Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SWUTC/07/167555-1		

4. Title and Subtitle Characterizing Truck Traffic in the U.S.-Mexico Highway Trade Corridor and the Load Associated Pavement Damage	5. Report Date April 2007 6. Performing Organization Code
7. Author(s) Feng Hong, Jolanda P. Prozzi, and Jorge A. Prozzi	8. Performing Organization Report No. Report 167555-1
9. Performing Organization Name and Address Center for Transportation Research University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78705-2650	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 10727
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes
Supported by general revenues from the State of Texas.

16. Abstract

As the biggest asset in the transportation infrastructure system, highways play a critical role in a nation's economic development. Paradoxically, while this development serves as a driving force it is also responsible for significant damage to the highway infrastructure.

The United States, together with Mexico and Canada, signed the North American Free Trade Agreement (NAFTA) in 1992 in an effort to eliminate a large number of tariff barriers to free trade and thus to enhance the economic development of the three countries. Since the ratification of NAFTA in November 1993, U.S. trade with Canada and Mexico has increased dramatically, resulting in a significant increase in truck movements in the countries. In 2004, the Supreme Court ruled against the requirement to undertake an environmental impact study before opening the U.S.-Mexico border, which paved the way for U.S. roads to be opened to long-haul Mexican carriers under NAFTA.

As a result of truck traffic surge, from the perspective of infrastructure preservation, concerns have been raised by highway agencies in the bordering states regarding the increased damage by the growing traffic.

Because of Texas' proximity to the industrial heartlands of both Mexico and the U.S., the Texas transportation infrastructure is perhaps more affected by the dynamics of free trade than any other state in the U.S. This study is conducted through historical traffic data collected in the U.S.-Mexico trade corridor in Texas. Axle load distributions were investigated in terms of their spatial and temporal characteristics. The main statistical features of traffic loadings, with respect to their damaging effects on highway infrastructure, are captured. An evaluation is presented regarding the prediction of traffic loads, which is not only based on historical data but also accounts for other relevant aspects involving policy and weight limit regulations.

The results presented in this report can furnish highway agencies with better evaluation tools for highway infrastructure management in the trade corridor. The findings could also facilitate policy decisions regarding truck weight regulations and border openings to foreign traffic. To this end, a balance between rational highway infrastructure deterioration and efficient truck freight transportation can be reached.

17. Key Words	18. Distribution Statement
U.S.-Mexico Trade, NAFTA, Truck Volumes, Vehicle Classification, Axle Loading, Weigh-in-Motion	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	58	

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Characterizing Truck Traffic in the U.S.-Mexico Highway Trade Corridor and the Load Associated Pavement Damage

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Research Report SWUTC/07/167555-1

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ABSTRACT

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EXECUTIVE SUMMARY

Introduction

The United States (U.S.), together with Mexico and Canada, signed the North American Free Trade Agreement (NAFTA) in 1992 in an effort to eliminate a large number of tariff barriers to free trade and to enhance the economic development of the three countries. Since the ratification of NAFTA in November 1993, U.S. trade with Canada and Mexico has increased dramatically. This has resulted in a significant increase in truck movements. A recent freight transportation study on trade and travel trends reported that two thirds of the value of the goods traded with Mexico and Canada is carried by truck. In terms of weight, about 35 percent of the U.S.-NAFTA-partner trade was moved by truck.

Furthermore the value of U.S.-Mexico truck trade increased from approximately $90 billion in 1996 to an estimated more than $180 billion in 2004. States along the U.S.-Mexico border – i.e., California, Arizona, New Mexico, and Texas - are arguably the most affected by NAFTA truck traffic concerning safety, the environment, and transportation infrastructure preservation. As such, the agreement restricted the movement of U.S. and Mexican trucks to a narrow commercial zone extending 3 to 20 miles into each country that was expected to be phased out by 2000. However, this enactment was postponed due to pressure from the Congress and Teamsters Union. Consequently, the moratorium on long haul trucking companies operating beyond these commercial zones was upheld. Over the past decade, ongoing litigation and disputes regarding the safety and emissions characteristics of Mexican trucks, as well as inspections and driver-related concerns have prevented the opening of the U.S.-Mexico border. However, in recent years many of these issues that prevented the implementation of the NAFTA trucking provisions have been addressed. For example, in 2004 the Supreme Court ruled against the requirement to undertake an environmental impact study before opening the U.S.-Mexico border, which paved the way for U.S. roads to be opened to long-haul Mexican carriers under the NAFTA. In anticipation of establishing an agreement between the U.S. and Mexico to address the outstanding issue concerning U.S. motor carrier safety inspections to be conducted inside Mexico, many Mexican motor carriers have started to prepare for cross-border operations.

Because of Texas's proximity to the industrial heartlands of both Mexico and the U.S., the Texas transportation infrastructure is perhaps more affected by the dynamics of free trade than any other state in the U.S. Between 1994 and 2000, the number of loaded northbound trucks crossing the Texas-Mexico border, excluding El Paso, increased from 659,949 to 2.4 million annually. During the same time period the number of loaded and empty southbound trucks, excluding El Paso, increased from 1.1 to 2.3 million. To further emphasize this point, Table 1 illustrates that 67 percent of the incoming U.S.-Mexico container trucks crossed the Texas-Mexico border in 2004.

Table 1: Incoming Truck Container Crossings by State, U.S.-Mexican Border

State	**1998**	**2000**	**2004**
Arizona	318,185	322,160	319,872
California	860,684	947,311	1,135,850
New Mexico	31,699	35,507	32,348
Texas	2,502,358	2,895,703	3,024,830
Total	**3,712,926**	**4,200,681**	**4,512,900**

Note: Full or empty truck containers entering the United States. The data include containers moving as in-bond shipments. Source: Mallet et al, 2005

This growth in truck-borne freight volumes is expected to continue, especially once Mexican trucking companies are allowed access to U.S. markets located beyond the border commercial zone. Furthermore, the characteristics of the NAFTA truck traffic might change after the border opens due to differences in for example, axle configurations, suspension types, and wheel loads between U.S. and Mexican trucking companies. Changing traffic loading characteristics will affect pavement performance, presumably producing accelerated damage to the road network and thus requiring increased maintenance and rehabilitation funding. The objective of this research is to analyze the infrastructure impact of changing truck traffic load characteristics on key NAFTA highway corridors in Texas.

Conclusions

This project analyzed the infrastructure impacts imposed by truck loads from data obtained at two WIM stations in two of the key U.S.-Mexico highway trade corridors in Texas. Both the spatial and temporal characteristics of truck loads were examined. The axle load distributions for different axle types (e.g., steering, single, and tandem axles) for the two dominant truck classes – Class 5 and Class 10 – as well as for all truck classes combined were presented. Finally, relevant statistics to illustrate the load associated pavement damage over time were calculated and presented. The most salient findings of this research are as follows:

1) The axle load distributions are different for different truck classes and axle types, partly because of differences pertaining to the distances and types of cargo moved by the different truck classes. However, typically the load distributions reveal a single mode or two modes (peaks).

2) There was a significant difference in the load distributions, as well as relevant statistics, of the Class 10 truck type by travel direction: southbound to Mexico and northbound from Mexico. Specifically, it was found that the southbound axle loadings were on average heavier than the northbound axle loadings. In addition, it was found that for each individual axle, the load impact on the pavement in the southbound direction was larger than on the pavement in the northbound direction. Finally, it was found that a higher percentage of the axle loadings in the southbound direction exceeded legal limits.

3) There has been a constant shift towards a heavier axle load distribution for Class 10 trucks since 1994, resulting in an increase in the load associated pavement damage over the same time period. Specifically, the pavement damage imposed by northbound Class 10 trucks was larger than the pavement damage imposed by the southbound truck traffic. The latter seems to have become "stable" or at least is starting to show little change.

4) By analyzing the directional and temporal characteristics of the axle load distributions a trend line for the northbound and the southbound load associated pavement damage was established. The researchers concluded that the LSF trend lines for the Class 10 trucks in each of the travel directions will converge in the future to a point at which truck capacities will be utilized to an optimum given the current regulations and weight enforcement level.

5) For Class 5, the second most popular truck class, no significant directional difference and temporal shift in the axle load distributions were observed at both WIM stations.

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DISCLAIMER

ACKNOWLEDGEMENTS

The authors recognize that support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center which is funded 50 percent with general revenue funds from the State of Texas.

Chapter 1. Introduction

The United States (U.S.), together with Mexico and Canada, signed the North American Free Trade Agreement (NAFTA) in 1992 in an effort to eliminate a large number of tariff barriers to free trade and to enhance the economic development of the three countries. Since the ratification of NAFTA in November 1993, U.S. trade with Canada and Mexico has increased dramatically. This has resulted in a significant increase in truck movements. A recent freight transportation study on trade and travel trends reported that two thirds of the value of the goods traded with Mexico and Canada is carried by truck (BTS, 2001). In terms of weight, about 35 percent of the U.S.-NAFTA-partner trade was moved by truck.

Furthermore the value of U.S.-Mexico truck trade increased from approximately $90 billion in 1996 to an estimated more than $180 billion in 2004 (Mallet et al, 2005). States along the U.S.-Mexico border – i.e., California, Arizona, New Mexico, and Texas - are arguably the most affected by NAFTA truck traffic concerning safety, the environment, and transportation infrastructure preservation. As such, the agreement restricted the movement of U.S. and Mexican trucks to a narrow commercial zone extending 3 to 20 miles into each country that was expected to be phased out by 2000. However, this enactment was postponed due to pressure from the Congress and Teamsters Union (Washington Post, 2004). Consequently, the moratorium on long haul trucking companies operating beyond these commercial zones was upheld. Over the past decade, ongoing litigation and disputes regarding the safety and emissions characteristics of Mexican trucks, as well as inspections and driver-related concerns have prevented the opening of the U.S.-Mexico border. However, in recent years many of these issues that prevented the implementation of the NAFTA trucking provisions have been addressed. For example, in 2004 the Supreme Court ruled against the requirement to undertake an environmental impact study before opening the U.S.-Mexico border (Washington Post, 2004), which paved the way for U.S. roads to be opened to long-haul Mexican carriers under the NAFTA. In anticipation of establishing an agreement between the U.S. and Mexico to address the outstanding issue concerning U.S. motor carrier safety inspections to be conducted inside Mexico, many Mexican motor carriers have started to prepare for cross-border operations.

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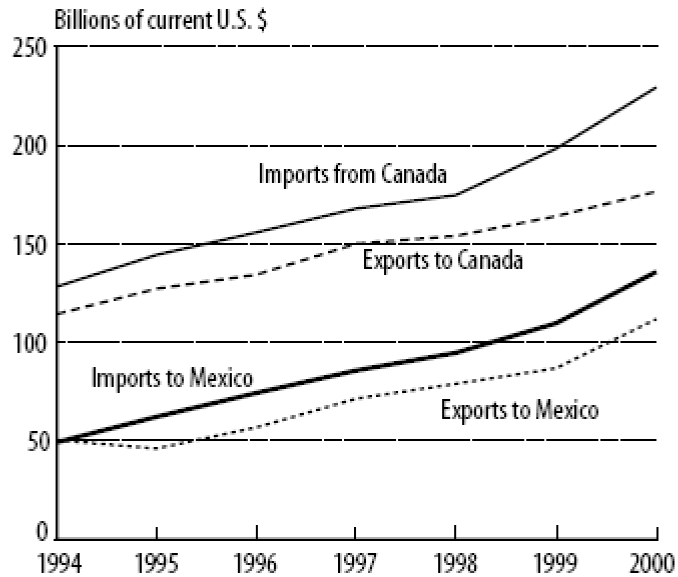
Chapter 2. Background

Highway infrastructure is impacted by both the number and the magnitude of traffic loads. Both traffic volume and axle loading should thus be analyzed when estimating traffic-related infrastructure damage. It is well established that trucks account for over ninety percent of traffic-related infrastructure damage since damage increases exponentially with axle weight (Huang, 2004). This section of the report illustrates the anticipated increase in truck traffic volumes on Texas's highway system, provides an overview of the vehicle classification system adopted, and highlights a number of recent studies on the load characteristics of trucks (i.e,, axle loadings) – the focus of this research.

2.1 Truck Volumes

The truck has become the dominant mode of transportation in the movement of freight in the U.S. According to the Bureau of Transportation Statistics (BTS, 2001), trucks had the largest market share in freight movements when measured in weight in 2000: 35 percent of the total cargo moved in the U.S. was transported by truck, followed by water, rail, and pipeline (BTS, 2001).

Truck transportation is, however, a derived demand. *Freight moves in response to the needs of its customers [e.g., large population centers, business and government customers]. In a period of economic expansion, more goods need to be moved to support production lines, construction, and consumer activity* (FHWA 1999). In this regard, the U.S. Census Bureau reported that the U.S. population grew about 28 percent between 1980 and 2003. Over the same period, economic activity measured in Gross Domestic Product (GDP) doubled and foreign trade quadrupled in real value (Mallet et al, 2005). Regarding the latter, Canada and Mexico are the first and second largest trade-partners with the U.S. Between 1994 and 2000, U.S. trade with Canada grew by 8.9 percent, while trade with Mexico increased by 16 percent (BTS, 2001). Figure 1 illustrates the upward trend in U.S. merchandise trade with Canada and Mexico between 1994 and 2000.



Sources: U.S. Department of Transportation, Bureau of Transportation Statistics, special tabulation, April 2001: based on total trade, air and water – U.S. Department of Commerce, U.S. Census Bureau, Foreign Trade Division, FT920 U.S. Merchandise Trade (Washington, DC: Various years); all land modes – U.S. Department of Transportation, Bureau of Transportation Statistics, Transborder Surface Freight Data

Figure 1: Value of U.S. Merchandise Trade with Canada and Mexico (1994-2000)

To meet the demand for increased freight movements resulting from an increase in population, economic activity, and international trade, both the number and utilization of trucks have increased. The FHWA reported an increase in the number of registered large trucks (trucks with six or more tires) from around 6 million in 1990 to approximately 8 million in 2002 (FHWA, website accessed 2006). Similarly, commercial truck travel has doubled over the past two decades as illustrated in Figure 2 (Mallet et al, 2005).

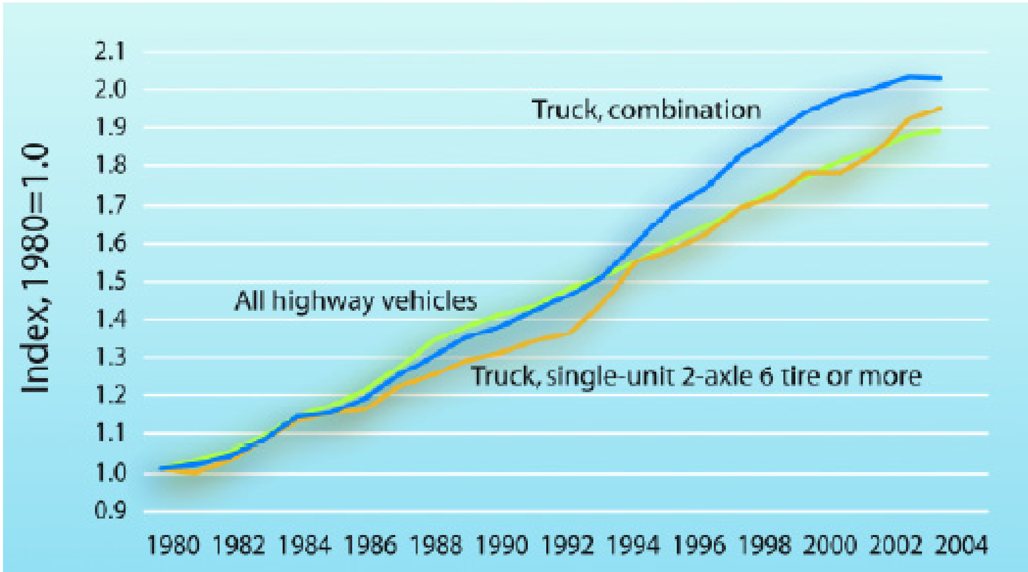


Figure 2: Highway Vehicle-miles Traveled (1980 to 2003)

Furthermore, it is expected that truck travel would continue to increase in the future. Figures 3 and 4 illustrate the estimated average daily truck traffic (ADTT) in 1998 and the projected ADTT for 2020. The figures reflect the expectation that domestic tons transported will increase by 60 to 70 percent, and that international shipments will increase by 85 percent more than that of the 2002 values. By 2020, it is estimated that trucks will be responsible for moving three quarters of total tonnage in the U.S., followed by rail (14 percent), water (7 percent), and air (less than 1 percent) (Mallet et al, 2005).

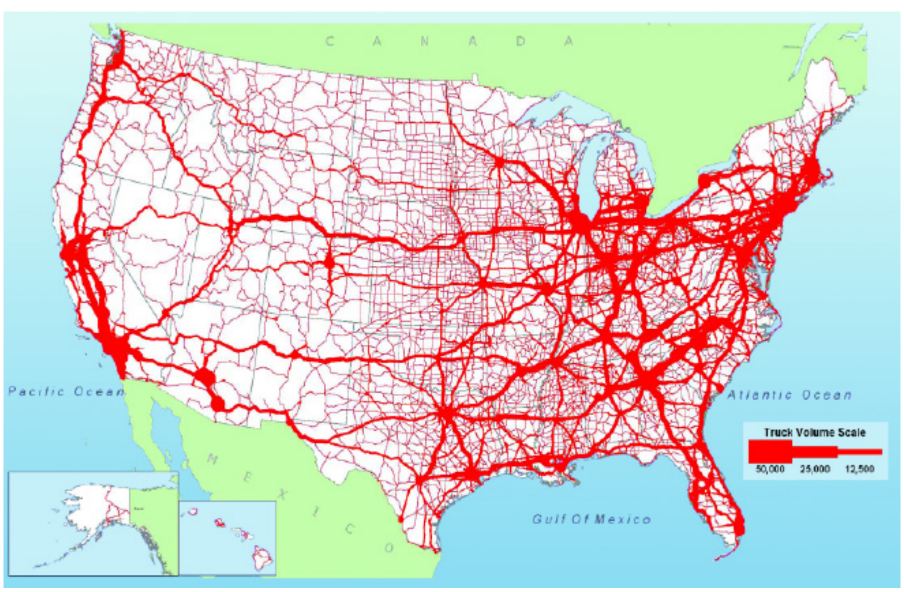


Figure 3: Estimated Average Daily Truck Traffic (1998)

Figure 4: Estimated Average Daily Truck Traffic (2020)

In Texas, the volume of truck movements increased dramatically in the 1990s, following nearly a decade of strong economic and trade growth. The advent of NAFTA resulted in Texas becoming the locus of international trade between the U.S. and Mexico. It is thus foreseen that international trade moving through Texas will increase at a higher rate than domestic trade in the coming 20 years (http://ops.fhwa.dot.gov/freight/) due particularly to continuing trade growth with Mexico. Figure 5 illustrates the estimated truck freight flows to, from, and within Texas in 1998. According to the FHWA Office of Freight Management and Operations, truck shipments in Texas will increase from 1,764 million tons in 1998 to 2,990 million tons in 2020, resulting in the percentage of weight carried by highway mode increasing from 57 to 63 percent. Figures 6 and 7 illustrate the AADTT on the Texas highway network in 1998 and the projected AADTT on the Texas highway network in 2020. In Texas, increased truck flows on the Interstate and U.S. highway systems will thus exacerbate congestion on certain key links of the highway network in urban areas and result in increased pressure on the rural system.

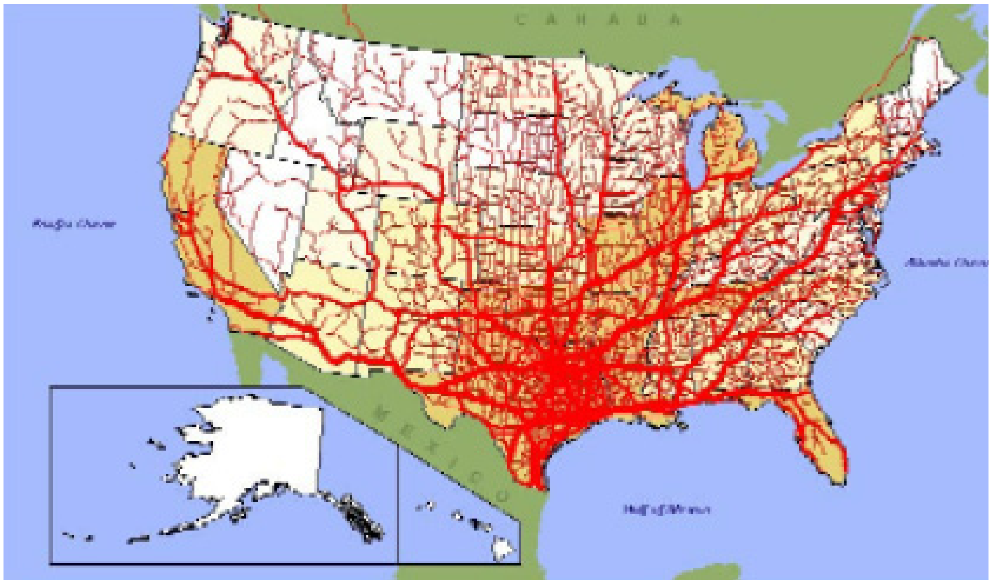


Figure 5: Truck Freight Flows (Tons) to, from, and within Texas (1998)

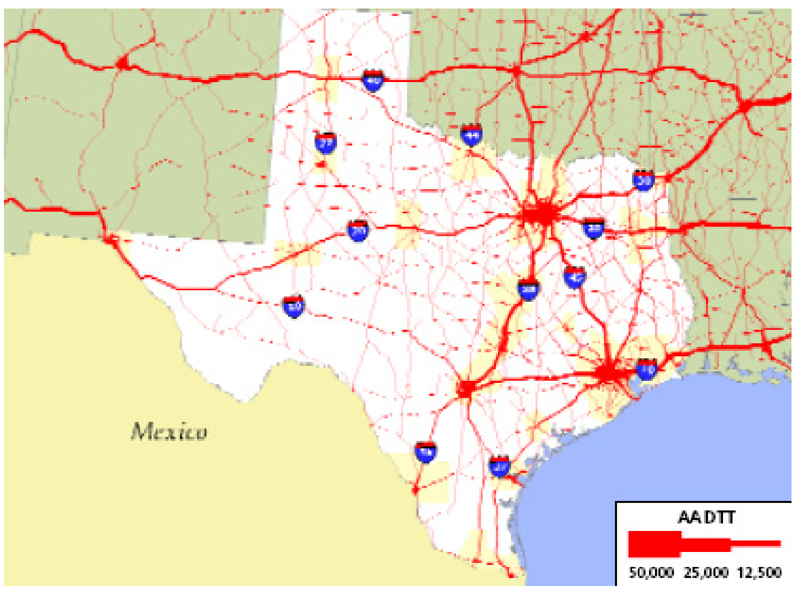


Figure 6: Estimated Average Annual Daily Truck Traffic in Texas (1998)

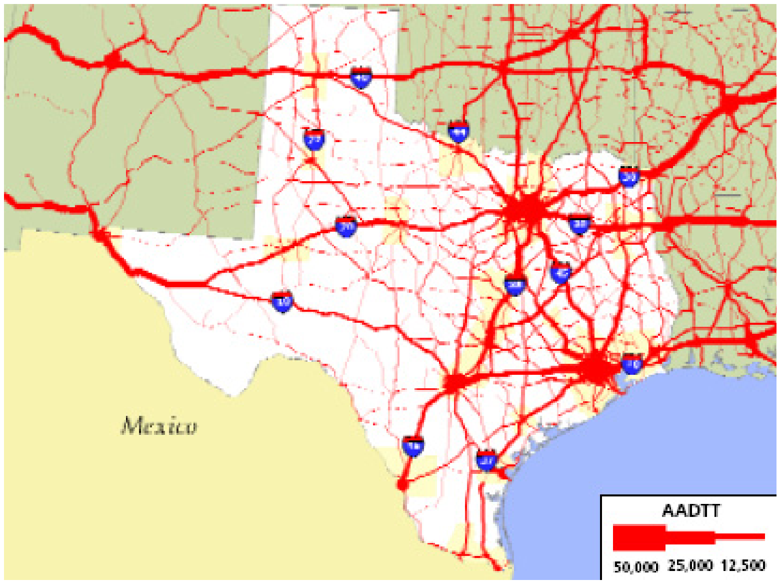


Figure 7: Estimated Average Annual Daily Truck Traffic in Texas (2020)

Four of the 20 busiest ports of entry along the U.S.-Canada and U.S.-Mexico borders are located in Texas (see Table 2). Furthermore, Laredo was the second busiest border crossing on the NAFTA border between 1997 and 2000, while Port Hidalgo in Texas showed the largest increase in number of truck crossings between 1997 and 2000. Opening the Texas-Mexico border to Mexican domiciled trucks could thus have a significant impact on Texas's highway system. It is thus timely to consider and prepare for the potential infrastructure impacts of Mexican trucks operating throughout Texas. This requires a better understanding of the loading characteristics of the long haul trucking fleet that is foreseen to operate eventually on Texas roads and to determine the associated infrastructure impacts. This exercise is crucial from both an infrastructure management and planning perspective.

Table 2: Top 20 NAFTA Border Truck Crossings into the United States: 1997 and 2000

Rank in 2000	Port Name	1997 ('000)	2000 ('000)	Average number of truck crossings per day (2000)	% Change (1997-2000)
1	Detroit, MI	1,420	1,769	4,848	24.6
2	Laredo, TX	1,251	1,493	4,091	19.3
3	Buffalo-Niagara, NY	1,054	1,198	3,282	13.7
4	Port Huron, MI	679	839	2,299	23.5
5	El Paso, TX	583	720	1,974	23.6
6	Otay Mesa/San Ysidro, CA	568	688	1,886	21.2
7	Blaine, WA	463	517	1,416	11.6
8	Champlain-Rouses Pt., NY	299	391	1,071	30.7
9	Hidalgo, TX	235	374	1,025	59.3
10	Brownsville, TX	248	299	820	20.9
11	Calexico East/ Calexico, CA	U	279	764	U
12	Alexandria Bay, NY	220	278	763	26.5
13	Nogales, AZ	243	255	698	4.9
14	Pembina, ND	152	214	587	40.9
15	Calais, ME	126	154	422	22.5
16	Sweetgrass, MT	112	146	400	30.5
17	Derby Line, VT	101	139	380	37.6
18	Houlton, ME	103	133	364	28.8
19	Highgate Springs, VT	99	133	364	33.9
20	Jackman, ME	87	128	350	47.1
Total, top 20 ports		**8,041**	**10,148**	**27,802**	**26.2**
Total, all ports		**9,215**	**11,574**	**31,709**	**25.6**

Key: U = data are unavailable

Note: Data represent the number of truck crossings, not the number of unique vehicles, and include both loaded and unloaded trucks. Data for the port of Calexico is typically reported as a combined total with Calexico East.

Sources: U.S. Department of Transportation, Bureau of Transportation Statistics, special tabulations, May 2001; based on data from U.S. Department of Treasury, U.S. Customs Service, Mission Support Services, Office of Field Operations.

2.2 Vehicle Classification and Axle Loading

2.2.1 Traffic Classification

The FHWA Traffic Monitoring Guide (TMG) categorizes vehicles into 13 classes based on the number and configuration of the axles. In the TMG, Class 4 to 13 is defined as trucks (FHWA, 2001). The vehicle classification schemes used in other states are the same or similar to the TMG. In this study, the PAT classification system that consists of 15 vehicle classes used in Texas was adopted (see Figure 8). Classes 4 to 15 include the truck classes. However, Class 15 also includes those vehicles not categorized in the other vehicle classes and records due to system errors. In general, the trucks traversing the typical interstate highway in Texas are categorized as Class 10 (or Class 9 according to the TMG scheme, or 18-wheelers, or 3S2). This vehicle class accounts for approximately 60 percent of the truck vehicle volume, followed by Class 5 (2 axle single unit trucks) and others (Prozzi and Hong, 2006a).

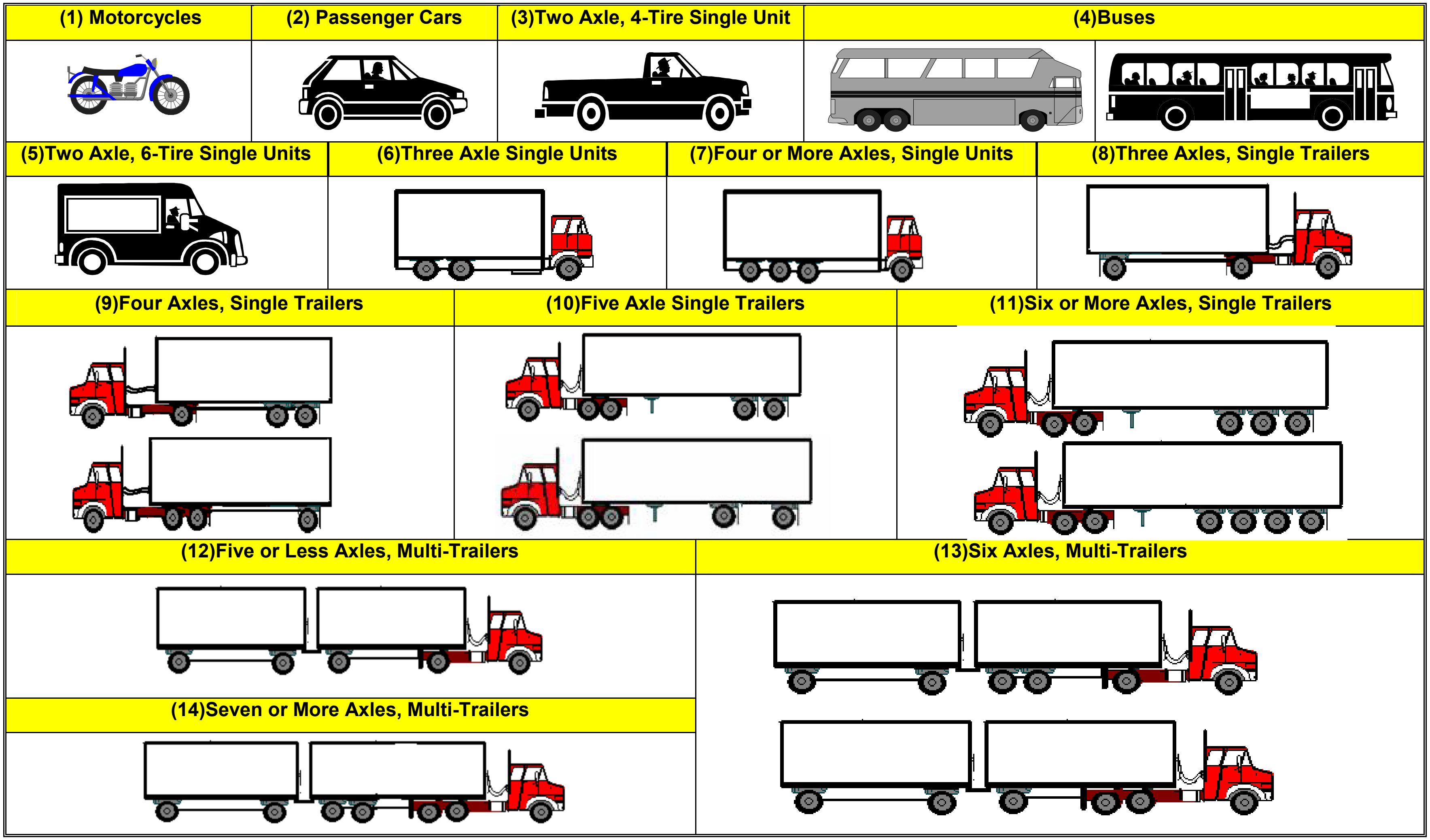


Figure 8: PAT Vehicle Classification Scheme Used in Texas

2.2.2 Vehicle & Axle Load Limit

From a system management perspective, axle loads have always been a major concern because of the significant impact of axle loads on transportation infrastructure. A series of measures have thus been adopted to protect the highway infrastructure from deteriorating. For example, federal interest in preserving the Interstate Highway system (Dwight D. Eisenhower System of Interstate and Defense Highways) dates back to the 1950s with the enforcement of vehicle weight and length, and subsequently width standards (FHWA, 2000). Currently, the federal axle load limits on the Interstate Highway system are (Electronic Code of Federal Regulations (e-CFR), 2006):

Single axle: 20,000 pounds

Tandem axle: 34,000 pounds

Gross vehicle weight: 80,000 pounds

Furthermore, the bridge formula may require a lower gross vehicle weight, depending on the number and configuration of axles in combination vehicles, to reduce the damage to bridges. Bridge Formula B calculates the maximum weight limit for any group of two or more consecutive axles as follows:

$$W = 500 \times \left(\frac{LN}{N-1} + 12N + 36 \right) \quad (1)$$

Where,

W: Overall gross weight in pounds;

L: Distance in feet between the extreme of the group of axles, and

N: Number of axles in the group under consideration.

Each state may adopt its own commercial vehicle weight standards, but Texas has adopted the Federal regulation (Belfield et al, 1999).

In comparison, the Mexican truck axle weight limits on "high type" roadways, which are comparable to the U.S. highway system, are listed as (Espinosa et al, 1993; FHWA, 2000):

Single axle (single wheel):	12,125 pounds
Single axle (dual wheels):	22,050 pounds
Tandem axle:	40,000 pounds
Gross vehicle weight:	171,000 pounds

It is thus evident that, with the exception of the weight limit for a single axle with single wheels (usually the steering axle), the typical non-steering axles in Mexico have a higher legal load limit compared to trucks in the U.S. This has resulted in some concern about the impact on the Texas transportation infrastructure should those Mexican trucks operate on the Texas highway system with these higher axle loads.

In the U.S., weight limits are enforced to protect the transportation infrastructure. In 2002, approximately 200 million weighs were made to monitor truck weight and preserve the highway infrastructure (Mallet et al, 2005). Half – 100 million weighs – were undertaken through WIM. Approximately 1 percent of the weighs exceeded the axle load limits. However, in 1987, a NCHRP report estimated that the overweight vehicle percentages were between 10 and 25 percent (Terrell and Bell, 1987). More recently, a survey in different U.S. states reported that the estimated percentage of overweight vehicles ranged from half-of-one-percent to as high as 30 percent (Straus and Semmens, 2006). The authors also concluded that an accurate estimate of the number of overweight vehicles can only be obtained if the monitored traffic data are available. In this regard, this study made use of the data collected with WIM equipment installed on two Texas highways to gain an insight into the impact of NAFTA truck traffic on the state's highway system.

Weigh-In-Motion (WIM)

Weigh-In-Motion (WIM) exhibits a number of advantages over static weighing, including: fewer personnel, less time, improved safety, and enhanced convenience in collecting load data. WIM has been widely used in many states across the U.S. California has installed around 100 WIM stations on its highway system (Lu et al, 2002). Texas has 20 WIM stations - predominantly distributed on rural highway

Chapter 3. Data Sources and Methodology

3.1 Data Sources

The axle load data analyzed in this study for each year were obtained by randomly selecting traffic records for two continuous days per quarter at two WIM sites[1] in Texas. A WIM traffic record sample of two days per quarter proved sufficient to provide precise estimates of load-related infrastructure damage (Hong and Prozzi, 2006). The WIM record for each passing vehicle captures detailed traffic information, including date and time of passage, lane and direction of travel, vehicle class, speed, wheel/axle weight, and axle spacing.

Two criteria were applied in selecting the WIM sites from which to sample load data to eventually study the potential impact of NAFTA truck traffic on Texas's infrastructure. First, the data had to meet a temporal requirement. In other words, the traffic data had to have a long enough time-span to study truck traffic changes for a number of years after the implementation of NAFTA. Second, the selected WIM sites had to be close to the Texas-Mexico border and located on a major NAFTA truck corridor. Among the 20 WIM sites in Texas, WIM stations D522 and D516 met these two criteria. Both these sites are on highways that run in the north-south direction. D522 is located on US281, near McAllen in Hidalgo County (Pharr District), which is neighboring Mexico. WIM records are available at this site from 1998 to 2002. D516 is located on I-35 near San Antonio. According to McCray and Harrison (1999), the segment between Laredo and San Antonio moves the highest NAFTA truck volume in Texas. WIM data are available for this site from 1994 to 2002. The geographical location of these two highways in reference to the Texas-Mexico border is illustrated in Figure 9.

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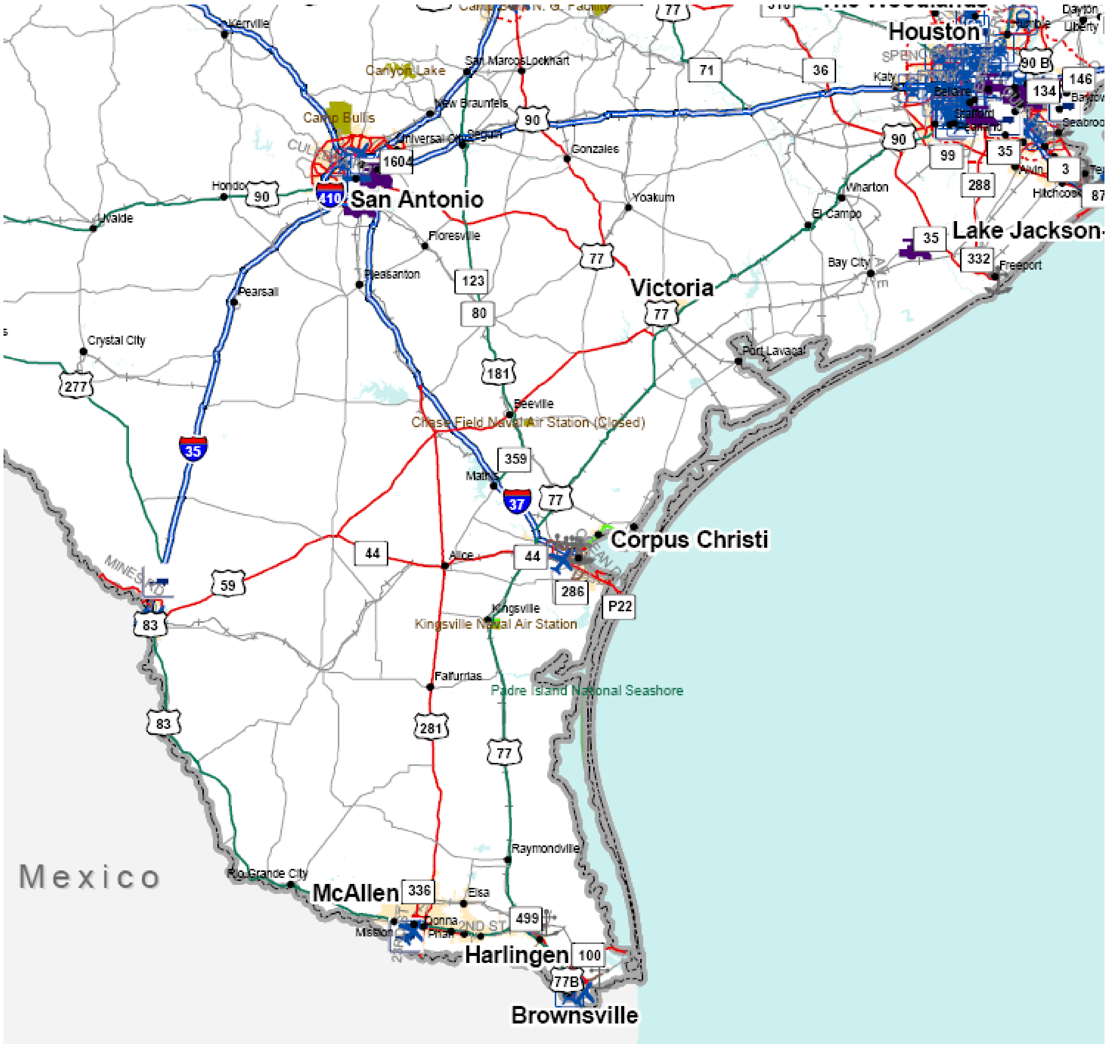
1 Texas's WIM system is administrated by the Transportation Planning and Programming (TP&P) Division of TxDOT. Axle load data, captured by the WIM system across Texas, are available since the beginning of NAFTA.



Source: U.S. Department of Transportation, FHWA:
http://www.fhwa.dot.gov/hep10/nhs/maps/tx/tx_texaseast.pdf, (FHWA, website accessed 2006)

Figure 9: US 281 and I-35 in East Texas

3.2 Methodology

This study focused on axle load data to investigate the potential impact of NAFTA truck traffic on Texas's highway infrastructure. WIM data from two sites - D522 and D516 - were analyzed to determine the change in axle loads since the implementation of NAFTA. Considering the differences in imports and exports from and to Mexico and the axle weight limits in the U.S. and Mexico, it was decided to analyze the traffic loading characteristics in each direction separately at both WIM sites. This allowed for a comparison between the two directions in terms of their traffic load statistics. Finally, the study focused on the three typical axle types: steering axle (usually single axle with single wheel), single axle (single axle with dual wheels), and tandem axles.

3.2.1 Axle Load Temporal and Directional Characteristics

WIM Station D522

Although the axle load characteristics of all truck traffic were explored, an in-depth analysis was undertaken of the two typical truck classes (i.e., Classes 10 and 5) since these two truck classes account for more than 80 percent of the total truck volume. Axle load characteristics can be analyzed by means of distributions, denoted as axle load spectra, and relevant statistics, such as the mean, standard deviation, third and fourth moment (Prozzi and Hong, 2006b).

a) Class 10

Class 10 vehicles have three axle types: single axle with single wheel (referred to as steering axle hereafter), single axle with dual wheels (referred to as single axle hereafter), and tandem axle. Figures 10 to 12 present the axle load spectra for the three axle types in the northbound and southbound directions in 2002. A bin width of 1 kip was used to establish the load spectra of the steering and single axles. For the tandem axle, a bin width of 2 kip was used.

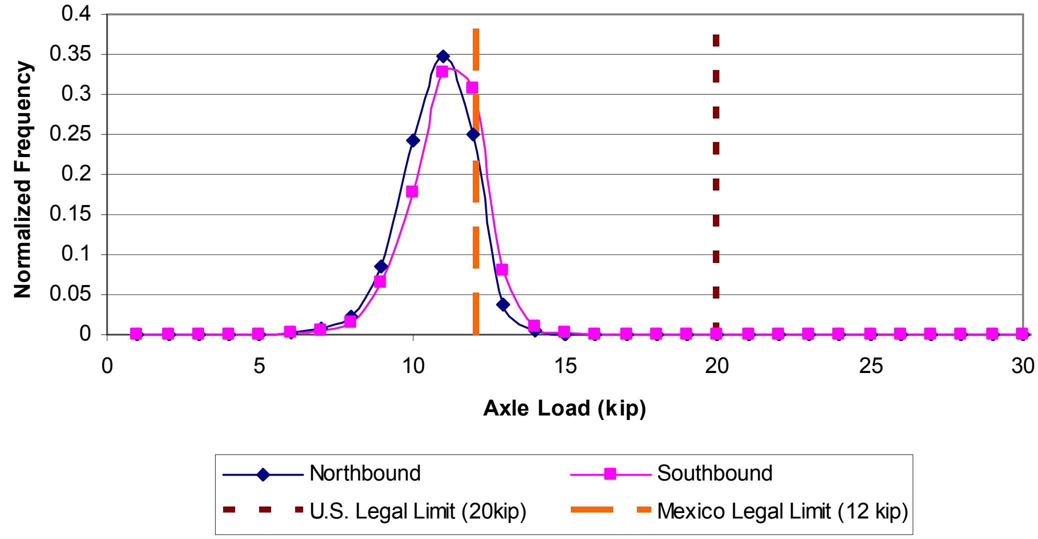


Figure 10: WIM D522 18-Wheeler Steering Axle Load Spectra in Northbound and Southbound Directions (2002)

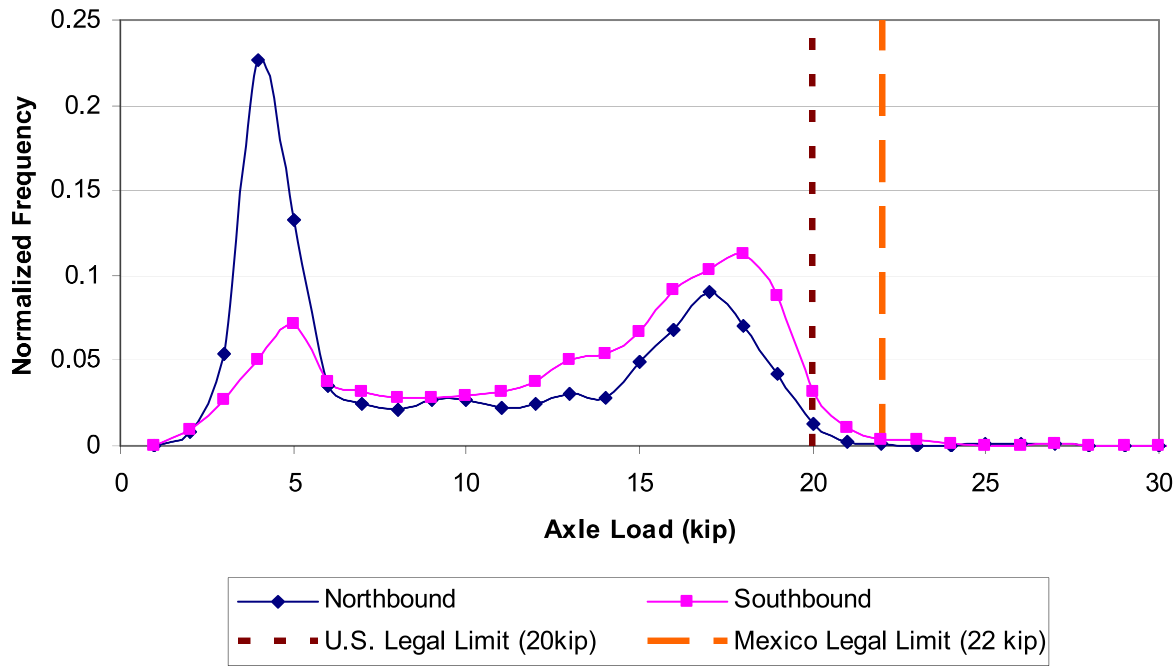


Figure 11: WIM D522 18-Wheeler Single Axle (Dual Wheels) Load Spectra in Northbound and Southbound Directions (2002)

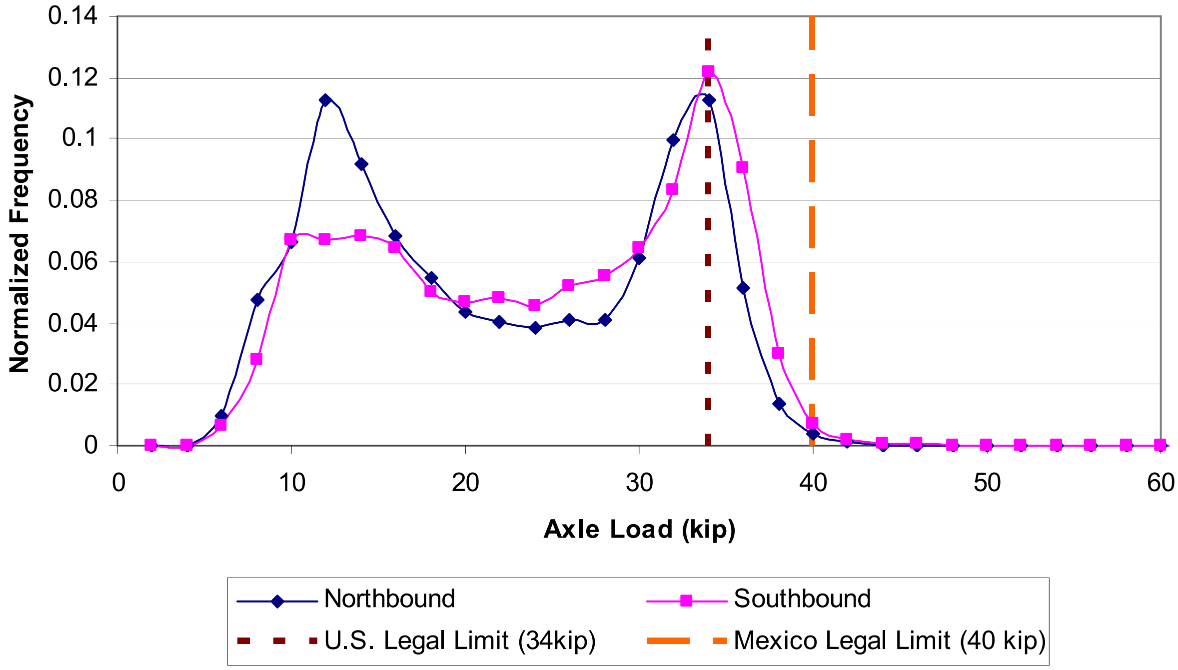


Figure 12: WIM D522 18-Wheeler Tandem Axle Load Spectra in Northbound and Southbound Directions (2002)

Interestingly, it is shown that for all three axle types, the northbound load spectra are to the right of the southbound load spectra. This was true for all four years from 1998 to 2001. This suggests that during these years the trucks entering Texas from Mexico were “lighter” than those entering Mexico from Texas. The differences in the directional load spectra could be attributed to different legal axle limits in the U.S. and Mexico, higher levels of weight enforcement in the U.S., and differences in the cargo characteristics being moved. First, the legal axle limits are generally higher in Mexico than in the U.S. Table 3 illustrates the percentages of axles of Class 10 trucks that exceeded the legal limits given U.S. and Mexican legal axle limits from 1998 to 2002. For example, the percentage of tandem axles that exceeded the legal limit were between 3 and 15 percent given the U.S. regulations, but almost zero under the Mexican regulations, because the legal axle limit in Mexico is 6 kip higher than in the U.S. This may suggest that the southbound trucks carry heavier payloads, because they are heading to Mexico that allows heavier legal axle limits, while the opposite is true for trucks traveling northbound into the U.S. Second, it is believed that the U.S. has a higher weight enforcement level than Mexico. Finally, differences in the cargo characteristics that move south and northbound may partly contribute to the directional difference in axle load spectra. For example, heavier and denser goods may be exported via truck to Mexico that what is imported via truck from Mexico. The differences in cargo moved and the associated impact on axle load spectra were considered beyond the scope of this study, but should be explored further.

Table 3: Percentages of 18-Wheeler Truck Axles Exceeding Legal Limits under Different Regulations (WIM Station D522)

Direction	Axle Type	Regulation	1998 (%)	1999 (%)	2000 (%)	2001 (%)	2002 (%)
Northbound	***Steering***	*U.S.*	0.0	0.0	0.0	0.0	0.0
		Mexico	0.6	1.2	1.7	3.3	4.3
	Tandem	*U.S.*	4.1	3.2	5.0	7.1	7.0
		Mexico	0.0	0.1	0.1	0.2	0.2
Southbound	***Steering***	*U.S.*	0.0	0.0	0.0	0.0	0.0
		Mexico	4.1	3.7	2.9	9.8	9.5
	Tandem	*U.S.*	12.1	9.2	7.8	15.0	13.1
		Mexico	0.2	0.2	0.4	0.4	0.3

Figures 13 to 16 illustrate the axle load spectra for the steering and tandem axles of Class 10 trucks between 1998 and 2000 in the northbound and southbound travel directions separately. Comparing these Figures, it is evident that the load spectra of the tandem axle shows two modes (peaks) as oppose to the one mode (peak) of the steering axle. The text box following Figure 16 elaborates the meaning of the different shapes of the tandem axle load spectra. Also, Figures 13 and 14 show that the axle load spectra of the steering axle are shifting right with time for both travel directions. The same right shift is not as evident in the case of the tandem load spectra. The implications of the two modes in the load spectra of the tandem axle and the rightward shift in the axle load spectra of the steering axle in terms of infrastructure damage over time are discussed in Section 3.3.

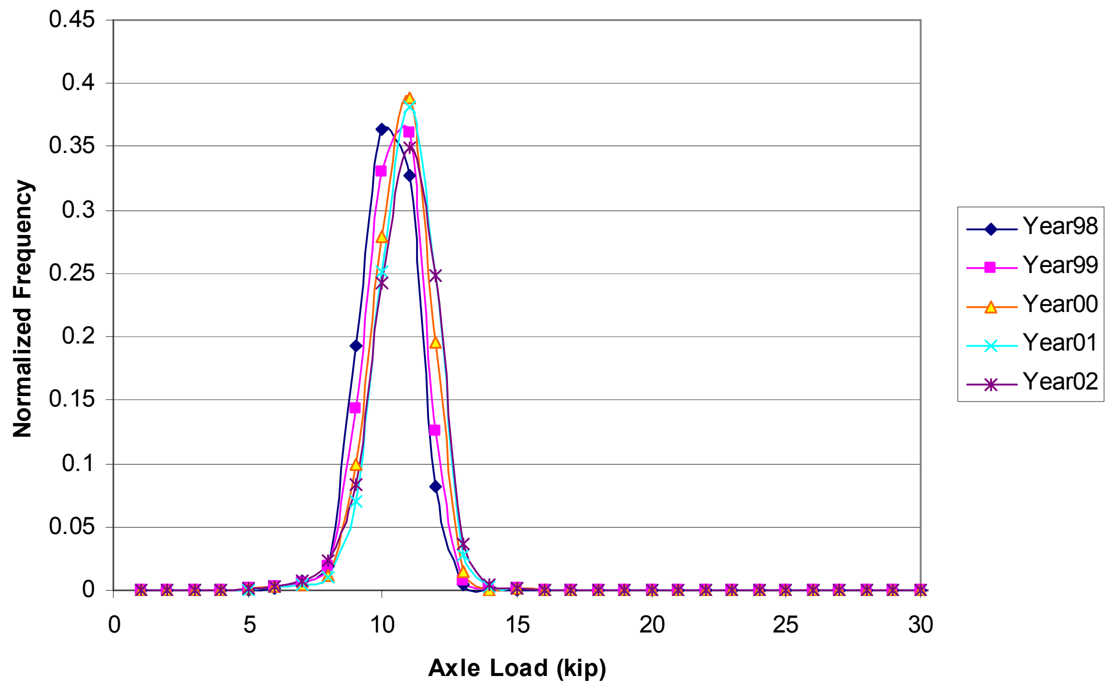


Figure 13: D522 18-Wheeler Steering Axle Load Spectra (Northbound)

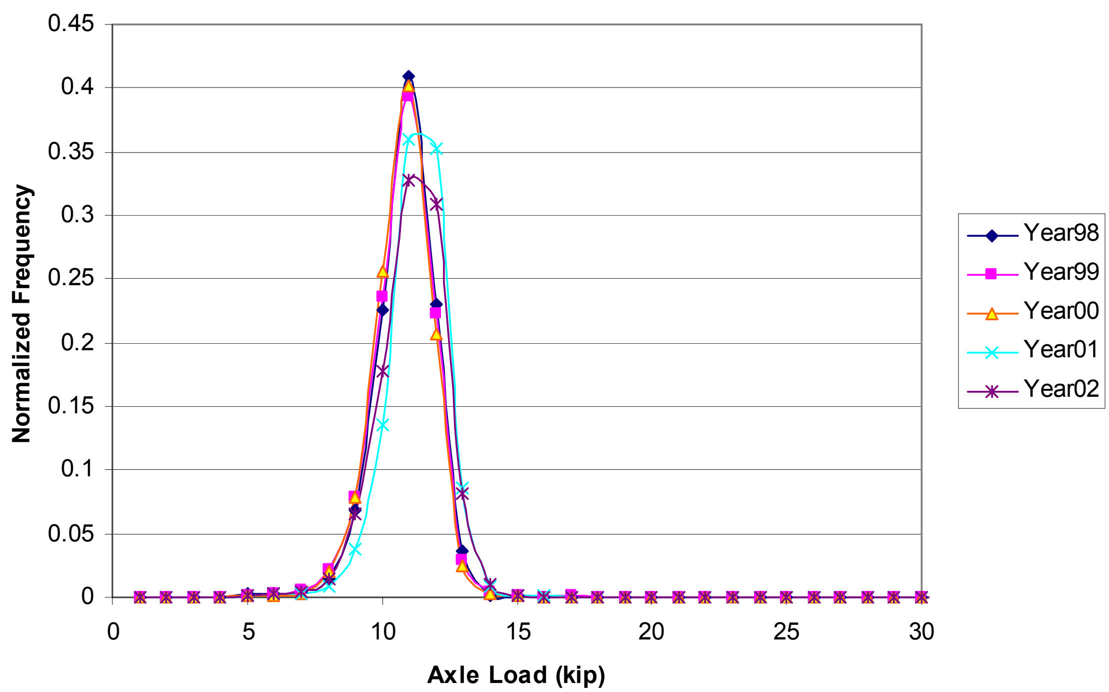


Figure 14: D522 18-Wheeler Steering Axle Load Spectra (Southbound)

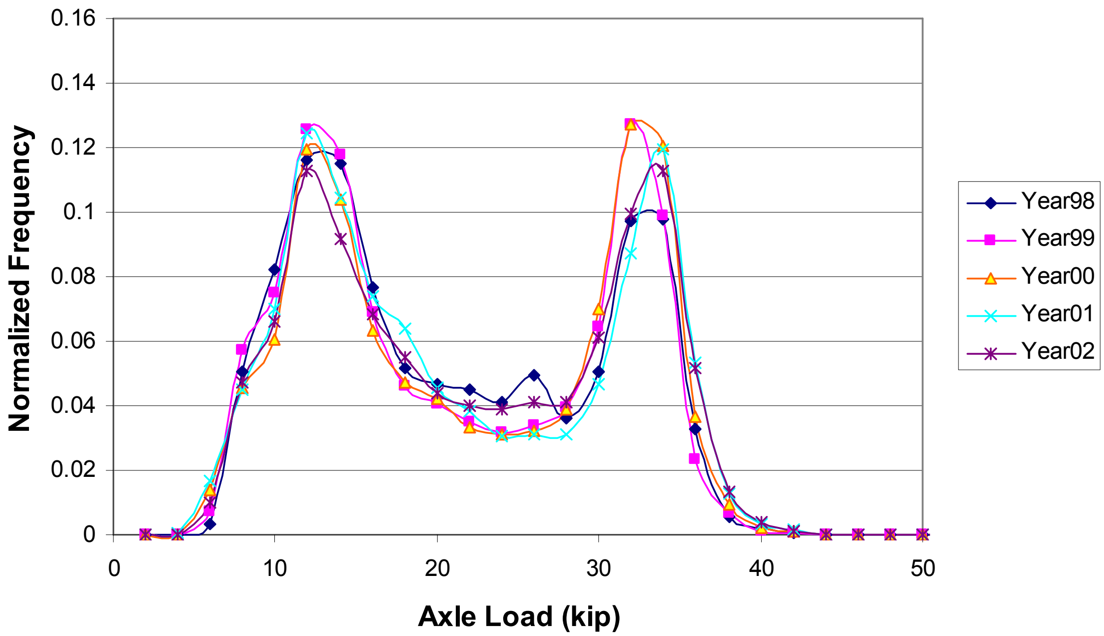


Figure 15: D522 18-Wheeler Tandem Axle Load Spectra (Northbound)

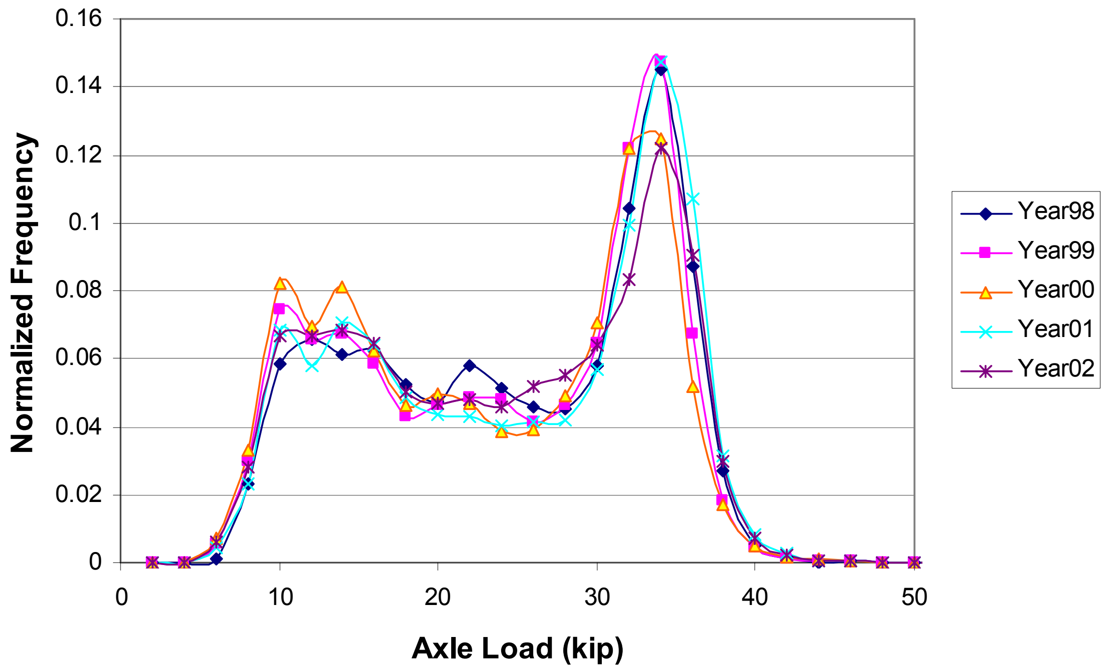
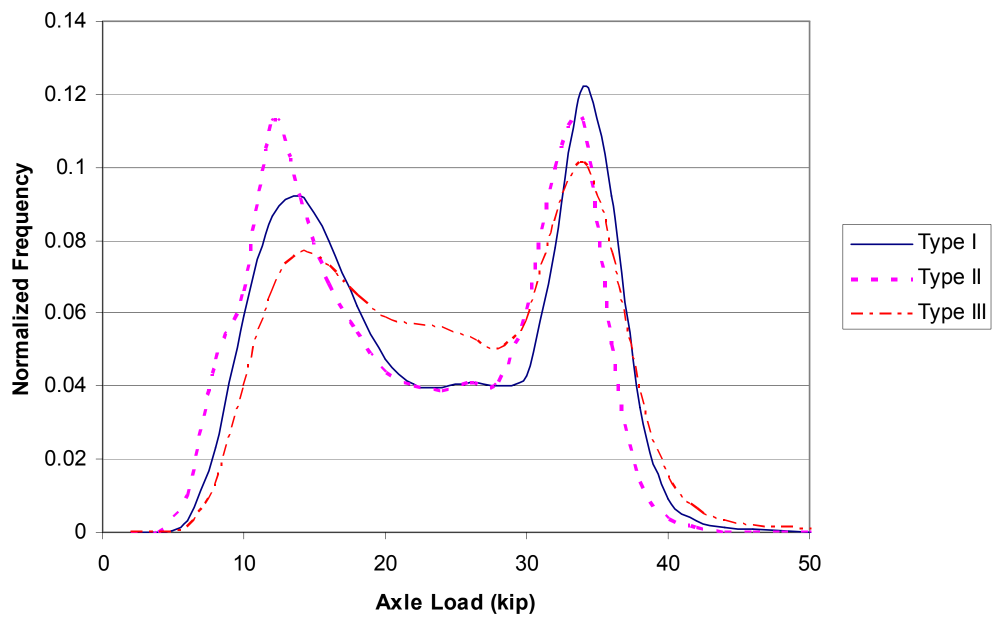


Figure 16: D522 18-Wheeler Tandem Axle Load Spectra (Southbound)

Axle Load Spectra Patterns for Tandem Axles on 18-Wheeler Trucks

Previous research has identified three typical patterns in terms of the height of the two modes (peaks) of a tandem axle load spectrum (Hong & Prozzi, 2006). Type I represents a "light" load spectrum with the left peak higher than right peak (see Figure below) [The left peak is not higher than the right peak]. Type II represents a "medium" load spectrum with the left and right peaks showing similar height. Type III represents a "heavy" load spectrum with the left peak lower than the right peak. Typically, the axle load spectrum of a tandem axle resembles one of these three patterns. From Figure 15, it is evident that the northbound load spectra demonstrate a Type II pattern, while the southbound load spectra demonstrate a Type III pattern (see Figure 16).



By exploring the differences in the load spectra for the two travel directions, it became evident that for both axle types, the northbound load spectra are slightly to the right of the southbound load spectra on the x-axis. This suggests that between 1998 and 2002 the Class 10 trucks that entered Texas were on average "lighter" than those entering Mexico. A more in-depth analysis of the difference in axle load spectra for the tandem axle by travel direction was undertaken, because the tandem axle is the dominant axle on Class 10 trucks and, more importantly, it reflects the payload more closely.

b) Class 5

The same procedure used to analyze the loading characteristics of Class 10 trucks was used to analyze the loading characteristics of Class 5 trucks, which represents the second largest percentage of total truck volume. The load spectra of the Class 5 trucks are illustrated in Figures 17 to 20 for the steering and single axles by travel direction, respectively. As can be seen, there is almost no difference in the axle load spectra for the two travel directions. Also, there is no evidence of a shift in the load spectra over time in both travel directions for either the steering or the single axles. Regarding axle loadings exceeding legal limits, almost zero percent of the steering axles exceeded the U.S. and Mexican axle load regulations. The same is true for single axles given U.S. regulations, while a very small percentage of the single axles exceeded the Mexican legal axle limits.

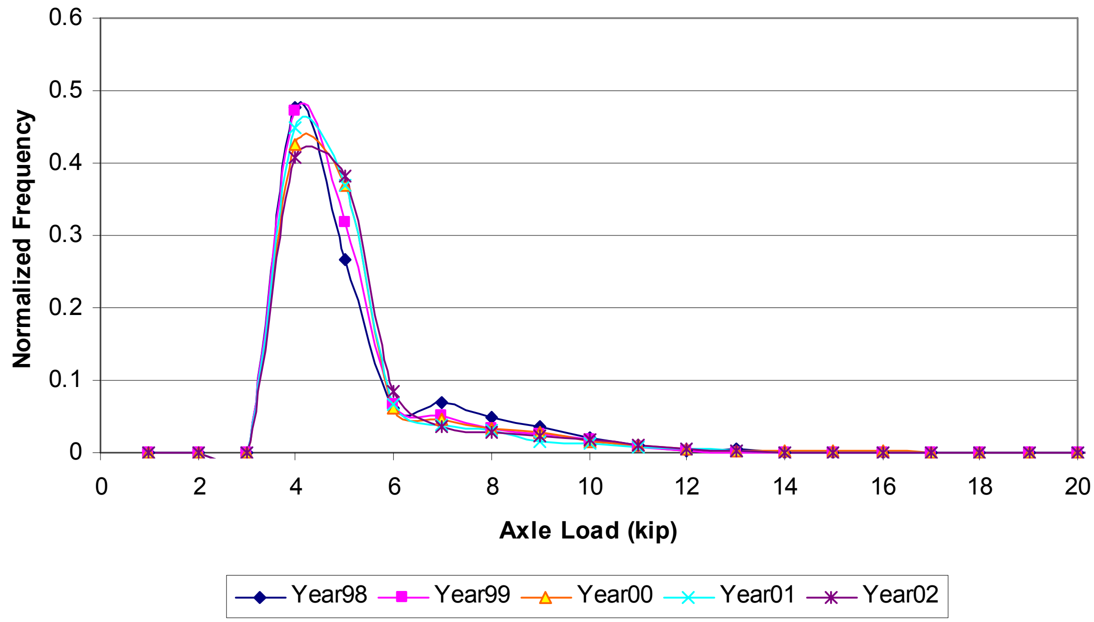


Figure 17: WIM D522 Class 5 Steering Axle Load Spectra (Northbound)

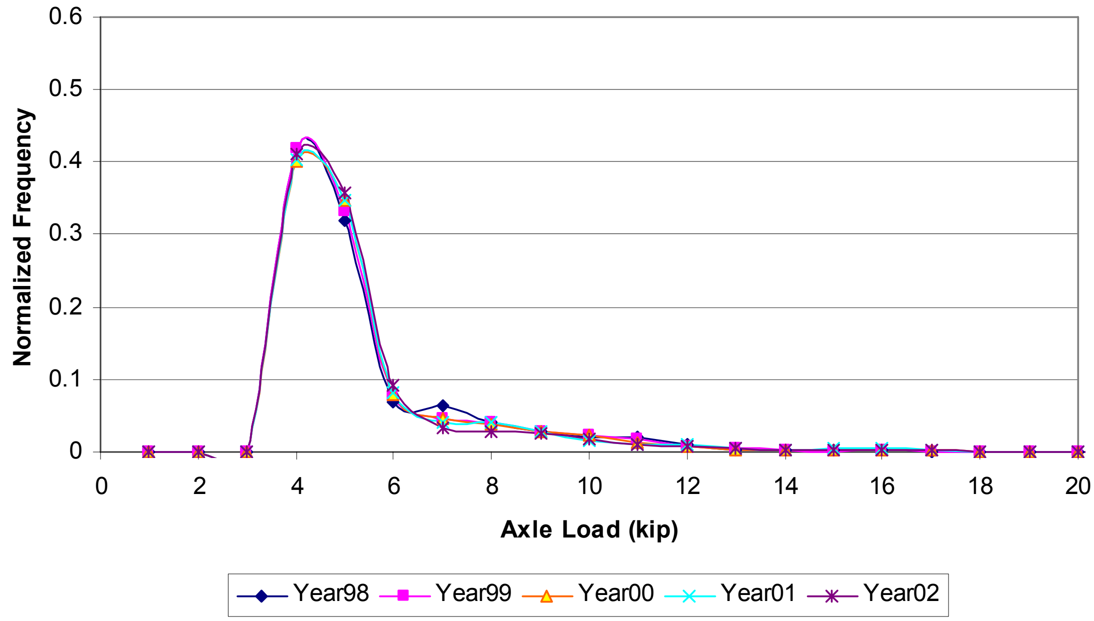


Figure 18: WIM D522 Class 5 Steering Axle Load Spectra (Southbound)

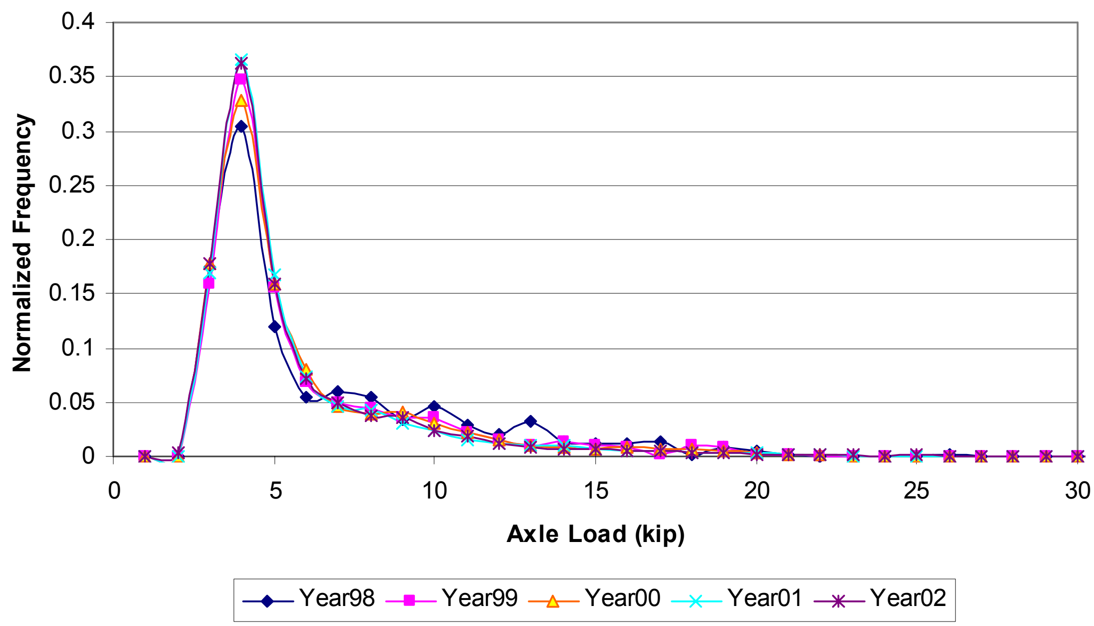


Figure 19: WIM D522 Class 5 Single Axle Load Spectra (Northbound)

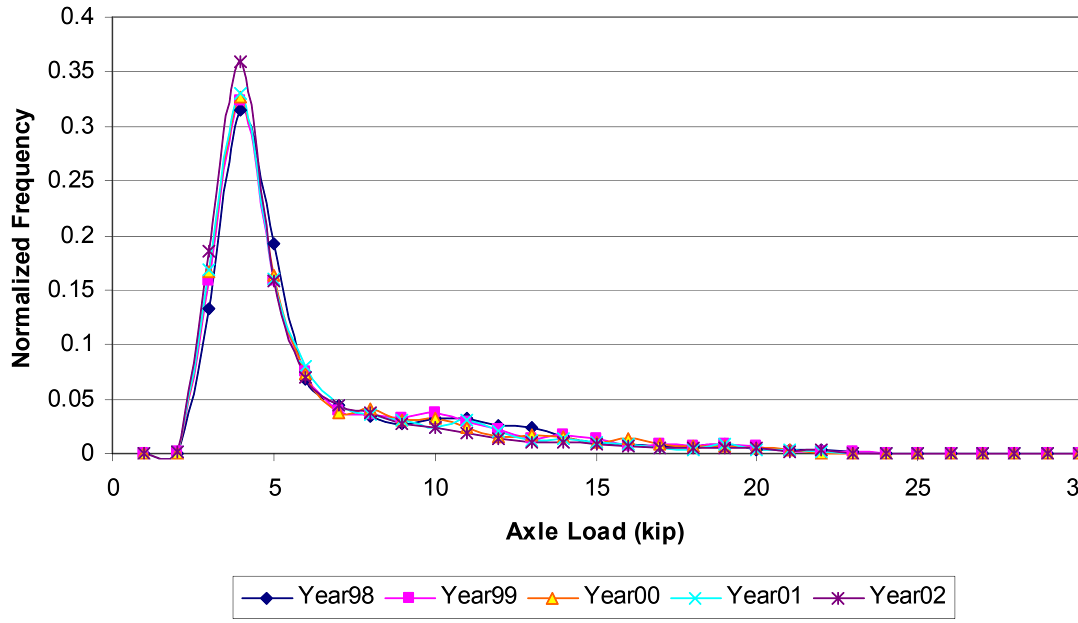


Figure 20: WIM D522 Class 5 Single Axle Load Spectra (Southbound)

c) All truck classes

In addition, the loading characteristics of all the truck classes combined were analyzed. Figures 21 to 26 show the axle load spectra for the three typical axles by travel direction between 1998 and 2002. As can be seen, the axle load distribution characteristics for all trucks are similar to that of Classes 10 and 5, since these two classes are the dominant truck types. For example, comparing the northbound steering axle load spectra for Class 10 (Figures 13) and for Class 5 (Figure 17) with the results for all trucks (Figure 21), it is evident that the load spectra for all trucks are almost a combination of that for Class 10 and Class 5. In the case of single axles, it can be shown that the northbound axle load spectra for all trucks (Figure 23) are similar to that for Class 5 trucks (Figure 19), because the majority of the single axles belong to Class 5 with some influence from Class 10. In the case of tandem axles, the counts are dominated by Class 10 trucks and thus the northbound axle load spectra for all trucks (Figure 25) are similar to the northbound axle load spectra for Class 10 trucks (Figure 15). The same analysis can be done for the southbound direction. To conclude, the analysis showed that the loading characteristics of all trucks are similar to that of the two dominant truck classes – Classes 10 and 5.

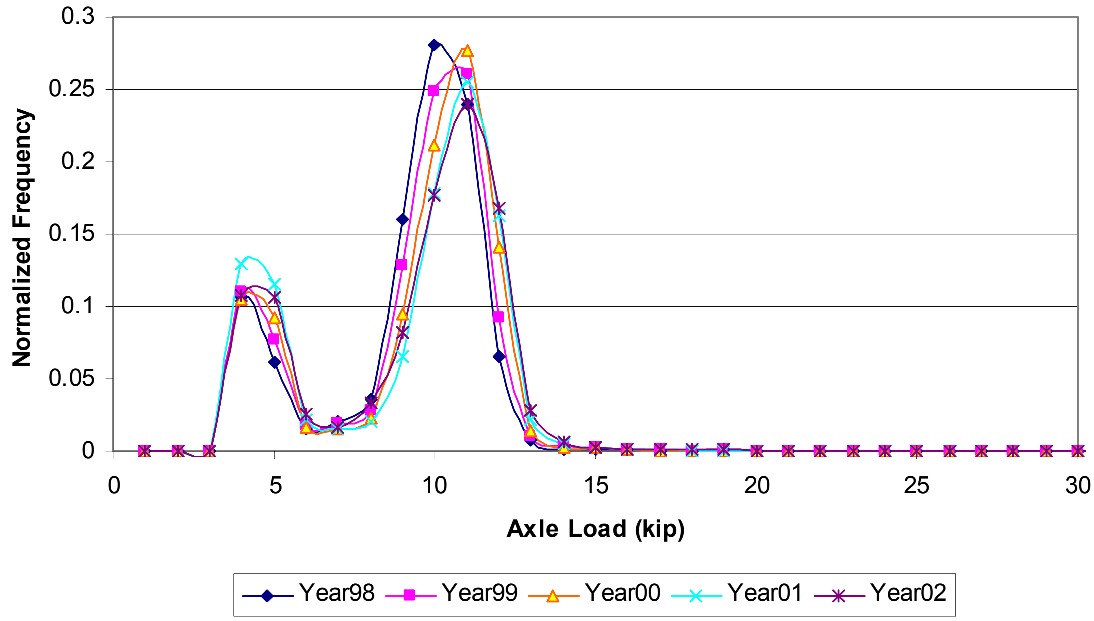


Figure 21: WIM D522 All Truck Steering Axle Load Spectra (Northbound)

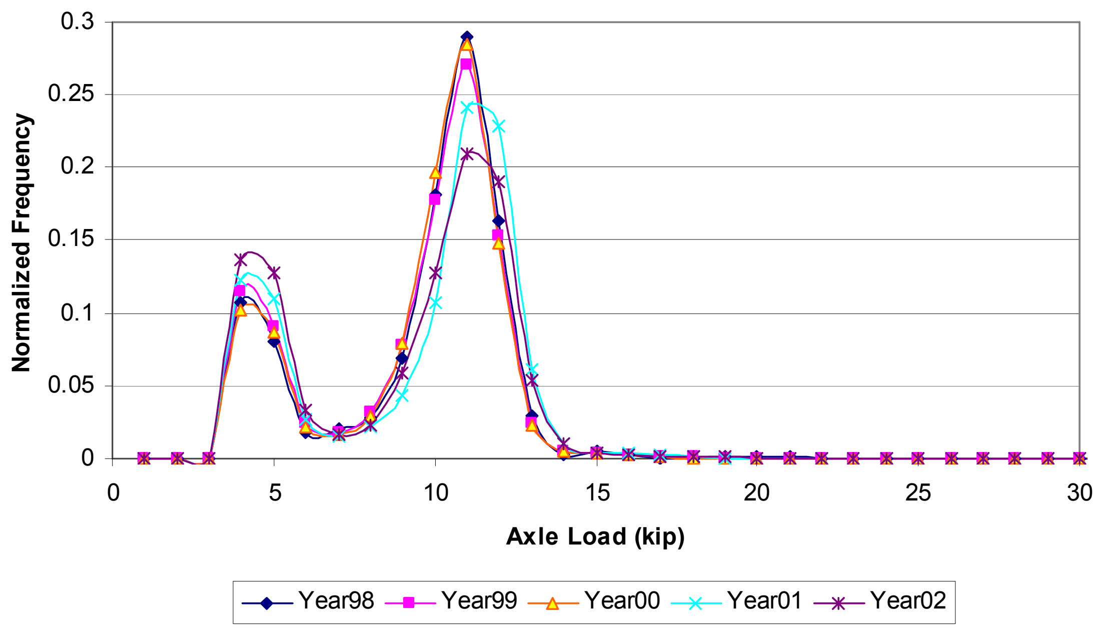


Figure 22: WIM D522 All Truck Steering Axle Load Spectra (Southbound)

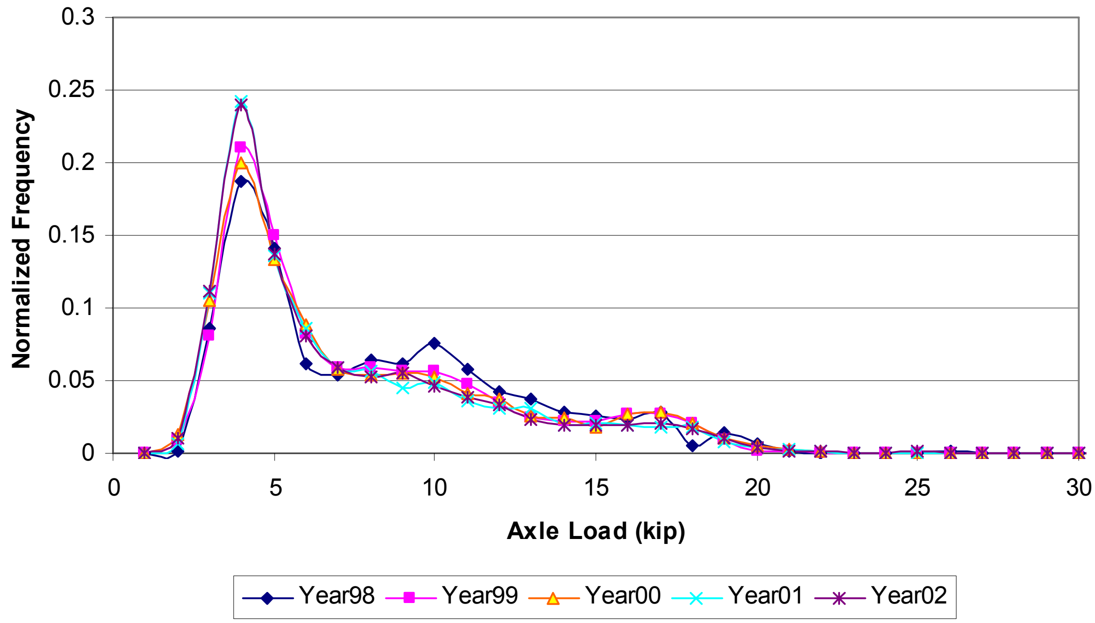


Figure 23: WIM D522 All Truck Single Axle Load Spectra (Northbound)

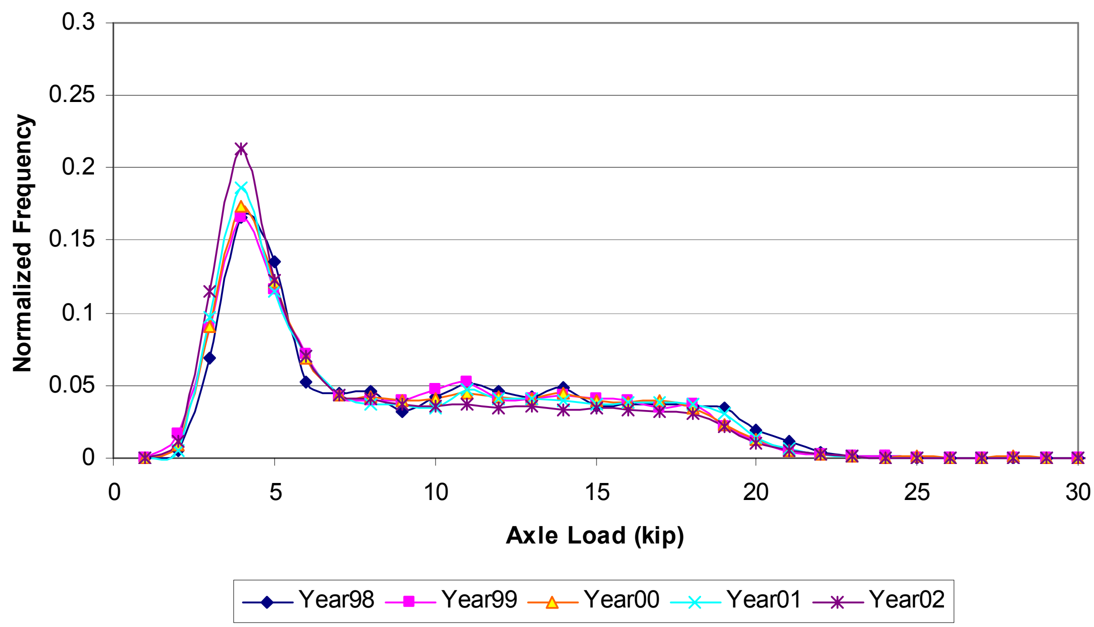


Figure 24: WIM D522 All Truck Single Axle Load Spectra (Southbound)

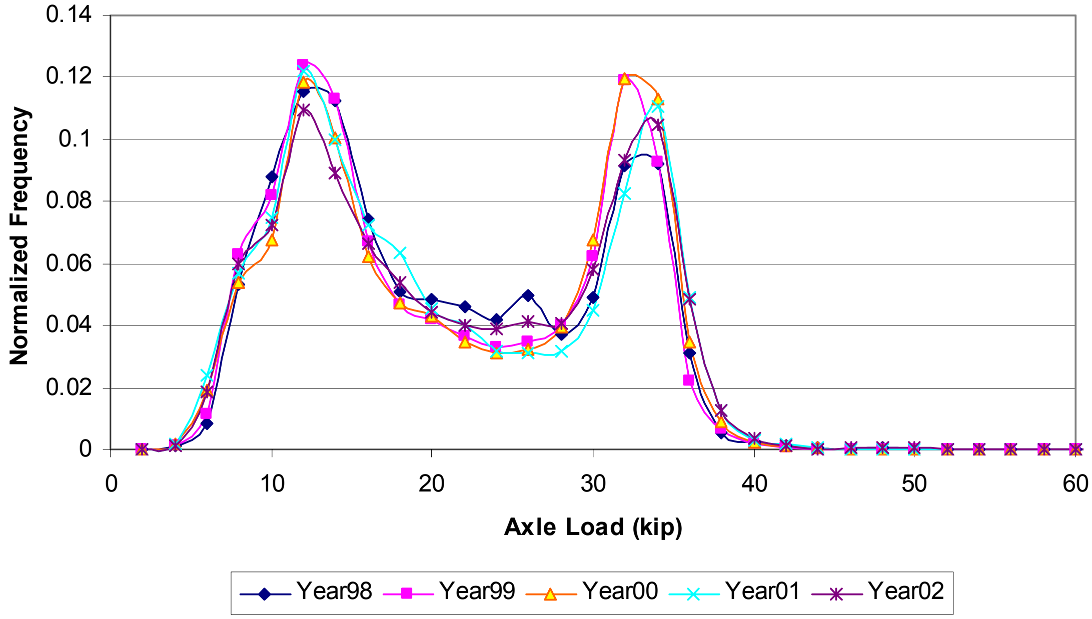


Figure 25: WIM D522 All Truck Tandem Axle Load Spectra (Northbound)

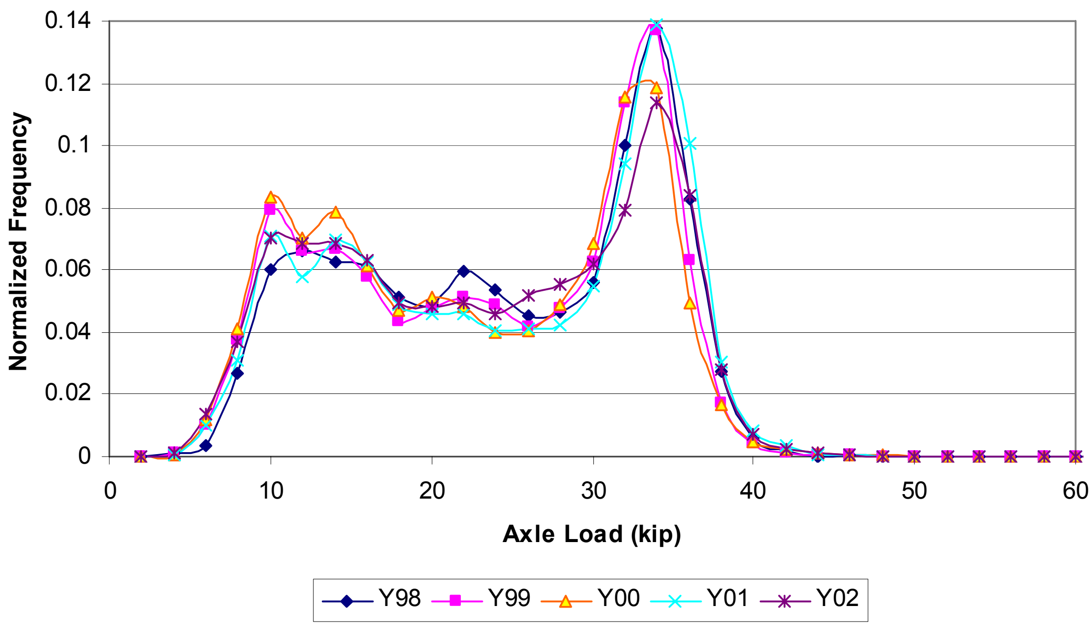


Figure 26: WIM D522 All Truck Tandem Axle Load Spectra (Southbound)

WIM Station D516

The same approach was adopted for analyzing the axle load data obtained at WIM station D516. The results in terms of load distribution pattern and directional and temporal characteristics were found to be very similar to that at WIM station D522. For illustration, the axle load spectra for the dominant truck class, Class 10, is shown herein. Figures 27 to 30 illustrate the steering and tandem axle load spectra of Class 10 trucks between 1994 and 2002 by travel direction, respectively. The load spectra for single axles are not listed, because the sample was found to be small.

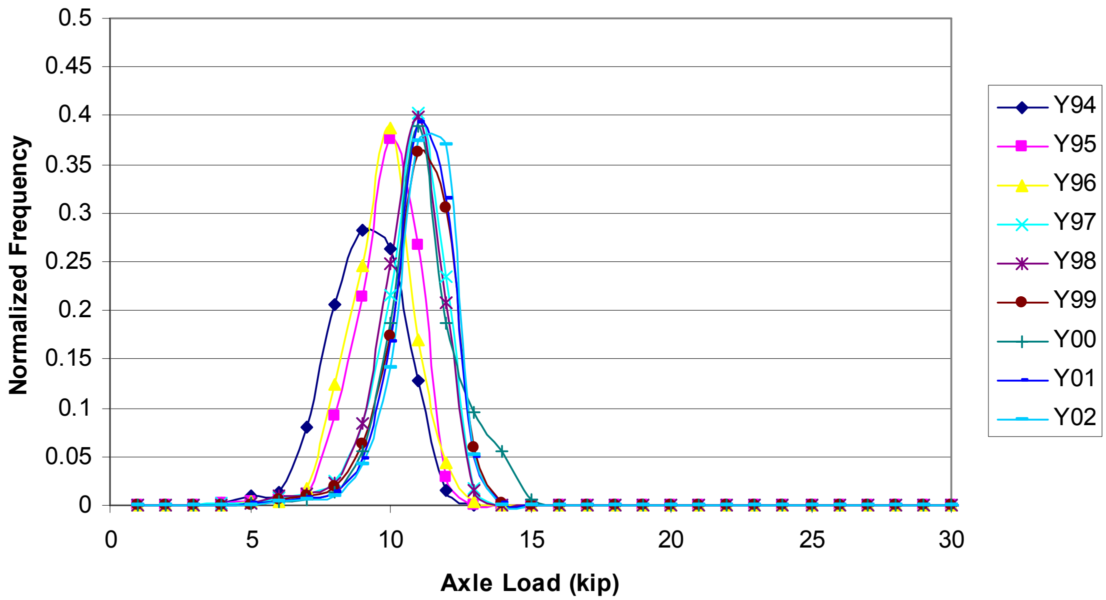


Figure 27: WIM D516 18-Wheeler Steering Axle Load Spectra (Northbound)

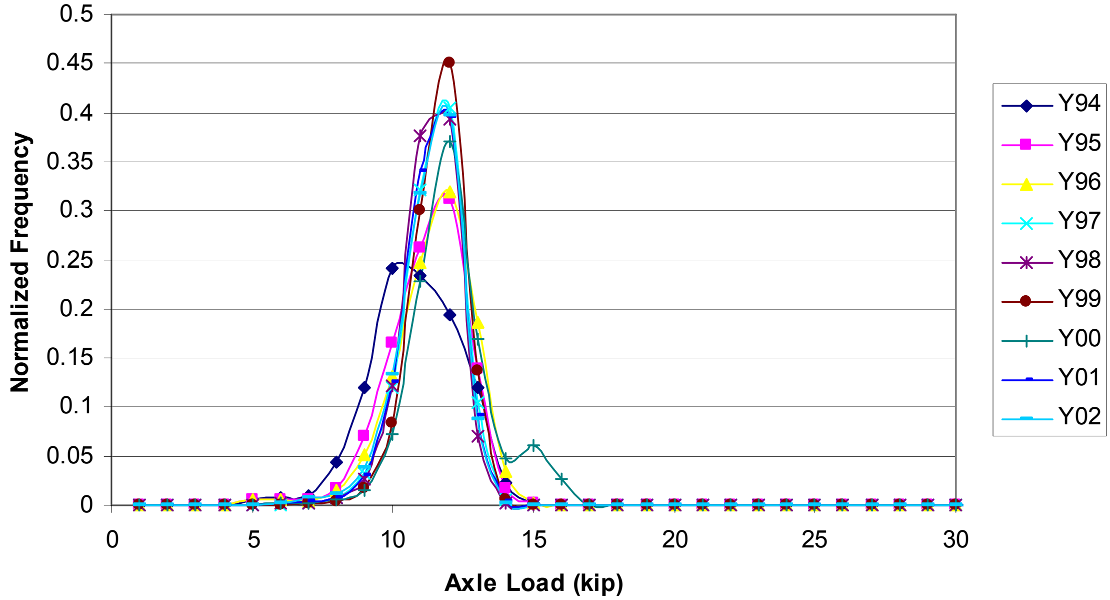


Figure 28: WIM D516 18-Wheeler Steering Axle Load Spectra (Southbound)

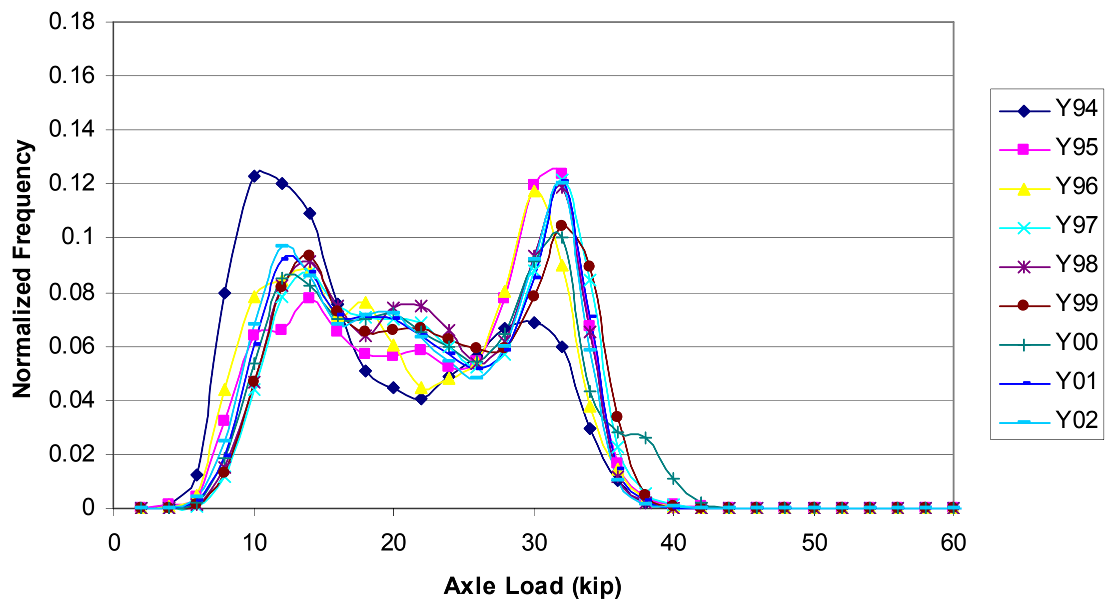


Figure 29: WIM D516 18-Wheeler Tandem Axle Load Spectra (Northbound)

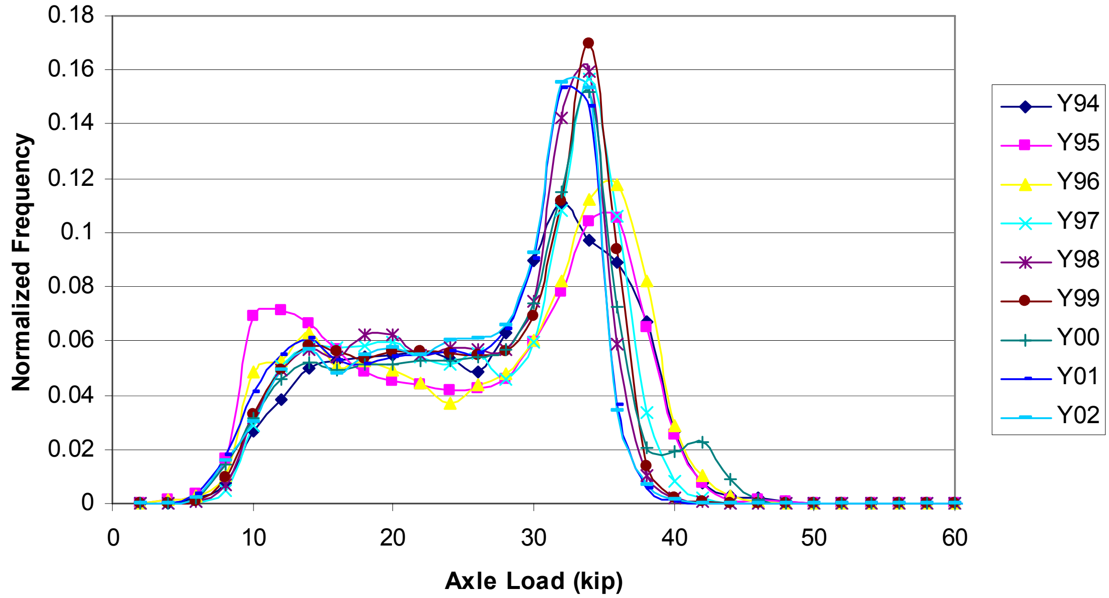


Figure 30: WIM D516 18-Wheeler Tandem Axle Load Spectra (Southbound)

From Figures 27 and 28, it is evident that the load spectra for the steering axle exhibit a constant shift to the right (to "heavier" loads) over the analysis period and that the southbound axles were heavier than the northbound axles. Second, for tandem axles, there is a significant difference between the load spectra patterns in the two traveling directions. The northbound traffic exhibit type I or a load spectra pattern between type I and II, while the southbound traffic exhibit a type III pattern. This implies that the northbound traffic carry lighter loads than the southbound traffic. Finally, the load spectra for the tandem axles did not show a significant shift over the analysis period.

In identifying the percentage of axles that exceeded legal axle limits, the emphasis was on tandem axles, because most of the payload is carried by these axles. Figure 31 illustrates the axle load distribution in both travel directions in 2002, as well as the legal U.S. and Mexican axle load limits. The results were similar to what was found at WIM station D522. Almost no tandem axles were found to exceed the Mexican axle load limits, but a significant percentage was found to exceed the U.S. axle load limits.

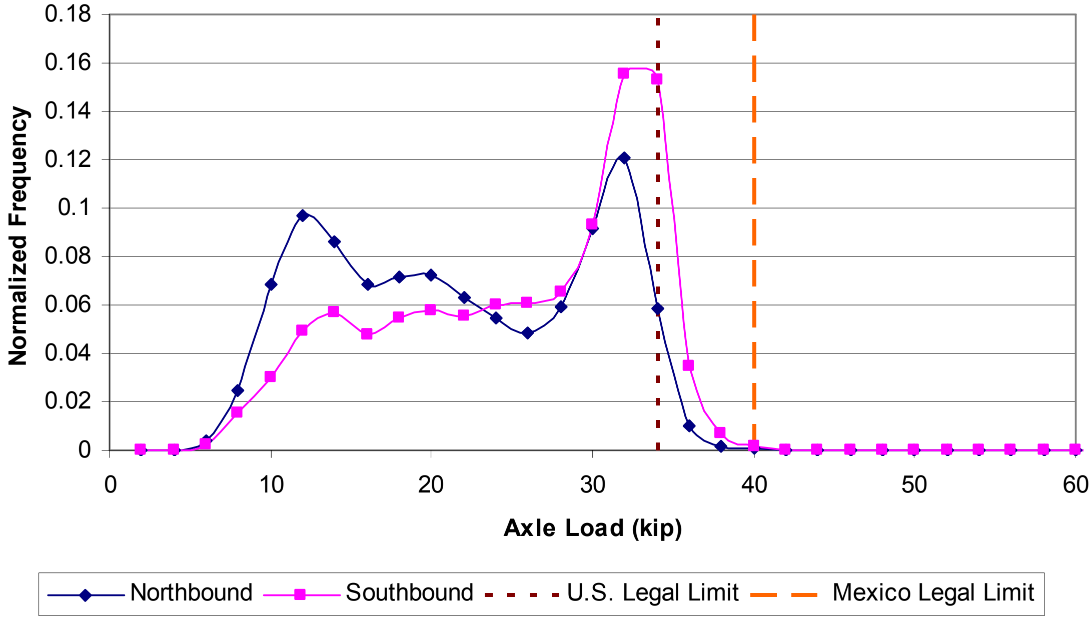


Figure 31: WIM D516 18-Wheeler Tandem Axle Load Spectra in Both Travel Directions (2002)

3.3 Statistical Analysis of Load-Related Highway Infrastructure Damage

The AASHO Road Test established that the damage of each individual axle load on a flexible pavement can be estimated according to the *fourth power law* (AASHTO, 1993; Huang, 2003). The *fourth power law* states that pavement damage by passing vehicles increases exponentially with an increase in their axle load. This relationship is denoted by the Load Equivalence Factor (LEF),

$$LEF = \left(\frac{x_i}{L_s}\right)^m \qquad (2)$$

Where,

x_i: Weight of axle load (lbs) in the *i*th bin, assuming that axle loads within each bin are identical;

L_s: Load weight on a standard axle with the same number of axles as x_i, usually 18 kip for the single axle and 33 kip for the tandem axle, but the latter depends on the pavement structure, and

m: Power (typically 4) denoting the relative damage to the pavement of a given load x_i.

As a result, the pavement load damage attributable to a given axle load distribution can be obtained by summing the contributions from all the loads x_r in the distribution, denoted as the load spectra factor[2] (LSF). The LSF (where m = 4) can be denoted as:

$$LSF = \sum_{i=1}^{R} \left(\frac{x_i}{L_s} \right)^4 f_i \tag{3}$$

Where,

R : Total number of load bins, and

f_i: Normalized frequency of load in the *i*th bin of a given load spectrum.

For illustration purposes, two statistics concerning the load spectra for the Class 10 trucks are presented: (1) the first moment, or mean, representing the magnitude of the average load, and (2) the fourth moment, representing the load-associated pavement damage. Table 4 presents these statistics for the traffic data obtained from WIM station D522. From Table 4, it is evident that between 1998 and 2002, the mean axle load and the load-associated pavement damage increased. In addition, it was found that for each individual axle, the load impact on the pavement in the southbound direction was larger than the load impact on the pavement in the northbound direction. This supports the earlier findings regarding the characteristics of the axle load distributions by travel direction.

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2 The *LSF* is the fourth sample moment statistic divided by a constant, L_s^4 (Prozzi and Hong, 2006b).

Table 4: Summary Statistics for Class 10 Axle Loads (WIM Station D522)

Statistics	Axle Type	Direction	Year				
			1998	**1999**	**2000**	**2001**	**2002**
Mean	***Steering***	*Southbound*	10.87	10.81	10.77	11.30	11.12
		Northbound	10.25	10.44	10.68	10.87	10.82
	Tandem	*Southbound*	24.72	24.20	23.41	24.92	24.20
		Northbound	21.05	21.19	22.16	21.47	22.17
LSF*	***Steering***	*Southbound*	0.14	0.14	0.14	0.16	0.16
		Northbound	0.11	0.12	0.13	0.14	0.14
	Tandem	*Southbound*	0.57	0.54	0.50	0.60	0.55
		Northbound	0.37	0.39	0.44	0.42	0.44

* LSF is a statistic associated with the fourth moment of an axle load distribution

Figures 32 and 33 show the change in the LSF over time for the steering and the tandem axles of Class 10 trucks by travel direction, respectively. The solid lines represent the linear trends. For both axle types, the slope of the lines implies that the pavement damage from northbound Class 10 trucks increased faster than that of southbound Class 10 trucks. The relatively "flat" slope (close to zero) of the southbound trend line might indicate that the LSF cannot increase further because of the legal axle load limits and the current weight enforcement level. Moreover, Figures 32 and 33 seems to indicate that the northbound LSF is approaching that of the southbound LSF, a process that might be accelerated when the border opens to Mexican truck traffic. From an axle load distribution viewpoint, the "light" load spectrum of northbound Class 10 traffic is thus evolving to a "heavy" load spectrum similarly to what is observed in the southbound direction. Particularly, for the tandem axle, a change from the existing northbound load spectra of Types I or II to Type III can be predicted with confidence given the current legal axle limits and level of weight enforcement. This finding has implications for highway agencies and transportation policy makers trying to forecast and evaluate load associated pavement damage.

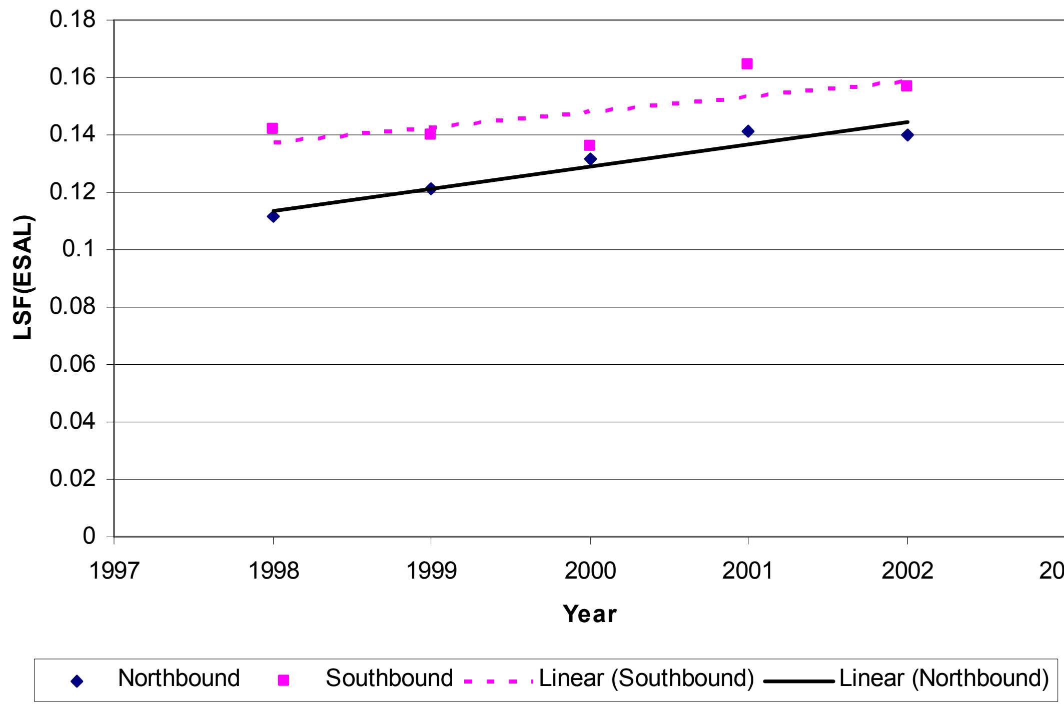

Figure 32: LSF for Class 10 Steering Axle over Time in Both Travel Directions (D522)

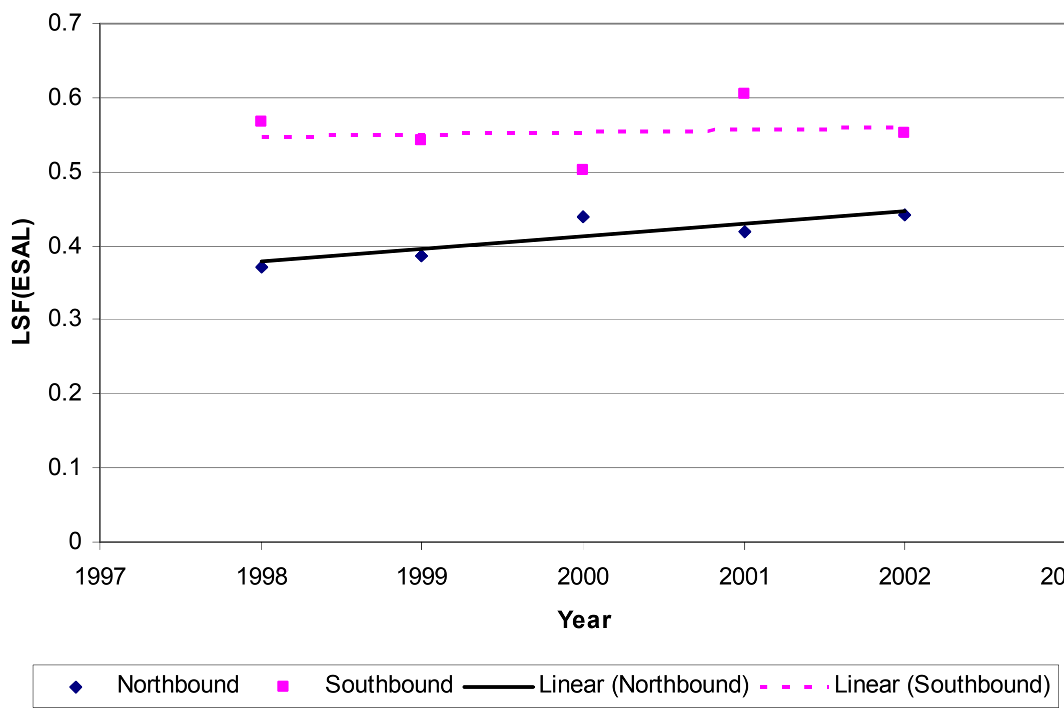

Figure 33: LSF for Class 10 Tandem Axle over Time in Both Travel Directions (D522)

Table 5 and Figures 34 and 35 show the same statistics for the Class 10 truck data obtained at WIM D516. In general, the results are similar to what were found at D522. In addition, since the information at D516 was available over a longer time period (i.e., 1994 to 2002) compared to D522 (i.e., 1998 to 2002) additional insight could be gained into the change in the load associated pavement damage over time. Figure 34 shows that the LSF for the steering axles in both travel directions increased over time, but that the increase slowed after 2000. On the other hand, Figure 35 shows that the LSF for the tandem axles in the northbound direction increased over time, but that the LSF in the southbound direction fluctuated and declined after 1997. This decline could be attributed to the 1997 Mexico Peso crisis and also improved weight enforcement levels.

Table 5: Summary Statistics for Class 10 Axle Loads (WIM Station D516)

Statistics	Axle Type	Direction	Year								
			1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Mean	***Steering***	*Southbound*	10.79	11.20	11.45	11.41	11.32	11.60	12.10	11.36	11.29
		Northbound	9.12	9.85	9.69	10.71	10.64	11.00	11.18	11.06	11.17
	Tandem	*Southbound*	26.86	25.24	26.52	26.18	25.53	25.81	26.51	24.89	25.33
		Northbound	18.78	22.82	21.32	22.98	22.44	22.89	22.73	22.17	21.75
LSF	***Steering***	*Southbound*	0.15	0.16	0.18	0.17	0.16	0.18	0.22	0.17	0.16
		Northbound	0.07	0.10	0.09	0.13	0.13	0.15	0.16	0.15	0.16
	Tandem	*Southbound*	0.70	0.66	0.73	0.64	0.56	0.60	0.69	0.53	0.54
		Northbound	0.25	0.41	0.34	0.41	0.38	0.41	0.42	0.38	0.36

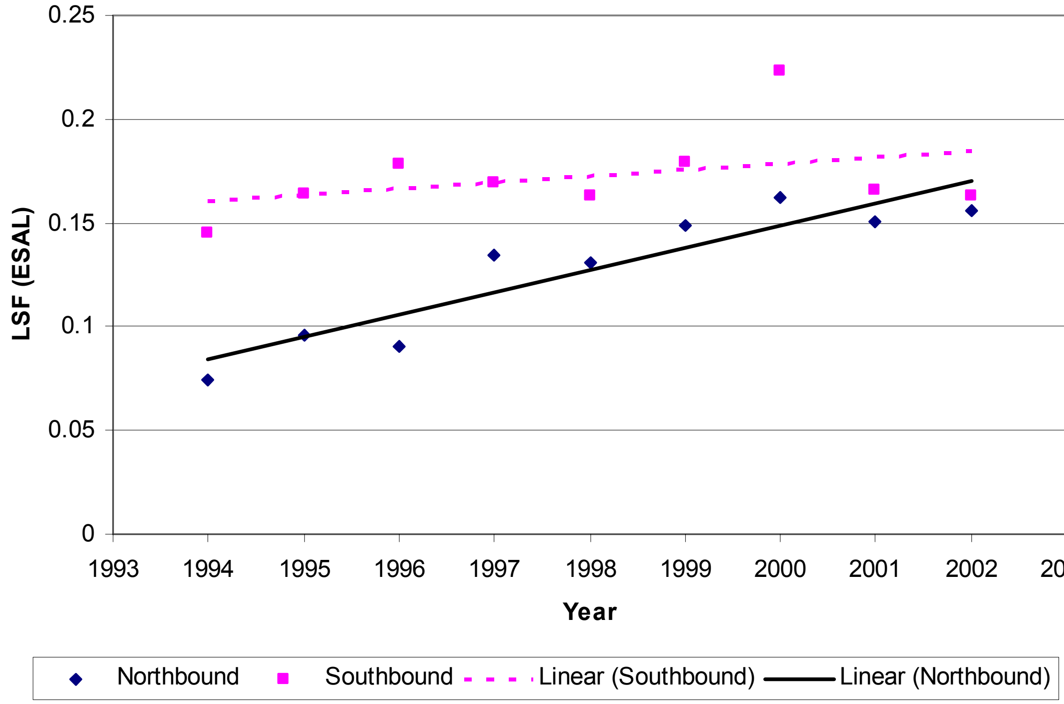

Figure 34: LSF for Class 10 Steering Axle over Time in Both Travel Directions (D516)

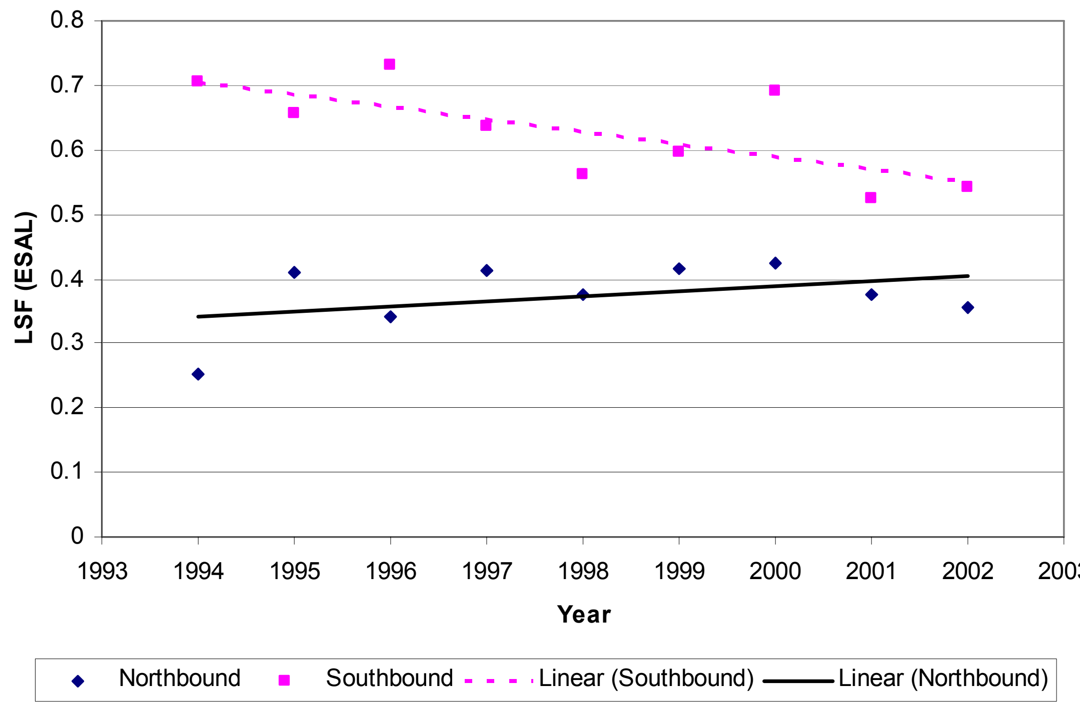

Figure 35: LSF for Class 10 Tandem Axle over Time in Both Travel Directions (D516)

To conclude, it is foreseen that the LSF trend lines in each of the travel directions will converge in the future to a point at which truck capacities will be utilized to an optimum given the current regulations and weight enforcement level.

Chapter 4. Conclusions

This project analyzed the infrastructure impacts imposed by truck loads from data obtained at two WIM stations in two of the key U.S.-Mexico highway trade corridors in Texas. Both the spatial and temporal characteristics of truck loads were examined. The axle load distributions for different axle types (e.g., steering, single, and tandem axles) for the two dominant truck classes – Class 5 and Class 10 - as well as for all truck classes combined were presented. Finally, relevant statistics to illustrate the load associated pavement damage over time were calculated and presented. The most salient findings of this research are as follows:

1) The axle load distributions are different for different truck classes and axle types, partly because of differences pertaining to the distances and types of cargo moved by the different truck classes. However, typically the load distributions reveal a single mode or two modes (peaks).

2) There was a significant difference in the load distributions, as well as relevant statistics, of the Class 10 truck type by travel direction: southbound to Mexico and northbound from Mexico. Specifically, it was found that the southbound axle loadings were on average heavier than the northbound axle loadings. In addition, it was found that for each individual axle, the load impact on the pavement in the southbound direction was larger than on the pavement in the northbound direction. Finally, it was found that a higher percentage of the axle loadings in the southbound direction exceeded legal limits.

3) There has been a constant shift towards a heavier axle load distribution for Class 10 trucks since 1994, resulting in an increase in the load associated pavement damage over the same time period. Specifically, the pavement damage imposed by northbound Class 10 trucks was larger than the pavement damage imposed by the southbound truck traffic. The latter seems to have become “stable” or at least is starting to show little change.

4) By analyzing the directional and temporal characteristics of the axle load distributions a trend line for the northbound and the southbound load associated pavement damage was established. The researchers concluded that the LSF trend lines for the Class 10 trucks in each of the travel directions will converge in the future to a point at which truck capacities will be utilized to an optimum given the current regulations and weight enforcement level.

5) For the second most popular truck class - Class 5 - no significant directional difference and temporal shift in the axle load distributions were observed at both WIM stations.

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