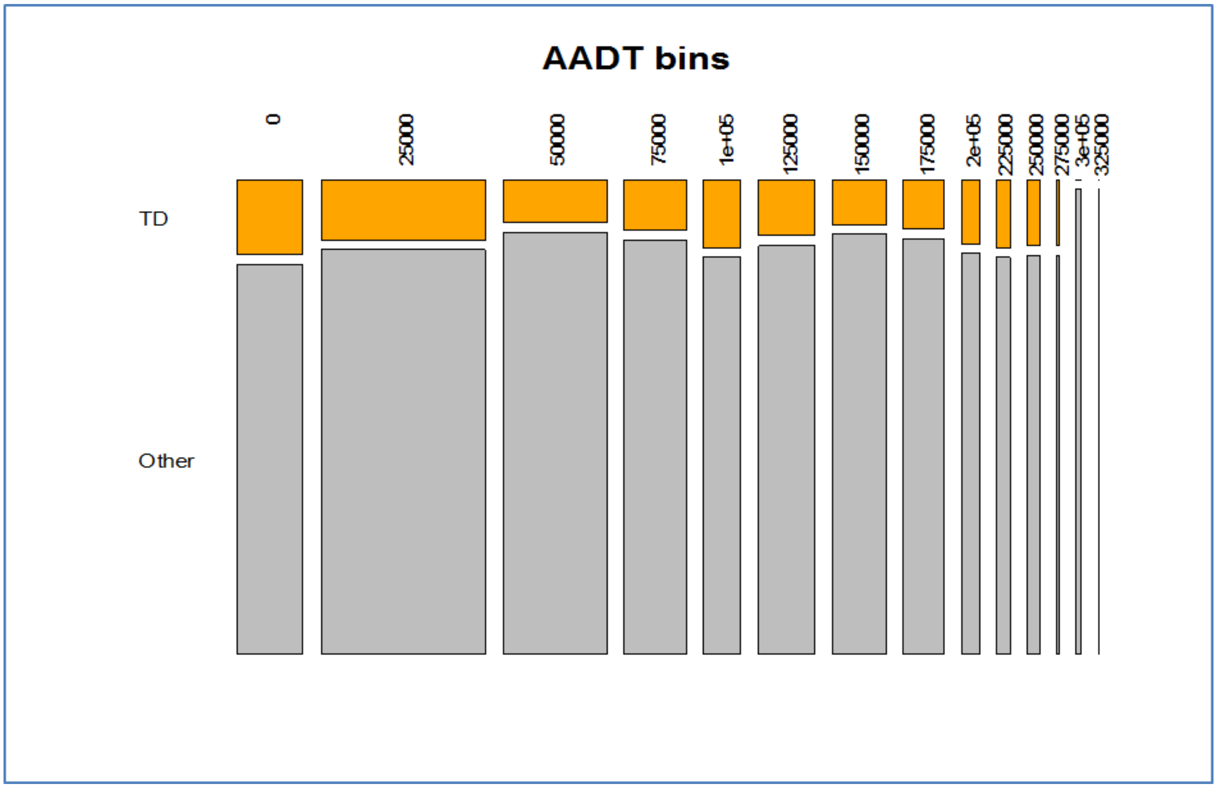


Figure 59. Proportion of TD Crashes by AADT.

In contrast with Figure 59, Figure 60 shows a clear increase in the proportion of TD crashes with an increase in the percentage of trucks. Most debris-related crashes occurred at road segments reported to have between 5 and 15 percent trucks (i.e., the 10 percent bin in the figure).

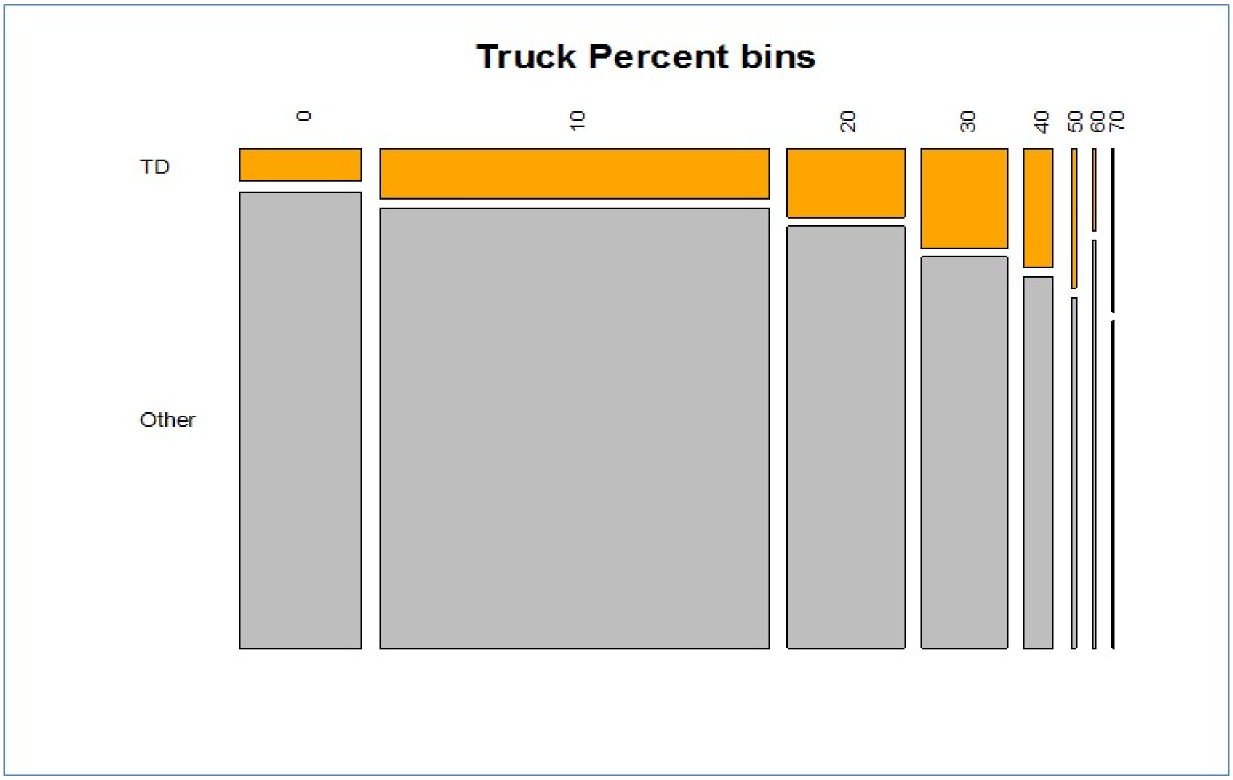


Figure 60. Proportion of TD Crashes by Truck Percent.

Figure 61 shows a clear increase in the proportion of TD crashes corresponding to increasing speed limits, similar to the trend in Figure 60.

Although most debris-related crashes occurred on roads with speed limits of 60 or 65 mph (i.e., the two widest bars in the figure), the number of debris-related crashes at roads posted 70 and 80 mph was noteworthy (though only about half as many as the number of crashes posted at 60 and 65 mph speed limits). In any case, high speed facilities have clearly an increased risk of TD crashes. However, additional confounding factors may be potentially in this trend: (a) the 60 and 65 mph locations are probably located in major urban centers while the 70+ mph sections are most likely in rural areas; (b) urban areas probably have more weaving and standing; and (c) urban centers may have warmer pavement from higher volumes, smog, and less wind, compared to rural areas.

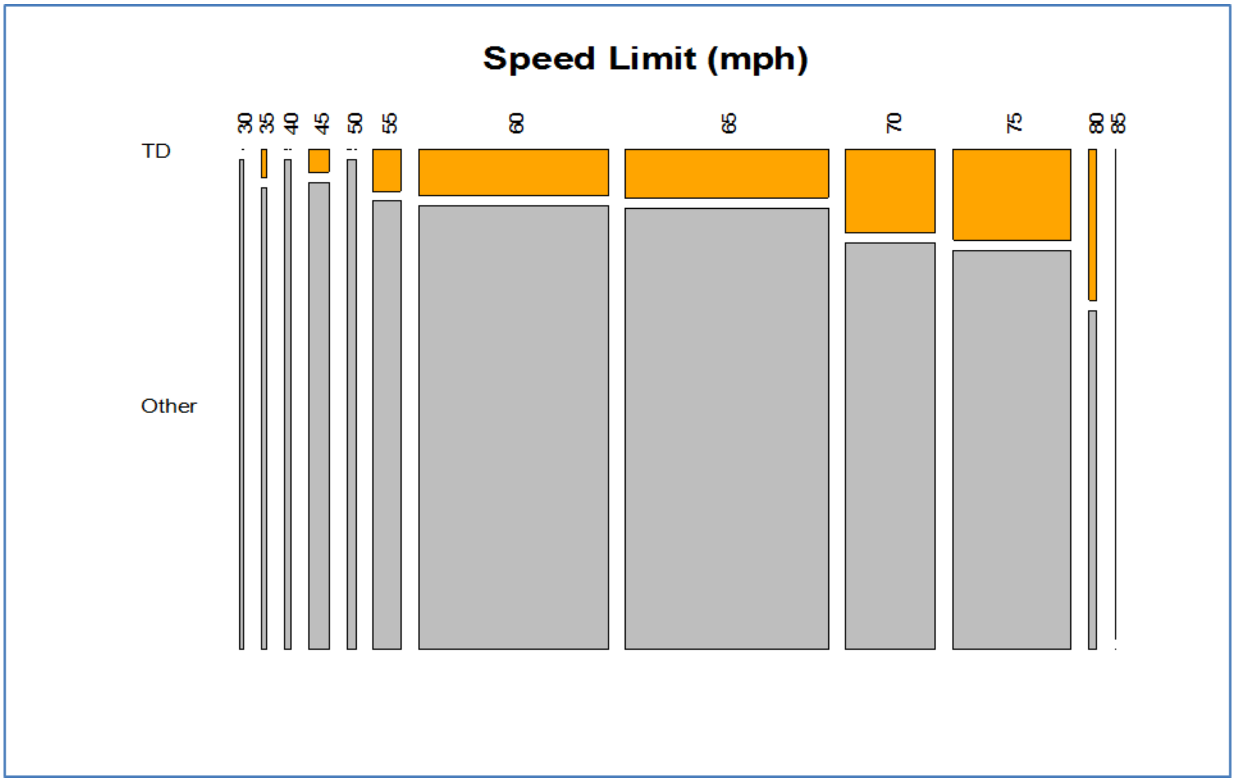


Figure 61. Proportion of TD Crashes by Speed Limit.

Altogether, debris-related crashes that occurred at roads posted between 60 and 75 mph constitute about three-quarters of all debris-related crashes.

Summary of Exploratory Analysis

This section explored how the proportion of observed TD crashes changes with varying levels of some variables of interest. This exploratory analysis found that among all debris-related crashes, the proportion of TD crashes does not seem to vary significantly with traffic volume (captured by AADT). In contrast, the likelihood of observing TD involvement was found to be higher at sites with a high truck percentage and at sites with higher speed limits.

Though the findings in the exploratory analysis are telling, it was not clear if such trends mask each other or any other factor. The next section will focus on a formal statistical analysis. Such a formal analysis should unveil the trends associated with each variable of interest while simultaneously controlling for trends associated with the rest of the variables.

STATISTICAL ANALYSIS

This section briefly describes the theoretical background of the selected methodology, preparation, analysis, and results of a safety analysis on the retrospective crash data gathered by this research.

Statistical Method

A logistic regression methodology is applicable to datasets collected retrospectively and prospectively. This analysis uses the set of all crashes with debris involvement to evaluate changes in the proportion of those crashes with TD involvement linked to changes in a set of variables of interest. A requirement for this methodology is that data points in the dataset be independent of each other. For that reason, the research team aggregated the crashes by control section prior to analysis.

Estimates, confidence intervals (CIs), and conclusions can be extracted from the coefficients and SEs from a model that adequately fits the data. The formal specification for the logistic regression is as follows:

$$Logit(\pi_{TD}|Debris) = \beta_0 + \boldsymbol{X}'.\boldsymbol{\beta}$$

Equation 7

Where,

$(\pi_{TD}\|Debris)$	=	Probability of TD involvement, given that a debris-related crash has occurred.
$Logit(\cdot)$	=	Log-odds function, defined as $Logit(\pi) = \log\left(\frac{\pi}{1-\pi}\right)$.
$\boldsymbol{X}$	=	Vector of explanatory variables.
$\boldsymbol{\beta}$	=	Vector of coefficients corresponding to $\boldsymbol{X}$ (estimated).
β_0	=	Intercept term (estimated).

The vector $\boldsymbol{\beta}$ and intercept β_0 are estimated by maximizing the likelihood function of the model and the data at hand. For a sufficiently large dataset, these estimates are expected to be unbiased and statistically efficient. It was possible then to estimate the SE for the estimated vector of coefficients.

This analysis models the conditional probability of TD involvement given that a debris-related crash has occurred. The natural measure of such probability is the proportion of TD crashes among all crashes recording debris involvement.

Interpretation of Coefficients

The statistical specification of the model links the logit transformation of the probability of TD crashes to a linear combination of independent variables. Because the logit transformation is the natural logarithm of the odds of $(\pi_{TD} | \; Debris)$, inferences about the impact of changing variables in the vector $\boldsymbol{X}$ to the probability of TD crashes are as follows: a marginal change of an independent variable represents a multiplicative change in the odds TD involvement on debris-related crashes. For example, the following relationship exists if there is a variable X_1 with two levels A and B whose coefficient in the regression is β_1:

$$\omega_{X_{i1}=A} / \omega_{X_{i1}=B} = \exp(\beta_1 \times [A - B])$$

Equation 8

Equation 8 indicates that the odds ratio (i.e., the ratio of odds of TD crashes when $X_1 = A$ to the odds of TD crashes when $X_1 = B$) is the exponential function of the difference between levels A and B multiplied by β_1, the regression coefficient corresponding to X_1.

Data Preparation

Prior to the analysis, data must be prepared in the format required by the methodology. As mentioned earlier, the research team aggregated the crashes by control section. Although it would be desirable to include in the analysis every crash identified, there were instances of crashes with at least one piece of data missing (e.g., AADT, speed limit). After removing those instances, the total number of debris-related crashes reduced to 1,869, and the number of TD crashes reduced to 224. When aggregating the data by control section, the 1,869 crashes grouped into 689 control sections (i.e., data points) for analysis. Table 11 shows the summary statistics of the resulting dataset.

An important observation about Table 11 regards the aggregation of the data. The shoulder widths were calculated as the average between the fields Shldr_Width_Left and Shldr_Width_Right in the crash record. Since the modeling effort was performed on the data aggregated in the 3 year period, time of the year was not explicitly considered as a covariate in the analysis.

Table 11. Filtered Dataset for Analysis (n = 689 Control Sections).

	Mean	Standard Deviation	Min	Max	Total
Total Debris Crashes	2.7	3.9	1	41	1,869
TD Crashes	0.3	0.7	0	4	224
AADT (vpd)	39,976.5	42,703.2	270	276,632	N.A.
Truck Percent (%)	16.5	12.2	0.9	70.9	N.A.
Number of Lanes	4.5	1.4	2.0	10	N.A.
Speed Limit (mph)	63.1	11.7	22.5	85	N.A.
Shoulder Width (ft)	12.7	6.1	0.0	38.0	N.A.
Median Width (ft)	33.9	39.7	0.0	500.0	N.A.
Presence of Horizontal Curve	0.2	0.4	0.0	1.0	N.A.

Note: N.A. = Not Applicable.

Instances where crashes in the same control section had different values in a variable of interest were averaged as well. The minimum speed limit value of 22.5 represents the average between 20 and 25 mph speed limits within a common control section.

Results

Using all the variables in the filtered dataset, the research team fitted a logistic model via maximum likelihood estimation. All statistical analyses were performed using open source statistical software (The R Development Core Team, 2013; Venables and Ripley, 2002).

The research team performed stepwise model selection to reduce redundant variables from the model. This procedure helps minimizing redundant information brought by overlapping variables. For example, it was expected that the variables “number of lanes” and “AADT” closely correlate (i.e., more daily vehicles are expected at facilities with more lanes); stepwise model selection helps to decide if it was meaningful to retain both variables in the model, and if not, which variable should be excluded. Stepwise model selection also helped avoiding the inclusion of an excessive number of variables, given the available amount of information in data.

After model selection, the research team checked the results against the raw data trends shown in the previous sections. Finally, the research team verified that the model assumptions were satisfactorily met, so that the significance and magnitude of findings are defendable. Table 12 shows the final model coefficients.

Table 12. Logistic Model Coefficients on Proportion of TD Crashes (n = 689).

	Estimate	Std. Error	z-value	p-value	Significance[a]
(Intercept)	−4.206138	0.753757	−5.58	2.40×10^{-08}	***
Speed Limit [Rural Highway]	0.021211	0.010404	2.039	4.15×10^{-02}	*
Speed Limit [Urban Highway]	0.013776	0.011147	1.236	2.17×10^{-01}	
Truck Percent	0.028342	0.008028	3.531	4.15×10^{-04}	***
Number Of Lanes	0.129505	0.053148	2.437	1.48×10^{-02}	*

Note: [a] p-value thresholds for significance symbols: º p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001

As explained earlier, the coefficients in Table 12 represent rates of change in the log-odds of TD crashes per unit of change of the corresponding explanatory variables. The last column in this table shows a qualitative measure of the strength of the evidence supporting that a given explanatory variable associates with changes in the odds of TD crashes. Except for the speed limit coefficient for urban highways, every coefficient in Table 12 was statistically significant at the 5 percent significance level. A statistical test on urban and rural speed limit coefficients indicated that their difference was statistically different from zero (0.0227 p-value on a 0.007735 z-statistic of the difference between coefficients), so both coefficients were retained in the model.

The coefficients in Table 12 indicate that the odds of TD involvement in crashes increase with increasing speed limits, truck percentages, and number of lanes. The findings about speed limits and truck percentages are consistent with the exploratory analyses documented earlier in this chapter. Regarding the number of lanes, this coefficient was most likely capturing the variability observed between facility types, per Figure 50.

Next, the research team investigated the magnitude of the associations implied by the statistical model. Table 13 shows the magnitudes of the association found between TD crashes and the variables in the statistical analysis. The interpretation of this table can be summarized in the following points:

- The odds of TD involvement increase by a factor of 1.15 with every 5 percent increase in truck percent.
- Similarly, the odds of TD involvement increase by a factor of 1.14 for each additional lane, other things equal.
- The odds of TD involvement also increase a factor of 1.11 for each increase of 5 mph in speed limit on rural highways.
- Finally, an increase of 5 mph in speed limit on urban highways corresponds with a multiplicative increase of 1.07 in the odds of TD involvement.

Except for speed limits on urban highways, Table 13 shows that all the odds ratios corresponding to variables of interest are larger than 1.00 at a 95 percent CI.

Table 13. TD Crash Odds Ratios for Select Increments of Explanatory Variables.

Risk Factor	Change in Variable	95% CI Lower Limit for Odds Ratio	Odds Ratio Point Estimate	95% CI Upper Limit for Odds Ratio
Speed Limit (Rural Highway)	+5 mph	1.00	1.11	1.23
Speed Limit (Urban Highway)	+5 mph	0.96	1.07	1.19
Truck Percent	+5 percent	1.07	1.15	1.25
Number of Lanes	+1 lane	1.03	1.14	1.26

In order to provide a sense of the relationships above, the research team prepared graphics from the statistical model.

Figure 62 shows how the conditional probability of TD crashes increases with increasing truck percentage, after controlling for speed limit and road character. This figure also shows that the conditional expectation of TD crashes was higher at facilities with more lanes in their cross-sections.

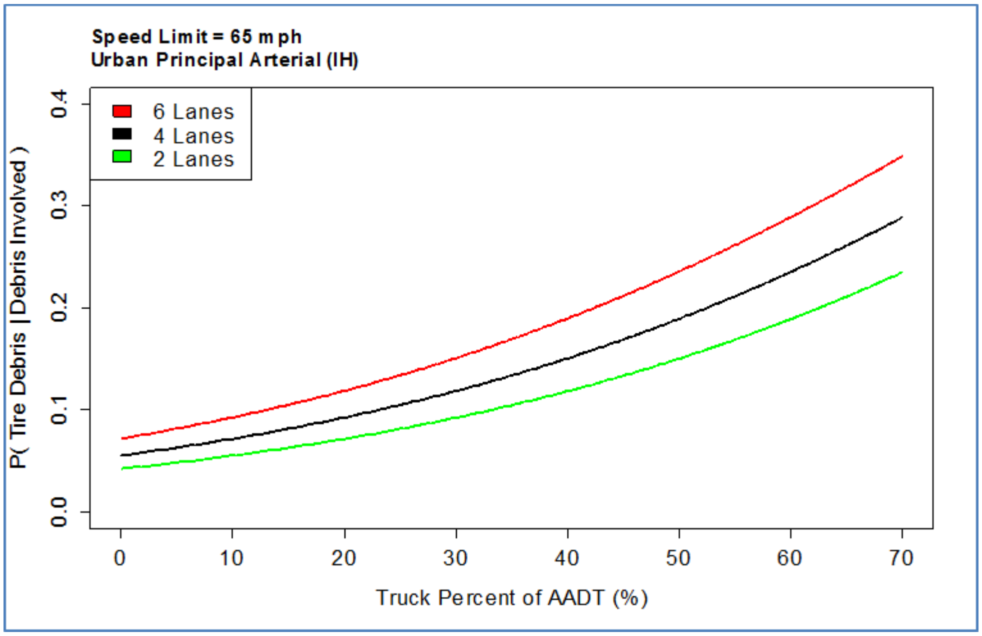


Figure 62. Probability of TD Given a Crash Occurred Involving Road Debris by Truck Percent and Number of Lanes.

Similarly, Figure 63 shows an increasing probability of TD involvement in freeway debris crashes with increasing truck percent, while controlling for rural or urban character.

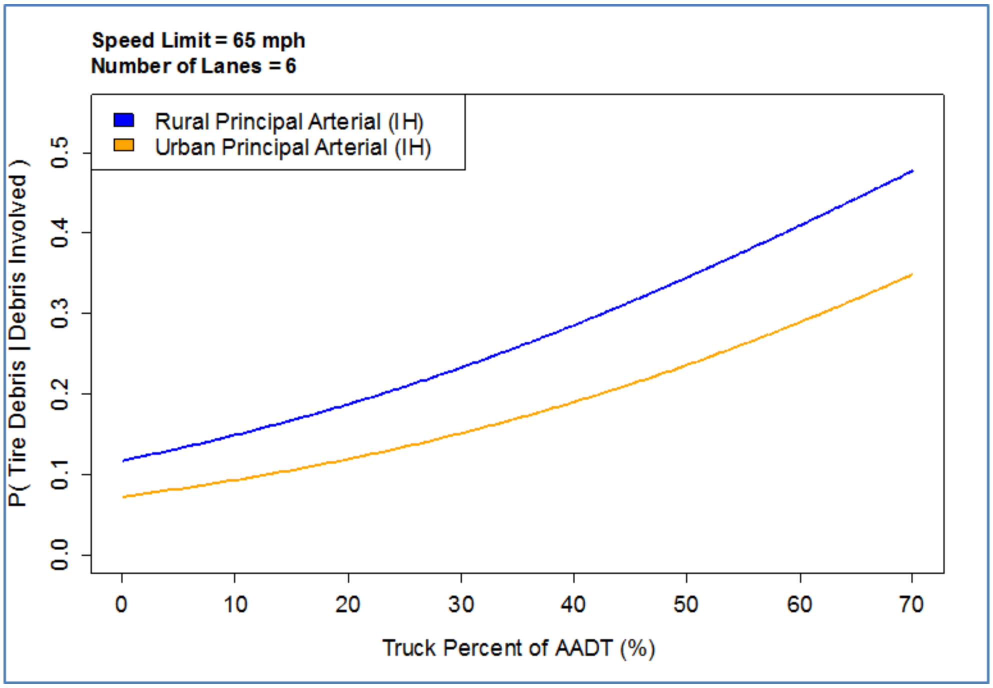


Figure 63. Probability of TD Given a Crash Occurred Involving Road Debris by Truck Percent and Roadway Type.

Figure 64 illustrates how the gap between rural and urban facilities in TD crash probability widens with increasing speed limit, after controlling for truck percent and number of lanes.

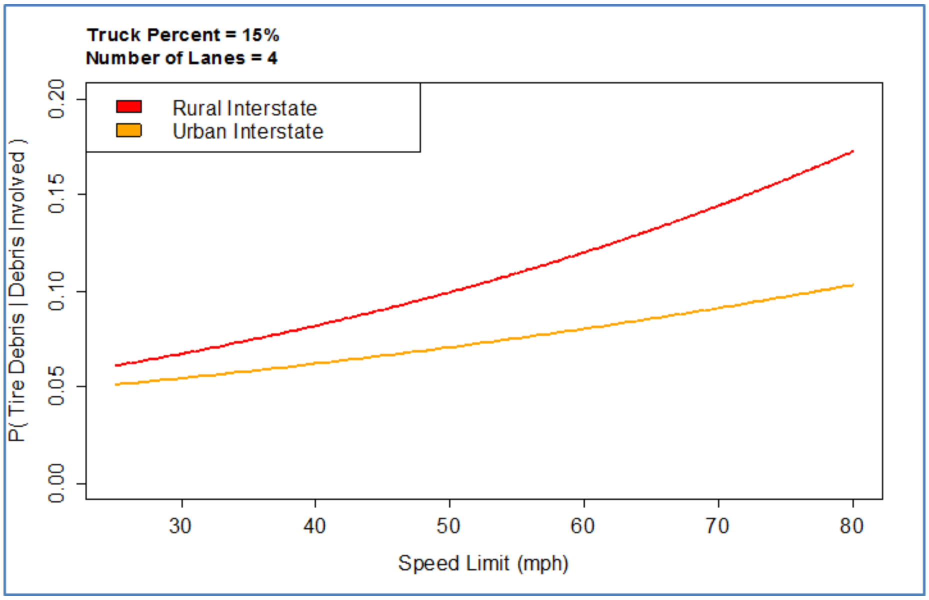


Figure 64. Probability of TD Given a Crash Occurred Involving Road Debris by Speed Limit and Road Character.

Finally, Figure 65 shows a relatively flat relationship between the probability of TD crashes with increasing speed limit after controlling for number of lanes and truck percent.

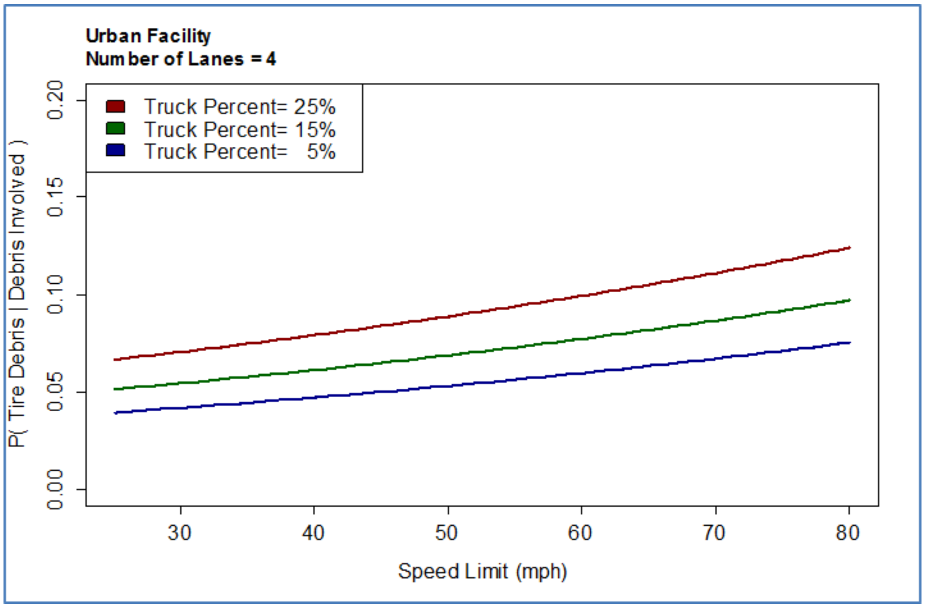


Figure 65. Probability of TD Given a Crash Occurred Involving Road Debris by Speed Limit and Truck Percent.

Interpretation of these plots should consider that the occurrence of a debris-related crash was an extremely rare event in the first place. The y-axis in Figure 62 through Figure 65 represents the conditional probability of TD involvement given that a debris-related crash has occurred; this probability was a conditional probability several orders of magnitude larger than the absolute (total) probability of TD involvement in crashes. If required, the total probability of TD involvement (given that a crash of any class has occurred) can be obtained by multiplying the conditional probabilities shown in Figure 62 through Figure 65 by 0.00419, which is the probability of crashes with road debris involvement among all Texas crashes during the last three years (this probability was estimated as the ratio of the 2,247 debris-related crashes identified to 536,868 crashes of any type during the same period, 2,247 / 536,868 = 0.00419).

Discussion of Results

This analysis found that the probability of TD involvement in Texas crashes increases with an increasing percentage of trucks, an increasing number of lanes, and a higher speed limit, and also increases at rural rather than urban facilities.

In regard to the positive association between TD crashes and percent of trucks, this finding was consistent with the hypothesis that crashes involving TD are more likely at sites with higher truck traffic because debris itself tends to appear at higher rates at those sites. This hypothesis will be revisited in the next chapter, in light of the results from the district visits.

In regard to the finding of an increased proportion of TD crashes on roads with more lanes, the research team considers one likely explanation was as follows: if TD was generated in the middle of the cross-section, then it would take longer—and probably more vehicles hits or near-hits—for that piece of TD to migrate to the shoulder at sites with more lanes compared to sites with fewer lanes. Another potential explanation is that there was an underlying relationship to traffic volume. This alternative explanation cannot be completely dismissed since these two variables (number of lanes and traffic volume) tend to vary together. Finally, this result may indicate a different weaving response to debris by the crash-involved driver and other drivers. In the case of rural two-lane roads, a driver may pull to the shoulder, with minimal risk of sideswiping someone in the process.

This research also found an increased risk of TD involvement in crashes at higher speed limits. This finding may suggest that higher operating speed may increase the risk of blowouts (since speed limit and operating speed should correlate positively). However, as in the previous finding, this association may be explained as a link to traffic volume because roads with higher speed limits typically carry more traffic.

Finally, this research found that the correlation between TD crashes and speed limit was stronger at rural facilities than at urban facilities. This finding suggests that differences between urban and rural environments, unaccounted for by this analysis, may have an impact on the likelihood of TD crash occurrence. One potential factor is the different frequencies of debris removal. The answers in the statewide survey indicated that the frequency of debris removal tends to be higher at urban facilities.

SUMMARY OF FINDINGS

The research team identified 2,247 crashes that were known to have involved road debris in Texas during the years 2012–2014. The research team then obtained and reviewed the crash narratives corresponding to the identified crashes. From this review, the research team identified crashes that involved TD specifically. About 20 percent of the debris-related crashes were found to involve tires, tire shreds, or other rubber objects that could be considered TD. However, about half of this subset of crashes consisted of crashes that involved debris generated during the crash, so were not considered TD crashes for the purposes of this research. In total, only 251 crashes were found that were caused by TD being present on the pavement before the occurrence of the crash. The trends observed for the frequency of TD crashes specifically contrast with those observed for the frequency of all debris-related crashes. Whereas TD crashes tend to occur more frequently on interstate freeways (both rural and urban, per Figure 51), crashes involving any type of debris tend to occur more often at urban freeways (interstate or otherwise, per Figure 45). In relative terms, tire-debris crashes tend to be overrepresented at rural freeways than on urban freeways (Figure 53). One potential explanation for this trend is the expected differences in truck percentage between rural and urban environments.

Overall, the exploratory analysis found that TD crashes are extremely rare among crashes. As Figure 54 shows, the percentage that this type of crash represented during the period 2012–2014 ranged between 0.01 percent at rural principal arterial roads in 2014 and 0.17 percent at rural interstates in 2012. This figure and Figure 52 show a decreasing trend during the last three years in the occurrence of these types of crashes. In contrast, Figure 53 shows that the general trend of total crashes in Texas was increasing rather than decreasing. The reasons for this contrast are unclear and merit further investigation. Two potential explanations could be the implementation of more aggressive debris removal or incorporation of new technology in debris removal activities.

The exploratory analysis also found a spike of TD crashes during the summer months, both in absolute frequency and in the proportion of all debris crashes. This finding was consistent with the information obtained from the statewide survey of TxDOT districts.

The research team performed a statistical analysis on the set of road debris crashes to identify risk factors that are associated with the involvement of TD in crashes. This analysis found positive associations between TD involvement and the following variables:

- Truck percent.
- Speed limit.
- Number of lanes.
- Rural character (compared to urban).

In general, the statistical analysis found that whenever any of these variables increases, the chances of TD involvement in roadway crashes tend to increase as well.

CHAPTER 6. METRICS OF TIRE DEBRIS ON TEXAS HIGHWAYS

This chapter summarizes the findings from all tasks of this project and documents the development of Texas-wide metrics of TD based on those findings.

ESTIMATION OF TD CHARACTERISTICS FROM FIELD DATA

Upon processing the field data (both actual TD pieces retrieved and the extensive photographic record of the field visits), the research team developed statewide metrics of the characteristics of TD on Texas highways. This section presents the basic metrics and required adjustments to develop statewide estimates.

Basic Quantities of TD

The research team first developed the building blocks for TD metrics by directly using the field data obtained during district visits. The following basic quantities were computed from the field images:

- Total_TD, the total number of debris pieces found.
- Total_TDw, the total weight of those TD pieces.
- Total_TD_L, the total number of TD pieces larger than 64 in.^{2}.
- Total_TD_Lw, the total number of TD pieces larger than 64 in.^{2}.

The estimates of weight were developed under the assumption that every piece of debris in the processed photograph database has a thickness density equal to the average metrics measured from the 62 samples of TD obtained the field. Statewide estimators of the total weight of TD carried under such assumptions should converge to the truth total by virtue of the law of large numbers.

Performance Evaluation of the Three-Stage Sampling Scheme and Adjustment of Results

This section presents a comparison of the observed quantities of TD to the sampling design variable, defined in Eq. 1. Total_TD was used for this evaluation. A plot of these variables evidenced direct proportionality, as expected, but also some degree of curvature, as shown in Figure 66. This figure shows a non-parametric trend line (in solid red) and the upper and lower limits associated with its confidence range (in dashed red). Additional to the flattening of the curve, the marginal boxplot distributions of this figure suggest some scaling effect on both variables. Figure 67 shows the relationship between the natural logarithms of the variables.

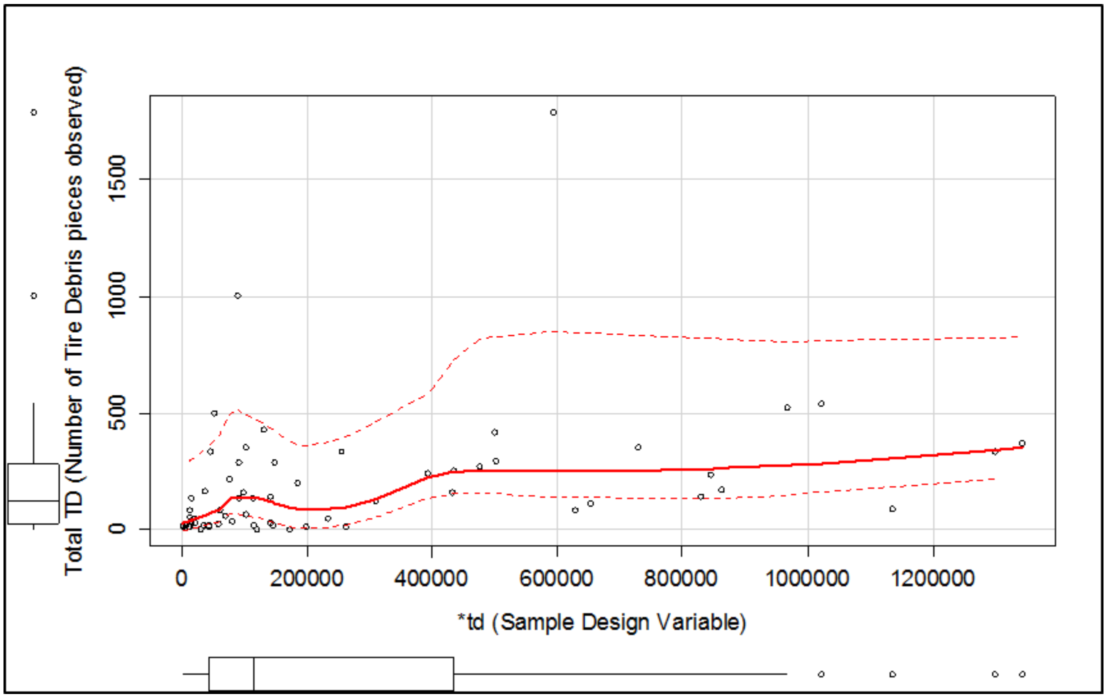


Figure 66. Relationship between Total TD and *td, the Sample Design Variable.

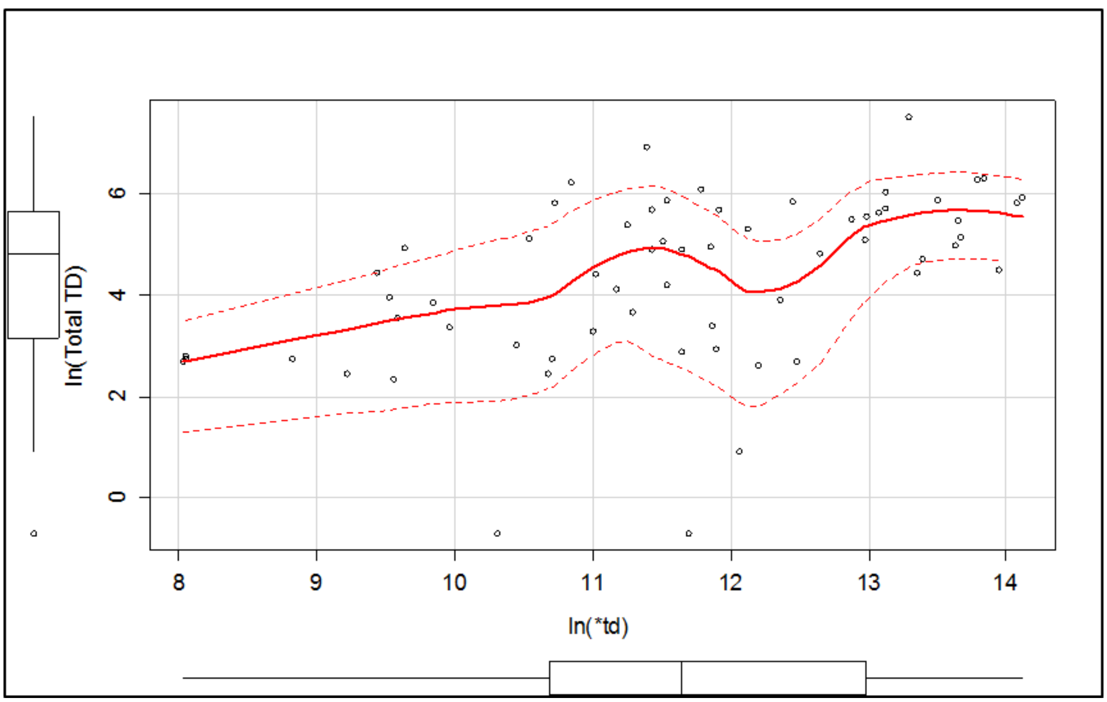


Figure 67. Relationship between Natural Logarithms of Total TD and *td.

The research team quantified this relationship using simple linear regression. The coefficient term for a constant multiplier was found statistically insignificant in the first analysis, indicating that the relationship between the transformed variables does not warrant an additional scale adjustment. A reduced model including only an exponent for the dependent variable was then fitted. Equation 9 shows the functional form of the estimated relationship between the variables of interest.

$$Total_{TD} = \ ^{*}td^{\beta}$$

Equation 9

Where β is the coefficient estimated by regression. The estimate for β was 0.40658, with a SE of ±0.01685. Leveraging on this newfound relationship, an improved estimate of Total_ TD can be developed, as defined in Equation 10:

$$\widehat{Total}_{TD} = TD_{t}^{*} = \ ^{*}td^{\beta}$$

Equation 10

Where TD_{T}^{*} is the improved estimate for $Total_{TD}$. The more direct application of Equation 10 is to improve follow-up studies that require sampling design for TD totals because it achieves a better approximation of the distribution of Total TD. Notwithstanding, in the context of this research, a more relevant use of Equation 10 is to perform a post-hoc adjustment of the estimates from a collected sample so as to mitigate any potential biases introduced by the previously unknown curvilinear nature of the relationship.

The research team performed 500 simulations of the three-stage sampling procedure implemented to obtain the field sample using the result in Equation 10 in combination with data from the RHINo file (i.e., the sampling frame). Each of these simulations entailed performing the three staged sampling procedure once on the RHINo. For each simulation, three estimates for the population value TD_{t}^{*} were computed: (a) the Horvitz-Thomson (HT) estimator, which relies solely on the sample and the probabilities of selection of its elements; (b) the ratio estimator, which relies on the samples and probabilities of selection as well, but also incorporates an ancillary variable (segment length in this sensitivity analysis) to increase the accuracy of estimation; and (c) the adjusted estimator, which was simply the arithmetic mean of the previous two estimators. Figure 68 shows the results of these simulations (per their $Total_{TD}$). This graph displays boxplots for each of the estimates and a horizontal green line indicating the true value of the $Total_{TD}$ quantity.

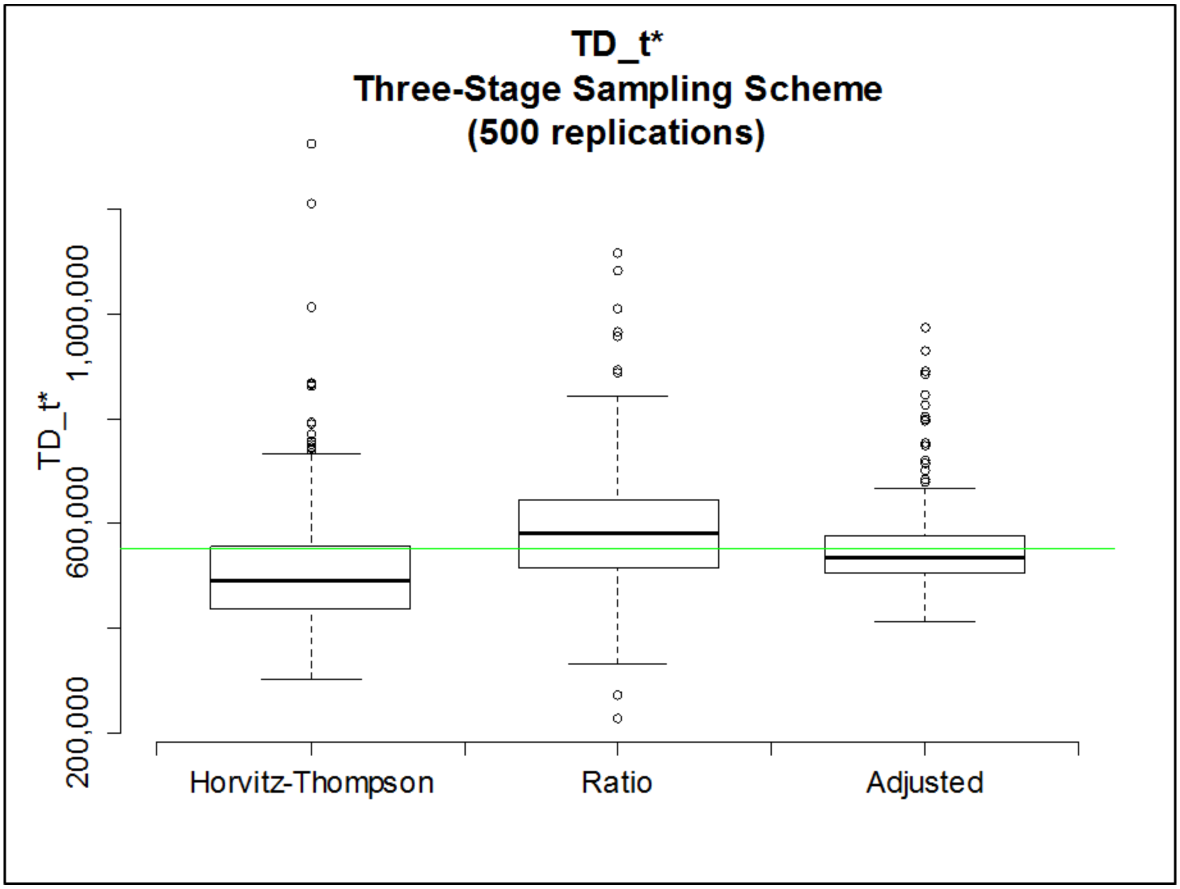


Figure 68. Comparison of Total TD Estimators of Interest.

Five observations can be extracted from Figure 68:

- The HT estimator has a negative bias when estimating the population total.
- In contrast, the ratio estimator has a positive bias, roughly equal in magnitude to the bias of the HT estimator.
- The ratio and HT estimators have very similar spreads otherwise.
- The adjusted estimator has a notably narrower spread than the other two estimators.
- The adjusted estimator appears free of bias.

The reason for the reduced spread of the adjusted estimator was the negative correlation between its two constituent quantities. That correlation was estimated from the simulations and found to be −0.230.

The following sections present tables reporting all three estimators for each variable of interest. The SEs for the first two estimates were obtained from the sampling weights, and the SEs for the adjusted estimates were computed by standard mathematical statistical procedures (Wackerly et al., 2008). For each table with statewide estimates, 95 percent CIs were constructed for the adjusted estimator. In cases when it was not possible to estimate the SE for the ratio estimate (urban freeways and rural principal arterials), the CIs were constructed using the SE from the HT estimate only.

BASIC CHARACTERISTICS OF TD IN TEXAS HIGHWAYS

As documented in Chapter 4, the research team retrieved 62 TD pieces that were subsequently measured in the laboratory. This section presents the results from those measurements and an initial set of statewide estimates about size and weight of a typical piece of TD on Texas highways.

Properties of TD Field Samples

The average density of the measured pieces was found to be 80.2 lb/ft^3, with a standard deviation of 7.24 lb/ft^3, a minimum of 67.4 lb/ft^3, and a maximum of 111.7 lb/ft^3. By comparison, the density of water is 62.4 lb/ft^3. The variability in the tire density measurements was likely attributed to differences in the ratios of steel to rubber in the debris pieces. The density of steel is 490 lb/ft^3, and the density of rubber is 70 lb/ft^3. The surface area of each piece of debris was also measured (as shown in Figure 39). The average thickness of each piece was calculated as the ratio of the volume to the surface area measurements. The thickness ranged from 0.20 in. up to 0.67 in., with an average thickness of 0.41 in. and standard deviation of 0.13 in.

Size and Weight of Average TD Pieces in Texas Highways

The photographic record of field visits was reduced and analyzed to estimate statewide metrics of TD. Table 14 shows the number of pieces identified and processed by facility type. It is clear from this table that the largest quantities of TD were found at urban freeways (interstates and other types), totaling 11,387 pieces. In contrast, only 1768 TD pieces were found at rural interstate freeways. Finally, the quantity of TD found at non-freeway highways amounted to 657 pieces.

Table 14. Number of TD Pieces Identified by Facility Type.

Facility Type	Number of TD Pieces
RURAL INTERSTATE	1,768
RURAL MINOR ARTERIAL	283
RURAL PRIN ARTERIAL	1,186
URBAN MINOR ARTERIAL	171
URBAN PRIN ARTERIAL (IH)	8,127
URBAN PRIN ARTERIAL (OTHER FREEWAY)	3,260
URBAN PRIN ARTERIAL (OTHER)	203
ALL HIGHWAYS	**14,998**

Using the reduced photographic record of field visits, the research team estimated the four basic quantities on the size of TD particles found during the visits. Table 15 shows estimates of the average size of TD pieces in squared inches. Researchers estimated that the typical TD piece in Texas highways is 47.1 in.^{2}, a metric that in reality could be as small as 38.6 in.^{2} or as big as 55.5 in.^{2}, with 95 percent confidence.

Table 15. Average Size of TD Pieces on Texas Highways (in.^{2}).

FUNC CLASS	HT Estim.	HT SE	Ratio Estim.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	46.6	15.0	31.5	7.0	39.0	15.0	9.6	68.5
RURAL MINOR ARTERIAL	56.7	0.7	35.3	2.2	46.0	2.2	41.8	50.2
RURAL PRIN ARTERIAL	64.3	3.4	105.7	N.A.	64.3	3.4	57.7	70.9
URBAN FREEWAY	48.9	0.4	36.6	N.A.	48.9	0.4	48.1	49.7
URBAN MINOR ARTERIAL	52.5	0.5	28.0	10.1	40.2	10.0	20.7	59.8
URBAN PRIN ARTERIAL	54.9	0.2	23.6	4.7	39.2	4.6	30.2	48.3
ALL HIGHWAYS	**56.2**	**4.0**	**37.9**	**2.74**	**47.1**	**4.3**	**38.6**	**55.5**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

When comparing adjusted estimates and their SEs, it appears that the average TD piece size was very consistent from facility to facility (i.e., big overlaps between CIs), with the notable exception of rural principal arterials, where the ratio estimator would bring the adjusted estimate significantly higher. Because an SE for such estimate was not possible to compute, the adjusted estimate is defined as simply the HT estimator.

Table 16 shows the estimates for the average TD piece in lb. This table indicates that the average piece of TD in Texas Highways weighs 0.88 lb, a metric that in reality could be between 0.72 lb and 1.04 lb, with 95 percent confidence.

Table 16. Average Weight of TD Pieces on Texas Highways (lb).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	0.87	0.28	0.59	0.13	0.73	0.28	0.18	1.28
RURAL MINOR ARTERIAL	1.06	0.01	0.66	0.04	0.86	0.04	0.78	0.94
RURAL PRIN ARTERIAL	1.20	0.06	1.98	N.A.	1.20	0.06	1.08	1.33
URBAN FREEWAY	0.91	0.01	0.69	N.A.	0.91	0.01	0.90	0.93
URBAN MINOR ARTERIAL	0.98	0.01	0.52	0.19	0.75	0.19	0.39	1.12
URBAN PRIN ARTERIAL	1.03	0.00	0.44	0.09	0.73	0.09	0.56	0.90
ALL HIGHWAYS	**1.05**	**0.07**	**0.71**	**0.05**	**0.88**	**0.08**	**0.72**	**1.04**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

All CIs for the average weight of TD pieces by facility type in this table tend to overlap. Similar to Table 15, this table shows that the various facility types had TD pieces of similar sizes.

Like the previous two tables, the estimates in Table 17 and Table 18 are given in in.^{2} and lb, respectively. These tables present the size and weight estimates for the average piece of TD whose individual sizes were estimated larger than 64 in.^{2} during the image analysis.

A threshold of 64 in.^{2} was selected for large pieces as previous research suggests that an object of 8 in. height or taller is likely to trigger evasive maneuvers from drivers (Kahl and Fambro, 1995).

Table 17 indicates that the average size of pieces larger than 64 in.^{2} was estimated to be 129.4 in.^{2}, an average size that could be as small as 113.2 in.^{2} and as large as 145.6 in.^{2}, with 95 percent confidence.

Table 17. Average Size of Large TD Pieces on Texas Highways (in.^{2}).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	101.8	21.0	64.8	3.1	83.3	20.5	43.2	123.4
RURAL MINOR ARTERIAL	123.3	1.1	71.1	1.4	97.2	1.6	94.1	100.3
RURAL PRIN ARTERIAL	145.7	6.5	270.2	N.A.	145.7	6.5	132.9	158.4
URBAN FREEWAY	123.1	1.5	93.8	N.A.	123.1	1.5	120.2	126.0
URBAN MINOR ARTERIAL	154.9	1.6	83.6	29.2	119.3	28.8	62.7	175.8
URBAN PRIN ARTERIAL	104.4	0.2	52.0	10.8	78.2	10.8	57.1	99.4
ALL HIGHWAYS	**129.4**	**8.3**	**94.4**	**N.A.**	**129.4**	**8.3**	**113.2**	**145.6**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

Some CIs in these tables do include the 64 in.^{2} threshold used to define large TD pieces (even a negative value for urban minor arterials). This is evidence of a wide SE rather than of computational issues. Similar to the metrics for all TD pieces, the size of large pieces appears consistent across facility types.

Finally, Table 18 shows the average weight of pieces of TD in excess of 64 in.^{2}. The average large TD piece weighs 2.42 lb, although the true average could be anywhere between 2.12 lb and 2.72 lb.

Table 18. Average Weight of Large TD Pieces on Texas Highways (lb).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	1.90	0.39	1.21	0.06	1.56	0.38	0.81	2.31
RURAL MINOR ARTERIAL	2.31	0.02	1.33	0.03	1.82	0.03	1.76	1.88
RURAL PRIN ARTERIAL	2.73	0.12	5.06	N.A.	2.73	0.12	2.49	2.96
URBAN FREEWAY	2.30	0.03	1.75	N.A.	2.30	0.03	2.25	2.36
URBAN MINOR ARTERIAL	2.90	0.03	1.57	0.55	2.23	0.54	1.17	3.29
URBAN PRIN ARTERIAL	1.95	0.00	0.97	0.20	1.46	0.20	1.07	1.86
ALL HIGHWAYS	**2.42**	**0.15**	**1.77**	**N.A.**	**2.42**	**0.15**	**2.12**	**2.72**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

ESTIMATION OF THE QUANTITY OF OBSERVABLE TD

Similar to the statewide estimates in the previous section, the research team constructed tables with the most direct metrics of TD that could be developed with the field data. Constructed from the four basic quantities previously described, these initial metrics represent the observable amount of TD on Texas highways. In principle, these estimates can be interpreted as the observable TD expected at any point in time. However, due to expected seasonality in the cycles of TD generation (an assessment of seasonality is presented later in this chapter), the representativeness of these numbers should be restricted to only the period when data collection occurred (July to November 2015).

Quantity of Observable TD

Table 19 shows the sample estimates for the total number of observable TD pieces on Texas highways at any point during the period of data collection (July to November 2015). According to this table, at any point between July and November 2015, there were between 178,200 and 663,200 pieces of TD on Texas highways. It is also clear from this table that most of that TD was located on urban and rural freeways (between 39,100 and 226,000 pieces on rural freeways and between 74,600 and 174,400 pieces on urban freeways).

Table 19. Total Observable TD on Texas Highways (Thousands of Pieces).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	189.4	46.3	75.5	26.2	132.5	47.7	39.0	226.0
RURAL MINOR ARTERIAL	22.5	5.9	56.0	9.4	39.2	9.9	19.8	58.7
RURAL PRIN ARTERIAL	69.0	15.2	78.5	N.A.	69.0	15.2	39.1	98.9
URBAN FREEWAY	134.5	20.9	114.5	20.1	124.5	25.4	74.6	174.4
URBAN MINOR ARTERIAL	3.0	1.3	41.1	9.2	22.0	9.0	4.3	39.8
URBAN PRIN ARTERIAL	2.4	0.6	39.2	13.1	20.8	12.9	-4.6	46.1
ALL HIGHWAYS	**420.7**	**123.7**	**717.2**	**N.A.**	**420.7**	**123.7**	**178.2**	**663.2**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

Similarly, Table 20 shows that between 70.4 and 289.7 metric tons of observable TD were present on Texas highways at any point between July and November 2015.

Table 20. Total Observable TD on Texas Highways (Metric Tons).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	81.3	22.8	32.7	13.9	57.0	23.8	10.4	103.7
RURAL MINOR ARTERIAL	10.2	2.0	26.4	0.3	18.3	2.0	14.5	22.2
RURAL PRIN ARTERIAL	26.3	5.6	32.2	N.A.	26.3	5.6	15.3	37.4
URBAN FREEWAY	59.7	8.1	48.8	N.A.	59.7	8.1	43.8	75.5
URBAN MINOR ARTERIAL	1.3	0.7	16.5	5.5	8.9	5.3	-1.6	19.3
URBAN PRIN ARTERIAL	1.2	0.4	17.8	5.0	9.5	4.9	-0.2	19.2
ALL HIGHWAYS	**180.0**	**56.0**	**304.4**	**N.A.**	**180.0**	**56.0**	**70.4**	**289.7**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

Although the number of sampled miles of each facility type is important to determining the width of the CIs, it is not the only influencing factor. Additionally, a CI can be wider or narrower because of the total number of miles of each facility type in Texas and because of the variability observed in the data collected from each facility type.

Table 21, indicates that between 36,700 and 124.700 pieces of large TD (i.e., 64 in.^{2} or larger) were to be found on Texas highways at any point between July and November 2015.

Table 21. Total Observable Large TD on Texas Highways (Thousands of Pieces).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	33.7	8.0	12.9	4.7	23.3	8.3	7.0	39.6
RURAL MINOR ARTERIAL	5.3	1.0	13.9	0.9	9.6	1.2	7.2	12.0
RURAL PRIN ARTERIAL	12.0	3.4	13.6	N.A.	12.0	3.4	5.4	18.6
URBAN FREEWAY	28.8	3.9	22.9	N.A.	28.8	3.9	21.2	36.5
URBAN MINOR ARTERIAL	0.5	0.2	6.5	1.4	3.5	1.4	0.8	6.2
URBAN PRIN ARTERIAL	0.4	0.1	8.7	4.6	4.5	4.6	-4.5	13.6
ALL HIGHWAYS	**80.7**	**22.4**	**140.1**	**N.A.**	**80.7**	**22.4**	**36.7**	**124.7**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

Table 22. Total Observable Large TD on Texas Highways (Metric Tons).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	27.6	5.6	9.9	3.0	18.7	5.7	7.6	29.9
RURAL MINOR ARTERIAL	5.5	1.3	14.3	N.A.	5.5	1.3	2.9	8.0
RURAL PRIN ARTERIAL	12.0	3.3	15.1	0.6	13.5	3.2	7.3	19.8
URBAN FREEWAY	30.5	4.2	24.2	N.A.	30.5	4.2	22.2	38.8
URBAN MINOR ARTERIAL	0.6	0.3	7.9	2.3	4.3	2.2	-0.1	8.6
URBAN PRIN ARTERIAL	0.4	0.1	7.4	3.9	3.9	3.9	-3.8	11.6
ALL HIGHWAYS	**76.6**	**18.5**	**142.0**	**N.A.**	**76.6**	**18.5**	**40.3**	**112.8**

Note: N.A. = Not Available; Segment Length was used as the ancillary variable to develop ratio estimates.

Finally, Table 22 indicates that between 40.3 and 112.8 tons of large debris (64 in.^{2} or larger) could be found on Texas highways at any point between July and November 2015.

Previous tables clearly indicate that the vast majority of observable TD was generated at freeway facilities. Surprisingly, rural principal arterials also exhibited significant amounts of observable TD. Finally, the tables suggest that there was little difference between urban minor and major arterials in terms of the amount of TD found at those facilities.

Limitations of Estimates of Total Observable TD

Next, this research developed estimates of frequency and weight of TD directly from the data obtained during field visits. Although this information is valuable, it only represents the expected amount of observable TD on Texas highways at any point in time (from July to November 2015). A more important goal of this research project was obtaining estimates of TD generation rates. Such rates would allow making projections of TD accumulated over time. It was necessary, then, to quantify the frequency of debris removal activities at the visited sites in order to estimate TD generation rates. An analysis conducive to estimating debris removal frequency is presented in the next section. Estimation of TD generation rates is presented at a later section.

FREQUENCY OF DEBRIS REMOVAL ACTIVITIES IN TEXAS ROADS

In principle, the information about debris removal frequency obtained from the practitioners in the statewide survey and the cost data obtained from TxDOT Maintenance Division (documented in Chapter 3) could be combined and used to develop rough estimates of the frequency of road debris removal. However, such estimates may not accurately reflect the specific conditions at the sites of data collection. The research team requested additional data on debris removal activities specific to the sites visited so to increase that the accuracy of TD generation-rate estimates.

TxDOT Maintenance Division provided the research team with data obtained from queries of two databases—Maintenance Management System (MMS), which contains records of maintenance activity conducted by TxDOT personnel, and SiteManager, which contains daily work reports for activities performed by contractors. Data from the SiteManager database were not available for FY 2013; however, inspection of debris removal activity trends suggested that the overall amount of effort remained roughly constant across the years for which data queries were available.

The database queries included records for each work order (WO) that occurred on the field-visit sites and involved function code 523, which is the code for debris removal. This code includes all debris, not exclusively TD, so it was not possible to obtain a direct estimate of TD removal rate or cost from the maintenance data. However, based on the interviews in the statewide survey of districts, TD represents the majority of debris that was removed from state-maintained highways. Hence, it was likely that much of the debris removal activity was driven by the presence of TD.

Exploratory Analysis

For this exploratory analysis, the queries of the MMS and SiteManager databases were combined with a spatial tolerance of 1 mi, and the following variables were retained: district, highway, beginning and ending reference marker, FY, month, work quantity (in miles), and cost (total of all cost components, including labor, equipment, etc.). The highway and reference marker variables were used to assign the maintenance activity records to specific highway segments. As a first step, the amount of debris removal work was compared for FY 2013–2015, as shown in Figure 69 and Figure 70.

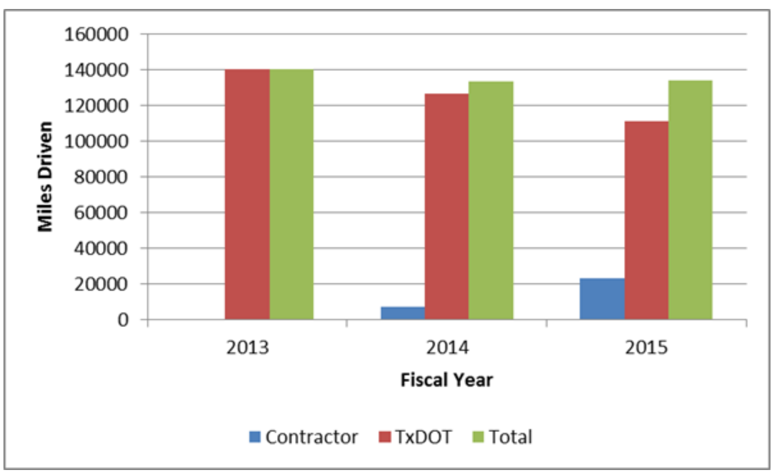


Figure 69. Annual Debris Removal Work Trends.

Across the three years, the amount of debris removal effort remained roughly constant, though the share of effort borne by contractors increased as the years passed. A reduction in miles driven by TxDOT personnel is notable. Figure 70 shows that the total cost of debris removal have increased as the years have progressed. The trends in Figure 69 and Figure 70 suggest that the cost of debris removal increases with increasing share of work by contractors. This is consistent with the trends found earlier (shown in Figure 16).

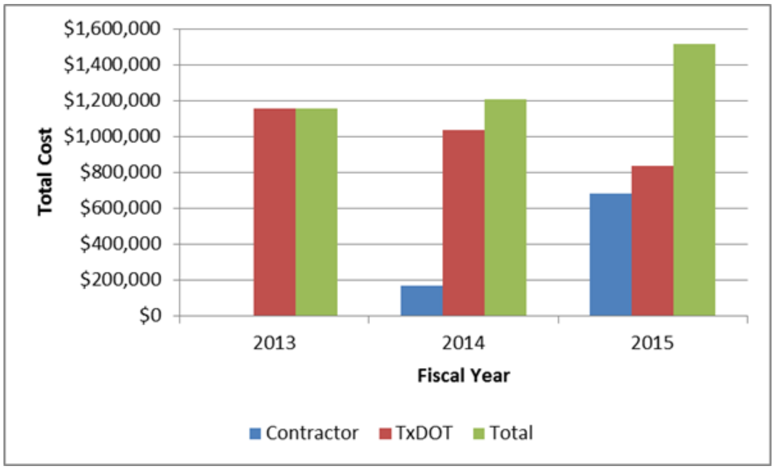


Figure 70. Annual Debris Removal Cost Trends.

Debris removal frequency was examined more closely by plotting monthly trends, as shown in Figure 71. Monthly fluctuations in frequency are apparent, though efforts remained roughly constant across the years. There is a notable shift in miles driven in fall and winter.

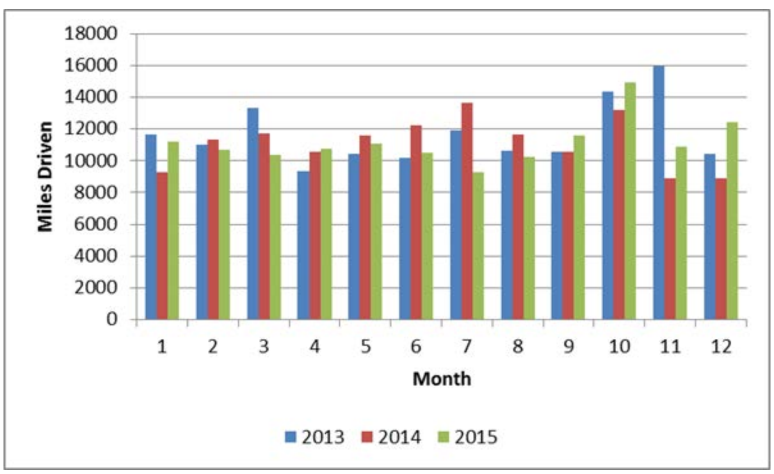


Figure 71. Monthly Debris Removal Work Trends.

The annual trends in debris removal frequency are plotted in Figure 72 for the seven districts represented by the data collection sites. As shown, the average number of miles driven exhibits clear differences between districts. At each district, fluctuations from year to year also appear to amount to notable variation.

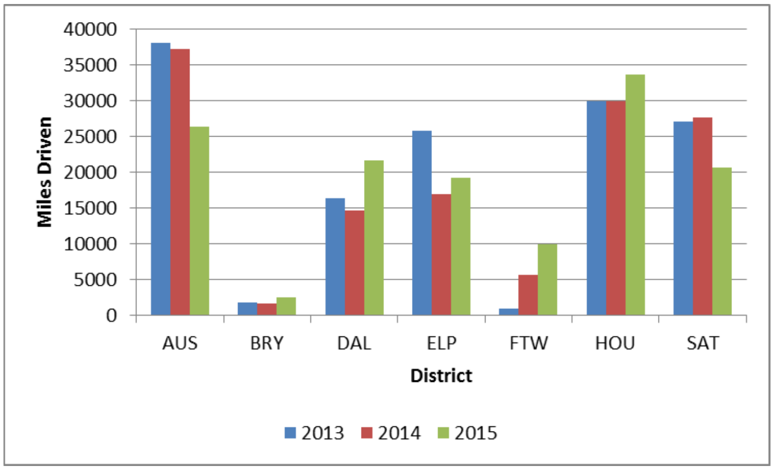


Figure 72. District Debris Removal Work Trends.

The measure of number of debris removal visits (as determined by the number of records in the merged MMS/SiteManager database) gives an estimate of debris removal frequency. However, inspection of the debris removal records revealed that some highway segments were visited multiple times in a single day, though the total mileage for each visit was small. Records of this type could simply indicate that the highway segment was visited once in a specific day, but three stops occurred because debris was found in three isolated spots. Hence, an estimate of debris removal rate based on number of logged visits may be biased high. Researchers determined that to obtain a more robust estimate of debris removal activity, the removal rate should be computed in terms of number of days when one or more removal visits occurred.

Site-by-Site Analysis

The research team developed a series of more targeted queries using structured query language to analyze the removal data by site. The research team put special emphasis on developing mitigation strategies to handle incomplete data since the estimates are intended to carry further analyses.

To study the completeness of the dataset at various levels of precision, queries of the MMS and SiteManager databases were recombined, and the research team varied the precision of the match based on the highway reference markers.

The two most recent FYs of data available are FY 2014 and FY 2015. In total, these FYs represent 11,212 WOs from state personnel and 1,981 from contractors recorded between September 1, 2013, and August 31, 2015, at the field-visit sites, or in close proximity.

Not all of the WOs could be matched to the sites in the sample. To be considered a match, the number of successful matches depends on how close the reported location of a WO was to the confines of a field-visit site. Table 23 and Table 24 show how the number of matched WOs changes by increasing the maximum thresholds allowed for the spatial matching.

Table 23. State-Force Work Debris Removal Orders.

Maximum Threshold Allowed for Spatial Match	Number of Work Order Matches	Percent of Work Orders Matched
1 mi	10,478	93%
5 mi	10,789	96%
10 mi	11,126	99%

Most of the state-force WOs are located within a mile of the confines of the sampled field-visit sites (93 percent). In the case of contractor-based work, the percentage of orders within a mile of the sites was somewhat reduced (79 percent). For both datasets, the vast majority of orders could be matched using a maximum threshold of 5 mi (96 percent of the state-force work and 98 percent of the contractor work).

Table 24. Contractor Work Debris Removal Orders.

Maximum Threshold Allowed for Spatial Match	Number of Work Order Matches	Percent of Work Orders Matched
1 mi	1,565	79%
5 mi	1,944	98%

As mentioned in the exploratory analysis, the most promising estimate of debris removal frequency was probably the number of dates with at least one matched WO. Table 25 summarizes the number of dates that could be matched by allowable thresholds for the spatial match.

Table 25. Number of Dates with At Least One Matched Work Order.

Maximum Threshold Allowed for Match	Number of Dates with State-Force WO	Number of Dates with Contractor WO	Total Number of Dates with WO
1 mi	1,204	8,310	**9,514**
5 mi	1,501	8,314	**9,815**

Next, the research team matched the dates with WOs to sites on a monthly basis. In total, 1,155 site-months were successfully matched using a threshold of 1 mi, and 1,163 were successfully matched using a threshold of 5 mi. Table 26 and Table 27 summarize the average number of monthly visits by type of facility and by the spatial match thresholds under consideration.

Table 26. Average Number of Visits per Month (1-mi Matches).

Reduced Class	AUS	BRY	DAL	ELP	FTW	HOU	SAT
Rural Freeway	14.1	2.7	11.7	6.4	N.A.	3.9	2.0
Rural Other Hwy	6.4	1.1	1.6	5.6	3.8	N.A.	5.4
Urban Freeway	9.3	6.0	12.1	9.1	8.0	9.7	13.0
Urban Other Hwy	11.1	1.2	1.0	7.0	1.6	2.8	15.0

Note: N.A. = Not Available.

For the most part, the estimates in Table 26 and Table 27 are very comparable. An important difference is that when matching by 1-mi threshold, no data are available for "Rural Freeways" in Fort Worth and for "Other Rural Highways" in Houston. By increasing the threshold to 5 miles, it is possible to obtain estimates for Houston but not for Fort Worth.

Table 27. Average Number of Visits per Month (5-mi Matches).

Reduced Class	AUS	BRY	DAL	ELP	FTW	HOU	SAT
Rural Freeway	14.1	2.6	11.9	6.4	N.A.	3.9	3.0
Rural Other Hwy	6.4	1.1	5.3	5.6	4.0	5.0	5.4
Urban Freeway	11.5	6.0	12.1	10.0	9.0	9.7	12.3
Urban Other Hwy	11.1	1.2	1.0	7.0	1.6	2.8	15.0

Note: N.A. = Not Available.

In total, the research team performed 83 field visits conducted at 74 sampled sites. In order to preserve the quality and resolution of the WO data, the following four-tier scheme was developed to assign estimates of monthly visits to each field visit:

1. For sites where abundant WO data were available, the research team computed the average frequency of monthly removal using a 1-mi threshold and only WO data within two months of the date of the field visit. Monthly visit estimates were obtained in this manner for a total of 37 out of the 83 field visits (i.e., including a visit for each of 74 total sites in the sample and second visits for a subset of nine sites). These estimates are considered the most robust within the probability sample of sites.
2. For sites where no WO data were available within two months of the field visit but with sufficient WO data at other time periods, the research team estimated the monthly removal frequency as the grand average of the number of dates per month that could be matched to that site using a threshold of 1 mi. In this fashion, estimates of the monthly removal frequency were obtained for additional 32 field visits, including eight out of the nine sites with two field visits.
3. For sites where the previous steps could not be implemented due to lack of WO data, the research team repeated Step 2 after relaxing the spatial match to a 5-mi threshold. Estimates for the monthly removal frequency were found for only two additional sites in this fashion.
4. The previous three steps yielded estimates for 71 field visits at 63 sites, out of a total of 83 field visits performed at 74 sites. The research team applied mean imputation to attempt to obtain estimates for the monthly removal frequency at the remaining 12 field visits. The imputed values were the average of monthly removal frequency at the closest facility of the same class. In nine of those 12 cases, the estimate came from similar facilities within the same district.

A preliminary analysis of the potential bias induced by the imputed values revealed important shifts in the estimates of various variables and a reduced precision of the test variables. Similar issues with classic imputation methods have been consistently documented in the statistical literature (van Buuren, 2012). Therefore, the research team determined to exclude the sites with imputed values from further analysis.

Using the sampling weights, the research team computed statewide estimates of the removal frequency on typical segments of Texas highways, as shown in Table 28.

Table 28. Average Removal Frequency at Texas Highways (Monthly Visits per Site).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	6.37	1.00	3.35	1.62	4.86	1.70	1.53	8.19
RURAL MINOR ARTERIAL	1.97	0.02	1.33	0.11	1.65	0.11	1.44	1.86
RURAL PRIN ARTERIAL	3.26	0.13	3.35	N.A.	3.26	0.13	3.01	3.52
URBAN FREEWAY	8.85	0.17	7.18	N.A.	8.85	0.17	8.53	9.18
URBAN MINOR ARTERIAL	2.46	0.02	1.95	0.38	2.21	0.38	1.47	2.95
URBAN PRIN ARTERIAL	7.77	0.04	4.20	1.39	5.98	1.38	3.28	8.69
ALL HIGHWAYS	**4.68**	**0.35**	**2.77**	**N.A.**	**4.68**	**0.35**	**3.98**	**5.37**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

The average debris removal frequency per Texas highway site was estimated to range between 3.98 and 5.37 visits per month. Interestingly, there was suggestive evidence of a higher debris removal frequency at urban freeways (average of 8.85 visits per month) than at rural freeways (average of 4.86 visits per month). This evidence is suggestive because the CIs for both estimates do not overlap (from 1.53 to 8.19 visits per month for rural freeways and between 8.53 and 9.18 visits per month for urban freeways). In fact, the CI for number of monthly visits at urban freeways only overlap (very marginally) with the CI for urban principal arterials. The following section details the calculation of TD generation rates using the estimates described in this section in conjunction with the data acquired during the field visits.

ESTIMATION OF TD GENERATION RATES

This section provides a theoretical framework to combine and analyze the field data and the debris removal frequency data to obtain statistical estimates of TD generation rates on Texas highways. In its simplest form, the TD generation rate has units of quantity of debris per unit of time. Generation rates can incorporate multiple measures of exposure (i.e., in the denominator), such as mileage or AADT. In any case, estimates of TD quantity from the field data provide a measure of the typical accumulation of TD between debris removal cycles. The next section describes a theoretical context in which TD generation rates are obtained from the observed quantity of TD combined with the additional debris removal rates estimates obtained using the WO data from the TxDOT Maintenance Division.

Queue Theory Framework

Queue theory is a branch of statistics that deals with stochastic processes where entities arrive and are processed randomly at a system providing a service. In its more general form, both the arrival rate and the service time of the entities may follow different probability distributions. Arrival and service rates may vary in relative independence, and as a result, a queue of entities waiting for service builds up and discharges cyclically over time. In this context, the observed quantities of TD from the field visits can be thought of as the queue of TD that is accumulating on the roads waiting to be served (i.e., to be removed).

Formulas are available for the average queue length as a function of the rates of arrival and the rate of service for a queue system. Among various alternatives, Little's Theorem is the most useful formulation for this research. Little (1961) showed that, regardless of the arrival and service rates distributions, the queue length relates to the rate of arrivals through the average waiting time of the entities in the queue. Equation 11 shows this fundamental relationship:

$$\boldsymbol{Q = \lambda \cdot W}$$

Equation 11

Where,

Q	=	Average queue length (number of entities).
λ	=	Rate of arrivals (entities per unit of time).
W	=	Average waiting time per entity in the queue (time).

It is clear from Equation 11 that if two of the involved quantities are known, the third can be determined. Site-specific estimates for W, such as the ones obtained in the previous section, can be combined with site-specific estimates for Q, obtained from the image analysis of field photographic data, to produce estimates for λ for each visited site.

Debris Generation Rates

The average waiting time for TD to be cleaned is simply half the average interval between visits in a month, assuming that all TD was cleaned from a site after a debris WO occurred (most likely along with other types of debris present at the time).

Table 29. TD Generation Rates on Texas Highways (Weekly TD Pieces per Mile).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	20.43	3.42	13.11	4.28	16.77	4.82	7.32	26.22
RURAL MINOR ARTERIAL	1.60	0.02	1.00	N.A.	1.60	0.02	1.56	1.64
RURAL PRIN ARTERIAL	9.43	0.53	6.73	2.35	8.08	2.29	3.59	12.56
URBAN FREEWAY	30.02	0.43	30.93	4.63	30.48	4.55	21.57	39.39
URBAN MINOR ARTERIAL	1.05	0.01	0.82	0.09	0.93	0.09	0.77	1.10
URBAN PRIN ARTERIAL	5.09	0.02	3.78	1.64	4.44	1.64	1.22	7.65
ALL HIGHWAYS	**13.20**	**1.04**	**8.24**	**2.32**	**10.72**	**2.31**	**6.19**	**15.26**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

First, the research team constructed sampling estimates for TD generation rates and other derivative metrics, similar to those in Table 15 through Table 22. Estimates for λ were obtained for each site. Combining these estimates with the sampling weights, statewide averages for TD generation rates and estimates by facility type were obtained, as shown in Table 29. The Texas-wide average rate of TD generation could be any value between 6.19 and 15.26 pieces of TD per week per mile. Table 30 shows generation rate estimates in terms of weekly lb of TD per mile. It was found that between 10.27 and 13.94 lb/week/mi of TD generate on average in Texas highways.

Table 30. TD Generation Rates at Texas Highways (Weekly lb per Mile).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	17.45	3.41	11.18	3.38	14.32	4.22	6.06	22.58
RURAL MINOR ARTERIAL	1.95	0.03	1.24	N.A.	1.95	0.03	1.89	2.00
RURAL PRIN ARTERIAL	9.88	0.61	7.32	1.09	8.60	1.12	6.40	10.80
URBAN FREEWAY	25.34	0.29	26.76	N.A.	25.34	0.29	24.78	25.90
URBAN MINOR ARTERIAL	0.92	0.01	0.69	0.07	0.80	0.07	0.67	0.93
URBAN PRIN ARTERIAL	6.14	0.03	4.03	1.67	5.09	1.67	1.82	8.36
ALL HIGHWAYS	**12.11**	**0.94**	**7.59**	**N.A.**	**12.11**	**0.94**	**10.27**	**13.94**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

Table 31. Large TD Generation Rates on Texas Highways (Weekly Pieces per Mile).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	3.87	0.66	2.24	0.82	3.05	0.93	1.23	4.87
RURAL MINOR ARTERIAL	0.44	0.01	0.28	N.A.	0.44	0.01	0.43	0.45
RURAL PRIN ARTERIAL	2.41	0.18	1.57	0.25	1.99	0.27	1.45	2.52
URBAN FREEWAY	5.36	0.06	5.19	N.A.	5.36	0.06	5.25	5.48
URBAN MINOR ARTERIAL	0.17	0.00	0.12	0.01	0.14	0.01	0.13	0.16
URBAN PRIN ARTERIAL	0.77	0.00	0.85	0.51	0.81	0.51	-0.19	1.81
ALL HIGHWAYS	**2.71**	**0.25**	**1.52**	**N.A.**	**2.71**	**0.25**	**2.23**	**3.20**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

Table 31 shows generation rates for pieces of large TD (64 in.^{2} or bigger). On average, 2.71 large TD pieces/mile/week (95 percent CI of 2.23 to 3.20) are generated on Texas highways.

Table 32 shows the generation rates of large TD in lb per week per mile. Researchers estimated that, on average, 6.01 lb of large TD per week per mile (95 percent CI from 4.95 to 7.07 lb per week per mile) are generated on Texas highways.

Table 32. Large TD Generation Rates on Texas Highways (Weekly lb per Mile).

FUNC CLASS	HT Estimate	HT SE	Ratio Estimate	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	7.94	1.27	4.53	1.96	6.24	2.07	2.18	10.30
RURAL MINOR ARTERIAL	1.13	0.02	0.72	N.A.	1.13	0.02	1.09	1.16
RURAL PRIN ARTERIAL	5.54	0.41	3.98	0.20	4.76	0.41	3.96	5.57
URBAN FREEWAY	12.02	0.13	12.34	N.A.	12.02	0.13	11.77	12.27
URBAN MINOR ARTERIAL	0.45	0.00	0.33	0.02	0.39	0.02	0.34	0.44
URBAN PRIN ARTERIAL	1.36	0.00	1.56	0.98	1.46	0.98	-0.45	3.38
ALL HIGHWAYS	**6.01**	**0.54**	**3.64**	**N.A.**	**6.01**	**0.54**	**4.95**	**7.07**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

Total Quantity of TD Generated in a Year

Using the generation rates presented in the previous section, yearly totals can be estimated for the quantity of TD in Texas highways. The estimates presented in this section are contingent to the year-round representativeness of the generation rates. Later in this chapter, an estimation of the seasonality in TD quantities is presented in order to better assess the expected fluctuation of TD generation rates and its impact on the total estimates presented in this section.

Table 33 shows yearly total estimates in thousands of TD pieces. Researchers estimated that 16.90 million pieces of TD were deposited during 2015 on Texas highways. The precision of this estimate was somehow limited (SE of 6.40 million pieces of TD), a circumstance that results in a wide CI for the estimate of the total yearly amount of TD (the true total could be anywhere between 4,349,900 and 29,446,100 pieces of TD in a year). However, the estimates for freeway facilities are more accurate. This research estimates that between 2.82 and 5.92 million pieces of TD were generated on urban freeways during the last year, while between 1.96 and 4.55 million pieces of TD were produced on rural freeways. Table 34 shows statewide TD totals in metric tons by facility type.

Table 33. Yearly Total TD Generated on Texas Highways (Thousands of Pieces).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	5,039.1	445.2	1,471.2	602.7	3,255.1	661.8	1,958.1	4,552.2
RURAL MINOR ARTERIAL	204.6	68.8	626.2	56.2	415.4	78.2	262.2	568.7
RURAL PRIN ARTERIAL	1,743.0	873.5	1,505.8	774.4	1,624.4	1,025.3	-385.2	3,634.0
URBAN FREEWAY	3,758.9	713.1	4,974.3	543.7	4,366.6	791.0	2,816.3	5,916.9
URBAN MINOR ARTERIAL	37.5	17.0	755.7	224.2	396.6	221.0	-36.5	829.6
URBAN PRIN ARTERIAL	116.1	65.1	2,076.5	846.9	1,096.3	834.3	-538.9	2,731.5
ALL HIGHWAYS	**10,899.2**	**4,081.7**	**22,896.8**	**5,960.3**	**16,898.0**	**6,402.2**	**4,349.9**	**29,446.1**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

Table 34. Yearly Total TD Generated in Texas Highways (Metric Tons).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	1,907.4	179.4	552.3	207.8	1,229.8	241.2	757.0	1,702.6
RURAL MINOR ARTERIAL	118.2	50.6	365.1	31.3	241.7	53.0	137.8	345.5
RURAL PRIN ARTERIAL	653.5	288.1	610.6	206.1	632.1	313.2	18.1	1,246.0
URBAN FREEWAY	1,549.1	251.3	2,040.3	N.A.	1,549.1	251.3	1,056.5	2,041.7
URBAN MINOR ARTERIAL	15.2	4.9	289.8	54.3	152.5	53.3	48.0	257.1
URBAN PRIN ARTERIAL	64.2	41.7	1,014.4	412.0	539.3	404.4	-253.4	1,331.9
ALL HIGHWAYS	**4,307.6**	**1,489.0**	**9,447.6**	**N.A.**	**4,307.6**	**1,489.0**	**1,389.2**	**7,226.1**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

Researchers estimated that between 1,389.2 and 7,226.1 metric tons of TD were deposited on Texas highways last year. Between 757.0 and 1,702.6 metric tons were deposited on rural freeways, while between 1056.5 and 2,041.7 metric tons of TD were deposited on urban freeways.

Table 35 shows statewide totals of pieces of large TD deposited by facility type last year. Researchers estimated that between 743,360 and 3,616,270 pieces of large TD were deposited on Texas highways. This research estimated that between 353,860 and 866,790 pieces of large TD were generated yearly on rural freeways, while between 473,630 and 981,700 pieces of large TD were produced on urban freeways.

Table 35. Yearly Total Large TD on Texas Highways (Thousands of Pieces).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	966.09	89.57	254.56	118.21	610.32	130.85	353.86	866.79
RURAL MINOR ARTERIAL	57.48	23.88	182.70	23.14	120.09	29.18	62.90	177.28
RURAL PRIN ARTERIAL	270.56	112.96	236.29	83.61	253.42	124.12	10.16	496.69
URBAN FREEWAY	727.67	129.61	874.21	N.A.	727.67	129.61	473.63	981.70
URBAN MINOR ARTERIAL	6.21	2.05	119.78	29.68	62.99	29.27	5.62	120.36
URBAN PRIN ARTERIAL	16.81	7.51	453.04	259.87	234.93	258.24	-271.22	741.08
ALL HIGHWAYS	**2,044.82**	**801.78**	**4,041.05**	**N.A.**	**2,044.82**	**801.78**	**473.36**	**3,616.27**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

As shown in Table 36, between 501.4 and 3,546.2 metric tons of large TD were left on Texas highways last year. This table shows that between 315.8 and 829.0 metric tons of large TD were deposited on rural freeways, while between 508.1 and 987.9 metric tons of large TD were deposited on urban freeways during last year.

Table 36. Yearly Total Large TD Generated on Texas Highways (Metric Tons).

FUNC CLASS	HT Est.	HT SE	Ratio Est.	Rt. Est. SE	Adjusted Estimate	Adj. Est. SE	95% CI Min	95% CI Max
RURAL FREEWAY	910.9	84.6	233.8	121.3	572.4	130.9	315.8	829.0
RURAL MINOR ARTERIAL	68.4	31.3	212.6	18.4	140.5	32.4	77.0	204.0
RURAL PRIN ARTERIAL	275.7	108.5	267.4	57.1	271.6	110.4	55.2	488.0
URBAN FREEWAY	748.0	122.4	948.4	N.A.	748.0	122.4	508.1	987.9
URBAN MINOR ARTERIAL	7.6	2.3	143.9	31.1	75.8	30.7	15.7	135.9
URBAN PRIN ARTERIAL	13.3	5.9	377.5	226.0	195.4	224.7	-245.0	635.8
ALL HIGHWAYS	**2,023.8**	**776.8**	**4,349.9**	**N.A.**	**2,023.8**	**776.8**	**501.4**	**3,546.2**

Note: N.A. = Not Available; TD_t^* was used as the ancillary variable to develop ratio estimates.

ESTIMATION OF SEASONAL VARIABILITY OF TD OCCURRENCE

As mentioned earlier, the research team selected a subsample of nine sites (seven from the Bryan District and two from the Houston District) to be visited twice for field data collection. The purpose of this second excursion was to quantify the seasonality of TD occurrence because the statewide interviews with TxDOT districts strongly suggested variability of TD quantities throughout the year. Combined, these nine sites amounted to 191.74 lane-miles of road (111.82 freeway lane-miles and 79.92 lane-miles on other highways). The corresponding centerline mileage was 50.61 miles.

Unfortunately, one of the two sites in the Houston District could not be matched with any WO data, so it could not be further analyzed. After removing the site with incomplete data, the subsample reduced to 122.40, with a total of 42.81 centerline miles. For this reduced subset, the dates when the first visit occurred ranged from July 23, 2015, to August 18, 2015, while the dates for the second visit ranged from November 10, 2015, to November 23, 2015.

While it was known that all sites in Bryan would be visited a second time, only three sites in Houston, weighed by proximity to College Station, were candidates for second visits. The sampling weights were adjusted to reflect this additional stage of sampling for second visits so that the estimates are still representative of the general conditions on Texas highways.

Using the data from the two visits at the subsample of sites, the research team computed metrics to assess the seasonal variation of TD. The estimates presented in this section are representative of the change of TD metrics between the summer and fall seasons.

Table 37 shows estimates of the change going from summer to fall in total amounts of TD. This table indicates that the total weight of all TD pieces generated weekly decreased about 15.8 metric tons on all Texas highways. In comparison, the yearly average week is estimated to have 82.8 metric tons generated, per Table 34 (82.8=4307.6/52). Both the count and weight of large TD was also found to decrease in a typical fall week compared to a week during the summer (7.2 thousand fewer pieces, and 10.0 fewer metric tons, respectively). Unfortunately, the four estimates in Table 37 are rather imprecise; all four 95 percent CIs range from negative to positive numbers.

Table 37. Summer-to-Fall Change in Total TD Generated Weekly (All Highways).

Total Quantity	HT Est.	HT Est. SE	Ratio Est.	Rt. Est. SE	Adj. Est.	Adj. Est. SE	95% CI Min	95% CI Max
Total TD (thousands of pieces)	4.7	13.7	1.8	32.8	3.2	32.5	−60.5	66.9
Total TD (metric tons)	−5.5	3.4	−26.1	11.4	−15.8	11.1	−37.6	6.0
Total Large TD (thousands of pieces)	−2.7	2.0	−11.8	6.3	−7.2	6.2	−19.3	4.9
Total Large TD (metric tons)	−3.7	1.9	−16.4	6.8	−10.0	6.7	−23.1	3.0

Note: TD_t^* was used as the ancillary variable to develop ratio estimates.

Table 38 shows the estimates of seasonal change in key average quantities. Bold type was used for estimates whose CIs did not contain zero and demonstrated with convincing statistical evidence that a seasonal change was identified in those quantities.

Table 38. Summer-to-Fall Change in Average Metrics of TD (All Highways).

Average Quantity	HT Est.	HT Est. SE	Ratio Est.	Rt. Est. SE	Adj. Est.	Adj. Est. SE	95% CI Min	95% CI Max
Observable TD (lb/mi)	−9.79	1.01	−7.11	N.A.	–9.79	1.01	**–11.77**	**–7.82**
Observable Large TD (lb/mi)	–6.67	0.64	–4.58	N.A.	–6.67	0.64	**–7.94**	**–5.41**
Number of Debris removal (visits/month)	–1.27	0.13	–1.44	0.36	–1.36	0.35	**–2.05**	**–0.67**
TD Generation Rate (pieces /mi/week)	0.60	0.32	0.22	0.78	0.41	0.77	–1.10	1.91
TD Generation Rate (lb/mi/week)	–2.24	0.20	–1.83	0.55	–2.03	0.54	**–3.08**	**–0.98**
Large TD Generation Rate (pieces /mi/week)	–0.47	0.05	–0.32	0.15	–0.40	0.14	**–0.68**	**–0.12**
Large TD Generation Rate (lb/mi/week)	–1.45	0.12	–1.13	0.34	–1.29	0.33	**–1.94**	**–0.64**

Note: TD_t^* was used as the ancillary variable to develop ratio estimates.

Except for the average number of TD per mile per week, all metrics in Table 38 have 95 percent CIs containing only negative values, which indicates a decrease of those quantities in the fall season, compared to the summer season.

Researchers estimated that debris removal frequency decreased during the fall by 1.36 visits/month. Researchers also estimated that the actual statewide change in monthly debris removal frequency could be as small as 0.67 fewer visits/month or as big as 2.05 fewer visits/month. In terms of quantity of TD per mile, this research found that between 0.98 and 3.08 fewer pounds of TD per mile are generated during a typical fall week compared to a typical summer week. A typical fall week was also found to have between 0.64 and 1.94 fewer pounds of large TD generated per mile compared to a typical summer week. More importantly, the amount of observable TD and large TD is significantly reduced during the fall than during the summer (between 7.82 and 11.77 fewer pounds of TD and between 5.41 and 7.94 fewer pounds of large TD), a reduction that coincides with a decrease in the odds of TD crashes during the fall, compared to the summer months (Figure 58).

COST OF TD FOUND IN TEXAS HIGHWAYS

Based on findings of this research, this section estimates the cost of TD removal and disposal in 2015. These calculations are based on conservative assumptions, making the resulting estimates conservative estimates of the actual costs.

Total Amount of TD Generated in Texas

The 2010 audit by TCEQ (2010) states that 26.0 million STUs were discarded in 2009. The estimate available from the previous year was 24 million. The research team obtained additional data from the TCEQ 2014 Scrap Tire Annual Report (TCEQ, 2015). From that report, the yearly scrap tire quantities were obtained for the 2012–2014 period, as shown in Table 39. Estimates for years 2007 and 2009 were obtained from two TCEQ audits prepared for the Texas Congress.

Table 39. Yearly Scrap Tire Disposed in Texas (Millions of STU*).

Category	2007	2009	2012	2013	2014	2015
Land Reclamation	11.6	5.0	4.2	1.7	3.1	N.A.
Tire-Derived Fuel	10.6	8.3	14.7	11.2	13.6	N.A.
Crumb Rubber	2.5	1.5	1.5	4.8	4.6	N.A.
Rubber Mulch	0.4	N.A.	N.A.	N.A.	N.A.	N.A.
Septic/Leachate Drainage	0.3	2.9	N.A.	N.A.	N.A.	N.A.
Other End Uses	1.1	1.3	N.A.	N.A.	N.A.	N.A.
Beneficial Uses	N.A.	N.A.	3.4	1.1	1.8	N.A.
End Uses Subtotal	**26.5**	**19.1**	**23.8**	**18.9**	**23.1**	**20.7****
Landfill Disposal	5.6	7.0	3.8	3.5	3.4	2.8***
Total	**32.1**	**26.1**	**27.7**	**22.4**	**26.5**	**23.6****

Note: N.A. = Not Available; STU = scrap tire unit.
* 1 STU = 20 lb of scrap tire material. This unit was used because scrap tire material can take many different forms.
** Data not available from TCEQ yet. These are linear projections for 2015 using data available from previous years.
*** The projected landfill quantity was estimated as the difference between the projected total and end uses subtotal.

Although mild, there was a downward trend in the amount of tire material shown in Table 39. Less scrap tires are being generated in Texas every year, as shown in Figure 73. Although this figure shows continuous lines, those lines are based on yearly totals. This figure also shows an increasing trend in the proportion of scrap tires that was repurposed every year.

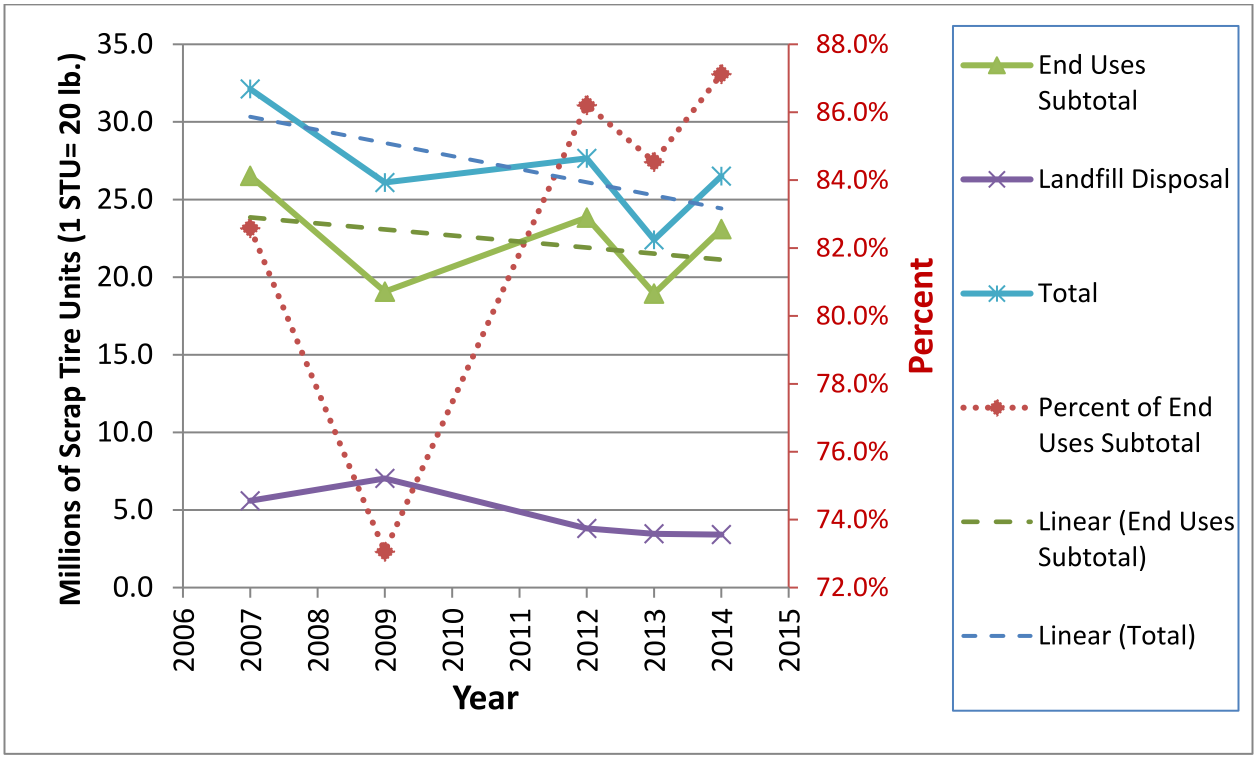


Figure 73. District Debris Removal Work Trends.

The total projected quantity of scrap tires for 2015 is equivalent to 214,096 metric tons. Similarly, the equivalent projected amount of scrap tires that ended up in landfills was 25,401 metric tons. In comparison, Table 34 shows that only about 4,307.6 metric tons of TD were generated on Texas roads in the same year.

Considering Table 34 and Table 39, jointly, TD represents between 0.6 percent and 3.4 percent of the total amount of scrap tires that are either repurposed or disposed of during a year in Texas. If all the TD generated in Texas highways in 2015 ended in landfills, then TD would represent between 5.5 percent and 28.4 percent of scrap tires that ended up in landfills.

Cost of TD to TxDOT

Two components of the cost are considered in this estimation: costs of debris removal activities and costs of final disposal.

Cost of Removal Activities

From the cost data received from TxDOT Maintenance Division, the cost of state-force-driven debris removal activities in TxDOT districts amounted to $13,757,155 during FY 2014 (i.e., from September 2013 to August 2014). The cost of debris removal work by contractors during the same period amounted to $5,201,867. In total, the statewide cost of debris removal was $18,968,021 during FY 2014. However, this cost does not distinguish between TD and other types of debris. From the survey of districts, 10 out of 12 interviewees estimated that TD represents about 53 percent of the total amount of debris they clean up from Texas highways. By allocating to TD the cost corresponding to that proportion of road debris, the research team estimated that it costs TxDOT $10,053,051 to clean up TD from Texas highways.

The research team projected the total amount of TD generated in 2014 from the 2015 data collected from field visits (see Table 34). From this exercise, about 5,385 metric tons of TD were generated in 2013 and about 5,231 metric tons in 2014. These estimates rely on the assumption that a significant proportion of generated TD goes into landfills each year; so, the yearly fluctuation in landfill quantities is reflective of the yearly fluctuations in generated TD. The research team implemented this assumption because TD is made up of irregular pieces containing significant amounts of metal, making them potentially difficult to process for other purposes. TD would represent a significant proportion of scrap tire material that ends in landfills, per Table 39.

Using the projections from 2013 and 2014, the research team estimated that there were 5,282 metric tons of TD generated on Texas highways during FY 2014. The researchers then estimated that the cost rate of removing TD from Texas highways was $1,903 per metric ton. This rate was equivalent to $17.3 per STU or $0.86 per pound of TD.

Disposal Fee

The average disposal fee under the Waste Tire Recycling Fund was $2 per tire (TCEQ, 2015; Crain Communication Inc., 2016). That program ended in 1997, but the fee has not changed much since then. On its website, the City of Waco (2016) lists 2016 fees of $2.50 or $5.00 per tire, depending on tire size. Assuming an average fee of $3.00 and transforming TD to STUs, it can be estimated that $1,746,209 were paid in disposal fees during FY 2014. The proportion of that cost that corresponds to contract work should have been already passed to

TxDOT by its contractors as cost of collection and disposal together. However, the proportion of that cost that corresponds to state-work miles driven (87.5 percent) must still be borne by TxDOT. Therefore, this research estimates that the additional quantity paid in disposal fees for the TD collected by state forces amounted to $1,527,933 in FY 2014. This amount disregards any third parties collecting additional fees from TxDOT when collecting, transporting, and disposing TD from district facilities.

Aggregated Cost of TD Removal and Disposal

When incorporating disposal fees, the cost rates for TD presented above increased to $2,192.6/metric-ton, $19.9/ STU, or $0.99/lb. This analysis estimates that TD collection and disposal cost TxDOT $11,580,984 in FY 2014.

Cost of TD to the General Public

It was expected that the costs associated with safety offset other operational costs of TD. Previous research has found that the safety aspect tends to dominate the costs of economic analyses of surface transportation studies (Fitzpatrick et al., 2015). Therefore, an economic assessment of TD crashes is presented in this section in order to estimate the cost to the general public.

The research team used the factors and methodology presented in a memorandum from the United States Department of Transportation (USDOT) about the value of a statistical life (VSL) (Thomson, 2016). As of June 2015, VSL was $9.4 million. In this methodology, factors to convert crashes to dollar amounts are given by injury levels. Table 40 shows adjusted factors developed by the research team from the recommended USDOT values (as of June 17, 2015.). These adjusted factors were developed to coincide with the KABCO scale from the National Safety Council because this scale corresponds to the severity levels in CRIS, whereas the USDOT values correspond to the Maximum Abbreviated Injury Scale (MAIS) of the Association for the Advancement of Automotive Medicine.

Table 40. Conversion Factors from VSL to Severity Levels.

Severity	MAIS Level	(Severity Level)/VSL
K	Unsurvivable	1.000
A	Critical and Severe	0.495*
B	Serious	0.105
C	Moderate and Minor	0.016*

* These values result from a weighted average of two MAIS severity levels. In both cases, a weight of 0.7 was applied to the lower severity and 0.3 to the higher severity.

The methodology uses 2013 as the base year and requires adjustments based on the consumer price index and real earnings values from the Bureau of Labor Statistics (2016). Table 41 shows the values corresponding to 2013 through 2015.

Table 41. Indices to Transform 2013 Dollars to 2015.

Index	2012	2013	2014	2015
Consumer Price Index	229.594	232.957	236.736	237.017
Real Weekly Earnings	$352.30	$356.23	$359.38	$363.85

The calculation was performed as follows:

1. The corresponding factors in Table 40 and Table 41 were applied to the fatalities and injuries reported for the 251 TD crashes identified for this research.
2. The aggregated annual cost was calculated for each year in the safety assessment (2012 to 2014).
3. A formula to estimate the baseline cost in 2015 was obtained by lineally regressing the non-fatality costs from 2012 through 2014 on the number of crashes.
4. Three estimates for 2015 were developed based on three different assumed total TD crashes for 2015.

Table 42 shows the crashes and severity outcomes for 2012 through 2014 and the 2015 projections. The cost of 2015 TD crashes cannot be determined exactly unless all TD crashes that occurred in 2015 are identified. Such identification would require repeating the examination of crash narratives as described in Chapter 5.

In lieu of such comprehensive procedure, the research team projected the number of TD crashes for 2015 based on a set of simple but realistic assumptions, as explained in the notes at the bottom of Table 42.

Cost of Non-fatal TD Crashes

As Table 42 shows, the cost of non-fatal TD crashes has been relatively stable and in clear decline since 2012. In that year, TD crashes cost the Texas public roughly $40 million. Even if the number of TD crashes did not increase in 2015, compared to 2014, it was projected that TD crashes cost the Texas public $32.8 million, accounting only for the general trend of reduced total cost in the last three years (i.e., Scenario A). If, on the other hand, the number of non-fatal TD crashes in 2015 was estimated from the three-year trend from 2012 to 2014, then it was expected that TD crashes cost the Texas public $39.3 million (Scenario B).

Table 42. Cost of TD Crashes in 2012–2014 and Cost Projections for 2015.

Year	Tot. Crashes	Fatal	Incap. Inj.	Non-Incap. Inj.	Posbl. Inj.	Total Inj.	Cost Non-fatal Crashes	Total Cost (including fatalities)
2012	93	3	4	20	18	42	$40,020,029.57	$67,506,313.61
2013	89	0	4	20	29	53	$42,713,600.00	$42,713,600.00
2014	69	0	4	14	17	35	$35,868,744.57	$35,868,744.57
Totals	**251**	**3**	12	54	64	130	**2015 Projections**	
2015[a]	69	0	-	-	-	-	$32,797,598.60[a]	$32,797,598.60[a]
2015[b]	82.7	0	-	-	-	-	$39,331,120.29[b]	$39,331,120.29[b]
2015[c]	82.7	1	-	-	-	-	$39,331,120.29[c]	$49,099,521.16[c]

[a] Projected costs in 2015 assuming the same number of crashes that happened in 2014, and adjusting for the linear trend observed in the cost of non-fatal crashes from 2012 to 2014.
[b] Projected costs in 2015 assuming only non-fatal crashes occurred, projected linearly from crashes observed in the three previous years. This projection also includes an adjustment for the decreasing linear trend observed in the total cost of non-fatal crashes from 2012 to 2014.
[c] Projected costs in 2015 assuming one fatal crash occurred along with the same number of non-fatal crashes in Scenario B.

Cost of Fatal TD Crashes

As can be seen in Table 42, the cost of fatal crashes has a severe impact on the overall costs of TD crashes. If one assumes the same number of non-fatal TD crashes from Scenario B, but a single fatal TD crash also occurred in 2015, then the overall cost of TD crashes goes from $39.3 million to $49.1 million (Scenario C).

CONCLUSIONS

This research quantified the amounts, physical characteristics, safety impact, and costs of TD generated on Texas highways.

One activity of the project consisted of a statewide survey of TxDOT districts. This survey revealed that TD removal practice varies widely by district, depending on the size of the network they maintain. Additionally, this survey yielded a preliminary estimate of TD removal (weekly at high-volume roads, less frequently at lower functional classes).

Cost data were requested from TxDOT Maintenance Division. The research team received cost and WO data from FY 2013 and FY 2014. An analysis of these data revealed key differences between districts in their amount of work in debris removal activities and in the contract structures they have in place in order to meet their debris removal work needs. Houston, Dallas, and Fort Worth were found to have similar trends on their debris removal work and costs; Austin and San Antonio were also found to have similar trends, though significantly different from Houston and Dallas. Amarillo, Beaumont, Brownwood, Childress, Laredo, Lufkin, Odessa, Paris, San Angelo, and Waco have similar costs and contract structures to Austin and San Antonio. Other districts showed trends of varying cost; on the lower end, some costs were comparable to Austin and San Antonio ($5 to $10 per mile driven), while on the higher end, some districts' costs compared to Houston and Dallas ($15 to $20 per mile driven). In general, unit cost of removal was found to increase with an increasing proportion of the work done by contractors.

The research team collected field data from a probability sample of sites representing seven randomly selected TxDOT districts. Among other metrics, average amounts of observable TD, TD generation rates, and total yearly amounts of TD were estimated from these data in combination with additional data provided by TxDOT Maintenance Division. That additional data allowed the estimation of debris removal frequency at the probability sample sites. It was estimated that, on average, there were between 70.4 and 289.7 metric tons of TD on Texas roads at any point between July and November 2015. Between 40.3 and 112.8 of those metric tons were TD pieces larger than 64 in.^{2}. Using the same data, researchers estimated that urban freeways are visited between 8.53 and 9.18 times a month for debris removal. The average number of visits corresponding to rural freeways was found to be significantly smaller urban freeways (average of between 1.18 and 8.19 visits per month). This evaluation found that, overall, between 10.27 and 13.94 lb of TD per mile were generated on Texas highways every week. The amount of that TD generation that constitutes pieces larger than 64 in.^{2} was found to be, on average, between 4.95 and 7.07 lb per mile per week. This research found that between 1,389 and 7,226 metric tons of TD were generated on Texas highways during the last year. The total amount of pieces of TD larger than 64 in.^{2} generated during the last year was estimated at between 501 and 3,546 metric tons.

The research team used field data in combination with frequency-of-removal data to quantify the seasonality of TD occurrence in Texas highways. For this evaluation on the seasonal change of TD metrics, a subset of sites in the probability sample was visited at two points in time. The analysis of data representing the summer and fall seasons indicated that there was a reduction in TD generated in the fall (an average reduction of between 0.98 and 3.06 lb generated per mile per week); a reduction in large pieces of TD generated in the fall (average reduction of between 0.64 and 1.94 lb generated per mile per week); and fewer visits to clean road debris during the fall (average of between 0.67 and 2.05 fewer removal visits per month).

This research also performed a safety evaluation of TD. A clear, decreasing yearly trend in this type of crashes was found. Although it was found that very few crashes of this type occur on Texas highways each year, a statistical association was found between the chances of TD crash occurrence and four risk factors. This research found that the odds of TD crashes increase by a factor of 1.11 for each increase of 5 mph in the speed limit at rural facilities (statistically significant at a 0.05 significance level). By comparison, that increase was found to be only a factor of 1.07 at urban facilities (statistically insignificant at a 0.05 significance level). The safety evaluation found that the odds of TD crashes increase by a factor of 1.15 per each 5 percent increase in the proportion of trucks in the AADT (statistically significant at a 0.05 significance level). This evaluation also found that the odds of TD crashes increase by a factor of 1.14 for each additional lane of traffic, after controlling for other factors (statistically significant at a 0.05 significance level).

Finally, this research developed projections of the yearly costs of removing and disposing TD, as well as the yearly costs to society of TD crashes in Texas. This research estimated that the cost of TD removal and disposal for TxDOT was between $10.1 and $11.6 million in FY 2014, depending on what proportion of TD was assumed to have been disposed in landfills. The cost of TD crashes to the Texas public in 2014 was found to be $35.9 million. Projections for 2015 yielded estimates of total cost of TD crashes ranging from $32.8 million to $49.1 million, depending on how many fatal and non-fatal TD crashes are assumed in the calculation.

The following subsections offer an interpretation of several findings of this research, how they compare to other research, and some assessments of their general implications.

The Impact of Different TD Removal Practices

This research found that, although safety of TD is not a major safety concern (only 251 TD crashes were found statewide in Texas between 2012 and 2014), the likelihood of these crashes varies in accordance with removal activities. Considering the differences between urban and rural environments, Table 19 strongly suggests that TD was more likely to be found at rural facilities compared to urban. Notably, Table 29 shows that TD generation rates tend to be larger on urban than on rural freeways. Also notably, the estimates in Table 28 indicate that removal activities occur more often on urban freeways than on their rural counterparts. Interestingly (and probably as a result), the safety analysis found that crashes involving pre-existing TD are less likely on urban freeways (Table 13).

Considering all these pieces of information together, it can be concluded that the highest frequency of removal activities at urban facilities tends to result in fewer amounts of observable TD at these facilities, despite their higher TD generation rates. This research found that TD crashes are measurably less likely at urban facilities, precisely were removal activities occur more frequently, and TD was found in fewer quantities. Using the findings in Table 12, the odds of a TD crash occurring at a 45 mph rural facility are 1.42 times larger than at a 45 mph urban facility. At 75 mph facilities, that gap was notably increased: the odds of a TD crash occurring at a rural facility are 1.79 times larger than at an urban facility. Although the chances of having a TD crash are very small (i.e., less than 1 percent of all crashes are TD crashes), the costs of these crashes (Table 42) suggest that more aggressive removal programs very likely have a measurable safety benefit.

It also appears that there was a safety benefit associated with the practice of assigning contractors to clean facilities where most TD was generated. This research found a measurable improvement in safety outcomes of TD at urban facilities, and the survey of districts indicated that private contractors tend to perform most scheduled debris removal activities on urban freeways, though state personnel conduct unscheduled debris removal operations when needed (Chapter 3). However, an in-depth economic analysis is recommended since this research also found that the average cost of debris removal activities increases with increasing percentage of work performed by contractors (per Figure 16).

The facts that summer months are more prone to TD crashes (per Figure 58) and that there is a measurable increase of observable large TD during the summer (per Table 38) constitutes further evidence of a potential safety benefit to improving debris removal practices.

Comparison of Developed Metrics of TD to Other Studies

This section reviews the findings of this research in the light of previous works found in the literature.

Generation Rates

The Virginia Study (Department of State Police, Virginia, 2000) monitored 658 mi of interstate highways during an eight-week period. The researchers found a total of 127,522 lb of TD during that period. That quantity translates into a rate of 24 lb/mi/week. Comparably, this TxDOT research project estimated the generation rates for various types of facilities in Texas, including freeways. Interestingly, this research found that the average generation rate of TD in Texas freeways in 2015 was between 24.78 lb/mi/week and 25.90 lb/mi/week at freeways in urban environments; such weekly generation rate was smaller at rural freeways, where it could have been as little as 6.06 lb/mi/week or as big as 22.58 lb/mi/week (see Table 30). In addition, this study found, as expected, that the generation rates are significantly smaller at facilities of lower functional classes, per results in Table 29 and Table 30.

TD Characteristics

The FHWA (2012) guidelines for recycled materials state average loose densities of tire shreds ranging from 24 lb/ft^3 to 33 lb /ft^3 and from 40 lb/ft^3 to 52 lb /ft^3 after compaction. However, the TD samples collected during this project had significantly higher densities (ranging from 67.4 lb/ft^3 to 111.7 lb/ft^3). Part of the explanation for this disparity, the research team believes, is that the densities in the FHWA guidelines refer to rubber materials at a point where they are ready to be recycled. In contrast, steel and other heavy materials should still be present in most of the TD shreds collected in this study. When densities of the TD samples were measured for this research, no piece floated on water, a fact that confirms that the density of all pieces collected had densities larger than water (62.4 lb/ft^3).

The same FHWA publication provides generic information about the characteristics of TD. According to that report, the typical tire shred size (from both passenger cars and trucks) varies from 1 in. to 18 in.; most common particles are from 4 in. to 8 in. Corresponding very closely to that report, this research found the average piece of TD in Texas highways was between 23.3 and 68.8 in.^{2} (see Table 15). If one assumes that those numbers correspond to an average piece roughly shaped as a square, the average width should be between 4.83 in. and 8.29 in.

Yearly Amount of TD

From the 2009 survey of roadway litter in Texas (NuStats 2010), it can be estimated that tire parts represented about 5 percent of their annual estimates, or 55 million pieces of roadway litter a year. In comparison, this study found that between 0.8 and 21.9 million pieces of TD were generated in in Texas highways in 2015. Despite the possibility of this contrast indicating a reduction in TD, two significant differences between the studies make the comparison somehow confounding: (a) the NuStats study collected and classified all debris pieces within their study segments; and (b) that study does not state how much area beyond the outer shoulders was included in their sites. Conversely, this study focused only in TD in close proximity with the pavement, excluding wide grass medians and buffers beyond outer shoulders. Also, this study focused on bigger TD pieces, as only TD observable from a vehicle at highway speeds could be classified, in contrast with the NuStats study that collected every piece of debris found at its sites.

The 1999 Arizona study (Carey, 1999) reports a statewide generation rate of 25.3 weekly tons of TD in 7 out of 9 ADOT maintenance districts. At that rate, it can be projected that 1,861 metric tons of TD were generated in Arizona during 1998. In comparison, this study estimated that between 1,389.2 and 7,226.1 metric tons TD were generated in Texas highways in 2015 (per Table 34).

Safety of TD

The safety estimates from the 2014 study for AAA (Forbes and Robinson, 2014) are very comparable with the safety assessment in Chapter 5 of this report. In their investigation, Forbes and Robinson found that less than 1 percent of all crashes involved TD. By comparison, this research found that in the case of Texas, the proportion of this type of crash ranged from 0.01 percent to 0.17 percent (Figure 54). Forbes and Robinson also estimated that 68 percent of crashes with vehicle debris involved pre-existing debris on the road. In comparison, this research found that pre-existing TD was a precipitating factor in 53 percent of all crashes that involved TD. However, the AAA study did not further analyze their crash data. This TxDOT project found four factors associated with increased risk of TD crash occurrence: (a) rural facilities over urban facilities, (b) higher speed limits, (c) higher percentages of truck traffic, and (d) additional travel lanes.

RECOMMENDATIONS

The research team expects that the metrics developed in this research will fill an important gap of knowledge about the quantity and characteristics of TD generated on Texas highways. The research team recommends that agencies and subcontractors responsible for debris removal use these metrics to improve the planning of their maintenance activities and to better anticipate resource needs. One example of such recommended implementation would be developing a smart spreadsheet based on the information in this research that, in combination with jurisdiction-specific road characteristics and other conditions, would allow agencies and contractors to explore various scenarios of interest and perform economic analyses.

One scenario of potential interest would be using the metrics in this research to evaluate the expected impact of varying debris removal rates, for example, by changing the contracting structure of debris removal. Another scenario of potential interest would be performing economic evaluations of various management strategies. In that regard, a jurisdiction may use the metrics in this report to evaluate the economic feasibility of acquiring specialized equipment, such as the Gator Getter™, considering the extent of jurisdiction's road network, the amount and characteristics of TD expected through the year, and the anticipated performance improvement and other benefits to the public.

REFERENCES

Andres, D. (1993). Synthesis of Highway Practice 184: Disposal of Roadside Litter. Washington, DC: Transportation Research Board.

Bareket, Z., Blower, D., and MacAdam, C. (2000). Blowout Resistant Tire Study for Commercial Highway Vehicles. Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Bureau of Labor Statistics. (2016, May 12). Latest Numbers. Retrieved from http://www.bls.gov. Accessed March 10, 2015.

Caltrans. (2015). Division of Research and Innovation: Automated Litter Bag/Debris Collection Vehicle. Retrieved from http://www.dot.ca.gov/newtech/researchreports/reports/2012/final_report_task_1103.pdf. Accessed May 30, 2016.

Carey, J. (1999). Survey of Tire Debris on Metropolitan Phoenix Highways. Phoenix, AZ: Arizona Department of Transportation.

The City of Waco Texas. (2016, May 9). Public Works—Solid Waste and Recycling Services. Retrieved from http://www.waco-texas.com/cms-solidwaste/page.aspx?id=256. Accessed March 10, 2015.

Conroy-Ben, O. and Christensen, T. (2013). Reducing Highway Litter. Salt Lake City, UT: Utah DOT.

Crain Communication Inc. (2016, May 16). Texas Scrap Tire Program Dies: Dealers Urged to Still Collect Fees. Retrieved from http://www.tirebusiness.com/article/19980119/NEWS/301199966/texas-scrap-tire-program-dies-dealers-urged-to-still-collect-fees. Accessed February 20, 2015.

Department of State Police, Virginia. (2000). Need for Standards for Recapped Tires. Retrieved from http://leg2.state.va.us/dls/h&sdocs.nsf/By+Year/HD242000/$file/HD24_2000.pdf. Accessed March 10, 2015.

EPA. (n.d.). Common Wastes and Materials—Scrap Tires. Retrieved from http://www.epa.gov/osw/conserve/materials/tires/basic.htm. Accessed February 20, 2015.

EPA. (1999). State Scrap Tire Programs. Washington, DC: EPA.

Federal Highway Administration. (2012). User Guidelines for Waste and Byproduct Materials in Pavement Construction. Washington, DC: FHWA.

Fitzpatrick, K., Brewer, M., Carlson, P., Iragavarapu, V., Pline, J., and Koonce, P. (2015). Potential MUTCD Criteria for Selecting the Type of Control for Unsignalized Intersections. Washington, DC: Transportation Research Board.

Florida Center for Solid and Hazardous Waste Management. (1998). The Florida Litter Study: 1998. Gainesville, FL: Florida Department of Environmental Protection.

Florida Department of Highway Safety and Motor Vehicles. (1996). Traffic Crash Facts 1996. Tallahassee, FL: Florida Department of Highway Safety and Motor Vehicles.

Forbes, G. (2009). NCHRP Synthesis 394: Reducing Litter on Roadsides. Washington, DC: Transportation Research Board.

Forbes, G., and Robinson, J. (2014). The Safety Impact of Vehicle Related Road Debris. Washington, DC: AAA Foundation for Traffic Safety.

Hargadon, A., Hoblit, B., and Olson, E. (2006). Automated Roadway Debris Vacuum (ARDVAC) Business Development Case Draft Report. Retrieved from http://ahmct.ucdavis.edu/pdf/ARDVAC_Final_Report_2006-06-11.pdf. Accessed March 18, 2015.

Kahl, K., and Fambro, D. (1995). Investigation of Object-Related Accidents Affecting Stopping Sight Distances. *Transportation Research Record*, Vol. 1500, pp. 25–30.

Keep America Beautiful Inc. (2013). About Us. Retrieved from http://www.kab.org. Accessed March 11, 2015.

Keep America Beautiful Inc. (2015). Keep America Beautiful Inc. 2003 Annual Review. Retrieved from https://www.kab.org/sites/default/files/KAB_2015_ANNUAL.pdf.Accessed May 30, 2016.

Lee, S., Lasky, T., and Velinsky, S. (2005). Mechanics and Robust Coordinated Control of the Automated Roadway Debris Vacuum Robotic Manipulator. *Mechanics Based Design of Structures and Machines: An International Journal*, Vol. 33, No. 1, pp. 119–145.

Lindquist, K., and Wendt, M. (2009). Retreaded Tire Use and Safety: Synthesis. Retrieved from http://www.wsdot.wa.gov/nr/rdonlyres/66366b14-f8b2-43a2-8495-16ce599469fa/0/retreadtiresynthesis9309.pdf. Accessed March 18, 2015.

Little, J. D. (1961). A Proof of the Queuing Formula L=λW. Operations Research, Vol 9, pp. 383–387.

Lohr, S. L. (1999). Sampling: Design and Analysis. Pacific Grove, CA: Duxbury Press.

Miami Dade. (2016, May 31). Disposal Facilities. Retrieved from http://www.miamidade.gov/solidwaste/disposal-facilities.asp. Accessed May 31, 2016.

Mid Atlantic Solid Waste Consultants. (2009). 2009 National Litter Survey and Litter Cost Study. Stamford, CT: Keep America Beautiful Inc.

NuStats. (2005). TxDOT 2005 Visible Litter Study. Austin, TX: Texas Department of Transportation.

NuStats. (2010). TxDOT 2009 Visible Litter Study. Austin, TX: Texas Department of Transportation.

Page, O., and Woodrooffe, J. (2009). Roadside Alligators and the UMTRI Tire Debris Survey. *Transportation Research Record*, Vol. 2096.

The R Development Core Team. (2013). R: A Language and Environment for Statistical Computing. Retrieved from http://www.R-project.org. Accessed April 2, 2015.

Ramsey, F., and Schafer, D. (2002). The Statistical Sleuth. Pacific Grove, CA: Duxbury.

Salem-Keizer Recycling and Transfer Station. (2016). Environmental Services. Retrieved from http://www.co.marion.or.us/PW/ES/disposal/Pages/2016-Rate-Increases.aspx. Accessed May 31, 2016.

Slepian, Z. (2012, November 13). The Average Projected Area Theorem—Generalization to Higher Dimensions. Retrieved from http://arxiv.org/pdf/1109.0595v4.pdf. Accessed April 2, 2015.

Strong, K., and Valdes-Vasques, R. (2014). CDOT Rapid Debris Removal Research Project. Denver, CO: Colorado DOT.

Texas Commission on Environmental Quality. (2010). Tracking the Fate of Scrap Tires in Texas: An Audit Report. Austin, TX: TCEQ.

Texas Commission on Environmental Quality. (2015). 2014 Scrap Tire Annual Report. Austin, TX: TCEQ.

Texas Department of Transportation. (2013). Pocket Facts. Retrieved from www.txdot.gov: http://ftp.dot.state.tx.us/pub/txdot-info/gpa/pocket_facts.pdf. Accessed August 25, 2015.

Texas Department of Transportation. (2014). Don’t Mess with Texas: Campaign Overview. Retrieved from http://www.dontmesswithtexas.org/the-campaign/. Accessed March 11, 2015.

Thomson, K. (2016, May 10). Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2015 Adjustment. Retrieved from https://cms.dot.gov/sites/dot.gov/files/docs/VSL2015_0.pdf. Accessed March 11, 2015.

Tillé, Y. and Matei, A. Sampling: Survey Sampling version 2.7. CRAN.R-project.org. [Online] 2015. http://CRAN.R-project.org/package=sampling. Accessed May 9, 2016.

Tire Disposal and Recycling Inc. (2006). Home. Retrieved from http://www.tiredisposal-recycling.com/DisplayPage.aspx?pageid=25. Accessed March 11, 2015.

TriLine Associates Inc. (1992). Highway Litter in Pennsylvania—1991. King of Prussia, PA: Pennsylvania Department of Transportation.

University of Michigan Transportation Research Institute. (2009). Roadside Alligators and Retread Tires. Ann Arbor, MI: UMTRI.

van Buuren, S. (2012). Flexible Imputation of Missing Data. Boca Raton, FL: CRC Press.

Venables, W. N., and Ripley, B. D. (2002). Modern Applied Statistics with S. Fourth Edition. New York: Springer.

Wackerly, D. D., Mendenhall III, W., and Scheaffer, R. L. (2008). Mathematical Statistics with Applications. 7th Edition. Toronto, Canada: Thomson.

Washington County Oregon. (2015). Solid Waste and Recycling. Retrieved from http://www.co.washington.or.us/HHS/SWR/Facilities/. Accessed March 11, 2015.

Washington State Department of Ecology. (2014). Waste Tires. Retrieved from http://www.ecy.wa.gov/programs/swfa/tires/. Accessed April 13, 2015.

Wise County TX. (2004). Public Works. Retrieved from http://www.co.wise.tx.us/public_works.htm. Accessed March 11, 2015.

Woodrooffe, J., Page, O., Blower, D., and Green, P. (2008). Commercial Medium Tire Debris Study. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

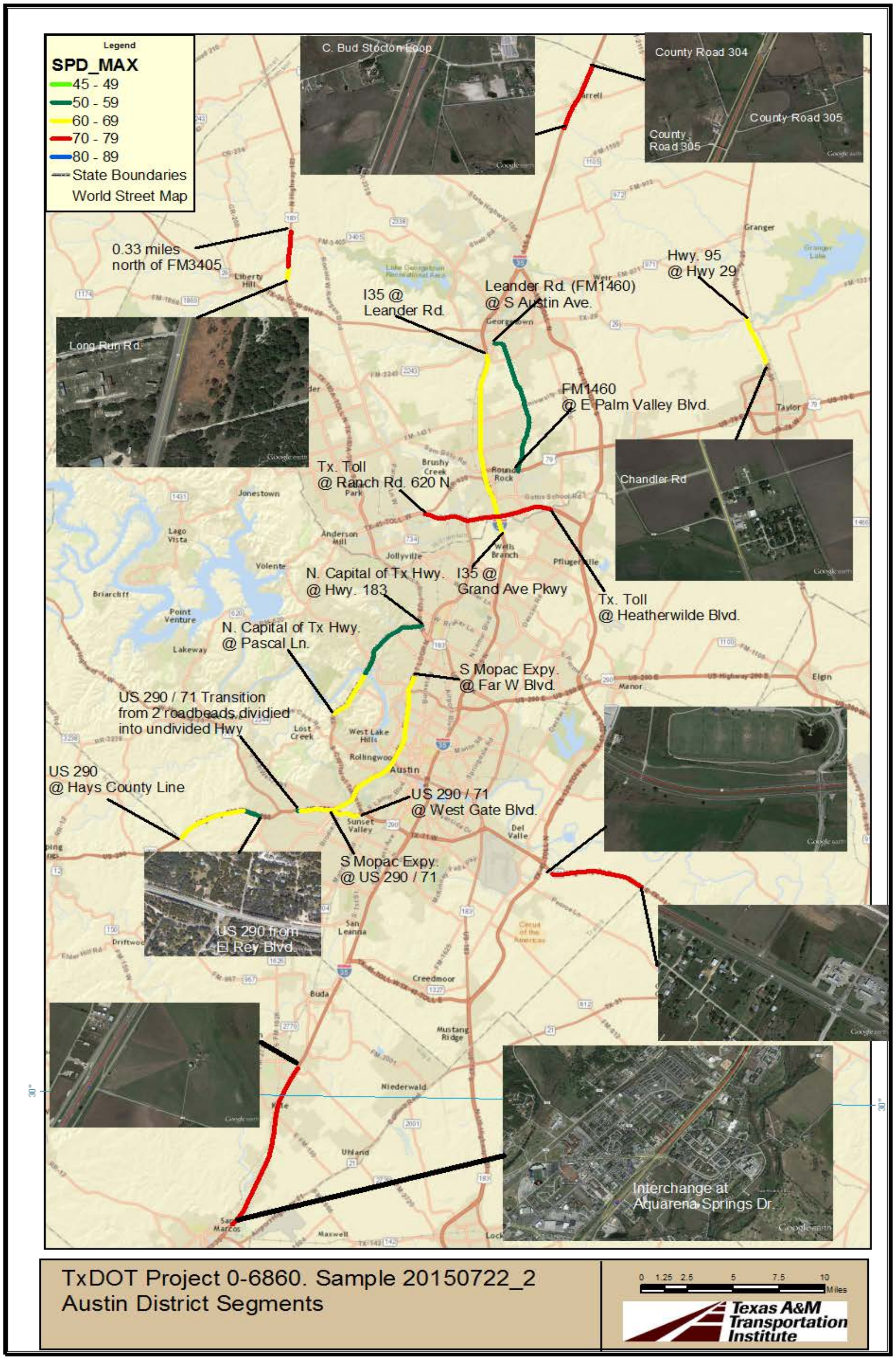
Work Safe USA Inc. (2015). Dump-Lok. Retrieved from http://Dump-Lok.com. Accessed March 11, 2015.

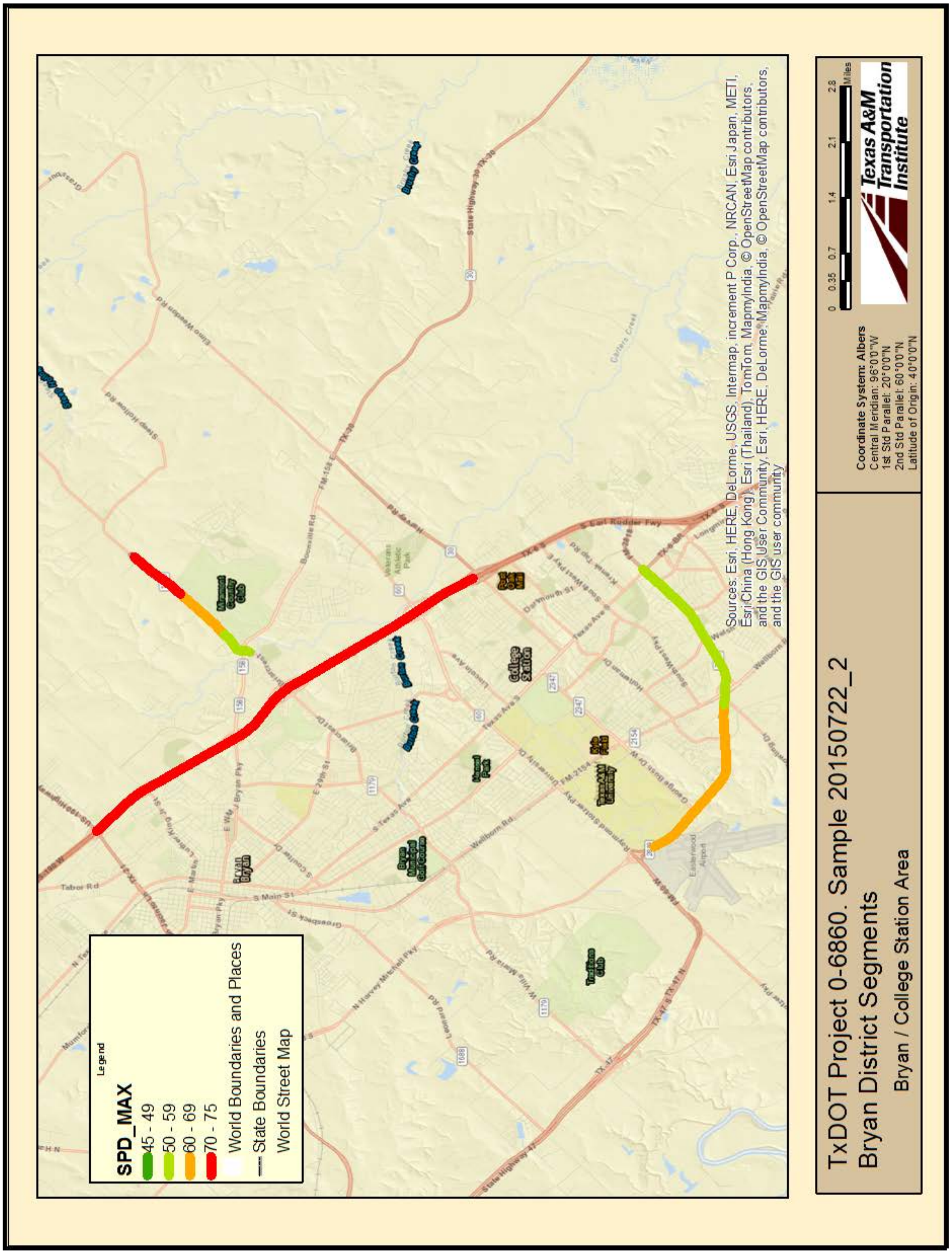
APPENDIX A. TEXAS DISTRICT CODES

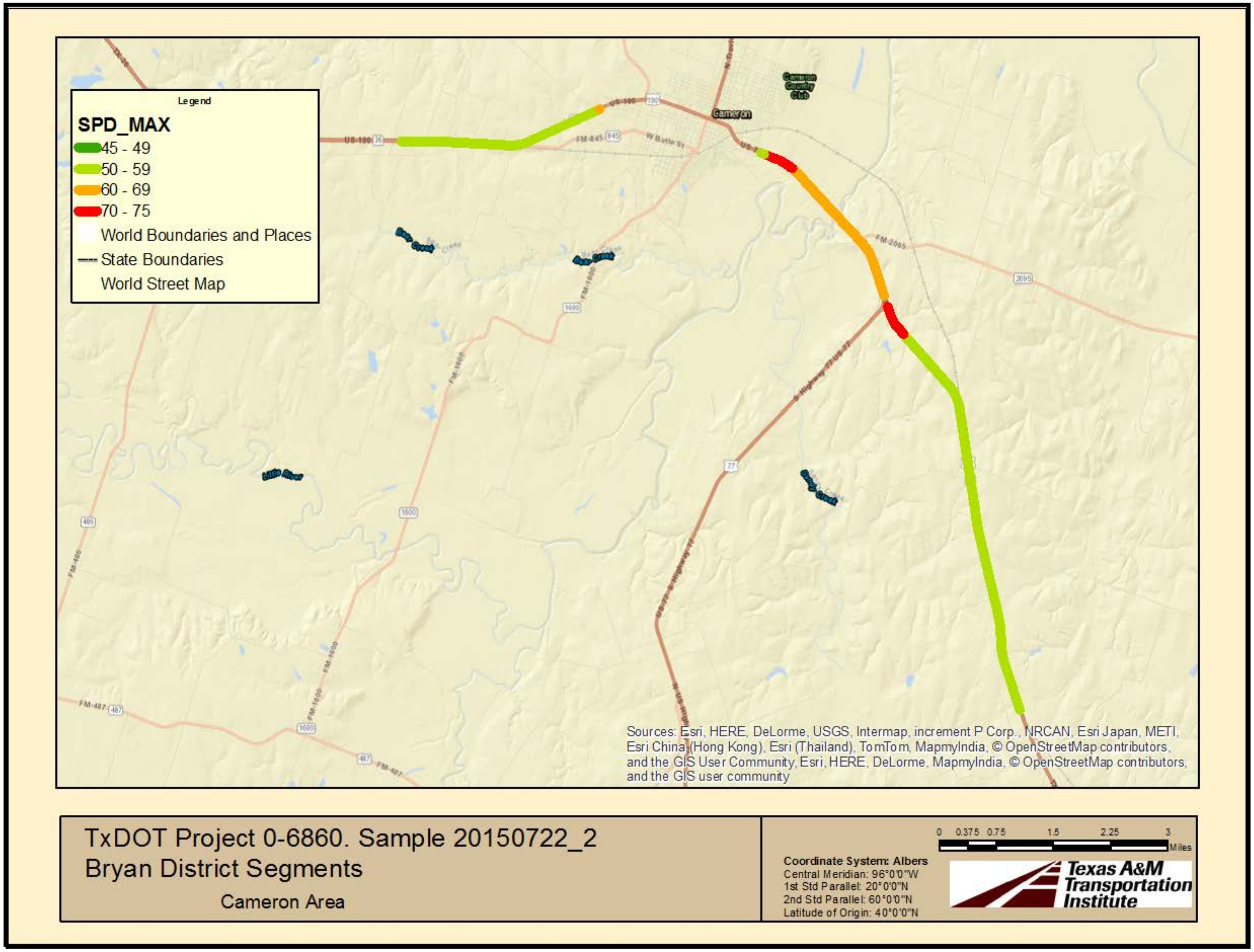
Code	District
ABL	Abilene
AMA	Amarillo
ATL	Atlanta
AUS	Austin
BMT	Beaumont
BRY	Bryan
BWD	Brownwood
CHD	Childress
CRP	Corpus Christi
DAL	Dallas
ELP	El Paso
FTW	Fort Worth
HOU	Houston

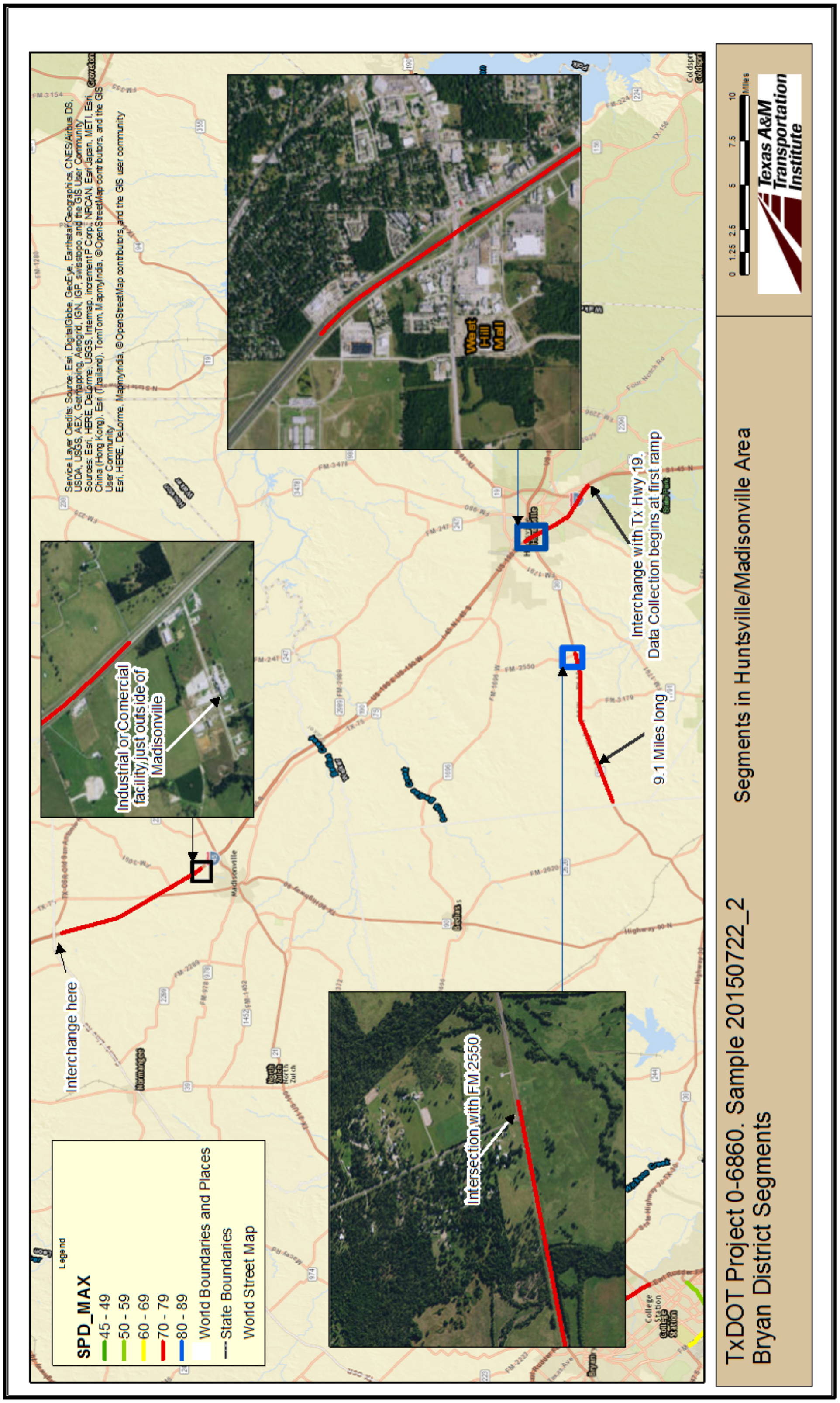
Code	District
LBB	Lubbock
LFK	Lufkin
LRD	Laredo
ODA	Odesa
PAR	Paris
PHR	Pharr
SAT	San Antonio
SJT	San Angelo
TYL	Tyler
WAC	Waco
WFS	Wichita Falls
YKM	Yoakum

APPENDIX B. MAPS OF DATA COLLECTION SITES

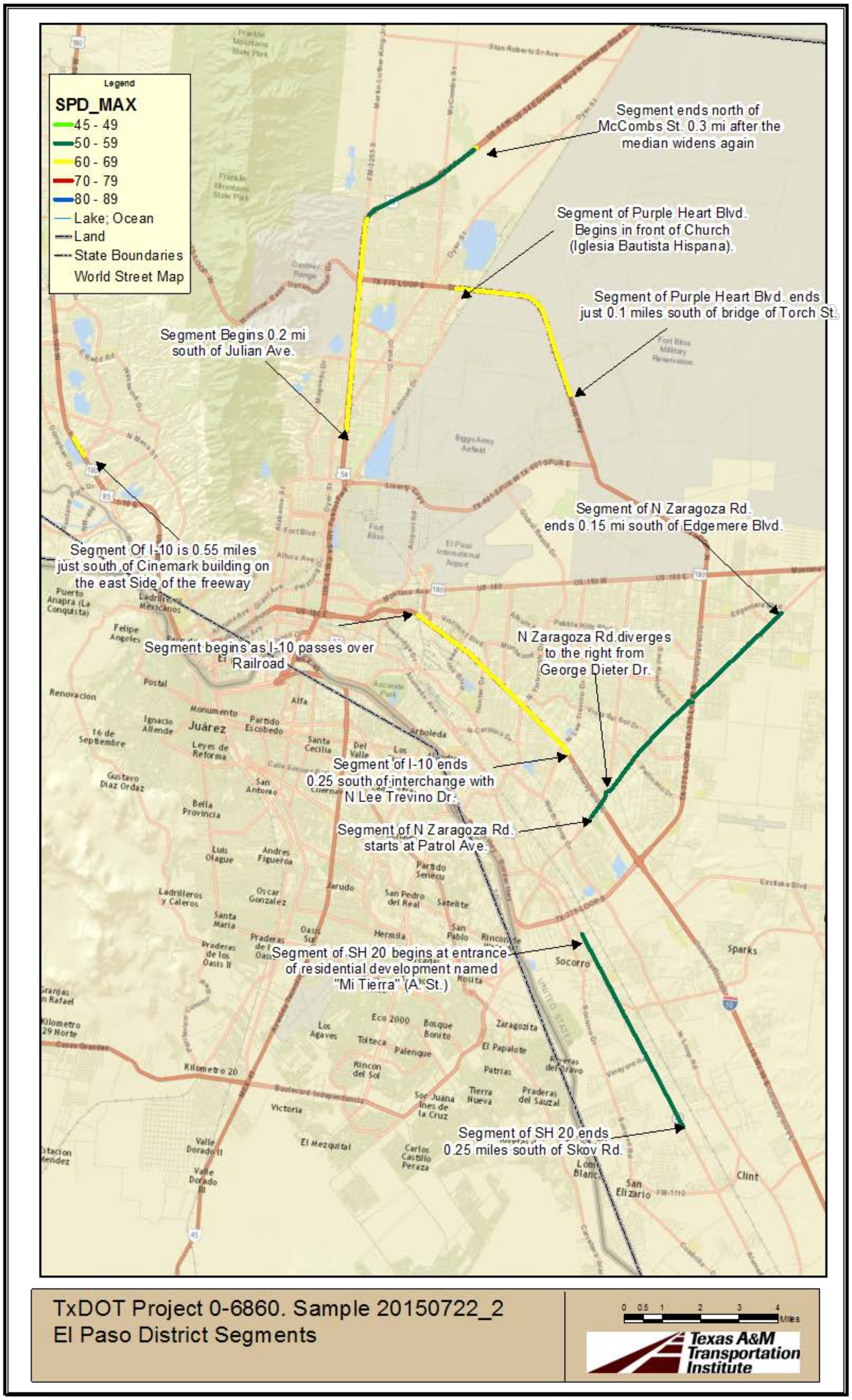


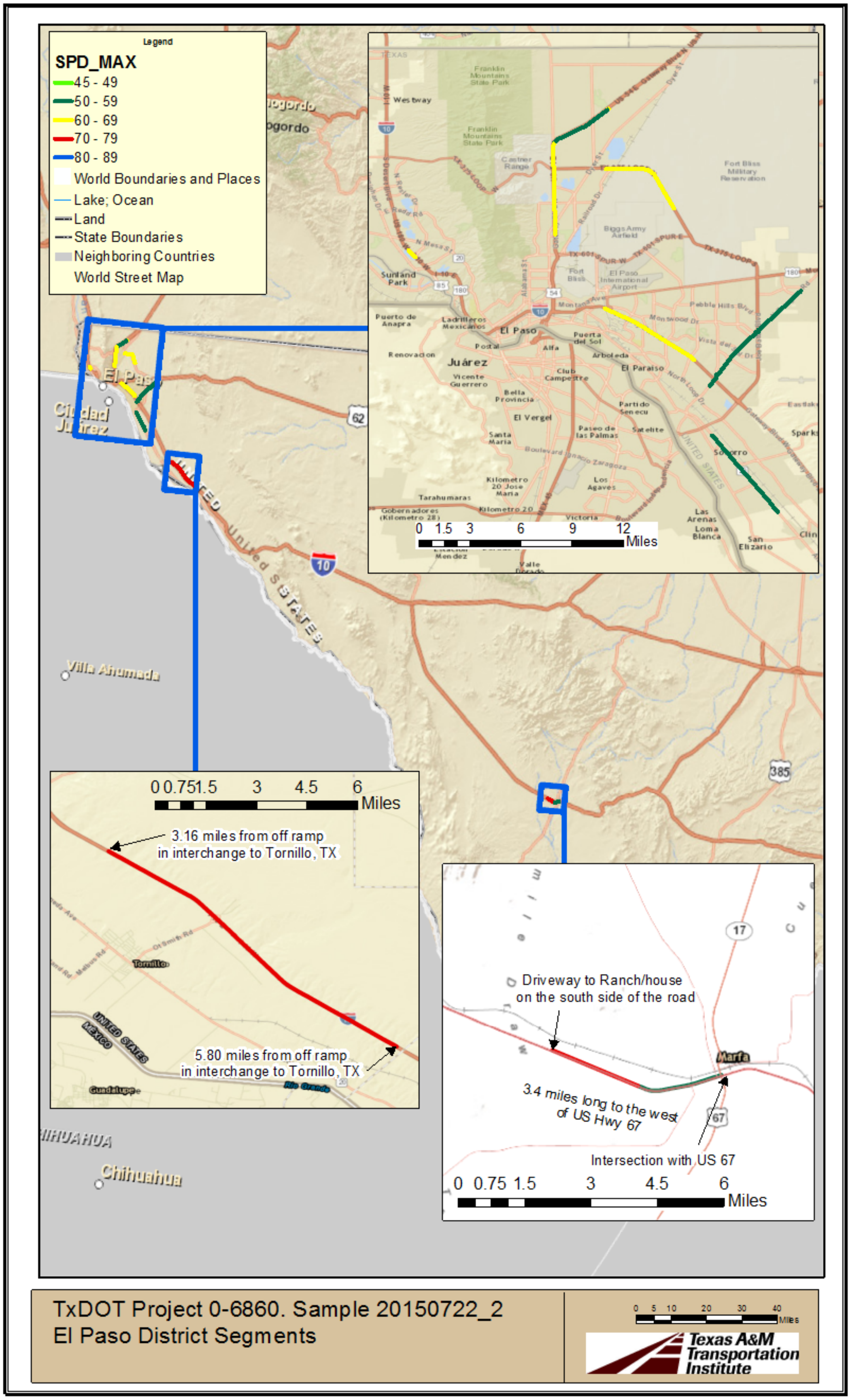

TxDOT Project 0-6860. Sample 20150722_2
Bryan District Segments
Bryan / College Station Area
Legend
SPD_MAX
45 - 49
50 - 59
60 - 69
70 - 75
World Boundaries and Places
State Boundaries
World Street Map
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community
Coordinate System: Albers
Central Meridian: 96°0'0"W
1st Std Parallel: 20°0'0"N
2nd Std Parallel: 60°0'0"N
Latitude of Origin: 40°0'0"N
0 0.35 0.7 1.4 2.1 2.8
Miles
Texas A&M Transportation Institute
College Station
Bryan

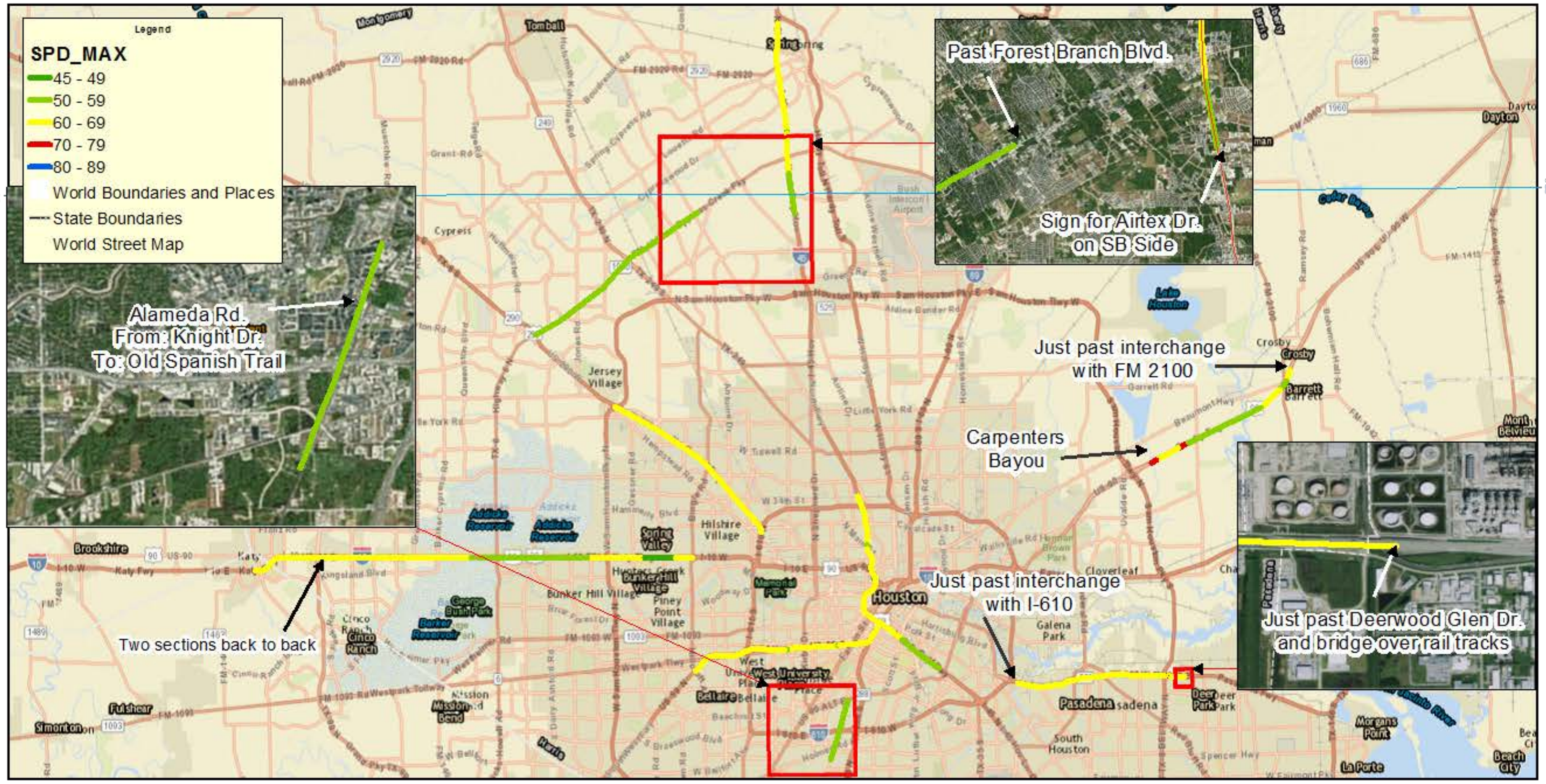

Legend
SPD_MAX
45 - 49
50 - 59
60 - 69
70 - 75
World Boundaries and Places
State Boundaries
World Street Map
Cameron
Cameron Country Club
Little River
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community
TxDOT Project 0-6860. Sample 20150722_2
Bryan District Segments
Cameron Area
Coordinate System: Albers
Central Meridian: 96°0'0"W
1st Std Parallel: 20°0'0"N
2nd Std Parallel: 60°0'0"N
Latitude of Origin: 40°0'0"N
0 0.375 0.75 1.5 2.25 3
Miles
Texas A&M Transportation Institute



TxDOT Project 0-6860. Sample 20150722_2
Bryan District Segments
Segments in Huntsville/Madisonville Area
Legend
SPD_MAX
45 - 49
50 - 59
60 - 69
70 - 79
80 - 89
World Boundaries and Places
State Boundaries
World Street Map
Interchange here
Industrial or Comercial facility just outside of Madisonville
Intersection with FM 2550
9.1 Miles long
Interchange with Tx Hwy 19. Data Collection begins at first ramp
Madisonville
Texas A&M Transportation Institute


Legend
SPD_MAX
45 - 49
50 - 59
60 - 69
70 - 79
80 - 89
Lake; Ocean
Land
State Boundaries
World Street Map
Segment ends north of McCombs St. 0.3 mi after the median widens again
Segment of Purple Heart Blvd. Begins in front of Church (Iglesia Bautista Hispana).
Segment of Purple Heart Blvd. ends just 0.1 miles south of bridge of Torch St.
Segment Begins 0.2 mi south of Julian Ave.
Segment of N Zaragoza Rd. ends 0.15 mi south of Edgemere Blvd.
Segment Of I-10 is 0.55 miles just south of Cinemark building on the east Side of the freeway
Segment begins as I-10 passes over Railroad
N Zaragoza Rd diverges to the right from George Dieter Dr.
Segment of I-10 ends 0.25 south of interchange with N Lee Trevino Dr.
Segment of N Zaragoza Rd. starts at Patrol Ave.
Segment of SH 20 begins at entrance of residential development named "Mi Tierra" (A St.)
Segment of SH 20 ends 0.25 miles south of Skov Rd.
TxDOT Project 0-6860. Sample 20150722_2
El Paso District Segments
0 0.5 1 2 3 4 Miles
Texas A&M Transportation Institute


Legend
SPD_MAX
45 - 49
50 - 59
60 - 69
70 - 79
80 - 89
World Boundaries and Places
Lake; Ocean
Land
State Boundaries
Neighboring Countries
World Street Map
El Paso
Juárez
0 1.5 3 6 9 12
Miles
0 0.75 1.5 3 4.5 6
Miles
3.16 miles from off ramp
in interchange to Tornillo, TX
5.80 miles from off ramp
in interchange to Tornillo, TX
Tornillo
Driveway to Ranch/house
on the south side of the road
3.4 miles long to the west
of US Hwy 67
Intersection with US 67
Marfa
0 0.75 1.5 3 4.5 6
Miles
Villa Ahumada
Chihuahua
United States
TxDOT Project 0-6860. Sample 20150722_2
El Paso District Segments
0 5 10 20 30 40
Miles
Texas A&M Transportation Institute



TxDOT Project 0-6860. Sample 20150722_2
Houston District Segments

Segments in Houston Area

0 1.25 2.5 5 7.5 10 Miles

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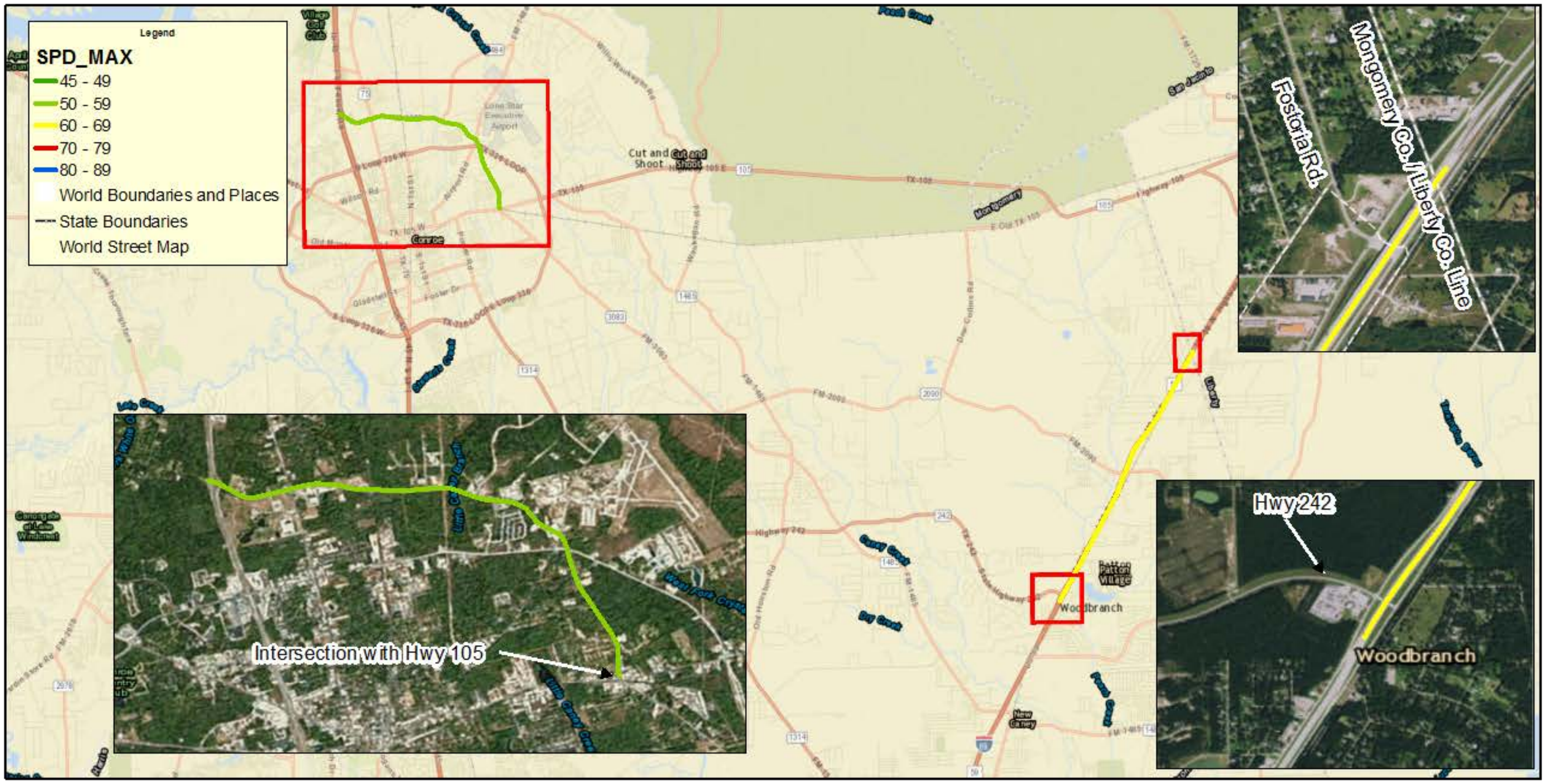

TxDOT Project 0-6860. Sample 20150722_2
Houston District Segments

Segments in Conroe Area

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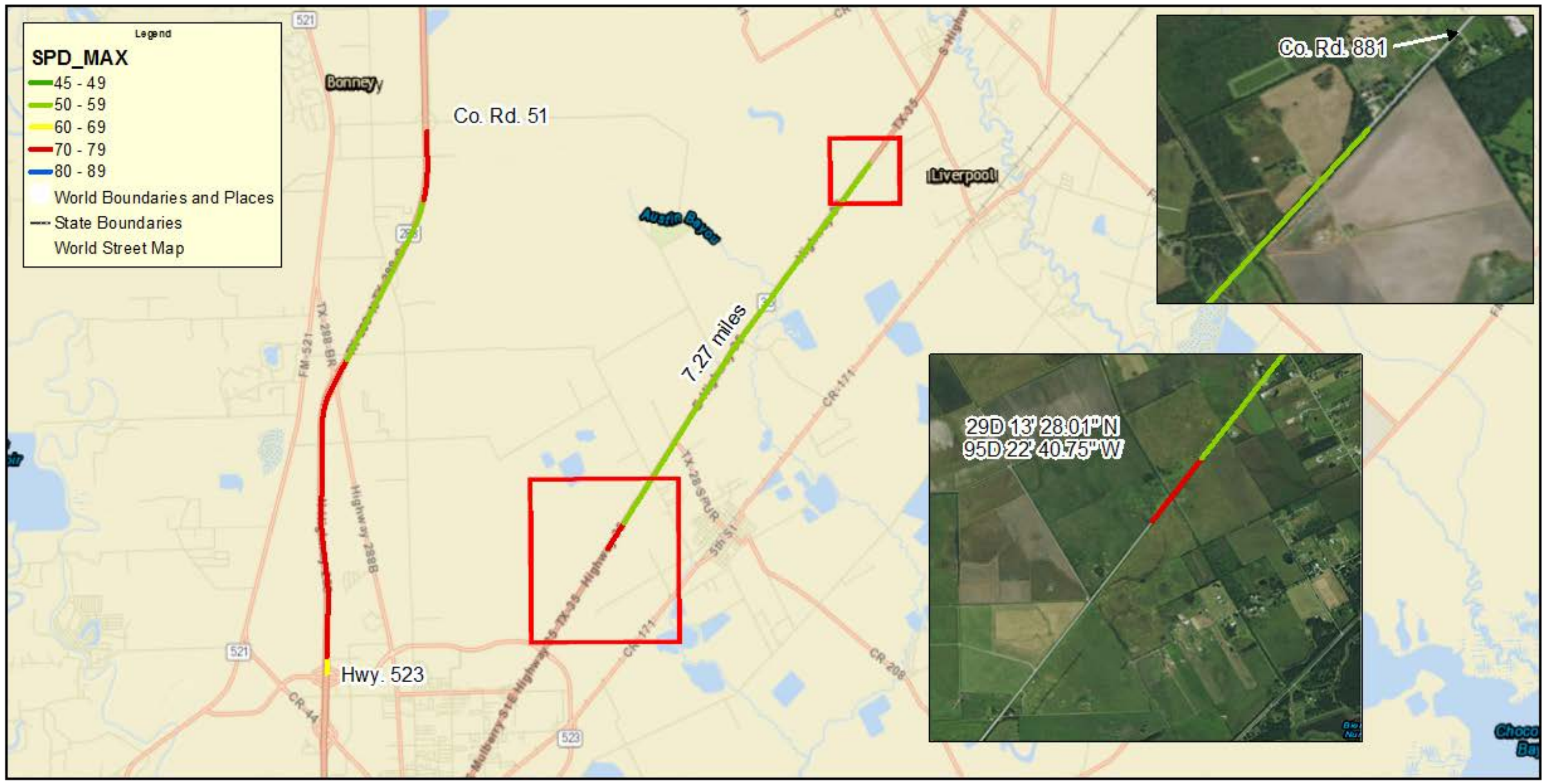

TxDOT Project 0-6860. Sample 20150722_2
Houston District Segments

Segments in Angleton/Liverpool Area

0 0.475 0.95 1.9 2.85 3.8 Miles

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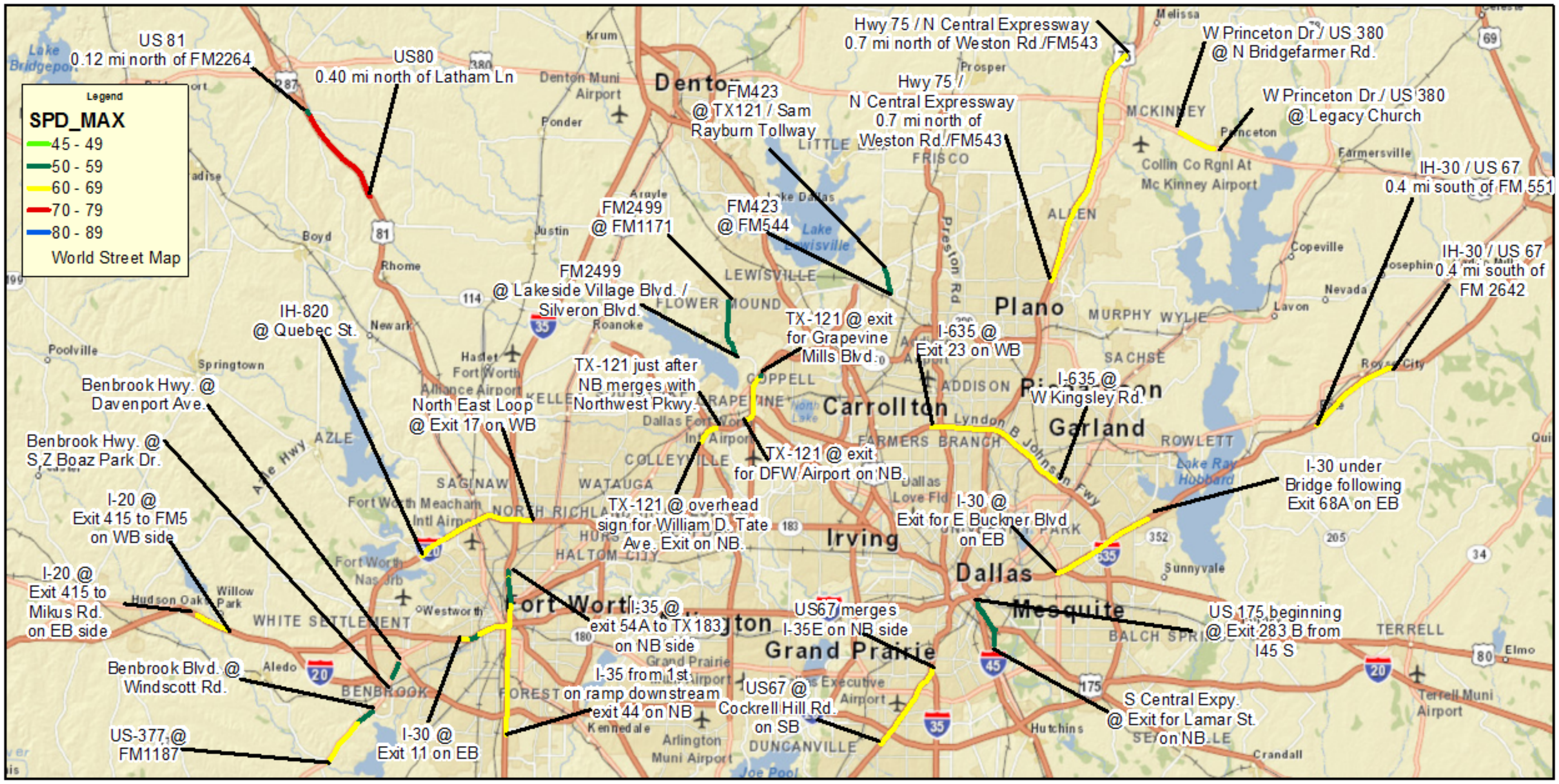
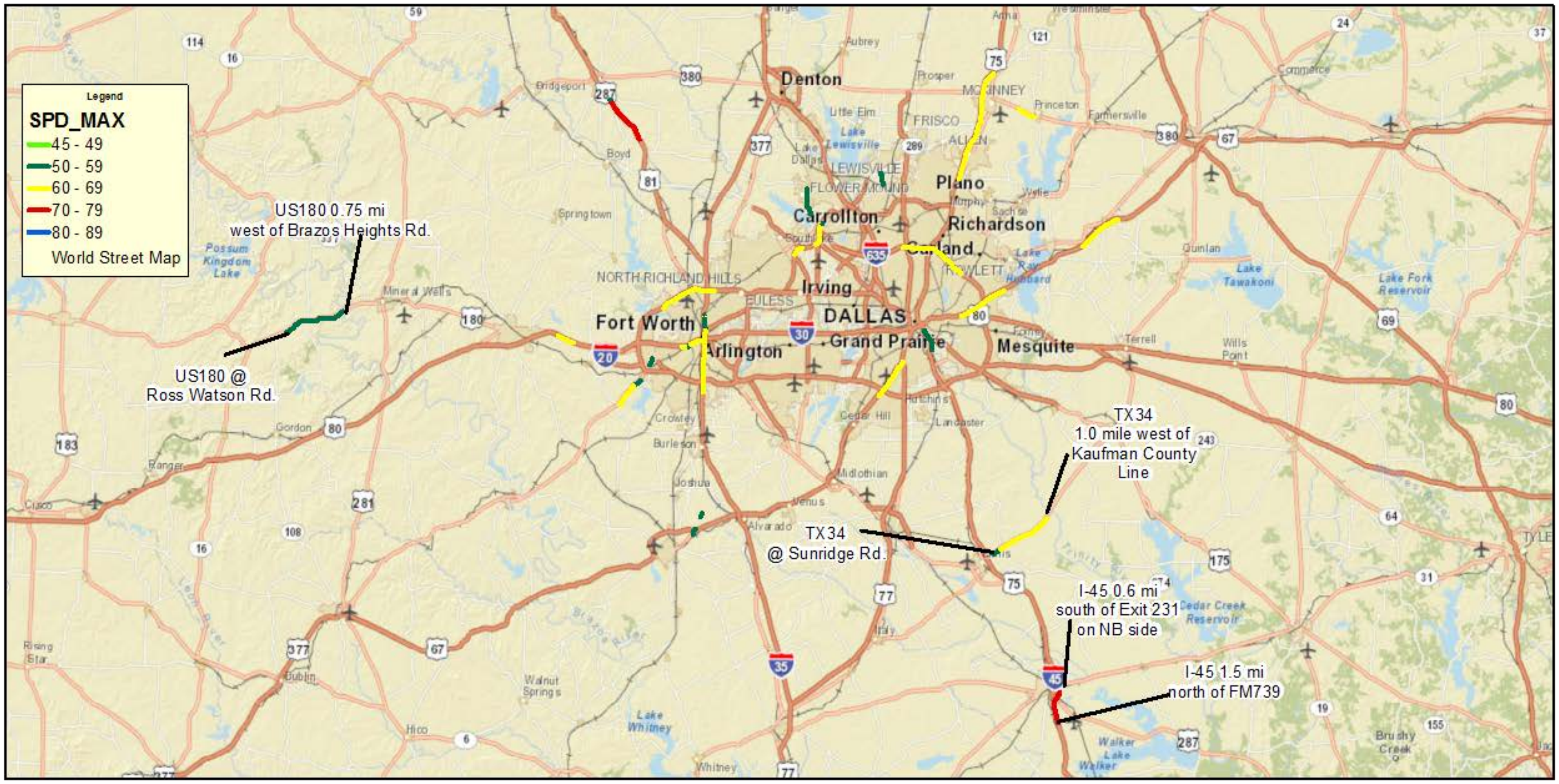


TxDOT Project 0-6860. Sample 20150722_2
Dallas District Segments

PAGE 1

Texas A&M Transportation Institute



TxDOT Project 0-6860. Sample 20150722_2
DAL & FTW Districts Segments

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Texas A&M Transportation Institute

APPENDIX C. DISTRICT SURVEY ON TIRE DEBRIS AT TEXAS HIGHWAYS

TxDOT Phone Interviews

Contact Information

Contact Person:

District: Position:

Telephone Number: E-mail:

Date of Survey: Click here to enter a date. Time of Survey: [Type a time here.]

Introduction

Hello. My name is and I am with the Texas A&M Transportation Institute (TTI).

We are currently working on a research project for the Texas Department of Transportation to identify roadway debris removal practices and the associated record keeping with an emphasis on tire debris. One task is a phone survey, for which I am calling you. This survey should take about 20 minutes to complete. We are looking for at least one TxDOT employee from each of the 25 district offices in the state of Texas. This is a voluntary survey, and if you decide not to participate or complete the survey there will be no penalty to you. Your responses to this survey will be confidential; your name, job title, and department will not be linked in any way to your answers in any publication resulting from this study. Research records will be stored securely and only members of the TTI research team will have access to the records. If you do participate, feel free to quit at any time. Are you the right person within your district to talk to about this topic?

If no: Can you please give me a different person in your district that would be the right person to talk with?

Contact Person:

Position:

Telephone Number: E-mail:

If yes: Are you willing to participate in this survey? ☐ Yes ☐ No

If no: Is there someone else that might be equally qualified to answer my questions? Would you feel free to provide his or her contact information?

If yes, please fill the information above.

If no: Thank you, for your time.

If yes: is now a convenient time to talk or would you prefer that I call you back at a later time?

If call back, date and time:
Date: Click here to enter a date.
Time: ☐

Before we begin, I want to remind you that that participation in the study is confidential and the records of this study will be kept private. Your participation is voluntary. If you have questions about the study, you may contact Research Supervisor, Raul Avelar, (979) 862-1651, r-avelar@tamu.edu. This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979) 458-4067 or irb@tamu.edu.

Policies

1. Does your agency have any written polices/practices regarding debris removal?
   ☐ Yes ☐ No
   If yes: May we get a copy of the document? ☐ Yes ☐ No
2. Does your agency have any written safety practices regarding debris removal? ☐ Yes ☐ No
   If yes: May we get a copy of the document? ☐ Yes ☐ No
3. Does your agency have any written safety practices regarding tire debris removal in partnership with other agencies, such as the fire department or law enforcement? ☐ Yes ☐ No
   If yes: May we get a copy of the document? ☐ Yes ☐ No

If no to any of the preceding three questions: Please briefly describe the methods that you typically use to remove debris from the road surface.

Cost

4. In your district, what is the average crew size devoted to debris removal?

5. How much of your resources are usually dedicated to debris removal?

   Scheduled man-hours (please also provide an estimate of average hourly rate of personnel involved):

   Unscheduled man-hours (please also provide an estimate of average hourly rate of personnel involved):

   Special equipment: (name of equipment, brief description, and estimate of operation and maintenance costs)

   Performance-based contracts (please provide an average yearly amount, contact information of contractor, and any other relevant information):

6. In case you could not provide a complete answer to the previous question, could you please estimate approximately how much does debris removal cost you in an average year?

   All debris:

   Tire debris:

Record-Keeping

7. Do you have a record log on all debris removal? ☐ Yes ☐ No

   If yes, please answer questions 8-10:

8. What type of information is provided in your record log on debris removal in general? (location, date, type of debris, weight of debris, etc.)

9. What type of information is provided in your record log specifically on tire debris removal? (location, date, weight of tire debris, volume percentage of all debris, weight percentage of all debris, retread, manufacturer, pattern, tire type, tread, size DOT, primary reasons for failure, etc.)

10. Do you have a copy of the record log that you can e-mail, fax, or mail to us? ☐ Yes ☐ No

11. Is your district registered as a tire handler entity with TCEQ's regulatory program for scrap tire management?
    ☐ Yes ☐ No
    If *yes*, please select any categories of scrap tire handler below that apply:
    Generator: ☐
    Transporter: ☐
    Processing or Recycling: ☐
    Storage Site: ☐
    Transportation Facility: ☐

12. Could you provide us with any copies of any tire manifests in your possession? ☐ Yes ☐ No

13. Do you have any records that indicate crash(es) that were attributed to tire debris or where the presence of tire debris was believed to be a triggering factor? Please describe:

Volume

14. How often do you go out to remove roadway debris (number of times per day, or week, or month, or per other unit of time)?

Scheduled:

Unscheduled:

15. Have you observed cycles to the generation of debris, such as seasonal fluctuations in temperature or traffic? ☐ Yes ☐ No

If *yes*, please describe:

16. Please estimate a percentage of debris that is removed annually from your district based on the categories below.

Tire debris

Other vehicle parts

Garbage/litter

Animals

Other (please explain in space provided)

17. What is the average volume of **<u>tire debris</u>** removal in your district, monthly or yearly, for any of the following:

by mile:

by weight:

by number or weight of tires and tire fragments:

18. On what types of roadways is debris most often found?

19. What are some roadways / roadway segments in your district where you commonly find or receive reports of debris?

20. Is there any type of debris you do not remove? If so, why?

Any additional comments on tire debris volume:

Follow-Up

We would like to come out for a field visit at some of the districts to obtain specific details regarding composition, volume and weight of tire debris. Would your district be interested in hosting one of the field visits? ☐ Yes ☐ No

If no: That's perfectly fine. We appreciate the time you have already given me today.

If yes: Thanks. That would be great. We will get back with you on when we would like to visit your district.