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Infrastructure-Friendly Vehicles to Support Texas Economic Competitiveness

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The researchers reviewed and extended the work done under Project 0-6736, Rider 36 OS/OW Vehicle Fees Study, and other similar efforts currently underway in Texas and other states and at the federal and international level to evaluate the effects of single, tandem, and tridem configurations on bridges and pavements, and developed guidelines for more infrastructure-friendly vehicle configurations. In addition, the researchers developed a cost recovery structure that adequately funds repairs to roads used by overweight trucks.</td></tr>
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List of Acronyms

AADTT	average daily truck traffic
AAR	Association of American Railroads
ATA	American Trucking Association
BCA	benefit/cost analysis
BRINSAP	Bridge Inspection and Appraisal Program
CVC	conventional vehicle configurations
DC	dry-cold
DMV	Department of Motor Vehicles
DOT	department of transportation
DW	dry-warm
ECF	equivalent consumption factor
EDF	equivalent damage factor
ESAL	equivalent single axle load
ETC	electronic toll collection
FHWA	Federal Highway Administration
GVW	gross vehicle weight
HB	House Bill
HGV	heavier goods vehicle
HMA	hot-mix asphalt
IH	interstate highways
ITF	International Transport Forum
LCV	long combination vehicle
LEF	load equivalency factor
MAP-21	Moving Ahead for Progress in the 21st Century Act
MCD	Motor Carrier Division
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NCVC	non-conventional vehicle configurations
NHS	national highway system
OBU	onboard unit
OOIDA	Owner-Operators and Independent Drivers Association
OS	oversize
OW	overweight
POE	port of entry

RMD	Rocky Mountain Double
RUC	road user charges
SB	Senate Bill
SH	State Highway
SN	structural number
TPD	Turnpike Double
TS&W	truck size and weight
USDOT	US Department of Transportation
VMT	vehicle miles traveled
WC	wet-cold
WW	wet-warm

Chapter 1. Introduction

1.1 Introduction

Texas's recent boom in the energy industry, along with the recovery of the nation's and state's economies, translated into an increase in freight movements that need to be accompanied by proper strategies and planning. The current legal federal axle load limits are 20,000 lbs. for a single axle, 34,000 lbs. for tandem axles (two axles spaced up to 4 feet apart), and 80,000 lbs. for total gross vehicle weight (GVW). GVW includes the weights of the truck, cargo, fuel, and driver. A few states are permitted to operate heavier trucks on the interstate highways (IH) and other national highway system (NHS) roadways due to the grandfather clause. The trucking sector is constantly advocating for higher GVW and axle load limits to increase their fleet productivity and reduce operating costs. Major challenges associated with the projected increase in the number of trucks and heavier loads are increased highway congestion and accelerated consumption of the state's transportation infrastructure.

An increase of the GVW and axle load limits would allow for more productive trucks to operate on Texas highways. Recent studies revealed that it might be possible to increase the current axle load and GVW limit in Texas by using alternative axle configurations that do not increase the consumption of the infrastructures (Prozzi et al., 2012). More productive trucks lead to potential benefits to the environment and the state's economy, such as reduced fuel consumption and decreased CO2 emissions (Jacoby, 2008). More productive trucks can carry heavier loads with no additional relative consumption of the highway infrastructure, which mitigates the increased consumption caused by overweight (OW) vehicles. In addition, a higher GVW limit would reduce the number of trucks needed to move the same amount of freight, helping to reduce congestion. Truck weight regulations play an important role in determining the efficiency and productivity of the nation's economy.

1.2 Research Objectives

Overweight loads are not typically transported on conventional five-axle truck configurations; rather, they are transported on specialized truck configurations to distribute the load. Moreover, transporting heavier loads using innovative truck configurations that distribute the load more efficiency potentially reduces the infrastructures consumption for an equivalent load on a conventional truck configuration. It is important to understand the feasibility of such alternative vehicle configurations, to assess the associated pavement and bridge consumption, and to estimate necessary user fees for maintaining the roadway infrastructure. The objective of this project was to develop methodology to quantify the relative consumption of different axle loads and vehicle configurations on pavements and bridges. Guidelines were developed for more infrastructure-friendly vehicle configurations based on both structural and economic analyses. Alternative vehicle configurations are proposed based on the results obtained by considering varying factors such as axle type, distance between axles, and load per axle. Finally, a cost recovery structure was developed that adequately funds repairs to roads used by OW trucks.

1.3 Organization of the Report

Chapter 2 provides an extensive literature review, which surveys the work done under Ride 36 and the previous studies conducted on the impacts of OW and oversize (OS) vehicle configurations. The literature review is divided into three parts: truck weight and axle load limits in the US and other countries, current truck classifications and configurations both in the US and abroad and alternative configurations proposed by other research studies, and cost and benefits of OW truck configurations.

Chapter 3 relays information regarding project advisory panel, while Chapter 4 describes the alternative configurations researchers determined by synthesizing the literature with previous TxDOT research project efforts. This chapter discusses the methodologies used to analyze pavement and bridge consumption and provides the results of pavement and bridge consumption of each alternative configuration, accompanied by a comparative analysis to identify the infrastructure-friendly vehicles.

Finally, Chapter 5 outlines the type and estimation of costs the OW vehicles cause in terms of roadway repair and maintenance. This is followed by brief reviews of cost allocation approaches and potential cost recovery methods. The chapter also provides case study guidelines for conducting a recommended cost recovery structure.

Chapter 2. Literature Review

2.1 Introduction

As part of this research project, the research team reviewed previous studies related to i) truck weight and axle load limits in the US and other countries, ii) current truck classifications and configurations both in the US and abroad, and iii) alternative configurations proposed by other research studies. The research team also reviewed the work performed under TxDOT Research Project 0-6736 (a.k.a. the Rider 36 Study, Prozzi et al., 2012) and similar work in Texas, the US, and worldwide to identify the most important issues, findings, and methodologies at both the federal and state levels to quantify the benefits and costs of modifying the GVW and axle load limits. This chapter summarizes the results of several previous studies that quantified the effect of the vehicle configuration on the relative consumption of highway infrastructure (including bridges and pavements). In addition, previous efforts to assess the economic and environmental impacts of changing the truck size and weight (TS&W) limits and regulations are included in this chapter.

2.2 Trends in Freight Modes

Table 2.1 shows the weight and value of shipments by transportation mode across the US during 2012. Truck transportation mode is currently the highest in terms of quantity and value of shipments across the country. It is estimated that trucking accounts for 64% of the value, 68% of the weight, and 32% of the ton-miles of all commercial freight activity in the US (Walton et al., 2010).

Table 2.1 Weight and value of shipments by transportation mode in 2012

Mode	Weight of shipments (million tons)				Value of shipments (million tons)			
	Total	Domestic	Exports[1]	Imports[2]	Total	Domestic	Exports[2]	Imports[2]
Total	**19,662**	17,523	901	1,238	**17,352**	13,927	1,392	2,033
Truck	**13,182**	12,973	118	92	**11,130**	10,531	309	289
Rail	**2,018**	1,855	82	82	**551**	400	55	96
Water	**975**	542	95	338	**339**	170	21	148
Air, air & truck	**15**	3	5	7	**1,182**	163	470	549
Multiple modes & mail[1]	**1,588**	453	540	595	**3,023**	1,697	478	848
Pipeline[1]	**1,546**	1,421	13	112	**768**	699	9	61
Other & unknown	**338**	277	47	14	**359**	267	51	41

[1]2007 total and domestic numbers for the multiple modes and the mail and the pipeline categories were revised as a result of freight analysis framework database.

[2]Data do not include imports and exports that pass through the United States from a foreign origin to a foreign destination by any mode.

2.3 Truck Weight and Axle Load Limits

Over time, the need for the US to remain economically competitive in a global market has resulted in improvements to the highway infrastructure network and development of more productive vehicle designs. The need to improve productivity and maintain economic growth in an increasingly competitive marketplace has motivated changes in state and national truck weight limits throughout the years. For these reasons, it is important to understand the events and motivations that resulted in the current regulatory framework of GVW and axle load limits. This section provides an overview of the evolution of the vehicle truck weight regulations at both federal and state levels, and a description of the current weight limits for trucks operating on Texas highways. The last part of this section contains examples of vehicles that cannot legally operate in Texas but are legal in other states and neighboring countries with different truck weight limits.

2.3.1 History of Federal and State Vehicle Weight Regulation

TS&W was not regulated at the federal level until the passage of the Federal-Aid Highway Act in 1956, as part of the planning and development of the Interstate and Defense Highway System. Prior to 1956, TS&W was regulated by the individual states. Maine, Massachusetts, Pennsylvania, and Washington were the first four states to establish GVW limits (from 18 kips in Maine to 28 kips in Massachusetts) in 1913; Pennsylvania was the first to limit the axle load to 18 kips (FHWA, 2000).

The Federal-Aid Highway Act in 1956 set federal limits for the IH System, limiting the GVW to 73,280 lbs. and the axle load to 18 kips for single axles and 32 kips for tandem axles. During the same year, Congress enacted the first "grandfather clause" through which those states with already established GVW or axle loads limits higher than those set by the 1956 Act were permitted to keep them (FHWA, 2000).

The next milestone in the TS&W history is the Federal-Aid Highway Act Amendments of 1974, which increased the GVW limit to 80 kips and the axle load limits to 20 kips and 34 kips for single and tandem axles, respectively. However, these new limits provided in the 1974 legislation were not mandatory for the states. Six contiguous states—Mississippi, Illinois, Indiana, Arkansas, Missouri, and Tennessee, referred to as the "barrier states"—did not adopt the new limits but rather kept the previous 73,380 lb GVW limit. The geographical barrier formed by this group of states forced "the costly process of unloading a portion of the cargo in the Midwest, and then loading the surplus in another truck" (Halverson, 1980), entangling the movement of freights between the west and east coasts. This situation ended when Congress enacted the Surface Transportation Assistance Act of 1982, forcing all states to adopt the 1974 GVW and axle load limits in the IH system. A grandfather clause was added in both the 1974 and the 1982 Federal Acts to allow states with previously established higher TS&W limits keep their regulation. The next grandfather clause occurred in the Intermodal Surface Transportation Efficiency Act of 1991, which froze the long combination vehicle (LCV) weights.

2.3.2 Current Federal Truck Weight Regulation

The current maximum allowable weight for vehicles operating on IHs on a single axle is 20,000 lb, or 34,000 lb on a tandem axle. Maximum weight for each axle group on a vehicle is determined using the bridge formula as explained in the next section. Federal law also imposes the following restrictions:

1. The combined weight on the entire set of axles on a vehicle (or GVW) is restricted to 80,000 lbs.
2. A set of two tandem axles may carry 68,000 lb. but shall be separated by at least 36 ft.

Individual states are not allowed to impose weight limits that are lower than the aforementioned federal limits on IHs. States shall bear the responsibility of implementing effective weight enforcement programs on federal-aid roads; a certification of such programs is mandatory for receiving federal highway funding (TRB, 2002).

2.3.3 History of Texas Weight Regulation

Texas's first TS&W regulation dated from 1929, which established tolerances for gross weights—as a function of the number of wheels per vehicle—as well as axle loads and tire pressure. The GVW and axle load were limited to 30 kips and 16 kips respectively (Prozzi et al., 2012). Since 1929, Texas has been regulating in-state truck size and weight of trucks. The passage of House Bill (HB) No. 583 amended Articles 833 and 834 of the 1925 Texas Penal Code. Amendments to Article 833 authorized the State Highway Commission to forbid the use of highways "by any vehicle or loads of such weight or tires of such character as will unduly damage such highway." The State Highway Commission and Commissioners' Court of any county were authorized to regulate the tonnage of trucks and vehicles "by reason of the construction of the vehicle or its weight and tonnage of the load shall tend to rapidly deteriorate or destroy the roads, bridges and culverts along road or highway" as per the amendments to Article 834 of the Penal Code. Senate Bill (SB) 10 set out the permitting system for non-divisible super-heavy or OS equipment on the public highways. A bond fee of $5 was charged, to be credited to the Highway Maintenance Fund to compensate for the sustained damage caused by the OS/OW vehicles. As per the SB 10 bill, the issued permits must include the details of the involved vehicle and equipment/entity being carried, along with the routing information such as highway and distance. The SB 11 bill set out the limits for weights and axle spacing for vehicles to operate on the public highways, as described in Table 2.2.

Table 2.2 Axle weight limits imposed by SB 11 Bill

Vehicle characteristics	Load restrictions
Four wheels or less	GVW < 22,000 lbs
Six wheels with axles spaced over 40 inches apart	GVW < 30,000 lbs
Load on the single axle for any vehicle	<16,000 lbs
Weight per inch of tire upon any wheel concentrated upon the surface of the Highway[1]	600 or 650 lbs/inch
Vehicles with axles spaced less than 8 feet apart	<10,400 lbs on single axle
	< 18,000 lbs on single axle with dual tires

[1]The pounds of inch per tire width is still used by the DMV-MCD in permitting rules, but the state has eliminated these requirements for regular truck axle weight enforcement. The weight per tire is strictly based on the maximum load rating as embossed on the tire by the tire manufacturer. DPS uses this maximum load to determine whether an axle is overloaded after weighing the vehicle with a portable scale. The pounds per inch of tire width used to enforce tire weights was 600 lbs per inch for high pressure tires (though 'high pressure' was not defined) and 650 lbs per inch for low pressure tires.

In 1950 the allowable GVW in Texas was 48,000 lbs. However, to help reduce the number of OW axle loads, the then Texas Highway Department and the legislature agreed to increase the GVW to 58,420 to allow truckers to add 9,000 lbs more cargo, plus roughly 1,420 lbs for an additional axle, tires, suspension, and brakes. This change encouraged truckers to move from a two-axle tractor with single axle semi-trailer (three-axle unit) to a four-axle unit, which reduced axle loads and pavement damage. However, the 1956 increase of the federal weight limit to 73,280 caused great concern for Texas, which had built thousands of miles of new FM roads based on the 58,420 weight limit—thus, about 20,000 center line miles of FM roads were load zoned at 58,420 lbs GVW, preventing trucks loaded to the higher federal limit from operating on the new FM road system. However, passage of the 1547/2060 (also known simply as the 1547 permit) permits effectively allowed 84,000 lb GVW trucks to operate on the load-zoned system; these loads are heavier than is allowed on the IH system. The load-zoned roadways comprise about 17% of the state mileage and are posted at 58,420 lbs GVW with no restriction on axle weight limits.

These regulations were enforced until 1971, with minor amendments in 1931 and 1949. The TS&W regulations have been modified many times and a chronological list of major legislative changes for OS/OW governance were documented in Prozzi et al. (2012). The most recent legislative amendment was enforced under HB 422 during 2011. Authorized OS/OW permit categories include single trip, general, crane and well servicing unit mileage, manufactured housing, portable buildings, super-heavy, and multi-state (Western Association of State Highway and Transportation Officials). In addition, specialty permits, exempt vehicles, and 1547/2060 permits are also allowed by the state. As per the 1547/2060 permit, the vehicles that exceed allowable axle loads by 10% or the maximum allowable GVW by 5% are permitted (Luskin et al., 2001).

2.3.4 Current Weight Limits in Texas

Texas's current TS&W regulation is defined in the Texas Transportation Code, Chapter 621: "General provisions relating to vehicle size and weight." This code specifies the maximum legal GVW as a function of the number of axles and the distance between the extremes of any group of two or more consecutive axles. The formula used to obtain the maximum legal weight is given by Equation 2.1.

Table 2.3 contains the maximum legal weights as a function of the number of axles and distance between the extremes of any group of two or more consecutive axles.

$$\boldsymbol{W = 500 * [(L * N/(N-1)) + 12 * N + 36]} \quad \textbf{(2.1)}$$

Where:

W is maximum overall gross weight on the group;
L is distance in feet between the axles of the group that are the farthest apart;
N is number of axles in the group.

Following are the maximum GVW and axle loads allowed on Texas highways without a permit:

- Gross - 80,000 lbs maximum
- Single axle - 20,000 lbs
- Tandem axle group - 34,000 lbs
- Tridem axle group - 42,000 lbs
- Quad axle group - 50,000 lbs
- A tire may not carry a weight heavier than the weight specified and marked on the sidewall of the tire.

The Texas Department of Motor Vehicles (DMV) Motor Carrier Division (MCD) annually processes more than 800,000 OS/OW permits. The permits are only allowed under certain special transportation circumstances, such as conveying indivisible industrial loads, for operation on the NHS system. Non-divisible loads are those that cannot be disassembled without damaging the value of the load or cannot be easily dismantled into smaller components within an 8-hour work day. TxDOT issues permits up to a GVW of 120,000 lb in the case of indivisible loads, but the permit holders are not allowed on IHs; otherwise, federal regulations would be violated. The MCD also issues divisible load permits, for loads that can be dis-assembled, such as the 2060 over-axle weight tolerance permits, or general single-trip OS/OW permits. MCD is allowed to issue permits to operate trucks exceeding legal weights limits by up to 5% in the case of divisible loads on State Highways; the load allowance is up to 10% on axle limits. The permitted loads may be categorized depending on the magnitude of GVW (TxDOT, 2011a).

- OW and mid-heavy weight classes: GVW from 80,001 lbs. to 254,000 lbs.
- Super-heavy class: 254,300 lbs. to heavier than 2,000,000 lbs.

Some permitted loads are OS but not OW, while others are OW but not OS. In addition, both OS and OW load permits are also available. The permitted vehicles travel distances as short as 10 miles to hundreds of miles of Texas state and county roads.

Table 2.3 Current Texas Permissible Weight Table

Distance in Feet	Axles					
	2	3	4	5	6	7
4	34,000					
5	34,000					
6	34,000					
7	34,000					
8	34,000	34,000				
8+	38,000	42,000				
9	39,000	42,500				
10	40,000	43,500				
11		44,500				
12		45,000	50,000			
13		45,500	50,500			
14		46,500	51,500			
15		47,500	52,000			
16		48,000	52,500	58,000		
17		48,500	53,500	58,500		
18		49,900	54,000	59,000		
19		51,400	54,500	60,000		
20		52,800	55,500	60,500	66,000	
21		54,000	56,000	61,000	66,500	
22		54,000	56,500	61,500	67,000	
23		54,000	57,500	62,500	68,000	
24		54,000	58,700*	63,000	68,500	74,000
25		54,500	59,650*	63,500	69,000	74,500
26		55,500	60,600*	64,000	69,500	75,000
27		56,000	61,550*	65,000	70,000	75,500
28		57,000	62,500*	65,500	71,000	76,500
29		57,500	63450*	66,000	71,500	77,000
30		58,500	64,000*	66,500	72,000	77,500
31		59,000	65,350*	67,500	72,500	78,000
32		60,000	66,300*	68,500	73,000	78,500
33			67,250*	68,500	74,000	79,000
34			68,200*	69,000	74,500	80,000
35			69,150*	70,000	75,000	
36			70,100*	70,500	75,500	
37			71,050*	71,050	76,000	
38			72,000*	72,000*	77,000	
39			72,000*	72,500	77,500	
40			72,000*	73,000	78,000	
41			72,000*	73,500	78,500	

Distance in Feet	Axles					
	2	3	4	5	6	7
42			72,000*	74,000	79,000	
43			72,000*	75,000	80,000	
44			72,000*	75,500		
45			72,000	76,000		
46			72,500	76,500		
47			73,500	77,500		
48			74,000	78,000		
49			74,500	78,500		
50			75,500	79,000		
51			76,000	80,000		
*These figures were carried forward from Article 6701d-11, Section 5(a)(4) when SB 89 of the 64th Texas Legislature amended it on December 16, 1974. The amendment provided that axle configurations and weights that were lawful as of that date would continue to be legal under the increased weight limits.						
+These figures apply only to an axle spacing greater than 8 feet but less than 9 feet.						

Source: http://www.txdmv.gov/component/k2/item/2123-permissible-weight-table

2.3.5 Current Weight Limits in Other States

A wide variety of permitting procedures are currently in practice across different states; however, a majority of these permits apply to single trips. A harmonization in vehicle weight and size regulations across the country is sought by some sectors of the trucking industry (AASHTO, 1995). Such harmonization across the states would ensure smoother interstate and international commerce. The grandfather clauses applied to each of the Federal Acts made the current TS&W regulation a "hybrid" system, with a GVW of 80,000 lbs as the standard interstate truck and a number of states (mostly in the west) with higher weight and size limits. For instance, Michigan allows operating truckloads of more than 160,000 lb on the IH system within the state's boundaries. Texas is not one of the grandfathered states and therefore it is limited by the federally established TS&W regulation on the IH system. Intuitively, the divisibility of the load should govern the permit enforcement; however, such a criterion is not necessarily used as the basis for decision-making when issuing permits to truck operators. Grandfather clauses, in a few cases, allow states to permit certain divisible loads; generally, these permitted loads do not exceed federal bridge formula limits (Walton, 2009). A dozen or more states allow GVWs that are greater than federal limits on the state roads.

The weight regulations in states neighboring Texas are a source for guidance as well as a means to create a more streamlined interstate shipping system. It is important to understand weight regulations set in place by states bordering Texas. The previous subsection described the current weight limits in Texas in detail. Apart from standard weight limits of Texas, an OS/OW vehicle permit has the following weight regulations: single axle–25 kips; tandem axle–46 kips; tridem axle–60 kips; quad axles–70 kips; five axles–81.4 kips; six axles–94.2 kips; seven/eight axles–depends on configuration. Note that there are additional restrictions concerning axle spacing and axle type to allow for these limits. Also, there are special state statutes for certain types of trucks, such as those hauling cotton seed or chili pepper modules, agricultural trucks during harvest, etc. So, in addition to permitted loads, there are also increased loads based on statutory limits. This is true in Texas and many other states.

In Arkansas, standard weight regulations match those of Texas except in the following two cases: 1) the steering axle (a single axle) must be between 12 and 20 kips and meet the tire manufacturer's weight rating, 2) the triple axle has a higher load limit of 54 kips (as opposed to 42 kips in Texas). Loads that exceed these weight restrictions require permits: single axle–20 kips; double axle–40 kips; triple axle–60 kips; quad axle–68 kips. The weight limits of OS/OW permits are on average lower than those of the Texas.

In Louisiana, standard weight regulations are divided between interstate and non-interstate roadways. Non-interstate weights are generally higher than their interstate counterparts. The interstate regulations for Louisiana are essentially the same as Texas for single, double, and triple axles. Louisiana state limits also include a weight limit of 50 kips on quad axles. It is important to note that Louisiana's GVW limit is 83.4 kips, which is higher than that of Texas. The permit limits are as follows: single axle–24 kips; tandem axle–48 kips; tridem axle–60 kips; quad axle–80 kips. The GVW limit is increased to 232 kips and can go higher if given special permission on certain corridors.

New Mexico has the same axle load limits for standard practice as those in Texas. The GVW, however, is 80.64 kips, which is slightly higher than the Texas limit. The permit requirements are not set out as a general set of values by NMDOT; instead, the limits are dictated by the particular route. Permits allow for GVWs as high as 200 kips.

In Oklahoma, standard load limits are the exact same as those in Texas. However, permit regulations call for the following limits: tandem axle–40 kips; tridem axle–60 kips; quad axle–65 kips; five axles–95 kips; six axles–115 kips; seven axles–135 kips; eight axles–150 kips. These limits are more liberal than those in Texas. It may be assumed that the marginal consumption of these OW trucks is mitigated by the permit cost.

Other major states include special restrictions based on vehicle configuration and route. For example, California, who has similar standard weight restrictions to Texas, has all permit limits set as a function of the axle configuration. Michigan sets permit restrictions based upon route, tire size, and vehicle gauge. Indiana seems to have standard "across-the-board" weight restrictions for its permits. To meet state-specific demands, Transportation Equity Act for the 21st century (TEA 21) included special provisions for four states: Colorado, Louisiana, Maine, and New Hampshire. Higher GVW (than 80,000 lb) is allowed on IHs to cater to specific needs, such as excess sugar cane transport during harvesting season in Louisiana. North Dakota has a very active fracking industry similar to that of Texas. The majority of their non-IH network allows 105,000 lb trucks to operate without a permit; IH routes are restricted to 80,000 lb GVW and a few non-federal routes are restricted to lower limits.

A couple of earlier studies, including the US Department of Transportation (USDOT)'s comprehensive truck size and weight study and the Transportation Research Board's truck weight study, provided alternative perspectives on uniformity and harmonization of truck weight limits across the country. These studies mentioned the downside of uniform weight regulations. Specifically, the local trucking requirements typically vary considerably and harmonization may not be able to efficiently serve the local demand. Perhaps a moderate level of harmonization is necessary to avoid unnecessary administrative charges and discomfort of unloading to the truckers, while allowing for local, situation-specific weight limits to the extent possible.

2.3.6 Current Weight Limits in Other Countries

Another interesting aspect to analyze when considering alternative GVW and axle load limits is the regulations and common types of trucks that operate in neighboring countries. The North American Free Trade Agreement (NAFTA), in effect since 1994, reduced barriers for the cross-border freight movement among Canada, United States, and Mexico. However, the weight limits differ significantly among the three countries, as shown in Table 2.4. The maximum legal GVW in Mexico is 106,700 lbs; Canada's is 95,700 lbs to 116,600 lbs (National Research Council, 2002). Although efforts to harmonize the TS&W regulations among the three nations have been unsuccessful, NAFTA initiated examination of new transport planning policies towards more efficient freight movements in the region (Walton et al., 2009). The harmonization of Texas TS&W regulations would allow for more harmonious trade among the three NAFTA partners.

US-Mexico land trade is concentrated at a limited number of ports of entry (POE); Texas's POEs are near Laredo, El Paso, and Hidalgo (Pharr/McAllen). Laredo and El Paso together handled about 56% of the Texas truck trade during 2010. Figure 2.1 shows the number of trucks entering the US from various states. It is evident that Texas handles more incoming trade from Mexico than do the other states that border Mexico. This is usually a good economic sign but the fact that the larger truck GVWs in Mexico will have a significant economic impact if those are not allowed to move in the US.

Table 2.4 Axle weights and GVWs (in lb)

Country	Steer	Drive	Tridem	GVW
Canada	12,100	37,400	52,800	102,300
Mexico	14,300	42,900	49,500	106,700
U.S.	12,000	34,000	42,000	88,000

Source: NCHRP RRD 362

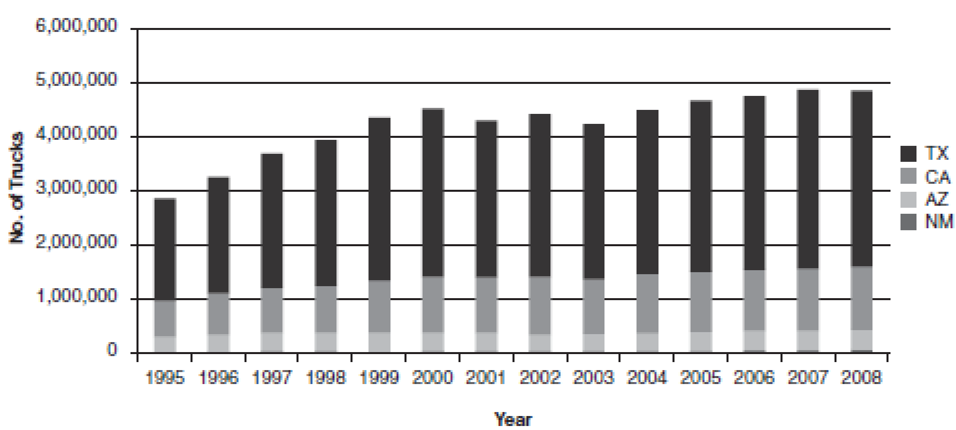


Figure 2.1 Trucks entering the US from Mexico

The GVW is evaluated based on the bridge formula. The bridge formulas established by the US and Mexico are different, as shown in Equations 2.2 and 2.3; these differing equations lead to different allowable GVWs for a given vehicle configuration.

(2.2)

$$GVW_{MX} = 870\left[\frac{L * N}{N-1} + 3.66 * N + 11\right]$$

where

GVW_{MX} = maximum gross vehicle weight (kg),
L = distance between extreme axles (m), and
N = number of axles

(2.3)

$$GVW_{US} = 500\left[\frac{L * N}{N-1} + 12 * N + 36\right]$$

where

GVW_{US} = maximum overall gross weight of the group (lb),
L = distance between extreme axles of the group (ft), and
N = number of axles in the group

As shown in Figure 2.2, the GVW of Mexican vehicles are relatively high compared to that of the US.

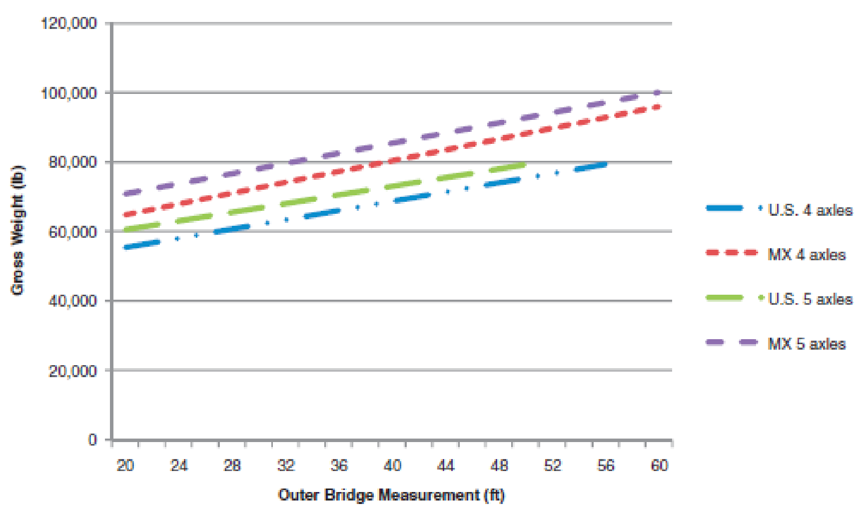


Figure 2.2 Comparison of bridge formulas to establish maximum GVW

In addition, the maximum allowable axle loads on the vehicles are also different from those allowed in Texas (see Table 2.5).

Table 2.5 Maximum axle load weight for non-divisible loads

Axle Type or Group	Tires per Axle	Maximum Weight/Tire (Metric Tons)	Load/Axle Type (Metric Tons) Load per Axle	Load/Axle Type (Metric Tons) Load per Axle Group
Single	2	3.3	6.6	6.6
Single	4	2.75	11.0	11.0
Single	8	2.75	22.0	22.0
Double	8	2.75	11.0	22.0
Double	16	2.75	22.0	44.0
Triple	12	2.75	11.0	33.0
Triple	24	2.75	22.0	66.0
Quadruple	8 per axle	2.25	18.0	Variable
Quadruple	12 per axle	2.25	27.0	Variable

Source: NOM-040-SCT-2-1995.

European countries also have a relatively higher truck weight limits than the US federal limits. For example, Denmark operates trucks up to 105,600 lbs on a six-axle semi-trailer. Australian B-trains carry up to 137,785 lbs and the B-trains in New Zealand carry up to 128,000 for high-productivity motor vehicles.

Both Canada and Australia allow heavier trucks and the B-train double is a popular type of connection design for two trailer units. However, these trucks are not permitted to operate on every portion of the system. In Canada and Australia, each province specifies the allowable weight limits and routes over which these heavier trucks can operate. In addition, the allowable weight limits for trucks in Canada and the northern US states are different during the winter and during the spring thaw. In some cases, trucks are not permitted to travel over certain routes during the spring due to very weak, wet subgrade conditions.

Australia has implemented performance-based standards for trucks: a company can propose a new configuration of axle weights and spacing, GVW, and total vehicle length and as long as the new configuration meets the performance specifications for overturning, off tracking, and other factors, it may be approved for operation.

2.3.7 Permit Fee from Other States and NAFTA Partner Countries

The permit fee in Texas should be comparable with that of neighboring states. Otherwise, trucks may choose an economic route through other states. To maintain economic competitiveness, it becomes imperative to understand the permit fee structure of neighboring states.

The states sharing a border with Mexico are California, Arizona, New Mexico, and Texas; Texas sees the greatest amount of truck traffic, as mentioned earlier. States that neighbor Texas are Louisiana, Arkansas, Oklahoma, and New Mexico. Therefore, it is important to understand the permit fee structure in these states, especially to list permit fees and compare them with those of Texas. Although there are several other factors that govern the choice of route, the cost of trip is significant factor affecting the route decision. Types of permit and permit fees charged by these agencies are compared below.

The Department of Highways in the state of Arkansas is responsible for issuing the OS/OW permits in the state. Only single-trip permits are issued individually for weight and dimension. A base fee of $17 is charged for each special permit along with charge for each ton to be hauled. The incremental fee charges are provided in Table 2.6.

Table 2.6 Incremental charges per ton in Arkansas

No more than 100 miles	$ 8.00
101 miles to 150 miles, inclusive	$ 10.00
151 miles to 200 miles, inclusive	$ 12.00
201 miles to 250 miles, inclusive	$ 14.00
Over 251 miles	$ 16.00

The size and weight permit division of the Department of Public Safety issues the permits for OS/OW vehicles in the state of Oklahoma. The fee was doubled for certain categories in the year 2010 and the current fees are listed in Table 2.7.

Table 2.7 Incremental charges per ton in Oklahoma

Type of permit	Fees as of July 01, 2010
Oversize – General type of equipment	$40
Overweight	$40
Per 1000 lbs of overweight	$10
Multi trip	$40 (per month)
Special movement fee (Newly mfg item)	$500
Special combination (Triples)	$240 per year
LCVs (Doubles)	$20
Annual vehicle (envelope)	$4000
Special purpose annual	Oversize $10 / Overweight $60

In New Mexico, a single-trip permit is issued at $25 ($35 for liquid load) with OW permits being charged at $0.025/mile/ton for a weight of over 86,400 lbs. Multi-trip permits are issued at $250 ($120 for liquid load) and are issued for a particular vehicle and specific load to move multiple times. Such permit is valid for 12 months or expiration of insurance, whichever is first.

The truck permit office of the Department of Transportation and Development is responsible for OS/OW permits in Louisiana. The type of permit and fee is primarily categorized based on cargo (27 different cargo types). The general permit fee is summarized in Table 2.8 while Table 2.9 presents the permit fees for single-trip OW (OS included) trucks.

Table 2.8 General types of permit and permit fees (Louisiana)

Type of permit	Permit fee
Single-trip oversize only	$10 per day/trip
Yearly oversize	$500.00—1 year to date—vehicles and loads that exceed the legal limitations on length, height and width—allows 14’4” in height, 12’0” in width, 90’0” in length and a 25’0” rear overhang
Annual OW [2]	$2500
Critical off-road semi annual	$0.07 per ton mile traveled
Monthly permit oversize only	$10 per day

Table 2.9 OW single permit fees for state of Louisiana

Gross weight (lbs)	Distance traveled in miles				
	0 - 50	51 - 100	101 - 150	151 - 200	Over 200
80,001 – 100,000	$30	$45	$65	$80	$100
100,001 – 108,000	$50	$95	$135	$180	$220
108,001 – 120,000	$70	$130	$190	$250	$310
120,001 – 132,000	$90	$170	$250	$330	$415
132,001 – 152,000	$120	$225	$335	$445	$555
152,001 – 172,000	$155	$295	$440	$585	$730
172,001 – 192,000	$190	$365	$545	$725	$905
192,001 – 212,000	$225	$435	$650	$865	$1080
212,001 – 232,000	$260	$505	$755	$1005	$1250
232,001 – 254,00	$295	$575	$860	$1145	$1420
Over 254,000	$10 + $0.50 per ton-mile in excess of 80,000lbs plus fee for structural evaluation				

The Enforcement and Compliance Division of the Arizona DOT is responsible for issuing OS/OW permits in the state of Arizona. However, permits for routes other than state routes should be procured from local authorities. The maximum limits for issuance of Class A permit are 120 ft. long, 14 ft. wide, and 16 ft. high and the load should be non-reducible and specified with combined weight of vehicle being less than 250,000 lbs. Table 2.10 shows the permit fee in Arizona.

Table 2.10 OW permit fees for state of Arizona

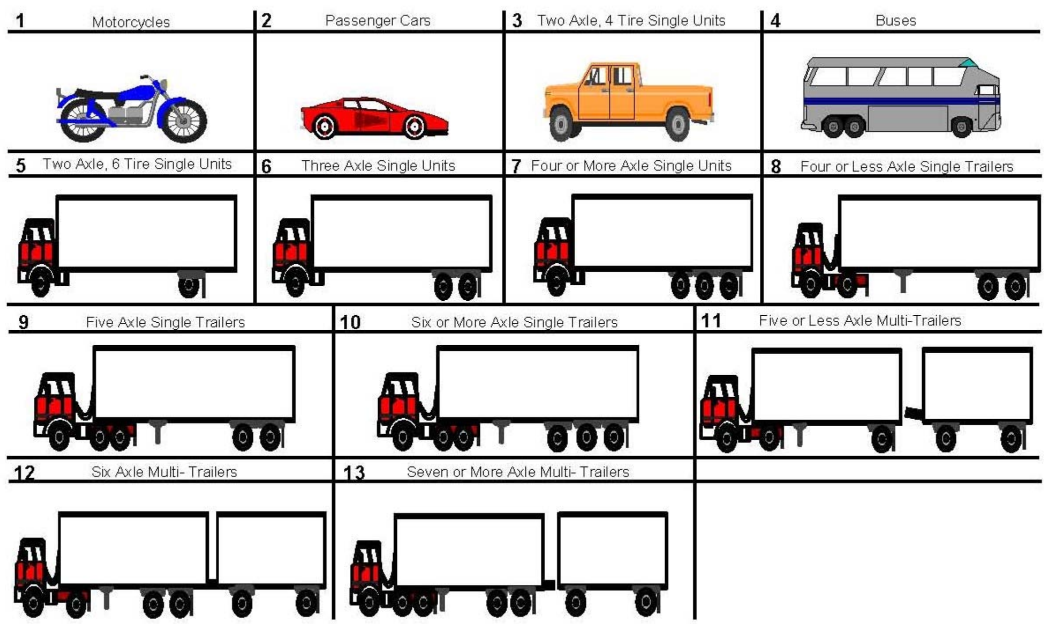
Type of permit	Permit fee
OS single trip	$15
OS 30-day	$30
OS/OW single trip	$75
OS/OW 30-day	$75

2.4 Vehicle Configuration

The nature of commodity transportation requires a certain amount of non-uniformity in truck vehicle configurations, but truck weight and size regulations must still be enforced. Distinguishing between mass-limited cargo and volume-limited commodities is crucial in designing vehicle configurations. Mass-limited cargo (high-density products) requires vehicle configurations that potentially allow for higher loads and distribute the loads to minimize the pavement consumption. On the other hand, volume-limited cargo (low-density products) requires LCVs with multiple trailers. Vehicle size and weight regulations largely influence truck manufacturers' future designs. This section outlines some of the studies that have proposed alternatives for vehicle configurations and regulations while also defining current truck classifications and configurations both in the US and abroad.

2.4.1 FHWA Vehicle Classification

Based on GVW, the Federal Highway Administration (FHWA) classifies trucks from Class 1 to Class 8, as shown in Figure 2.3 and Table 2.11. The most commonly used commercial truck configurations, such as the five-axle tractor semi-trailer, fall under Class 9. A wide variety of vehicle configurations exist under this class, which are constructed by rearranging vehicle axles and trailer types. Typically, the power units are compatible with a wide variety of trailer combinations, enabling a range of vehicle configurations. Thus, truck manufacturers do not produce unique truck configurations, due to the wide variety of commodities being transported. In contrast, for passenger cars the vehicle configurations are comparable between manufacturers.



Source: 2006 NYSDOT traffic data report

Figure 2.3 FHWA vehicle classes

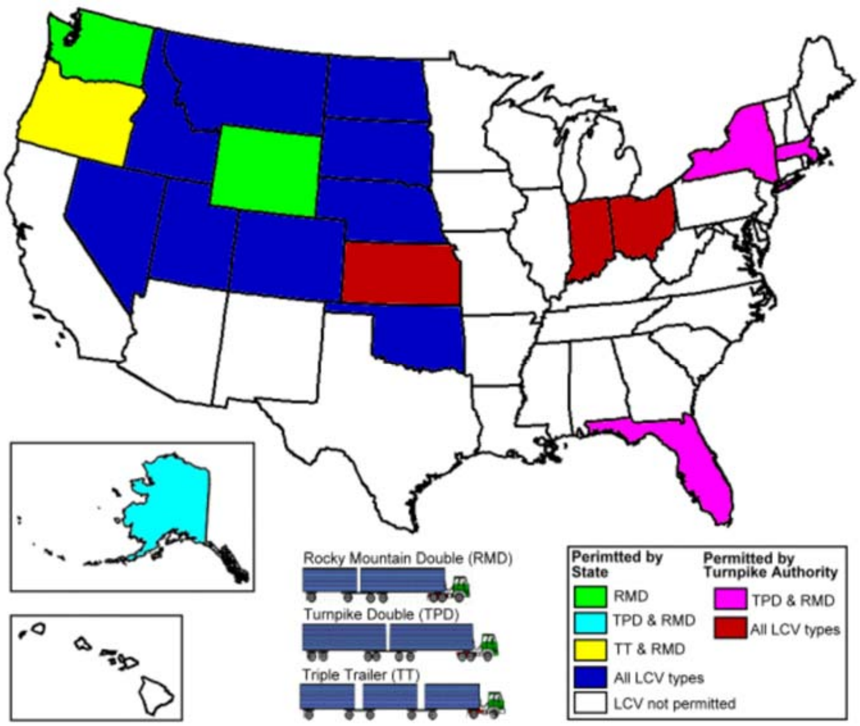
Table 2.11 Truck classification by GVW

Gross Vehicle Weight Rating (lbs)	Federal Highway Administration		US Census Bureau
	Vehicle Class	GVWR Catagory	VIUS Classes
<6,000	Class 1: <6,000 lbs	Light Duty <10,000 lbs	Light Duty <10,000 lbs
10,000	Class 2: 6,001 – 10,000lbs		
14,000	Class 3: 10,001 – 14,000 lbs	Medium Duty 10,001 – 26,000 lbs	Medium Duty 10,001 – 19,500 lbs
16,000	Class 4: 14,001 – 16,000 lbs		
19,500	Class 5: 16,001 – 19,500 lbs		
26,000	Class 6: 19,501 – 26,000 lbs		Light Heavy Duty: 19,001 – 26,000 lbs
33,000	Class 7: 26,001 – 33,000 lbs	Heavy Duty >26,001 lbs	Heavy Duty >26,001 lbs
>33,000	Class 8: >33,001 lbs		

Source: FHWA

2.4.2 Long Combination Vehicle (LCV) Configurations

An LCV is defined as any combination of a truck-tractor and two or more trailers or semi-trailers that operate on the IH system at a GVW greater than 80,000 lbs. In addition, the overall length of LCVs in the US usually exceeds 75 ft. (Abdel-Rahim et al., 2007). The maximum weights and lengths of LCVs vary from state to state, with the longest trucks at 120 ft. in length (Alaska) and the heaviest trucks at 164,000 lbs. GVW (Michigan's 11-axle "caterpillar truck"). Figure 2.4 shows a map with the state and turnpike authorities allowed to operate LCVs. LCV configurations are allowed on a smaller portion of the road network in the western states.



Source: Walton et al., 2009

Figure 2.4 Grandfathered states allowed operating LCVs

2.4.3 Vehicle Configurations Analyzed in Previous Studies

2.4.3.1 TxDOT Research Project #0-6095

In a TxDOT study (0-6095), the potential use of LCVs was evaluated with reference to the current freight system in Texas (Walton et al., 2009). The following are the most common LCV configurations operating in the US:

1) The Rocky Mountain Double (RMD), formed by a semi-trailer combination consisting of a 48-ft trailer followed by a 28-ft trailer; the maximum GVW of RMD ranges between 105.5 and 129 kips. The RMD is the most commonly used LCV in the country with its predominant regions being the northwest and New England.
2) The Turnpike Double (TPD) is formed by two 48-ft trailers with one steering axle and two tandem axles on each trailer. The TPD is slightly less common than the RMD. The maximum GVW of a TPD ranges between 105.5 and 147 kips.
3) The triple-trailer, which typically operates with three 28.5-ft trailers with one steering axle and two single axles on each trailer. The maximum GVW of triple-trailer is132 kips. Unlike the RMD and the TPD, the triple has a relatively narrower turning radius pattern that is similar to the standard five-axle 18-wheeler.

Figure 2.5 provides a closer view of these configurations.

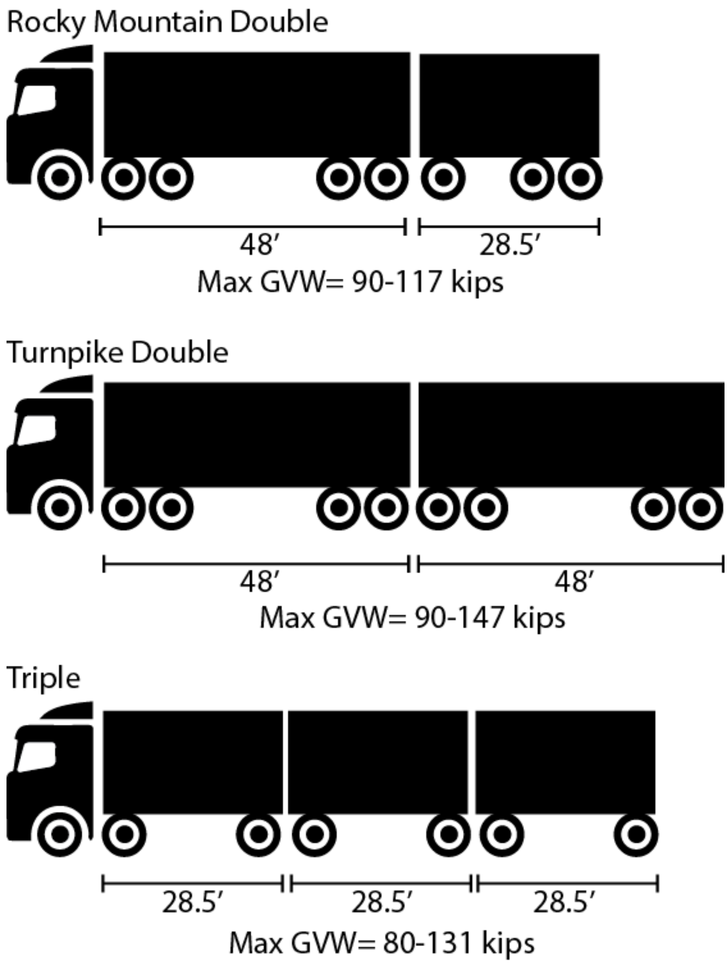


Figure 2.5 LCV configurations operated in the US

TxDOT 0-6095 used the aforementioned LCV configurations as a guideline; however, the study tested the feasibility of vehicles that fit the needs of trucking companies for shipping along major corridors. The following three configurations were tested as part of the pavement and bridge analysis (see Figure 2.6):

1. Single axle with 7 kip + Tandem axle with 36 k + Tridem axle with 54k (GVW of 97,000 lb)
2. Single axle with 12 kip + Tandem axle with 31.5 k + Tandem axle with 31.5 k + Tandem axle with 31.5 k + Tandem axle with 31.5 k (GVW of 138,000 lb)
3. Single axle with 12 kip + Tandem axle with 19.5 k + Tandem axle with 19.5 k + Tandem axle with 19.5 k + Tandem axle with 19.5 k (GVW of 80,000 lb)

The double 53-ft trailer configurations were tested as either "maxed-out on load" or "light." The maxed-out variant reaches a maximum weight of 138 kips, whereas the light variant reaches maximum volumetric capacity at a GVW of 90 kips; in other words, one weighs out and the other cubes out.

Source: Walton et al., 2009

Figure 2.6 Vehicle configurations used in TxDOT project 0-6095

Table 2.12 shows the VMT by vehicle configuration and the respective operating weight in the year 2000. In 2000, TPDs and RMDs were the most dominant proportions of LCV VMT at 50% and 42%, respectively; triple-trailers contributed only about 8% of the LCV VMT (Walton et al., 2009). A significant portion of the LCVs are cubed out at GVWs that are less than 80,000 lbs.; for about 40% to 44 % of the LCV vehicle miles traveled (VMT), trucks were operating at less than 80,000 lbs. in the year 2000. Table 2.12 also suggests that for about 17% to 20% of the LCV VMT, trucks were operating at loads larger than 105,000 lbs. and less than 140,000 lbs.

Table 2.12 VMT by vehicle configurations and weights

Vehicle Configuration[1]	**Percentage of Year 2000 VMT by Operating Weight**					**Year 2000 VMT (million)**
	45–60,000	**65–80,000**	**85–100,000**	**105–120,000**	**125–140,000**	
5-axle (CS5T)	27%	33%	10%	<1%	0	81,069
Double (DS5)	32%	43%	6%	0	0	5,263
6-axle (CS6)	22%	24%	26%	5%	1%	6,049
RMD (DS7)	23%	21%	28%	14%	3%	632
TRPL (TRPL)	11%	29%	37%	15%	5%	126
TPD (DS8+)	23%	21%	28%	14%	3%	759

[1]The configurations listed are included in the categories shown in parenthesis in the Federal Highway Cost Allocation Study.

Source: 1997 Federal Highway Cost Allocation Study, Appendix C, Table C-8

2.4.3.2 USDOT Comprehensive Truck Size and Weight Study in the Year 2000

In 2000, the USDOT's comprehensive truck size and weight study evaluated the impact of various vehicle configurations on safety and productivity. The following five vehicle size and weight scenarios were analyzed (USDOT, 2000).

- *Scenario 1:* Uniformity of truck size and weight regulations was assumed, as was a GVW of 80,000 lbs. on all interstate routes, including grandfathered states.
- *Scenario 2:* To enhance the North American trade, axle load limits on the tridem axles were increased to 44,000 lbs. and 51,000 lbs., which are consistent with Mexico and Canada.
- *Scenario 3:* LCVs were allowed across the national road network. Although larger LCVs are restricted, triples and doubles with 33 ft. trailers were assumed to be allowed with relaxed restrictions.
- *Scenario 4:* Trailers longer than 53 ft. were allowed. In addition, both grandfathered rights and non-interstate roadway weight limits were restricted.
- *Scenario 5:* Triples combinations were assumed to be allowed across the national road network with a GVW of 132,000 lbs.

The study reported productivity gains for scenarios with heavier vehicle weights. LCVs were found to be most promising in terms of productivity gains. Although LCVs received lesser support due to safety concerns, many states were interested in increasing the GVWs of six-axle tractor-semi trailers.

2.4.3.3 The Turner Proposal

The Turner proposal (Morris, 1989) recommended increasing the total number of axles to reduce the axle or axle group loads while allowing for higher GVWs. The Turner study investigated the feasibility of reducing legal single axle loading to a maximum of 15,000 lbs. and a tandem axle to 25,000 lbs., while raising the GVW to 112,000 lbs.; the study proposed increasing the overall vehicle length. The study evaluated a wide range of axle weights, length limits, and other vehicle characteristics. The study sought to identify the vehicle configurations that minimize pavement wear and bridge costs. The following configurations were examined in the study.

1. Seven-axle tractor-semitrailer (tri-axle tractor and tri-axle semitrailer);
2. Nine-axle double (tandem tractor and two tandem-axle semitrailers coupled by a tandem-axle dolly of either the single-drawbar or double-drawbar design);
3. Eleven-axle double (tandem tractor and two tri-axle trailers);
4. Nine-axle B-train double (tandem-axle tractor, a four-axle semitrailer with a fifth wheel permanently affixed at the rear of its frame, and a tandem-axle semitrailer).

The selection of the vehicle configurations was based on the following criteria:

1) lower axle loads on axle groups to reduce the pavement consumption per vehicle-mile,

2) geometric compatibility with existing roads to avoid off-tracking due to longer vehicles, and

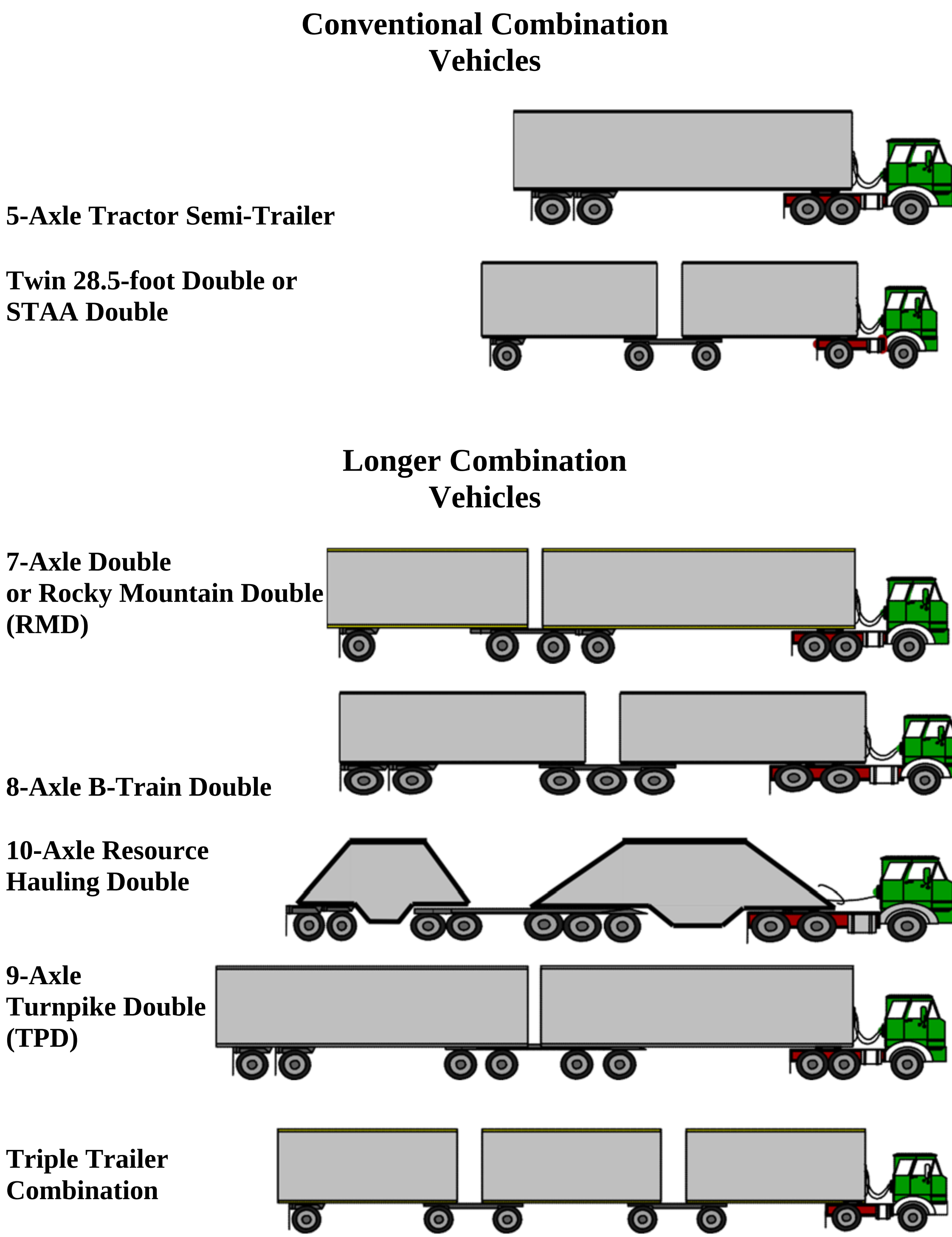
3) similarity to the existing technology to accelerate the implementation of the prototype configurations by the industry.

Vehicle configuration parameters such as tire pressure, tire diameter, tire type (dual or wide-base), axle spacing, etc., impact the pavement consumption. One may design non-conventional vehicle configurations to maximize the load-carrying capacity while minimizing the infrastructure damage. It is important to investigate the impact of such alternative and non-conventional vehicle configurations on infrastructure consumption.

The Turner study mentioned that a nine-axle double with twin 33-ft trailers and a practical maximum gross weight of 111,000 lbs. was the most attractive vehicle configuration in terms of productivity. It was estimated that Turner's truck prototype would consume pavements by as much as half the existing vehicle fleet. The study also recommended maximum weights on the axle groups as follows: 15,000 lbs. on a single axle; 25,000 lbs. on a tandem axle; 28,000 lbs. on a tandem drive axle; 40,000 lbs. on a tridem axle; and 50,000 lbs. on a quad axle. It is also important to note that the study did not recommend any upper limit on the GVW, although a bridge formula was established.

2.4.3.4 Western Uniformity Scenario

The Western uniformity scenario analysis was very similar to the USDOT's comprehensive truck weight and size study; however, this study was tailored to the western state conditions. The major goal of this study was to investigate the feasibility of harmonizing the LCV weight and size regulations across western states. Participating states included in the analysis were Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, North Dakota, Oklahoma, Oregon, South Dakota, Utah, Washington, and Wyoming. Although Texas, California, New Mexico, and Arizona were also invited to join, these states opted not to participate in the scenario analysis. The Western uniformity scenario study considered a larger percentage of the rural network in the analysis. The study investigated seven vehicle configurations to evaluate the productivity gains attained by replacing the current US truck fleet with the proposed configurations (Figure 2.7).



Source: WUSA, 2004

Figure 2.7 Vehicles considered in Western Uniformity Scenario

2.4.3.5 MAP-21 Study

In accordance with the Moving Ahead for Progress in the 21st Century Act (MAP-21), the USDOT conducted a comprehensive truck size and weight limits study. The study investigated the effects of operating trucks at federal weight limits and in excess of the existing limits and evaluated the impacts of alternative vehicle configuration on infrastructure consumption. The vehicle configurations shown in Table 2.13 were examined as part of this study.

Table 2.13 Configurations examined in MAP-21

Configuration	# Trailers or Semi-Trailers	# Axles	Gross Vehicle Weight (pounds)
1) 5-axle vehicle [Control Vehicle]	1	5	80,000
	1	5	88,000
2) 6-axle vehicle	1	6	97,000
	1	6	91,000
3) Tractor plus two 28 or 28 ½ foot trailers [Control Vehicle]	2	6	80,000
4) Tractor plus twin 33 foot trailers	2	6	80,000
5) Tractor plus three 28 or 28 ½ foot trailers	3	7	105,500
6) Tractor plus three 28 or 28 ½ foot trailers	3	9/10	129,000

Source: Rayman, 2013

2.4.4 Vehicle Configurations Currently Used in Other Countries

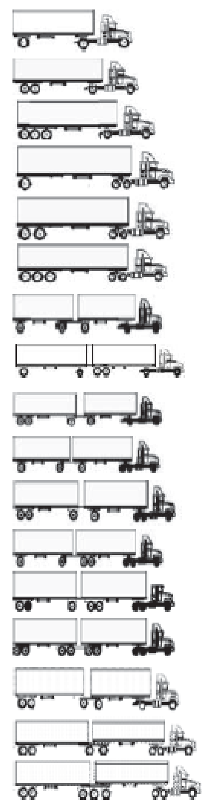
In Mexico, standards are established by the federal government through the Secretaría de Comunicaciones y Transportes (SCT). Mexican states do not have the authority to establish different standards. Figure 2.8 shows the details of typical permitted configurations in Mexico; the T3-S3-S2 configuration is provided in Figure 2.9.

Texas and Arizona use different procedures to permit trucks exceeding allowable weights and dimensions across the US-Mexico border. For example, in Arizona, Mexican LCVs with two 40-ft trailers go to a staging yard where the trailers are decoupled so that two separate power units pull the individual trailers to their US destinations; this helps to reduce the number of international border crossings. The OW corridor operating between the Texas Port of Brownsville and the Veteran's Bridge at Los Tomates allows permitted trucks to haul Mexican weights. The load and vehicle dimensions cannot exceed 12 ft. wide, 15 ft. 6 in. high, or 110 ft. long. The Arizona DOT has implemented single-trip OW permit allowing trucks carrying fresh produce within the Mexico/Arizona commercial zone to operate with a GVW up to 90,800 lbs. on a five-axle tractor-semitrailer. Among other requirements, the carrier must use sealed containers, comply with Arizona axle load limits, and follow specific routes designated on the permit.

Most of the Mexican truckers use T3-S2 53-ft semitrailers due to ease of crossing. These vehicles are different to US five-axle trucks in terms of length. Most Mexican trucks operating at the Port of Brownsville have shorter inner and outer bridge lengths compared to Texas/federal limits. At the Hidalgo County Regional Mobility Authority, the inner and outer bridge lengths are typically longer than legal limits. Heavier weights up to 102,515 lbs. (against 80,000 lbs.) are carried.

Table 2.14 compares the GVW of each Mexican vehicle with the equivalent vehicles (if any) in the US and Canada. This table shows that GVW limits for Mexican vehicles are at least 1.3 to 1.5 times greater than the GVW limits in the US. In terms of length, a few configurations that carry heavier loads are much shorter while a few others are longer. It should be noted that Mexican live loads for road design are higher than those of the US to accommodate heavier and shorter trucks (Normativa para la Infraestructura del Transporte, Section N-PRY-CAR-6-01-003/01). Figure 2.10 shows the Mexican live load configuration.

Vehicle Type	No. of Axles	No. of Tires	Truck Configuration
T2-S1	3	10	
T2-S2	4	14	
T2-S3	5	18	
T3-S1	4	14	
T3-S2	5	18	
T3-S3	6	22	
T2-S1-R2	5	18	
T2-S2-R2	6	22	
T2-S1-R3	6	22	
T3-S1-R2	6	22	
T3-S1-R3	7	26	
T3-S2-R2	7	26	
T3-S2-R3	8	30	
T3-S2-R4	9	34	
T2-S2-S2	6	22	
T3-S2-S2	7	26	
T3-S3-S2	8	30	



Source: NOM-012-SCT-2-2008.

Figure 2.8 Current commercial vehicle configurations allowed in Mexico

Figure 2.9 T3-S3-S2 LCV used in Mexico

Table 2.14 Comparison of dimensional and weight limits for similar vehicles in the United States, Mexico, and Canada

Vehicle	Limit	NOM-012-SCT-2-2008[a]	U.S. Comparable Vehicle	Canadian Comparable Vehicle[b]
T2-S1-R2	Weight T (lb)	52.0 (114,000)	36.4 (80,000)	41.9 (92,200)
	Length m (ft)	31.0 (102)	18.7 (61.5)	25.0 (82.0)
T2-S1-R3	Weight	60.0 (132,000)	NA[e]	NA
	Length	31.0 (102)	NA	NA
T2-S2-R2	Weight	60.0 (132,000)	NA	NA
	Length	31.0 (102)	NA	NA
T3-S1-R2	Weight	60.5 (133,100)	NA	NA
	Length	31.0 (102)	NA	NA
T3-S1-R3	Weight	67.5 (148,500)	NA	NA
	Length	31.0 (102)	NA	NA
T3-S2-R2	Weight	67.5 (148,500)	48.0 (105,500) [RMD]	53.5 (117,700) [RMD]
	Length	31.0 (102)	29.0 (95)	31.0 (101.7)
T3-S2-R3	Weight	75.5 (166,100)[c]	NA	NA
	Length	31.0 (102)	NA	NA
T3-S2-R4	Weight	80.0 (176,000)[c]	58.6 (129,000) [TPD]	53.5 (117,700) [TPD]
	Length	31.0 (102)	32.3 (106)	41.0 (134.5)
T3-S2-S2	Weight	65.5 (144,100)	NA	NA
	Length	31.0 (102)	NA	NA
T2-S2-S2	Weight	58.5 (128,700)	NA	NA
	Length	31.0 (102)	NA	NA
T3-S3-S2	Weight	68.0 (149,600)	56.8 (125,000) [B-train][d]	62.5 (137,500) [B-train]
	Length	25.0 (82)	33.5 (110)	25.0 (82.0)

[a]These Mexican GVW figures correspond to ET and A highway classification limits. The extra weight applies to trucks with pneumatic suspension.
[b]Limits according to MOE among provinces. Actual provincial limits vary.
[c]These two types of combinations are allowed an extra 4.5 tons gross weight until 2013.
[d]Usually operates under permit.
[e]NA: not applicable.

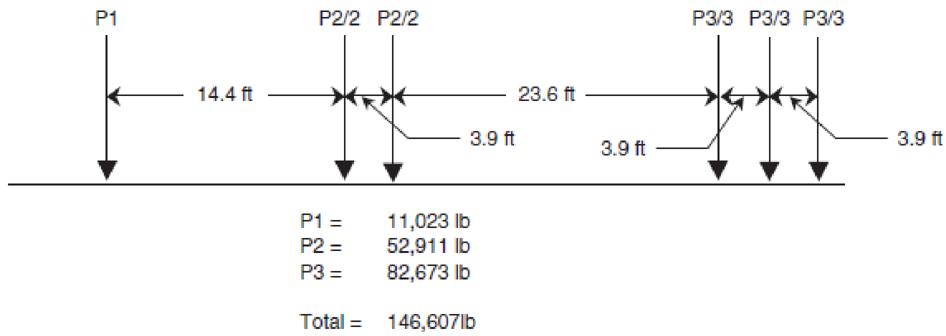


Figure 2.10 Mexican live load configuration

The OECD (Organization for Economic Co-operation and Development) study on safety, productivity, infrastructure wear, fuel use, and emissions assessment of the international truck fleet found that the US has the lowest weight limits of all countries examined, including Australia, Canada, the European Union, Mexico, and the UK. Changing the bridge formula can create an environment of opportunity for vehicle designers to create more productive configurations.

Australia has many different types of OS trucks, the most notable being the triple road train. This particular vehicle has three beds for cargo, each of which has a tandem axle in the front and a tridem in the back. The double road train has the same axle configuration; however, it only uses two beds. The triple can only be used on the Stuart Highway whereas the double has access to a more expansive network in South Australia. It is a common theme of Australian truck restrictions to only allow access of certain vehicles to certain roadways. Figure 2.11 shows the triple and double road train vehicle configurations that are used in Australia.

Figure 2.11 Australian double road train at 36.5m long (79.0t) and triple road train at 53.5m long (115.5t)

The UK has fewer truck configurations. The Denby B-Train, which is the most common trucks in the UK, resembles the standard B-Train that is used in other countries. However, the UK version includes a command steer axle on the first trailer; this delivers some of the drive train to the trailer, which improves steering capability and (according to the manufacturer) improves the fuel efficiency of the vehicle. A shortcoming of the Denby is that it was not intended to exceed weight limits; rather, it is designed to provide maximum cubic capacity. The Denby was described by its designer as a "lightweight" heavy vehicle. The UK is also currently running experiments with longer HGVs (heavier goods vehicles); it is anticipated that these vehicles will provide better efficiency both economically and environmentally. The HGV vehicles are restricted to the 44 metric ton weight limit for six-axle vehicles; however, these trucks are about 60 feet long.

The trucking system of continental Europe is very similar to the UK. The most noticeable difference between European trucks and North American is that European trucks have the "cab over engine" setup, whereas North American trucks have the engine block in front of the cab. This means that there is less length "spent" on the cab of the truck and more can be put into the trailer section to meet length requirements. Additionally, in an initiative called EuroCombi (see Figure 2.12), there is a push to implement a series of newly designed trucks that can meet the growing economic demand of Europe without placing further burdens on roads and bridges or causing any safety concerns. The existence of poor infrastructure repair and funding plans within the EU nations fueled the EuroCombi initiative. The proposed trucks use dollies and tractor trailers to modify the way loads are distributed amongst axles. The newer vehicle is anticipated to reduce the road consumption.

Source: Wikipedia

Figure 2.12 EuroCombi configuration example (60ft)

2.5 Costs and Benefits of OW Trucks

2.5.1 Cost and Benefit Perspectives

The possibility of being able to increase the current GVW limit in Texas by using alternative axle configurations that do not increase the consumption of the surface transportation infrastructure opens up the discussion of what other significant costs and benefits can come from increasing the GVW and axle load limits to create more productive trucks. This is an issue that has been debated extensively. Indeed, "the benefits and costs of increasing federal size and weight limits have been debated for decades" (ICF International, et al., 2011). The effort to identify infrastructure-friendly trucks (i.e., trucks that effectively impose no additional impact when weight and size limits are allowed to increase) will benefit from the use of benefit/cost analysis (BCA) to find those truck size and weight limits that provide for the best of both worlds: productivity for businesses with minimal external costs.

When discussing the costs and benefits of modifying the GVW and axle load limits, it is important to differentiate the various stakeholder perspectives, because what may be a cost to one entity may constitute a benefit to another entity; differences in the value of the cost or benefit may also be a factor. This section attempts to outline some of the different perspectives of various stakeholders and the stakeholders' perceptions of costs and benefits.

2.5.1.1 Federal Government

MAP-21 required the FHWA to conduct a comprehensive truck size and weight study that answers two questions:

- What difference is there in highway safety risks (accident severity and frequency), infrastructure damage, and delivery of effective enforcement between trucks operating at and below current federal size and weight limits compared to trucks that operate above those limits?
- What would the impact be in these same areas if a change were to be made to current federal truck size and weight limits?

To begin answering those questions, the FHWA undertook a set of desk scans for the following potential impacts:

- Bridge Structure
- Enforcement and Compliance
- Highway Safety and Truck Crash
- Modal Shift
- Pavement

Those desk scans can presumably be indicative of what the federal government considers the impacts to consider for significant costs and benefits. This report incorporates the findings of those desk scans in to the discussion of each potential impact. Those same potential impacts are seen in other federal publications, including (ICF International, Delcan Corporation, Cheval Research, 2011).

Unique to the federal level perspective is consideration of the costs and benefits associated with "harmonizing" truck size and weight regulations so that all states are subject to the same uniform regulations. Table 2.15 presents the results of an analysis of the impacts of harmonization, with consideration given to the impacts listed above in addition to traffic operations, shipper costs, and railroad revenue.

Table 2.15 Summary of impacts of harmonization of state truck size and weight rules

Type of Impact	Metrics	Impacts in Federal Uniformity Scenario (80,000 lbs max GVW)	Impacts in Western Uniformity Scenario (129,000 lbs max GVW)
Freight distribution by type of truck	VMT by truck configuration	Significant decrease in VMT traveled by doubles, triples, and 6-axle single trailers. Increase in VMT by 5-axle single trailers.	Significant shift of VMT from single trailers to double- and triple-trailers
Mode share	Percentage	Mode shift not analyzed	Little or no shift from rail to truck
Safety	Crash rate involving trucks per million truck VMT; rate of fatal truck crash per million truck VMT	Net impact is unclear: reduced VMT by longer, heavier trucks would reduce crash severity and possibly number of accidents, but increase in total truck VMT would likely increase number of accidents	Net impact is unclear: decrease in total truck VMT would likely reduce number of accidents; but more VMT by longer, heavier trucks would increase crash severity and possibly number of accidents
Fuel consumption	Gallons of diesel	Higher due to increase in truck VMT	Lower due to decrease in truck VMT, but partially offset by reduced fuel economy of heavier trucks
Air quality	Tons of emissions	Higher due to increase in fuel consumption	Lower due to decrease in fuel consumption
Traffic operations	Vehicle-hours of delay; cost of congestion	Slight increase in number of vehicle-hours of delay due to increase in truck VMT	Slight decrease in delay due to fewer truck VMT, but offset somewhat by effect of longer, heavier trucks on traffic flow
Shipper costs	Dollars	Higher due to increase in cost-per-ton-mile	Lower due to decrease in cost-per-ton-mile
Railroad revenues	Dollars	Higher due to decreased competition from longer, heavier trucks	Lower due to increased competition from longer, heavier trucks

The 2000 *Comprehensive Truck Size and Weight Study* by the FHWA also looked at the impacts of harmonization. Table 2.16 presents the results:

Table 2.16 Harmonization scenario impacts

Impacts	Scenario Impacts		
	Uniformity	North American Trade	LCVs Nationwide
VMT	3.2% higher	10.2% lower	23.4% lower
Pavement	No Significant Impact		
Bridge	13% lower	33 - 42% higher	34% higher
Safety	Truck Specific Impacts		
Geometric	No major impact	13% higher	965% higher
Energy	2% higher	6% lower	14% lower
Noise	Proportional to VMT		
Air Quality	Roughly Proportional to VMT		
Congestion	0.5% higher	1% lower	3% lower
Rail Return on Investment	Not Applicable	43% lower	56% lower
Shipper Costs	3% higher	5 – 7% lower	11% lower

Source: Fekpe and Blow, 2000

Presumably, the federal government's perspective reflects the general public's point of view.

2.5.1.2 State Government

State agencies are responsible for the permitting, inspection, and enforcement of OS/OW loads and for maintenance of the pavement and bridges, so their concerns will necessarily emphasize those impacts.

2.5.1.3 Local Public Agencies

CTC & Associates (2015) examined from the city's and county's perspective the impacts of truck weight limit increases for the Minnesota DOT, especially in terms of local roadways. Their report considered the following impacts:

- Pavement
- Bridges
- Safety
- Traffic and congestion
- Geometric design
- Energy and emissions

2.5.1.4 Businesses

A search of the US Chamber of Commerce website does not reveal any official positions regarding an increase in the GVW and axle load limits of trucks. The impact on businesses mostly comes down to the change in shipping costs, and how shipping costs change in response to an increase in GVW and axle load limits continues to be an area of research.

2.5.1.5 Trucking Industry

Disagreement actually exists within the trucking industry about increasing the truck size and weight limits. As expected, the American Trucking Association (ATA), which generally represents the larger trucking companies, supports an increase in truck size and weight, especially on IHs, because of the improved economic productivity and safety and reduced emissions and logistics costs (ATA, 2009). The ATA points out additional benefits of allowing heavier trucks on IHs instead of on secondary roads (ATA, 2009):

- Lowered pavement maintenance costs
- Mitigation of traffic congestion

The ATA also considered the pros and cons of uniformity of regulations at the national level, and ATA determined:

> "Federal one-size-fits-all regulation prevents trucking companies from using their safest, cleanest, most pavement-friendly vehicles where such use would be appropriate. ATA believes that states, not the federal government, are in a better position to determine whether these more productive vehicles should be allowed to operate on their highway systems. Congress should reform federal law to give states greater flexibility." (ATA, 2015)

It is not stated why ATA prefers a state-by-state approach, as ATA also points out that the current US federal weight limits are the lowest in the developed world, which puts US businesses at a competitive disadvantage. Overall, ATA is most concerned with the productivity impacts of truck size and weight limits. A representative of the ATA at a conference about evaluating the federal regulations noted that the following increase in trucking costs is making productivity a critical issue for the trucking industry (Fekpe and Blow, 2000):

- Hours of service rules
- Driver pay
- Fuel prices
- Environmental control costs
- Ergonomic regulations
- Impacts of highway pavement and bridge deterioration

Those types of costs motivate the ATA to want truck size and weight increases. Looking at the impacts of policies that affect those types of costs to the trucking industry would integrate a more comprehensive assessment of the productivity gains and losses associated with size and weight restrictions.

From another perspective within the trucking industry, truck size and weight increases are seen as a net cost to the industry. The Owner-Operators and Independent Drivers Association (OOIDA) states on their website:

> "Relaxing restrictions on weights and sizes would have a tremendously negative impact on the level of safety and structural integrity of our nation's highways, endanger all highway users and increase the cost of insurance required for trucking companies.
>
> Proponents present an argument of improved efficiency and fuel savings. However, as an organization that represents individuals who drive trucks for a living, OOIDA believes any meaningful discussions of improving productivity in the shipping industry must include the aspect of loading and unloading times. Truckers spend between 30-40 hours per week waiting at docks for shippers and receivers to load or unload." (OOIDA, 2015)

This contrast between the different opinions of two trucking industry groups show why it is useful and important to examine the truck size and weight issue from several perspectives, since aspects of an issue not raised by one stakeholder (ATA) are raised by another (OOIDA), such as those aspects of productivity to consider.

2.5.1.6 Railroads

Railroads see trucks as both partners and competitors. The railroad industry points out that they own and operate their own infrastructure, whereas trucks do not. Therefore, railroads, in addition to maintaining their fleet, must also pay for and maintain their infrastructure. The Association of American Railroads (AAR) points out heavier trucks do not necessarily pay for their fair share of damage to the highways (pointing to the USDOT's 2000 *Highway Cost Allocation Study*) (AAR, 2015). That raises an equity issue for them. Additionally, railroads, concerned about the investment made in their infrastructure, are concerned about diversion of freight from rail to trucks (Fekpe and Blow, 2000). Equity and economic costs concern the railroad industry. The AAR's official policy position is that the federal government should continue existing truck size and weight allowances, and not allow an increase (AAR, 2015). Addressing the AAR's concerns would require identifying the infrastructure-friendly trucks that do cover the costs of their consumption, or at the very least, do not increase the unpaid costs.

2.5.1.7 Individual versus System Level

Two other perspectives critical to distinguish in assessing the costs and benefits is whether the BCA analysis is at the level of an individual truck or all the trucks in the system. As will be explained throughout the sections on the different impacts considered from increasing truck weight and size, the ratio of benefits to costs associated with an increase for a single truck can flip the other way when considering the entire system of trucks. For instance, a single larger, heavier truck may consume more pavement than a smaller, lighter truck, resulting in a better benefit-cost ratio for the smaller lighter truck. However, if a fleet of heavier trucks replaces many smaller, lighter trucks, then the reduction in the number of trucks may result in more benefits. Again, BCA must clearly indicate the perspective taken. The following sections of this report look at each potential impact and associated costs and benefits of GVW and axle load limit restrictions.

2.5.2 Potential Impacts of Modifying GVW and Axle Load Limits

2.5.2.1 Reduction in Number of Trucks

Allowing for an increase in the GVW and axle load limits would seem to allow for a reduction in the total number of trucks on the road, a contention supported by the results of the following studies.

Woodrooffe (2001) found using single semitrailer configurations (instead of larger, heavier trucks) would result in an 80% increase in truck movements and 40% cost increase for shippers compared with using high-capacity vehicles in Alberta, Canada.

Vierth et al. (2008) studied the use of high capacity vehicles in Sweden and found, depending on commodity group, the cost per truck trip would decrease 5 to 12%, but to move the same quantity of freight required 35 to 50% more number of trucks (on average one Swedish truck of maximum size equaled 1.37 maximum EU sized trucks). International Transport Forum (ITF) (2010, p. 18) reported the use of B-Double trucks (Figure 2.13) in Australia reduced the number of articulated vehicles on the road from a low estimate of 6,700 to a higher estimate of 20,000.

Source: Wikipedia for Road Trains

Figure 2.13 Double truck in Australia

The reduction in the number of trucks is not in and of itself a cost or a benefit, but a reduction in the number of trucks in the road can impact the following other factors that contribute to the determination of costs or benefits of changing GVW and axle load limits:

- Safety
- Enforcement
- Industry costs
- Pavement and bridge consumption
- Air emissions and fuel consumption

For example, the ITF states:

> "Higher capacity vehicles can result in fewer vehicle-kilometers travelled for a given amount of freight transported. This is particularly true in relation to the volume of goods that can be carried per truck. Load volume rather than weight now often determines the number of trucks required. The reduction of truck numbers is contingent on avoiding a major decline in vehicle load factors. Modular systems that couple standard trailers provide valuable

> flexibility for matching loads and for facilitating intermodal transfers. Case study results (Alberta and Saskatchewan in Canada, Sweden and Australia) suggest that the use of higher capacity vehicles has reduced the amount of truck traffic on the road, with benefits for safety and the environment, including reducing fuel consumption and CO2 emissions." (ITF, 2010, p. 9).

The Victoria Department of Transport (2008) found an 11% reduction in fuel consumption as a result of Australia allowing two B-coupled semi-trailers (Figure 2.14). Additionally, ITF (2010, p. 21) states that replacing lower capacity trucks with fewer higher capacity trucks could improve overall road safety, the subject of interest in the next section.

2.5.2.2 Safety

Tons of research, probably quite literally, has been conducted on the impacts of truck size and weight on highway safety since this is one of the top concerns from the general public and policymakers. Rather than provide an extensive overview of the research, this section references some of the work that has already done a scan of the more recent literature.

To understand the concern and the motivation for looking at safety, Straus and Semmens (2006) reported that in Arizona, an average of 100 people are killed in large-truck collisions each year, and that large truck traffic fatalities are highest in two lanes (75.5%) and four lanes (12.2%), which are the size of the facilities of non-interstate roads. Fatalities involving large trucks are greatest where the posted speed limit is 55 mph (37.8%) and 60 mph or higher (35%).

A more recent study in 2013 found that in 2011, 3,757 people were killed in crashes involving large trucks and 88,000 more were injured (Sowards, Eastham, Matthews, and Pennington, 2013).

Regarding the safety history of larger, heavier trucks, the MAP-21 *Comprehensive Truck Size and Weight Study* included a desk scan of the safety issues associated with increasing truck weight (USDOT, 2013). Either because the trucks are not in operation on the roadways, because vehicle, crash, and exposure data have limitations, or statistical significance did not exist, the "recent studies based on observing the effect of larger and heavier trucks on total system crash rate or the total truck rate were inconclusive" (p. 46). The USDOT (2013) study mentioned Carson (2011) and AASHTO (2009) as the two most recent surveys of research on truck size and weight issues that include safety. AASHTO (2009) concluded from their study of OS/OW truck crashes that accident severity increases and accident rates decrease as trucks become larger and heavier. Carson (2011) prepared a comprehensive overview of the literature regarding the safety of larger trucks. Figure 2.14 provides the general findings from that report.

General Findings

- Changes in truck size and weight limits can affect highway safety by: (1) increasing or decreasing truck traffic; (2) causing or requiring changes in vehicle design and performance that may affect crash rates and severity; or (3) causing trucks to shift to highways with higher or lower crash rates.
- Limitations in available crash and exposure data challenge the ability to definitively relate truck size and weight conditions to highway safety levels.
- Operating environment—particularly road class—has consistently been observed to significantly influence truck-related highway safety, with Turnpikes/Interstates being generally safer irrespective of truck size or weight.
- With some consistency, heavier trucks (higher GVWs) were associated with lower crash rates (attributable to fewer required truck trips to haul a given amount of freight) but higher crash severities.
- With some consistency, larger, heavier trucks were observed to have the same or slightly higher crash risk based on vehicle handling and stability characteristics:
  - Double trailer trucks are prone to rearward amplification that can have a detrimental safety effect.
  - Higher centers of gravity increase potential for rollover or ramp-related crashes.
- Results relating truck configuration and safety are inconsistent:
  - Double trailer trucks have been estimated to have higher, lower, and the same crash rates and severities when compared to single trailer/tractor-semitrailer configurations.
  - LCVs have been estimated to have higher and lower crash rates and severities when compared to other truck configurations, although recent research suggests superior safety performance.
- Changes in driver qualifications and vehicle/roadway design can potentially offset the safety drawbacks of some larger, heavier vehicles.
- International efforts have defined safety performance measures—based on vehicle stability and control characteristics—to help assess the safety-related impacts of changes in truck size and weight limits.

Figure 2.14 Carson's (2011) general findings of safety and truck size and weight

Obviously, safety is a priority regardless of perspective (businesses, government, and the general public). What could potentially reduce the costs is the argument that increasing allowable GVW and axle load limits reduces the number of trucks on the road, which could reduce the number of accidents (but still needs to take in to consideration the effect of the additional weight). But both the MAP-21 *Comprehensive Truck Size and Weight Study* and the 2011 National Cooperative Highway Research Program (NCHRP) study conclude it is difficult to relate truck size and weight to traffic safety, thus complicating any estimation of costs and benefits.

2.5.2.3 Fuel Consumption, Energy Efficiency, and Air Emissions

This section on environmental impact begins with a real-world example of the reductions in fuel and emissions possible from a business choosing to switch to a truck with a higher GVW. Table 2.17 presents the results of an internal analysis conducted by Anheuser-Busch of their truck fleet operations on two Texas routes to estimate the impact of implementing a six-axle 97-kip GVW tractor semi-trailer in place of the current 18-wheeler loaded to 80 kips GVW (Jacoby, 2008). The increased cargo in the case of a 97-kip six-axle truck would vary from approximately 15 kips to 15.5 kips after subtraction of the added axle (Prozzi et al., 2013).

Table 2.17 Anheuser-Busch analysis of reduction in trips

Route	Trucks per week (80,000 lbs GVW)	Trucks per week (97,000 lbs GVW)	Change in cargo per truck (lbs)	Reduction in diesel fuel/ week (gallons)	Reduction in CO2 emissions/ week (lbs)
Houston to San Antonio (198 miles)	128	96	15,000	807	17,996
Houston to Waco (219 miles)	1,126	845	15,000	7,824	174,475

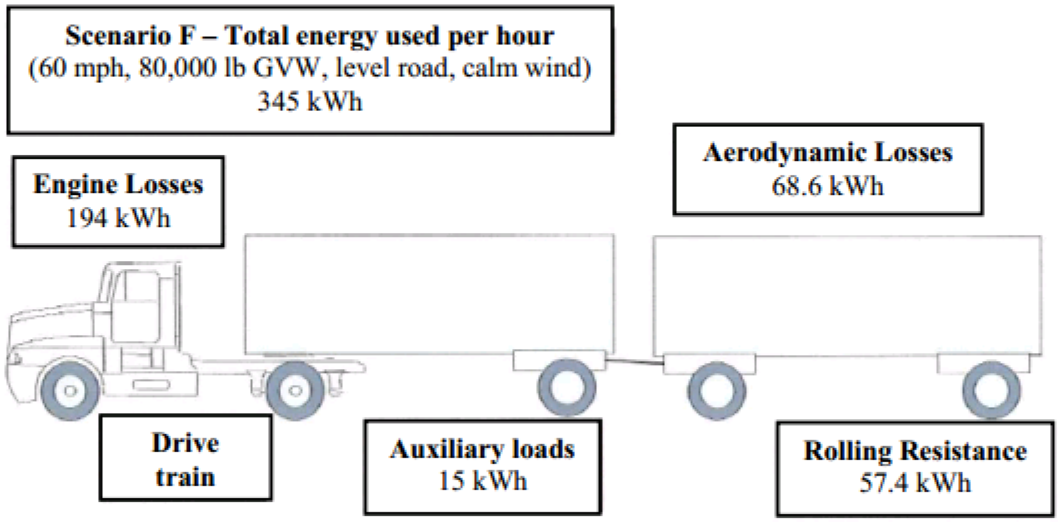
Source: Jacoby, 2008

A more productive truck (i.e., one that has higher allowable weight and axle limits) would reduce the fuel consumption and the CO_2 emissions. Reducing fuel consumption results in significantly lower operating costs. Fuel is typically one of the greatest expenditures for truck operators.

Other studies about the impact of increasing the GVW on fuel consumption, energy efficiency, and emissions also reported reductions in fuel consumption (and fuel costs) and CO_2 emissions (Walton et al., 2009). The primary variables considered in fuel consumption for large trucks are:

- Vehicle mass,
- Tire rolling resistance and
- Overall vehicle aerodynamic drag.

Woodrooffe and Pont (2011) describe a method that estimates the power required to overcome aerodynamic drag and tire rolling resistance at constant cruising speed of 60 mph on a level road with no wind. As an example from Woodrooffe et al. (2011), Figure 2.15 shows a scenario (F) of total energy consumption per hour, with the contribution of each truck section to the total. The amount of CO_2 produced per kWh is estimated as follows for the scenario F truck: The amount of diesel fuel consumed for the Scenario F vehicle is approximately 6.3 miles per gallon, which is 9.52 gal/hr or 36.05 liters/hr. Since the amount of CO_2 emissions produced by diesel fuel is 2.668 kg/liter, the amount of CO_2 produced per hour is 96.18 kg.



Source: Woodrooffe & Pont (2011)

Figure 2.15 Results for estimation of energy consumption and emissions

ITF (2010, p. 9) points out that "size and weight regulations limit aspects of truck design such as the length, wheelbase, width, height, axle loads, axle spacing, and GVW. These factors directly influence fuel consumption." Increasing the gross weight at which a vehicle operates will increase its fuel consumption.

Coyle (2007) studied the effects of payload on the fuel consumption of trucks and found that fuel consumption increases on average by 0.112 miles per gallon for every ton of payload added for the distribution truck (articulated trucks at up to 44 tons gross combination weight). They also found that a 44-ton truck becomes more fuel efficient than a 32-ton truck when payload exceeds 17 tons. They also found that incorrect use or poor maintenance of a lift axle can have a big impact on fuel consumption. The fuel consumption of trucks driven by the same engine with the same design of cab varies enormously with the weight and aerodynamic properties of the trailer they haul and with the configuration of axles and tires on the trailer.

Figure 2.16 presents the table of miles per gallon reported in the USDOT (2000) *Truck Size and Weight Study* for different roadway configurations; however, diesel fuel use depends on other factors than just configuration, such as weight, speed, and roadway grade. Generally, however, a truck with the same weight but longer configuration does not mean a higher rate of fuel use (USDOT 2000).

Configurations	GVW (pounds)					
	40,000	60,000	80,000	100,000	120,000	140,000
Three-axle Single-Unit Truck	5.11	4.42				
Four-axle Single-Unit Truck	4.80	4.15				
Five-Axle Semitrailer		5.44	4.81	4.31		
Six-Axle Semitrailer		5.39	4.76	4.27		
Five-Axle STAA Double		5.95	5.29	4.76		
Seven-Axle Rocky Mt. Double			5.08	4.58	4.36	4.16
Eight-Axle (or more) Double			5.08	4.82	4.58	4.36
Triple-Trailer Combination			5.29	5.01	4.76	4.54

Source: USDOT, 2000

Figure 2.16 Fuel consumption by truck configuration

Computational analyses show that in many instances trucks with higher allowable weights can perform equally if not better than smaller, lighter trucks for fuel efficiency and emissions (ITF, 2010). But again, this is because of considering (or rather, assuming) the reduction in the number of trucks on the road.

With that said, estimating the economic costs and benefits of fuel use and emissions from increasing the allowable weight is a complex process highly dependent on assumed conditions and scenarios. In fact, the 1997 *Federal Highway Cost Allocation Study* tried to develop a cost estimate of air pollution attributable to motor vehicles and the resources needed prohibited the development of such estimates for the scenarios considered (USDOT 2000). At the time of the USDOT 2000 *Truck Size and Weight Study*, the relationship between vehicle weight and emissions was not understood because the EPA's models did not differentiate between the vehicle classes (and thus the different vehicle weights).

Therefore, at this stage of the research, the interest is in understanding in general the factors to consider. Factors considered in estimating changes in emissions into the BCA include (USDOT 2000):

- Mortality (death)
- Morbidity (illness)
- Visibility impairment
- Soiling
- Materials damage
- Effects on plants and wildlife

Related to the issue of fuel consumption, energy efficiency, and emissions, is the impact of allowing larger trucks on the rail industry, which generally has a smaller environmental footprint. The next section looks at the issue of freight being diverted from rail to truck as a result of increasing allowable GVW and axle load limits.

2.5.2.4 Mode Diversion

The shifting of freight from truck to rail or from rail to truck introduces a wide range of potential costs and benefits to consider in an analysis. From the railroad perspective, anything that makes rail less attractive will affect their revenue negatively (and the environment, according to most analyses). From the trucking perspective, anything that makes trucks more attractive will affect their revenue positively. As stated before, the trucking and rail industries are both partners and competitors, making for an interesting, dynamic relationship. This concern is also acknowledged by ITF (2010, page 9), which states “The introduction of HCVs (high-capacity vehicles) can therefore have positive impacts on rail markets as well as negative impacts, depending on whether road and rail are complements or substitutes.”

Additionally, there are other factors affecting choice of mode that may counteract any effects of increasing the allowable GVW and axle load limits on trucks—such as location, speed, and pricing—that require consideration.

Studies suggest that allowing LCVs to operate in more states would divert a significant share of the freight market from rail to trucks (Picher, 1995; Maze, 1994), resulting in greater congestion and energy use. The AAR estimated an 11% diversion of current rail ton-miles to truck (ICF, 2001) whereas trucking associations argued a much lower impact (Maze, 1994). Carson (2011) summarized the results of a 1990 Transportation Research Board study that estimated the change in rail ton-miles for different truck size and weight proposals (Table 2.18). Most resulted in a decrease in rail ton-miles and transport costs.

Table 2.18 Estimated freight diversion from rail to truck for various size and weight proposals

TRUCK SIZE AND WEIGHT PROPOSALS			RAIL TON-MILES	TRANSPORT COSTS[1,2] ($ millions)
1	Grandfather Clause Elimination	No exemptions in federal limits	↑0.8%	↑230[3]
2	Uncapped Formula B	No 80,000-lb GVW cap; only federal bridge formula controls	↓2.2%	↓750[4]
3	NTWAC	Permit program for specialized hauling	↓0.9%	↓310[5]
4	Canadian Interprovincial Limits	Higher GVW and minimum axle spacing instead of bridge formula	↓6.6%	↓2,240[6]
5	TTI Bridge Formula	Alternate formula developed for FHWA	NA	NA
6	TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights	↓0.0%	0
7	Uncapped TTI HS-20 Bridge Formula	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only TTI HS-20 bridge formula controls; less permissive when applied to 7+ axle vehicles	↓2.5%	↓850[7]
8	Combined TTI HS-20/ Formula B	Higher single-unit/shorter combination vehicle weights (Proposal 6) and no 80,000-lb GVW cap; only federal bridge formula controls (Proposal 2)	↓2.5%	↓860[8]
9	New Approach	Variation of Proposal 8 with lower axle weights for 80,000-lb+ vehicles	NA	NA
10	Freightliner	Exempts steering axles from bridge formula to encourage use of set-back axles	NA	NA

[1] All costs are in 1988 dollars and were calculated assuming a discount rate of 7 percent.
[2] Competitive railroad rate decreases would reduce shipper costs; however, this effect is not included because it represents a redistribution from railroads to shippers rather than a net decrease in costs.
[3] Competitive rate decreases by railroads would reduce shipper costs by an additional $50 million.
[4] Competitive rate decreases by railroads would reduce shipper costs by an additional $210 million.
[5] Competitive rate decreases by railroads would reduce shipper costs by an additional $90 million.
[6] Competitive rate decreases by railroads would reduce shipper costs by an additional $620 million.
[7] Competitive rate decreases by railroads would reduce shipper costs by an additional $240 million.
[8] Competitive rate decreases by railroads would reduce shipper costs by an additional $240 million.

Source: Carson, 2011

From the public's perspective, a shift of freight from rail to truck could result in changes to external costs such as fuel consumption/energy use, and thus air emissions. Interestingly, in Europe there is a focus on shifting commodities to rail, so programs benefiting truck movement are seen as counter to efforts to encourage use of more rail

(Honefanger, et al., 2007). Knight et al. (2008) estimated an increase in CO_2 emissions and other environmental costs because of a shift from rail to road in response to Great Britain allowing for 60 ton heavy goods vehicles. ITF (2010) recognizes the difficulty for estimating the potential modal share because the impacts vary across countries due to differences in markets and rail and road freight shares.

Again, as with other factors such as safety, estimating the impacts of increasing allowable GVW and axle load limits is not straightforward.

The next section looks at the costs specific to the trucking industry.

2.5.2.5 Trucking Costs

Carson (2011) provides a succinct summary of the findings of research regarding the costs to industry of increasing the allowable GVW and axle load limits (Figure 2.17).

General Findings

- Increased truck size and weight limits consistently result in industry cost savings.
- The magnitude of industry cost savings varies by carrier type, the nature of transportation services offered, and typical commodities transported.
  - Truckload carriers and low density cargoes (cargos that will fill available cargo space before reaching the legal weight limit) benefit most from larger truck sizes.
- Industry cost savings are expressed in terms of per mile or per ton-mile vehicle operating unit costs or more commonly, as aggregate annual shipping or transport costs.
- Estimated industry cost savings—attributable to increased truck size and weight limits and subsequent use of alternative configurations—generally range from 1.4 to 11.4 percent of annual transport costs in the United States.

Figure 2.17 Carson's (2011) general findings regarding industry costs

Carson (2011) also summarized the percent change in cost per ton-mile from a 1991 study by Jack Faucett Associates, Inc. called *The Effect of Size and Weight Limits on Truck Costs*. What should catch the eye in Table 2.19 are the negative signs, indicating a decrease in the cost per ton-mile from changing from the five-axle 48-ft semi to other truck configurations with more axles.

Other related cost savings from having axle load distribution on more axles include enhanced brake capacity, with shorter stopping distances (safety benefit) and reduced brake fade (trucking cost savings) (ITF, 2010, p. 8).

Table 2.19 1991 Estimates of percent change in cost per ton-mile for different truck configurations

CONFIGURATION	PERCENT CHANGE IN COST PER TON-MILE													
	Dry Van				Refrigerated Van		Flatbed		Tank		Hopper		Dump	
	Truckload		Less-than-truckload											
	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW	Change	GVW
5-axle, 36-ft semi													-14.63%	78,000
5-axle, 48-ft semi	Base		Base		Base		Base		Base		Base		Base	
6-axle, 40-ft semi													-12.62%	81,000
													-5.86%	77,000
6-axle, 48-ft semi	-8.47%	86,500			-9.33%	86,500	-8.36%	86,500	-6.12%	86,500				
	3.54%	54,000			1.71%	80,000	3.16%	79,500	4.72%	80,000				
5-axle, twin 28-ft	-10.46%	59,800	-8.21%	63,200	16.55%	80,000					5.34%	80,000		
	6.09%	80,000												
9-axle, twin 28-ft	-15.33%	108,000			-9.53%	108,000	-14.60%	108,000	-13.01%	108,000	-10.98%	108,000	-21.48%	108,000
	35.51%	80,000			52.81%	80,000	37.43%	80,000	37.95%	80,000	41.53%	80,000	30.04%	80,000
9-axle, twin 33-ft	-19.34%	113,500	-11.20%	77,200	-14.12%	113,500	-18.97%	113,500	-17.85%	113,500	-16.49%	113,500	-25.34%	113,500
	40.83%	80,000			59.86%	80,000	42.37%	80,000	40.80%	80,000	43.49%	80,000	35.62%	80,000
9-axle, twin 36-ft, 42-ft, or 48-ft	-36.65%	95,200			-19.88%	129,000	-24.90%	129,000	-23.67%	129,000	-25.91%	129,000	-26.79%	117,000
	-22.06%	127,400			98.82%	80,000	70.11%	80,000	65.00%	80,000	57.94%	80,000	40.90%	80,000
7-axle, Rocky Mountain Double	-27.93%	76,400			-11.22%	105,500	-17.27%	105,500	-15.84%	105,500	-13.56%	80,000		
	29.34%	80,000			42.06%	80,000	26.67%	80,000	27.01%	80,000	22.86%	102,000		
7-axle, triple	-29.75%	83,400	-30.32%	93,000	-4.40%	116,000	-21.56%	116,000	-18.62%	116,000	-20.92%	116,000		
	48.13%	80,000	-14.07%	80,000	96.97%	80,000	40.21%	80,000	42.70%	80,000	39.14%	80,000		

Source: Carson, 2011

In addition to operating costs are logistics costs, which include:

- Loading and unloading,
- Storage,
- Loss and damage,
- Delivery time unreliability, and
- The cost of capital on goods in transit and in inventory.

Studies have acknowledged and looked into the economic costs associated with traffic delay for shippers. Traffic delay reduces productivity for freight movement and imposes a cost for the general traveling public. Gong, et al. (2012) studied how traffic delay incurs operational costs to shippers. Interviews and surveys revealed that en route transportation delay was the most important component of delay, followed by delay at the item collection point. Interestingly, delay at transfer points is not considered a significant, although this may be due to the type of shipping being done because direct shipping does not require use of transfer points such as distribution centers.

Not included in the estimation of changes in the logistics and operating costs are the capital costs associated with switching to trucks with higher GVW and axle load limits. Truck costing models (e.g., Berwick and Farooq, 2003) can provide costs for different truck configurations and trip characteristics considering factors such as annual miles, trip distance, truck speed, and loading/unloading time (which was mentioned earlier as an important cost to consider when assessing productivity of larger trucks by OOIDA). Variables and fixed costs are considered, as well as economies of size and utilization, with the latter the most important because high use of a truck lowers average fixed costs (Berwick and Farooq, 2003). The costs of acquisition of the new trucks to take advantage of new truck size and weight limits would need to be part of a BCA.

Permits for operating on the roadways with an OS/OW load represent variable costs for the trucking industry. The next section explores the issues and costs and benefits associated with permitting, inspection, and enforcement.

2.5.2.6 Permitting, Inspection, and Enforcement

General Practices

Changing the axle load limits and/or GVW may result in either increased or reduced demands on public agencies to permit, inspect, and enforce weight limits. The FHWA's more recent MAP-21 *Comprehensive Truck Size and Weight Study* work included a desk scan of studies that looked at the costs associated with enforcement (FHWA, 2013). The desk scan found five key studies that looked at the costs and benefits with different types of enforcement (FHWA, 2013). It should be noted that industry appreciates inspections and enforcement for ensuring fair competition (Honefanger, et al., 2007).

NTC (2009) focused more on the costs and benefits of implementation of an enforcement strategy (as opposed to actual enforcement activities). The study found the costs of the strategy for the enforcement agency (in 2008 Australian dollars) summed to $3.1 million. Considering low, medium, and high benefit scenarios, the study estimated benefits as a result of the strategy in the range of:

- $13 million and $65 million for reduction in heavy vehicle crash costs
- $0.6 to $2.8 million for reduced road wear
- $1.2 million and $6 million for improved enforcement efficiency

In terms of net present value over a five-year period, the benefit-cost ratio came between 4 to 1 for the low benefit scenario and 20 to 1 for the high benefit scenario.

Rooke et al. (2006) looked at the costs to European enforcement agencies for use of weigh in motion (WIM) systems under three scenarios intended to improve safety and reduce damage caused by OW vehicles. Table 2.20 summarizes the monetary amount (in euros) attributed to each scenario.

Table 2.20 WIM scenario cost

Scenario	Enforcement cost per year	Enforcement cost per year per officer	Enforcement cost per year per overloaded vehicle
Manual selection	€ 160,000	€ 53,333	€ 145
WIM for pre-selection	€ 422,500	€ 70,417	€ 75
WIM for direct enforcement	€ 322,150	-	€ 3

Source: USDOT, 2013

Straus and Semmens (2006) prepared a report for the Arizona DOT revealing from a survey of other states that mobile enforcement is useful for OW truck detection and deterrence and that the budget for a mobile enforcement unit in a state was $3.7 million a year. URS (2005) found 100 WIM sites (at $150,000 each) could be built for the cost of one fixed scale site ($15 million each), with the annual operating costs of 100 WIM sites one-quarter that of the annual cost of the fixed scale.

The USDOT (2000, p. VII-7) found that trucks with more axles require more time to weigh. For example, in Michigan, an 11-axle truck takes two hours to weigh with portable scales.

As the USDOT (2000) study found, more axles will most likely require more time to weigh, so infrastructure-friendly trucks may increase enforcement costs. On the other hand, how the enforcement is done, through strategies (e.g., using WIM data to target enforcement, using mobile versus fixed sites) and technologies (e.g., virtual weigh stations), could lower the time or other costs.

Pursuing answers to the following questions may help in determining what the impact, and the associated costs and benefits, may be:

- How would a change to allow an increase affect the number of inspections? The inspection procedure and time?
- What process and/or technology changes would need to be made to detect violations of the increased size and weight restrictions?

Regarding quantifying the benefits associated with enforcement, in a scan of European enforcement of size and weight restrictions, the most common quantified benefit reported was of the number of OW penalties issued (e.g., citations, warnings) per total number of trucks inspected (Honefanger, et al., 2007). Translating that in to a monetary benefit would include the revenue from the citations. Other studies quantify the benefits, such as reduction in pavement consumption) of using certain enforcement strategies and technologies (e.g., virtual weigh stations, use of WIM data to target enforcement). For more information, the FHWA's *Comprehensive Truck Size and Weight Study* desk scan (FHWA, 2013) of enforcement and compliance provides a useful resource.

Generally, research findings show that revenue from permits does not cover maintenance required as a result of movement of OS and OW trucks on the roadways (as the American Association of Railroad asserts). Additionally, Bilal et al. (2010) found that having more axles on a truck reduces pavement deterioration and consequently, damage repair cost, but could decrease the revenue to be derived from OW permitting. So a shift to more infrastructure-friendly trucks could affect permitting revenue.

It should be noted that enforcement of truck size and weight restrictions can be quite a challenge. The West Virginia Division of Highways wanted to quantify the percentage of OW trucks on its highways that were not getting permits, or were getting permits, but not for the weight or size actually shipped. The industry was deciding the risk of getting caught was not enough of a concern. Indeed, the research results at a macroscopic level from WIM station and permit data indicated that only 6% of the OW vehicles likely had permits for the period analyzed (Chou, Nichols, Sanghong, and Cetin, 2013).

Enough may not be spent on adequate enforcement to protect the infrastructure, resulting in increased maintenance costs. Would the increase in allowable GVW and axle load limits help reduce the number of non-permitted and non-compliant trucks? How much would need to be spent on enforcement under any truck size and weight restrictions scenario? As with all the other impacts mentioned in this report, an estimation of the costs and benefits related to enforcement would need to consider a set of interrelated issues.

Texas Practices

Three agencies are directly involved with inspection and enforcement of size and weight restrictions of trucks in Texas. Any policy that changes size and weight restrictions may necessarily affect the costs of inspection and enforcement activities, which in Texas are conducted or evaluated by these three agencies:

- Texas Department of Motor Vehicles (TxDMV)
- Texas Department of Public Safety (TxDPS)
- Texas Department of Transportation (TxDOT)

The Rider 36 Study (Prozzi, et al., 2012) reported the permitting, inspection, and enforcement activities of those three agencies. The MCD of the TxDMV processes over 800,000 OS/OW permits every year. Permits are required when exceeding the allowable GVW and axle limits. The TxDMV is also responsible for reviewing permit violations. The TxDMV gives to TxDOT a report of all the size and weight violations and of all the bridge hits each month, which TxDOT evaluates for compliance, but does not handle the individual cases. In 2012, the year of the completion of the Rider 36 Study, there were 332 size and weight investigations completed, 82 contested cases, and 18 closed contested cases, for a total of 432 cases in 2012 handled by the TxDMV (Prozzi, et al., 2012). That number of cases was higher than in previous years (Table 2.21). The enforcement division in 2012 included nine full-time employees and one assistant.

Table 2.21 TxDMV Enforcement Division investigations 2008–2012

Year	No of Investigations
2012	332
2011	350
2010	210
2009	120
2008	71

TxDPS conducts the majority (95%) of the inspections and enforcement in the field, with cities and counties conducting the others if they are trained through the Motor Carrier Safety Alliance Program (Prozzi, et al., 2012). In 2011, the TxDPS completed 37,626 inspections, with each inspection taking on average 1 hour of a trooper's time (at $47/hour). Table 2.22 presents a summary of the inspection and enforcement activity in 2011 (Prozzi, et al., 2012).

Table 2.22 TxDPS inspection and enforcement activity, 2011

Inspections	Tickets	Violations	Warning	Weight Tickets	Weight Violations	Weight Warnings	Size Tickets	Size Violations	Size Warning
37,626	30,290	68,491	38,201	28,641	65,988	37,347	1,649	2,502	854

As of 2012, total commissioned personnel that worked on commercial vehicle enforcement totaled 514; non-commissioned personnel (e.g., the inspectors, investigators, and field supervisors) totaled 263. It is clear that inspection and enforcement requires agency resources, which must be accounted for in assessing the costs and benefits of imposing size and weight restrictions.

The next few sections look at some of the more relatively minor impacts (noise, facility and roadway design, and utilities) before getting in to the more "heavy hitters" of pavement and bridge consumption.

2.5.2.7 Noise Emissions

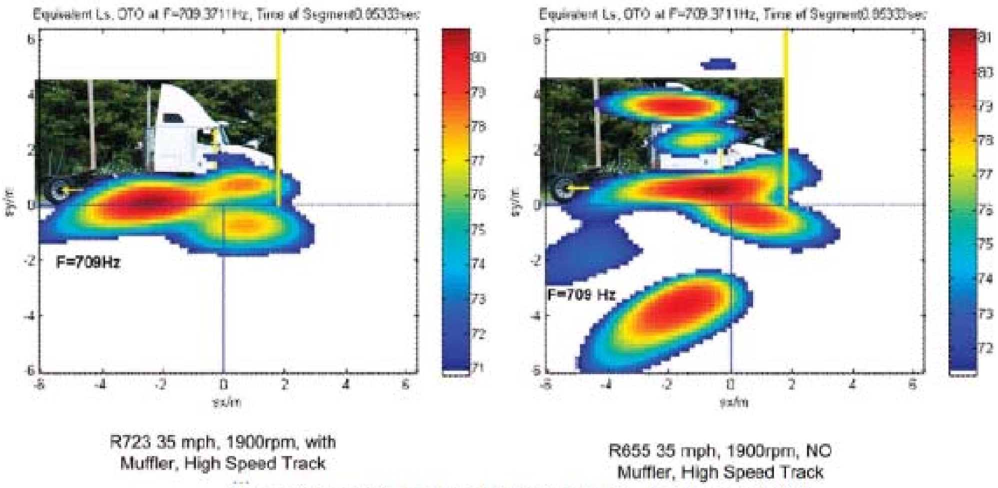
Noise emissions associated with trucks come from the following sources and vary by vehicle type and operating conditions (e.g., speed, slopes) (USDOT 2000 and Gurovich et al., 2009):

- Engine (typically as a function of the rpm)
- Exhaust pipe (especially from engine compression brakes)
- Tires (dominates as noise source above 30 mph, depends on pavement type)
- Muffler shell
- Exhaust stack outlet
- Engine block
- Intake
- Fan
- Aerodynamics

The design of the truck systems affects the amount of noise produced, such as in these aspects:

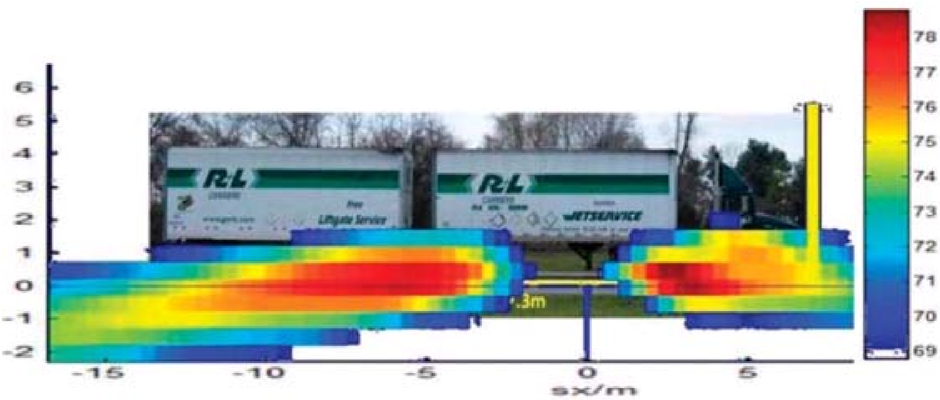
- Location and orientation of the exhaust system
- Powertrain configuration
- Exterior shrouds and air deflectors affect aerodynamics

The extent of the maintenance for all those systems also affects the amount of noise (Gurovich et al., 2009). Figure 2.18 presents an example of the difference in noise emissions from truck components. On the left, the truck has a muffler; on the right, the truck does not. Figure 2.19 shows a noise emission profile primarily for truck tire noise.



Source: (Gurovich, Plotkin, Robinson, Blake, & Donavan, 2009)

Figure 2.18 Noise emissions for truck with and without muffler



Source: (Gurovich, Plotkin, Robinson, Blake, & Donavan, 2009)

Figure 2.19 Tire noise from double container truck

Truck noise on a roadway begins to be the dominate noise when truck traffic is at least 3% of total traffic, and the noise emissions increases as truck traffic increases (for example, an increase in percentage of trucks in traffic from 5% to 20% would result in an increase of 2.5 decibels, with decibels measured on a logarithmic scale) (USDOT 2000).

Therefore, determining noise emission costs and benefits involves a tug of war between the possible additional noise emissions from having more tires on an infrastructure-friendly truck and the potential reduction in the number of trucks on the roadway because larger, heavier trucks replace smaller trucks with fewer tires. Again, this is where deciding to consider the individual or system level impacts become critical.

To assess the monetary cost associated with changes in noise emissions, most studies use changes in residential property value (using a hedonic pricing method), with more noise resulting in lower residential value, and thus higher noise emission costs.

The USDOT (2000, Volume 3, Chapter 10, p. X-4) only considered noise emissions costs for residential property values along freeways because previous studies were limited to freeway locations and truck volumes on non-freeway urban roads are relatively low compared to freeways.

Table 2.23 summarizes from several studies the estimated relative costs between modes of noise emission impact, and across the studies the cost in 2007 US$ per VMT. The studies show a low of 0.031 to high of 0.200 for US$ per VMT. The estimates are dated and the trucks not divided in to the different possible types of trucks, but the information in the table provides a relative comparison.

Table 2.23 Selected urban noise studies summary table

Publication	Costs		Cost Value	2007 US $ / VMT
FHWA (1997)	Automobile		0.11	0.001
Scope: Urban highways	Pickup & Van		0.10	0.001
Cost value units:	Buses		1.72	0.022
1997 cents per Vehicle-mile	Combination Trucks		3.73	0.048
	All Vehicles		0.24	0.003
Delucchi and Hsu (1998)	Cars (Urban Arterial)		1.18	0.002
	Medium trucks		7.02	0.011
Cost value units:	Heavy trucks		20.07	0.031
1991 USD per 1,000 VMT	Buses		7.18	0.011
	Motorcycle		8.71	0.013
CE Delft (2008)	Car	Day	0.76	0.014
Scope: Urban roads		Night	1.39	0.025
Cost value units:	Motorcycle	Day	1.53	0.027
2,000 Euro cents per vehicle-km		Night	2.78	0.050
	Bus	Day	3.81	0.068
		Night	6.95	0.124
	Heavy truck	Day	7.01	0.125
		Night	12.78	0.200

Source: Litman 2009, reproduced at http://bca.transportationeconomics.org/benefits/noise/estimate

Therefore, finding the costs associated with noise emissions necessarily involves considering the characteristics of the locations of where many of the heavier trucks travel. The more dwelling units there are, the greater the impact. The FHWA's Traffic Noise Model (TNM, most recent being V 2.5), required to be used on all federal-aid highway projects, could be used to assess potential costs and benefits from allowing heavier trucks. The NM includes five built-in vehicle types (FHWA, 2012):

- Automobiles (two axles, four tires, generally GVW 9,900 lbs. or less)
- Medium Trucks (cargo vehicles with two axles, six tires, GVW more than 9,900 lbs. and less than 26,400 lbs.)
- Heavy Trucks (cargo vehicles with three or more axles, GVW greater than 26,400 lbs.)
- Buses
- Motorcycles

The TNM allows for user-defined vehicles, so trucks of different axles and weight configurations can be defined by setting values for the following parameters (FHWA, 2011):

- Minimum A-level emissions (those heard by humans) at very low speeds
- Reference level at 50 mph, and
- Slope

Those parameter values must be obtained by measuring A-level noise emissions as a function of speed for the user-defined vehicle type under the following reference conditions:

- Cruise throttle
- Level grade
- Dense-graded asphalt pavement or Portland cement concrete

The TNM considers noise emission levels for vehicles accelerating away from the following traffic control devices:

- Stop signs
- Toll booths
- Traffic signals
- On-ramp start points

Other inputs include such elements as roadways, receivers (e.g., dwelling units) and building rows, pavement types, and sound barriers. The resulting output of TNM includes the following:

- Change in minimum dB
- Change in average dB
- Change in maximum dB
- Number of dwelling units impacted

The changes in noise levels are then translated, through a chosen method such as willingness to pay, to determine the approximate change in the property value of the dwelling units affected.

With heavier trucks most likely primarily moving through rural areas, the impacts on dwelling units may be low, and thus the impacts low. The costs associated with any changes in noise emissions from use of a larger, heavier truck will increase in urban areas, so this factor to consider for BCA must necessarily consider the actual truck and the location the truck is driving through. The next section looks more closely at the potential impacts on roadway and facility design.

2.5.2.8 Roadway and Facility Design

Carson (2011) yet again becomes another useful reference for understanding the impacts of larger trucks on roadway design (Figure 2.20).

General Findings

- Geometric design features most affected by increased truck size and weight include horizontal curves, intersection turning radii, passing sight distance, sight distance at intersections and railroad grade crossings, and ramp interchanges.
- Increases in trailer lengths are most problematic in terms of current highway geometric designs—the longer the trailer, the greater the vehicle's off-tracking.
- Estimated costs to upgrade existing geometric features to accommodate larger, heaver trucks are significant but highly variable depending on truck configuration and the extent of roadway network to be redesigned.
- Wider trucks operating on rural two-lane highways have been observed to elicit undesirable/unsafe actions by oncoming drivers.

Figure 2.20 Carson's (2011) general findings of impacts on highway geometrics

Carson (2011) provides a survey of the domestic and international experience of the impacts of larger trucks on roadway design. NCHRP Report 505 *Review of Truck Characteristics as Factors in Roadway Design*, published in 2003, provides guidance on how to accommodate larger trucks on the US highway system.

A review of the geometric design requirements for infrastructure-friendly vehicles may reveal potential costs (e.g., reconstruction of existing highways) that should be considered in a BCA.

What seems to be lacking in the literature is a discussion of the costs for industry on having to accommodate the larger trucks (if needed) at the facilities at the origins, destinations, and places in between. For instance, how would a more infrastructure-friendly truck maneuver on a facility site designed for smaller, conventional trucks? Facility design and roadway design should both be considered.

The next section very briefly discusses another design element in roadway sections: utilities.

2.5.2.9 Utilities

A study looked in to whether or not OS/OW vehicles could potentially impact the utilities buried under the roadways (Kraus et al., 2014). Kraus et al. (2014) found that the current Texas Utility Accommodation Rules (UAR), which specify technical design and engineering requirements for buried utilities, are adequate for polyvinyl chloride (PVC) and concrete pipe. Any exceptions to the UAR may put the utilities at risk.

Above ground utilities may of course be impacted by increasing the GVW and axle load limits if there is an increase in size. The costs associated with any damage to utilities may need to be estimated.

The next section moves away from these relatively minor impacts to the pavement and bridge impacts made by large trucks, which motivates most of the research and concerns about truck size and weight.

2.5.2.10 Highway Infrastructure Consumption and Damage

The motivation behind limiting the vehicle and transported cargo weight is to prevent the rapid deterioration or early failure of the surface transportation infrastructure. Pavement structures and bridges are designed to last a certain amount of time, or for a projected volume and load spectrum of traffic; for instance, a flexible pavement structure is generally designed to last 20 years. Each vehicle consumes a portion of the pavement or bridge capacity, which will depend on factors such as the vehicle's load and axle configuration. A general rule is that, for a given axle configuration, the heavier the load, the greater the consumption of the highway infrastructure components. The following sub-sections provide basic concepts of pavement and bridge consumption, and summarize the approaches used by related research projects to quantify consumption of the highway infrastructure components, and then how that consumption can be quantified in to costs and benefits.

<u>Pavement Consumption</u>

The phrase "pavements feel axles, not trucks" summarizes how to view pavement consumption (Prozzi, et al., 2012). The effect of each axle, either a single axle or a group of axles (i.e., tandem, tridem, or quad), on a pavement structure is usually considered independent of the effect of the previous axle group. Therefore, the unit of load when analyzing a pavement consists of axles, not vehicles. The State of Michigan's laws limit axle loads not GVW because research has shown pavement consumption depends on axle loads (MDOT, 2013). Factors commonly used to quantify relative consumption include axle load, axle configuration, number of wheels per axle, and pavement structural characteristics such as layer thickness and material properties.

A classic and widely used approach to account for the relative consumption that different vehicles have on the pavement structure consists of converting the spectrum of loads and axle configurations to equivalent single axle loads (ESALs). An ESAL is calculated as the product of the number of axles of a certain type and load, and the corresponding load equivalency factor (LEF). The LEF is a scale factor that accounts for the relative consumption of a particular axle and weight with respect to an 18,000-lb single axle with dual wheels. The ESAL concept was developed based on the analysis of the results of the AASHO Road Test, from which the LEF values were obtained considering four variables:

- Axle load;
- Axle configuration;
- Structural number (SN) for flexible pavements, or slab thickness (D) for rigid pavements;
- Terminal serviceability level.

The tables with the LEF values for each of the four variables can be found in the AASHTO 1993 *Pavement Design Guide*. Various studies (e.g., Deacon, 1969; Scala et al., 1970; and Christianson, 1986) have analyzed the results from the AASHTO Road Test, leading to a number of formulas to obtain the LEF values. A finding from one of these studies (Scala et al., 1970) became one of the fundamental principles of pavement engineering: the so-called "fourth-power law." Scala suggested that the LEF values vary by the fourth power of the ratio of the loads, independently of the pavement structure. By this principle, if the load on a given axle doubles, the pavement consumption (in terms of serviceability, which is primarily related to roughness) produced by that axle becomes 16 times higher. Once the LEF values for each axle of the truck are obtained, the truck's ESAL is calculated as the sum of the individual LEFs.

To illustrate the point that "pavements feel axles, not trucks," Table 2.24 presents the calculation of ESALs for three different trucks. The first truck is an 18-wheeler loaded with the maximum legal GVW of 80 kips. The second and third alternatives are a Class 10 truck loaded with 90 kips and 97 kips, respectively. The axle configuration and distribution of the load on each axle is presented in the table. The last column of each sub-table contains the LEF values for each axle type corresponding to a flexible pavement with SN = 5.0 and terminal serviceability of 2.5. The resulting ESAL number for each truck is reported on the TOTAL row under the LEF column.

Table 2.24, as might be expected, shows that the 97-kip six-axle truck presents an ESAL number (2.604) greater than the 80-kip 18-wheeler (2.379), which means the 97-kip six-axle truck consumes more pavement than the 18-wheeler. It should be noted that the consumption is calculated in terms of loss of serviceability in this context. Further, the 90-kip Class 10 truck has a lower ESAL number (2.007) than the 80-kip Class 9 (2.379). Therefore, the six-axle truck loaded with 10,000 lbs of additional cargo will consume less pavement life than the Class 9 18-wheeler.

Therefore, one cannot just look at truck weight to determine potential pavement consumption. Allowing higher GVW and axle load limits does not necessarily mean an increase in pavement consumption costs.

In fact, Table 2.24 suggests that it might be possible to increase the current GVW without reducing the expected lifecycle of the pavement, leading to potential benefits. However, axle configurations that are more pavement-friendly may not necessarily be friendly to the bridges. Additionally, use of more sophisticated state-of-the-art methodologies (other than ESALs and LEFs) to quantify the consumption of the pavements may lead to different conclusions. This is a finding presented in the next two sections looking at the equivalent damage factor (EDF) and Rider 36 methodologies.

Table 2.24 LEF values of an 80-kip Class 9 truck and 90-kip and 97-kip Class 10 trucks

	Axle Config.	LOAD (kips)	LEF
Class 9	single	12	0.189
5 axles	tandem dual	34	1.095
80kips	tandem dual	34	1.095
	TOTAL	**80**	**2.379**

	Axle Config.	LOAD (kips)	LEF
Class 10	single	12	0.189
6 axles	tandem dual	34	1.095
90kips	tridem dual	44	0.723
	TOTAL	**90**	**2.007**

	Axle Config.	LOAD (kips)	LEF
Class 10	single	12	0.189
6 axles	tandem dual	34	1.095
97kips	tridem dual	51	1.32
	TOTAL	**97**	**2.604**

Other Methodologies to Quantify Pavement Consumption

The concept of ESALs offers the benefit of translating the mixture of traffic loads and axle types into one number. A major limitation of the use of LEFs, however, is the limited capability of extrapolating from the conditions of the AASHTO Road Test. The relative damage factors are not valid for new axle configurations; higher tire pressure;

different vehicle characteristics (e.g., newer suspension systems or tire width); and pavement structures or environmental conditions not included in the experiment. More recent studies incorporate the effect of more variables and consider new types of axles in the quantification of relative damage of pavements.

➢ *EDF Methodology*

A mechanistically based factor, the equivalent damage factor (EDF), which is analogous to the LEF, has been developed to quantify the relative damage of a pavement (Prozzi et al., 1997a and 1997b). The EDF maintains the concept of the LEF in that it expresses the equivalent damage to a specific pavement with respect to a standard axle loaded to 18 kips. Some of the improvements introduced by the development of the EDF are the following:

- Differentiates between single axles with single wheels and dual wheels;
- Incorporates the effect of tire pressure;
- Incorporates multiple failure criteria;
- Can be developed for each type of pavement;
- Can be selected to address a particular region or state;
- Accounts for the effects of the environment such as, temperature and precipitation; and
- If properly calibrated, accounts for local conditions.

An EDF may be calculated using the following relationship, which was originally suggested by Prozzi et al. (1997a, 1997b). This framework establishes the EDF (as shown in Equation 2.4) for different axle loads, configurations, and tire pressures.

$$EDF = GEF \times ALF \times CSF \qquad \textbf{(2.4)}$$

Where

GEF: Group Equivalency Factor
ALF: Axle Load Factor
CSF: Contact Stress Factor

The EDF concept was adapted and applied in two past TxDOT Research Projects: 0-4169, *Managing Rural Truck Traffic in Texas* (Prozzi et al., 2006), where the EDFs were used to estimate the damage of rural truck traffic in Texas; and 0-5372, *Testing of the HB2060 Pads* (Gossain et al., 2006), where the factor was used to assess the effect of the permits that resulted from HB 2060.

In an example provided in a paper derived from the 0-4169 project, a Class 8 three-axle semi-trailer truck with EDFs of 1.2, 2.0, and 2.0 for each axle group gives a total EDF of 5.2, which translates to the truck reducing the life of the pavement by a factor of 5.2 relative to the standard axle (single dual-wheeled axle with a load of 18k lbs) (Prozzi et al., 2003). Increasing the weight on each axle group by 25%, resulting in EDFs for each axle group of 1.6, 4.1, and 4.1, results in a total EDF of 9.8. With only a 25% overloading of the axles comes an almost double the reduction in life of the pavement. The EDF methodology quantifies the impacts of GVW and axle weight limitations, and in this example, more weight on an axle results in lowered pavement life.

The following section reviews another pavement consumption methodology recently used for the Rider 36 Study.

- *Rider 36 Methodology*

In order to evaluate the pavement consumption of any vehicle configuration, a previous TxDOT research project, Rider 36, developed a methodology for establishing equivalencies between OS/OW loads based on the concept of "equivalent consumption" to the pavement structure using mechanistic-empirical pavement analysis procedures (Prozzi, et al., 2012). The Rider 36 project developed a modular approach to estimate the pavement consumption for any truck configuration and axle loading; this is discussed in the section on bridge consumption. Pavement consumption of a vehicle configuration is estimated as the cumulative pavement consumption caused by all the individual axle group loadings. The concept of EDF was adopted in Rider 36 study, which is renamed the equivalent consumption factor (ECF). ECF is affected by pavement structure and environmental conditions; in other words, the pavement consumption for a given vehicle configuration varies with the pavement structural number (SN), which is determined by the sum of the individual pavement layer thickness and stiffness.

The pavement consumption was measured in terms of the extent of pavement distresses such as rutting or surface deformation, load-associated fatigue cracking, and riding quality in terms of roughness. In other words, two different vehicle and load combinations are defined to equally consume pavement life, if both require equal number of applications to reach a given threshold distress level on the total pavement structure.

The number of axle passes required to reach a given terminal distress value were estimated using the AASHTO Darwin-ME software program. A single ECF value was obtaining by weighting the ECF values corresponding to different distress criteria.

Using the Darwin-ME outputs, the study developed empirical models to calculate ECF as function of SN, axle type and axle load. These empirical models allow the cumulatively ECF for any given vehicle configuration to be calculated by adding the ECF values corresponding to each axle type and load combination.

Immediately after the completion of the Rider 36 project, a study was conducted by the Rider 36 research team under a special request of the TxDOT Administration. In this study, pavement and bridge consumption analyses were performed to evaluate:

- 90,000-lb GVW six-axle tractor semi-trailer trucks and
- 97,000-lb GVW six-axle twin semi-trailer trucks operating with different axle configurations and weight distributions.

This study was reported as part of TxDOT report 0-6581-CT-6: *RTI Special Studies for TxDOT Administration in FY 2013*, Task 17: "Oversize and Overweight Vehicle Analysis" (Prozzi et al., 2013).

The relative consumption of each truck configuration was quantified using the methodology developed for TxDOT Research Project 0-6736: *Rider 36 OS/OW Vehicle Fees Study* (Prozzi et al., 2012). Following are the main assumptions of the analysis:

- 100,000 VMT per year (based on information from SAFERSYS.ORG database for long-haul truck companies operating in Texas);
- 50% or 50,000 loaded VMT (trucks are loaded in one direction);
- Travel on 80% legal load limit routes and 20% load-zoned routes.

The analysis included different axle weights to investigate the change in pavement and bridge consumption rates due to changes in axle weight distributions and weight distributions with imbalanced axle loads. The legal minimum 51-ft outer bridge length was assumed for each truck to simplify the comparisons.

The main conclusions and recommendations from the analyses conducted to evaluate the 90,000-lb and 97,000-lb GVW different truck configurations are the following:

- The analysis shows that the 90,000-lb and 97,000-lb GVW six-axle trucks selected for the analysis have higher consumption rates than an 80,000-lb five-axle truck. The cost ratios vary from 1.29 to 1.89 for the 90,000-lb trucks and from 1.80 to 2.56 for the 97,000-lb trucks, depending on the location of the tridem axle, the type of trailer tandem axle, and the axle weight distribution between axles.
- Benefits in terms of reduced truck trips and congestion, reduced fuel costs for truck fleet operators, and reduced CO_2 emissions are the potential benefits of implementing a 90,000-lb GVW six-axle truck in Texas. Greater benefits could accrue if a 97,000-lb GVW six-axle truck was implemented, although cost ratios would be larger.
- The marginal costs for each 90,000-lb and 97,000-lb GVW six-axle truck were calculated and can be used to evaluate potential OS/OW permit fees or other methods for providing revenue to offset the increased pavement and bridge consumption costs.

Importance of Pavement Consumption Methodology for Cost Estimation

As mentioned at the start of this section on pavement consumption, use of more sophisticated state-of-the-art methodologies to quantify the consumption of the pavements may lead to different conclusions regarding the consumption of pavement by truck type and configuration. The review of the EDF and Rider 36 methodology and example calculations shows that to be the case. Therefore, the choice of methodology for estimating the pavement consumption will affect the estimated costs and benefits associated with increasing the GVW and axle load limits. It should be noted that the AASHTO-based methodology is based on vehicle technology of the 1950s while the EDF and ECF methodologies have been calibrated based on the most recent results of FHWA's Long-Term Pavement Performance (LTPP) studies.

Impacts of Axle Technologies

Cole et al. (1996) found that a passive-axle suspension system and optimized suspension stiffness and damping resulted in a 5.8% reduction in pavement damage by minimizing the dynamic impact of axle loads. Chowdhury et al. (2013) reports that "dynamic forces from axle loading cause most pavement fatigue failures. When heavy loads exceed typical vehicle speeds, damage may accelerate by a power of four and service life can decrease by 40% or more (Luskin and Walton, 2001)."

Estimating Pavement Consumption Costs

Pavement consumption cost may be calculated using empirical or engineering approaches. An empirical approach is typically based on the estimated pavement wear and costs of pavement maintenance; on the other hand, the engineering approach is based on theoretical relationships. In earlier efforts, maintenance and rehabilitation costs were analyzed with little or almost no consideration to reconstruction cost. In most studies that used the engineering approach, rehabilitation alone was included, neglecting reconstruction, and periodic and routine maintenance activities.

The Rider 36 study estimated pavement consumption costs and then determined an approximate cost per ESAL per mile, utilizing a modified proportional method for allocating pavement consumption costs to OW trucks. The Rider 36 research team recommended an average permit fee of:

- $0.037 per ESAL-mile for travel on flexible pavements, and
- $0.029 per ESAL-mile for travel on rigid pavement

These values are expressed in 2011 dollars. The modified proportional method is a variation of one of the three of the most widely used methods for allocating highway congestion costs to those responsible for causing pavement consumption:

- Incremental method: assumes a pavement structure for the lightest vehicle, then determines the costs of having to strengthen the pavement for the next lightest vehicle.
- Proportional method: allocates costs based on vehicular characteristics that can be proportions of a total, such as ESAL and VMT
- Modified incremental method: allocates costs attributed to specific vehicle classes; once those are accounted for, additional highway costs attributed to other vehicle classes based on a proportionality

In Indiana, they adopted a comprehensive approach for asset damage cost estimation on the basis of practical and realistic maintenance, rehabilitation, and reconstruction practices—addressing key gaps in the impractical assumption of perpetual application of only a single type of overlay applied at fixed intervals and many others. Their pavement consumption estimates came out to:

- $0.006 per ESAL-mile on IHs and
- $0.218 per ESAL-mile on state highways (SH)

Their findings indicate that ignoring reconstruction or maintenance costs may result in underestimation of the actual pavement damage cost by 79% to 83%. Up to 86% underestimation of the actual pavement damage cost is possible, if the asset life cycle analysis assumes only rehabilitation treatments applied at fixed intervals. Moreover, this approach yields relatively much higher permit costs, making it difficult to maintain economic competitiveness with neighboring states.

For South Carolina, Chowdhury et al. (2013) analyzed truck models with two, three, four, five, six, and seven axles on flexible pavements with SNs ranging from 3 to 7 as per the South Carolina DOT (SCDOT) (SCDOT, 2008) guidelines. The costing analysis was based on the ESAL consumption method, which was adopted from the Ohio DOT (ODOT, 2009). The study was restricted to flexible pavements only as South Carolina predominantly uses asphalt pavements. The analysis was performed on three pavement design scenarios: i) No trucks, ii) Traffic with trucks but not OW, iii) Traffic with 8.3% OW trucks (based on WIM data from St. George). The required SN to accommodate each scenario was determined. The replacement cost of pavement construction was based on typical prices for materials used to construct each pavement layer obtained from SCDOT. Table 2.25 presents the resulting consumption cost per mile for each truck configuration.

Table 2.25 Unit pavement damage cost per mile for different truck configurations

Truck Type	ESAL at the Legal Weight Limit	ESAL at the Maximum Overweight Limit	Per Mile Damage for a Truck Loaded at the Legal weight limit[2]	Per Mile Damage for an Overweight Truck Loaded up to the Maximum Overweight Limit[3,4]	Additional per Mile Damage for an Overweight Truck above the Legal Weight Limit up to the Maximum Overweight Limit
2-axle, 35-40 kips	1.820	3.020	$0.3482	$0.6690	$0.3207
3-axle, single unit, 46-50 kips	1.248	1.727	$0.2413	$0.3858	$0.1446
3-axle, combination, 50-55 kips	2.293	3.322	$0.4368	$0.7350	$0.2982
4-axle, single unit, 63.5-65 kips	1.842	2.035	$0.3524	$0.4534	$0.1010
4-axle, combination, 65-70 kips	2.534	3.690	$0.4818	$0.8155	$0.3338
5-axle, 80-90 kips	2.369	3.760	$0.4509	$0.8310	$0.3801
6-axle, 80-90 kips	1.286	1.914	$0.2484	$0.4269	$0.1785
6-axle, 90-100 kips	1.286	2.999	$0.2484	$0.6644	$0.4160
6-axle, 100-110 kips	1.286	4.469	$0.2484	$0.9862	$0.7378
7-axle, 80-90 kips	0.660	1.062	$0.1313	$0.2404	$0.1091
7-axle, 90-100 kips	0.660	1.679	$0.1313	$0.3754	$0.2441
7-axle, 100-110 kips	0.660	2.528	$0.1313	$0.5613	$0.4300
7-axle, 110-120 kips	0.660	3.658	$0.1313	$0.8086	$0.6773
7-axle, 120-130 kips	0.660	5.108	$0.1313	$1.1260	$0.9947
8-axle, 80-90 kips	0.503	0.808	$0.1019	$0.1848	$0.0829
8-axle, 90-100 kips	0.503	1.268	$0.1019	$0.2855	$0.1836
8-axle, 100-110 kips	0.503	1.976	$0.1019	$0.4403	$0.3385
8-axle, 110-120 kips	0.503	2.775	$0.1019	$0.6153	$0.5135
8-axle, 120-130 kips	0.503	3.885	$0.1019	$0.8583	$0.7565

Virginia and Wisconsin have employed OS/OW permit procedures that are very similar to the other states. Both states charge permit fees in terms of cost-per-ESAL-mile and compared the enforced fee structure with those of neighboring states to ensure economic competitiveness.

Determining pavement consumption costs requires knowing the type, configuration, weight, and numbers of trucks in the fleet using Texas' roadways and the type of roadway and its attributes. As an example, TxDOT project 0-6513 evaluated the impact of developments in various energy sectors and their corresponding influence on the Texas transportation system infrastructure. The permitted route, truck configuration, individual axle weights, and axle spacing were used in developing characteristics of OS/OW loads for pavement consumption analysis.

Results indicate that pavement consumption was least on the IH sections and relatively higher on US and state highways. The reduction in pavement service life due to movement of wind turbine components on Interstate, US, and state highways was determined to be 1.9%, 15.2%, and 20.2%, respectively, suggesting an overall reduction in service life (weighted based on VMT proportions traversed) at 9.1%. Most importantly, since the haul distances were quite long compared to other sectors, the damage predicted is expected to be system wide rather than confined locally. The natural gas sector had most significant effect, owing to high truck volumes and heavy axle weights, whereas in the crude oil sector, production traffic (transportation of crude oil from tank batteries to pipeline breakout station) was more detrimental than construction traffic, which was attributed to their nature of the operation.

In an earlier study of Arizona roads, Straus and Semmens (2006) estimated:

- OW vehicles impose somewhere between $12 million and $53 million per year in uncompensated damages,
- Arizona budgets about $5.8 million per year for mobile enforcement efforts, and
- A doubling of the mobile enforcement budget was 50% effective toward eliminating illegally OW vehicles from Arizona roadways, resulting in savings from avoided pavement damage ranging from $6 million to $27 million per year.

More examples of studies that quantified pavement and bridge consumption and used methodologies to estimate fees to help recover pavement and bridge maintenance costs include Dey et al. (2014), Chowdhury et al. (2013), Adams et al. (2013), and Yang et al (2014).

<u>Bridge Consumption</u>

Methodology

A bridge is generally designed to accommodate bending stresses and shear stresses under a hypothetical design vehicle intended to represent the entire truck fleet in the forecasted traffic. The concept of consumption of a bridge is given by the repetitive nature of highway loads, which is associated with fatigue effects on the material. Fatigue is a cumulative process in which repetitive stress cycles accumulate damage until failure occurs. Every truck will consume a portion of the bridge capacity.

The relative consumption caused by a particular truck will depend on the vehicle weight, the bridge span length, and member section dimensions. Previous studies have indicated that increasing weight limits will have a marginal effect on pavement consumption, but a much more dramatic effect on bridge consumption, especially for short heavy trucks (ready mix, dump trucks, garbage and recycling trucks, and tractor semitrailers that operate with less than the legal inner and outer bridge lengths based on special state statutes).

The AASHTO bridge specifications include fatigue curves that assume a 75-year design life for different details in a bridge (AASHTO, 1990). These curves have the general format represented by Equation 2.5, and assume stress ranges compatible with inventory rating loads (see Figure 2.21). The exponent m provides information about the relative consumption of loads and type of structural detail. For example, the welded steel attachments of a steel bridge have an m value of 3.0, meaning that if the stress amplitude is doubled, the fatigue damage will increase by a factor of eight for that element. The consumption of different truck weights is usually accounted by assuming a linear damage accumulation law (Miner's rule, Equation 2.5).

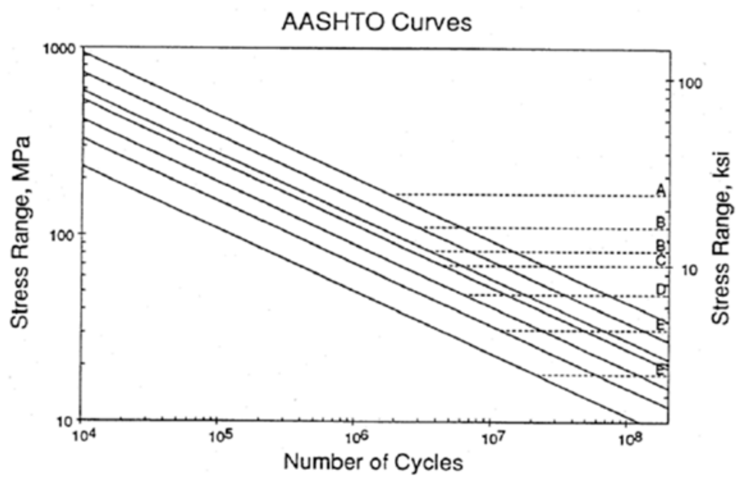
$$NS^m = C \text{ or } logN = logC - m * logS \quad \textbf{(2.5)}$$

Where

N is the number of cycles or load applications;

S is the stress range (difference between the maximum and minimum stress caused by a vehicle passage at the location of concern);

C is a constant depending on the fatigue strength of the detail; and m is a parameter that depends on the material (e.g., 3.0–3.5 for steel, 3.5 for prestressed concrete, and 4.1 for concrete slab 101).



Source: AASHTO, 1990

Figure 2.21 AASHTO fatigue curves for steel bridges

The relative bridge consumption for a given truck can be estimated using a simplified approach based on Equation 2.5, for which it is assumed that live load moment ratios are acceptable surrogates to measure stress ranges. The equation to estimate the relative consumption of bridges for different GVW and axle configurations is presented in Equation 2.6. The resulting ratio from Equation 2.6 is analogous to the LEF used to calculate relative consumption of a pavement structure.

$$\text{RelativeConsumption} = \left(\frac{M_{\text{alternativeGVW\&AxleConfig}}}{M_{\text{standardGVW\&AxleConfig}}}\right)^m \quad \textbf{(2.6)}$$

Where $M_{standardGVW\&AsleConfig}$ and $M_{alternativeGVW\&AxleConfig}$ are the live load moments for the standard and alternative GVW and axle configuration respectively; and *m* is a parameter that depends on the material (from Equation 2.5).

This methodology was successfully used in two recent TxDOT Research Projects: 0-6095: *Longer Combination Vehicles & Road Trains for Texas* (Walton et al., 2010) and 0-6736: *Rider 36 OS/OW Vehicle Fees Study* (Prozzi et al., 2012). The bridge consumption analyses conducted for these two projects used information about each bridge on the state-maintained network contained in the TxDOT Bridge Inspection and Appraisal Program (BRINSAP) database. Moment ratios using BRINSAP information can be calculated at a network level using computerized routines developed in a previous FHWA study (Weissmann et al., 2002).

Estimating Bridge Consumption Costs

Different methodologies to translate quantified bridge consumption into costs (or cost savings in the case of a reduction of impacts) have been developed and used (rather than explain here, refer to studies such as Chowdhury et al. [2013] and Prozzi et al. [2012]). As an example, Table 2.26 presents the bridge damage cost per mile for trucks loaded at the legal and maximum overweight limit in a study done for the South Carolina DOT. It is interesting to see, for instance, that an eight-axle truck with the same amount of weight as a seven-axle (100–110 kips) has a lower per mile damage cost but that's not the case for other axle-weight combinations. It is true for pavements that axles, not weight, triggers consumption costs—but this is not really the case for bridges.

Table 2.26 Unit bridge damage cost per mile for different truck configurations

Truck Type	Per Mile Damage for a Truck Loaded at the Legal Weight Limit	Per Mile Damage for an Overweight Truck Loaded up to the Maximum Overweight Limit	Additional per Mile Damage for an Overweight Truck above the Legal Weight limit up to the Maximum Overweight Limit
2-axle, 35-40 kips	$0.0040	$0.0058	$0.0018
3-axle, single unit, 46-50 kips	$0.0062	$0.0075	$0.0013
3-axle, combination, 50-55 kips	$0.0075	$0.0094	$0.0020
4-axle, single unit, 63.5-65 kips	$0.0061	$0.0067	$0.0006
4-axle, combination, 65-70 kips	$0.0067	$0.0092	$0.0025
5-axle, 80-90 kips	$0.0074	$0.0111	$0.0037
6-axle, 80-90 kips	$0.0101	$0.0139	$0.0038
6-axle, 90-100 kips	$0.0101	$0.0191	$0.0090
6-axle, 100-110 kips	$0.0101	$0.0262	$0.0161
7-axle, 80-90 kips	$0.0115	$0.0152	$0.0037
7-axle, 90-100 kips	$0.0115	$0.0201	$0.0087
7-axle, 100-110 kips	$0.0115	$0.0267	$0.0152
7-axle, 110-120 kips	$0.0115	$0.0354	$0.0239
7-axle, 120-130 kips	$0.0115	$0.0469	$0.0355
8-axle, 80-90 kips	$0.0121	$0.0157	$0.0036
8-axle, 90-100 kips	$0.0121	$0.0204	$0.0083
8-axle, 100-110 kips	$0.0121	$0.0265	$0.0144
8-axle, 110-120 kips	$0.0121	$0.0344	$0.0223
8-axle, 120-130 kips	$0.0121	$0.0446	$0.0325

Source: Chowdhury et al. (2013)

Infrastructure Damage Costs (Other than Pavement and Bridge)

Bridge and pavement consumption costs and cost savings tend to be the focus and the bulk of the infrastructure "consumption" to occur by OS/OW trucks; however, other infrastructure elements, such as traffic and railroad signals, signs, bridges (not from driving over, but from hitting a structural element), etc., can also become damaged by trucks.

A review of the crashes involving OS/OW trucks in fiscal years 2010-2013 in the TxDOT Crash Record Information System (CRIS) database revealed a total of 1,137 crashes, of which 259 (23%) involved damage to TxDOT property costing an estimated $9.7 million (Prozzi, et al., 2012). Unfortunately, fatalities and incapacitating injuries occurred. The extent to which that damage potentially increases or decreases in response to allowing higher GVWs and axle load limits requires further study.

2.6 Findings of Literature Review

The literature review presented in this chapter provides a summary of existing weight limitations and OW practices at both federal and state levels. Weight regulations and permit fee policies from states that border Texas as well as from other countries were reviewed. The review was helpful to identify a possible range of axle loads and GVWs for which the potential infrastructure consumption estimation is needed. In particular, the axle and vehicle loads that harmonize with the Mexican trade through international crossings and ports will be of particular interest.

One of the major goals of this literature review was to identify potential vehicle configurations that are suitable for the current research project. This literature review assisted in identifying the most plausible vehicle configurations for performing this research project. A brief overview of several vehicle configurations analyzed as part of several important earlier studies was provided.

In addition, this section identified the most important benefits and costs of modifying the GVW and axle load limits. For each factor, this literature review explored the methods to estimate the impact of each factor and the methods to quantify monetarily the impact in to a cost or benefit, with the goal of using this input to conduct a generalized BCA for infrastructure-friendly trucks.

Chapter 3. Develop Project Advisory Panel and Solicit Input

As part of this study, the research team identified leaders within the industry that provided significant insight into the future of truck configurations. These individuals were reached out in an effort to solicit input concerning the practical design limitations of non-conventional vehicles configurations and to identify potential benefits and costs relating to potential changes in the TS&W regulations. The following were the initially identified individuals:

- John Woodrooffe, Industry Expert, University of Michigan's Transportation Research Institute
- Kenneth Allen, Consultant, formerly with HEB
- Ken Leicht, Frito Lay
- Randy Mullett, Vice President of Government Relations, Con-way Inc.
- Matt Stalter, Pepsi
- Skip Yeakel, Volvo
- John Billing, Consultant on TS&W and Canadian Truck Technology

Mr. Woodrooffe currently serves as the Head Vehicle Safety Analytics, Director Commercial Vehicle Safety and Policy Program for the University of Michigan's Transportation Research Institute (UMTRI). The team met with Mr. Woodrooffe in January to discuss the project effort, garner insight into additional panel members, and to further understand the existing trends with respect to size and weight from a federal prospective. The following individuals were identified at this meeting as potential advisory panel members:

- Tom Kearney, Transportation Specialist, FHWA
- Luke Loy, Federal Motor Carrier Safety Administration (FMCSA)

Advisory members that were involved in operations were contacted for discussion in February. These individuals were able to provide insight on the technologies that are needed from an industry prospective with three areas of focus identified: the power unit, the trailer, and external items. There was also indication that connected vehicles would be important for efficiencies in the future. With respect to weight concerns, there was little concern since the hub and spoke network configurations used do not require extra weight. With respect to configurations, there was no interest in tridem and quads within the less-than-truckload (LTL) industry due to the cubing out before entry. It was noted that there is a big push from the 28.5 ft to the 33 ft trailer for the industry; however, there is resistance from the labor and safety perspectives. Twin 33s are currently legal in only 17 states, while triples are legal in others. Due to this, investments into these configurations are not being considered. However, it was noted that changes in TS&W regulations could show savings benefits of 1 billion miles/year should 18% of the current miles be saved from the efforts.

Chapter 4. Pavement and Bridge Consumption Analysis

4.1 Introduction

The motivation behind limiting the vehicle and transported cargo weight is to prevent the rapid deterioration or early failure of the surface transportation infrastructure. Pavement structures and bridges are designed to last a certain amount of time, or for a projected volume and load spectrum of traffic. Each vehicle consumes a portion of the pavement or bridge capacity, which will depend on factors such as the vehicle's load and axle configuration.

The infrastructure damage is related to the axle arrangement and load distribution of the tractor-trailer assemblies. A wide variety of axle configurations are generally available for tractor-trailers to cater the gamut of transportation loads. Increasing the axle and gross vehicle load limits is attractive to the transportation industry; however, it translates into increased infrastructure damage. A general rule is that, for a given axle configuration, the heavier the load, the greater the consumption of the highway infrastructure components. The main purpose of this part of the study was to investigate the possibility of rearranging the axle configurations to cater increased truck loads without additional pavement and bridge consumption or with marginal increase in infrastructure consumption. The following steps were accomplished in finding infrastructure-friendlier truck configurations. These steps are described in this chapter.

- Selecting typical OW trucks.
- Assessing the consumption different axle loads and axle configurations cause to different pavement and bridge structures.
- Establishing general relationships between the ECF and the axle loads considering different climatic regions, traffic levels, facility type, and the SN of pavements.
- Finding the ECF of selected truck configurations with regard to three failure criteria: rutting, fatigue cracking, and roughness.
- Finding the bridge consumption of selected truck configurations.
- Investigating infrastructure-friendlier truck configurations.

4.2 Selecting Truck Configurations

The evaluation of GVW and axle load limits requires a thorough analysis of the effect that different truck characteristics have on the consumption of pavement and bridge capacity. This analysis includes a variety of trucks that are currently used in other states but are not currently legal in Texas, such as the 97-kip six-axle truck or the RMD, as well as hypothesized trucks with new proposed configurations encompassing varying factors such as type of axles and number of wheels per axle. Researchers have identified several vehicles by thoroughly surveying the vehicle configurations used across different studies in the literature. The alternative vehicle configurations are divided into two main groups: conventional vehicle configurations (CVC) and non-conventional vehicle configurations

(NCVC). The CVC group comprises of vehicles that are currently not legal in Texas but operate in other states, Canada and Mexico. The NCVC group consists of vehicles with non-conventional configurations.

4.2.1 Conventional Vehicle Configurations (CVC)

A total of nine different vehicle scenarios have been identified based on the axle arrangement and included in the experimental design. These vehicle configurations are further divided into 21 different vehicles by varying the individual axle loads. A comprehensive list of vehicles with different axle loads and axle configurations is provided in Table 4.1. Figures 4.1 to 4.7 illustrates the vehicle configurations corresponding to the vehicle scenarios. A brief description of the rationale behind the selection of these configurations is provided below.

The USDOT has recently conducted a comprehensive truck size and weight limits study in accordance with the Moving Ahead for Progress in the 21st Century Act (MAP-21) (Rayman, 2013). The study investigated the effects of operating trucks at Federal weight limits and in excess of the existing limits, and evaluated the impact of alternative vehicle configuration on infrastructure consumption. In a previous TxDOT study, the potential use of LCVs was evaluated with reference to the current freight system in Texas (Walton et al., 2009). The study evaluated configurations that are suitable for both mass-limited and volume-limited cargo. Another study was conducted by the Rider 36 research team under a special request of the TxDOT administration immediately after the completion of the Rider 36 project (Prozzi et al., 2013). The study investigated the infrastructure consumption of several vehicle configurations with different axle groups and loads.

The research team incorporated the same vehicle scenarios considered by the USDOT and LCV studies into the experiment design with a variety of axle loads. In addition, six-axle vehicle configurations that were investigated as part of the Rider 36 follow-up study are also included, but with increased axle loads. Multiple vehicles were generated under each vehicle configuration scenario by varying the axle loads as shown in Table 4.1. Table 4.1 provides the GVW; vehicle dimensions; number of axles; number of single, tandem, and tridem axles; respective axle loads; and tractor and trailer arrangements for all the proposed experimental vehicles.

4.2.2 Non-Conventional Vehicle Configurations (NCVC)

NCVCs are the vehicles with potential to be considered by truck manufacturers and are not currently commercially available. By including the non-conventional configurations into the experimental design, researchers can explore new opportunities to reduce the infrastructure consumption while meeting the transportation demand. The main idea is to understand the sensitivity of vehicle parameters to the pavement consumption and to identify the optimal vehicle parameters that produce minimal pavement consumption for a given cargo load. The NCVCs may be formed using existing CVC configurations as a reference but by modifying the following variables.

1. Number of axles and axle load
2. Distance between axles

3. Number of wheels per axle
4. Tire pressure

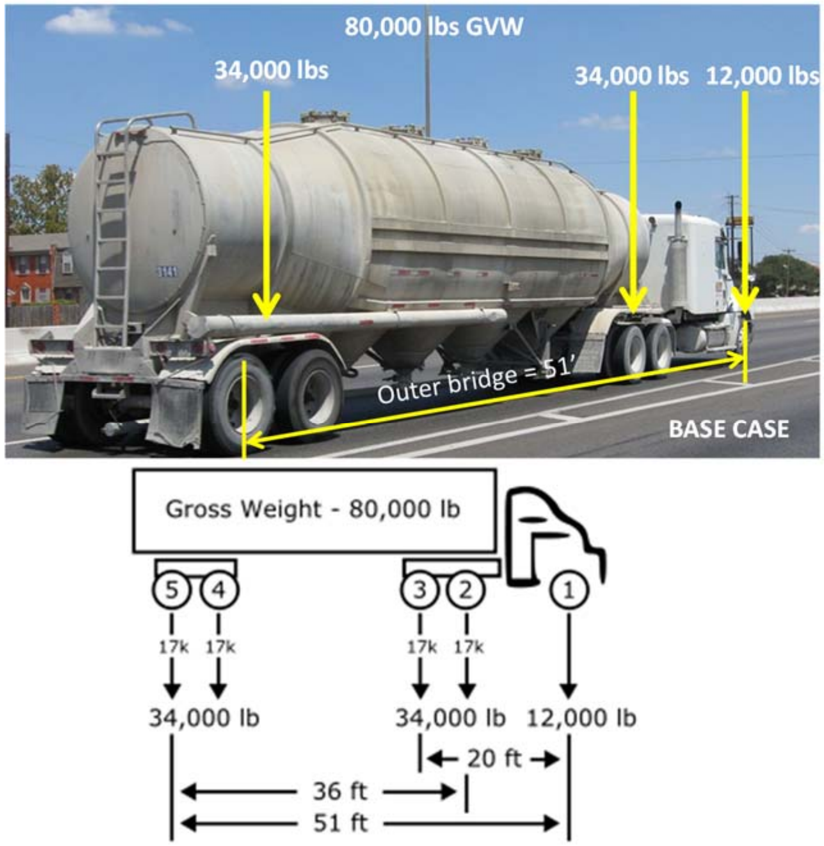


Figure 4.1 Base and Scenario 'A' vehicle configuration (18-wheeler)

Figure 4.2 Scenario 'B' vehicle configuration

Figure 4.3 Scenario 'C' vehicle configuration

Figure 4.4 Scenario 'D' vehicle configuration

Figure 4.5 Scenario 'E' (28 or 28.5 ft trailers) and Scenario 'F (33ft ft trailer) vehicle configuration

Figure 4.6 Scenario 'G' vehicle configuration

Figure 4.7 Scenario 'H' vehicle configuration

Table 4.1 Scenarios for alternative CVCs

Scenario	Veh #No.	Dimensions	# Axles	GVW (lbs)	Tractor				Semi-Trailer/Trailer #1			Semi-Trailer/Trailer #2		Semi-Trailer/Trailer #3	
					Steer	Non-steer									
					Single	Single	Tandem	Tridem	Single	Tandem	Tridem	Single	Tandem	Single	Tandem
Base	1	Outer Bridge 51ft	5	80,000	12,000		34,000			34,000					
A	2	Outer Bridge 51ft	5	88,000	12,000		38,000			38,000					
B	3	Axle spacing 14ft & 35ft	6	90,000	12,000		36,000				42,000				
	4		6	90,000	12,000		42,000				36,000				
	5		6	97,000	7,000		36,000				54,000				
	5b		6	97,000	12,000		34,000				51,000				
C	6	Outer Bridge 51ft	6	91,000	7,000			48,000		36,000					
	7		6	97,000	12,000			51,000		34,000					
	8		6	97,000	12,000			45,000		40,000					
D	9	Outer Bridge 51ft	6	97,000	12,000			51000	2*17,000						
	10		6	97,000	12,000			45000	2*20,000						
E	11	28 or 28.5ft trailers	6	97,000	11,000		26,000		20,000			2*20,000			
	12		6	80,000	11,000		18,000		17,000			2*17,000			
F	13	33ft trailers	6	97,000	11,000		26,000		20,000			2*20,000			
	14		6	80,000	11,000		18,000		17,000			2*17,000			
G	15	Axle Spacing 18ft, 37.4ft, 15ft, 37.8ft	9	138,000	10,000		32,000			32,000			2*32,000		
	16		9	90,000	10,000		20,000			20,000			2*20,000		
G'	15a	Axle Spacing 18ft, 41ft, 19ft, 41ft	9	138,000	10,000		32,000			32,000			2*32,000		
	16b		9	90,000	10,000		20,000			20,000			2*20,000		
H	17	28 or 28.5ft trailers	7	106,000	11,000	20000			15,000			2*15,000		2*15,000	
I	18	28 or 28.5ft trailers	10	129,000	12,000	11000				28,000		11,000	28,000	11,000	28,000

4.3 Pavement Consumption

In this section, a pavement consumption estimation methodology that employs AASHTOWare Pavement ME Design™ is described. The same approach as developed in Rider 36 was used to identify the pavement consumption of each selected truck configuration.

4.3.1 Methodology

Pavement deterioration is generally measured in terms of the evolution of distresses such as surface rutting, fatigue cracking and roughness. The pavement deterioration is dependent on underlying pavement structure, soil type, traffic level, and climate. Traffic loads play a key role in the consumption of pavement life. Pavements are typically designed for a predicted amount of traffic called design-traffic such that the pavement reaches a terminal distress criterion at the end of its design life under the design-traffic. The traffic required to completely consume/fail the pavement at the end of its design life (reaching a terminal distress criterion) defines the pavement life or performance.

Pavement life was estimated for different axle loads and configurations. Three different axle groups were considered in this research study: single, tandem and tridem axles. Table 4.2 provides the range of axle loads and configurations that were included as part of this analysis.

Table 4.2 Axle loads and configurations

Single Axles (kips)	Tandem Axles (kips)	Tridem Axles (kips)
8	18	30
10	22	36
12	26	42
14	30	48
16	34	54
18	38	60
20	42	
22	46	
24		

Pavement consumption is largely influenced by the type and strength of the underlying pavement structure. A stronger pavement may not be as responsive as a weaker pavement structure to an overloaded traffic. A weaker pavement structure may be more expensive to operate OW traffic than a structurally sound pavement. It is important to account for the influence of pavement structure on the pavement consumption. Researchers identified about 100 pavement sections including thick and thin asphalt pavements and concrete pavement across Texas. In addition, the pavement consumption analysis should reflect the effect of facility type, traffic level and climate region. For this purpose, the pavement sections were selected from four facility types (IH, SH, US, and FM) with three different traffic levels of low, medium, and high. In addition, five climatic conditions were considered including dry-cold (DC), wet-cold (WC), dry-warm (DW), wet-warm (WW), and mixed-type weather. These five climatic conditions represent different environmental conditions across Texas.

In this study, the researchers used the ECF approach (developed in Rider 36) to estimate the pavement consumption different axles and truck configurations caused to the pavement. ECF is defined as the ratio of the number of passes of single axles carrying 18 kips load required to fully consume/fail a pavement at the end of design life (reaching terminal distress threshold), and that of the selected axle/trucks (Equation 4.1).

$$ECF = \frac{\#Passes\ of\ single\ axle\ with\ 18kips\ for\ full\ consumption}{\#Passes\ of\ an\ axle\ (or\ vehicle)\ for\ full\ consumption} \quad \textbf{(4.1)}$$

In order to unify criteria, the following distress thresholds were agreed with TxDOT personnel to define pavement failure in terms of three dominant distress mechanisms:

- 0.5 inches of rutting (surface deformation);
- 10% of the cracked area (load-associate fatigue cracking); and
- 125 inches/mile of roughness in terms of the International Roughness Index (IRI).

Equivalently, one may measure the pavement consumption of an axle (or a vehicle) in terms of the time (in months) taken to reach a terminal distress level for a fixed number of vehicle passes per day (the average daily truck traffic, or AADTT). The number of vehicle passes per day should be kept constant while comparing axles using the pavement consumption based on the pavement life time. ECF is defined in terms of time required to fully consume a pavement with a fixed number of vehicle passes per day (or pavement life) as shown as Equation 4.2.

$$ECF = \frac{Pavement\ life\ for\ N\ passes\ of\ single\ axle\ with\ 18kips\ load}{Pavement\ life\ for\ N\ passes\ of\ an\ axle\ load\ (or\ a\ vehicle)} \quad \textbf{(4.2)}$$

The number of passes per day (*N*) is selected such that the pavement structure attains the terminal threshold value (in terms of rutting, cracking or roughness) at the end of its design life (20 years in this case) under single axles carrying 18 kip loads only. Therefore, *N* is the total number of passes of single axle loaded to 18 kips required to attain full pavement consumption/failure at the end of design life. The number of such passes required to fully consume the pavement under ESAL at the end of design life is not necessarily the same across the three distress types. In other words, the design number of vehicle passes of ESAL to fail the pavement in terms of rutting (N_{rut}), cracking ($N_{cracking}$) and roughness (N_{IRI}) are not necessarily the same; therefore, the ECF values are dependent on the threshold criterion. Separate ECF values are estimated for each distress type.

4.3.2 Performing Mechanistic-Empirical Analysis

Pavement consumption corresponding to an axle load/axle configuration was estimated using the mechanistic empirical analysis in AASHTOWare Pavement ME

Design™ Version 2.1 software. This software builds upon the mechanistic-empirical pavement design guide, and expands and improves the features in the accompanying prototype computational software. This software is essentially an improved version of the earlier DARWin ME™ software, which was adopted during the Rider 36 study by the research team. The study team created a series of simulation scenarios to estimate the number of passes of any given axle/axle configuration required to completely consume the underlying pavement structure at the end of design life. This is regarded as the pavement consumption of the respective axle/ axle configuration. The study team used the existing pavement structural information (obtained using TxDOT maintained databases) to create a virtual single lane pavement sections carrying only the selected axle/axle configuration.

The software requires traffic, climatic, and structural inputs for performing the mechanistic analysis. The traffic inputs include the number of axles per axle configurations and monthly distribution of axle loads corresponding to the respective configuration. Uniform axle loads are assumed across the year for single, tandem, and tridem axles; however, monthly variations may be incorporated while performing a corridor-level analysis. As mentioned earlier, a several traffic scenarios were used to input other traffic-related inputs such as AADTT, percentage trucks, traffic growth rate, etc. Each traffic scenario comprises one selected axle/axle configuration only and traffic growth rate is assumed to be zero. The wheel base attributes were assigned to represent typical vehicles, while ensuring compatibility to each experimental configuration. The climatic information is incorporated into the analysis using the climatic station data provided within the AASHTOWare Pavement ME Design™ software. The software generates a virtual climatic station for each pavement section by interpolating the climatic information from the nearest climatic stations to the specific project. A pavement section is randomly selected from the pool of flexible pavement sections identified by the research team.

The output of the pavement performance analysis contains mean predicted rutting, cracking and roughness values along with the distress values at a pre-specified reliability level. Reliability accounts for model error while predicting the distress values using transfer functions. The distress value at the reliability is always higher than that of the mean predicted distress value. Researchers chose mean distress value over the distress value at the specified reliability for pavement consumption calculations.

As part of the AASHTOWare analysis, stresses and strains are calculated using linear elastic layer assumptions, which are realistic at low strain levels. The software uses transfer functions that convert strains into the relevant distress values. Rutting, cracking and roughness are predicted at the end of each month during the analysis period. The number of passes (per day) ($N_{rut}, N_{crack}, and\ N_{IRI}$) necessary to reach the terminal threshold at the end of design life (20 years) under ESALs (single axles carrying 18 kips load) is estimated corresponding to rutting, cracking and roughness. The time in months required to attain the terminal distress values is calculated under each axle load axle configuration using the estimated number of vehicle passes ($N_{Rutting}, N_{Cracking}, and\ N_{Roughness}$). The ECF is defined in terms of the ratio of 240 months (the pavement life for n passes of standard 18-kip single axle load) to the time required to fully consume a pavement with n passes of a given axle load/axle configuration. The ECF calculation must be done separately for each distress criteria. In general, there are three ECFs for each axle load/ axle configuration; $ECF_{Rutting}$, $ECF_{Cracking}$, and $ECF_{Roughness}$. Figure 4.8 shows an example representing the results of ECF calculation of different axle loads for one of the flexible pavements. As shown in Figure 4.8, ECF can be zero for an axle. It means that *n* passes of that axle do not cause any damage to the pavement. On the other hand, ECF can be less than one. An ECF lower than one indicates that under that specific traffic, the pavement will take longer than 20 years to reach the preset failure criteria. Conversely, an ECF of more than one means that the pavement will reach its failure condition in less than 20 years.

Axle Type	Axle Load (kip)	n-Rut	Rut-Month	Rut-ECF	n-IRI	IRI-Month	IRI-ECF	n-Crack	Crack-Month	Crack-ECF
Single	8	71	inf	0	328	324	0.741	501	inf	0
Single	10	71	inf	0	328	308	0.779	501	inf	0
Single	12	71	inf	0	328	293	0.819	501	inf	0
Single	14	71	inf	0	328	277	0.866	501	inf	0
Single	16	71	415	0.578	328	259	0.927	501	387	0.620
Single	18	71	240	1	328	240	1	501	240	1.000
Single	20	71	145	1.655	328	219	1.096	501	156	1.538
Single	22	71	91	2.637	328	197	1.218	501	105	2.286
Single	24	71	59	4.068	328	174	1.379	501	74	3.243
Tandem	18	71	inf	0	328	296	0.811	501	inf	0
Tandem	22	71	inf	0	328	274	0.876	501	inf	0
Tandem	26	71	329	0.729	328	250	0.960	501	inf	0
Tandem	30	71	169	1.420	328	224	1.071	501	340	0.706
Tandem	34	71	93	2.581	328	197	1.218	501	203	1.182
Tandem	38	71	52	4.615	328	170	1.412	501	129	1.860
Tandem	42	71	30	8	328	143	1.678	501	86	2.791
Tandem	46	71	18	13.333	328	118	2.034	501	60	4
Tridem	30	71	inf	0	328	277	0.866	501	inf	0
Tridem	36	71	330	0.727	328	254	0.945	501	inf	0
Tridem	42	71	160	1.5	328	229	1.048	501	269	0.892
Tridem	48	71	86	2.791	328	202	1.188	501	156	1.538
Tridem	54	71	49	4.898	328	173	1.387	501	96	2.500
Tridem	60	71	28	8.571	328	146	1.644	501	62	3.871

Figure 4.8 An example of ECF computation

4.3.3 Results

4.3.3.1 Relationships between ECF and Axle Loads for Flexible Pavements

In order to understand the consumption different axles induce on a pavement structure, ECF values were computed for three axle groups: single axle loads from 8 to 24 kips, tandem axle loads from 18 to 46 kips, and tridem axle loads from 30 to 60 kips. Figure 4.9 depicts the plots of the three ECFs (i.e., $ECF_{Rutting}$, $ECF_{Cracking}$, and $ECF_{Roughness}$) versus axle loads for a given pavement section. As presented in Figure 4.9 in each axle group, the heavier the load, the greater the consumption of the highway infrastructures. The results indicate that rutting is more influenced by tandem and tridem axle loads. On the other hand, cracking is more affected by single and tandem axles. On the other hand, as shown in Figure 4.9, all axle groups have approximately the same impact on pavement consumption from roughness perspective. The graph of $ECF_{cracking}$ vs. axle loads shows that some of tridem axles have lower ECF values as compare to tandem and single axles even though they carry heavier loads.

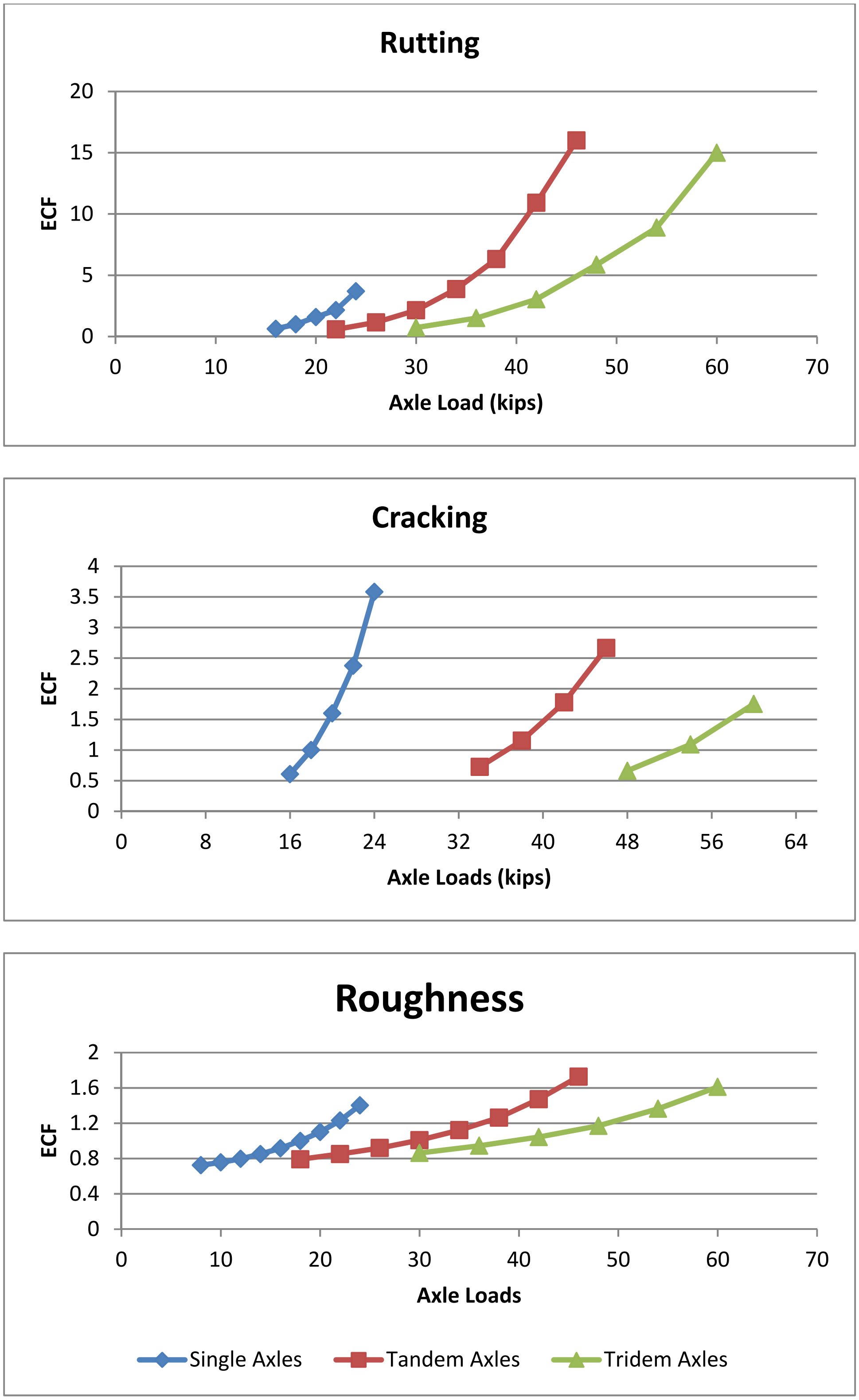


Figure 4.9 Plots of a) $ECF_{Rutting}$, b) $ECF_{Cracking}$, and c) $ECF_{Roughness}$, versus axle loads.

4.3.3.2 Model Development

The main purpose of this part of the study was to generalize the relationship between three ECFs and axle loads by considering the type of pavements. To address this objective, all ECF data for different axle types (single, tandem, and tridem) under four environmental conditions and various traffic levels were computed and a database was compiled. The correlations between ECF values and axle loads were plotted and investigated. By applying a series of statistical analyses, a series of equations that capture the relationship of ECF and axle loads were evaluated. Those equations were assessed for three types of pavements; thick and thin asphalt pavements, and concrete pavements given the three failure criteria. Finally, the equation that best captured the relationship was selected. The detailed procedures for finding the equations for rutting, cracking, and IRI are provided in the following paragraphs.

To determine an appropriate ECF model, the following group of equations (Equations 4.3, 4.4, and 4.5) were evaluated for $ECF_{cracking}$ and $ECF_{rutting}$ values calculated for 81 thick and thin asphalt pavements. The ECF data showed good conformity to these three equations for both rutting and cracking mechanisms. Figures Figure 4.10 and 4.11 provide two examples of the fit of three equations to single, tandem, and tridem axles for cracking and rutting, respectively. The pavement in the examples is hot-mix asphalt (HMA).

$$\mathbf{ECF} = \left(\frac{\mathbf{L}}{\mathbf{b*18}}\right)^{\mathbf{c}} \quad \mathbf{(4.3)}$$

$$\mathbf{ECF} = \mathbf{d} + \mathbf{a} * [\mathbf{ln}\left(\frac{\mathbf{L}}{\mathbf{b*18}} + \mathbf{1}\right)]^{\mathbf{c}} \quad \mathbf{(4.4)}$$

$$\mathbf{Ln(ECF)} = \mathbf{a} * [\left(\mathbf{ln}\left(\frac{\mathbf{L}}{\mathbf{b*18}} + \mathbf{1}\right)\right)^{\mathbf{c}} - \left(\mathbf{ln(2)}\right)^{\mathbf{c}}] \quad \mathbf{(4.5)}$$

Where

ECF stands for equivalent consumption factor, *L* is magnitude of an axle load (kips), and *a, b, c*, and *d* are unknown constants to be determined.

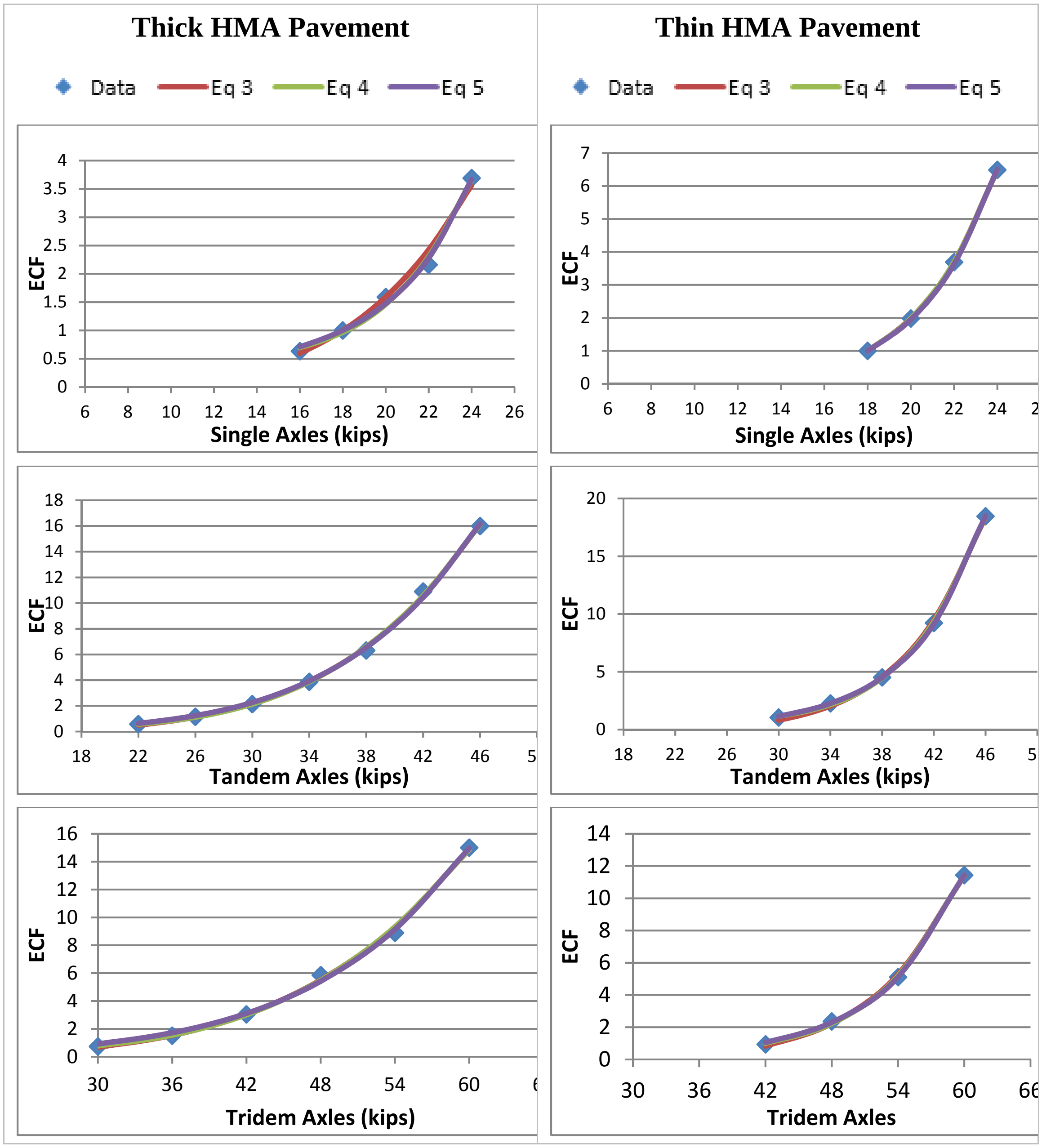


Figure 4.10 ECF$_{Rutting}$ for a thick and thin asphalt pavements.

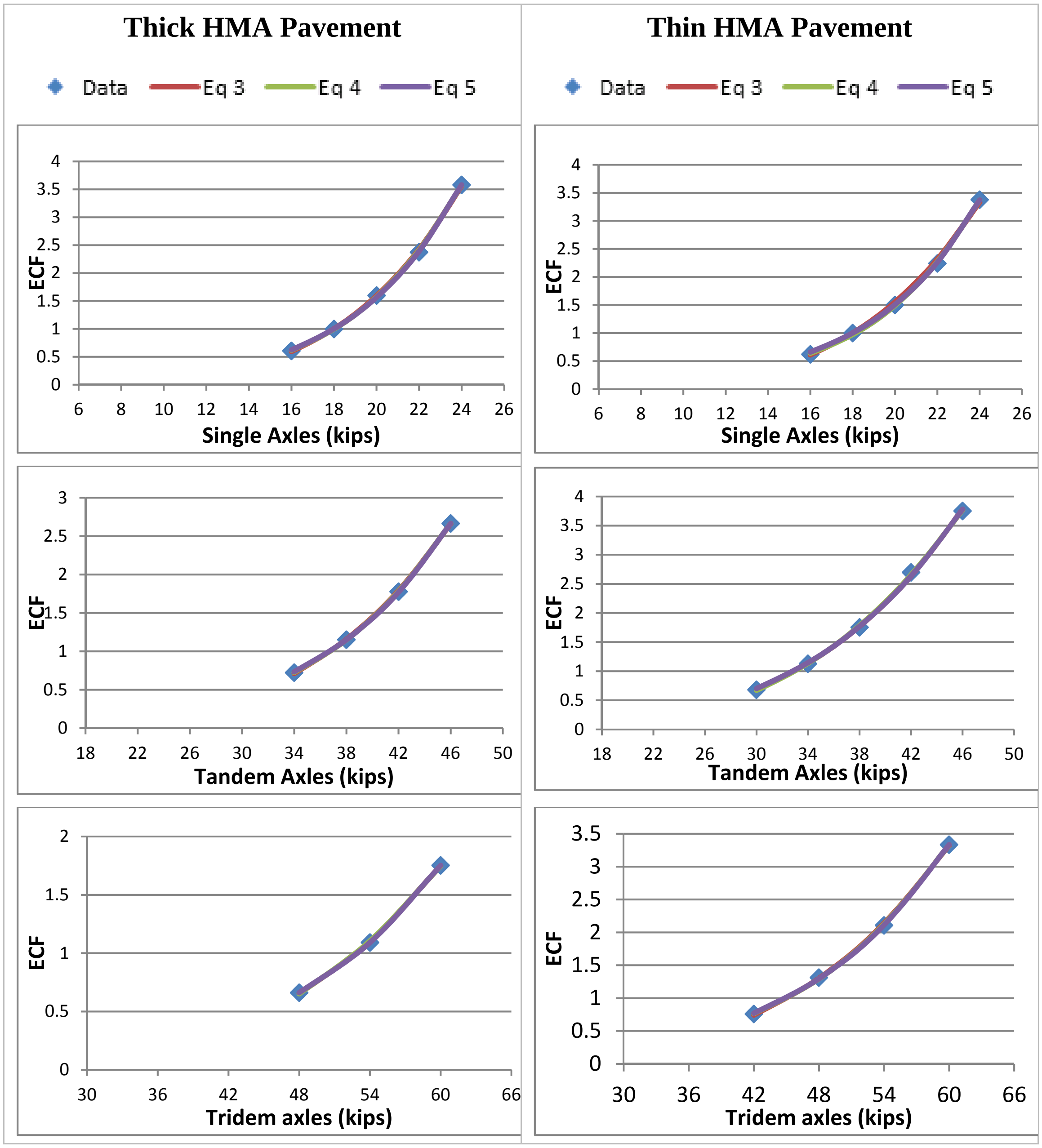


Figure 4.11 $ECF_{cracking}$ for a thick and thin asphalt pavements.

To obtain a simpler but more meaningful relationship, Equation 4.6 was later added to the group of equations in place of Equation 4.4. Equations 4.3, 4.5, and 4.6 were used to evaluate the values of ECF_{IRI}.

$$\mathbf{ECF = a^{\exp\left(\frac{L}{b*18}-1\right)-1}} \qquad \textbf{(4.6)}$$

The results indicated that the Equation 4.6 fits very well with ECF_{IRI} data of thick asphalt sections but it is not accurate for thin sections. Figure 4.12 represents an example highlighting this situation. Furthermore, the evaluation of the roughness results revealed that the Equation 4.3 is not an appropriate to find the relationship between ECF and axle loads for a number of pavement structures. Finally, Equation 4.5 was found to be the best equation among all since it was compatible with data of three failures for both thick and thin pavements. Equations 4.3 and 4.6 were eliminated and the study was continued by considering the Equation 4.5 as the best one.

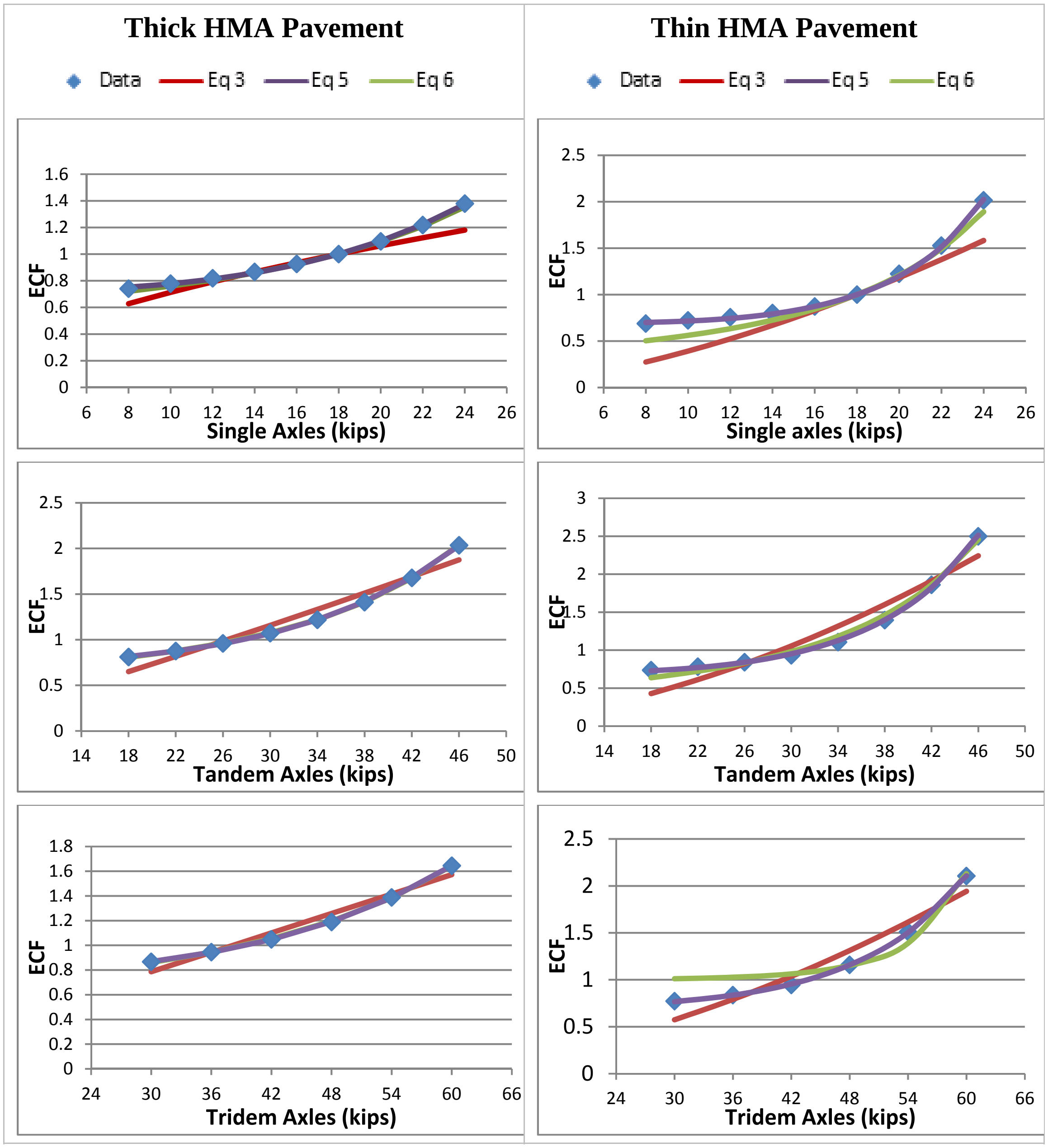


Figure 4.12 ECF_{IRI} for a thick and thin asphalt pavements.

4.3.3.3 Optimization

By applying non-linear optimization, the parameters of the Equation 4.5 (i.e., *a*, *b*, and *c*) were found for all axle groups (single, tandem, and tridem), pavement sections, and distress types. It should be indicated that it was not feasible to find a unique equation form that could capture the effects of single, tandem, and tridem axle loads; therefore, separate parameters were defined for each axle group. It should also be noted that during the process of developing the ECF model, the "b_1" parameter (which represents the group equivalency factor for single axles) is equal to one, but it is being kept in the context as b_1.

Table 4.3 and 4.4 show an example of parameter values calculated for a thick and a thin asphalt pavement, respectively. As the tables demonstrate, there are nine parameters that should be calculated for each type of failure on each pavement structure. The fact that the parameter values differ from pavement to pavement indicates that the ECF for any given axle load is influenced by pavement material properties, pavement SN, level of traffic, and environmental conditions. The purpose of analysis is to develop a unique general equation be applicable for different axle load combinations and pavements. To address this aspect of the analysis, a cross-correlation analysis between parameters and their relationship to pavement properties and other factors such as traffic and climatic regions was carried out. The results of eight combinations of pavements and failure mechanisms are provided next.

Table 4.3 Parameter values for a thick asphalt pavement

Rutting								
Single axles			Tandem axles			Tridem axles		
a_1	**b_1**	**c_1**	**a_2**	**b_2**	**c_2**	**a_3**	**b_3**	**c_3**
4.633	1	3.291	9.510	1.372	0.791	6	1.712	1.192
Cracking								
8.395	1	0.980	7.979	2.039	1.046	8.431	2.941	1.044
Roughness								
1.199	1	3.268	1.082	1.659	3.477	1.01	2.214	3.667

Table 4.4 Parameter values for a thin asphalt pavement

Rutting								
Single axles			Tandem axles			Tridem axles		
a_1	**b_1**	**c_1**	**a_2**	**b_2**	**c_2**	**a_3**	**b_3**	**c_3**
15.308	1	0.741	7.097	1.623	1.975	7.735	2.311	1.976
Cracking								
5.902	1	1.538	14.822	1.825	0.427	7.889	2.498	0.982
Roughness								
2.594	1	5.320	2.065	1.737	4.708	2.309	2.423	5.178

Results for Rutting for Thick Pavements

Figure 4.13 depicts pairwise relationship between *a*, *b*, and *c* parameters corresponding to three axle groups. The b_2 values are approximately equal to c_2 values.

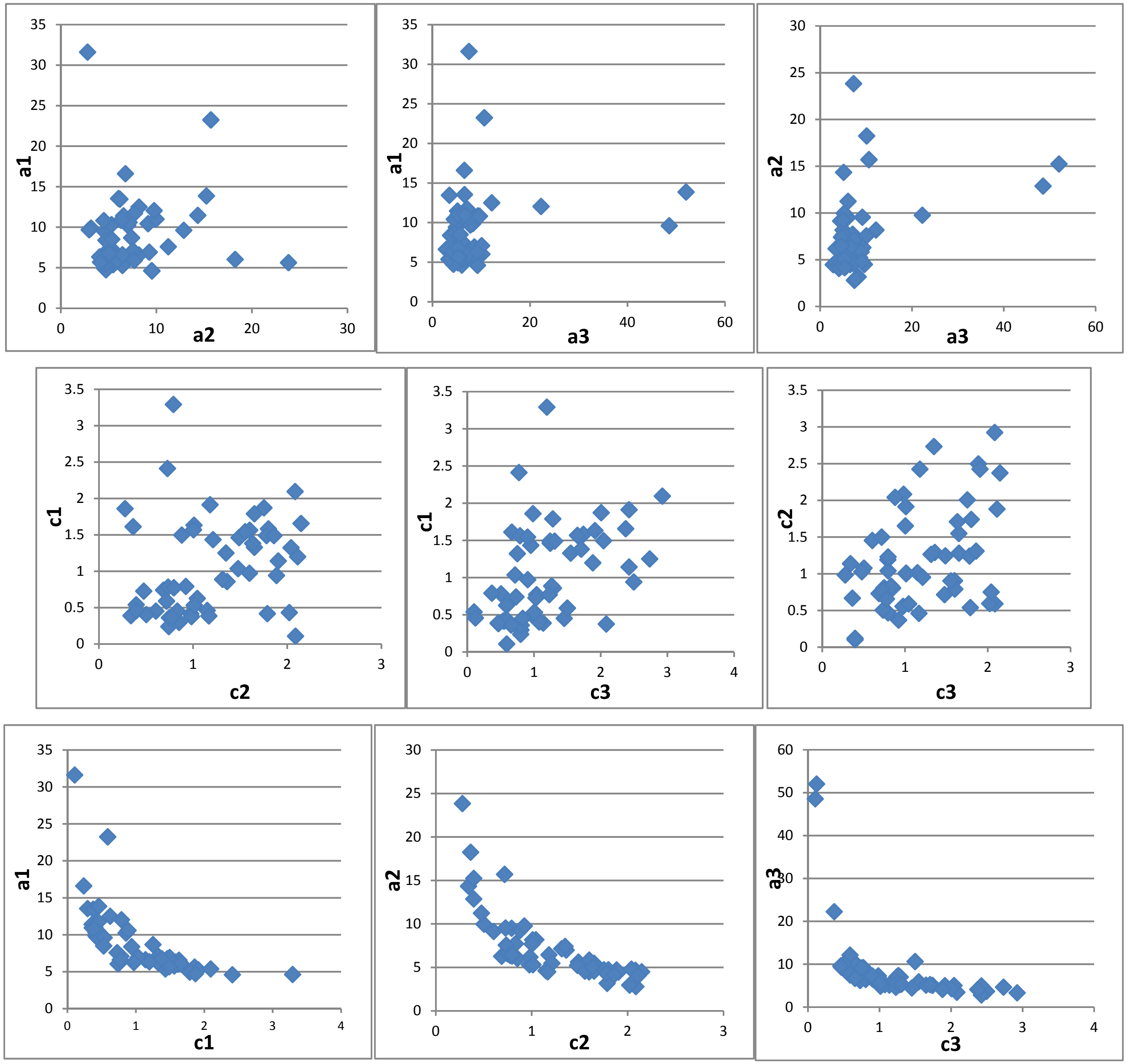
The same was observed for b_3 values with respect to c_3 values. Therefore, average values were calculated for b_2 and b_3. Following are the average of b values used for developing ECF model:

- Single Axles: $b_1 = 1.00$
- Tandem Axles: $b_2 = 1.43$
- Tridem Axles: $b_3 = 1.84$

In Equations 4.7 and 4.8, b_2 and b_3 parameters were set as 1.43 and 1.84, respectively. By means of non-linear optimization, new updated values for a and c, labelled $a*$ and $c*$, were obtained for tandem and tridem axles. The pairwise correlation between parameters were evaluated and provided in Figure 4.14. In some cases, such as c_1^*-c_2^* and c_1^*-c_3^*, the data were randomly distributed and no relationship could be established.

For Tandem Axle Loads: $$\mathbf{Ln(ECF) = a_2^*[\left(ln\left(\frac{L}{1.43*18}+1\right)\right)^{c_2^*} - \left(ln(2)\right)^{c_2^*}]} \quad \textbf{(4.7)}$$

For Tridem Axle Loads: $$\mathbf{Ln(ECF) = a_3^*[\left(ln\left(\frac{L}{1.84*18}+1\right)\right)^{c_3^*} - \left(ln(2)\right)^{c_3^*}} \quad \textbf{(4.8)}$$


a1
a2
a1
a3
a2
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c1
c2
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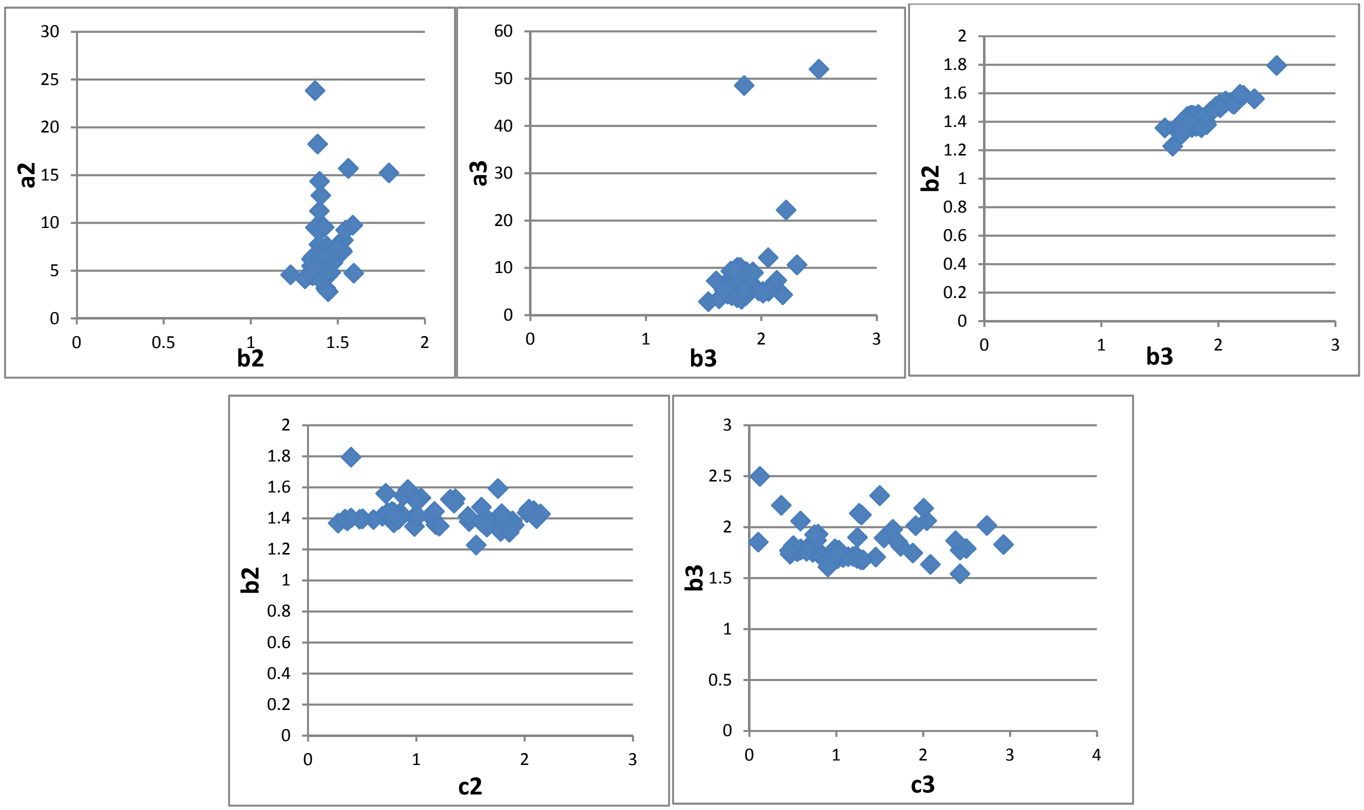


Figure 4.13 Relationship between "a", "b", and "c" values based on rutting and thick HMA pavement

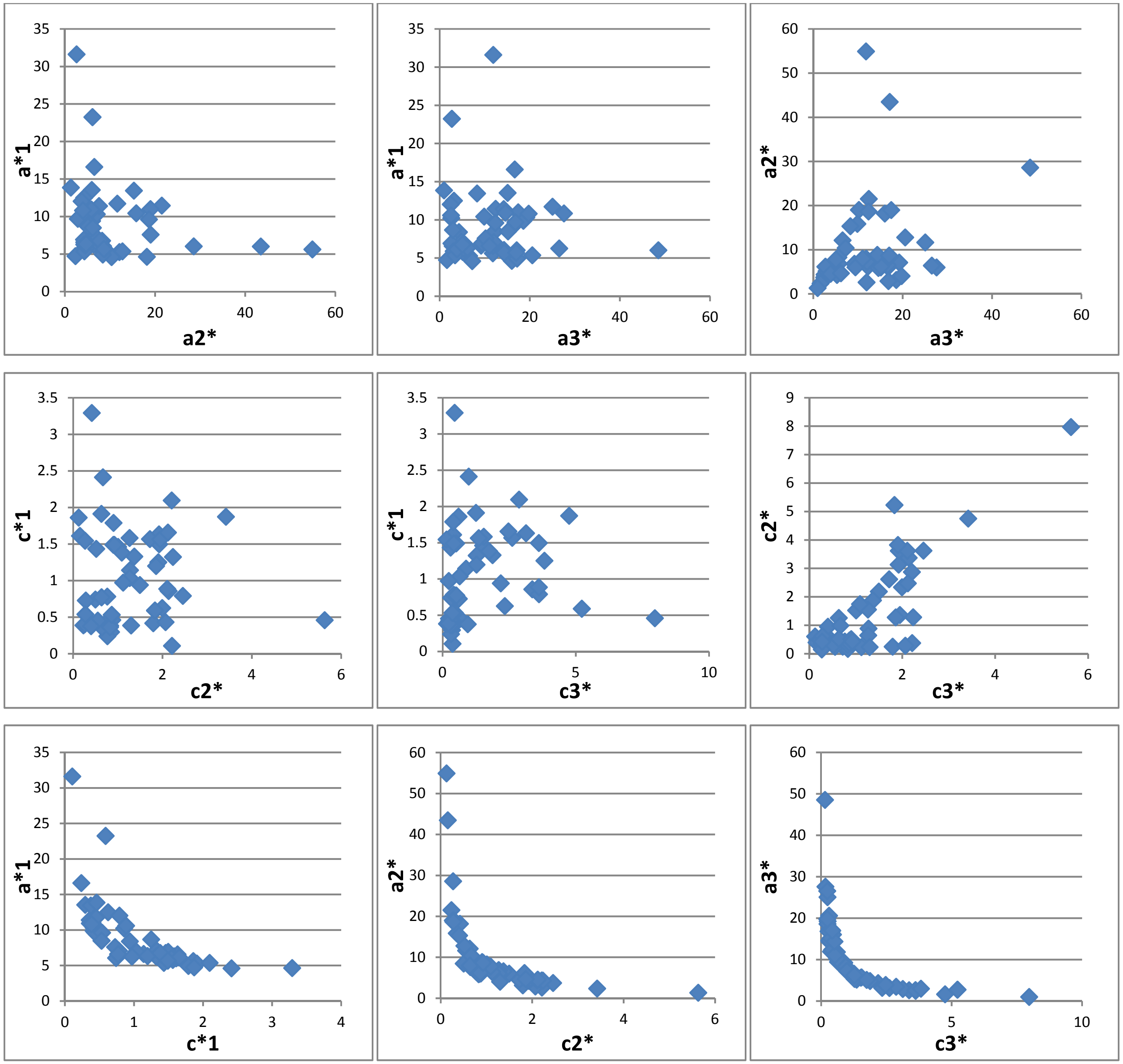


Figure 4.14 Relationship between "a", and "c*" values based on rutting and thick HMA pavement*

Figure 4.14 shows that the relationship between a_1^* and c_1^* follows a similar trend as the relationship between a_2^* and c_2^*, and a_3^* and c_3^*. Accordingly, all axle groups were combined together into a unique specification form. The new specification form has two constants, labelled "aa'' and "cc", instead of six constants, as before. The resulting equation to determine ECFs for thick asphalt pavement using the rutting failure criterion is as follows:

$$\mathbf{Ln(ECF) = aa[\left(ln\left(\frac{L'}{18}+1\right)\right)^{cc} - (ln(2))^{cc}]} \tag{4.9}$$

Where,

L' is

For a Single Axle: *weight of single axle*

For a Tandem Axle: *L' = Weight of a Tandem axle/1.43*

For a Tridem Axle: *L' = Weight of a Tridem axle/1.84*

The relationship between the parameters aa and cc was also evaluated. Figure 4.15 shows an exponential relationship between "*aa*" and "*cc*" with R-squared = 77%. This relationship was used to recalculate cc. As a result, the $ECF_{Rutting}$ model (Equation 4.10) with one parameter (cc^*) was developed for studied thick asphalt pavements. Furthermore, a relationship between the pavement SN and *cc** is required to generalize this model to all thick asphalt pavements.

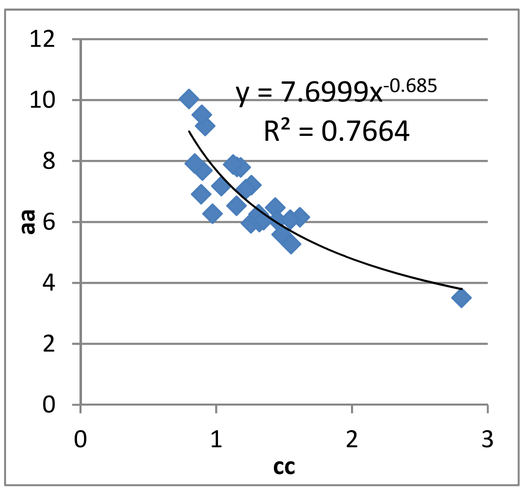


Figure 4.15 Relationship between parameters aa and cc

$$\mathbf{Ln(ECF) = (7.7\, cc^{*(-0.7)})\,[\left(ln\left(\frac{L'}{18}+1\right)\right)^{cc^*} - (ln(2))^{cc^*}]} \tag{4.10}$$

For consistency, the AASHTO method was used to calculate the SN of all pavement structures. The information regarding layer thickness, layer coefficients, modulus of asphalt sections, and pavement SNs are provided in Appendix A. It is to be noted that the AASHTO method was not applicable for cement-stabilized sections. Figure 4.16 presents the plot of *cc** values versus SN and the histogram of *cc**. No clear relationship could be established between SN and *cc**. Furthermore, as can be seen in Figure 4.16, *cc** values are distributed over a wide range of values from 0.4 to 1.6. Therefore, it is not possible to use the average value.

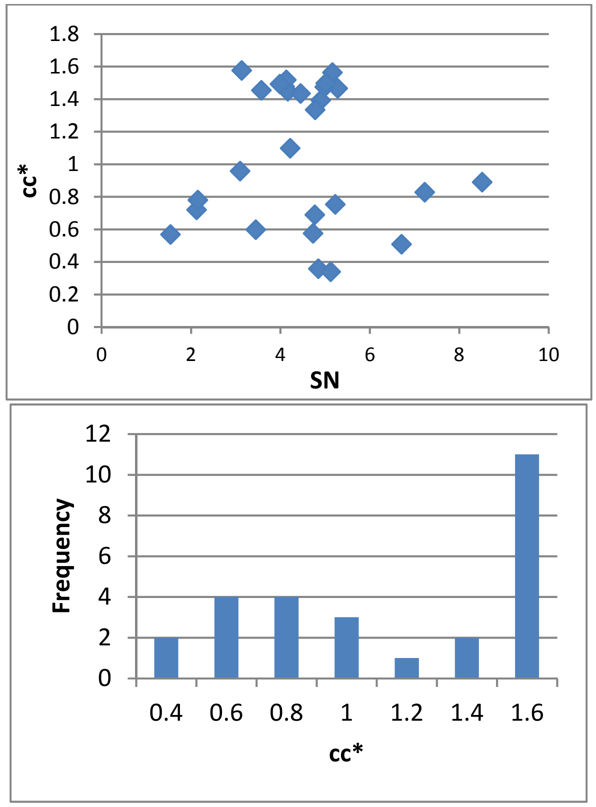


Figure 4.16 a) Relationship between cc and SN, b) distribution of cc^**

The cc^* values corresponding to different levels of traffic and climatic regions were calculated using linear estimation. Figure 4.17 shows the results of the aforementioned analysis. As can be seen in Figure 4.17, sections with medium traffic located in DW regions have the lowest value of *cc**. Pavement sections subjected to high level of traffic in WC, WW, and DW regions and sections located DC and WC regions with medium level of traffic have approximately similar *cc** values. As illustrated in Figure 4.17, the *cc** values corresponding to WW sections increases as the traffic level increases. Further statistical analyses were performed using Equation 4.10 for different values of L/18. The results indicated that, for L/18 greater than one, ECF gets lower as *cc** increases.

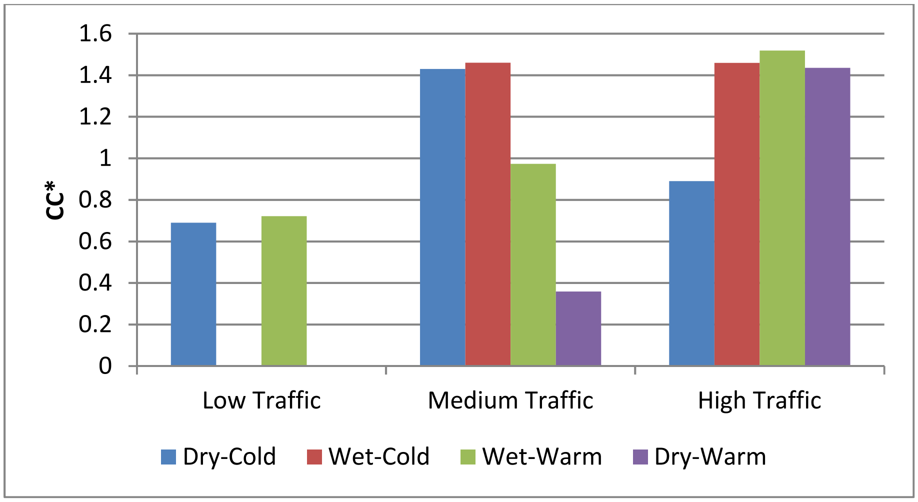


Figure 4.17 Parameter cc based on rutting for thick asphalt pavements*

Results for Cracking Stress and Thick HMA Pavements

The same procedure as the one described for rutting was applied for the fatigue cracking data to develop the $ECF_{Cracking}$ model. Initially, the parameters *a*, *b* and *c* were calculated for each axle group separately. The scatter plots of b vs. c (shown in Figure 4.18) indicated that b_2 and b_3 values are almost constant with respect to c_2 and c_3. Accordingly, the average values for b_2 and i were calculated. Following are the average values of *b* parameters corresponding to three axle groups:

- Single Axles: b_1=1.00
- Tandem Axles: b_2 =1.92
- Tridem Axles: b_3 = 2.65

After substituting the average values of *b* in the corresponding equations, nonlinear optimization was applied to calculate the new values for the parameters *a* and *c*, labelled *a** and *c** for different axle groups. The resulting equations to determine ECFs for thick asphalt sections using the cracking failure criterion are as follows:

$$\textbf{Single Axle Loads: Ln(ECF)} = a_1^*[\left(\ln\left(\frac{L}{18}+1\right)\right)^{c_1^*} - \left(\ln(2)\right)^{c_1^*}] \quad \textbf{(4.11)}$$

$$\textbf{Tandem Axle Loads: Ln(ECF)} = a_2^*[\left(\ln\left(\frac{L}{1.92*18}+1\right)\right)^{c_2^*} - \left(\ln(2)\right)^{c_2^*}] \quad \textbf{(4.12)}$$

$$\textbf{Tridem Axle Loads: Ln(ECF)} = a_3^*[\left(\ln\left(\frac{L}{2.65*18}+1\right)\right)^{c_3^*} - \left(\ln(2)\right)^{c_3^*}] \quad \textbf{(4.13)}$$

Where

L is axle load in kips, and the a^* and c^* are regression parameters.

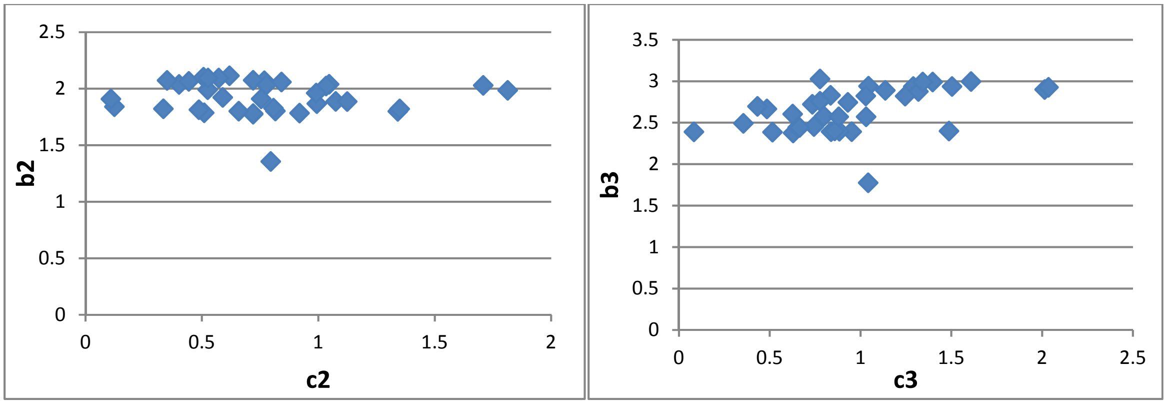


Figure 4.18 Relationship between b and c for cracking of asphalt pavements

The relationship between the SN and the obtained parameters was also evaluated. The relationships between *a** and SN and also *c** and SN were evaluated. These scatter plots, as presented in Figure 4.19, show no clear relationship between parameters and SN. However, by careful observation, it can be found that there are two distinct groups of pavement between the SN values of 4 and 5. These two groups are highlighted in Figure 4.20. Information in terms of climatic regions, traffic level, and facility type associated with those groups was extracted. However, analyzing data did not shed any insight to establish any common feature between pavements within each group.

Another attempt was made by creating the plot of latitude versus longitude positions of the sections to find any potential relationship between pavements within each group. An example is provided in Figure 4.21. All in all, the research team was not able to find any correlation between two groups.

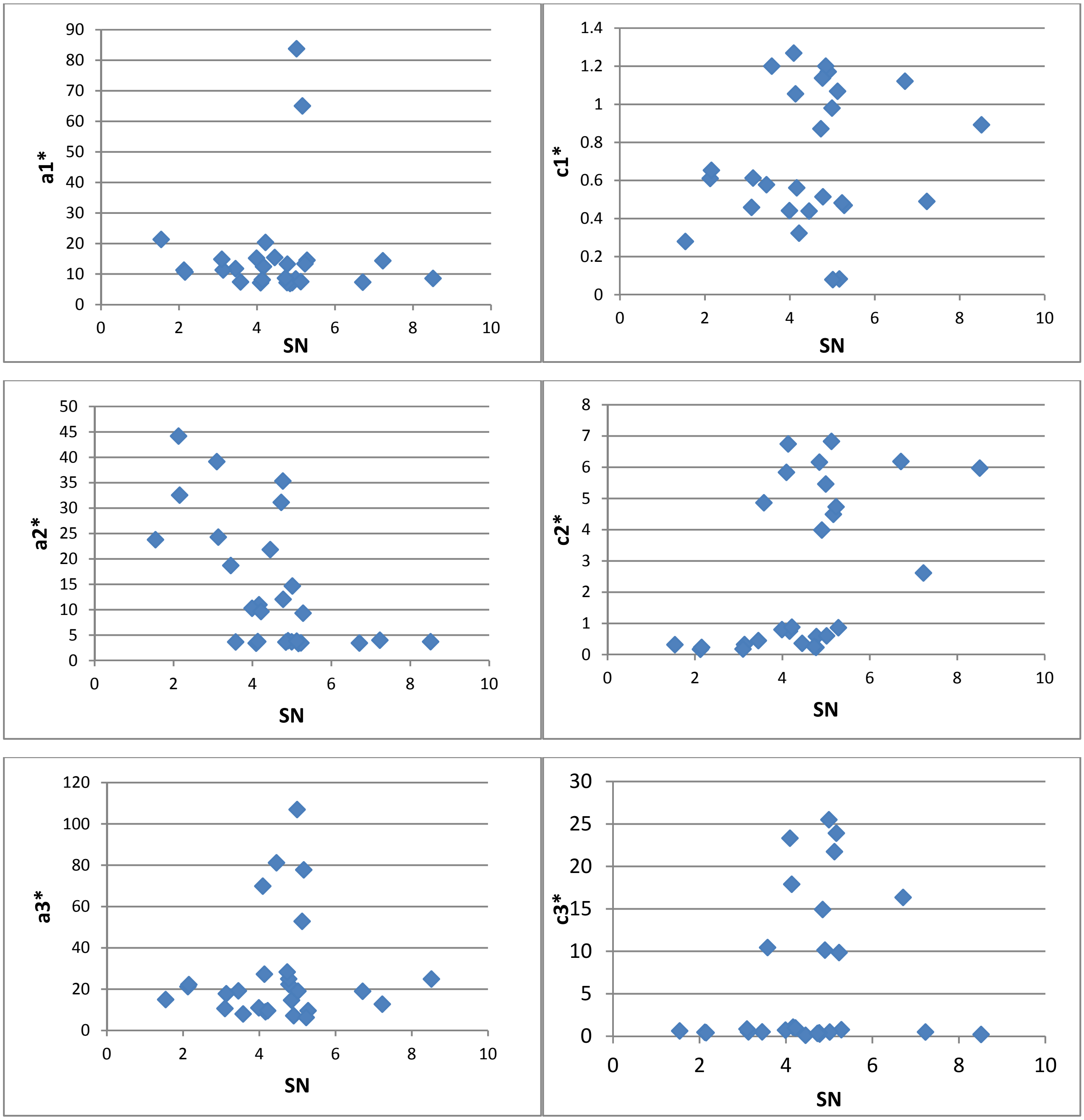


Figure 4.19 Relationship between “a” and “c*” constants and SN*

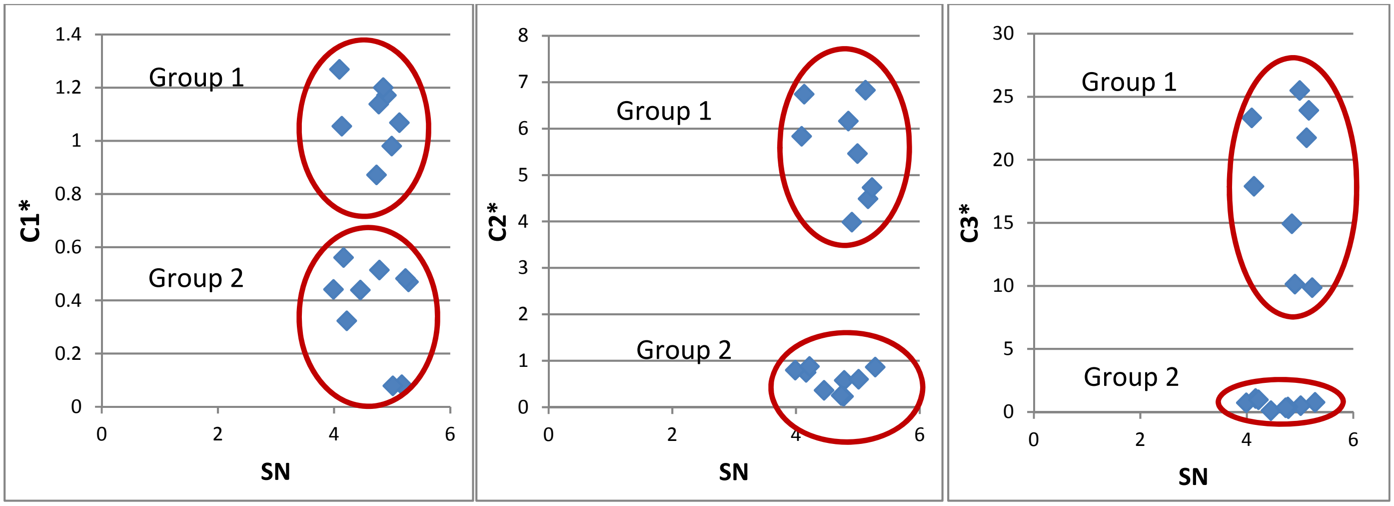


Figure 4.20 Demonstration of two groups in "c" plots*

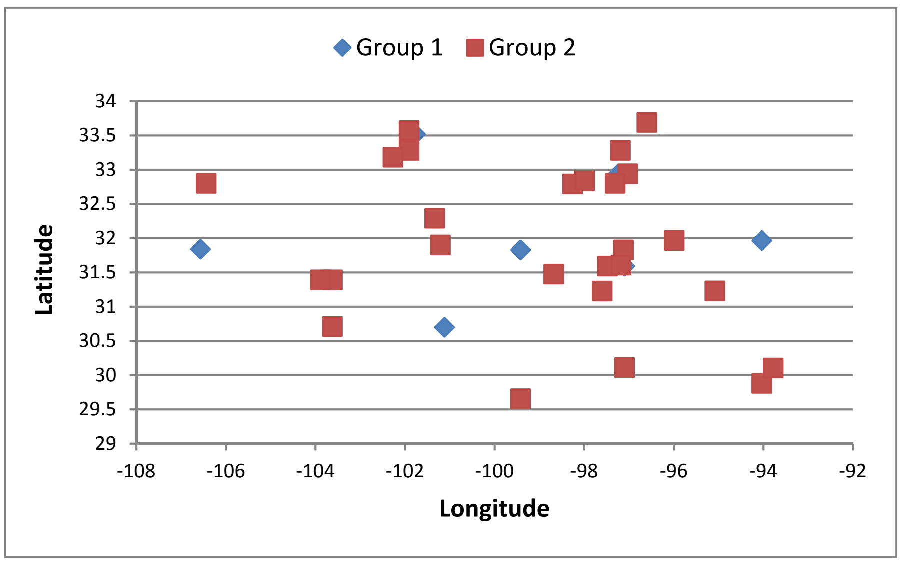
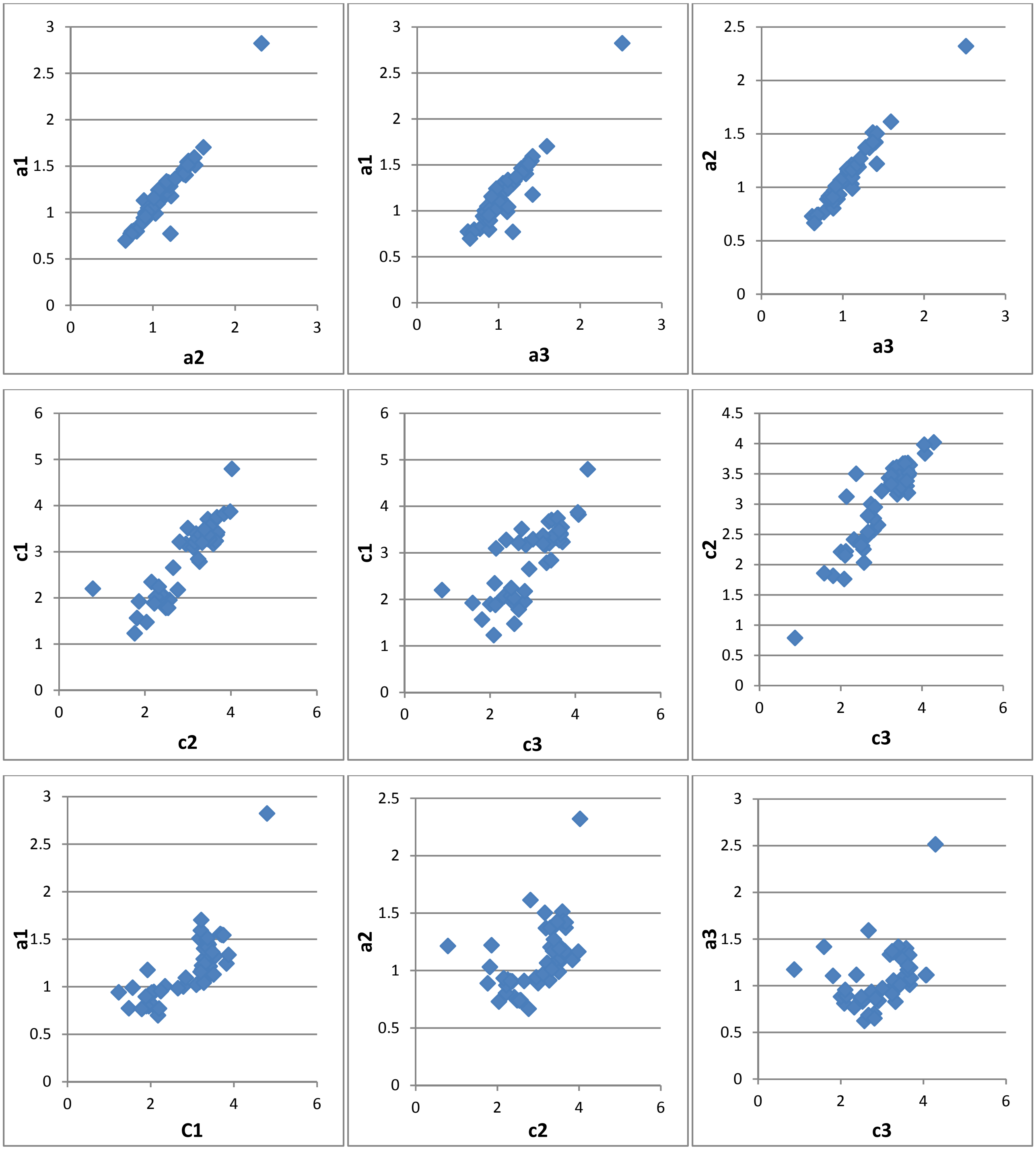


*Figure 4.21 Latitude vs. Longitude graph for Groups 1 and 2 for c1**

<u>Results for Roughness and Thick HMA Pavements</u>

To develop the $ECF_{Roughness}$ model for thick asphalt pavements, initial values of a, b and c were calculated for each axle group separately. As shown in Figure 4.22, scatter plots were provided to establish potential correlations between the calculated parameters. Figure 4.22 illustrates that there is an approximately linear relationship between axle groups' parameters. For example, a_1 is linearly related to a_2.


a1
a2
a1
a3
a2
a3
c1
c2
c1
c3
c2
c3
a1
C1
a2
c2
a3
c3

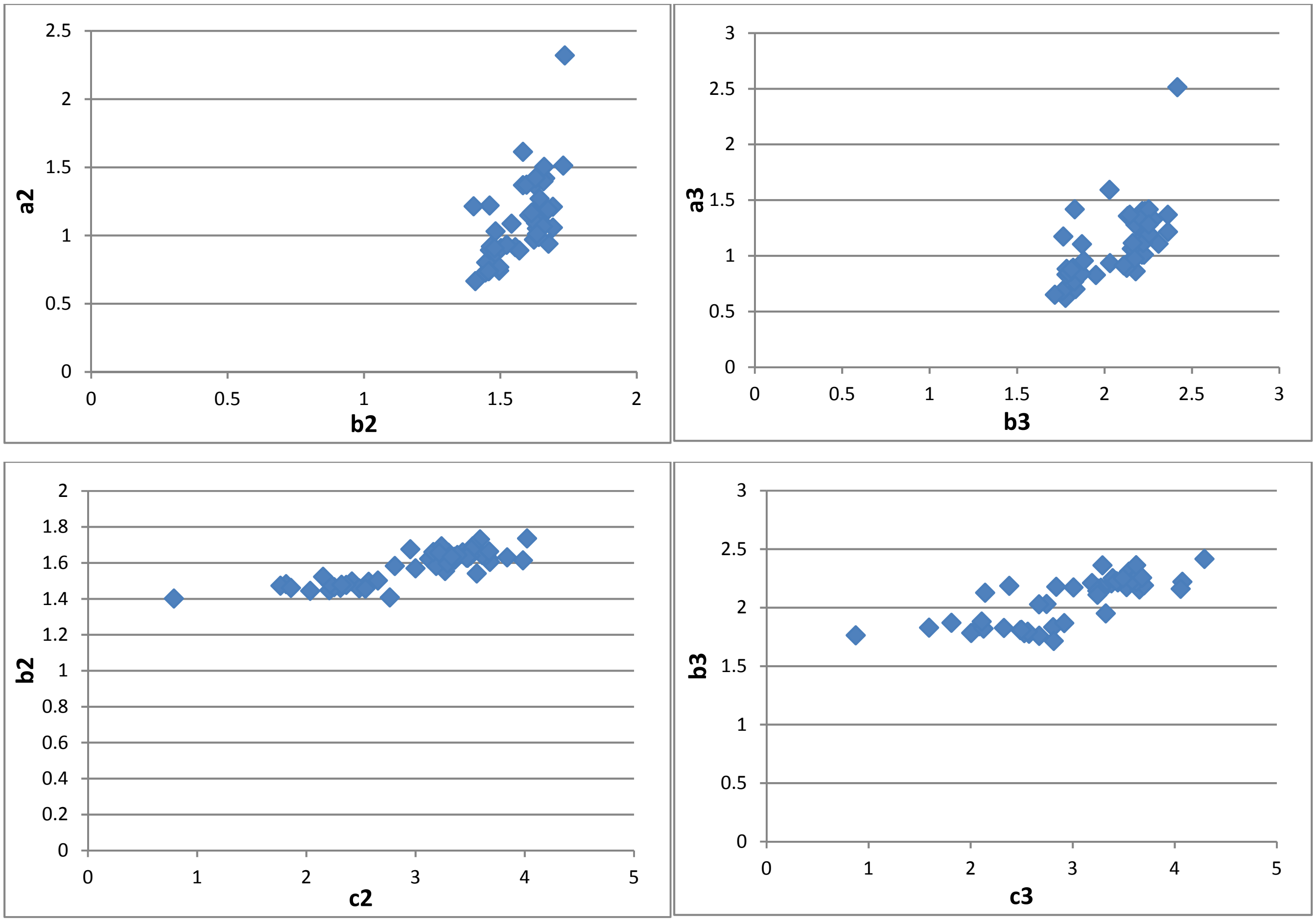


Figure 4.22 Relationship between a, b* and c* for roughness of thick asphalt pavements*

In the same manner as rutting and cracking, average values of b were calculated for different axle groups. Following are the average values of parameter b corresponding to three axle groups:

- Single axle group: $b_1 = 1.00$
- Tandem axle group: $b_2 = 1.58$
- Tridem axle group: $b_3 = 2.06$

Followings are the corresponding equations obtained using average values of parameter b to calculate the ECF for each axle group. These updated equations were optimized to find a* and c* for each axle group. To quantify the effect of pavement strength on $ECF_{Roughness}$, a* and c* were correlated with SN. As shown in Figure 4.23, a* and c* are approximately constant for different pavements. Accordingly, the average values of these parameters were calculated to develop the final model.

$$\textbf{Single Axle Loads: } \mathbf{Ln(ECF)} = \mathbf{a_1^*}[\left(\mathbf{ln}\left(\frac{\mathbf{L}}{\mathbf{18}}+\mathbf{1}\right)\right)^{\mathbf{c_1^*}} - \left(\mathbf{ln(2)}\right)^{\mathbf{c_1^*}}] \qquad \textbf{(4.14)}$$

$$\textbf{Tandem Axle Loads: } \mathrm{Ln(ECF)} = a_2^*\left[\left(\ln\left(\frac{L}{1.58*18}+1\right)\right)^{c_2^*} - \left(\ln(2)\right)^{c_2^*}\right] \qquad (4.15)$$

$$\textbf{Tridem Axle Loads: } \mathrm{Ln(ECF)} = a_3^*\left[\left(\ln\left(\frac{L}{2.06*18}+1\right)\right)^{c_3^*} - \left(\ln(2)\right)^{c_3^*}\right] \qquad (4.16)$$

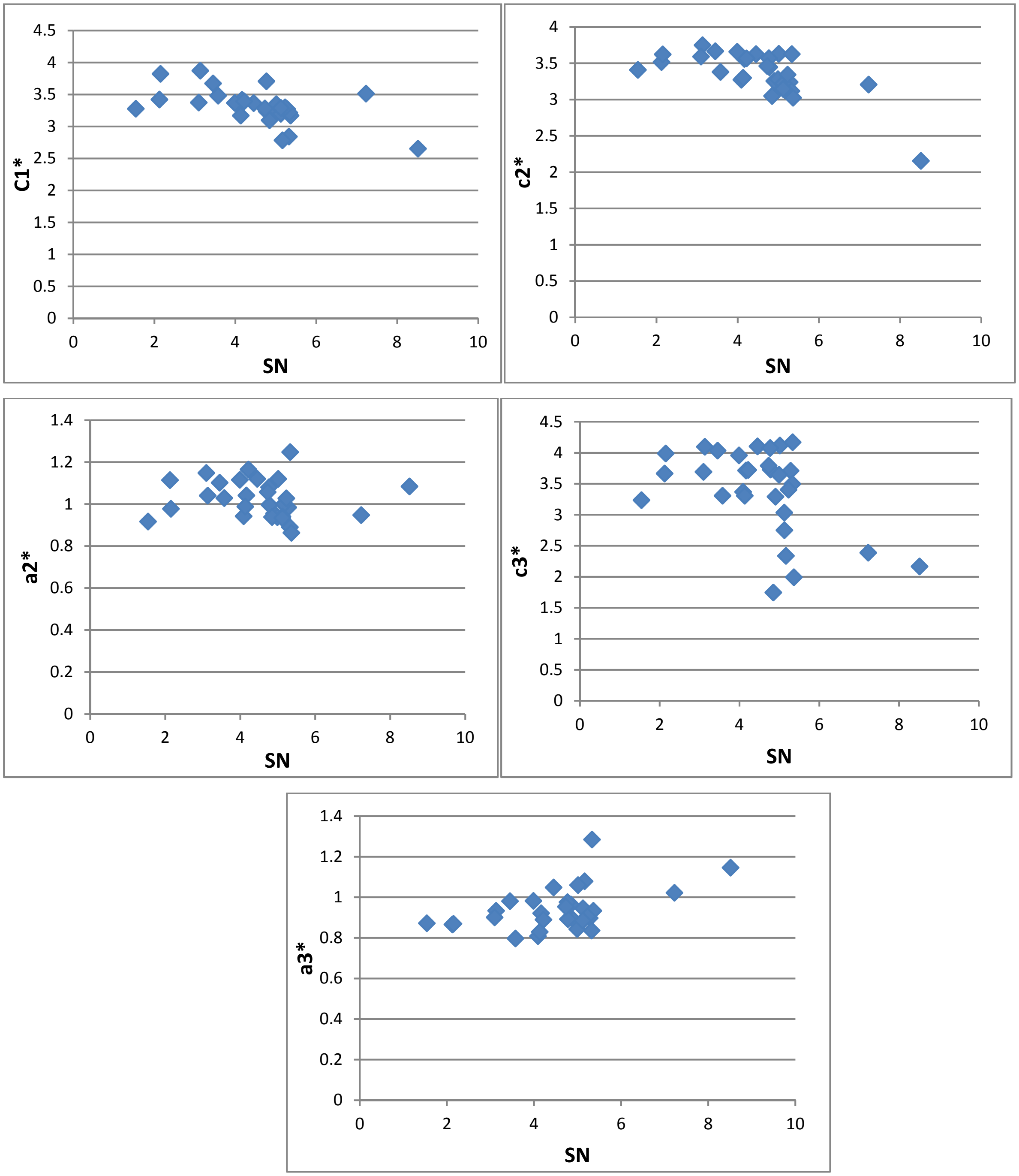


Figure 4.23 Relationship between "a", and "c*" values and SN*

Based on the aforementioned relationships, it was agreed to use an average value of each constant for roughness criteria. Table 4.5 provides the final values of parameters. As a result, following is the final expression of equations for thick asphalt sections for roughness criterion:

$$\textbf{Single Axle Loads: } \mathbf{Ln(ECF) = 1.285}\left[\left(\ln\left(\frac{L}{18}+1\right)\right)^{3.312} - (\ln(2))^{3.312}\right] \quad \textbf{(4.17)}$$

$$\textbf{Tandem Axle Loads: } \mathbf{Ln(ECF) = 1.024}\left[\left(\ln\left(\frac{L}{1.58*18}+1\right)\right)^{3.361} - (\ln(2))^{3.361}\right] \quad \textbf{(4.18)}$$

$$\textbf{Tridem Axle Loads: } \mathbf{Ln(ECF) = 0.941}\left[\left(\ln\left(\frac{L}{2.06*18}+1\right)\right)^{3.402} - (\ln(2))^{3.402}\right] \quad \textbf{(4.19)}$$

Table 4.5 Final values of constants

Single Axles			Tandem Axles			Tridem Axles		
a1*	b1	c1*	a2*	b2	c2*	a3*	b3	c3*
1.285	1	3.312	1.024	1.58	3.361	0.941	2.06	3.402

Results for Rutting and Thin HMA Pavement

In order to develop $ECF_{Rutting}$ model for thin asphalt pavements, 30 projects were extracted from TxDOT database and ECF were calculated for different axle loads and configurations. The same method as that for thick pavements was followed for the 30 sections to find the best ECF model. The relationship between axle loads and ECF values was evaluated for all thin pavements. The research team observed that it was possible to generate a unique equation for three axle groups (Equation 4.20) with different b values.

$$\mathbf{LN\ (ECF) = aa}\left(\left(\mathbf{Ln}\left(\frac{L}{b_{(1,2,3)}*18}\right)\right)^{cc} - (\ln(2))^{cc}\right) \quad \textbf{(4.20)}$$

The values of the parameter b for each axle group were obtained as follow:

- Single Axles : b_1 = 1.00
- Tandem Axles : b_2 = 1.68
- Tridem Axles : b3 = 2.36

Next, by using the ECF data of all axle groups, unique set of parameters aa and cc was calculated to be used in the general equation. After careful investigation, the research team realized a strong relationship between aa and cc values. Figure 4.24 depicts the scatter plot of aa versus cc. As can be seen, the trend between aa and cc can be approximated by an exponential relationship. Equation 4.21 was obtained using the exponential relationship between aa and cc parameters. The researchers recalculated cc according to the Equation 4.21, which was labelled cc*.

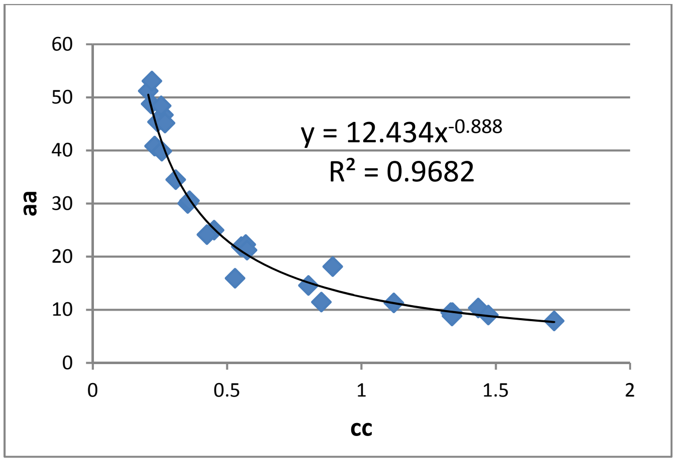


Figure 4.24 Relationship between aa and cc for rutting of thin pavement

$$\mathbf{LN\ (ECF) = (12434}cc^{-0.888})((\mathbf{Ln}\left(\frac{w}{b_{(1,2,3)}*18}\right))^{cc} - (\ln(2))^{cc}) \quad \mathbf{(4.21)}$$

To find out if the SN relates to cc*, the pavement SNs were calculated and plotted against cc*. The calculation of SN was undertaken using the same approach as that for thick sections. The required information of pavement structures and calculated SNs are provided in Appendix A. Figure 4.25 depicts graphs of cc* with respect to SN. As shown in Figure 4.25, data are randomly distributed and there is no strong relationship between the SN and parameter.

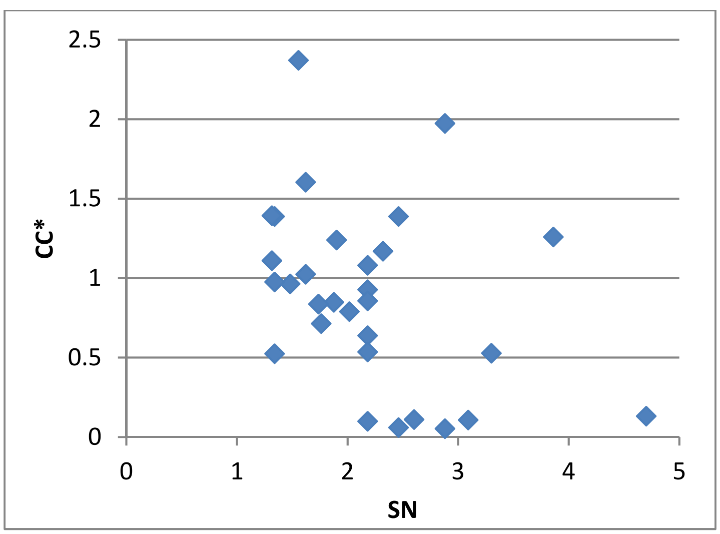


Figure 4.25 Relationship between cc and SN*

Figure 4.26 presents the plot of cc^* values corresponding to different levels of traffic and climatic regions. The plot indicates that the cc* values of thin sections located in WW and DW decrease slightly as the traffic changes from low to medium level. Further statistical analyses using Equation 4.21 showed that for L/18 greater than one, ECF gets lower with higher cc* values. Sections with smaller ECF will have longer service lives.

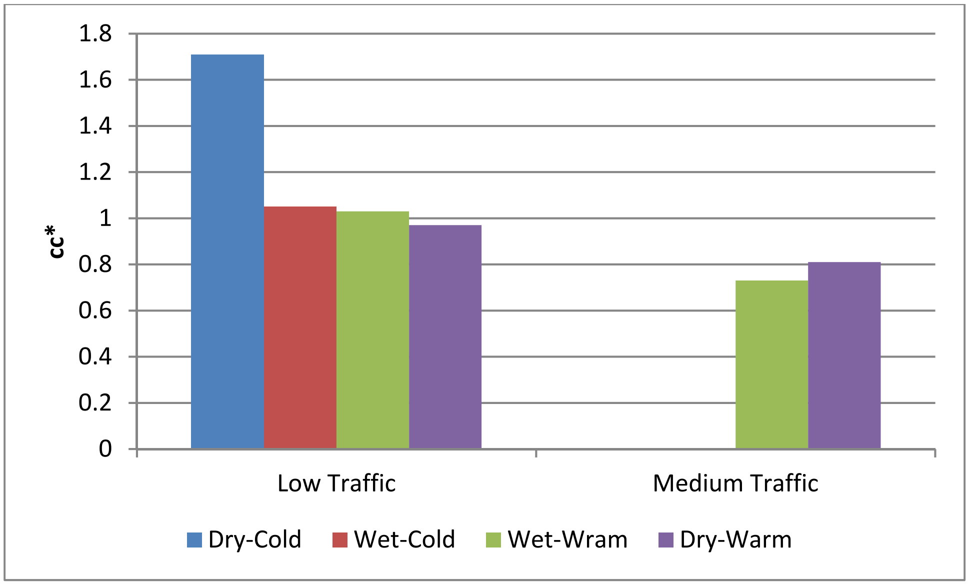


Figure 4.26 The value of "cc" based on rutting and thin HMA pavements*

Results for Cracking and Thin Asphalt Pavement

The development of $ECF_{Cracking}$ for thin pavement was undertaken using the same approach as that for rutting. Following are the average values for the parameter b obtained using cracking data:

- Single Axles: $b_1 = 1.00$
- Tandem Axles: $b_2 = 1.84$
- Tridem Axles: $b_3 = 2.54$

Figure 4.27 presents the relationship between aa and cc. As can be seen in Figure 4.27, these two parameters have a strong relationship with an R-squared = 0.99. Using an exponential model, cc* was estimated. The relationship between cc* values and SN can be seen in Figure 4.28. This figure depicts two groups of sections, which are dispersed between SN =1 and SN = 5; Group 1 with cc* values around 0.1 and Group 2 with cc* values around 1.6. Group 1 contains 73% of sections. Various characteristics such as traffic, pavement material properties, and climate conditions were evaluated for these two groups. Since both groups include pavements with SN in the range of 1 to 5, SN could not be used as a variable to capture the difference between these two groups. By comparing two groups, it was also found that both groups include sections with different traffic levels. Therefore, traffic level does not affect cc*. In addition, there was no significant distinction in the type of soil and base of the projects of two groups. Furthermore, pavements of each group are located in various facility types. As a result, existing information did not help to find any notable feature between two groups.

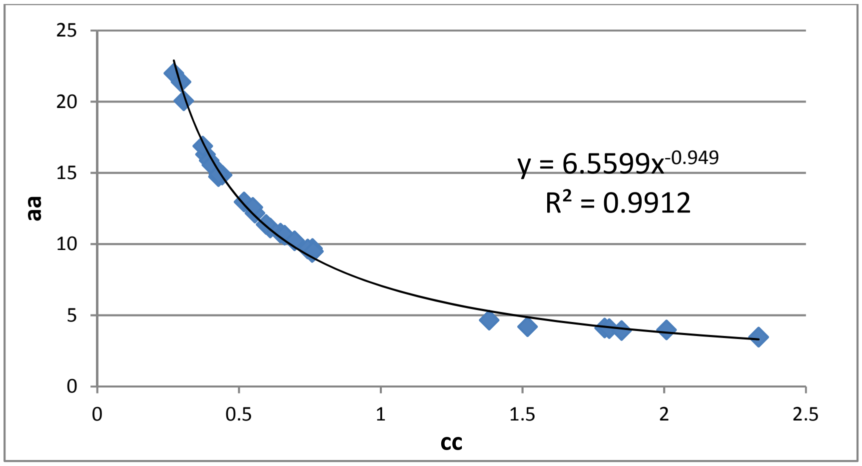


Figure 4.27 Relationship between "aa" and "cc" based on cracking and thin HMA pavement

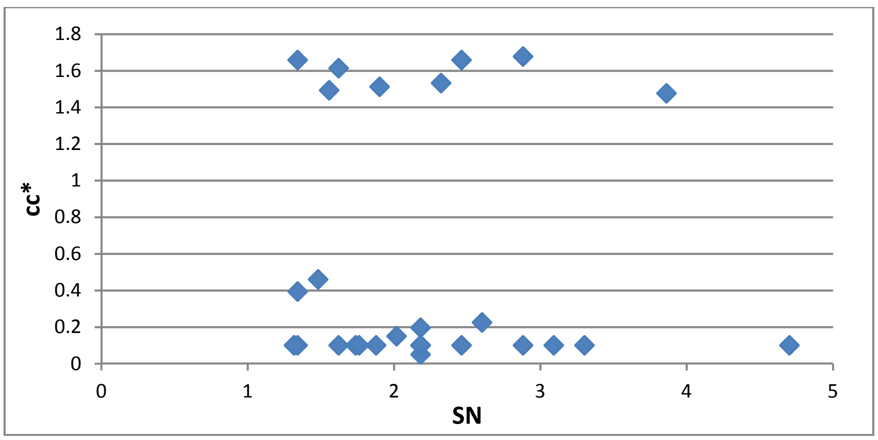


Figure 4.28 Relationship between "cc" and SN*

<u>Results for Roughness and Thin HMA Pavement</u>

To develop an ECF model for the roughness criterion for thin asphalt pavements, initial values of a, b, and c were calculated for each axle group separately. Subsequently, in the same manner as that for rutting and cracking mechanisms, the average values of b were calculated for different axle groups:

- Single axle group: $b_1 = 1.00$
- Tandem axle group: $b_2 = 1.74$
- Tridem axle group : $b_3 = 2.41$

Figure 4.29 shows the pairwise relationship between a and c values versus SN. Two groups can be differentiated from the a versus SN plots: Group 1 with a values less than one, and Group 2 with a values larger than one.

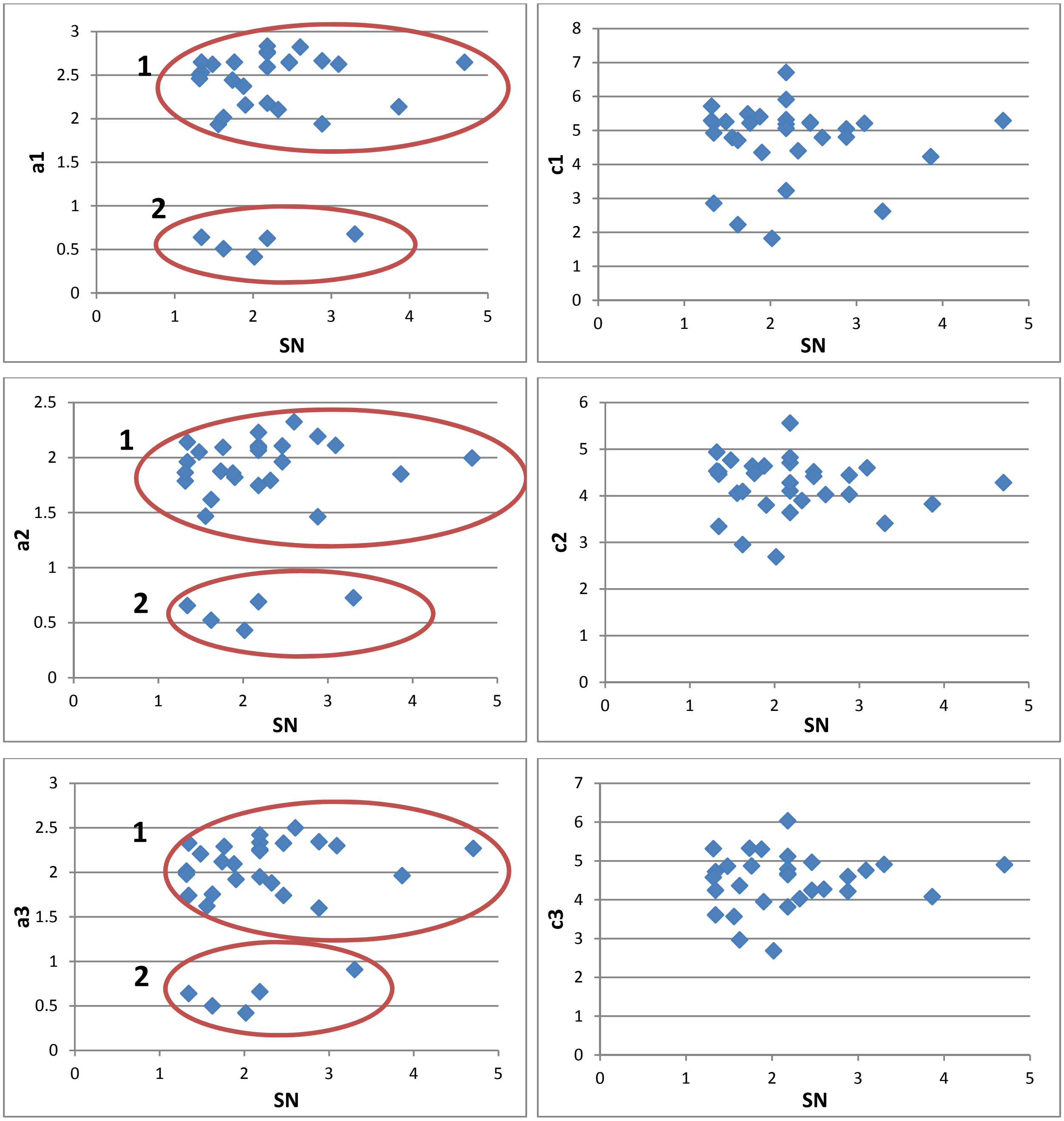


Figure 4.29 The relationship between "a", "c" and SN

These two groups were evaluated in terms of their characteristics such as weather condition, traffic levels, and facility type. This analysis did not result in any common feature between sections of each group. In addition, sections were plotted according to their latitude and longitude to assess any potential relationships between sections of each group. As Figure 4.30 indicates, latitude and longitude data of section could not be used as a distinctive indicator between Groups 1 and 2.

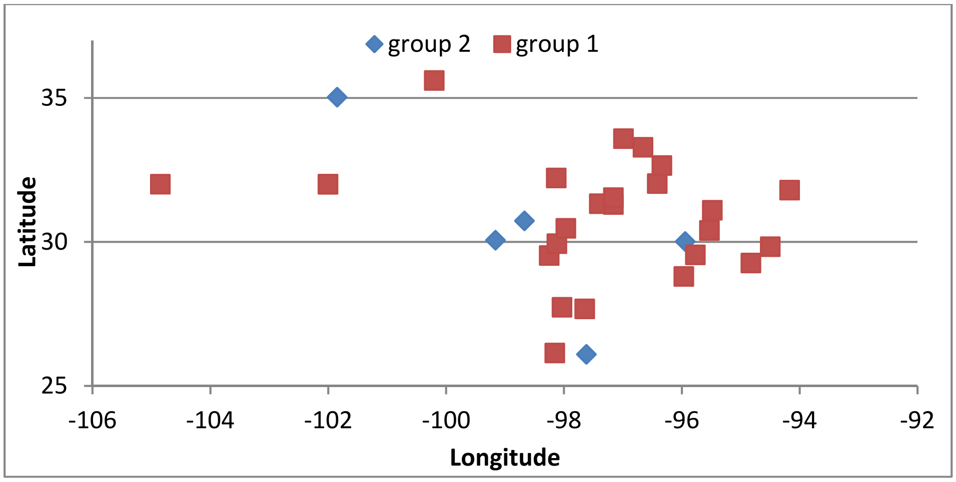


Figure 4.30 Latitude vs. longitude graph for groups 1 and group 2 defined in "a" graphs

<u>Relationships between ECF and Axle Loads for Concrete Pavements</u>

In the case of concrete pavements, the study team used the same approach for determining ECFs as that for asphalt pavements. However, it is important to note that different failure mechanisms should be used for rigid pavement consumption calculation. In addition, the research team used 30 years as the design life in the consumption analysis. The two failure criteria to evaluate ECFs for different axle loads and configurations on concrete pavements were:

- 1 punchout/mile, and
- 120 inches/mile of roughness in terms of IRI.

To determine, an ECF model for concrete pavements, the research team first calculated the ECF values for different axle loads and ten pavement sections. Two equations (Equations 4.22 and 4.23) were assessed for punchout and roughness failure criteria.

$$\mathbf{Ln\ ECF = a * Ln\ (\frac{\mathit{L}}{\mathit{b}*18})} \quad \textbf{(4.22)}$$

$$\mathbf{Ln\ ECF = a *\ (\frac{\mathit{L}}{\mathit{b}*18} - 1)} \quad \textbf{(4.23)}$$

It should be noted that it was not feasible to establish a unique equation that captures the effect for single, tandem and tridem axle groups; therefore, separate parameters were defined for each axle group:

- Single Axles: a_1, b_1
- Tandem Axles: a_2, b_2
- Tridem Axles: a_3, b_3

A comparative analysis of ECF values versus axle loads was used to assess the appropriateness of two proposed equations. The results showed that Equation 4.22 better captured this relationship. Likewise, the punchout results indicated that Equation 4.22 is an appropriate option to find the relationship between ECF and axle loads. Figure 4.31 and Figure 4.32 provide an example of the relationships between ECF values and the equations for roughness and punchout of a randomly selected section.

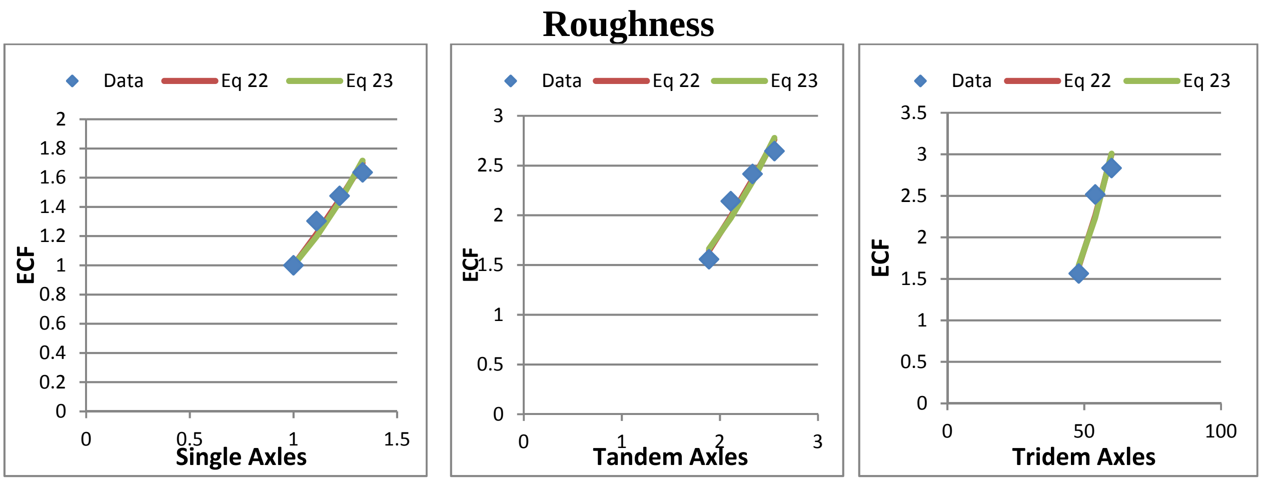


Figure 4.31 Two equations and $ECF_{Roughness}$ of a concrete pavement

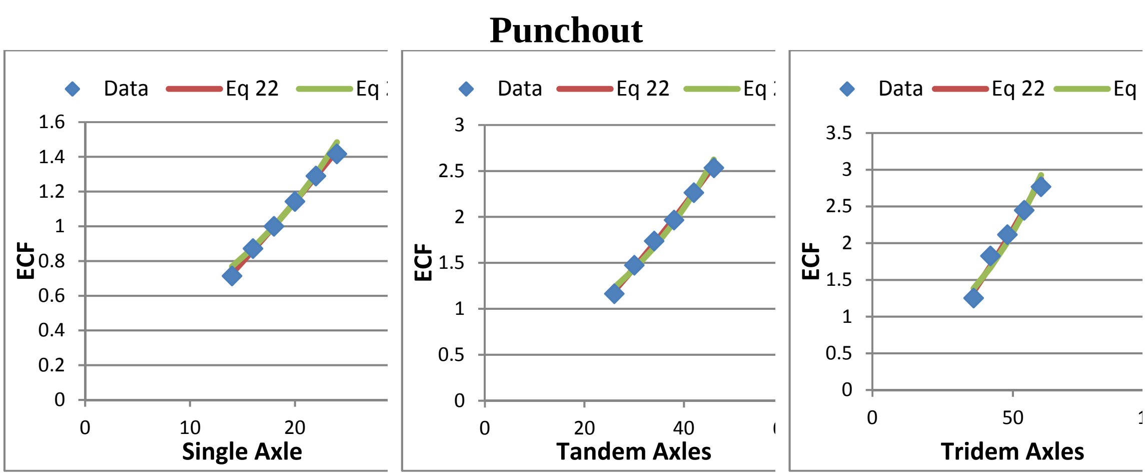


Figure 4.32 Two equations and $ECF_{Punchout}$ of a Concrete pavement

By applying non-linear optimization, parameters *a* and *b* for Equations 4.22 were found for all axle groups, pavement sections, and distress criteria. The next step was to find a general equation that could be applied to all axle load combinations. To this purpose, the relationship between parameters values and slab thickness (*D*) was investigated.

Results for Roughness

A number of scatter diagrams were produced and are provided in Figure 4.33 to depict the relationship between parameters and pavement thickness and also to illustrate the correlation between a_1, a_2, and a_3.

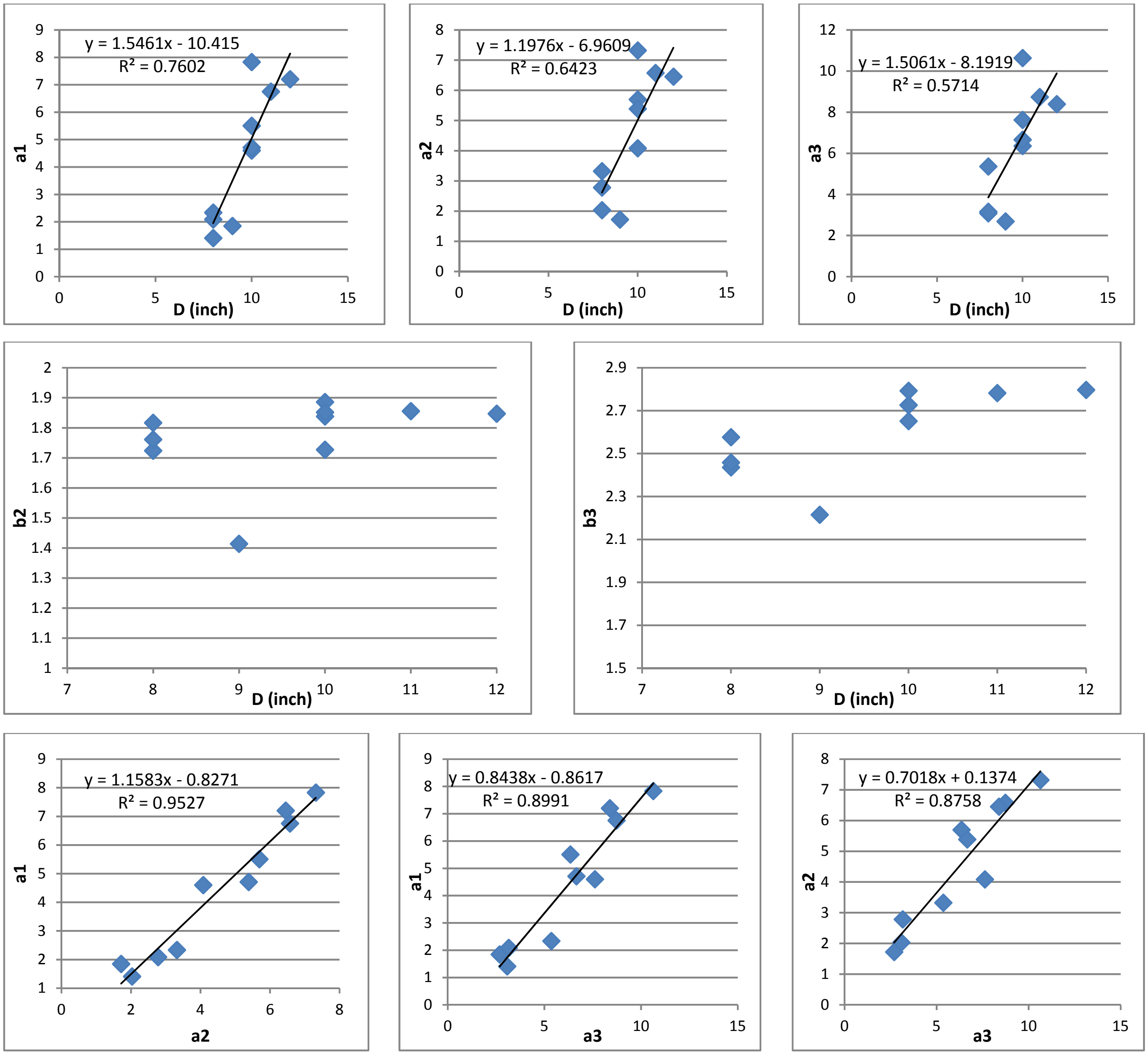


Figure 4.33 Relationships between parameters and correlation to slab thickness (D)

As shown in Figure 4.33, the parameter a corresponding to different axle groups are correlated. Furthermore, there is a linear relationship between the parameter *a* and the slab thickness *D*. Based on these trends, the ECF equation was modified to Equation 4.24:

$$\mathbf{Ln\ ECF = (E + F * D)\ Ln\ (\frac{L}{b_{1,2,3} * 18})} \qquad \mathbf{(4.24)}$$

In this equation:

D stands for the thickness of the concrete slab, and

E, F, and b are regression parameters.

Using Equation 4.24, unique values for E and F could be calculated for all axle groups. However, due to the lack of a significant correlation between b and slab thickness, three different values of the parameter b were defined for three axle groups:

- Single Axles: b1 =1.00
- Tandem Axles: b2
- Tridem Axles: b3

The parameters calculated for 10 sections are provided in Table 4.6. Relatively small differences between parameters' values for 10 rigid sections led the researchers to use the average of values of parameters to create the general ECF model.

Table 4.6 Model constants fo concrete sections based on rutting criterion

Section	E	F	b_1	b_2	b_3	D (inch)
1	0.92	0.11	1.00	1.48	1.96	9
2	0.98	0.38	1.00	1.79	2.58	10
3	0.95	0.14	1.00	1.73	2.35	8
4	0.99	0.47	1.00	1.84	2.64	10
5	0.99	0.54	1.00	1.87	2.73	11
6	0.99	0.42	1.00	1.87	2.65	10
7	0.95	0.19	1.00	1.80	2.38	8
8	0.99	0.51	1.00	1.88	2.76	12
9	0.97	0.29	1.00	1.76	2.44	8
10	0.97	0.71	1.00	1.88	2.73	10
	Average	Average	Average	Average	Average	
	0.972	0.378	1.00	1.792	2.524	

Following is the final equation for calculating the ECF for roughness criterion on rigid pavements:

$$\mathbf{Ln\ ECF = (0.971 + 0.378D)Ln\ (\frac{L}{b*18})} \qquad \mathbf{(4.25)}$$

Where,

- Single axle group: b = 1.00
- Tandem axle group: b= 1.79
- Tridem axle group: b= 2.52

Results for Punchout

An $ECF_{punchout}$ model for rigid pavements was developed using the same method as that for the $ECF_{Roughness}$ model. Figure 4.34 shows scatter plots of *a* versus *D*, *b* versus i, and also plots between a_1-a_2, a_2-a_3, and a_1-a_3.

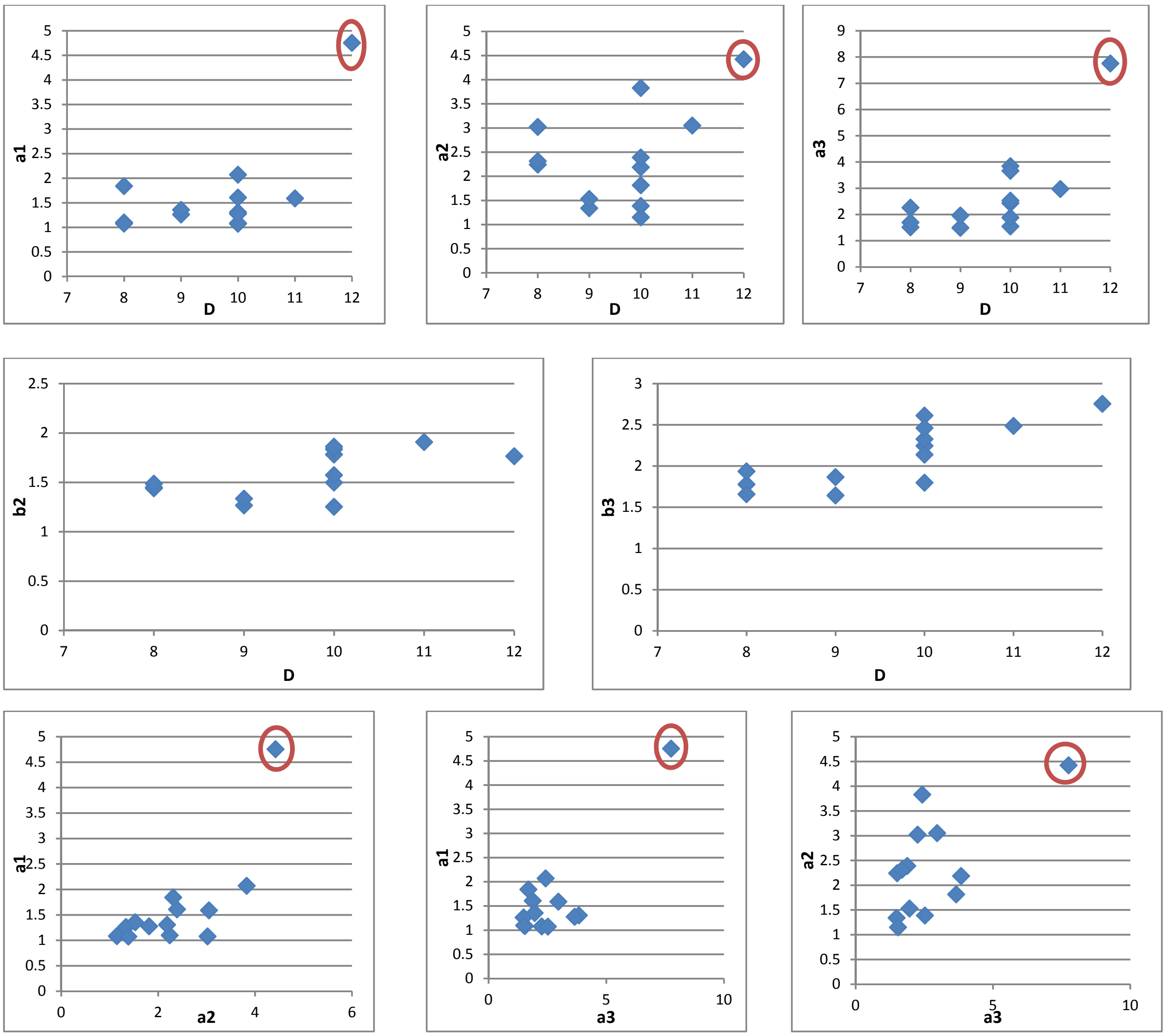


Figure 4.34 Relationships between parameters and their correlation to slab thickness (D)

In Figure 4.34, the discrepancy between one section and the rest of the sections could be observed. This section was considered an outlier and it was removed from the subsequent statistical analysis. Average values for *a* and *b* were calculated for different axle groups. Equation 4.26 shows the final relationship for ECF of punchout for rigid pavements:

$$\mathbf{Ln\ ECF = a\ Ln\ (\frac{L}{b*18})} \quad \textbf{(4.26)}$$

Where

L : axle load in kip, and

a and b : regression parameters as follows:

- Single Axles: a = 1.38, b = 1.00
- Tandem Axles: a = 2.18, b = 1.55
- Tridem Axles: a = 2.31, b = 2.00

4.3.4 Pavement Consumption of Alternative Truck Configurations

As mentioned earlier, the performance of a pavement structure is not specifically affected by the entire truck; rather, it is affected by the truck's individual axles or axle groups (tandem, tridem, or quad). Given that, the truck's ECF can be computed using the linear combination of ECF values of individual axles. As part of this research study, the research team compared the ECF of experimental truck configurations computed using Equation 4.1 with the summation of their axles' ECF. The ECF values were computed for all pavement structures with respect to three failure mechanisms: rutting, fatigue cracking, and roughness. For instance, truck configuration # 3, an OW truck loaded to 90,000 lbs., with 12,000 lbs. on the steering axle, 36,000 lbs. on tandem axle, and 42,000 lbs. on tridem axle, results in $ECF_{rutting}$ = 6.88 on a selected thick pavement. The summation of aforementioned axles' ECF results in 6.50. This example clearly shows that the overall pavement consumption due to a combination of different axles is equivalent to the sum of the consumption caused by each individual axle. A similar exercise was performed on each truck and asphalt section. Figure 4.35 provides graphic illustrations of the vehicles $ECF_{Rutting}$ and $ECF_{Cracking}$ against corresponding summation of axle's ECF. Similar approach was performed for roughness failure mechanisms. In the case of roughness, the research team found that data obtained do not follow the same pattern as rutting and cracking. In some cases, a significant difference was observed between the results of two aforementioned methodologies.

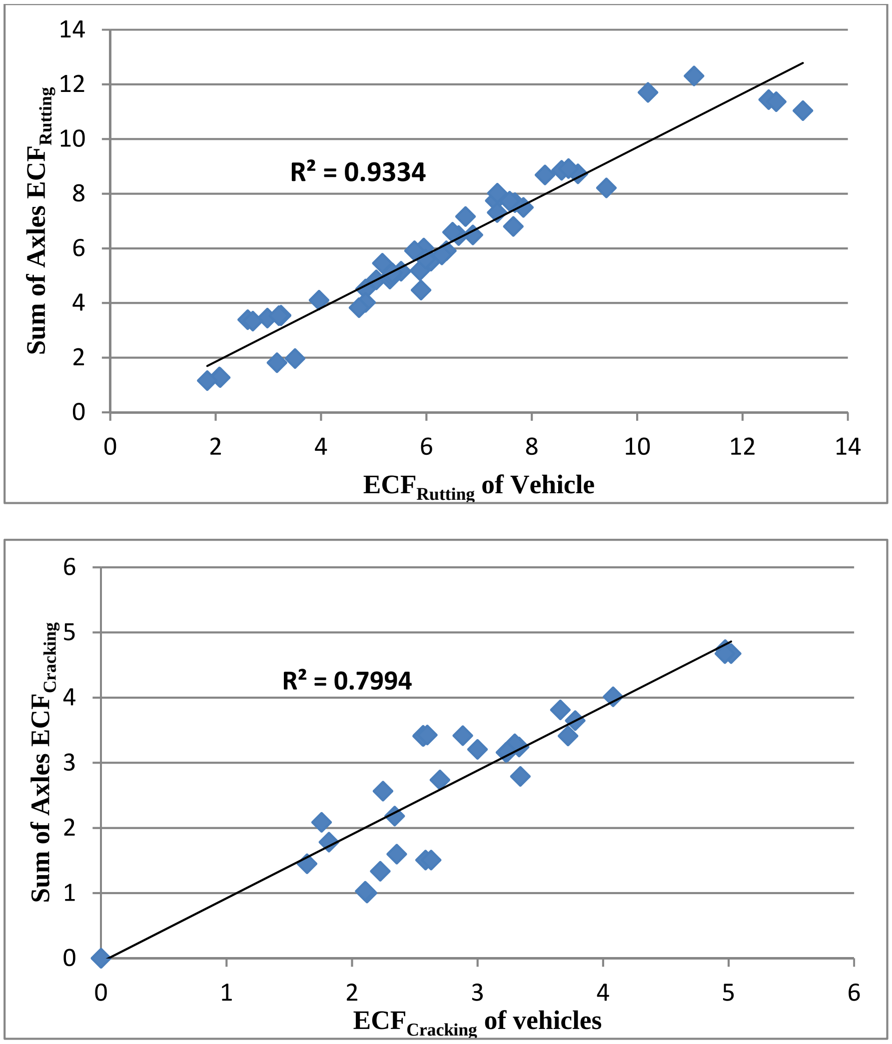


Figure 4.35 Equivalency between two methods for calculating a truck's ECF

4.4 Bridge Consumption

This section discusses the methodology the research team used to calculate the consumption different truck configurations cause to bridge structures. It also provides the results of bridge consumption cost analysis. The objective of this analysis is to provide an estimate of the bridge consumption cost for the identified truck configurations, by considering county, urban/rural area, and highway classification. It is to be noted that one of the truck configurations is the standard 18-wheeler (interstate semi-trailer at 80k GVW), which provides a baseline case for incremental cost calculations. The estimated costs are provided per one-way trip and per mile.

4.4.1 Bridge Consumption Methodology

The data available in the National Bridge Inventory (NBI)'s BRINSAP database allows for the application of simplified methodologies to estimate bridge consumption for load configurations at the policy level. Applying Equation 4.27 twice, once for the inventory rating load and again for the OS/OW permit load, and then subtracting one result from the other, one obtains Equation 4.28. At the policy level, it is not feasible to calculate actual stress ranges for bridge details. Digital descriptions of bridge cross sections and other characteristics are not available; even if they were, computational demands would make this task unfeasible within this project's time frame. An acceptable method successfully used in previous OS/OW studies involves using live load bending moments as surrogates for the stress range (Imbsen et al., 1987; Weissmann and Harrison, 1992; and Weissmann, et al., 2002). This approach substitutes the stress ranges in Equation 4.28 with bending moments, defining the bridge consumption ratio as depicted in Equation 4.29. Simply put, Equation 4.29 states that the bridge consumption ratio induced by a bending moment of an inventory rating load passage on a given bridge is equal to 1. Loads inducing bending moments twice as large as the inventory rating bending moment lead to a bridge consumption ratio of two to the power "m", where "m" is a function of the bridge material. Altry et al., 2003 and Overman et al., 1984, recommend "m" values that can be matched to the corresponding BRINSAP structure type codes.

$$logN = C - mlogS \quad \textbf{(4.27)}$$

Where

N-number of cycles or load applications
S-stress range
m- Constant: material dependent
C-Constant

$$\frac{N_{Inventory}}{N_{OSOW}} = \frac{S_{OSOW}^m}{S_{Inventory}^m} \quad \textbf{(4.28)}$$

Where

$N_{Inventory}$ – Number of load applications for the inventory rating load
N_{OSOW} – Number of load applications for the OS/OW load
$S_{Inventory}$ – Stress range for the inventory load
S_{OSOW} – Stress range for the OS/OW load
m – Constant: material dependent

$$ConsumptionRatio = \left(\frac{M_{OSOW}}{M_{Inventory}}\right)^m \quad \textbf{(4.29)}$$

Where:

MInventory – Live load bending moment for the inventory rating load
MOSOW – Live load bending moment for the OS/OW load
m – Constant: material dependent

The bridge consumption in dollars due to the passage of a given load is estimated by using Equation 4.29 combined with a consumable asset value for the bridge. The recently completed Federal Truck Size and Weight study recommends that the current asset value of a bridge is $235 per square foot of deck area. Previous highway cost allocation studies established that the asset value of a bridge should be allocated according to Table

4.7, with 11% of the bridge asset value attributable to loads that are over HS20-44 (FHWA, 2000). HS20-44 is a standardized bridge design load, and current bridge inventory ratings are usually represented as multiples of the HS20 design load when recorded in NBI/BRINSAP.

Table 4.7 Bridge asset value percentages for GVW Categories

Vehicle Class	Percent Allocation
Passenger Vehicles	65.02%
Trucks	
Single Unit	7.67%
Combinations	
under 50 kips	2.68%
50 - 70 kips	5.15%
70 - 75 kips	8.41%
Over HS20-44 Loading	11.08%
TOTAL =	**100.00%**

With the help of computerized routines, Equation 4.30 is applied on a bridge-by-bridge basis to all bridges in each county, urban/rural area, and highway classification used in this analysis. Bridge asset consumption results for each bridge are summarized and aggregated to determine an overall cost for a given mileage of a given highway class in a given area of a given county. This is divided by the mileage to get a cost-per-mile for bridge consumption.

$$Consumption_{OSOW} = [(Area)(235)(0.11)\left[\frac{M_{OSOW}}{M_{Inventory}})^{m}\right]] \div (2{,}000{,}000) \quad \textbf{(4.30)}$$

Where

$M_{Inventory}$ - Live load bending moment for the inventory rating load
M_{OSOW} - Live load bending moment for the OS/OW load
m - Constant: material dependent
235 - Asset value for a bridge in dollars per bridge deck square foot
0.11 – The bridge asset value responsibility for heavy trucks (see Table 4.7)
2,000,000 – Number of allowable load cycles that define bridge design life according to the AASHTO.

The computer program Moment Analysis of Structures (MOANSTR) is used to calculate live load moment ratios required by Equation 4.30. The MOANSTR program's core is a finite differences routine that calculates live load moment envelopes generated by OS/OW configurations and NBI/BRINSAP rating loads. The MOANSTR routine, developed by members of the UTSA research team, incorporates previous research by Matlock (Matlock et al. 1986) and others (Weissmann and Harrison, 1992 and Weismann et al. 2002). MOANSTR calculates moment envelopes and identifies the maximum live load bending moments (positive and negative) induced by the OSOW configuration and the inventory rating load.

4.4.2 Data Preparation

The steps listed below summarize the data preparation that was necessary to obtain mileages, assign a consistent highway classification as well as urban/rural area to each bridge, and arrive at the cost results previously discussed.

Step 1: Assign a consistent urban/rural classification to each bridge.
First, urban/rural classifications were retrieved from both RHiNo and BRINSAP, using their functional system variables. Urban/rural classification using the "functional_system" RHiNo variable does always not match the urban/rural classification using BRINSAP's equivalent variable, which is item 26/26A of the coding guide. It was necessary to resolve all inconsistencies.

Step 2: Develop a highway classification system that is consistent between RHiNo and BRINSAP.
First, it was necessary to assign a RHiNo classification to each bridge. As depicted in Table 4.8, highway classifications in RHiNo do not always match those used in BRINSAP (items 5.2 or 5.2A, depending on whether the bridge is located on the inventory route or passes under it). Every time the two classifications did not match, GIS was used to assign to the bridge the same classification as the RHiNo segment where each it is located.

Table 4.8 RHiNo and BRINSAP On-System Highway Classifications

RHiNo Variable Value	Highway Classification	BRINSAP Variable Value	Highway Classification
BF	Business FM	25	Business IH
BI	Business IH	27	Business SH
BS	Business SH	26	Business US
BU	Business US	41	Federal Lands Road
FM	FM	15	FM/RM
FS	FM Spur	11	IH
IH	IH	24	NASA1
PA	Principal Arterial	19/99	Other
PR	Park Road	16	Park Road
RE	Recreational Road	17	Recreational Road/Spur
RM	RM	13	SH
RR	Ranch Road	14	SL or Spur
RS	RM Spur	51	State Lands Road
SH	SH	20	Toll Road
SL	SL	12	US Spur
SS	State Spur		
UA	US Alt.		
UP	US Spur		
US	US		

Once each bridge had a RHiNo classification, the following was done:

- Using RHiNo, determine the total centerline mileage within each county and urban/rural area for each highway classification.
- Using BRINSAP and the RHiNo highway classification of each bridge, determine the number of bridges in each county, urban/rural area, and each RHiNo highway classification.
- Not every area in each county actually had bridges in each RHiNo classification; thus, it was necessary to aggregate some classifications to ensure meaningful results (see Table 4.9).

Step 3: Identify and eliminate from the analysis parallel bridges, culverts, and tunnels.

BRINSAP has variables identifying these situations. Culverts and tunnels are straightforward, and so is travel direction. However, an additional data treatment was necessary to eliminate parallel bridges in the same traffic direction, which are sometimes present. BRINSAP item 101 was used but several cases had to be visually checked in online maps and pictures using the geographical coordinates of the bridge. The data treatment to eliminate all parallel bridges was necessary due to the nature of the RHiNo data format that reports centerline mileage. Considering more than one parallel bridge in the same location to calculate the consumption due to one truck pass would artificially increase the cost.

Step 4: Calculate the bridge consumption of all on-system bridges.
The previous steps resulted in an analysis database with all pertinent BRINSAP variables, the aggregated highway classification developed as described in step 2, an urban/rural area consistent with RHiNo, and no parallel structures or structures other than on-system bridges. This database was used to calculate the moment ratio and costs for each bridge, which were then added up by highway classification, area, and county, to obtain the final results reported in the spreadsheets which will be discussed in the next section (see Figure 4.36 and Figure 4.37).

4.4.3 Results Description

Urban/rural information comes from RHiNo 2013, data item "functional system." As mentioned earlier, the highway classifications had to be grouped in similar classes, in order to ensure a representative number of bridges in each county, urban/rural area, and highway class. Table 4.9 shows the aggregated classifications used in this analysis, with an explanation and the RHiNo classification comprised.

Table 4.9 Highway classes used in the bridge analysis

Bridge Analysis Classification	Comprises	
	Description	*RHiNo 2013 Classification*
FM/RM/PR	FM-RM-RR-PR-Rec. Roads and their spurs	FM,FS,PR,RE,RM,RR,RS
IH	IH main lanes and frontage road segments with bridges	IH
SH	State highways	SH
SL/SS/BR/OSA	State loops, State spurs, their business roads, and all on-system arterials.	BF,BI,BS,BU,PA,SL,SS
US	US highways, alternatives, and spurs	US,UP,UA

The bridge consumption results were provided as one Excel workbook per vehicle configuration. All workbooks have two sheets. The sheet titled "lookup by county" contains the following:

1) The first two columns of Table 4.1 above,
2) A sketch of the truck configuration,
3) The percent of bridge statewide exceeding the operating rating for that configuration, and
4) A summary (pivot) table where the user can select a county and retrieve the configuration's bridge consumption cost per mile per (one-way) trip.

Figure 4.36 illustrates a screen capture of the summary table for Bexar County. It is very important to note two Excel pivot table features:

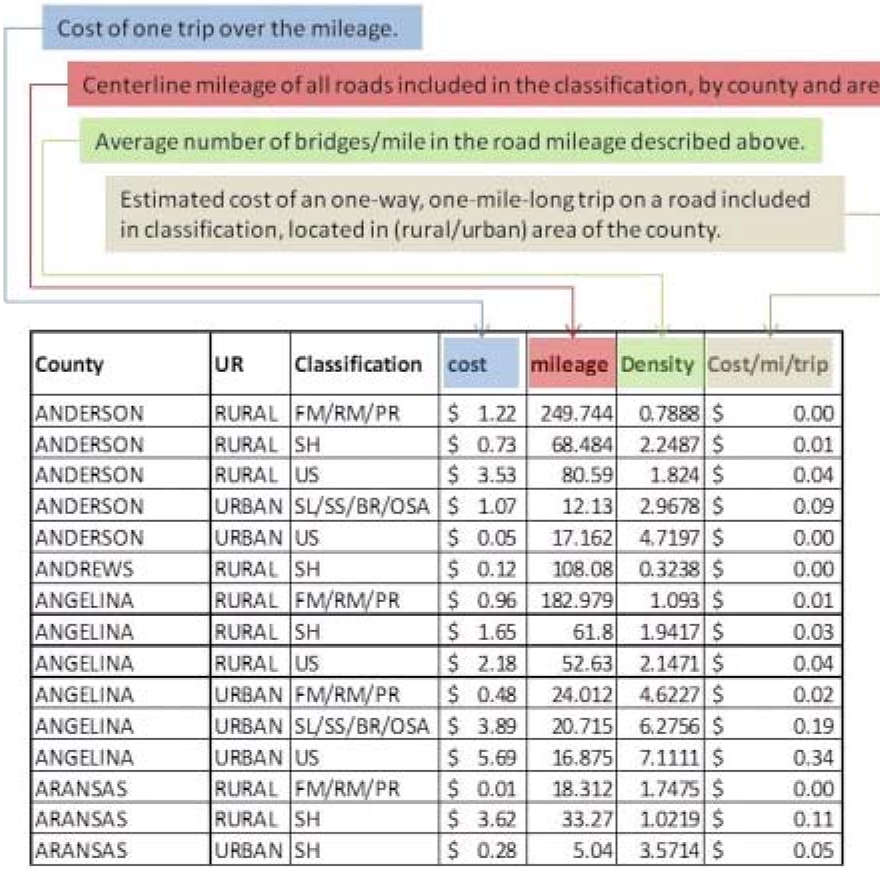
1) Some new versions of Excel no longer automatically update the pivot table after selecting a new option; it may be necessary to refresh it every time a new county is selected.
2) Excel pivot table gives correct results ONLY for each county. Choosing the option "all" DOES NOT give correct statewide results, due to the way Excel automatically calculates pivot tables. If the user desires to results aggregated in any way other than county (such as TxDOT District or statewide), s/he should go to the data sheet with complete results (discussed next).

Select county	BEXAR	
Cost/mile/trip	Area	
Classification	RURAL	URBAN
FM/RM/PR	$ 0.02	$ 0.03
IH	$ 0.07	$ 0.74
SH	$ 0.06	$ 0.29
SL/SS/BR/OSA	$ 0.03	$ 0.15
US	$ 0.03	$ 0.49

Figure 4.36 Screen capture of the data summary by county

The other sheet in each workbook is titled after the configuration number. It contains a table with 1187 data rows and a sketch of the vehicle configuration. Figure 4.37 shows a partial screen capture of the data with a detailed explanation of the data columns.

The cost of any specific one-way route can be estimated by multiplying the unit cost by the route mileage, taking care to match highway class, and urban/rural area. For round trip, double the cost. If a route contains a segment with multiple highway classifications, the highest classification should be used. When estimating a route cost, is important to assign each route segment to its proper urban or rural area. The average costs generally are considerably different due to the higher bridge density in urban areas.



County	UR	Classification	cost	mileage	Density	Cost/mi/trip
ANDERSON	RURAL	FM/RM/PR	$ 1.22	249.744	0.7888	$ 0.00
ANDERSON	RURAL	SH	$ 0.73	68.484	2.2487	$ 0.01
ANDERSON	RURAL	US	$ 3.53	80.59	1.824	$ 0.04
ANDERSON	URBAN	SL/SS/BR/OSA	$ 1.07	12.13	2.9678	$ 0.09
ANDERSON	URBAN	US	$ 0.05	17.162	4.7197	$ 0.00
ANDREWS	RURAL	SH	$ 0.12	108.08	0.3238	$ 0.00
ANGELINA	RURAL	FM/RM/PR	$ 0.96	182.979	1.093	$ 0.01
ANGELINA	RURAL	SH	$ 1.65	61.8	1.9417	$ 0.03
ANGELINA	RURAL	US	$ 2.18	52.63	2.1471	$ 0.04
ANGELINA	URBAN	FM/RM/PR	$ 0.48	24.012	4.6227	$ 0.02
ANGELINA	URBAN	SL/SS/BR/OSA	$ 3.89	20.715	6.2756	$ 0.19
ANGELINA	URBAN	US	$ 5.69	16.875	7.1111	$ 0.34
ARANSAS	RURAL	FM/RM/PR	$ 0.01	18.312	1.7475	$ 0.00
ARANSAS	RURAL	SH	$ 3.62	33.27	1.0219	$ 0.11
ARANSAS	URBAN	SH	$ 0.28	5.04	3.5714	$ 0.05

Figure 4.37 Sample of the Excel sheet with 1187 data rows

In summary, the product of the bridge consumption analysis is a network level bridge consumption cost per VMT by county, urban/rural area, and the aggregated highway class depicted in Table 4.9. It provides a useful tool to estimate the bridge consumption costs of different truck configurations for any given route in any county; nevertheless, such estimates are less accurate than a project level analysis of specific routes or corridors, basically for two reasons:

1) A corridor or route analysis calculates each specific bridge consumption cost rather than use average costs by factorial cells, and

2) The network-level analysis presented here depends on averages by highway class, area, and county, which in turn required resolving some inconsistencies among RHiNo and BRINSAP based on network-level type of reasoning and/or judgment, as previously discussed. This does not occur in a route-specific analysis where each individual bridge is considered.

4.5 Comparative Analysis

In this section, a comparative analysis was performed to identify infrastructure friendlier vehicle configurations from both pavement and bridge perspectives. The ECF values corresponding to different distresses were quantified and an average ECF value was calculated for each truck configuration by averaging the ECF values based on the three different distresses. In terms of bridges, statewide cost for each truck configuration was also obtained using the methodology explained in the previous section. Table 4.10 presents the ECFs and bridge cost of eighteen selected truck configurations.

In order to identify pavement-friendlier configuration, the research team first compared 21 alternative trucks using the ratio of ECF and bridge cost to those of base case which are named as pavement factor and bridge factor in Table 4.10, respectively. Furthermore, the research team compared the truck configurations based on pavement and bridge factors as a function of their GVW. Table 4.10 reports the ECFs, pavement and bridge factors, pavement and bridge factors per kips, and kips per pavement and bridge factor (%). The ECF values and bridge costs of the vehicles producing less damage than the base vehicle configuration are highlighted in red.

Figure 4.38 illustrates bridge and pavement factor values for the twenty one vehicle configurations evaluated. The figure shows GVW (kips) per bridge and pavement unit of consumption of the selected vehicle configurations. The pavement and bridge consumptions of the given vehicle are expressed relatively to that of base vehicle configuration are presented in Figure 4.40. These plots assist to identify the pavement friendlier vehicles. Figures 4.38 and 4.40 show that vehicles with IDs of 13, 15, 18 and 19 consume pavements and bridges at a lower rate than the base case and other vehicle configurations. Higher GVW per bridge/pavement consumption indicates infrastructure-friendlier trucks. According to Figure 4.39, vehicles with IDs of 13, 15, 18, and 19 are less damaging to pavements and bridges relative to the base case and other vehicle configurations. Vehicles 13, 15, 18, and 19 represent the LCV scenarios E, F, G, and G' respectively, which consist of more than one trailer. In summary, the results show that the LCVs consisting of two trailers are friendlier to the pavement and bridges compared to other truck configurations.

Table 4.10 Equivalent consumption factors and bridge cost for different vehicle configurations

Veh ID	#. Veh	GVW (lb)	ECF	Bridge Cost ($)	Bridge Factor	Pavement Factor	Bridge (kips/Cons)	Pavement (kips/Cons)	Bridge (Cons/kips)	Pavement (Cons/kips)
1	Base	80,000	3.97	3,447	1.00	1.00	80.0	80.0	1.25%	1.25%
2	2	88,000	5.86	4,874	1.41	1.48	62.2	59.6	1.61%	1.68%
3	3	90,000	4.02	5,237	1.52	1.01	59.2	88.9	1.69%	1.13%
4	4	90,000	5.30	5,803	1.68	1.34	53.5	67.4	1.87%	1.48%
5	5	97,000	6.09	8,378	2.43	1.53	39.9	63.2	2.51%	1.58%
6	5b	97,000	5.07	7,288	2.11	1.28	45.9	75.9	2.18%	1.32%
7	6	91,000	4.77	6,509	1.89	1.20	48.2	75.7	2.08%	1.32%
8	7	97,000	5.07	8,110	2.35	1.28	41.2	75.9	2.43%	1.32%
9	8	97,000	5.54	6,870	1.99	1.40	48.7	69.5	2.05%	1.44%
10	9	97,000	4.91	8,556	2.48	1.24	39.1	78.4	2.56%	1.28%
11	10	97,000	5.14	7,320	2.12	1.29	45.7	74.9	2.19%	1.33%
12	11	97,000	5.49	4,373	1.27	1.38	76.5	70.1	1.31%	1.43%
13	12	80,000	3.11	2,249	0.65	0.78	122.6	102.1	0.82%	0.98%
14	13	97,000	5.49	3,509	1.02	1.38	95.3	70.1	1.05%	1.43%
15	14	80,000	3.11	1,815	0.53	0.78	151.9	102.1	0.66%	0.98%
16	15	138,000	6.09	8,560	2.48	1.53	55.6	89.96	1.80%	1.11%
17	15a	138,000	6.09	7,067	2.05	1.53	67.3	89.9	1.49%	1.11%
18	16	90,000	1.84	1,950	0.57	0.46	159.1	194.2	0.63%	0.51%
19	16b	90,000	1.84	1,565	0.45	0.46	198.3	194.2	0.50%	0.51%
20	17	106,000	4.64	4,096	1.19	1.17	89.2	90.7	1.12%	1.10%
21	18	129,000	4.08	7,357	2.13	1.03	60.4	125.5	1.65%	0.80%

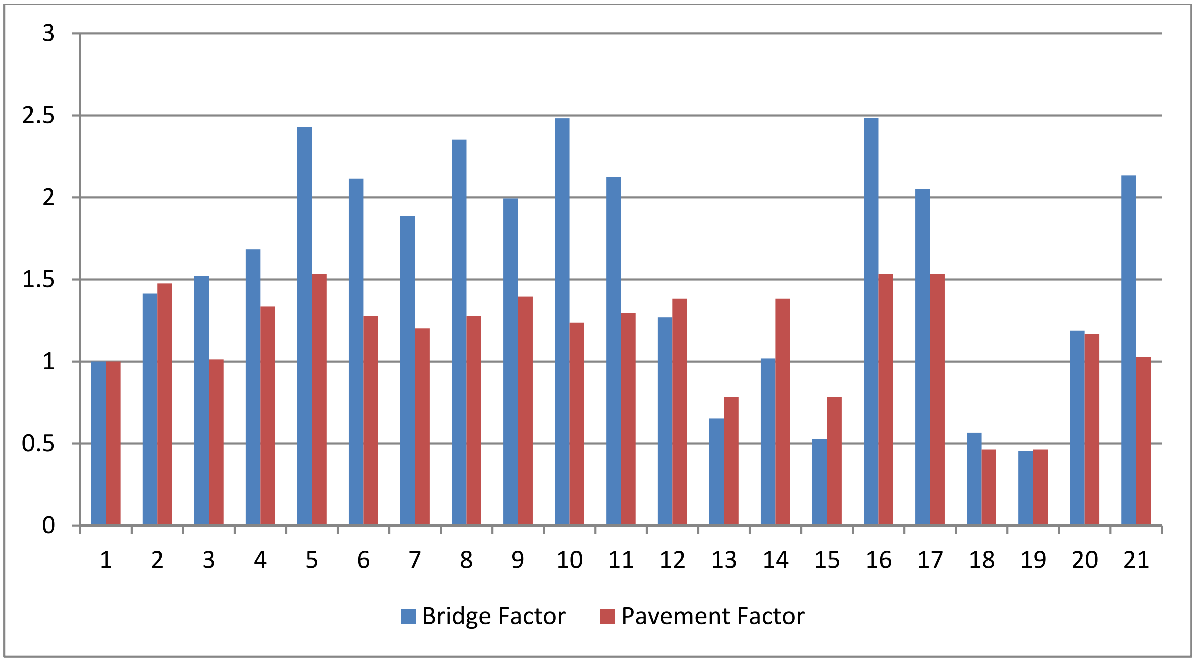


Figure 4.38 Bridge and pavement factor of vehicle configurations

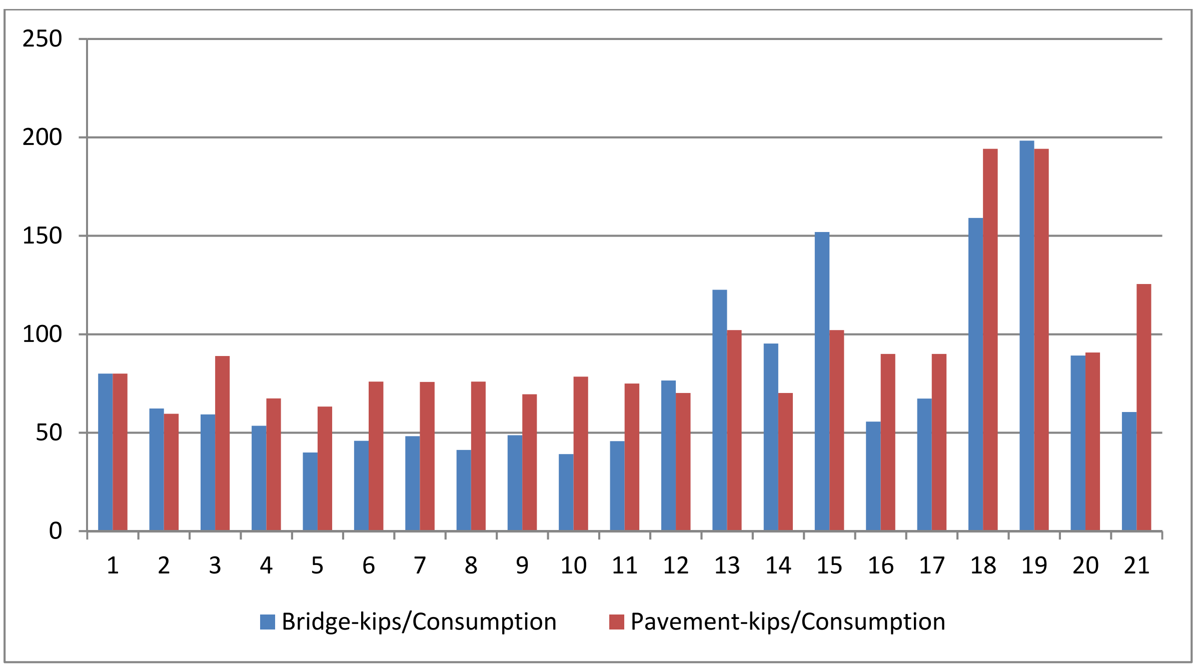


Figure 4.39 GVW (kips) per bridge and pavement consumption of vehicle configurations

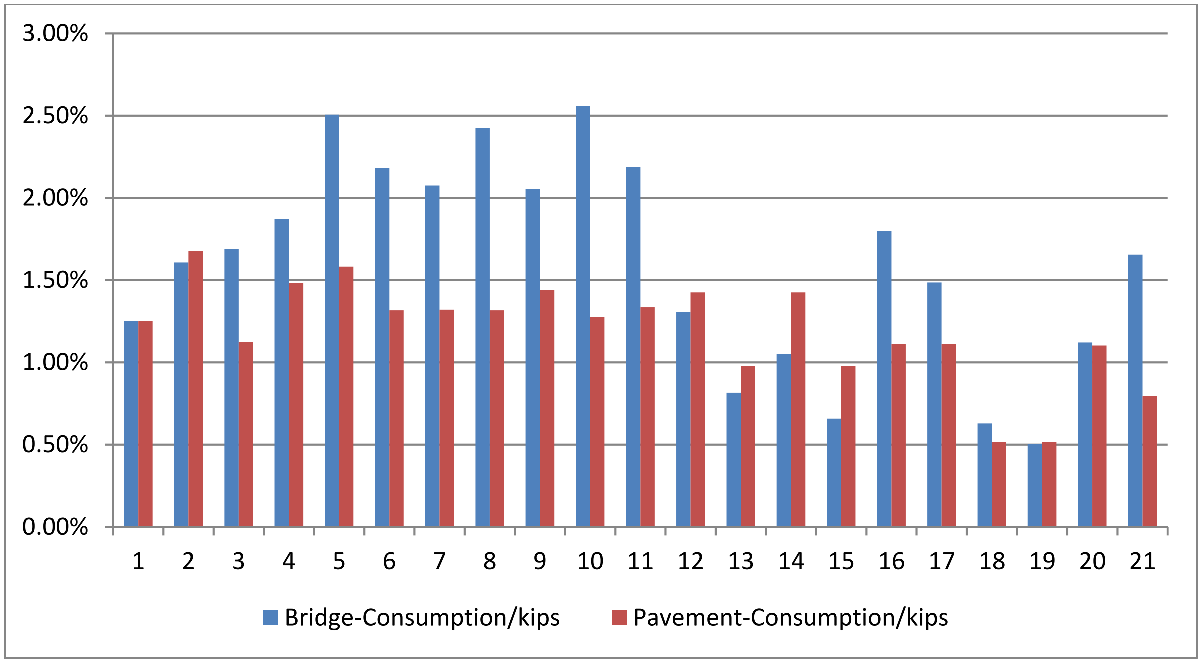


Figure 4.40 bridge and pavement consumption per GVW (kips) of vehicle configurations

Figure 4.41 shows the relationship between the bridge factor and the length of tractor-semitrailer. The graph shows that as the length of truck configurations increases, the bridge consumption factor decreases, and other factors such as axle type, axle distribution, and GVW remain the same. Note that the length does not significantly affect the ECF for pavements.

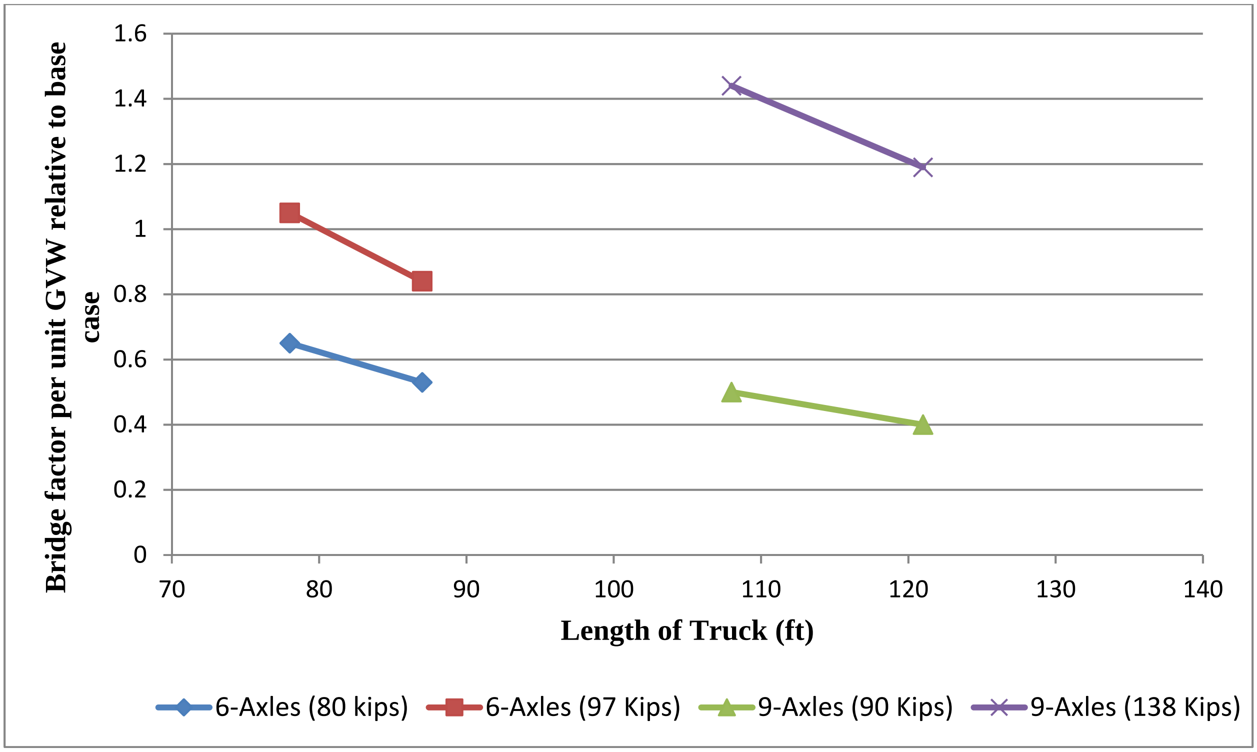


Figure 4.41 Relative bridge consumption per GVW vs. length

To find other potential infrastructure-friendly configurations, the bridge and pavement consumption factor of five-axle, six-axle, and nine-axle trucks were plotted versus their GVWs. Trucks with the same axle distribution were grouped together. Groups are labelled according to the number of axles and distribution of axles. Axle distributions provide the order (from front axle to rear axle) and type of axles. For instance, "S, Ta, Tr" represents a truck configuration containing a single steering axle, followed by a tandem, and a tridem axles. Figure 4.42 and Figure 4.43 report the bridge and pavement factor values of truck configurations in each group. A trendline of each group is provided on these figures. These graphical illustrations of pavement and bridge factors versus GVW help us find configurations that can carry loads heavier than 80 kips while producing relatively low damage to the surface transportation infrastructure relative to the base case (80 kips, five-axle truck). These results indicate that it is possible to design six-axle (S, Ta, S, S, S) and nine-axle (S, Ta, Ta, Ta, Ta) trucks carrying GVW within the range of 90 to 120 kips with pavement and bridge factors less than one. Trucks with pavement and bridge factors less than one consume pavements and bridges lesser than base case.

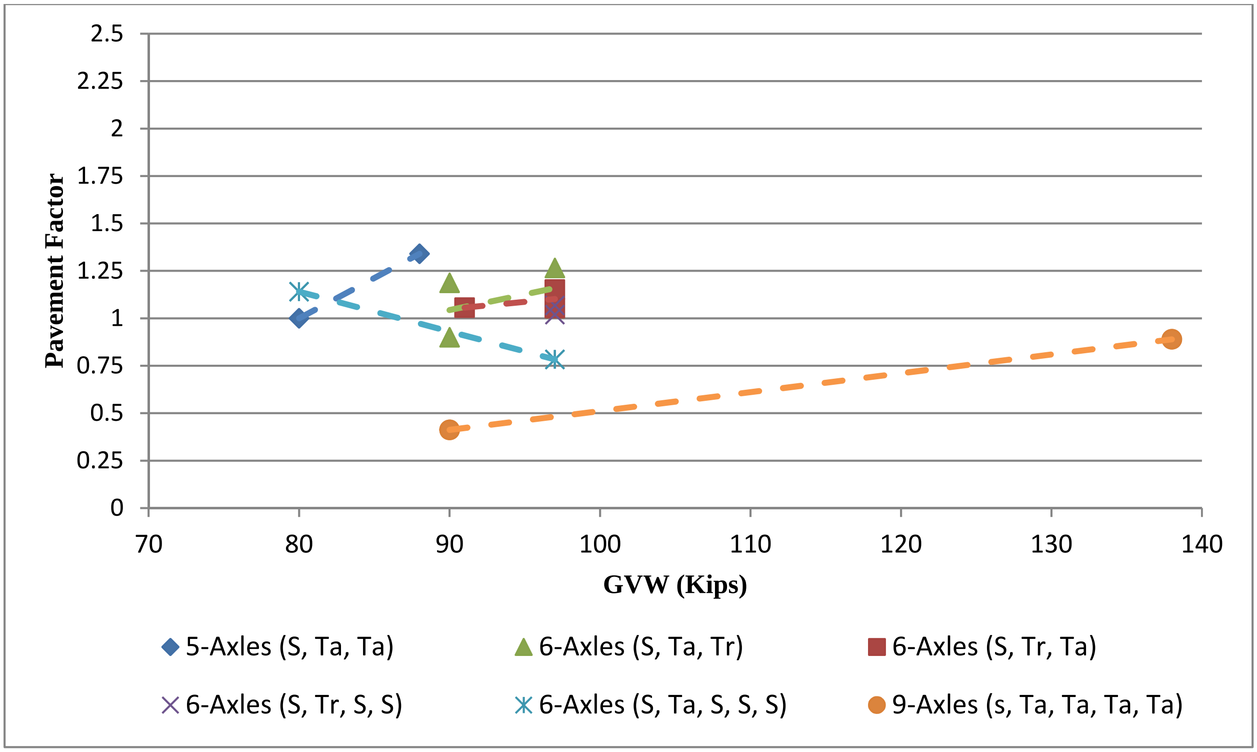


Figure 4.42 ECF per GVW (kips) of vehicle configurations relative to base case

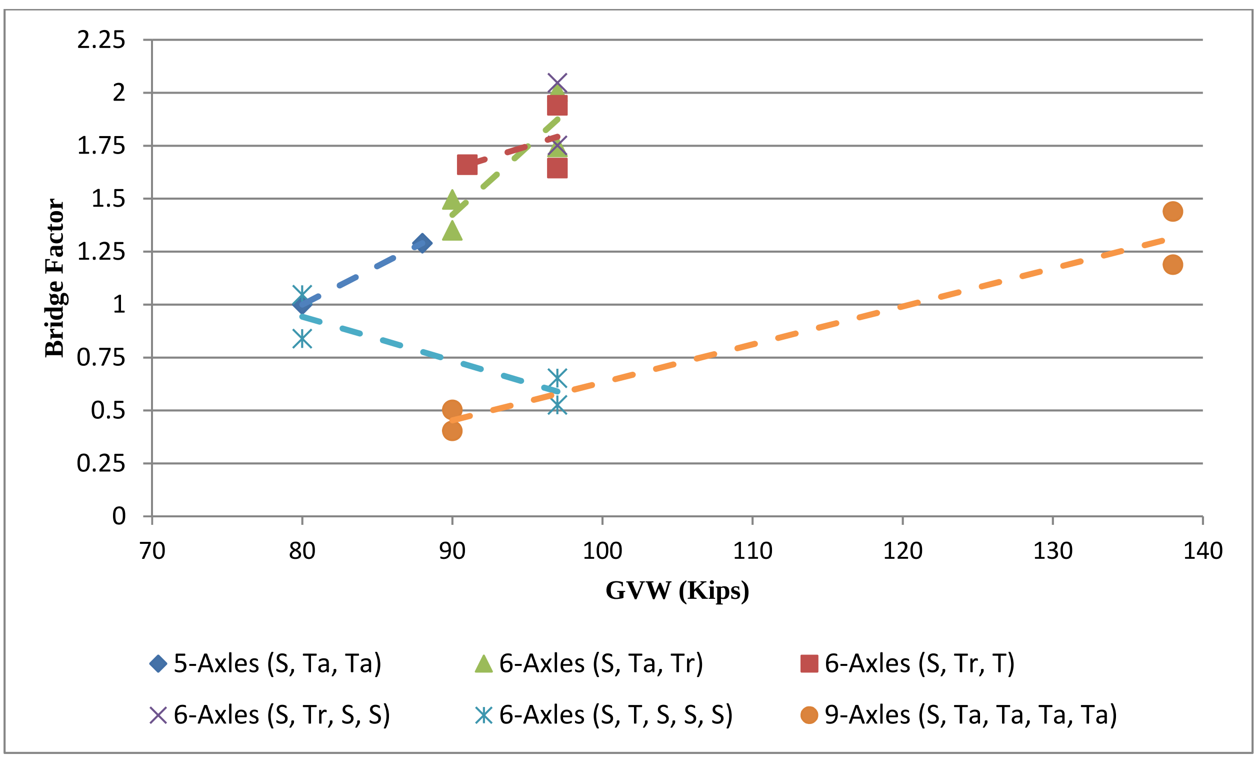


Figure 4.43 ECF per GVW (kips) of vehicle configurations relative to base case

Chapter 5. Cost Recovery Structure

5.1 Introduction

This section primarily focuses on cost recovery structures that fund repairs to roads used by OW vehicles. Although the axle groups and weights are configured to accommodate the increase in GVW, the OW vehicles can still cause increased pavement and bridge consumption rates and impose additional costs to the transportation network. Because of that, the primary objectives of this section are to:

- Review estimated costs imposed by use of OW vehicles and ways to allocate costs to different vehicle classes
- Explore cost recovery structures that can generate additional revenue to find pavement repairs needed due to accelerated consumption by OW vehicles. Review and summarize state use of weight-distance tax in the US, including:
  - State fuel taxes
  - OW truck permit fees
  - Truck registration fees
  - Truck sales tax
  - Truck tire sales taxes
  - Fully integrated privately operated electronic system that can recapture costs associated with operation of OW trucks associated with the oil and gas industry in the shale development regions of the state
  - Alternative tools such as vehicle-miles travelled fees and weight-miles fees (e.g., Kentucky, New Mexico, New York, Oregon)

The findings for these objectives are reported in this chapter as follows. This chapter briefly describes estimation of costs incurred as a result of OW vehicles on the roadways, the types of costs, and estimated costs considered, and then provides updates, where feasible, for those costs. This is followed by brief reviews of cost allocation approaches, since the estimated costs need to be allocated to the OW vehicles. In addition, this chapter explores potential cost recovery methods. It includes a summary of the research on weight-distance taxes in the US and internationally, provided in a table format describing how the tax- and fee-based methods recover costs and which states and countries use those recovery methods. Feasible cost recovery options are also presented in this chapter. The chapter's final section summarizes the researchers' exploration of the potential implementation of OW vehicle cost recovery methods on a specific freight corridor in Texas (a process detailed in project product 0-6817-P3, *Case Study Guidelines*).

5.2 Cost Estimation

5.2.1 Background

Cost estimation of the impacts of OW vehicles on Texas' roadways occurred in response to the 82nd Texas Legislature requiring TxDOT to conduct a study with the following goals:

- To evaluate increased pavement and bridge consumption by OS/OW vehicles
- To provide recommendations for permit fee and fee structure adjustments to the Governor and the Legislative Budget Board by December 2012

The Rider 36 Study (TxDOT Project 0-6736) had the following primary objectives:

- Evaluate current OS/OW activity (for both permitted and unpermitted loads) and routes to calculate the costs attributable to each vehicle configuration;
- Develop and implement an analysis framework of the bridge cost responsibilities of OS/OW loads by modeling bridge life consumption induced by permitted loads;
- Assess other cost elements associated with road safety and damage to appurtenances; and
- Develop an approach to analyze future OS/OW activity and calculate overall costs.

The Rider 36 report summarized the industry and stakeholder input, the pavement and bridge consumption cost methodologies, cost recovery methods, cost and revenue analyses, and permit fee and structure recommendations. This chapter highlights the costs considered and estimated (as well as those not considered) and the cost recovery methods reported in Rider 36. Where possible, the Rider 36 costs are reported along with updated costs.

5.2.2 Costs Considered and Estimated

The Rider 36 study focused on developing a cost recovery method based on pavement and bridge consumption caused by OW vehicles. The research team also estimated the costs associated with:

- infrastructure damage caused by vehicles exceeding the limit in width, height, or length (e.g., damage to bridges and traffic signals from being hit by large vehicles);
- administration and enforcement;
- litigation for damage claim cases referred to an attorney by the MCD.

Table 5.1 summarizes the estimated rates and the methodology used in the Rider 36 study for the costs considered in developing permit fees. The following section elaborates upon the estimated costs and estimation methodology for the pavement and bridge consumption rates since those are most applicable to OW vehicles.

Table 5.1 Cost rates considered in Rider 36 permit fee estimation

Cost	Units	Description of the Cost	Estimation Methodology
Pavement Consumption Rate	$/ESAL/VMT	Pavement consumption cost per loaded VMT for a specific load and vehicle configuration in the case of a routed single-trip permit or the normalized cost per loaded VMT for a non-routed or exempt vehicle.	Estimated additional costs to increase the thickness of the primary structural layer; apportioned to OS/OW fleet.
Bridge Consumption Rate	$/VMT	Bridge consumption cost per loaded VMT for a specific load and vehicle configuration in the case of a routed single-trip permit or the normalized cost per VMT for a non-routed or exempt vehicle.	Separated by routed and non-routed permits; calculated consumption for a given permit load across all bridges.
Overwidth Rate	$/VMT	Cost per VMT for a specific load and vehicle configuration that exceeds the legal width limits; rate dependent on overwidth categories.	Existing MCD rates; increases as width increases.
Overheight Rate	$/VMT	Cost per VMT for a specific load and vehicle configuration that exceeds the legal height limits; rate dependent on overheight categories.	Existing MCD rates; increases as height increases.
Overlength Rate	$/VMT	Cost per VMT for a specific load and vehicle configuration that exceeds the legal or typical design vehicle length limits; rate dependent on overlength categories.	Based on review of overlength LCV operations in other states; increases as length increases.
Apportioned Costs for TxDMV-MCD	$	Costs associated with development, implementation, continued maintenance, and upgrade of the TxPROS permit system, staffing, and salaries for MCD.	FY operating budget
Apportioned Costs for TxDMV Enforcement	$	Costs associated with DMV enforcement section operations, including investigations related to a pattern of OS/OW TxDPS citations for a given carrier.	Section budget
Apportioned Costs for TxDPS Commercial Vehicle Enforcement	$	Costs associated with TxDPS size and weight enforcement related to OS/OW vehicles.	FY operating budget

Cost	Units	Description of the Cost	Estimation Methodology
Apportioned Costs for TxDOT	$	Costs for bridge and sign bridge envelope surveys and other information related to OS/OW operations; infrastructure upgrades such as modifying or replacing a bridge to increase clearance or redesigning an intersection to accommodate OS/OW loads.	Estimated number of surveys, improvements, etc. X estimated cost/item.
Apportioned Costs for Office of Attorney General	$	Court costs associated with TxDOT property damage claims and DMV enforcement investigations related to OS/OW operations referred to an attorney.	Estimated number of yearly court cases X estimated attorney fees payable by TxDOT
Base Fee Paid to TxDOT	$	As established by state statute to compensate for reductions in other OS/OW registration or fee revenue sources redirected by the legislature.	N/A
Base Fee Paid to General Revenue	$	A portion of the base fee is currently paid to general revenue (Fund 1), non-apportioned.	N/A

Table 5.2 shows how the current TxDOT MCD single-trip mileage permits and quarterly hubometer permit fees are calculated (Prozzi et al., 2012, p. 165). Those types of permits are generally for cranes, oil well servicing equipment, and other vehicles that do not carry a load. For each permit, the actual mileage to be traveled is multiplied by the total rate per mile (calculated based on charges per mile for weights, width and heights over the legal limit) and then by three other items—the highway use factor, registration reduction, and indirect cost share.

As discussed in the Rider 36 Study, the 25% registration reduction is not applied in practice due to the complexity of determining the maximum allowable GVW for a vehicle and calculating the reduction factor. Additionally, the indirect cost share is determined by the state comptroller each year and accounts for statewide OS/OW support services.

Table 5.2 Current MCD cost recovery structure for single-trip mileage permits

Factor	Units	Description of the Factor
Actual Mileage to be Traveled	VMT	Vehicle miles traveled
X		
Highway Use Factor	--	A factor of 0.6 is applied for single-trip mileage permits and 0.3 for quarterly hubometer time permits.
X		
Registration Reduction	--	A 25% registration reduction if the permitted vehicle is registered for the maximum legal load.
X		
Total Rate per Mile	$/VMT	Charges per mile for weights, widths and heights over the legal limit.
X		
Indirect Cost Share	--	Determined by the state comptroller each year and is a flat rate.

The proposed new single-trip routed permit fee proposed in the Rider 36 Study is summarized in Equation 5.1:

$$\text{Total Permit Fee Cost} = \text{Consumption and infrastructure operations and safety impact costs} + \text{Apportioned costs and fees} \quad \textbf{(5.1)}$$

The total consumption cost is the total cost (in dollars) due to reduced pavement and bridge life. The infrastructure operations and safety impact costs are the total costs (in dollars) from operations and safety impacts due to the width, height, and length of the OS/OW load that exceeds legal or design vehicle limits. Each of the cost components in these two categories is presented in units of dollars per VMT or dollars per ESAL per vehicle mile. Each component is multiplied by the total VMT and a load factor to determine the final cost included in the permit fee. Table 5.2 summarizes each cost component and Table 5.3 summarizes the cost factors applied to each cost component in Table 5.2.

Table 5.3 Proposed MCD permit consumption, infrastructure operations and safety impact cost recovery components

Cost	Units
Pavement Consumption Rate	$/ESAL/VMT
+	
Bridge Consumption Rate	$/VMT
+	
Overwidth Rate	$/VMT
+	
Overheight Rate	$/VMT
+	
Overlength Rate	$/VMT

Table 5.4 Loaded VMT calculation

Factor	Units	Description of the Factor
Total VMT	VMT	The single-trip VMT while carrying the load or the estimated number of quarterly or annual VMT associated with a currently permitted, non-routed, or exempt OS/OW vehicle.
X		
Load Factor	--	A factor multiplied by the total VMT to determine the loaded VMT for permit fee calculations. For example, in the case of a truck that is loaded in one direction and returns empty, the factor = 0.5 x total VMT = loaded VMT.

Also included in the proposed single-trip routed permit fee are a number of apportioned costs and base fees, listed previously in Table 5.1. These cost components (in units of dollars) are included to incorporate costs that may not be directly considered in the current MCD permit fee structure, but are associated with OS/OW loads. The costs are the same for each permit in order to create a level playing field that distributes consumption and infrastructure operations and safe impact costs among all permit purchasers.

5.2.3 Costs Not Considered or Included

Literature review idenitifed the benefits and costs of operating vehicles with higher GVW but that do not increase pavement consumption because of axle configurations. The following potential costs and benefits (genereally, the externalities of the operation of the OW vehicles) were not considered in Rider 36 as costs to recover from use of OW vehicles:

- Change in number of trucks
    - Not always the case, since many permits are for non-divisible loads such as transformers or wind turbine blades, which cannot be divided among more trucks.

- Traffic safety (collisions with other vehicles on the road)
  - For example, during the TXTA Heavy Container Summit in Houston, Houston Police indicated they were against 97,000 lb containers since crash severity is significantly increased if an OW truck hits a car.
- Fuel consumption, energy efficiency, and air emissions
  - The less fuel consumed (due to fewer number of OW trucks with a higher fuel consumption rate consuming less fuel overall than more legal weight trucks with lower fuel consumption rate), the less revenue from fuel taxes, which results in fewer funds for highway maintanence. So although reducing fuel consumption for energy efficiency and air emissions is beneficial in an environmental sense, it does result in less funding.
- Mode diversion
- Industry costs (other than fuel, such as repairs and logistics)

A cost recovery method may consider include recovering those associated costs.

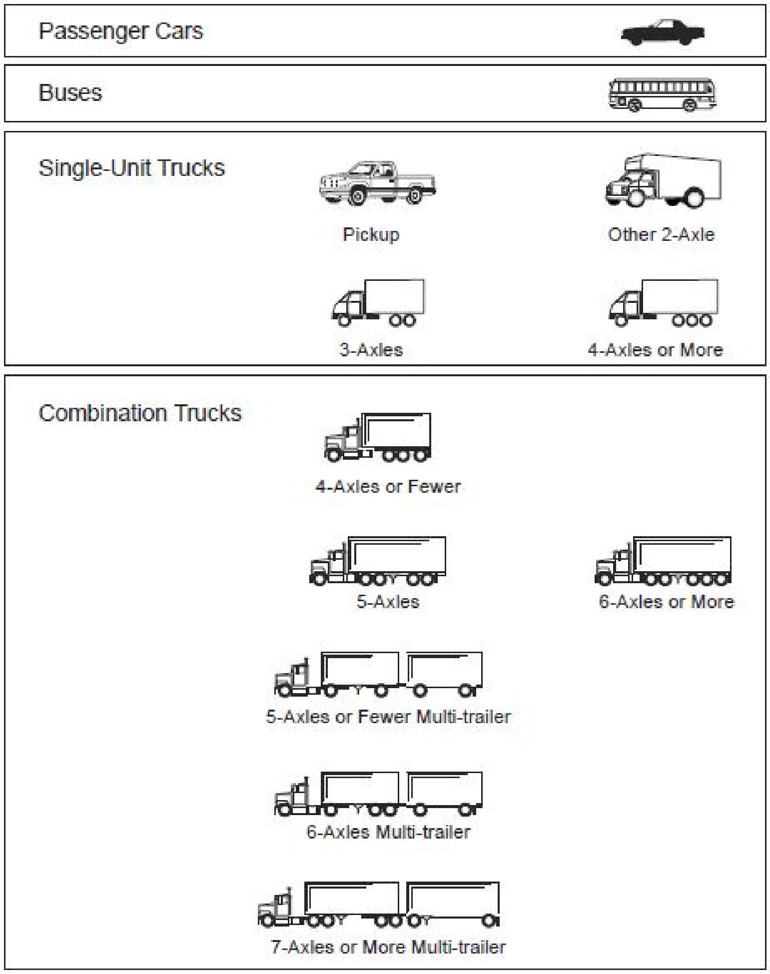
5.3 Cost Allocation Responsibility

5.3.1 Background

Cost allocation refers to the distribution of previously estimated infrastructure and highway costs across all vehicle classes. For the purposes of this study, the costs allocated to trucks that are over the federal and state of Texas legal limit of 80,000 GVW will be of most importance. This section reviews cost allocation options discussed in TxDOT and federal cost allocation studies and cost allocation options considered in the Rider 36 study.

5.3.2 Vehicle Classes

The most recent federal Highway Cost Allocation Study (HCAS) was completed in 1997 and allocated costs over 20 vehicle classes. A Texas HCAS was completed by the Center for Transportation Research in 2000 (revised October 2002). The Texas HCAS included 12 vehicle classes, represented in Figure 5.1.



Source: Luskin et al., 2000

Figure 5.1 Texas HCAS vehicle types

The Texas HCAS included passenger cars, buses, four classes of single-unit trucks (including a pickup truck), three classes of tractor-semitrailer combinations, and three classes of tractor-multi-trailer combinations. The 1997 federal HCAS included additional classes for truck-trailer combinations and additional truck classes based on number of axles.

5.3.3 Approach

The major motivation behind the completion of an HCAS is to establish and evaluate the fairness or equity in the share of highway system costs. The most common approach for cost allocation, named the cost-occasioned approach, was first adopted by the state of Oregon in 1937, but has now been used by the FHWA as well as nearly every state to perform an HCAS (NCHRP 2008). The underlying philosophy of the cost-occasioned approach is that each user (and therefore, each vehicle class) should pay the highway costs that it "occasions" or creates (FHWA 1997).

However, the cost-occasioned approach is limited to highway agency obligations and expenditures when distributing the costs across the various vehicle classes. A competing method, called the marginal cost approach, focuses instead on the economic cost of additional highway use increments by each vehicle class. In addition to the highway agency obligations and expenditures (represented as infrastructure costs), the marginal cost approach also considers environmental and other social costs (such as noise) occasioned by each vehicle class that are not represented in DOT budgets (FHWA 1997).

For both cost allocation methods, the costs related to construction of a base facility that serves as a capacity and traffic service for all vehicle types are separated from the costs required to provide the durability to carry projected traffic loadings over the pavement's design life (FHWA 1997). The allocation procedures for pavement and bridge construction and replacement costs are fairly streamlined. The Rider 36 estimated the pavement and bridge costs allocated to OS and OW vehicles.

The environmental and other social costs included in the 1997 FHWA federal HCAS were allocated to different vehicle classes using various methods. For example, construction costs for safety improvements were distributed based on passenger car equivalent (PCE)-weighted VMT while environmental enhancement costs were distributed based only on VMT. There are several costs that are occasioned only to trucks, such as costs of the commercial vehicle information systems project; motor carrier safety assistance program development and enforcement; commercial driver's license development and enforcement; truck sales; and truck loading, terminal, and transfer facilities.

5.3.4 OW Vehicles

Although neither the 1997 FHWA federal HCAS nor the Texas HCAS include a specific class of OW vehicles, the federal HCAS does perform analysis using various truck weights. The study computes the equity ratios for each vehicle class, calculated as the shares of revenue contributed by each vehicle class divided by the shares of highway costs that vehicle class occasions. An equity ratio of 1.0 indicates that the vehicle class in question pays exactly the amount of highway costs that it generates. A value greater than 1.0 indicates overpayment and a value less than 1.0 indicates underpayment of federal highway user fees.

The equity ratio for automobiles was calculated as 1.0 in the 1997 federal HCAS while the equity ratio for combination trucks was less than 1.0. Furthermore, the study concluded that combination trucks weighing less than 50,000 pounds will pay 60% more in user fees than their share of highway costs (equity ratio = 1.6), while combination trucks weighing over 80,000 pounds will pay only 60% of their share of highway costs (equity ratio = 0.6). The study included the following table (Table 5.5) summarizing the overpayment (recorded as positive) and underpayment (recorded as negative) of selected trucks.

Table 5.5 2000 Federal over and underpayment by selected vehicles

Table ES-4. 2000 Federal Over and Underpayment by Selected Vehicles								
	3-axle Single Units		4+ axle Single Units		5-axle Semitrailer		6-axle Semitrailer	
Registered Weight	Total (000s)	Per Vehicle	Total (000s)	Per Vehicle	Total (000s)	Per Vehicle	Total (000s)	Per Vehicle
20,000	$204	$244						
30,000	$7,956	$236	$29	$1,229				
40,000	$8,803	$151	$1,189	$1,122				
50,000	($32,519)	($116)	$307	$220	$12,945	$1,811	$235	$2,132
60,000	($164,588)	($634)	($18,448)	($816)	$43,594	$1,538	$1,414	$2,104
70,000	($119,386)	($2,059)	($88,205)	($2,039)	$20,372	$603	$2,732	$1,508
80,000	($7,207)	($3,260)	($143,292)	($2,966)	($591,971)	($561)	$27,370	$342
90,000			($18,367)	($3,672)	($109,044)	($3,864)	($21,286)	($2,188)
100,000			($9,057)	($4,193)	($17,987)	($5,176)	($41,391)	($4,985)
110,000					($9,389)	($6,022)	($33,239)	($7,746)
120,000							($67,497)	($10,710)
Total	($306,739)		($275,845)		($651,480)		($134,212)	

Source: FHWA 1997

As expected, the study also concluded that the cost responsibility (in cents per mile) was much greater for combination trucks than for automobiles or single unit trucks and that the cost responsibility increased with increasing registered weight for both single unit and combination trucks. Table 5.6 details the cost responsibility per mile for vehicles on both registered weight and operating weight bases. It should be noted that the cost responsibility on the basis of registered weight is lower than on the basis of operating weight since trucks will not be operating at their registered weights at all times (e.g., empty truck trips).

Table 5.6 2000 Comparison of federal cost responsibility on registered weight and operating weight basis

Table V-19. 2000 Comparison of Federal Cost Responsibility on Registered Weight and Operating Weight Basis		
	Cost Responsibility (cents per mile)	
Vehicle Class/ Registered Weight	Registered Weight Basis	Operating Weight Basis
Autos	0.65	0.65
Pickups and Vans	0.65	0.65
Buses	2.57	2.57
All Passenger Vehicles	0.66	0.66
Single Unit Trucks		
<25,000 pounds	1.75	1.81
25,001 - 50,000 pounds	4.38	6.26
>50,000 pounds	14.60	37.25
All Single Unit Trucks	3.51	3.51
Combination Trucks		
<50,000 pounds	2.78	2.42
50,001 - 70,000 pounds	4.25	5.50
70,001 - 75,000 pounds	6.25	9.50
75,001 - 80,000 pounds	7.08	12.36
80,001 - 100,000 pounds	12.50	20.57
>100,001 pounds	16.60	48.96
All Combinations	6.90	6.90
All Levels of Government Cost Allocation	5.48	5.48

Source: FHWA 1997

5.3.5 Rider 36 Cost Allocation

The research team for Rider 36 study explored different cost recovery methods and decided to pursue a consumption-based fee structure for OS/OW permits and to adopt a modified version of the proportional cost determination method for determining the OW permit fees. The proportional method allocates highway costs based on vehicular characteristics.

For the Rider 36 study, the research team decided to use the equivalent damage factor and equivalent consumption factor as the cost allocation vehicle characteristic for pavement consumption. Since pavements respond to axle loads, not the entire truck, equivalent damage and consumption takes in to account weights of individual axles and axle group configurations, which is used to determine pavement consumption. The cost recovery methodology is based on the assumption that the fees recover the cost of providing additional structure adequate to support OW loads, as an addition to the design traffic used by TxDOT to design the original pavement structure layer thicknesses and materials, such as increasing the thickness of the main structural course or improving material quality. From the results of the pavement cost allocation method, the Rider 36 research team proposed an average permit fee of 3.7¢ and 2.9¢/ESAL/mile on rigid and flexible pavements, respectively.

For bridge consumption, the Rider 36 research team chose to assume a $190 per square foot of deck area asset value of a bridge (an estimate from the Texas 2030 Committee report). Using previous highway cost allocation studies as a guide, 11% of the bridge asset value is attributable to heavy trucks (loads over HS20-44, a standardized bridge design load). Since it is not possible at the network level to estimate the actual stress ranges for each bridge in the system, the research team used an equation that multiplied the area (in sf) of the bridge multiplied by $190/sf and 0.11 (for the value attributable to heavy trucks) with the quotient from dividing the live load bending movement for the inventory (non-OW rating load) over the live load bending moment for the OS/OW set to the power of *m* selected based on the material of the bridge (e.g., concrete slab, steel continuous girder, and pre-stressed concrete beam). From this methodology emerged cost-per-bridge and cost-per-VMT estimates for routed and non-routed loads (Tables 5.7 and 5.8).

Table 5.7 Bridge consumption costs per mile (routed)

GVW Category	Miles	Bridge Consumption ($)	$/mile
80-120k	3,939,917	909,968	0.23
120-160k	1,104,370	416,613	0.38
160-200k	534,260	259,374	0.49
200-254k	239,610	214,603	0.90

Table 5.8 Bridge consumption costs per mile (non-routed)

Truck Type & Loaded Annual Mileage	Region	Randomly Assigned Miles	Total Bridge Consumption Cost ($)	$/mile
LP Gas Bobtail	West	34,700	2,224	0.064
	East	34,960	2,274	0.065
35,000 miles	*Average*			*0.065*
Ready Mix	West	22,453	2,058	0.092
	East	20,837	2,511	0.120
20,000 miles	*Average*			*0.106*
Garbage & Recycling	West	17,031	1,411	0.083
	East	16,165	1,943	0.120
17,000 miles	*Average*			*0.102*
Cotton Module	West	14,352	1,592	0.111
	East	14,004	2,414	0.172
15,000 miles	*Average*			*0.142*
Chilli Pepper Module	West	14,108	673	0.048
	East	14,420	1,191	0.083
15,000 miles	*Average*			*0.065*
Aggregate Hauler	West	44,553	2,070	0.046
	East	42,073	3,212	0.076
45,000 miles	*Average*			*0.061*
Grain Hauler	West	9,884	468	0.047
12% Statute	East	7,709	614	0.080
9,000 miles	*Average*			*0.064*
Grain Hauler	West	9,122	377	0.041
2060 Permit	East	7,709	577	0.075
9,000 miles	*Average*			*0.058*
Logging	West	36,561	1,038	0.028
	East	31,040	1,646	0.053
36,000 miles	*Average*			*0.041*
Milk	West	61,217	1,468	0.024
	East	62,025	2,892	0.047
63,000 miles	*Average*			*0.035*

5.4 Cost Recovery Methods

The previous sections reviewed the estimated costs of impacts of and methods to allocate costs to OW vehicles. This section reviews the following possible ways to recover the costs associated with the consumption of pavement and bridges, damage to infrastructure, and other impacts:

- State fuel taxes
- OW truck permit fees
- Truck registration fees
- Truck sales tax
- Truck tire sales taxes
- VMT and weight-miles fees
- Corridor truck fees

5.4.1 State Fuel Taxes

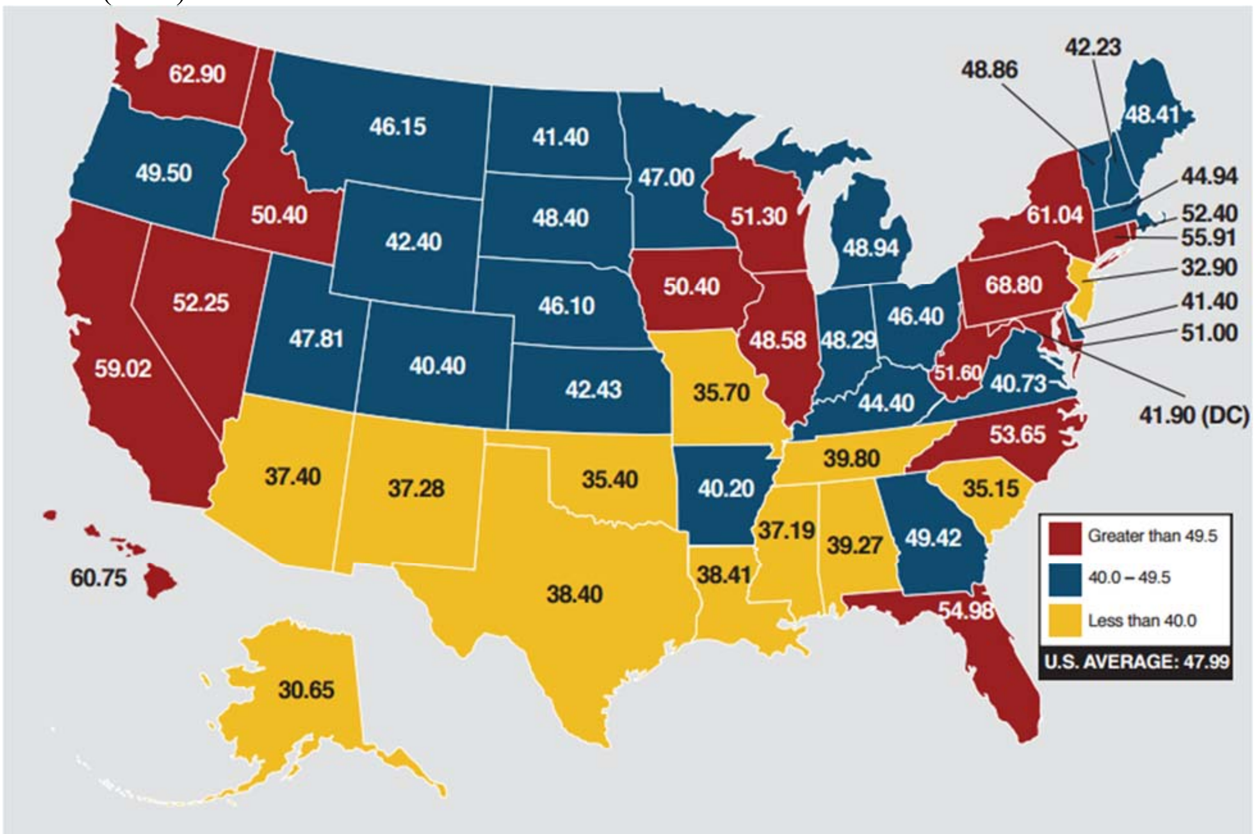
The State of Texas fuel tax is currently set at 20¢ per gallon of fuel, which is paid by every gasoline-powered motor vehicle operator regardless of vehicle type, size, weight, or configuration. In Texas, diesel fuel taxes are paid by the commercial distributor (gas station operator) at the bulk terminal at the time of purchase, but ultimately the truck operator pays the cost of the diesel fuel tax at the pump.

OW trucks would generate additional fuel tax revenue due to the increased fuel consumption required to carry the load; however, the increased consumption rate would necessarily be related to a number of factors not directly associated with the truck weight and resulting pavement damage. Thus, a 1995 Ford truck tractor with an inefficient engine and transmission and a worn drive train would likely not have the same fuel economy as a 2013 Volvo truck tractor with an engine and drive train designed for today's operating conditions. Differences in fuel economies of 1 mile per gallon can result in substantial differences in fuel taxes paid by the truck operator. In this example, therefore, a truck operator with an older, inefficient truck carrying exactly the same OW amount as a modern, more efficient truck tractor would most likely pay more in fuel taxes. This may be somewhat justified if the costs of mitigating the air quality impacts of older engines are recovered with the additional fuel tax revenue.

Other differences resulting in different fuel revenues from OW vehicles of similar type and loads can be related to driver operating behaviors, the average driving speed, terrain conditions, and other factors. Thus, although fuel taxes are historically the primary method by which TxDOT receives revenue for roadway maintenance, fuel taxes may not be the most equitable means for recovering costs due to OW truck operations.

In addition, state and federal lawmakers have been reluctant to raise fuel taxes due to the far-reaching effects on all sectors of the economy. The Texas state fuel tax has remained unchanged at 20¢ per gallon of gasoline or diesel fuel since October 1991. The federal fuel tax of 18.4¢ per gallon of gasoline or 24.4¢ per gallon of diesel fuel has remained unchanged since October 1997 (FHWA 2012). Only seven states have a cheaper diesel fuel tax than Texas with Pennsylvania taxing at the highest rate of 65.1¢ per gallon. Texas retains one of the lowest state fuel taxes in the US (see Figure 5.2).

In Texas, 75% of motor fuel tax revenue is paid to Highway Fund 6 and 25% is paid to the school fund. However, some of the motor fuel tax receipts have been diverted from these two funds to pay for other state expenditures (Figure 5.3). The Texas 2030 Committee estimated that as much as $213 million of the $4.5 billion (4.7%) collected per year is diverted from these funds, resulting in $160 million in lost revenue for Highway Fund 6 (2011).



Source: American Petroleum Institute

Figure 5.2 State fuel tax rates (including federal tax) as of January 1, 2016

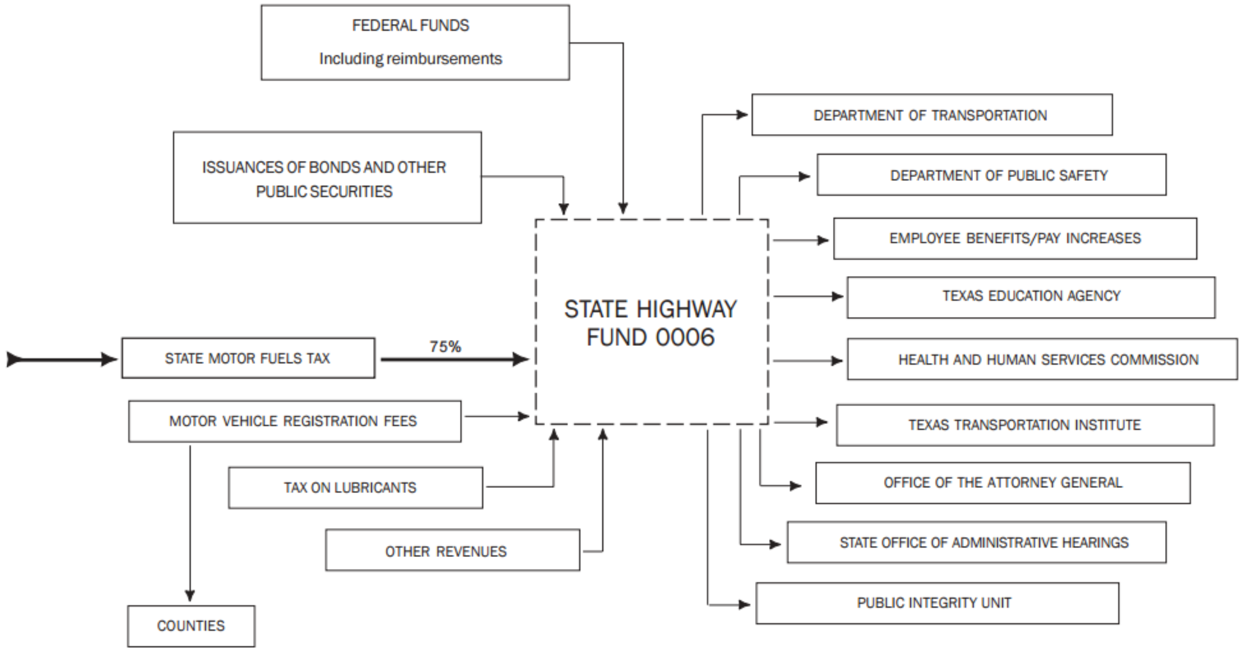


Figure 5.3 Use of State Highway Fund 6

5.4.2 OW Truck Permit Fees

OW truck permit fees have traditionally been a method to recoup some of the costs associated with OW truck operations. However, as was thoroughly documented in the Rider 36 study, current permit fee rates are approximately 20–25% of the permit costs necessary to fully recover the accelerated pavement structure consumption costs based on annual permit sales that have recently exceeded 800,000 per year. In addition, the Rider 36 research team provided recommended permit fee costs for currently exempt OW vehicles that pay no permit fees for operating at above legal limits. It has been suggested by the research team that capturing even a portion of the difference between current permit fees and the appropriate fees based on the results of the Rider 36 study and establishing new permit fees for exempt vehicles could provide TxDOT with a substantial revenue source.

The Rider 36 study concluded that based on the number of permits sold in 2011 and the estimated number of exempt vehicles operating in Texas under 20-plus different size and weight exemptions, the State could potentially generate an additional approximately $500 million in revenue which is directly associated with increased infrastructure (pavement and bridge) consumption. The researchers could adjust these permit fees to reflect only accelerated pavement consumption rates for this study as a starting point for evaluating the TxDMV OW permits as a cost recovery mechanism.

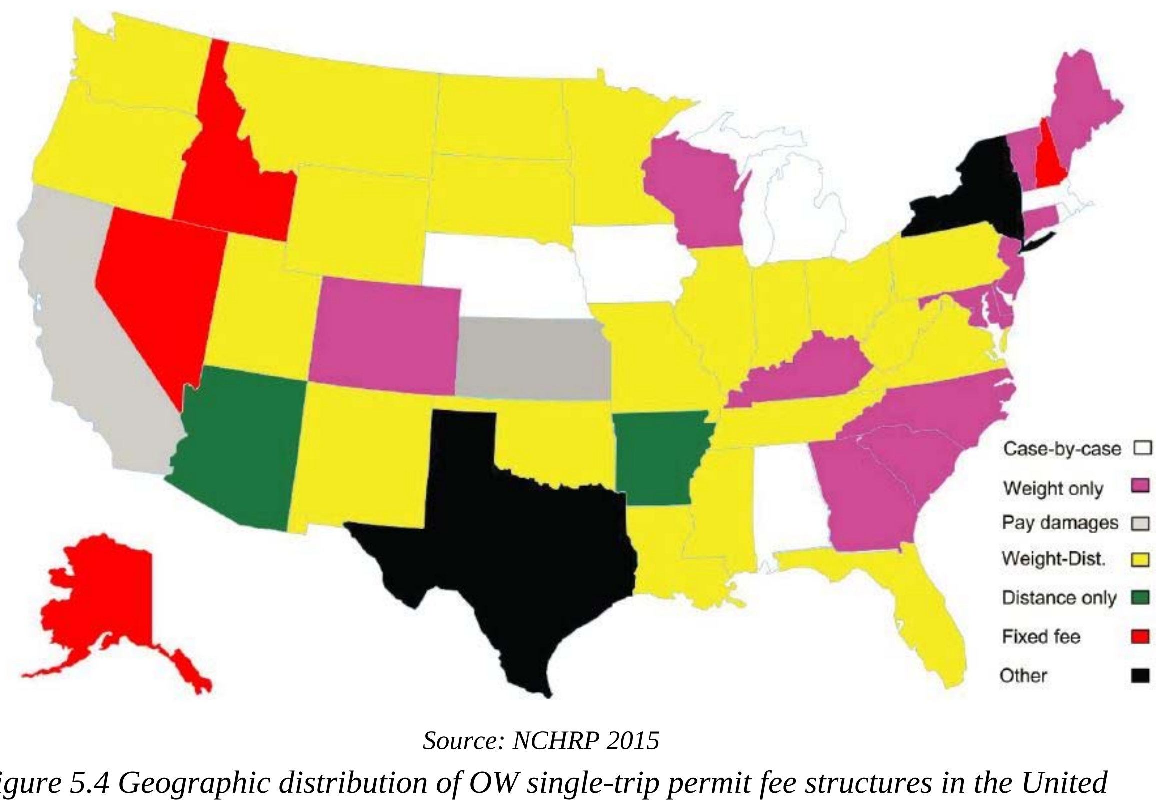
Only a percentage of certain the OS/OW permit fees are paid to Highway Fund 6 as discussed in the Rider 36 study. A portion of the overaxle weight tolerance permit revenue is paid to counties. Portions of certain types of permits are paid to the General Fund, not Highway Fund 6.

It should be noted that some OW units can actually be empty—carrying no cargo at all. The tare weight of the truck and trailer exceeds allowable load limits and would therefore need to be permitted. This is also important, as pointed out in the Rider 36 study, since some types of OW vehicles may only be OW 50% of the time and thus should not pay consumption rates/VMT when unloaded. This can become rather complicated depending on the type of vehicle. For example, trucks operating OW during harvest may operate OW only 3 out of 12 months and only in one direction; they are empty otherwise. Other examples include garbage trucks that start out empty and become loaded by the end of the route, then travel to the dump or landfill to discharge the load. This will also be true for companies like Coal City Cob (CC Cob) that transport hazmat waste: they might have several collection points and then travel to a hazmat landfill to discharge the load.

Another complicating issue is that pavements that carry OW loads might be at a different condition levels along their design life curve when the OW load is applied. Although usually not feasible, the best approach would be to provide a new or newly rehabilitated pavement for OW trucks to travel on—this would reduce maintenance costs for the trucks due to roughness and other types of distress and the cost recovery mechanism could provide funds to maintain the route. This is likely more in line with the geo-fenced, fully integrated system considered in this report.

5.4.2.1 Comparison to Other States

The NCHRP performed a study titled *Practices for Permitting Superheavy Load Movements on Highway Pavements* (2015). As part of the study, the OW fee structures for each state were determined. Figure 5.4 presents a geographical distribution of the OW single-trip permit fee structures by state across the United States. Many states employ a weight-distance formula for calculating the single-trip permit fee structure.



Source: NCHRP 2015

Figure 5.4 Geographic distribution of OW single-trip permit fee structures in the United States

Also included in the NCHRP study was a table of the superload single-trip permit fees. The research team has updated and amended that table to include the single-trip permit fees for all OW vehicles (SCRA 2015). Table 5.9 presents these permit fees. Please note that these single-trip permit fees only apply to OW vehicles and do not take into account any OS permit fees required. Additionally, the GVW legal limit applies to standard five-axle trucks unless otherwise stated.

Table 5.9 OW permit fees by state

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Alabama	GVW 80–100: $10 GVW 100–125: $30 GVW 125–150: $60 GVW > 150: $100	80
Alaska	$30 + $20 if GVW > 150	Based on axle limits
Arizona	Single-trip registration: $12/trip =< 50 miles; $48/trip > 50 miles, Use fuel fee: $16/trip =< 50 miles; $65/trip > 50 miles, Class A OW permit fee: $75	80
Arkansas	$17; additional charges/ton over legal limit: < 101 miles: $8 101–150 miles: $10 151–200 miles: $12 201–250 miles: $14 > 250 miles: $16	80
California	$16	80
Colorado	$15 + $5/axle	Interstate: 80; Non-Interstate: 85
Connecticut	$23 + $3 transmission fee	80
Delaware	$10 + $5 for each 8 kips over legal limit	80
District of Columbia	$30	80

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Florida	GVW < 95: $0.27/mile GVW 95–112: $0.32/mile GVW 112–122: $0.36/mile GVW 122–132: $0.38/mile GVW 132–142: $0.42/mile GVW 142–152: $0.45/mile GVW 152–162: $0.47/mile GVW 162–199: $0.003/1,000 lbs/mile GVW > 199: $0.003/1,000 lbs/mile	80
Georgia	GVW < 150: $30 GVW 150–180: $125 GVW > 180: $500	80
Hawaii	$5	88
Idaho	$71	80
Illinois	$5; Extra charges ($10–$280) based on weight and mileage for GVW < 120 Additional $50 fee for GVW > 120	80
Indiana	$20 base fee; additional charges: GVW < 108: $0.35/mile GVW 108–150: $10 + $0.60/mile GVW > 150: $35 + $1.00/mile + $10/bridge (min $100) Extra Heavy OW Trip: $42.50	80
Iowa	$10	80
Kansas	$20	Interstate: 80; KS, US Highways: 85.5
Kentucky	$60	80
Louisiana	GVW < 254: fee ($30–$1420) based on weight and mileage GVW > 254: $10 + $0.50/mile/ton over 80 kips + structural evaluation fee ($125–$850)	Interstate: 83.4; Non-Interstate: 88

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Maine	GVW < 85: $6 GVW 85–90: $8 GVW 90–95: $10 GVW 95–100: $12.50 GVW 100–105: $15 GVW 105–110: $18 GVW 110–115: $21 GVW 115–120: $25 GVW > 120: $27.50	Interstate: 80; Special Commodity Non-Interstate: 100
Maryland	$50 base fee; additional charges: GVW < 120: $30 GVW 120–200: $30 + $5/ton over 120 kips + $8/structure GVW > 200: $30 + $5/ton over 120 kips + $20/structure + administrative costs	80
Massachusetts	GVW < 130: $40 GVW > 130: $300	80
Michigan	$50	80
Minnesota	$15 + mileage fee ($0.00–$0.20/mile) based on axle group weights and axle spacing	80
Mississippi	$0.05/mile/1,000 lbs over 80 kips	80
Missouri	GVW < 160: $15 + $20/10,000 lbs over legal limit GVW > 160: $15 + $20/10,000 lbs over legal limit + bridge and roadway analysis fee ($425-$925) based on mileage	80
Montana	< 101 miles: $10 101–200 miles: $30 > 201 miles: $50 Additional charges: $3.50-$70 based on total excess axle weight (5–100 kips) For total excel axle weight > 100 kips: $70 + $3.50/5,000lbs over 100 kips	80

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Nebraska	$20	Interstate: 80; Non-Interstate: 95
Nevada	$25	80
New Hampshire	GVW < 90: $9.50 GVW 90–100: $10.50 GVW > 100: $10.50 + $2/1,000 lbs over 100 kips	80
New Jersey	$10 + $5/ton over GVW legal limit + $5/ton over legal axle weight + transaction/service charges ($12 + 5%)	80
New Mexico	$25 + $0.025/mile/ton over legal limit	86.4
New York	$40–$360 depending on commodity	80
North Carolina	$12 + $3/1,000lbs over 132 kips; additional $100 if GVW > 132	80
North Dakota	$15 service/routing fee; additional charges: GVW < 150: $20 GVW 150–160: $30 GVW 160–170: $40 GVW 170–180: $50 GVW 180–190: $60 GVW 190–200: $70 GVW > 200: $70 + $0.05/mile/ton over 200 kips	Interstate: 80; State Routes: 105.5
Ohio	$135 + $0.04/mile/ton over 120 kips	80
Oklahoma	$40 + $10/1,000 lbs over 150 kips (with 8 axles)	80
Oregon	$8 + ton-mileage fee ($0.01-$2.601/ton/mile)	80
Pennsylvania	Varies by commodity	80
Rhode Island	$20	80
South Carolina	$30; if GVW > 130, additional $100 + $3/1,000 lbs over 130 kips + engineering analysis ($100-$350)	Interstate: 80; Non-Interstate: 80.6
South Dakota	$25: additional $0.02/mile/ton if GVW > 85 kips (5 axles)	80

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Tennessee	$15 + $0.05/mile/ton + bridge analysis fee ($100–actual cost)	80
Texas	GVW < 120: $210; GVW 120–160: $285 GVW 160–200: $360 GVW > 200: $435 + vehicle supervision fee	80
Utah	$60 + ton-mileage fee ($65–$450)	80
Vermont	$35; if GVW > 150, additional $800–$10,000 for engineering inspections	80
Virginia	$20 + $0.10/mile/ton	80
Washington	GVW < 205.5: $0.07–$3.87/mile based on weight GVW > 205.5: $4.25/mile + $0.50/mile/5,000 lbs over 205.5 kips	105.5
West Virginia	$20 + $0.04/mile/ton over legal limit	80
Wisconsin	GVW < 90: $20 GVW 90–100: $35 GVW 100–110: $45 GVW 110–120: $55 GVW 120–130: $65 GVW 130–140: $75 GVW 140–150: $85 GVW > 150: $105 + $10/1,000 lbs over 150 kips	80
Wyoming	$0.06/mile/ton over legal limit (min $40)	117
Alberta	C$15 + C$0.03/km/metric ton	Based on axle limits
British Columbia	Distance fee (C$0.95–C$21.40/10 km) based on weight	140
Manitoba	C$0.036/km/metric ton over legal limit	82.5
New Brunswick	C$50–C$500 based on number of axles	Based on axle limits

State/Province	Single-Trip Permit Fees (GVW in kips); 2014$	GVW Legal Limit (kips)
Nova Scotia	GVW < 110.2 kg: C$30.41 GVW 110.2–134.9: C$60.81 GVS 134.9–153.9: C$91.42 GVW > 153.9: C$243.44	109.1
Ontario	GVW < 120 and < 62 miles: C$125 GVW < 120 and 62–310 miles: C$200 GVW < 120 and > 310 miles: C$260 GVW > 120: C$700	Based on axle limits
Prince Edward Island	C$25	116.3
Saskatchewan	C$11 + C$0.036/km/ton over legal limit	5-Axle: 87; 6-Axle: 102.4
Yukon	C$15 + fee based on axle weight-distance traveled	140

The NCHRP report additionally calculated the per-mile or per-ton-mile permit fees for states using a weight-distance approach. The per ton-mile fees are highly variable between states, ranging from $0.006/ton/mile in Florida to $0.50/ton/mile in Louisiana for vehicles with GVW over 254 kips (as Table 5.10 demonstrates).

California, Georgia, Michigan, and Ohio appear to apply only a standard administrative fee for OS/OW permits. Illinois and North Carolina have a structured administrative fee, with higher weight or higher dimension vehicles (or a combination of both) paying a higher fee. Florida enforces a per-mile structure based on tonnage groups for OW permits. For example, a truck weighing up to 95,000 lbs is $0.27/mile while a truck weighing over 95,000 up to 112,000 lbs pays $0.32/mile.

New York and Pennsylvania employed permit fees based on commodities. New York has an administrative fee varying between $40 and $360 for single permits. Pennsylvania had by far the most complicated structure, with either administrative, per-mile, or per-mile-ton fee structures for each commodity.

Table 5.10 Summary of per-mile super heavy commercial vehicle permit fees

State/Province	Unit Permit Fee ($/ton/mi); GVW in kips (2012$)
Florida	$0.0057/ton/mi for GVW < 95 to 0.006/ton/mi for GVW > 199
Indiana	$0.008/ton/mi for GVW 108–150 to $0.0133/ton/mi for GVW > 150
Louisiana	$0.50/ton/mi for GVW > 254 kips
Mississippi	$0.025/ton/mi
Montana	$0.056/ton/mi for GVW > 100 kips
New Mexico	$0.025/ton/mi for GVW > 86.4 kips
North Dakota	$0.05/ton/mi for GVW > 200 kips
Oregon✓	$0.01–$2.601/mi depending on GVW and number of axles
Pennsylvania	$0.03/ton/mi over registered weight
South Dakota	$0.02/ton/mi in excess of a GVW, given the number of axles
Tennessee	$0.05/ton/mi
Virginia	$0.1/ton/mi
Washington✓	$4.25/mi regardless of GVW + $0.20/ton/mi for GVW > 100
West Virginia	$0.04/ton/mi overweight
Wyoming	$0.06/ton/mi
Alberta	C$0.03/metric tonne/km
Saskatchewan	C$0.036/km/metric tonne in excess of registered weight

✓fee is for entire vehicle.
$/ton/mile unless otherwise noted.

A study conducted by the National Center for Freight & Infrastructure Research & Education at the University of Wisconsin-Madison in 2013 evaluated cost recovery options due to OS/OW operations. A survey of state DOTs determined the breakdown of carrier fees and agency costs across six scenarios. The study concluded that OS/OW permit fees do not recover the costs of issuance. The permit fees are not designed to be a cost recovery method, but often are set based on the actual agency costs of issuing the permit. Therefore, the permit fees do not take operational or infrastructure damage costs into consideration.

5.4.2.2 Vehicle Miles Traveled and Weight-Miles

Some OW permit fee structures incorporate VMT and weight-miles. This section focuses on those types of fee structures and on the particular method of using installed, privately operated electronic systems to monitor the number of miles driven by an OW vehicle to charge accordingly.

As discussed earlier in this report, taxes and fees associated with the vehicle at time of purchase or registration does not do as well. Sorenson and Taylor (2005) explained the reasoning for pursuing alternatives to fuel taxes, explored the technology options and enforcement methods, and institutional, implementation, political, and political acceptance issues of implementing an alternative to the fuel tax that captures actual use of the roadway network through weight-distance truck tolls. Sorenson and Taylor (2005) identified the following countries with weight-distance truck tolls for case studies:

- Australia: Austroads' Intelligent Access Program truck monitoring proposal
- Austria: "GO" weight-distance truck toll,
- Bristol (United Kingdom): Combined truck toll/cordon toll demonstration,
- Germany: "Toll Collect" weight-distance-emissions truck toll,
- Switzerland: "HVF" weight-distance-emissions truck toll, and
- United Kingdom: Proposed weight-distance-emissions truck toll.

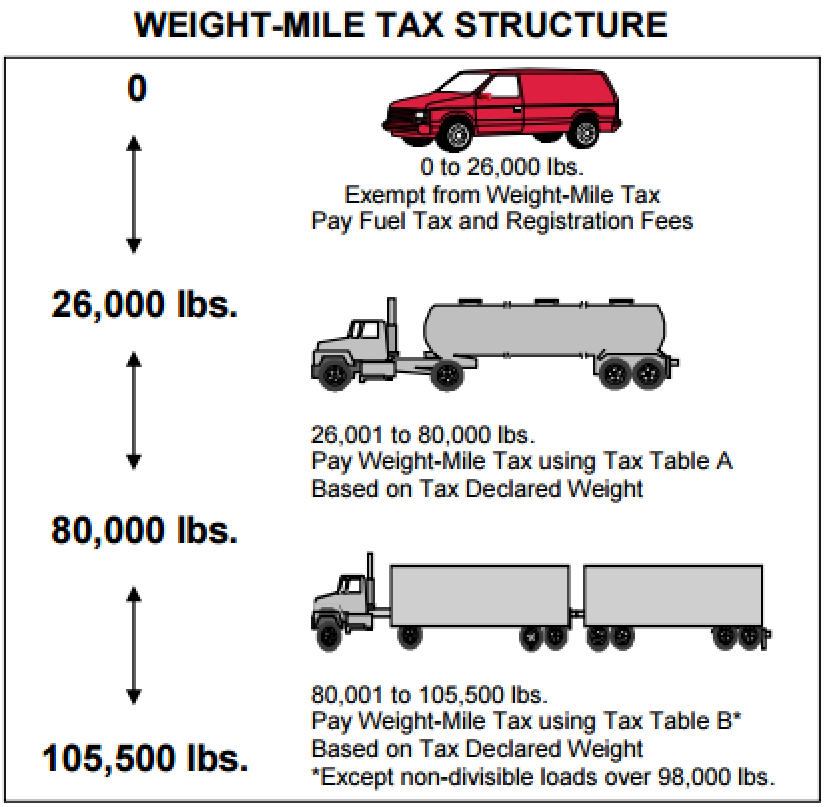
The following cities have general distance-based user fees for vehicles (not necessarily OW vehicles):

- Oregon: Road user fee "OReGO" pilot program
- Seattle: Distance-based congestion pricing pilot program
- The Netherlands: "Mobimiles"

The research team has been in discussions with TxDOT Administration and has attended working meetings during discussions regarding establishment of 'geo-fencing' of shale development regions to support recapturing accelerated infrastructure consumption costs. In this scenario, management processes similar to those already implemented in countries such as New Zealand and Australia would be considered for equipping heavy trucks servicing the oil and gas sector with equipment that monitors the distance travelled within the 'geo-fenced' area, plus other identification information used for computing/collecting OW truck operating fees on a daily basis by direct, electronic withdrawal from the truck operators' bank account. These systems are also being evaluated by Oregon as a means of replacing a paper permit system. This section provides an overview of the Oregon and New Zealand programs.

The first phase of OReGo, Oregon's road user fee program, allows Oregon residents an option to pay a road usage charge by miles they drive, with the charges reduced by the fuel tax they incur. The program is limited to 5,000 cars and light-duty commercial vehicles and does not apply to OW vehicles. There is a separate weight mile tax that applies to vehicles with a gross weight over 26,000 pounds (Figure 5.5). A motor carrier may record their miles on paper or with on-board recording devices, vehicle tracking systems, or other electronic data recording systems. The resulting highway use tax can then be reported with one of three methods, depending on weight of the vehicle, commodity being transported, purpose of the transportation, and highways traveled (State of Oregon, 2014):

- Monthly mileage
- Quarterly mileage
- Flat monthly (an option only for trucks moving certain commodities)



Source: http://www.myorego.org/

Figure 5.5 Oregon Weight-Mile Tax Structure

Outside of the Unites States, many countries have implemented a distance-based truck toll, notably in Europe (Conway and Walton, 2009). Some countries have implemented or proposed programs that use innovative technologies and tracking systems to more accurately charge vehicles based on their usage (Sorenson and Taylor, 2005). These programs include the following:

- Australia – Autoroads' Intelligent Access Program truck monitoring proposal;
- Austria – "GO" weight-distance truck toll;
- Bristol (United Kingdom) - Combined truck toll/cordon toll demonstration;
- Czech Republic – "MYTO CZ" weight-distance-emissions truck toll;
- Germany – "Toll Collect" weight-distance-emissions truck toll;

- The Netherlands – “Mobimiles” distance-based user fee proposal;
- New Zealand – Road User Charges (RUC) weight-distance truck toll;
- Switzerland – Heavy Vehicle Charge weight-distance-emissions truck toll; and
- United Kingdom – proposed weight-distance-emissions truck toll.

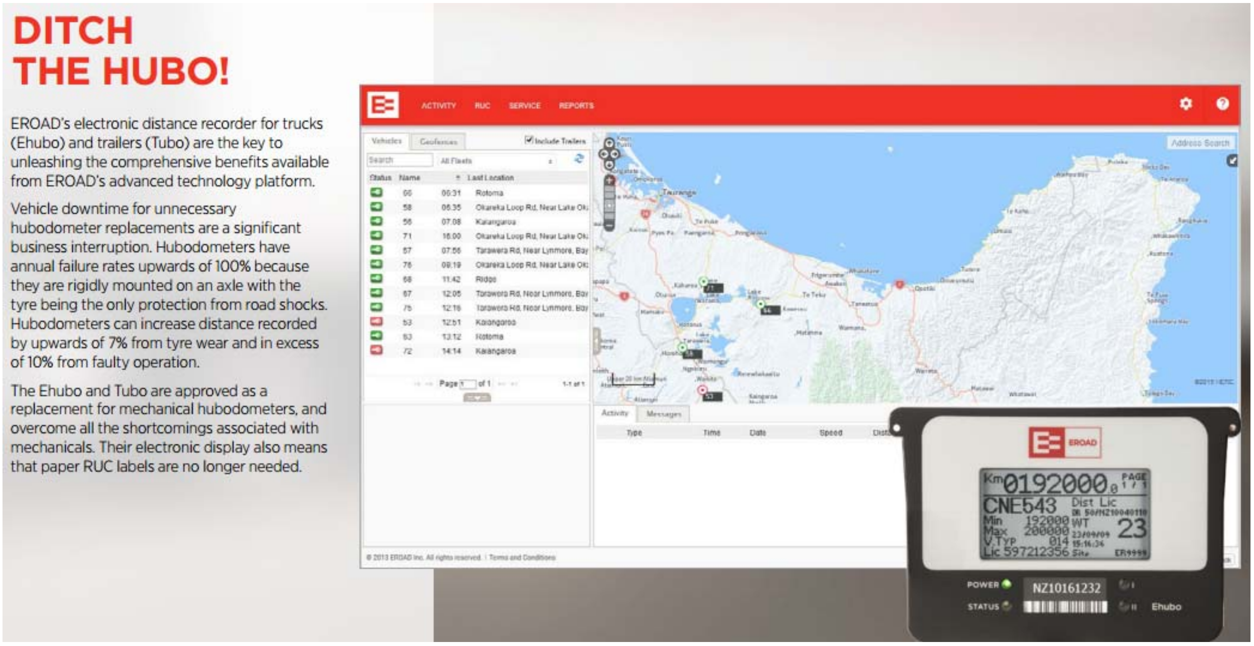
The systems in use in Germany, New Zealand, and Switzerland will be further examined in this report, due to their widespread implementation of innovative methods.

New Zealand

New Zealand implemented a similar system of measuring distance traveled, but for OW vehicles. As an alternative to mechanical hubodometers and paper RUC licenses, New Zealand allows use of electronic distance recorders and electronically displayed RUC licenses. As with Oregon’s program of allowing users to select their choice of mileage reporting companies, electronic system providers enter into agreements with the New Zealand Transport Agency to provide RUC services (issuance of RUC licenses, collection of revenue) to transport operators (New Zealand Government, 2015) (Figure 5.6).

The New Zealand RUC is unique in that users can choose a distance recorder from an approved list. Many hubometers (called hubodometers by the New Zealand Transport Agency) and two electronic distance recorders have been approved for use with this system. The approved electronic distance recorders are the EROAD (Figure 5.6) and ibright eRUC (Figure 5.7) (New Zealand Transport Agency, 2016). Both of these electronic distance recorders allow GPS tracking of vehicles and also permit users to purchase RUC licenses through their system for display on the electronic units, even across a trucking fleet.

RUCs are taxes paid by all diesel-powered vehicles and vehicles over 3.5 tons. Since petroleum, liquid petroleum gas, and compressed natural gas powered vehicles already meet most of their share of the cost to maintain the land transport network with the fuel excise duty (fuel tax) that is included with the price of fuel, they are not subject to the RUC. The price of diesel does not include the fuel tax because non-land-network users (estimated at 36% of diesel sales, such as those using off-roads) would be taxed for a network they don’t use, so the government decided to tie actual distance driven to the costs of using the road network (New Zealand Government, 2015).



Source: http://www.eroad.com/

Figure 5.6 Example of private electronic vehicle miles reporting system

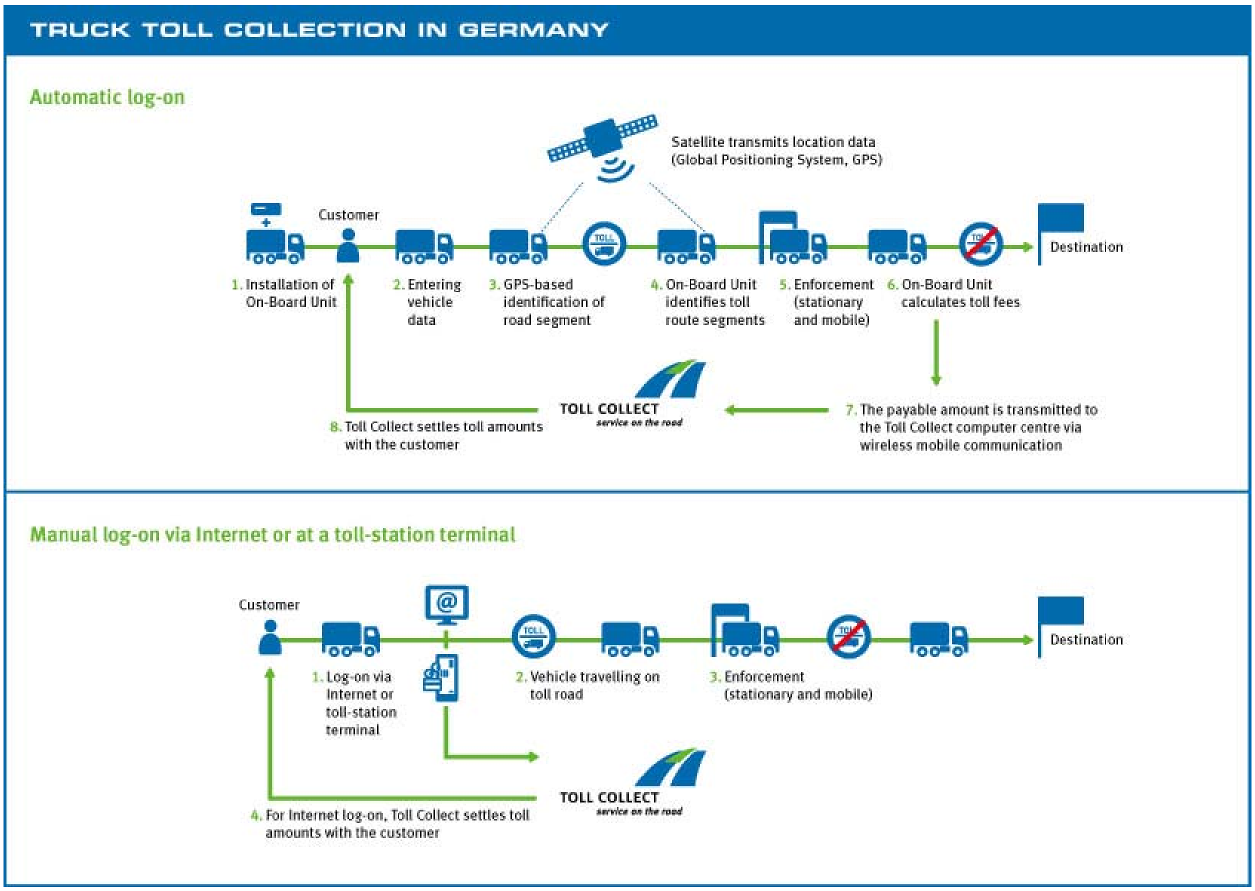
Source: International Telematics, 2014

Figure 5.7 ibright eRUC Electronic Distance Recording Unit

<u>Germany</u>

The German Toll Collect system requires all motor vehicles or vehicle combinations with a GVW of 7.5 tonnes (16,535 lbs) or more and designed or used exclusively for goods transport to pay the weight-distance-emissions based toll (Toll Collect, 2016). The toll is enforced on all German motorways and selected federal trunk (B-letter designated) roads. The weight charges are based on the number of axles, with all trucks falling into categories of two, three, four, five, or more axles. Sorenson and Taylor (2005) note that this axle-based system is a "problematic surrogate" for weight, since pavement consumption costs do not necessarily correlate to the number of axles. Toll charges range from €0.081 per kilometer ($0.145 per mile) for two-axle trucks with the S6 or Euro 6 emissions class to €0.218 per kilometer ($0.389 per mile) for trucks with five or more axles in the S1, Euro 1, Euro 0, or no emissions class (Toll Collect, 2016).

The Toll Collect system is summarized in Figure 5.8. Truckers have an option of installing an onboard unit (OBU), which allows the truck's position to be tracked by GPS to determine distance traveled and calculate the total toll amount. Routes can also be pre-booked manually online or at a toll station terminal for those truckers that do not often use the German road system (Toll Collect, 2016).



Source: Toll Collect 2016

Figure 5.8 German Toll Collect System

As of July 20, 2016, one million OBUs have been installed for use with the German Toll Collect system. The unit is installed in a DIN slot (Figure 5.9) or on the dashboard and clearly displays the toll rate (per km) and total toll amount. The OBU is provided to each truck for free, but remains the property of Toll Collect GmbH. Truckers must pay the following costs (Toll Collect, 2016):

- OBU installation;
- OBU removal after use;

- Change of vehicle registration or change of vehicle data in a service center; and
- Travel time to service center and vehicle idle time during this work.

Source: Toll Collect 2016

Figure 5.9 DIN slot OBU for German Toll Collect

<u>Switzerland</u>

The Switzerland Heavy Vehicle Charge (HVC) is paid by all Swiss and foreign vehicles with a total maximum permitted weight exceeding 3.5 tonnes (7,716 lbs). The fee is based on weight and emissions class and ranges from CHF 0.0228 per tonne-km ($0.0339 per ton-mile) for vehicles with the Euro 4, 5, or 6 emissions class to CHF 0.0310 per tonne-km ($0.0460 per ton-mile) for vehicles with the Euro 0, 1, or 2 emissions class. All Swiss heavy vehicles subject to the charge must be fitted with a GPS-equipped Emotach OBU or, in special cases, a log book and tag unit. The first Emotach unit for each vehicle is provided by the Directorate General of Customs at a cost of around CHF 1,100 ($1,119.53). Truckers or transport companies must pay for the installation of this unit, costing between CHF 300 ($305.29) and CHF 700 ($712.59). Foreign vehicles must use a self-service machine to track mileage upon entrance to and exit from the country. The recording equipment is summarized in Figure 5.10 (Switzerland Federal Customs Administration, 2013).

Source: Switzerland Federal Customs Administration, 2013

Figure 5.10 Switzerland HVC recording equipment

The Emotach recording unit can be switched on or off upon crossing a Swiss border. This process is completed by a short-range microwave radio link using radio beacons installed above the road (Figure 5.11). Additionally, truck drivers must note when their truck tractors are connected to a trailer and input information regarding the trailer into the OBU (Switzerland Federal Customs Administration, 2013).

Source: Switzerland Federal Customs Administration, 2013

Figure 5.11 Overhead radio beacons in Switzerland

5.4.3 Corridor Truck Fees

Project 0-6820, *A Process for Designating and Managing Overweight Truck Corridors at Coastal Ports and Border Ports of Entry*, is investigating an economic model for evaluating potential routine OW truck corridors that serve coastal ports in Texas such as the SH 4/SH 48 corridor at the Port of Brownsville. The State Legislature authorized development of a routine OW corridor from the Port of Brownsville to the Texas-Mexico border along SH 4/SH 48. For instance, six-axle tractor-semi trailer trucks operating at 125,000 lbs GVW pay a single permit fee of $30, a portion of which is used for administration of the permitting system. The remainder accrues to a fund to pay for maintenance of pavement and bridge infrastructure along the corridor. In this case, there is a direct relationship between operation of an OW truck and cost recovery through dedicated permit fees. The permits allow for truck movement between the Veterans International Bridge and the Port of Brownsville via International Boulevard (SH 48) (Figure 5.12).

Source: https://texas.promiles.com/brownsville/

Figure 5.12 Permit route in Brownsville

For OW trucks crossing the Pharr-Reynosa International Bridge and wanting to reach warehouses in Pharr, McAllen, and Mission, HB 474 (provided in Appendix B) allows those trucks to use specific routes (Figure 5.13). The permit revenue from the corridor fees goes to the Hidalgo County Regional Mobility Authority and TxDOT for infrastructure repairs.

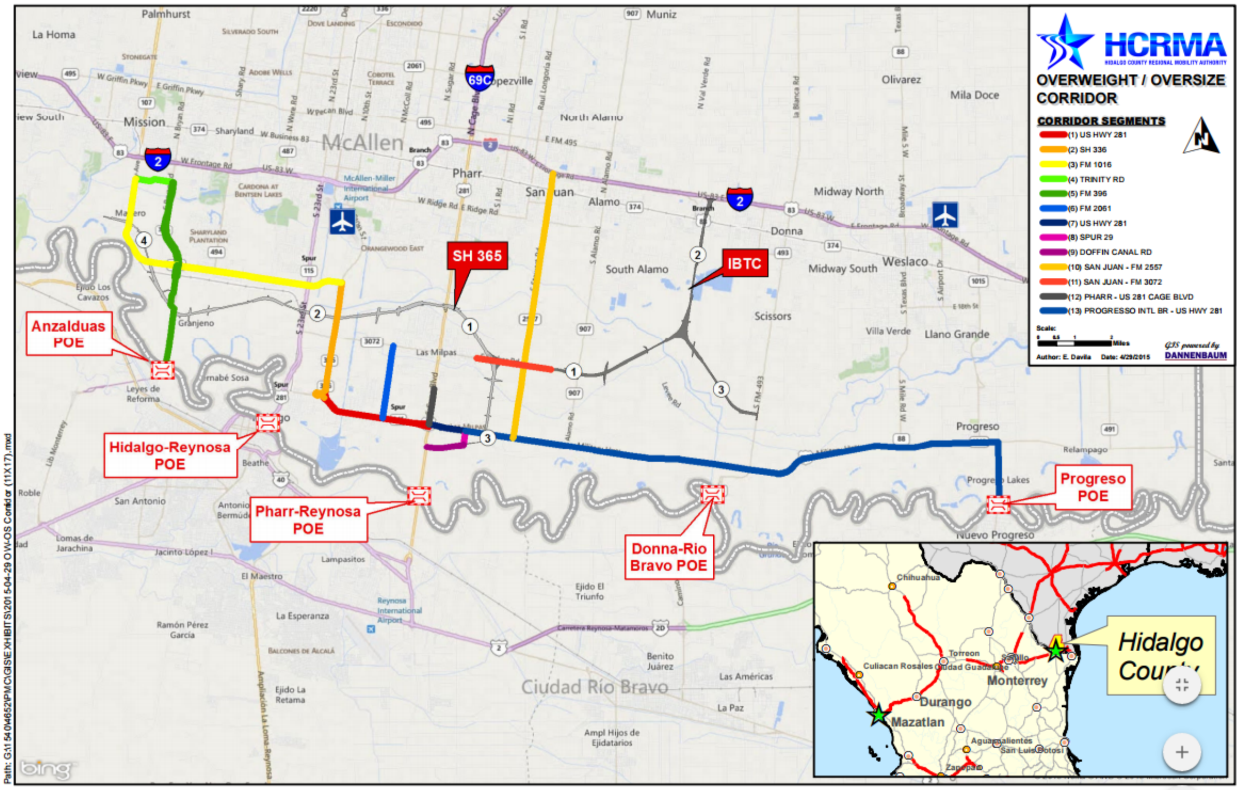


Figure 5.13 Pharr-McAllen-Mission permitted OW routes (Hidalgo County)

Similarly, Port Freeport's specialized OS/OW permits allow for movement of OS/OW vehicles on roadways shown in Figure 5.14.

Source: https://texas.promiles.com/freeport/

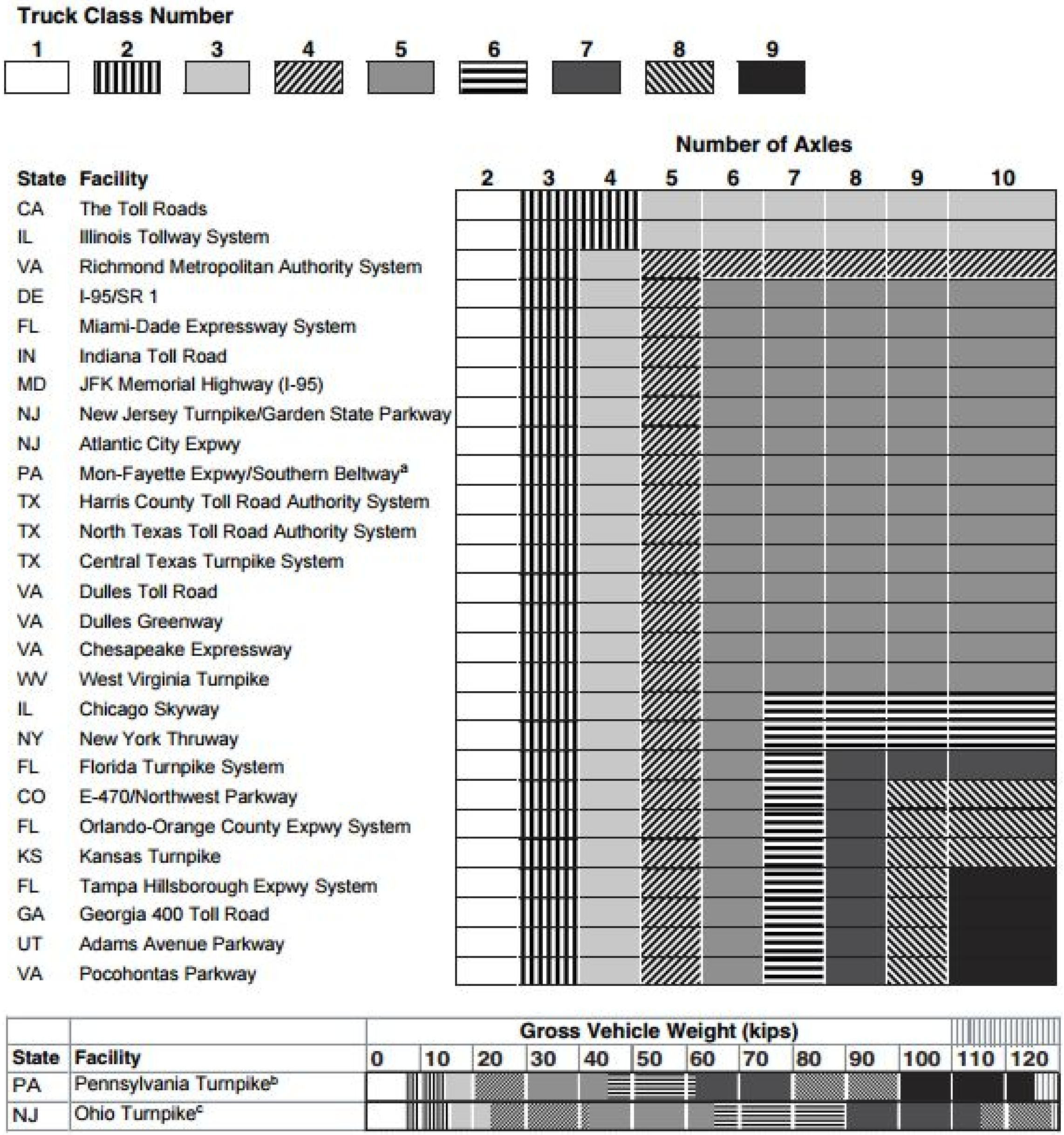
Figure 5.14 TxDOT heavy lift corridor map for Brazoria County

A corridor of this type could also be geo-fenced and a system developed that uses an electronic toll-tag type system to identify the presence of an OW vehicle within the limits of the routine OW truck corridor and determine the OW permit fee based on distance traveled and load above legal limits. In this scenario, the truck would simply be fitted with an electronic toll-tag and the corridor would be instrumented with toll-tag readers and other equipment necessary to record the identity and bill the truck operator. Linking the presence of the truck on the corridor to the actual OW load amount would require a weigh station or sensor at entrance to the tolled highway facility.

Many US toll roads charge vehicles a variable fee based on distance traveled on the corridor and the number of axles or weight of the vehicle. Conway and Walton (2009) summarize the classes of trucks on United States toll roads in Figure 5.15. All but two of the toll roads identified charge vehicles based on the number of axles. GVW or the number of axles alone are not necessarily the best indicators of pavement or bridge consumption. Axle spacing is required to more accurately gauge a truck's consumption (Conway and Walton, 2009). Nonetheless, the number of axles is an easily-identifiable characteristic for toll operations. A majority of the axle-based classification systems group trucks with five or six or more axles into the same category.

Many of these toll roads are equipped with entry and exit barriers through which all vehicles must pay upon entrance to and exit from the road. These barriers are equipped with ticket/cash and/or electronic toll collection (ETC) lanes. A typical entry/exit plaza on the New Jersey Turnpike can be seen in Figure 5.16. The large capital and operational costs of these entry and exit barriers are a significant obstacle to these corridor-type toll facilities. On the New Jersey and Pennsylvania Turnpikes, for example, exits from the facilities are limited to major interchanges.

Conway and Walton (2009) note that a number of US facilities have implemented ETC-only tolling on designated lanes or routes. It is anticipated that ETC-only tolling may reduce the costs of implementing and maintaining a corridor-type facility of this nature, even allowing traffic to proceed at highway speeds through toll booths.



Source: Conway and Walton, 2009

Figure 5.15 Toll rate structures on US toll roads

Source: The Louis Berger Group, 2016

Figure 5.16 New Jersey Turnpike entry/exit plaza

5.3.2 Truck Registration Fees

Truck registration fees are another revenue source that could potentially provide funding to TxDOT for accelerated pavement damage. However, again, it would be difficult to directly relate the truck registration fee to accelerated consumption since at the time of purchase it might be difficult, even for the truck operator, to know the average load that will be transported using the new truck tractor.

As has been pointed out in many studies, a truck tractor can be attached to any semi-trailer and therefore the truck-semi-trailer might be hauling dry bulk cement at 80,000 lbs GVW one month, a goose-neck trailer with a heavy construction equipment with total weights varying between 100,000 to 120,000 lbs. during the following week, and groceries in a refrigerated box van for the following 2 months.

Figure 5.17 provides a geographical representation of the five-axle combination registration fees for each state as of January 1, 2008, along with average registration fees for each of the Western Association of State Highway and Transportation Officials 18 member states, the 10 largest state economies, and the 10 largest state outbound truck freight shipment volumes (Texas 2030 Committee 2011). The truck tractor trailer combination registration fee of $840 for Texas is significantly lower than the averages for each of the three categories presented in the Figure 5.17 and also significantly lower than the national average of $1,338. An increase in the current registration fee of $840 was recommended by the Texas State Comptroller of Public Accounts. It is anticipated that this registration fee increase would result in approximately $7 million in additional revenue, to be deposited entirely in the Texas Highway Fund.

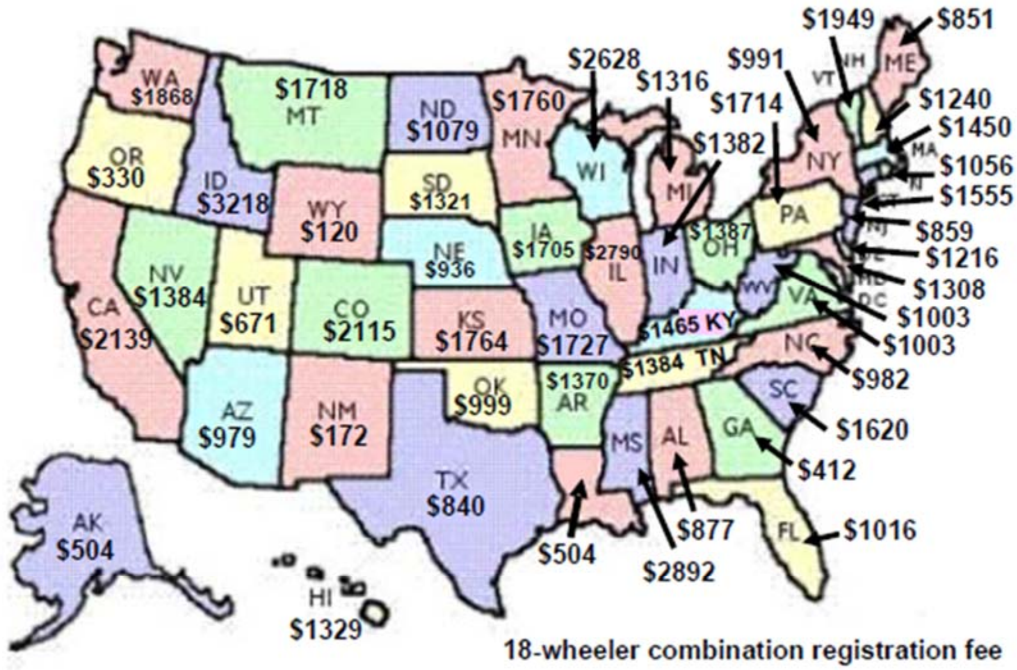


Exhibit E44. 5-Axle Combination Registration Fees.

Other comparisons for Texas' 5-axle combination registration fee with peer states are given below:

- Average 5-axle combination registration fee for the Western Association of State Highway and Transportation Officials 18 member states = $1,167 [WASHTO 2011].
- Average 5-axle combination registration fee for the 10 largest state economies including: California, Texas, New York, Florida, Illinois, Pennsylvania, New Jersey, Ohio, Virginia, North Carolina = $1,373 [USDC 2011].
- Average 5-axle combination registration fee for the 10 largest state outbound truck freight shipment volumes including: California, Texas, Illinois, Ohio, Florida, Georgia, Pennsylvania, Indiana, Michigan, North Carolina = $1,398 [RITA 2005].

Source: 2030 Committee, 2011

Figure 5.17 Five-axle combination registration fees

Despite the disparity between the five-axle combination registration fee in Texas and the four categorical averages, two states bordering Texas—New Mexico and Louisiana—have registration fees of $132 and $504, respectively, which are significantly lower than the registration fee in Texas. The large disparity between Texas and these two border-states illustrates the dangers of jurisdiction shopping. Under the International Registration Plan, commercial vehicles can be registered in a single jurisdiction rather than all jurisdictions through which they travel. Carriers may search for the cheapest or most convenient state (or jurisdiction) to register their vehicles in order to reduce costs and increase convenience (Texas 2030 Committee, 2011; Jasek et al., 2003). Should Texas increase truck registration fees, an increasing number of carriers may register their vehicles in jurisdictions outside Texas.

5.4.4 Truck Sales Tax

Truck sales tax represents another potential cost recovery mechanism, although this method poses the same challenges in associating the sales tax to OW truck operations as do truck registration fees. The State Senate Sub-Committee on Transportation has suggested that a portion of the vehicle sales tax should accrue to TxDOT since there is a direct and recognizable relationship between vehicle sales and the need to fund infrastructure development (and vehicles on the road) (Mitchell 2015). Regardless of whether the vehicle is OS/OW or not, the vehicle still consumes pavement and bridge life. The often quoted relationship between consumption by a car and consumption by an 80,000 lb five-axle truck is that one truck consumes as much pavement as 9,000 passenger cars.

Options for recovering costs with truck sales taxes include maintaining or increasing the tax rate and diverting a portion of that tax revenue to TxDOT.

A 12% federal truck and trailer sales tax is required for trucks over 33,000 pounds GVW and trailers over 26,000 pounds (loaded capacity). The current sales tax rate for motor vehicles in Texas is 6.25%, the same rate as the general state sales tax.

Table 5.11 provides the motor vehicle sales tax rates for all 50 states and the District of Columbia (Florida Department of Revenue 2015).

An increase in tax rate may prompt large truck fleet operators to choose to buy their trucks in another state with a lower vehicle sales tax. Tax rates in Texas and surrounding states are as follows:

- New Mexico - zero
- Arkansas - 6.5%
- Oklahoma - zero
- Colorado - 2.9%
- Louisiana - 4%

Many large truck fleet operators register their trucks in states with lower registration fees—for example, Coca-Cola box vans operate all over Texas but none are registered in Texas. Coca-Cola owns their own truck fleet. For a large truck fleet operator, the sales tax costs could potentially shift purchases to other states. For example, a new Freightliner three-axle tractor costs about $160,000. At 6.5% sales tax, this works out to be $10,400. If the fleet manager purchases 25 new tractors, the company could save over $250,000 buying them in Oklahoma or New Mexico. The potential of this happening could affect effectiveness of increasing truck sales tax to recover costs.

In addition, as with fuel sales tax, there may be reluctance to increase motor vehicle sales taxes to provide additional revenue.

Table 5.11 Vehicle sales tax

State/District	Vehicle Sales Tax
State/District	Vehicle Sales Tax
Alabama	2%
Alaska	None
Arizona	5.6%
Arkansas	6.5%
California	7.5%
Colorado	2.9%
Connecticut	General: 6.35% Vehicles with sale price > $50,000: 7%
Delaware	None
District of Columbia	None
Florida	6%
Georgia	Titled in Georgia: None Not titled in Georgia: 4%
Hawaii	None
Idaho	6%
Illinois	6.25%
Indiana	7%
Iowa	None
Kansas	6.15%
Kentucky	None
Louisiana	4%
Maine	5%
State/District	Vehicle Sales Tax
Maryland	None
Massachusetts	6.25%
Michigan	6%
Minnesota	6.5%
Mississippi	Motor vehicles and trucks < 10,000 lbs: 5% Semi-trailers and trucks >10,000 lbs: 3% Motorcycles: 7%
Missouri	4.225%
Montana	None
Nebraska	5.5%
Nevada	8.1%
New Hampshire	None
New Jersey	7%
New Mexico	None

State/District	Vehicle Sales Tax
New York	4%
North Carolina	None
North Dakota	5% (off-road vehicles only)
Ohio	5.75%
Oklahoma	None
Oregon	None
Pennsylvania	6%
Rhode Island	7%
South Carolina	5% ($300 maximum)
South Dakota	None
Tennessee	7%
Texas	6.25%
Utah	4.7%
Vermont	6%
Virginia	4.1% (increasing to 4.15% July 1, 2016)
Washington	6.80%
West Virginia	Motor vehicles > $500: 5% Motor vehicles < $500: $25
Wisconsin	5%
Wyoming	4%

Several states do not tax the purchase of motor vehicles. The current Texas vehicle sales tax rate appears to be one of the higher sales tax rates among its peers.

5.4.5 Truck Tire Sales Taxes

Truck tire sales taxes are yet another potential revenue source. The federal government currently imposes a sales tax on heavy truck tires based on the apparent relationship between heavy truck tire sales and highway infrastructure consumption. The federal tire tax rate is $0.0945 for each 10 pounds of the maximum rated load capacity exceeding 3,500 pounds. However, as with fuel taxes, truck registration fees, and truck sales taxes, it will be challenging to construct a cost recovery method that associates the marginal increase in truck tire sales taxes to accelerated pavement consumption.

A number of other states charge a small fee for tire recycling or disposal, often due at the time of purchase of the new tire. Previously, Texas had a tire recycling fee of $2 per tire, but the administration and management of the program was too cumbersome, so it was delegated to companies that sell tires who charge the fee and are supposed to ensure the tire is recycled.

Revenue collected from a state tire fee generally gets directed towards a state environmental agency. For example, New Jersey applies a $1.50 fee on the sale of new motor vehicle tires. The revenue is directed to the New Jersey Department of Environmental Protection Tire Management and Cleanup Fund. Any excess revenue is directed to the NJDOT to support snow removal operations (NJ Department of the Treasury 2014).

Louisiana charges a much higher waste tire cleanup and recycling fee. For each passenger/light truck tire, $2.00 is collected; $5.00 is collected for each medium truck tire; and $10.00 for each off-road tire. These fees are due at the time of sale and the revenue is collected by the Louisiana Department of Environmental Quality. Oklahoma also employs a tire fee related to size. The fee is $1.00 for tires with a rim diameter of 17.5 inches or less, $2.50 with a rim diameter greater than 17.5 inches but less than or equal to 19.5 inches, and $3.50 for tires with a rim diameter greater than 19.5 inches.

In contrast to the unit fee structures charged by Louisiana, New Jersey, and Oklahoma, the state of North Carolina levies a scrap tire disposal tax of 2% for tires with a rim diameter less than 20 inches and 1% for tires with a rum diameter of 20 inches or more. Since it is anticipated that truck tires will have a rim diameter greater than 20 inches, North Carolina appears to give trucks a tax break on tires. However, the revenue for this tax is applied to scrap tire disposal, so it does not contribute to a cost recovery structure for OW vehicles.

5.5 Selection of Preferred Cost Recovery Method and Implementation Technique

The research team studied the cost recovery methods identified and then selected a recommended set of methods for use on a specific Texas freight corridor. The corridor selected includes the following segments:

- State Highway (SH) 146 from W. Barbours Cut Boulevard in La Porte, Harris County to Fitzgerald Road in Mont Belvieu, Chambers County (17.5 miles);
- SH Spur 330 from interchange with SH 146 to W. Baker Road in Baytown, Harris County (2.3 miles).

The corridor selection process is described in project product 0-6817-P3, *Case Study Guidelines*).

5.5.1 Cost Recovery Method Selection

As discussed, OW truck permit fees, including weight-, axle- or distance-based fees, can specifically target OW vehicles for their impacts on the infrastructure of a freight corridor. Since the corridor selected for estimating the impacts of such approaches within a Texas context is relatively short (19.8 miles on all segments), a distance-based fee is not recommended. It would involve substantial system requirements in terms of entry/exit barriers on various segments of the corridor, significantly increasing the cost of implementation for a relatively small benefit. Additionally, since all trucks permitted under the proposed corridor and permit system would need to begin or end their journey on Barbours Cut Boulevard, the permit system costs could be minimized by the construction of one entry/exit barrier at the entrance to the Port of Houston Barbours Cut Container Terminal.

The weight limit discussed for this corridor is 97,000 lbs. This weight limit is currently under consideration for approval for OW transport of ocean cargo shipping containers by the Texas Legislature in House Bill 3061 (Appendix C). Since the proposed weight limit is only 17,000 lbs greater than the existing weight limit of 80,000 lbs, it is not anticipated that a weight-based permit system would make considerable difference in permit fee price, especially over the limited length of the proposed corridor. A weight-based system would necessitate additional administrative and infrastructure requirements (such as scales) that would add significant costs to the permit program.

A standard permit fee system is recommended. This cost recovery structure allows for straightforward implementation and administration of the OW truck corridor. Should the corridor be extended to include additional road segments or should heavier vehicles be permitted on the proposed corridor, a weight-, axle- or distance-based fee structure should be implemented to more equitably recoup costs from trucks using the corridor.

Several different types of OW truck permits may be used for this corridor, including one or more of the following:

1. TxDMV Annual Permit – one significant permit purchase allows a truck to carry as many loads as needed within a one-year timeframe. This type of permit allows for minimal transactions and simple system administration. However, companies or trucks that transport relatively few OW loads per year will be at a significant disadvantage due to the high cost of the permit. Permit will be administered by the TxDMV rather than the Port of Houston, potentially allowing the corridor to be extended a significant distance from the port.
2. Port of Houston Single-Trip Permit – a separate permit is required for each one-way OW truck trip. This type of permit provides more equitability with regards to infrastructure consumptions as trucks are required to purchase a permit for each trip. Administrative costs are higher as more transactions are required. The permit is issued by the Port of Houston, with a large percentage of revenue (e.g., 85% at the Port of Brownsville) deposited in Fund 6 for use by TxDOT and the remaining used for administration of the system.
3. TxDMV Single-Trip Permit – similar to existing OW truck permit fee in Texas. All revenue is deposited into General Fund, and administrative costs would be minimal, as the system already exists.
4. Booklet of Permits – truckers could purchase a booklet of permits, using each permit as needed when a load is transported to or from the Port of Houston. This system would allow more flexibility for trucks transporting numerous OW loads and require fewer permit purchase transactions.
5. Toll Tag System – toll tags would be installed on all trucks transporting OW loads to or from the Port of Houston. System would require significant costs for the installation of tag-reading systems and possibly paying for installation of toll tags. However, the system could be partially automated, limiting operating costs once in place.

In any of the above methods, the following costs should be included in the fee calculations:

1. Pavement Consumption – calculated as a cost per ESAL per loaded VMT. A typical five-axle tractor-trailer configuration carrying a loaded container

operating at 97,000 lbs could be used to determine the pavement consumption costs along the proposed corridor;

2. Bridge Consumption – calculated as a cost per loaded VMT. For this corridor, the bridge consumption costs corresponding to an urban SH road in Harris and Chambers counties are specifically used for calculations (Weissman and Weissmann, 2015). As above, a typical five-axle tractor-trailer configuration carrying a loaded container operating at 97,000 lbs could be used to determine the bridge consumption costs along the proposed corridor;
3. Safety Costs – any preventative safety costs or estimated punitive damages associated with OW vehicle operations along the proposed corridor;
4. System Operational and Maintenance Costs (including weigh-in-motion/permit tag costs, if applicable);
5. Administration Costs;
6. Enforcement Costs.

Inclusion of these costs will ensure that the permit fee pays for the administration resources required to operate the system while accurately allocating increased pavement and bridge consumption costs to OW vehicles.

5.5.2 Implementation Method Selection

To implement the permit fee cost recovery system, one entry/exit barrier should be constructed at the entrance to the Port of Houston Barbours Cut Container Terminal. All OW trucks would be required to purchase or provide a valid corridor OW truck permit in order to pass through this entry/exit barrier.

Two technological implementations could be used on Barbours Cut Boulevard to aid in managing the permit fee system:

- Toll Tags – as previously discussed, these tags could be used to identify vehicles entering or exiting the port so that the permit system could be partially automated. These tags would allow trucks to pass through the entry/exit barrier at normal or slightly reduced speeds, decreasing total trip time.
- Weigh-in-Motion Scales – these scales could be used to identify vehicles that are operating OW (between 80,000 and 97,000 lbs GVW) that require a permit and furthermore, ensure that no vehicles are traveling over the proposed weight limit of 97,000 lbs GVW. Further supporting the construction of an entry/exit barrier with a weigh-in-motion scale is new legislation introduced by the International Maritime Organization. A new amendment to the Safety of Life at Sea (SOLAS) regulation VI/2 requires that the gross mass of a packed container be verified in order for that container to be loaded onto a container ship regulated by SOLAS (International Maritime Organization, 2016). The new amendment came into effect on July 1, 2016. These scales could aid the Port of Houston in determining weights of containers upon their entrance to the container terminal. Trucks would be weighed at their entrance to the port and then again after depositing their container (or when leaving the port). These weights could then be linked to the

Barbours Cut Container Terminal database that manages loading of containers onto cargo ships.

Should the corridor be extended to include longer segments or to include heavier weight classes, the introduction of the toll tag and weigh-in-motion systems could assist in administration of the system. Toll tag readers would need to be installed at additional locations along the corridor, wherever OW trucks are permitted to enter or leave the corridor, to determine the distance traveled of each truck. However, the weigh-in-motion scales would only need to be administered on Barbours Cut Boulevard since each trip would still begin or end at the Port of Houston Barbours Cut Container Terminal.

5.6 Conclusion

This chapter explored the OW truck cost recovery methods. Though a number of cost recovery methods are used to recover infrastructure costs from motor vehicles and trucks, OW permit fees most specifically target OW trucking operations. The state of Texas currently employs a weight-grouped permit fee system. A number of U.S. states and countries worldwide have introduced a VMT or weight-distance based fee for OW truck trips. Agencies in Germany, New Zealand, and Switzerland have used GPS-enabled onboard units to determine the total distance vehicles traveled. Corridor-based fee charging systems are also common across the United States. A number of state toll roads charge vehicles based on the number of axles or truck weight.

This study recommends the implementation of an OW truck permit fee system on segments of SH 146 and Spur 330 north of the Port of Houston Barbours Cut Container Terminal. The total length of the corridor is 19.8 miles, ending at areas of industrial activity in the vicinity of IH 10 east of Houston. Due to the short length of the proposed corridor and the minimal increase in permitted weight, a straightforward permit fee system has been recommended. Numerous charging schemes could be used on this corridor, including an annual permit, single-trip permits, a booklet of permits, or a toll tag system.

Should the corridor be extended or should heavier vehicles be permitted to operate on this corridor, a weight-distance based system is recommended. A weight-distance permit system more equitably recoups consumption costs from OW vehicles. The introduction of toll tags or weigh-in-motion scales could allow for partial automation of the permit system and easily allow further expansion of the corridor and implementation of a weight-distance system.

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Appendix A. Pavement Structures and Calculated SNs

Thick HMA Sections Information and Their Calculated Structural Number

Section	Layers	Thickness (in)	Resilient Modulus (psi)	Dynamic modulus T=70 F f=1 Hz	Coefficient	SN
1	Asphalt Concrete	2.75		524110	a1= 0.467	2.126
	Non-stabilized Base:Crushed stone (A-1-a)	6	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
2	Asphalt Concrete	2		502680	a1= 0.460	4.902
	Asphalt Concrete	5		6.86E+05	a1=0.516	
	Non-stabilized Base:Crushed stone (A-1-a)	10	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
3	Asphalt Concrete	1.5		615637	a1=0.497	5.281
	Asphalt Concrete	4.5		7.87E+05	a1=0.541	
	Non-stabilized Base:Crushed stone (A-1-a)	15	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
4	Asphalt Concrete:	2		449757	a1=0.440	8.514
	Asphalt Concrete:	11		7.87E+05	a1=0.541	
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-7-6)	semi-inf	8000			
5	Asphalt Concrete	2		615637	a1=0.497	5.324
	Asphalt Concrete	8		7.87E+05	a1=0.541	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	semi-inf	8000			
6	Asphalt Concrete	1.5		524110	a1=0.467	1.541
	Non-stabilized Base:Crushed stone (A-1-a)	6	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
7	Asphalt Concrete	2		6.86E+05	a1=0.516	2.153
	Non-stabilized Base:Crushed stone (A-1-a)	8	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
8	Asphalt concrete	2		615637	a1=0.497	4.092
	Asphalt concrete	6		6.86E+05	a1=0.516	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	semi-inf	8000			
9	Asphalt Concrete	6		6.86E+05	a1=0.516	4.779
	Non-stabilized Base:Crushed stone (A-1-a)	12	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
10	Asphalt Concrete	5	NA	615637	a1=0.497	4.164
	Non-stabilized Base:Crushed stone (A-1-a)	12	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
11	Asphalt Concrete	4	NA	615637	a1=0.497	4.992
	Asphalt Concrete	4	NA	7.87E+05	a1=0.541	
	Non-stabilized Base:Crushed stone (A-1-a)	6	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
12	Asphalt Concrete	10		6.86E+05	a1=0.516	5.164
	Non-stabilized Base:Crushed stone (A-1-a)	12	30000			
	Subgrade:CH (A-7-6)	semi-inf	8000			
13	Asphalt concrete	2		615637	a1=0.497	3.576
	Asphalt concrete	5		6.86E+05	a1=0.516	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	semi-inf	8000			
14	Asphalt concrete	2		615637	a1=0.497	5.128
	Asphalt concrete	8		6.86E+05	a1=0.516	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	seni-inf	8000			
15	Asphalt concrete	2		615637	a1=0.497	5.128
	Asphalt concrete	8		6.86E+05	a1=0.516	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	semi-inf	8000			
16	Asphalt Concrete	2		475650	a1=0.450	4.133
	Asphalt Concrete	6		7.76E+05	a1=0.539	
	Subgrade:CH (A-7-6)	12	8000			
	Subgrade:CH (A-7-6)	semi-inf	8000			

17	Asphalt Concrete	2	NA	475650	a1=0.450	3.988
	Asphalt Concrete	3.4	NA	615637	a1=0.497	
	Non-stabilized Base:Crushed stone (A-1-a)	10	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
18	Asphalt Concrete	2		6.86E+05	a1=0.516	5.363
	Asphalt Concrete	8		7.87E+05	a1=0.541	
	Subgrade: (A-7-6)	12	8000			
	Subgrade: (A-7-6)	semi-inf	8000			
19	Asphalt Concrete	3		615637	a1=0.497	4.847
	Asphalt Concrete	6.5		6.86E+05	a1=0.516	
	Subgrade: (A-7-5)	12	16000			
	Subgrade: (A-7-5)	semi-inf	16000			
20	Asphalt concrete	4.5		598466	a1=0.492	5.012
	Non-stabilized Base:Crushed stone (A-1-a)	20	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
21	Asphalt concrete	4.5		598466	a1=0.492	4.452
	Non-stabilized Base:Crushed stone (A-1-a)	16	30000		a2=0.14	
	Subgrade:CH (A-7-6)	semi-inf	8000			
22	Asphalt Concrete	8		598466	a1=0.492	5.333
	Non-stabilized Base:Crushed stone (A-1-a)	10	30000		a2=0.14	
	Subgrade:A-3	10	24500			
	Subgrade:CH (A-7-6)	semi-inf	8000			
23	Asphalt Concrete	3		615637	a1=0.497	3.450
	Non-stabilized Base: (A-1-a)	14	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
24	Asphalt Concrete	3		6.86E+05	a1=0.516	4.769
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Non-stabilized Base: (A-3)	11	29000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			
25	Asphalt Concrete	3.5		6.86E+05	a1=0.516	5.228
	Asphalt Concrete	5		6.85E+05	a1=0.516	
	Non-stabilized Base: (A-1-a)	6	30000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			
26	Asphalt Concrete	2		6.86E+05	a1=0.516	7.227
	Asphalt Concrete	12		6.85E+05	a1=0.516	
	Subgrade: (A-6)	12	14500			
	Subgrade: (A-6)	semi-inf	14500			
27	Asphalt Concrete:	2		502680	a1=0.460	4.730
	Asphalt Concrete	2.5		6.85E+05	a1=0.516	
	Non-stabilized Base: (A-1-a)	8	30000		a2=0.14	
	Non-stabilized Base: (A-3)	10	29000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
28	Asphalt Concrete	2		6.86E+05	a1=0.516	4.217
	Asphalt Concrete	4		6.85E+05	a1=0.516	
	Non-stabilized Base: (A-1-a)	8	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
29	Asphalt Concrete	2		6.86E+05	a1=0.516	3.133
	Non-stabilized Base: (A-1-a)	15	30000		a2=0.14	
	Subgrade: (A-7-6)	semi-inf	8000			
30	Asphalt Concrete	2		615637	a1=0.4197	5.123
	Asphalt Concrete	8		6.85E+05	a1=0.516	
	Subgrade: (A-7-5)	12	16000			
	Subgrade: (A-7-5)	semi-inf	16000			
31	Asphalt Concrete	2		6.86E+05	a1=0.516	3.097
	Asphalt Concrete	4		6.85E+05	a1=0.516	
	Non-stabilized Base: (A-1-a)	10	30000			
	Subgrade: (A-6)	semi-inf	14500			
32	Asphalt concrete	2		6.86E+05	a1=0.516	6.711
	Asphalt concrete	11		6.85E+05	a1=0.516	
	Subgrade: (A-6)	12	14500			
	Subgrade: (A-6)	semi-inf	14500			
33	Asphalt Concrete:	2		615637	a1=0.497	2.674
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			

Thin HMA Sections Information and Their Calculated Structural Number

CSJ	Layers	Thickness (in)	Mr (psi)	Dynamic M T=70 F f=1 Hz	Layer Coefficint	SN
1	Asphalt Concrete	1		552495	a1= 0.477	1.557
	Non-stabilized Base: (A-1-a)	9	25000		a2= 0.12	
	Subgrade: (A-5)	semi-inf	15500			
2	Asphalt Concrete	1		632158	a1= 0.502	1.342
	Non-stabilized Base: (A-1-a)	6	30000		a2= 0.14	
	Subgrade: (A-6)	semi-inf	14500			
3	Asphalt Concrete	1		552495	a1=0.477	2.017
	Non-stabilized Base: (A-1-a)	11	30000		a2 = 0.14	
	Subgrade: (A-6)	semi-inf	14500			
4	Asphalt Concrete	1		552495	a1= 0.477	1.877
	Non-stabilized Base: (A-1-a)	10	30000		a2 = 0.14	
	Subgrade: (A-7-5)	semi-inf	13000			
5	Asphalt Concrete	1		552495	a1= 0.477	1.737
	Non-stabilized Base: (A-1-a)	9	30000		a2= 0.14	
	Subgrade: (A-7-5)	semi-inf	13000			
6	Asphalt Concrete	1		552495	a1= 0.477	1.317
	Non-stabilized Base: (A-1-a)	6	30000		a2= 0.14	
	Subgrade: (A-6)	semi-inf	14500			
7	Asphalt Concrete	1		552495	a1= 0.477	1.317
	Non-stabilized Base: (A-1-a)	6	30000		a2= 0.14	
	Subgrade: (A-5)	semi-inf	15500			
8	Asphalt Concrete	1		632158	a1= 0.502	2.181
	Non-stabilized Base: (A-1-a)	12	30000		a2= 0.14	
	Subgrade: (A-7-6)	semi-inf	11500			
9	Asphalt Concrete	1		632158	a1= 0.502	1.482
	Non-stabilized Base: (A-1-a)	7	30000		a2= 0.14	
	Subgrade: (A-6)	semi-inf	14500			
10	Asphalt Concrete	1		632158	a1 = 0.502	2.182
	Non-stabilized Base: (A-1-a)	12	30000		a2 = 0.14	
	Subgrade: (A-5)	semi-inf	15500			
11	Asphalt Concrete	1		632158	a1 = 0.502	1.342
	Non-stabilized Base: (A-1-a)	6	30000		a2= 0.14	
	Subgrade: (A-6)	semi-inf	14500			
12	Asphalt Concrete	1		632158	a1= 0.502	2.882
	Non-stabilized Base: (A-1-a)	17	30000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			
13	Asphalt Concrete	1		632158	a1= 0.502	2.882
	Non-stabilized Base: (A-3)	17	29000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
14	Asphalt Concrete	1		632158	a1= 0.502	2.322
	Non-stabilized Base: (A-1-a)	13	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
15	Asphalt Concrete	1		632158	a1= 0.502	1.622
	Non-stabilized Base: (A-1-a)	8	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			

16	Asphalt Concrete	1		632158	a1= 0.502	1.342
	Non-stabilized Base: (A-1-a)	6	30000		a2=0.14	
	Subgrade: (A-7-5)	semi-inf	13000			
17	Asphalt Concrete	1		632158	a1= 0.502	1.622
	Non-stabilized Base: (A-1-a)	8	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
18	Asphalt Concrete	1		632158	a1= 0.502	3.302
	Non-stabilized Base: (A-1-a)	8	30000		a2=0.14	
	Non-stabilized Base: (A-3)	12	29000			
	Subgrade: (A-6)	semi-inf	14500			
19	Asphalt Concrete	1		632158	a1= 0.502	2.182
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
20	Asphalt Concrete	1		632158	a1= 0.502	2.462
	Non-stabilized Base: (A-1-a)	14	30000		a2=0.14	
	Subgrade: (A-7-5)	semi-inf	13000			
21	Asphalt Concrete	1		632158	a1= 0.502	2.182
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
22	Asphalt Concrete	1		632158	a1= 0.502	3.862
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Non-stabilized Base: (A-3)	12	29000			
	Subgrade: (A-6)	semi-inf	14500			
23	Asphalt Concrete	1		632158	a1= 0.502	1.902
	Non-stabilized Base: (A-1-a)	10	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
24	Asphalt Concrete	1		632158	a1= 0.502	2.183
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			
25	Asphalt Concrete	1		632158	a1= 0.502	3.092
	Non-stabilized Base: (A-1-a)	18.5	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
26	Asphalt Concrete	1		632158	a1= 0.502	2.182
	Non-stabilized Base: (A-1-a)	12	30000		a2=0.14	
	Subgrade: (A-5)	semi-inf	15500			
27	Asphalt Concrete	1		632158	a1= 0.502	2.462
	Non-stabilized Base: (A-1-a)	14	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
28	Asphalt Concrete	1		632158	a1= 0.502	4.702
	Non-stabilized Base: (A-1-a)	6	30000		a2=0.14	
	Non-stabilized Base: (A-3)	24	29000		a2 = 0.14	
	Subgrade: (A-6)	semi-inf	14500			
29	Asphalt Concrete	1		632158	a1= 0.502	2.602
	Non-stabilized Base: (A-1-a)	15	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			
30	Asphalt Concrete	1		632158	a1= 0.502	1.762
	Non-stabilized Base: (A-1-a)	9	30000		a2=0.14	
	Subgrade: (A-6)	semi-inf	14500			

Appendix B. HB 474

By: Munoz, Jr. H.B. No. 474

A BILL TO BE ENTITLED
AN ACT

relating to an optional procedure for the issuance of a permit by a certain regional mobility authority for the movement of oversize or overweight vehicles.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF TEXAS:

SECTION 1. Chapter 623, Transportation Code, is amended by adding Subchapter Q to read as follows:

SUBCHAPTER Q. REGIONAL MOBILITY AUTHORITY PERMITS

Sec. 623.320. OPTIONAL PROCEDURE. This subchapter provides an optional procedure for the issuance of a permit by a regional mobility authority for the movement of oversize or overweight vehicles carrying cargo on certain roads located in Hidalgo County.

Sec. 623.321. DEFINITION. In this subchapter, "authority" means the regional mobility authority authorized to issue permits under Section 623.322.

Sec. 623.322. ISSUANCE OF PERMITS. (a) The commission may authorize a regional mobility authority to issue permits for the movement of oversize or overweight vehicles carrying cargo in Hidalgo County on:

(1) the following roads:

(A) United States Highway 281 between its intersection with the Pharr-Reynosa International Bridge and its intersection with State Highway 336;

(B) State Highway 336 between its intersection with United States Highway 281 and its intersection with Farm-to-Market Road 1016;

(C) Farm-to-Market Road 1016 between its intersection with State Highway 336 and its intersection with Farm-to-Market Road 396; and

(D) Farm-to-Market Road 396 between its intersection with Farm-to-Market Road 1016 and its intersection with the Anzalduas International Bridge; or

(2) another route designated by the commission in consultation with the authority.

(b) The authority authorized under this section must serve the same geographic location as the roads over which the permit is valid.

Sec. 623.323. PERMIT FEES. (a) The authority may collect a fee for permits issued under this subchapter. The fee may not exceed $80 per trip.

(b) Fees collected under Subsection (a) shall be used only for the construction and maintenance of the roads described by or designated under Section 623.322 and for the authority's administrative costs, which may not exceed 15 percent of the fees collected. The authority shall make payments to the Texas Department of Transportation to provide funds for the maintenance of state highways subject to this subchapter.

Sec. 623.324. PERMIT REQUIREMENTS. (a) A permit issued under this subchapter must include:

(1) the name of the applicant;

(2) the date of issuance;

(3) the signature of the designated agent for the authority;

(4) a statement of the kind of cargo being transported, the maximum weight and dimensions of the equipment, and the kind and weight of each commodity to be transported;

(5) a statement of any condition on which the permit is

issued;

(6) a statement that the cargo may be transported in Hidalgo County only over the roads described by or designated under Section 623.322; and

(7) the location where the cargo was loaded.

(b) The authority shall report to the department all permits issued under this subchapter.

Sec. 623.325. TIME OF MOVEMENT. A permit issued under this subchapter must specify the time during which movement authorized by the permit is allowed.

Sec. 623.326. SPEED LIMIT. Movement authorized by a permit issued under this subchapter may not exceed the posted speed limit or 55 miles per hour, whichever is less. A violation of this provision constitutes a moving violation.

Sec. 623.327. ENFORCEMENT. The Department of Public Safety has authority to enforce this subchapter.

Sec. 623.328. RULES. The commission may adopt rules necessary to implement this subchapter.

SECTION 2. This Act takes effect immediately if it receives a vote of two-thirds of all the members elected to each house, as provided by Section 39, Article III, Texas Constitution. If this Act does not receive the vote necessary for immediate effect, this Act takes effect September 1, 2013.

Appendix C. House Bill 3061

84R20270 JTS-F

By: Anchia H.B. No. 3061

Substitute the following for H.B. No. 3061:

By: Anchia C.S.H.B. No. 3061

A BILL TO BE ENTITLED
AN ACT

relating to the movement of vehicles transporting ocean cargo shipping containers; authorizing a fee.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF TEXAS:

SECTION 1. Subchapter B, Chapter 623, Transportation Code, is amended by adding Section 623.0172 to read as follows:

Sec. 623.0172. OCEAN CARGO SHIPPING CONTAINERS. (a) In this section, "ocean cargo shipping container" means an enclosed, standardized, reusable container that:

(1) is used to pack, ship, move, or transport cargo;

(2) is designed to be carried on a trailer or semitrailer and loaded onto a vessel for ocean-borne transportation; and

(3) when combined with vehicles transporting the container, has a gross weight that exceeds the limits allowed by law to be transported over a state highway.

(b) The department may issue an annual permit for the movement of a sealed ocean cargo shipping container moving in overseas international commerce on a trailer or semitrailer with three axles if the combination of vehicles transporting the container has:

(1) a single axle weight of not more than 20,000 pounds;

(2) a tandem axle weight of not more than 40,000 pounds;

(3) a tri-axle weight of not more than 60,000 pounds; and

(4) a gross weight of not more than 97,000 pounds.

(c) The department shall restrict vehicles operating under a permit under this section to routes that:

(1) do not include:

(A) roadways or bridges that the department determines through sound engineering principles should not be used for overweight vehicles; or

(B) federal highways, if the department determines that the operation of a vehicle under a permit under this section on those highways would result in the loss of federal highway funding; and

(2) end at a facility in this state at which the sealed container will be loaded on a ship or train in the course of overseas international shipment.

(d) The department may adopt rules necessary to implement this section, including rules:

(1) governing application for a permit under this

section; and

(2) requiring additional safety and driver training.

(e) The department shall set the amount of the fee for an annual permit issued under this section in an amount not to exceed $7,000, of which:

(1) 90 percent shall be deposited to the credit of the state highway fund; and

(2) 10 percent shall be deposited to the credit of the Texas Department of Motor Vehicles fund.

SECTION 2. This Act takes effect January 1, 2016.