RATE OF DETERIORATION OF BRIDGES AND PAVEMENTS AS AFFECTED BY TRUCKS

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16. Abstract

The largest loads on public road systems disproportionately inflict the greatest damage to highway infrastructure. Simultaneously facing both increasing demand for overweight loads and deteriorating pavement and bridges, the South Carolina Department of Transportation commissioned this study to investigate the impact of heavy vehicle traffic on pavements and bridges in South Carolina and to develop policy recommendations based on technical analysis and the modern institutional environment in South Carolina. To conduct this study, Clemson University estimated pavement and bridge deterioration, investigated the adequacy of standard practices in state agencies for dealing with this deterioration, and characterized how stakeholders in South Carolina's trucking industry perceive those practices.

The pavement models revealed that overweight trucks reduce pavement service life significantly beyond design standards. Results from the bridge model indicated that bridge damage increased exponentially with an increase in truck weight. Recovering damage for South Carolina's highways will require a flat fee of $65 per trip, but traditional flat fees for overweight loads fail to charge fairly according to the differing level of damage from distributions of vehicle weights, axle configurations, and trip length. Several alternative fee structures are presented, such as an axle-based system in which permits will cost between $24 and $175 per trip according to load, vehicle configuration, and trip distance.

Stakeholder interviews indicated differing opinions on the objectives of user fees for permitting overweight loads; however, many stakeholders indicated a need to address illegal loads and establish consistent fee structures across the Southeastern mega-region. SCDOT and trucking industry representatives should work together in an ongoing focus group to develop common understanding of issues, consensus around objectives, and provisions for fairness that will address industry concerns.

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Truck, overweight, pavement, bridge, deterioration, infrastructure, user fee, permit

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NOMENCLATURE

AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway Transportation Officials
ArcGIS	A Geographic Information System (GIS) software
CDM Smith	A consulting company
CPI	Consumer Price Index
DARWin-ME	Mechanistic Empirical Pavement Design software
DM	Decision Maker
ESAL	Equivalent Single Axle Load
FE	Finite Element
FHWA	Federal Highway Administration
GVW	Gross vehicle weight
HAZUS-MH	A federal database of bridge replacement cost
IHS Global Insight	A private company TRANSEARCH is a IHS product
HMA	Hot Mix Asphalt
Legal Weight Limit	Maximum allowable weight without an overweight permit
LS-DYNE	Finite Element (FE) modeling software
Maximum Overweight Limit	Maximum allowable weight with an typical overweight permit
NBI	National Bridge Inventory
RITA	Research and Innovative Technology Administration
SC	South Carolina
SCDOT	South Carolina Department of Transportation
SCDPS	South Carolina Department of Public Safety
SN	Structural Number
TRANSEARCH	A proprietary freight movement database
VISSIM	Traffic simulation software
VISUM	Traffic modeling software
VMT	Vehicle Miles Traveled
WIM	Weigh-in-Motion

EXECUTIVE SUMMARY

The modern freight industry has been pushing the limits of traditional standards for truck size and weight. Adding to the problem, freight loads that exceed design standards are accelerating the deterioration of the pavement and bridge infrastructure. Additionally, competitive modern commerce is continuously demanding loads well in excess of the current standards established by various federal and state departments of transportation (DOTs). Consequently, some state DOTs are now reassessing the impact of oversize and overweight loads, as well as the fee structures used for permitting these exceptions.

Facing an exceptional challenge of maintaining state roadways with ever-shrinking financial resources, the South Carolina Department of Transportation (SCDOT) commissioned this study to examine multiple facets of the impact of overweight trucking. The objectives of this study were to:

- Investigate the impact of heavy vehicle traffic on pavements and bridges in South Carolina; and
- Develop policy recommendations based on technical analysis and the modern political and institutional environment in South Carolina.

Clemson University conducted this study to i) model pavement and bridge deterioration, ii) investigate the adequacy of standard practices in state agencies for dealing with this deterioration and iii) understand how trucking industry perceives those practices.

The primary concern with any pavement design is the amount of truck traffic that the pavement must endure throughout its life. Pavement damage costs due to overweight trucks were estimated using truck distributions based on the weigh-in-motion (WIM) data collected at the St. George WIM station on I-95.

Though bridges compose a small percentage of total highway mileage, their costs, construction time, and traffic disruption upon failure or temporary closing significantly impact highway system performance. Moreover, the catastrophic nature of bridge failures in terms of fatality, property loss, and traffic disruption necessitates maintaining the structural integrity and serviceability of bridges and merits substantial consideration. Pavement and bridge deterioration analysis revealed that pavement and bridge damages increase significantly with incremental weights. Combined bridge and pavement damage costs per mile for different overweight truck types, as estimated in this study, are summarized in the following table.

Additional damage costs for overweight trucks allowed by typical SC overweight permits[1] (2012 US $)

Truck Type	Damage cost per mile
2-axle, 35-40 kips	$0.32
3-axle, single unit, 46-50 kips	$0.15
3-axle, combination, 50-55 kips	$0.30
4-axle, single unit, 63.5-65 kips	$0.10
4-axle, combination, 65-70 kips	$0.34
5-axle, 80-90 kips	$0.38
6-axle, 80-90 kips	$0.18
6-axle, 90-100 kips	$0.42
6-axle, 100-110 kips	$0.75

Truck Type	Damage cost per mile
7-axle, 80-90 kips	$0.11
7-axle, 90-100 kips	$0.25
7-axle, 100-110 kips	$0.45
7-axle, 110-120 kips	$0.70
7-axle, 120-130 kips	$1.03
8-axle, 80-90 kips	$0.09
8-axle, 90-100 kips	$0.19
8-axle, 100-110 kips	$0.35
8-axle, 110-120 kips	$0.54
8-axle, 120-130 kips	$0.79

[1] *Damage costs due to additional weight (i.e., from the legal weight limit to the maximum weight limit)*

User fees to recover costs for overweight vehicles are of five basic structures: flat, distance based, weight based, weight and distance based, and axle based. Each type has inherently unique characteristics related to fairness, precision of allocation, and implementation complexity. The incidence of each type of user fee will fall in various ways according to vehicle types and industries using those vehicles. While South Carolina's trucking stakeholders contributing their perspectives to this study did not reveal consensus on how overweight fees in the state should evolve, but some common points did emerge from multiple interviews. Fundamentally, representatives of well-intentioned shipping companies expressed concern that raising fees will encourage illegal trucking without permits, and the effectiveness of enforcement is nationally unclear since staffed weigh stations have given way to automated transponders. Enforcement planning must coincide with a revision of South Carolina's overweight fees. Other considerations should include effects of overweight fee policies across jurisdictions and consistency in the mega-region.

To recover additional costs of damage imparted by overweight trucks for load in excess of the legal weight limit in an axle based fee structure, damage fee will vary between $24 and $175 per trip for different overweight truck types, while a flat fee structure will charge all overweight trucks $65 per trip (including $10 adminstrative permit processing fee). Consideration of axle load, axle configuration and trip length in the fee structure will reflect damage imparted by each overweight truck more accurately. The fee estimates provided in this study do not consider user fees paid through fuel tax, vehicle registration, or other fees. Under the current fee structure, overweight trucks in South Carolina pay $30 for a single trip permit, and $100 for an annual permit which is equivalent to 3.33 trips. These flat fees do not consider the relative damage due to incremental increases in vehicle weights and trip distances. An Ohio DOT study found that with an annual permit, on average, 24.8 trips were made by an overweight truck.

Interviews showed that fundamentally, South Carolina’s trucking stakeholders do not hold common ideas on the objective of overweight permits and fee structures. South Carolina will not likely find fee revisions politically viable until a consensus develops among stakeholders on the objectives of overweight permitting and fees. Since no consensus is reached among stakeholders at this point, proactive mitigation strategies, such as pavement and bridge design for overweight loading should be considered and pursued. SCDOT and trucking industry representatives should work together in an ongoing focus group to develop common understanding of issues, consensus around objectives, and provisions for fairness that will address industry concerns.

1.0 Introduction

As the American highway system has faced an ever growing funding shortfall over the last decade, and legacy state highways are falling into disrepair, the topic of infrastructure management has increased in importance. National forums have engaged in debate over how to generate funds for road maintenance, and upgrade capacity to support ever increasing traffic demand. Between 1990 and 2003, vehicle-miles travelled (VMT) increased at an average annual rate of 2.32% while truck ton-miles increased much faster at an average annual rate of 3.06%. Among all modes of freight transportation, share of highway freight transportation increased from 24% in 1990s to 28% in 2003 (USDOT, 2007). Moreover, trucks and other heavy vehicles inherently inflict the greatest deterioration due to their large gross vehicle weights (GVW) and individual axle loads. Long-term trends toward larger and heavier trucks have exacerbated vehicle impact on road infrastructure. Additionally, the proportion of trucks configured with multiple units increased from 24% in 1980 to 28% in 2002 (RITA, 2006).

Aging transportation infrastructure, dwindling maintenance budgets, and increasing traffic demand, particularly the increase in the frequency and weight of trucks, are posing a significant challenge to the US transportation grid in terms of operations and safety. With the fourth largest state-maintained road network in the US under similar duress, South Carolina has been proactively developing strategies to provide the safest mobility to motorists. This study is a part of that proactive approach, and focuses on quantification of infrastructure damage imparted by overweight trucks (i.e. trucks above legal weight limits).

1.1 South Carolina Surface Transportation System

Like every other state department of transportation in the US, the South Carolina Department of Transportation (SCDOT) faces the pressures of maintaining state roadways for the motoring public while attempting to do so with an ever-shrinking availability of financial resources. This problem started decades ago and South Carolina decision makers made a move to have heavy vehicles over the legal weight limits pay for the excessive wear they inflicted on state roads. Charged with the task of providing services to truckers and enforcing the laws necessary for protecting and maintaining that infrastructure, SCDOT implemented a user fee for overweight trucks. This fee structure provided some revenue to repair the damage these heavy trucks have caused to South Carolina’s pavements and bridges.

The user fee established decades ago no longer satisfies the financial needs of South Carolina’s state highway system. The changing freight industry, and increased traffic and freight demand have resulted in a situation where the existing user fee cannot satisfactorily support the upkeep of the pavements and bridges in the state. The following difficulties arise in assessing the mismatch of the modern situation and the existing South Carolina fee structure:

- No consolidated information exists on the extent of the problem in terms of heavy-vehicle traffic volume in South Carolina.

- Current pavement and structural conditions in South Carolina have not been adequately evaluated to allow determination of how overweight trucks accelerate deterioration.
- The legacy fee structure has not been examined in the context of changing freight demand, rising cost of maintenance, and changing heavy-vehicle policies across the nation.

Due to this confluence of conditions, multiple factors must be addressed at once in order to update South Carolina's policies for heavy vehicles. At a basic level, the infrastructure needs must be determined, and policy measures must be reconsidered. A comprehensive study determining the exact dimensions of the damages overweight trucks cause to South Carolina pavements and bridges can inform decision makers to restructure current policies and business practices to deal with modern situations. This study involves the examination of both engineering and policy analysis related to overweight truck operation in South Carolina. Because South Carolina has an economic and political landscape that will likely result in trucking remaining the preferred means for the distribution of goods well into the future, a study was needed to assess how to preserve the state transportation infrastructure by optimizing the use of the system and provide guidance regarding policies for overweight truck loads that would result in fair compensation for current and future stress on the system. This research provides assistance to SCDOT policymakers to maintain its transportation infrastructure as the economic viability of South Carolina rests in large part on transportation infrastructure.

1.2 Study Objectives

The objectives of this study were:

- to investigate the impact of heavy vehicle traffic on pavements and bridges in South Carolina, and
- to create policy recommendations based on technical analysis, and the modern political and institutional environment in South Carolina.

The remainder of this report is broken down in four primary parts and appendices. Part I discusses freight transportation activities in the US, and freight traffic demand in South Carolina. Pavement and bridge deterioration analyses and findings are presented in Part II. Part III presents damage cost recovery analysis. Finally, conclusions and recommendations are presented in Part IV. Appendices provide additional details on method, data, and analyses.

Part I: Heavy-Vehicle Activity

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Addressing the impact of heavy vehicles on pavements and bridges entails far more complexity than a physical engineering solution. The technical problem is entwined with a web of multiple stakeholders; policy regimes at state, local, and federal levels; global forces such as economic cycles; and, site-specific travel demand, road networks, and pavement and bridge life cycles. To assess the impact of overweight trucks, one of the primary tasks is to fundamentally characterize the context of pavement and bridge deterioration due to heavy vehicles. States have established routine exceptions, but the permitting rules are inconsistent from state to state. For shippers, this heterogeneous nature can confuse interstate overweight trucking operations over long corridors crossing several states, which suggests a need for coordination among neighboring states to communicate about reasonable loads that can traverse multi-state corridors.

2.0 Trends in Truck Freight Demand

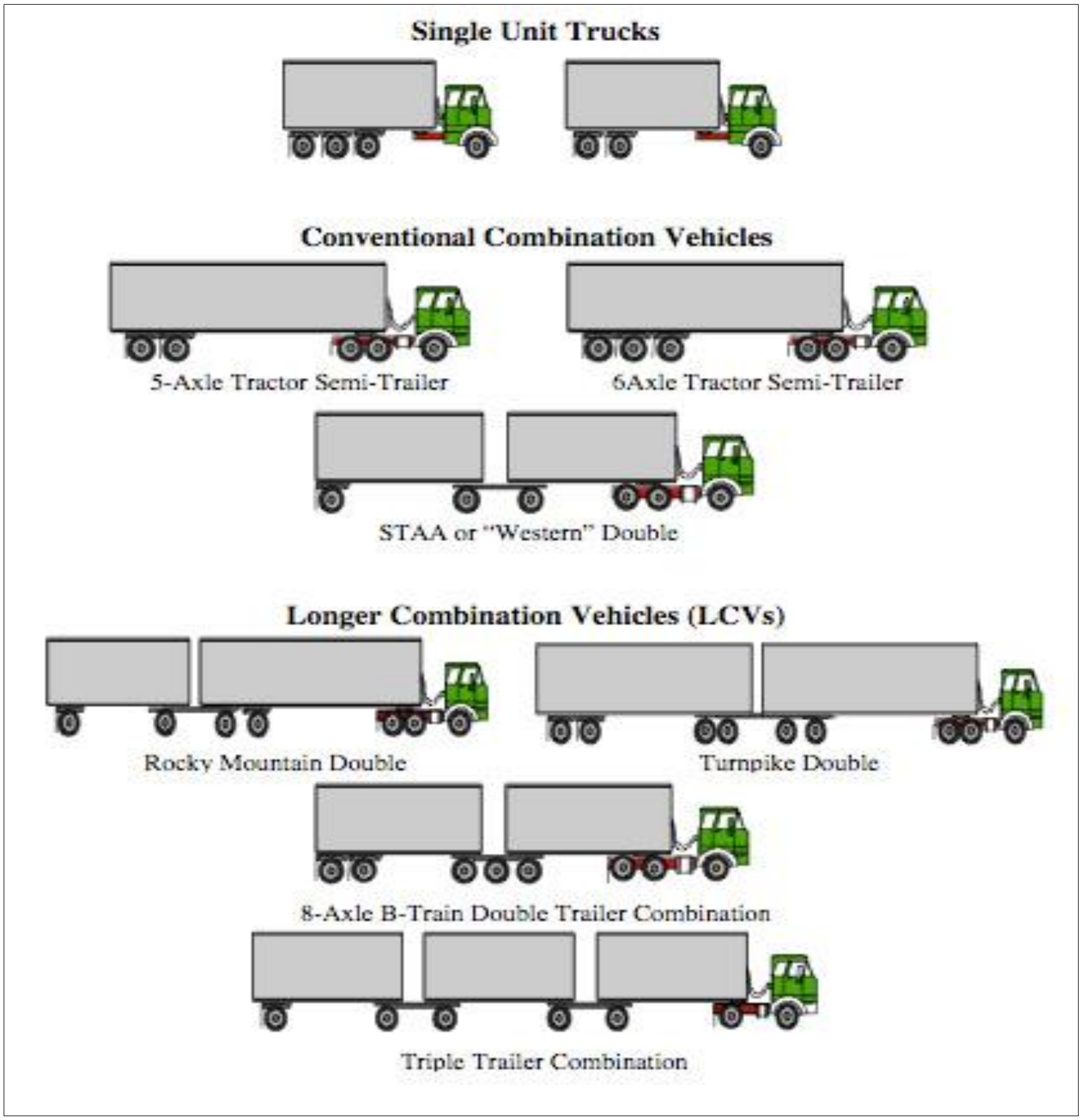
The Federal Highway Administration (FHWA) has predicted an overall 73% increase in shipment volume from 2008 to 2035 with a concurrent increase in truck freight by 72% (Table 1) (FHWA, 2010). The confluence of these trends has led to increased demand for the public highway system to support heavier loads, but the existing infrastructure was not designed to meet modern demand. With decaying infrastructure and limited resources to build new highway systems, transportation agencies must maintain existing highways at acceptable levels to support this increased demand (ASCE, 2009).

Table 1 Projected Weight of Shipments by Mode (Millions of Tons)

Shipment Type	2008	2035	Change	Annual Change
Truck	13,243	22,813	72.3%	2.7%
Rail	2,007	3,525	75.6%	2.8%
Water	632	1,041	64.8%	2.4%
Air, air & truck	13	61	355.2%	13.2%
Intermodal	1,661	2,598	56.4%	2.1%
Pipeline & unknown	3,940	7,172	82.0%	3.0%
Total	**21,496**	**37,211**	**73.1%**	**2.7%**

Source: Federal Highway Administration, 2010

While trucking loads have increased, the size of individual loads has also increased. Freight shippers have used multi-unit trucks (Figure 1) to minimize their transportation costs (RITA, 2006). The FHWA identified a trend of heavy vehicles increasing their vehicle miles (Table 2 and Figure 2), which increased axle loadings on pavements and gross vehicle weights on bridges (FHWA, 2010).



Source: Federal Highway Administration, 2000

Longer combination vehicles are not legal in South Carolina.

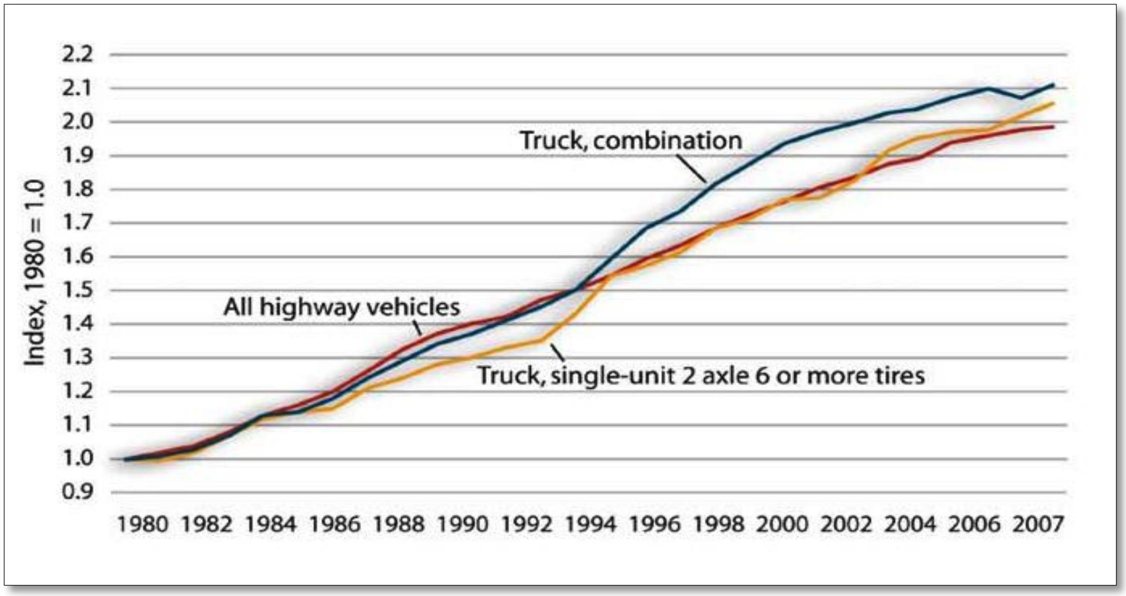
Figure 1 Truck Configurations have Grown Versatile as Freight has Evolved

International trade treaties have increased this heavy-vehicle traffic by allowing cross border operation of trucks from other countries. The Texas-Mexico trade corridor showed a rapid change in truck traffic and volume after 1993 when the North American Free Trade Agreement (NAFTA) partially opened US highways to Mexican trucks with different axle configurations (Hong et al., 2007). A Texas study estimated a $7.7 billion investment was needed to increase the load-carrying capacity of Texas highway bridges alone, while a significant cost would be simultaneously incurred in rerouting existing traffic during construction (Luskin and Walton, 2001).

Table 2 Truck Vehicle Miles Traveled by Average Weight: 1987-2002

Average Weight (pounds)	1987 VMT (millions)	2002 VMT (millions)	Change
Total	89,972	145,624	62%
Light-heavy	10,768	26,256	144%
10,001 to 14,000	5,440	15,186	179%
14,001 to 16,000	2,738	5,908	116%
16,001 to 19,500	2,590	5,161	99%
Medium-heavy	7,581	11,766	55%
19,501 to 26,000	7,581	11,766	55%
Heavy-heavy	71,623	107,602	50%
26,001 to 33,000	5,411	5,845	8%
33,001 to 40,000	4,113	3,770	-8%
40,001 to 50,000	7,625	6,698	-12%
50,001 to 60,000	7,157	8,950	25%
60,001 to 80,000	45,439	77,489	71%
80,001 to 100,000	1,254	2,950	135%
100,001 to 130,000	440	1,571	257%
130,001 or more	185	329	78%

Source: Federal Highway Administration, 2010



Source: Federal Highway Administration, 2010

Figure 2 Highway Vehicle Miles Traveled: 1980-2007

3.0 Federal and State Weight Limits

States began establishing regulations to preserve transportation infrastructure as early as 1913 and the federal government established the first national standards with the Federal-Aid Highway Act of 1956 (FHWA, 2000). The Federal-Aid Highway Act Amendments of 1974 refined the national weight standards based on research from the American Association of State Highway Transportation Officials (AASHTO), and only minor modifications have appeared afterward (FHWA, 2000). Table 3 indicates current federal weight limits for interstates.

Table 3 Federal Weight Standards for Interstate Highways

Weight	Axles
20,000 pounds (9,072 kilograms) per axle	Single axles
34,000 pounds (15,422 kilograms) per axle pair	Tandem axles
80,000 pounds (36,287 kilograms) or Federal Bridge Formula (FBF)	Gross vehicle weight

Source: Federal Highway Administration, 2000

While these federal regulations appear standard, several anomalies are still inherent in standard practices. Three states’ maximum gross vehicle weight limits on interstates are higher than the federal 80,000-pound (36,287-kilogram) limit (Table 4). On non-interstate highways, thirteen states have allowed gross vehicle weights higher than 80,000 pounds (36,287 kilograms). A different combination of seventeen states has exceeded federal single-axle weight limits on interstate and non-interstate highways. Twelve states have allowed interstate loads to surpass federal tandem-axle limits, and twenty states have allowed excessive weights on non-interstate highways.

Table 4 Interstate Gross Vehicle Weight Standards Exceeding Federal Limits

State	Standard
Oregon	105,500 pounds (47,854 kilograms)
Washington	105,500 pounds (47,854 kilograms)
Wyoming	117,000 pounds (57,070 kilograms)

Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

For situations where shippers cannot fit their loads to federal and state regulations, states have created permitting structures for oversized and/or overweight loads through a combination of parameters. These overweight loads on trucks are classified in two different types: divisible and non-divisible. Non-divisible means loads that cannot be broken down into smaller pieces, whereas divisible loads mean weight can be divided or reduced to maintain the legal limit. Most of the states do not issue overweight permits for divisible loads.

3.1 Distribution of Overweight Permits

States have established permitted exceptions for either single use or blanket coverage (multiple uses, monthly use, seasonal use, or annual use). In most states, truckers using single-use permits must perform the trip within a specified period of time, usually 3 to 5 days. Data collected from the web sites of state departments of transportation in 2011, and the Truck Sizes and Weights Manual (J.J. Killer & Associates, 2011) revealed 21 states had single-trip permits with fees ranging from $5 to $135 irrespective of either weight or total distance traveled. States issue annual permits in a goal to reduce related administrative permit processing costs as well as to ease permit applications for overweight trucking companies. Overall there is a growing trend of more annual permits of non-divisible overweight loads (a 28% increase between 2005 and 2009) than single permit increase of 21% (Table 5). A similar case is true for divisible overweight permits. Annual permits with a flat fee can benefit trucking companies by reducing time spent applying for permits for every trip and by reducing the overall fee paid. Flat annual permits allow unlimited trips during the year.

Table 5 Distribution of Permit Types

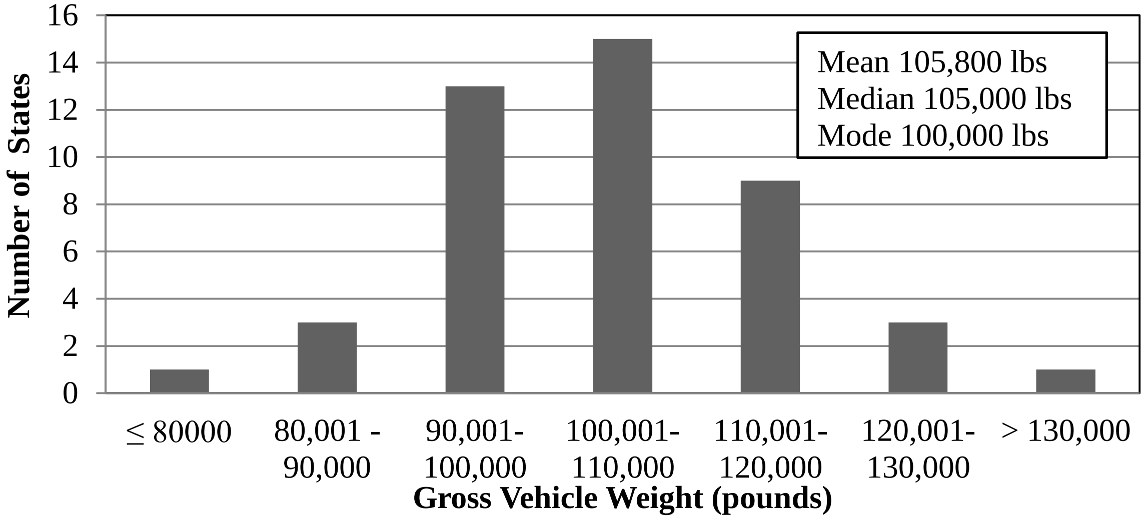
Permit Type	**Year 2005**	**Year 2009**
Non-divisible single trip permits (thousands)	2,712	3,286
Non-divisible annual permits (thousands)	233	299
Divisible single trip permits (thousands)	288	370
Divisible annual permits (thousands)	393	574
Total Permits (thousands)	**3,626**	**4,529**

Source: Federal Highway Administration, 2010

To account for infrastructure deterioration with an annual permit, states must estimate how many trips per year a permit will generate, the average distance each trip will cover, and the amount of excess weight the truck will carry. Although some states consider distance and amount of overweight in setting fees for annual permits, most states charge fixed rates for annual permits irrespective of distance and excess weight. A 1995 study indicated annual permitting generated less revenue than single-use permitting (Moffett and Whitford, 1995) as an annual permit is not associated with the total number of trips.

3.1.1 Allowable Gross Vehicle Weight

Gross vehicle weight directly relates to the impact of truckloads on bridge deterioration. Whereas the federal government has limited gross vehicle weight up to 80,000 pounds (36,287 kilograms), states have been willing to allow much heavier loads with permits, as Figure 3 indicates. The most commonly permitted weights in the US for five-axle semi-trailer range from 100,001 pounds (45,360 kilograms) to 110,000 pounds (49,895 kilograms), with a mean of 105,800 pounds (47,990 kilograms) and the maximum reach 132,000 pounds (59,874 kilograms). Five states have not specified a maximum allowable gross vehicle weight.

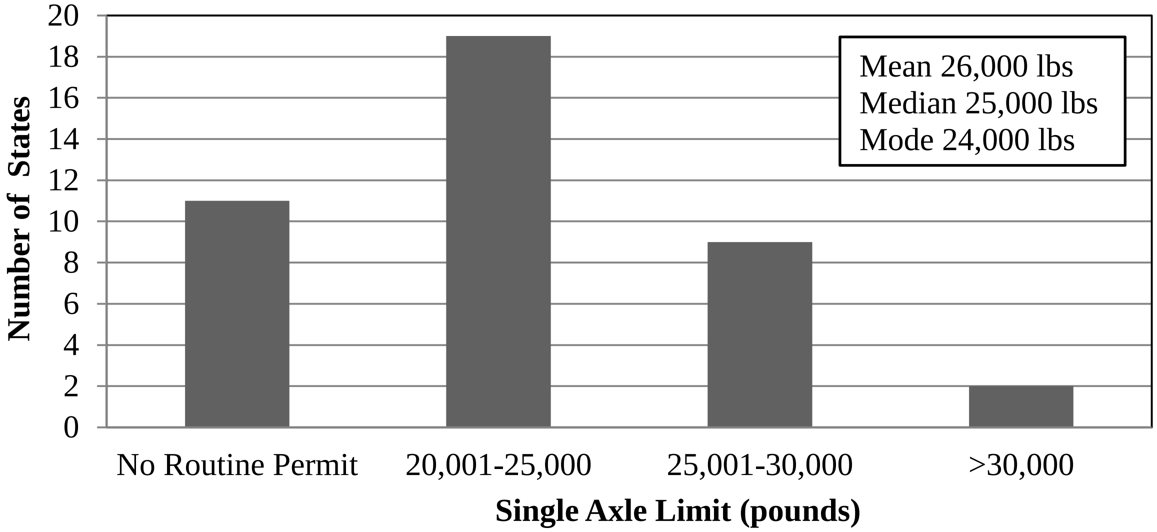


Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

Figure 3 Routinely Permitted Allowable Limits for 5-Axle Semi-Trailers

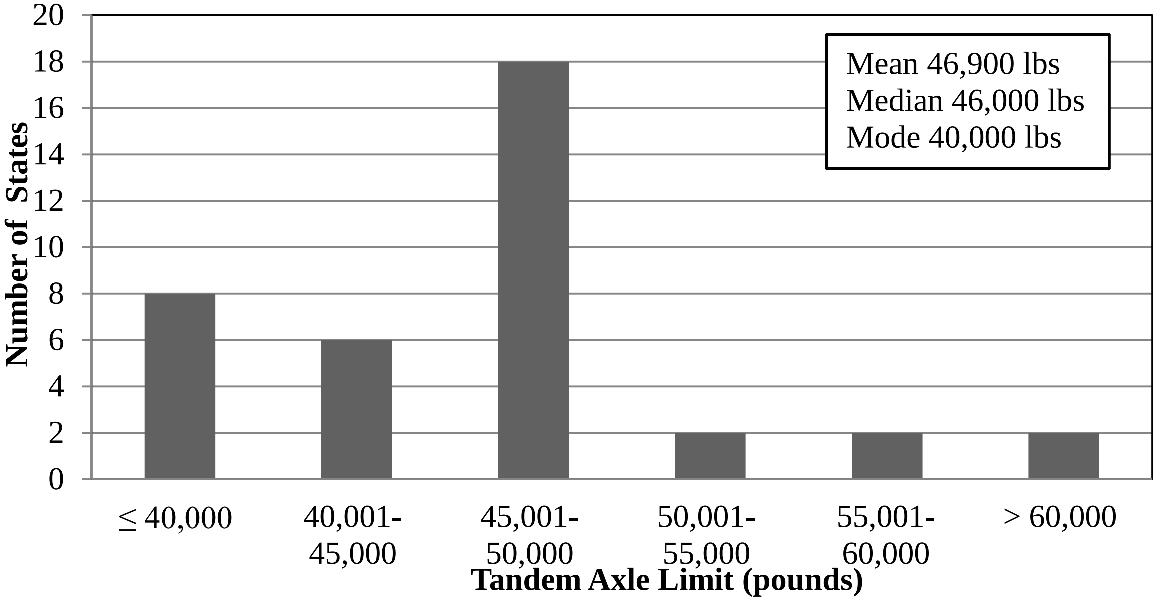
3.1.2 Allowable Axle Weights

In addition to maximum allowable gross vehicle weight, any load can be classified as overweight if any axle load exceeds the axle weight limit. In certain states, the number of axles (or implicitly, the weight per axle) is considered in maximum loading thresholds. The maximum permitted load allowed for a single axle ranges from 20,000 pounds (9,072 kilograms) to 45,000 pounds (20,412 kilograms) (Figure 4). Nine states have not specified a maximum single-axle limit. Figure 5 shows that limits on tandem axles range from 34,000 pounds (15,422 kilograms) to 65,000 pounds (29,484 kilograms) with 7 states setting the most common limit at 40,000 pounds (18,144 kilograms). Twelve states have no specified maximum for tandem axles.



Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

Figure 4 Routine Permit Allowable Limit (Single Axle)

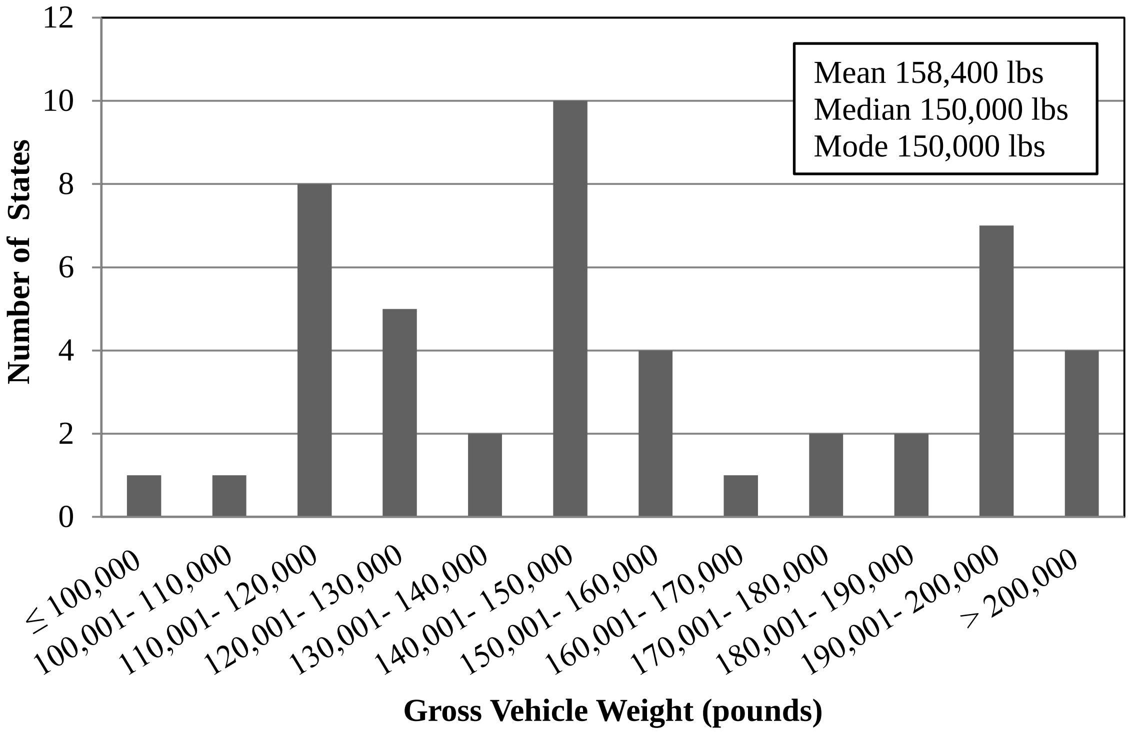


Data sources: J.J Keller & Associates, Inc, 2011, and state departments of transportation

Figure 5 Routinely Permitted Tandem Axle Weights

3.1.3 Super-Load Classification

For loads in excess of the upper thresholds of regular overweight permits known as "super-loads," states have often required a route study to avoid excessive infrastructure damage or failure and to verify infrastructure capacity and safe operation. Permit structures have included super-loads only in terms of gross vehicle weight (no explicit consideration of axles) especially to protect the load carrying capacity of bridges along the specific super-load route. While some states have implicitly or explicitly prohibited highway operations for trucks that exceeded the maximum overweight limit allowed with typical overweight permits, others have simply allowed super-load provided a permit has been issued. For example, New Mexico has allowed loads as high as 200,000 pounds (90,718 kilograms) or more, but has imposed additional fees for such weight and relied on engineering studies to verify the load carrying capacity of the route where the truck with super-load will travel. Figure 6 indicates the distribution of super-loads states have permitted. Three states have not specified the load beyond which a special permit is required, and they deal with super-loads on a case by case basis.



Data sources: J.J Keller & Associates, Inc, 2011, and state departments of transportation

Figure 6 Routinely Permitted Weights for Super-Loads among States

3.2 Consideration of Distance and Weight

To measure a load’s impact on infrastructure further, several European countries have implemented distance-based permits using advanced Global Positioning System (GPS) technologies to track total vehicle miles traveled (Luskin et al., 2000). As infrastructure deterioration solely depends on weight and total distance travelled by specific load, user charges or permit fees that account for these factors is most appropriate to recover infrastructure damage cost. Eighteen states in the US consider the length of a trip to calculate the permit fee for excessive weight beyond legal limits. In particular, Oregon implemented this policy comprehensively for all commercial vehicles (overweight and oversize trucks included) and monitors for compliance (Oregon DOT, 2008). Permit offices can monitor distance through driver reporting, spot checking, on-board units, or GPS. However, the technological monitoring systems can be politically challenging to implement. The trucking industry has voiced opposition to weight-distance taxation (ATA, 2012; Moffett and Whitford, 1995).

4.0 Freight Demand Estimation for South Carolina

In the estimation of pavement and bridge damage due to overweight trucks, the first task was to estimate freight demand on South Carolina’s state-maintained highway system. The South Carolina Statewide Freight model is based on TRANSEARCH, which is a proprietary freight movement database developed by IHS Global Insight using multiple public and private freight data sources. This database has been used for the most recent state freight demand models extensively. CDM Smith Inc. (a private company) maintains the South Carolina freight demand model for SCDOT. For this study, CDM Smith provided the statewide freight movement projection database in an ArcGIS model to the research team(CDM Smith, 2012). This database provided freight truck estimates on major state freight corridors for the years 2004, 2008, 2013, 2018 and 2023. The following subsections describe the estimation of freight demand on different functional classes in South Carolina, truck traffic composition, truck configuration, VMT, and truck trip length.

4.1 Freight Demand on Different Functional Highway Classes

To estimate pavement and bridge damage caused by different truck types, the average annual daily truck traffic (AADTT) on different functional classes of SCDOT maintained highways were compiled using the TRANSEARCH database and a statistical analysis was conducted to determine the 85th -percentile AADTTs for 2011 as summarized in Table 6. These 85th -percentile AADTTs for year 2011 were utilized to design typical pavement sections, as presented in the "Pavement Deterioration" section of this report.

Table 6 AADTT Estimates for Different Functional Classes in South Carolina

Functional Class	**AADTT, 85th percentile**
Rural Interstate	13,150
Rural Arterial	1,210
Rural Collector	570
Rural Local	640
Urban Interstate	14,080
Urban Freeway/Expressways	10,870
Urban Arterial	1,700
Urban Collector	1,940
Urban Local	730

4.2 Truck Traffic Composition

In this study, truck classification data was collected from the St. George weigh-in-motion (WIM) station on I-95 from November 2010 to May 2011 (SCDPS, 2012a). Table 7 presents the summarized truck type distribution at the St. George WIM station. The data shown on Table 7 includes the only truck type distributions available to the research team; thus they were applied to all truck routes considered in this study.

Table 7 Truck Type Distribution at the St. George WIM Station (2010-2011)

FHWA Vehicle Class	FHWA Vehicle Class Description	Axle Grouping	Percentage
5	Single unit 2-axle truck	2-Axle	8.84%
6	Single unit 3-axle truck	3-Axle	1.15%
7	Single unit 4 or more-axle truck	4-Axle	0.05%
8	Single trailer 3 or 4-axle truck	3-Axle	9.10%
		4-Axle	
9	Single trailer 5-axle truck	5-Axle	75.97%
10	Single trailer 6 or more- axle truck	6-Axle	2.30%
		7-Axle	
11	Multi trailer 5 or less-axle truck	5-Axle	2.52%
12	Multi trailer 6-axle truck	6-Axle	0.02%
13	Multi trailer 7 or more-axle truck	7-Axle	0.06%
		8-Axle	

The mapping between the FHWA vehicle class and axle group is also shown in Table 7. Truck distribution by axle group is shown in Table 8. To group the trucks by axle group, it was assumed that half of the FHWA Class 8 trucks had 3 axles and half of them had 4 axles. The same assumption was also applied to the class 10 trucks and Class 13 trucks.

Table 8 Truck Axle Group Distribution at the St. George WIM Station (2010-2011)

Axle Group	Percentage
2-Axle	8.84%
3-Axle	5.70%
4-Axle	4.60%
5-Axle	78.49%
6-Axle	1.17%
7-Axle	1.18%
8-Axle	0.03%

4.3 Truck Models

To estimate fatigue damage caused by trucks with different weights and axle configurations, truck models representative of the South Carolina truck population were developed based on truck gross vehicle weight distribution, truck axle configuration distribution, and truck weight limits in South Carolina. Three different gross vehicle weights (GVW) were assigned to each axle group to represent the truck weight distribution within each axle group. These gross vehicle weights are summarized in Table 9.

Table 9 Truck Gross Vehicle Weight Groups

GVW Group	Group Description
GVW1	80% of the SC legal weight limits
GVW2	SC maximum weight limit with typical overweight permits
GVW3	Maximum truck weight allowed beyond maximum weight limits

The SCDOT legal weight limits for different axle groups were obtained from the South Carolina Code of Laws (SC Code of Laws, 2012) while the SCDOT maximum weight limits were obtained from the SCDOT website (SCDOT, 2012a). The *maximum considered truck weight* for each axle group was determined using the maximum observed truck weight in the size and weight inspection violations data provided by the South Carolina Department of Public Safety (SCDPS, 2012b) and overweight truck permit data (SCDOT, 2012b). More information about the SCDOT overweight truck permit data can be found in Appendix A-1. Table 10 shows the SCDOT legal weight limits and maximum weight limits. Table 11 shows the three levels of GVWs for all axle groups utilized in this study. Truck weight distributions, axle spacing, and axle load distributions are presented in Appendix A-1 and A-2.

Table 10 SCDOT Gross Vehicle Weight Limits

Truck Type	Legal Limit (kips)	Maximum Limit (kips)
Two axle single unit	35	40
Three axle single unit	46	50
Four axle single unit	63.5	65
Three axle combination	50	55
Four axle combination	65	70
Five axle combination	80	90
Six axle combination	80	110
Seven axle combination	80	130
Eight axle combination	80	130

Source: SC Code of Laws, 2012; SCDOT, 2012a

Table 11 Truck GVW Levels in Each Axle Group

Axle Group	GVW1 (kips)	GVW2 (kips)	GVW3 (kips)
2-Axle	28	40	48
3-Axle(a)	40	55	70
4-Axle(b)	52	70	90
5-Axle	64	90	130
6-Axle	64	110	139
7-Axle	64	130	200
8-Axle	64	130	170

(a) Note that the legal weight limit and maximum overweight limit for a 3 axle single unit truck (46 kips and 50 kips, respectively) and 3 axle combination truck (50 kips and 55 kips, respectively) are different (Table 10) and the values of a 3 axle combination truck were used to determine the GVW1 and GVW2 of 3 axle trucks.

(b) Note that the legal weight limit and maximum weight limit for a 4 axle single unit truck (63.5 kips and 65 kips, respectively) and a 4 axle combination truck (65 kips and 70 kips, respectively) are different (Table 10) and the values of 4 axle combination truck were used to determine the GVW1 and GVW2 of 4 axle trucks.

4.4 Estimated Vehicle Miles Traveled

Vehicle miles traveled (VMT) is the most commonly used performance measure in transportation system analysis. The total damage imparted to pavements and bridges by any truck depends on the total vehicle miles traveled. To estimate unit damage cost due to different truck types, the VMT in 2011 on SCDOT maintained highways were estimated. Primarily 2011 VMT was collected from the 2011 Highway Statistics for South Carolina (FHWA, 2012). VMT on SCDOT maintained highways were then adjusted using the statewide total lane miles and SCDOT maintained lane miles. Total lane miles on all South Carolina highways and SCDOT maintained highways are presented in Table 12 (CDM Smith, 2013). Utilizing the FHWA passenger vehicle and heavy vehicle VMT estimate, the average truck percentage on different functional classes were estimated (Table 13) (FHWA, 2012). Truck VMT on SCDOT maintained highways were estimated using truck percentages from Table 13 and are presented in Table 14. To estimate the percentage of trucks above legal axle or gross vehicle weight limits, WIM observations were utilized. An analysis of WIM data from the St. George weigh station on I-95 revealed that, on average, 8.3% of total truck observations were overweight, either by axle or gross vehicle weight. This estimate was used to compute statewide overweight truck VMT.

Table 12 Statewide and SCDOT Maintained Highway Lane Miles (Year- 2011)

Functional Class	**Total SC Lane Miles**	**SCDOT Maintained Lane Miles**
Rural Interstate	2,376	2,376
Rural principal Arterial	3,860	3,860
Rural Minor Arterial	7,266	7,247
Rural Major Collector	21,057	20,734
Rural Minor Collector	4,307	3,952
Rural Local	63,669	25,661
Urban Interstate	1,424	1,424
Urban Freeway/Expressways	322	322
Urban Principal Arterial	3,955	3,952
Urban Minor Arterial	4,076	3,968
Urban Major Collector	5,180	4,646
Urban Local	21,988	12,205
Total	**139,480**	**90,347**

Table 13 Percentages of Trucks on Different Functional Classes (Year- 2011)

Functional Class	**Truck Percentage**
Interstate Rural	23.45%
Other Arterial Rural	12.40%
Other Rural	9.18%
All Rural	13.98%
Interstate Urban	10.06%
Other Urban	5.56%
All Urban	6.64%
Total Rural and Urban	9.07%

Table 14 SCDOT Maintained Highways VMT (Year- 2011)

Functional Class	**SCDOT Maintained Highway, Daily VMT 2011**	**SCDOT Maintained Highway, Daily Truck VMT 2011**
Rural Interstate	20,442,020	4,792,818
Rural Principal Arterial	9,446,629	1,171,446
Rural Minor Arterial	13,518,756	1,676,418
Rural Major Collector	13,188,164	1,211,170
Rural Minor Collector	699,462	64,237
Rural Local	2,625,464	241,116
Urban Interstate	16,725,902	1,682,109
Urban Freeway/Expressways	2,226,133	223,880
Urban Principal Arterial	19,843,849	1,102,329
Urban Minor Arterial	14,845,836	824,688
Urban Major Collector	8,491,119	471,683
Urban Local	3,255,881	180,865
Total	**125,309,215**	**13,642,759**

To determine the operational effects of truck traffic, a micro simulation model of 106 miles of Interstate 85 in South Carolina was developed using the VISSIM micro-simulator. Several scenarios with varied levels of truck distributions within the traffic stream were modeled for year 2011. Truck percentages among other traffic on the I-85 corridor were increased by 5% and 10 % from the existing average percentage of trucks in the corridor in each simulation experiment. No significant change in travel time along the corridor was observed due to increases in truck traffic.

4.5 Overweight Truck Trip Length

Pavement and bridge damage cost due to overweight trucks depends on each overweight trip length. Currently, for any overweight permit in South Carolina, trucks need to provide trip origin and destination, but trip length does not need to be reported in a permit application. In this study, the average trip length of each truck class was estimated using annual mileage reported in the 2002 South Carolina Economic Census data (US Census, 2004). Assuming trucks operate five days a week and each truck makes one trip per day, Trip length estimates for different truck types in South Carolina were estimated (Table 15).

Table 15 Estimated Overweight Truck Trip Length

Truck type	Average Annual VMT	Average Trip Length (miles)
2-axle Single Unit	19,900	75
3-axle Single Unit	26,000	100
4-axle Single Unit	70,300	270
3-axle Combination	33,100	125
4-axle Combination	70,300	270
5-axle Combination	42,200	160
6-axle Combination	42,200	160
7-axle Combination	42,200	160
8-axle Combination	42,200	160

5.0 Summary of Heavy-Vehicle Activity

The trucking industry has utilized the surface transportation system as their primary means of mobility, and their demands are growing in terms of the frequency of trips, size and weight of the trucks used to haul freight. Concurrently, the US surface transportation infrastructure, particularly the bridges and pavements on which these trucks operate, are woefully inadequate to meet this growing demand. The freight carried by overweight trucks causes a disproportionate amount of damage to these pavements and bridges, which are already in disrepair because of a lack of proper maintenance. Consequently, there is a critical need to quantify damage due to overweight trucks before strategies can be developed for its mitigation, an issue of paramount importance to transportation stakeholders nationwide. When some shipments cannot fit within legal weight limits, states issue overweight permits with a damage fee. Unfortunately, more oversight is necessary. One such strategy entails mandating that trucking firms routinely using overweight trucks share the responsibilities for infrastructure maintenance. In the first part of this report (Sections 2 and 3), a brief historical trend in freight truck demand was presented, which was followed by an estimate of freight demand in South Carolina.

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Part II: Impacts of Heavy Vehicles

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Increasing demand and decreasing support for maintenance has resulted in degradation in the overall highway service capacity. An Arizona study found that overweight trucks alone caused approximately $12 million to $53 million in annual uncompensated pavement and bridge damage in the state (Straus et al., 2006).

Experimental analysis has shown that the greatest damage to pavement is associated with axle weight, axle spacing, and thickness of pavement layers; in contrast, bridge damage has been attributed mostly to heavy gross vehicle weight (Luskin and Walton, 2001). Unless engineers across the nation anticipate the 72.3% increase in truck loads indicated in Table 1 and act accordingly, growing volumes of heavy loads will accelerate the deterioration of the transportation infrastructure. This study estimated damage to pavements and bridges in South Carolina due to overweight trucks.

6.0 Pavement Deterioration

Engineers design pavement thickness according to the traffic demand anticipated throughout the pavement's service life. Designers represent single and multi-axle traffic over the pavement service life as Equivalent Single Axle Loads (ESALs) of 18-kip (80-kN). Engineers who planned and designed the original interstate pavements of the 1960s designed for 5 - 10 million EASLs. Many modern pavement designs have had to accommodate 50 - 200 million ESALs to support the current traffic demand. This increase in traffic has required rehabilitation techniques to bring the original infrastructure to modern base standards.

6.1 Relevant Studies on Pavement Deterioration Due to Trucks

Roadways have a range of standards from high-standard interstates to low-standard local streets. A truck that will cause little or insignificant damage to interstates might cause significant damage to local streets. An Ontario study examined the relative impact of regular trucks on different types of roadways and concluded that pavement damage costs for a typical truck over 1 km (0.62mi) of roadway might vary from $0.004 for a high-standard freeway to $0.46 for a local street (Hajek et al., 1998).

Most pavement deterioration can be associated with vehicle type or weight. Although light passenger vehicles are the dominant users of highways, they are not considered in pavement design due to the relatively low amount of damage imparted by these vehicles compared to trucks. Therefore, freight traffic is the primary traffic input considered in pavement design. The heavier truck loads develop excessive stress and strain on different pavement structural layers, and results in different form of distress and ultimate pavement fatigue failure. Pavement damage increases exponentially with increase of vehicle axle load magnitude (Luskin and Walton, 2001; WSDOT, 2001). Pavement damage due to one heavy freight truck could be equivalent to that of thousands of light weight passenger vehicles. Due to limited axle numbers in buses, loaded articulated bus could cause much more damage compared to heavy trucks (Pavement Interactive, 2013).

Though only a small percentage of trucks operate beyond legal weight limits, they account for significant amount of total pavement damage (Luskin and Walton, 2001, Liu, 2007). To manage permitted and illegal overweight trucks, an Arizona study estimated a savings of $4.50 in pavement damage for every $1 invested in mobile enforcement (Luskin and Walton, 2001). A study in Egypt estimated that increasing axle weight limits from 10 tons to 13 tons will reduce pavement service life by half, and overweight loads beyond maximum pavement load bearing capacity should not be allowed in any circumstance due to sudden structural failure (Salem et al., 2008).

The emergence of modern truck configurations, as indicated in Figure 1, has necessitated evolution in pavement design to handle the effect of load and configuration (FHWA, 2010). A Michigan study found that single and tandem axles of trucks had a more significant impact on cracking than trucks with multiple axles (tridem and higher). Conversely, the trucks with multiple axles elicited more detrimental effect on pavement rutting than single- and tandem-axle trucks. No correlations appeared between axle configurations and pavement roughness (Salama et al., 2006). Another study found that larger axle combinations reduced pavement fatigue damage while increasing rutting (Chatti et al., 2004; FHWA, 2000). A study of overloaded tridem and trunnion axles reported differing impacts depending on the flexible or rigid pavement within the roadbed. While tridem axles cause the most damage to flexible pavements, trunnion axles cause more damage to rigid pavements with identical axle loads (Hajek et al., 1998).

While transportation professionals have mostly focused on truck loadings, other factors have also contributed to pavement deterioration (e.g., vehicle design). Research has 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 (Cole et al., 1996). 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).

Advances in pavement design are accommodating modern refinements in awareness of the impact of weight, as well as other factors. New pavement modeling techniques have the potential to use diverse geographic and traffic-demand scenarios (Hajek et al., 1998; Sadeghi et al., 2007; Salem, 2008). It is quite evident from the literature that trucks cause disproportionately higher damage to pavement than passenger cars because of their higher weights and axle configurations.

6.2 Pavement Deterioration Modeling Method

The objective of this portion of the study was to determine the influence of overweight truck traffic on pavement performance. This analysis was performed for flexible pavements using truck models having two, three, four, five, six, and seven axles. The analysis included a sensitivity analysis to assess the impact that each truck model classification had on the flexible pavement designs that were representative of pavement structures utilized for different roadway classes in South Carolina.

The analysis was conducted on pavement structures that were designed to meet structural numbers (SN) ranging from 3 to 7 in accordance with the SCDOT Pavement Design

Guidelines (SCDOT, 2008). It should be noted that these designs were created to simplify the analysis by varying one pavement layer (HMA Base Course) and keeping the other layers constant. The thickness of the Hot Mix Asphalt (HMA) Surface Course, HMA Intermediate Course, and Graded Aggregate Base Course were based on typical pavement designs provided by the SCDOT. The thickness of the HMA Base Course was calculated based on the desired SN. The HMA Base Course was selected as the variable because it is the pavement layer that would mostly be increased in thickness in practice to improve the load carrying capacity. However, the use of a 1-in. layer thickness as used for the pavement having SN = 3.136 is not recommended because it is less than the minimum thickness of this type of mixture. A SN of 3.136 was selected instead of a SN of 3.0 because the thickness of the HMA Base Course would be less than 1-in. for an SN equal to 3.0. These designs were used to limit the variables in the sensitivity analysis.

The analysis was conducted two ways: (1) based on equivalent single-axle loads (ESALs) in accordance with the SCDOT Pavement Design Guidelines and (2) based on DARWin-ME output. A detailed description of the complete pavement analysis is available in Appendix B.

6.3 Estimation of Pavement Deterioration

This section presents the design method adopted to estimate the cost associated with the damage to pavements due to overweight trucks. The analysis procedure used to accomplish this was based on a similar analysis conducted by the Ohio DOT (ODOT, 2009). This analysis focused on flexible pavements because asphalt is the predominant paving material used in South Carolina from a system perspective (i.e., all functional classes). The analysis was based on the entire SCDOT pavement network and each functional class was analyzed separately to account for differences in pavement design and truck traffic for each. As with the analysis presented in Section 6.2, all pavements were assumed to have the same HMA Surface Course, HMA Intermediate Course, and Graded Aggregate Base Course thicknesses as illustrated in Figure 7 and the thickness of the HMA Base Course varied depending on the pavement design.

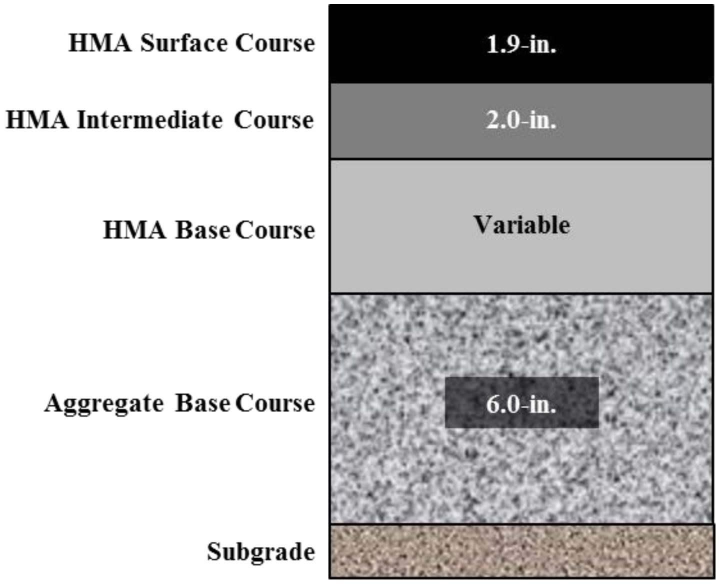
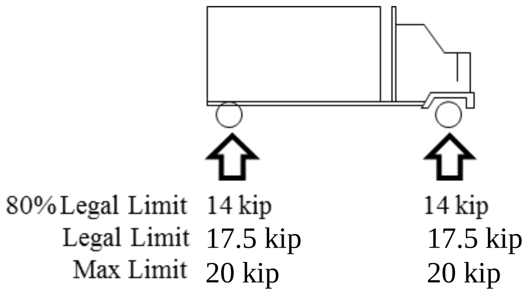


Figure 7 Schematic of Flexible Pavement Design Dimensions

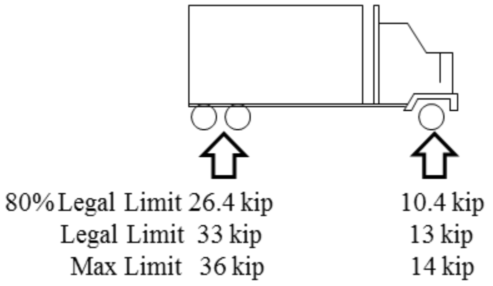
The primary concern with any pavement design is the amount of truck traffic that the pavement must endure throughout its life. The truck configurations included in Figure 8 were used in this analysis; however, the analysis was based on a distribution of trucks and not just a single truck. This change was made for this analysis to more accurately represent the damage (or design changes) that would result from having only a portion of the truck traffic be considered overweight, which was a more realistic scenario. In this study, it was assumed that 8.3% of the trucks in each truck category were loaded to the respective maximum limit based on WIM data collected at the St. George WIM station on I-95. The AADTT for each functional class included in this analysis is included in Table 6. The distribution of truck types is included in Table 8 and was based on the WIM data. To estimate the cost of pavement damage cost due to overweight trucks, three pavement design scenarios were developed:

Scenario 1: No trucks in the traffic (minimum design scenario)
Scenario 2: Traffic includes trucks but no weights exceeding legal weight limits
Scenario 3: Traffic includes trucks where 8.3% of trucks were overweight

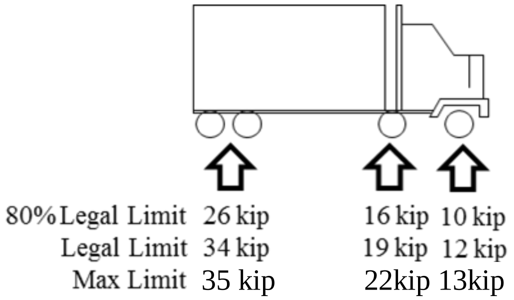
The pavement design utilized the procedures set forth by the SCDOT Pavement Design Guidelines (2008), which uses an equivalent single axle load (ESAL) approach to determine the required structural number to accommodate a given number of design ESALs (AASHTO, 1993). As the ESAL factor does not change significantly between SN of 5 and 7, a standard highway flexible pavement section with a structural number (SN) of 5 and a terminal serviceability index (P_t) of 2.5 was assumed to estimate the corresponding damage of each weight category of each truck type, which was used to develop the pavement damage ESALs. The ESAL Factor was based on the truck configuration (Figure 8) and the respective ESAL factor for each individual truck type (Table 16). Based on the required number of design ESALs (Equation 1), the required structural number (SN) for each pavement design was determined.



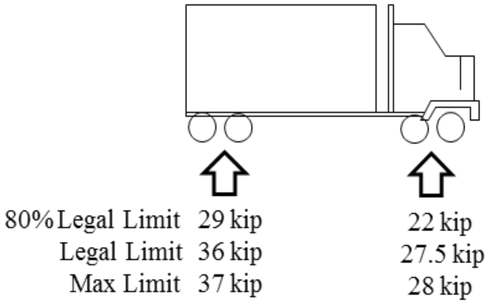
Truck Category A21



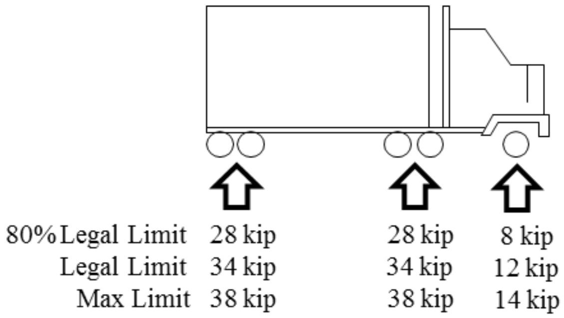
Truck Category A31/32



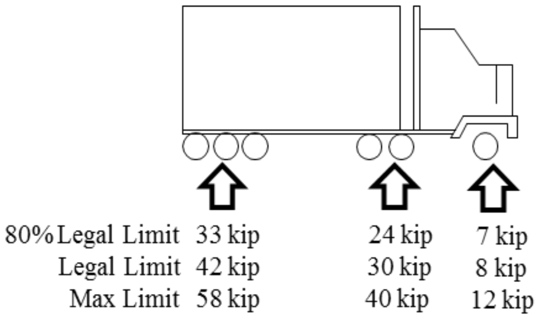
Truck Category A41/44/45



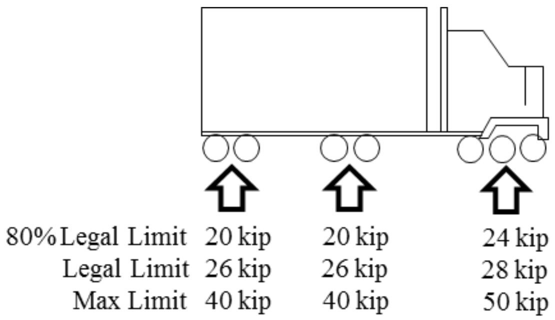
Truck Category A42/43



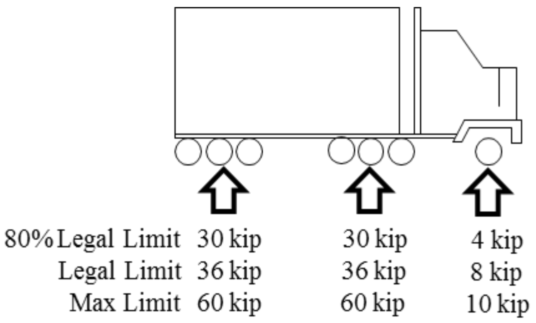
Truck Category A51/52



Truck Category A61/62



Truck Category A71



Truck Category A72

Figure 8 Truck Categories and Load Distribution for Different Load Scenarios

Table 16 ESAL Factors for Pavement Design Scenarios

Truck Category (See Figure 8)	Distribution of Truck Type in Traffic Stream	ESAL Factor for 80% Legal Limit	ESAL Factor for Max Limit
A21	8.84%	0.720	3.020
A31/32	5.70%	0.498	1.727
A41/44/45	4.55%	1.075	3.690
A42/43	0.05%	0.757	2.035
A51/52	78.49%	1.024	3.760
A61/62	1.17%	0.501	4.469
A71	0.60%	0.299	5.380
A72	0.60%	0.292	5.108
Combined ESAL Factor with No Overweight Trucks (Scenario 2)		0.954	
Combined ESAL Factor with 8.3% Overweight Trucks (Scenario 3)			1.174

The required HMA Base Course thickness was then calculated based on the required structural number (SN) for each functional class. All of the pavement design inputs are summarized in Appendix B (Table B.1). Table 17 summarizes the number of ESALs for design Scenarios 2 and 3 along with the structural number (SN) and HMA Base Thickness (H_3) required to accommodate the number of ESALs.

Equation 1: Equivalent Single-Axle Loads (ESALs) for Pavement Design Life

$$ESALs = AADTT \times G \times f_d \times f_l \times 365 \times ESAL\ factor$$

where,
AADTT, average annual daily truck traffic
$f_{d,}$ directional distribution factor (0.5)
$f_{l,}$ lane distribution factor (0.95)
ESAL factor, equivalent single axle loaf factor, from Table 16
G, growth factor = $\frac{(1+r)^n-1}{r}$
r, growth rate (2%)
n, design life (20 years)

Table 17 Pavement Design Specifics Used in Damage Estimation for Different Roadway Functional Classes

Functional Class	No Overweight Trucks (Scenario 2)			8.3% Overweight Trucks (Scenario 3)		
	ESALs	SN	H_3 (in)	ESALs	SN	H_3 (in)
Rural Interstate	52,840,256	8.07	15.50	65,043,806	8.28	16.12
Rural Principal Arterial	4,862,107	5.98	9.35	5,985,019	6.15	9.85
Rural Minor Arterial	2,290,414	5.40	7.65	2,819,389	5.55	8.09
Rural Major Collector	2,571,693	5.48	7.88	3,165,630	5.64	8.35
Rural Local	56,577,248	8.14	15.71	69,643,862	8.35	16.33
Urban Interstate	43,678,600	7.89	14.97	53,766,249	8.09	15.10
Urban Freeway	6,831,060	6.24	10.12	8,408,705	6.41	10.62
Urban Principal Arterial	7,795,445	6.35	10.44	9,595,816	6.52	10.94
Urban Minor Arterial	2,933,337	5.58	8.18	3,610,797	5.74	8.65

6.4 Estimation of Pavement Costs

To determine the cost of the damage attributed to overweight trucks, it was first necessary to determine the replacement cost for each pavement design scenario included in the analysis. The replacement cost of pavement construction was based on typical unit prices for the materials used to construct each pavement layer. Table 18 provides unit construction cost data for the different pavement layers. These unit costs include installation and were based on actual cost data provided by SCDOT for 2011.

Table 18 Unit Construction Cost for Flexible Pavement Layers

Pavement Layer	Unit Cost
HMA Surface Course (Type A)	\$4.62 per inch/yd^2
HMA Surface Course (Type B)	\$4.22 per inch/yd^2
HMA Intermediate Course (Type B)	\$4.14 per inch/yd^2
HMA Base Course (Type A)	\$3.76 per inch/yd^2
Graded Aggregate Base	\$5.62 per 6-inch thickness/yd^2

Based on the pavement design for each traffic scenario for different highway functional classes (Table 17) and the unit costs provided in Table 18, the construction cost per lane-mile was estimated for each design scenario as summarized in Table 19. The total SCDOT highway network pavement replacement costs were calculated using per lane-mile costs and the total lane-miles for each functional class in the SCDOT network as summarized in Table 20. A minimum design scenario of a pavement section with a 1.9 inch HMA surface course and 6 inch graded aggregate base course was assumed when there was no truck traffic on highways (scenario 1). Based on this analysis, considering 8.3% of overweight trucks in the normal truck traffic (scenario 3) will result in an estimated increase in pavement replacement costs by more than \$1.1 billion.

Table 19 Pavement Cost Estimates Related to Overweight Trucks

Functional Class	Estimated Cost per Lane-Mile (2011 $)	
	No Overweight Trucks (Scenario 2)	8.3% Overweight Trucks (Scenario 3)
Rural Interstate	569,944	586,356
Rural Arterial	401,801	415,036
Rural Collector	356,801	368,448
Rural Local	362,889	375,331
Urban Interstate	575,503	591,915
Urban Freeway/Expressways	555,915	559,356
Urban Arterial	422,183	435,418
Urban Collector	430,654	443,889
Urban Local	370,831	383,272
The absolute minimum pavement design at an estimated cost of $96,012 per lane-mile.		

Table 20 Pavement Replacement Costs for SCDOT Maintained Roadways

Functional Class	Total Lane-Miles	Estimated Total Cost (2011 $)	
		No Overweight Trucks (Scenario 2)	8.3% Overweight Trucks (Scenario 3)
Rural Interstate	2,376	1,354,142,109	1,393,134,871
Rural Arterial	11,107	4,462,827,371	4,609,831,531
Rural Collector	24,687	8,808,210,479	9,095,734,717
Rural Local	25,661	9,311,997,874	9,631,244,901
Urban Interstate	1,424	819,291,974	842,655,760
Urban Freeway/Expressways	322	179,182,525	180,291,677
Urban Arterial	7,920	3,343,648,472	3,448,469,933
Urban Collector	4,646	2,000,989,333	2,062,485,366
Urban Local	12,205	4,525,913,209	4,677,754,200
Total	**90, 347**	**34,806,203,346**	**35,941,602,957**

The pavement replacement cost was divided into three categories to distribute among all vehicle types depending on their damage contribution. These costs were distributed by considering two damage factors: i) miles of travel (VMT), and ii) relative damage to pavement (in terms of ESALs). In Table 21, three cost items were separated where;

a) minimum pavement cost that was shared by all vehicles irrespective of relative damage (Scenario 1) and distributed to all vehicle types including overweight trucks by miles of travel (VMT),

b) additional cost to accommodate truck with no overweight loads according to Scenario 2 (when there was no overweight truck traffic on the system, and required pavement thickness dictated by the AADTT demand where trucks were within legal weight limit) was distributed to all trucks based on relative damage factor ESAL, and

c) additional pavement cost above Scenario 2 representing costs required to increase pavement thickness to accommodate overweight trucks (Scenario 3) which were distributed to overweight trucks only by ESAL factor.

Table 21 Total Pavement Replacement Cost (2011 $)

Functional Class	**Additional Pavement Cost (For Overweight Trucks)**	**Minimum Pavement Cost (No Truck Traffic)**	**Pavement Cost for All Trucks**
Rural Interstate	38,992,763	228,116,831	1,126,025,278
Rural Arterial	147,004,161	1,066,411,045	3,396,416,326
Rural Collector	287,524,238	2,370,209,839	6,438,000,640
Rural Local	319,247,027	2,463,735,128	6,848,262,746
Urban Interstate	23,363,786	136,683,643	682,608,331
Urban Freeway/Expressways	1,109,152	30,946,588	148,235,938
Urban Arterial	104,821,460	760,405,439	2,583,243,033
Urban Collector	61,496,033	446,110,157	1,554,879,176
Urban Local	151,840,991	1,171,807,258	3,354,105,952
Total	**1,135,399,611**	**8,674,425,928**	**26,131,777,419**

To distribute the pavement cost to respective vehicle types, design VMT and ESAL-miles were estimated for a pavement design life of 20 years with a traffic growth factor of 2% based data from 2011 (Table 22). VMT estimates utilized in damage cost distribution were discussed in Section 4.4. Total ESAL-mile by overweight trucks was estimated through multiplying overweight truck VMT by overweight truck average ESAL factor. Regular truck within legal limit ESAL-mile was estimated through multiplying regular truck VMT by regular truck average ESAL factor. All truck ESAL-mile was calculated by adding overweight truck ESAL-mile with ESAL-mile of regular trucks within legal limit. Then unit damage costs were estimated and shown in Table 23.

Table 22 Design VMT and ESAL-Miles for 20 Years of Pavement Design Life

Estimate	**Daily 2011**	**20 Years Total**
Total VMT	125,309,215	1,111,430,084,065
Light vehicles VMT	111,666,456	990,425,631,610
All truck VMT	13,642,759	121,004,452,455
Overweight truck VMT	1,132,349	10,043,369,554
Regular weight truck VMT	12,510,410	110,961,082,901
Overweight truck ESAL-mile	4,085,515	36,236,477,350
Regular weight truck ESAL-mile	11,934,931	105,856,873,088

Table 23 Unit Pavement Damage Cost Estimates (2012 $)

Cost Items	Design Life Total	Unit Cost[1]
Total VMT	1,111,430,084,065	$0.0079 per mile
All truck ESAL-mile	142,093,350,438	$0.1870 per ESAL-mile
Overweight truck ESAL-mile	36,236,477,350	$0.0319 per ESAL-mile

Per mile damage cost for each truck type loaded to the legal weight limit and the maximum overweight limit for each overweight truck type are summarized in Table 24. Column 6 in Table 24 is the per mile additional pavement damage cost for overweight trucks for carrying additional loads between the legal weight limit and the maximum overweight limit.

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[1] Damage cost values converted from the base year 2011 to the year 2012 with a CPI of 1.17%.

Table 24 Unit Pavement Damage Cost Per Mile for Different Truck Types (2012 $)

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

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[2] Per mile damage includes first two cost items shown in Table 23.
[3] Per mile damage includes all three cost items shown in Table 23.
[4] Maximum weight allowed in typical SC overweight permits.

7.0 Bridge Deterioration

Bridges represent a relatively small percentage of total lane miles compared to pavements, but bridge construction and maintenance costs, and traffic disruption after failure are significantly higher than pavements. In the following subsections, bridge damage quantification method due to overweight and regular trucks is outlined.

7.1 Relevant Studies on Bridge Deterioration due to Trucks

Although bridges comprise a small percentage of total highway mileage, their costs, construction time, and traffic disruption upon failure or temporary closing significantly impact highway system performance. Moreover, the catastrophic nature of bridge failures in terms of user fatality, property loss, and traffic disruption necessitates maintaining the structural integrity and serviceability of bridges and merits substantial consideration.

According to the 2013 ASCE Infrastructure Report Card, more than 24% of the bridges in the US were deemed “functionally obsolete” (ASCE, 2013). Moreover, 30% of bridges are more than 50 years old and are approaching the target design life of 75 years. In order to eliminate deficient bridges by 2028, an annual investment of $20.5 billion is needed while the current annual investment is only $ 12.8 billion (ASCE, 2013).

Overweight truck loading is one of the greatest concerns to many state departments of transportation. The presence of overweight trucks means load demands may be greater than the design loads, which not only compromises the safety of bridges, but may also cause accelerated bridge deterioration. Because overweight trucks could produce a higher stress range, they could significantly reduce the service life of the bridge or even cause fatigue failure. The impact of overloading is more significant for existing bridges because corrosion and other deteriorations may already have occurred in existing bridges due to years of exposure to deicing agents and environmental elements (Jaffer and Hansson, 2009). The occurrence of cracks combined with overweight trucks would result in higher stress ranges and ultimately reduce the bridge fatigue life.

An Indiana study (Chotickai and Bowman, 2006) evaluated the steel bridge fatigue damage caused by overweight vehicles along a high traffic volume highway in Northern Indiana. Weigh-in-motion (WIM) data was used to get the truck weight distribution. The FHWA Class 9 trucks and Class 13 trucks were found to be the two most common truck types (Chotickai and Bowman, 2006). The maximum weights for these two types of trucks were 150,000 lbs and 200,000 lbs, respectively. The average truck gross weight for all trucks in both directions on this highway was 52,368 lbs (Chotickai and Bowman, 2006). Class 9 trucks had an average gross weight of 54,356 lbs and Class 13 trucks had an average weight of 119,459 lbs. Strain gages were installed to obtain the strain range and to estimate fatigue damage. According to Chotickai and Bowman (2006), fatigue failure was not a concern for the bridges in Indiana because overweight trucks, which could cause significant fatigue damage, made up less than 1% of the whole truck population in Indiana.

In a recent study of steel and prestressed concrete bridge fatigue damage caused by increased truck weight, researchers selected five steel bridges and three prestressed concrete bridges on Minnesota highways for instrumentation and loading (Altay et al., 2003). For comparison purposes, the selected bridges were also modeled using the SAP2000 software and the remaining fatigue lives were calculated for all eight bridges. They found that for prestressed concrete bridges, a 10% to 20% increase in allowable gross vehicle weight did not have a significant impact on the fatigue life of bridges because of a very small increase in the stress range (Altay et al., 2003). In fact, the analysis results showed that prestressed bridges have infinite fatigue lives. For most modern steel bridges, a 20% increase in truck weight would not cause fatigue issue. However, for certain steel bridges with very high traffic volumes and very poor fatigue details, fatigue might be a safety concern (Altay et al., 2003).

Creating standards for assigning maximum allowable loads on bridges for different truck types has been particularly difficult. State and local agencies use the Federal Bridges Formula (FBF) or modified FBF to determine the maximum allowable load on bridges. This formula gives advantages to multi-axle trucks by allowing them to carry more weight and restricts small trucks (FHWA, 1990). While many bridge studies and models exist, researchers cannot generalize many findings because the specific bridge conditions, traffic patterns, truck fleets, and environmental conditions were not replicated elsewhere. Some findings were limited to infrastructure or bridges of certain types.

Rebar is a critical component in reinforced concrete bridges. Helgason et al. concluded that factors including stress range, yielding stress, bar size, and shape affected the fatigue strength of rebars (Helgason et al., 1976). Among these factors, the stress range was the most critical factor in determining a rebar's fatigue life. The fatigue life of rebars can be estimated with parameters including stress range, minimum stress, rebar yield stress and nominal bar diameter (Helgason et al., 1976):

Equation 2: Bridge Fatigue Life

$$\mathrm{Log\,N} = 4.419 - 0.0392 * \sigma - 0.013 * \sigma_{\mathrm{min}} + 0.0079 * \mathrm{G} + 7.8059 * \mathrm{D}_{\mathrm{nom}} - 8.4155 * \mathrm{D}_{\mathrm{nom}}{}^{2} + 2.799 * \mathrm{D}_{\mathrm{nom}}{}^{3}$$

where,
N, fatigue life in number of stress cycles
σ_{min}, minimum stress during stress cycle in ksi
G, rebar yield strength in ksi
$\mathrm{D}_{\mathrm{nom}}$, nominal rebar diameter in inches

Figure 9 shows a typical rebar fatigue curve, in terms of the stress range (S) versus the number of cycles (N). The fatigue curve is commonly known as the S-N curve. According to Helgason et al. (1976), there is a limiting stress range (endurance limit), below which the rebar is assumed to have infinite fatigue life (Figure 9).

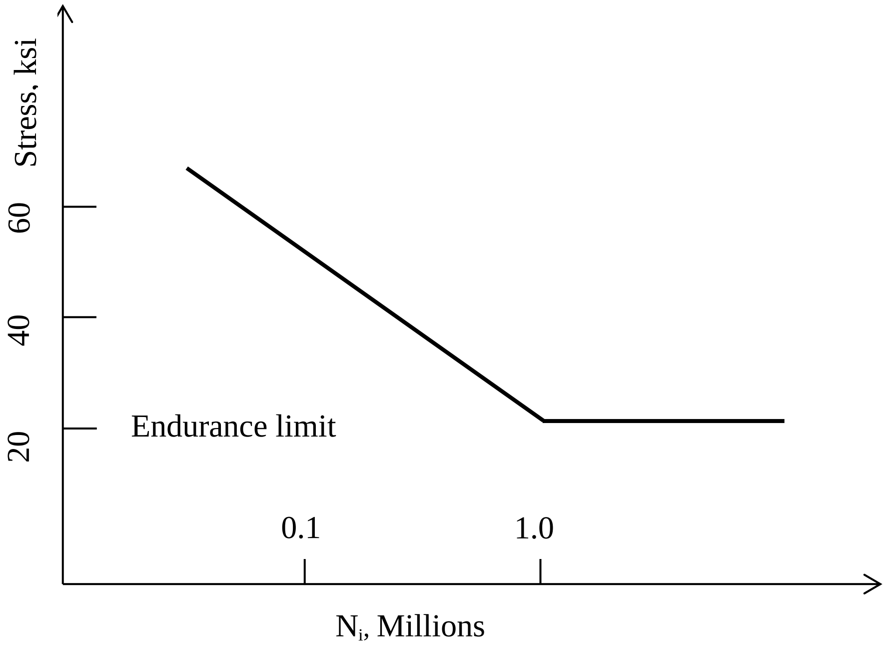


Figure 9 Rebar S-N Curve (Helgason et al., 1976)

From Figure 9, one can see that the endurance limit is around 20 ksi. A rebar is expected to be able to sustain unlimited number of cycles if its stress range is below this limit (Helgason et al., 1976). Note that the fatigue experiments by Helgason et al. were tested to a maximum of five million cycles. However, a recent fatigue study with large number of cycles (Giga-cycles) shows that there is a further fatigue strength drop beyond the endurance limit determined by Helgason et al. (see Figure 10). The slope of the fatigue curve in the Giga-cycle region is similar to that of the High-cycle fatigue region. More details on the Giga-cycle fatigue can be found in (Bathias and Paris, 2005).

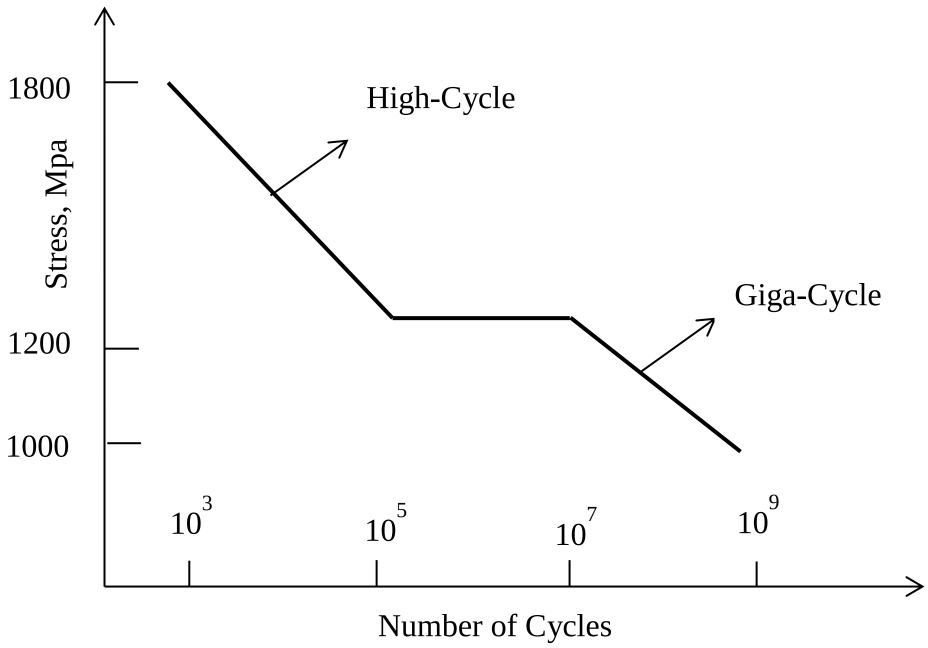


Figure 10 Gigacycle S-N Curve (Bathias and Paris, 2005)

An investigation on the fatigue behavior of pretensioned concrete girders was conducted by Overman et al. (1984). This study included an extensive literature review and full-scale fatigue tests of flexural prestressed concrete girders. In the Overman et al. study, it was found that among the different fatigue failure mechanisms of prestressed concrete girders, the most common fatigue failure was the fatigue fracture of prestressing strands (Overman et al., 1984). To estimate the prestressing strands fatigue life, the following equation by Paulson et al. (1983) can be used:

Equation 3: Prestressed Strand Fatigue Life

$$\mathrm{Log\,N} = 11 - 3.5 \times \mathrm{Log}\,\sigma$$

where,
N, fatigue life in number of stress cycles
σ, prestressing strand stress range in ksi

AASHTO LRFD specification provides a design fatigue truck with a gross vehicle weight of 54 kips and front axle spacing of 14 feet and rear axle spacing of 30 feet (AASHTO, 2007). AASHTO LRFD states that the maximum design ADT (average daily traffic) under normal conditions is limited to around 20,000 vehicles per lane. This maximum design ADT can be used to estimate the single-lane average daily truck traffic ($\mathrm{ADTT_{SL}}$), by multiplying it with the fraction of truck traffic shown in Table 25 (AASHTO, 2007).

Table 25 Distribution of Truck Traffic (AASHTO, 2007)

Highway Classification	Percentage of Trucks in Traffic
Rural Interstate	0.20
Urban Interstate	0.15
Other Rural	0.15
Other Urban	0.10

7.2 Bridge Deterioration Modeling Method

The bridge damage modeling methodology is summarized in Figure 11. The first step was to develop a series of representative truck models to represent the truck population in South Carolina (Figure 11). These truck models (with different truck weights and axle configuration) were developed based on the truck gross weight distribution, truck axle configuration distribution, and truck weight limits in South Carolina. Details of truck models are presented in Appendix A-2.

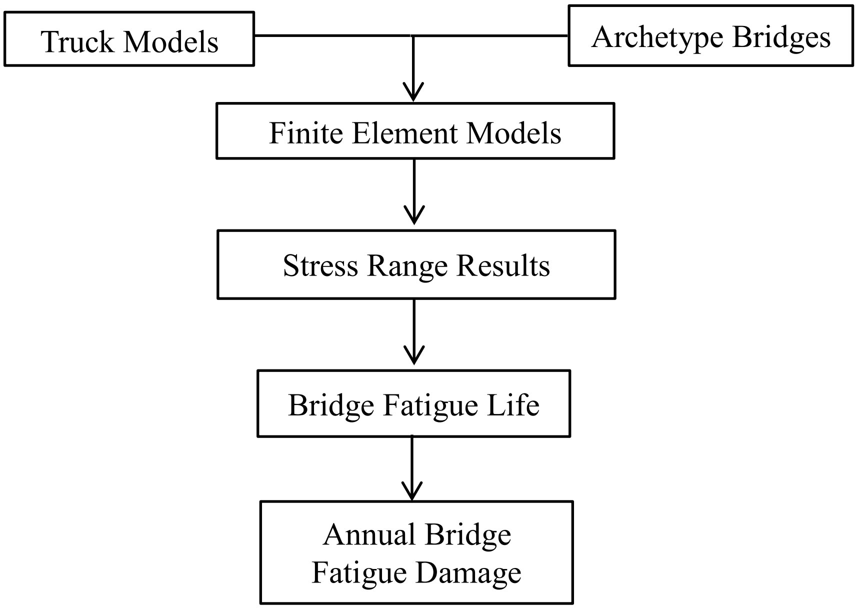


Figure 11 Bridge Damage Modeling Method

Due to the large number of bridges in South Carolina (9,271 bridges), it was not feasible to create a finite element (FE) model for each bridge. The second step was to develop Archetype bridges to represent groups of bridges which share common features and structural characteristics. Bridge information such as the material, span length, count, location, etc. were obtained from the National Bridge Inventory database (NBI, 2012). Four types of Archetype bridges were modeled to quantify bridge damage due to trucks for this project (Table 26). The selection details of Archetype bridges are described in Appendix C.

Table 26 Archetype Bridge Properties

Archetype	Archetype Description
1	Reinforced concrete slab bridge with span of 10m (33ft)
2	Prestressed concrete beam bridge with span less than 20m (66ft)
3	Prestressed concrete beam bridge with span 20m (66ft) to 35m (115ft)
4	Prestressed concrete beam bridge with span 35m (115ft) to 45m (148ft)

The third step was to build finite element (FE) models for all Archetype bridges using a finite element program, called LS-DYNA (LS-DYNA, 2010). In this step, the FE models were developed and analyzed with combinations of Archetype bridges and truck models. The details of the four Archetype bridge FE models are discussed in Appendix D.

The fourth step was to solve the finite element models built in the third step and to record the stress ranges for each analysis. In this step, the supercomputing facility at Argonne National Laboratory was utilized to run simulation models. The fifth step was to calculate bridge fatigue life for all Archetype bridges using the stress ranges calculated form the FE analysis. Findings of the fatigue analysis are discussed in the next subsection. Details of fatigue life analysis can be found in Appendix E. The final step was to quantify the annual bridge fatigue damage for all Archetype bridges.

7.3 Annual Bridge Fatigue Damage

The annual bridge damage caused by a truck model is defined as the annual consumed fatigue life by a particular truck model (N_{Ci}) divided by the bridge fatigue life of this truck model (N_i). The total bridge fatigue damage (D) is the sum of fatigue damage from all truck models, as shown in Equation 4.

Equation 4: Bridge Fatigue Damage

$$\mathbf{Fatigue\ Damage\ (D)} = \frac{\mathbf{Consumed\ Fatigue\ Life}}{\mathbf{Bridge\ Fatigue\ Life}}$$

$$= \sum \left(\frac{\mathbf{N_{Ci,1}}}{\mathbf{N_{i,1}}} + \frac{\mathbf{N_{Ci,2}}}{\mathbf{N_{i,2}}} + \frac{\mathbf{N_{Ci,3}}}{\mathbf{N_{i,3}}} \right)$$

where,

$N_{Ci,1}$, $N_{Ci,2}$, $N_{Ci,3}$, number of loading cycles consumed for the *i-th* truck model with gross vehicle weight levels 1 to 3 (GVW1, GVW2, GVW3), respectively

$N_{i,1}$, $N_{i,2}$,, $N_{i,3}$, allowable number of loading cycles for the *i-th* truck model with gross vehicle weight levels 1 to 3 (GVW1, GVW2, GVW3), respectively

i, truck type

Note that the bridge fatigue damage (*D*) is a unitless quantity, where *D* equal to zero means no damage and *D* equal to one means the particular bridge has used up its fatigue life (i.e., complete damage under repetitive fatigue loading). A sample calculation of annual bridge fatigue damage is given in Appendix F.

7.4 Bridge Damage Cost Estimation Method

To estimate bridge damage costs due to overweight trucks, bridge fatigue damage models and bridge replacement cost models were combined and used as inputs for the bridge cost estimation method outlined in Figure 12, and each step is discussed in the next subsections.

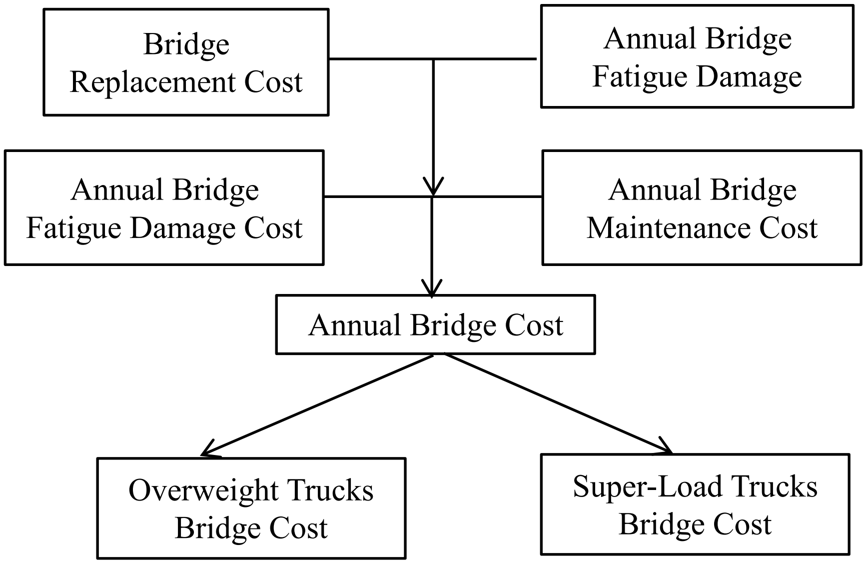


Figure 12 Bridge Cost Estimation Method

7.5 Bridge Cost Estimation Models

To estimate the damage costs caused by truck traffic on bridges, the replacement costs of individual bridges must first be determined. The bridge replacement costs used in this study were derived from the bridge replacement cost database in the HAZUS-MH program (HAZUS-MH, 2003). The HAZUS-MH program is established for loss estimation under extreme natural hazard events (e.g., earthquakes); hence not all the bridges are accounted for in the HAZUS-MH program. The HAZUS-MH database contains the replacement costs for approximately half of the bridges in South Carolina (4,096 bridges). The total number of bridges in South Carolina is 9,271. For those bridges that are not in the HAZUS-MH database, their replacement costs were estimated using the bridge cost models, developed as part of this study using the replacement costs of the 4,096 bridges available in the HAZUS-MH database.

The first step in developing the bridge cost model was to match the longitude and latitude coordinates of the 4,096 bridges with known replacement costs in the HAZUS-MH program to that in the NBI database. Next, the 9,271 bridges in NBI database were grouped together according to their material type and structural type.

For those bridge cost groups that have more than five known bridge replacement costs (obtained from the HAZUS-MH database), the bridge replacement costs were fitted to two power equations, one as a function of the total structure length, and the other as a function of the total structure area. For each bridge cost group, the RMS (root mean square) errors of the fitted power equation curves for both the total structure length and total area models were calculated. The model with the smaller RMS value was selected as the cost model for the bridge cost group. The selected model or equation was then used to compute the replacement costs of those bridges that were not accounted for in the HAZUS-MH database.

For the bridge cost groups that have less than five known bridge replacement costs, an average unit area cost was determined and used as the replacement cost to compute the replacement costs for the rest of the bridges in the same cost group. For bridge cost groups that were unable to establish a cost model or unit area cost, a cost model or unit area cost from a similar bridge cost group was assigned to this cost group. More details on the development of bridge cost models can be found in Appendix G.

The total replacement cost for all bridges in South Carolina was determined to be approximately $7.615 billion (2003 US $). Note that the estimated total bridge asset value was derived from the bridge replacement cost database in the HAZUS-MH program, which was based on the 2003 US $. Using consumer price index (CPI), these costs were converted from 2003 US $ to 2012 US $ and the total bridge replacement cost in 2012 US dollar was found to be $9.491 billion.

7.5.1 Annual Bridge Cost

The annual bridge cost considered in this study included two components: (1) the annual bridge fatigue damage cost due to truck traffic, and (2) routine bridge maintenance cost. The annual bridge maintenance cost was obtained directly from the SCDOT bridge maintenance division, while the bridge damage cost was obtained using the fatigue analysis. The procedure for determining the annual fatigue damage cost is summarized in the following steps:

Step 1: Compute the allowable bridge fatigue life (N) for each truck model (i) using the FE analysis results
Step 2: Compute the annual consumed bridge fatigue life (N_C) for each truck model
Step 3: Compute the annual bridge fatigue damage (D)
Step 4: Determine the bridge replacement cost (C_R)
Step 5: Compute the annual bridge fatigue damage cost (C_D)

Once the total annual bridge fatigue damage cost in South Carolina was calculated using the steps shown above, the annual bridge maintenance cost was then added to the fatigue damage cost to obtain the total annual bridge cost in South Carolina. More details for each step are discussed in the following sections.

7.5.1.1 Annual Bridge Fatigue Damage Cost in South Carolina

A sample calculation of annual bridge fatigue damage cost is given in Appendix H, using an assumed AADTT of 4,000 and a bridge replacement cost of $1 million dollars. To compute the annual bridge fatigue damage cost for all bridges in South Carolina, the estimated average daily traffic data in the NBI database (NBI, 2012) and the actual bridge replacement costs were used. The ADTT for each bridge was computed using the ADT (average daily traffic) multiplied by its truck percentage from the NBI database (NBI, 2012). In the NBI database, the truck percentage for some bridges is listed as zero. For those bridges with a zero truck percentage, a nominal ADTT equal to 1% of the ADT was assumed. It should be noted that the ADT entries in the NBI database were not all recorded for the same year. A 2% annual increase in ADT was used to adjust and normalize the ADT of all bridges to year 2012.

Table 27 shows the total bridge replacement costs and the associated damage costs for the four Archetype bridges. The total replacement cost for those bridges that were not represented by the four Archetype bridges, shown as “Others” in Table 27, was determined by subtracting the sum of the replacement costs of the four Archetype bridges from the total bridge replacement cost in South Carolina (i.e. $9.491 billion 2012 US $). Also shown in Table 27 are the annual damage cost ratios, as a fraction of the total replacement cost for each Archetype bridge group. The damage cost ratio for each Archetype was computed as the annual bridge fatigue damage cost divided by the total replacement cost of the Archetype bridge group. For bridges in the “others” category their total annual bridge fatigue damage cost was estimated using the average damage cost ratio of the four Archetype bridges multiplied by their bridge replacement cost ($5.825 billion). As shown in Table 27, the total annual bridge fatigue damage cost in South Carolina was found to be approximately $30.446 million (2012 US $).

Table 27 Annual Bridge Fatigue Damage Cost in South Carolina

Archetype Bridge	Bridge Replacement Cost (US $)	Annual Bridge Fatigue Damage Cost (US $)	Annual Damage Cost Ratio
A1	1,646,866,993	3,491,516	0.0021
A2	1,224,251,506	5,761,460	0.0047
A3	594,491,719	1,701,961	0.0029
A4	200,493,784	651,344	0.0032
Others	5,824,693,711	18,839,665	0.0032
All	9,490,797,713	30,445,947	

7.5.1.2 Annual Bridge Maintenance Cost in South Carolina

As stated previously, the total bridge cost included both fatigue damage cost and maintenance cost. The annual bridge maintenance cost was obtained from the SCDOT maintenance cost schedule for the period of July 2010 to June 2011 (SCDOT, 2012c). The total annual cost for activities related to routine bridge maintenance excluding bridge replacement was found to be approximately equal to $6.555 million dollars (2012 US $) (Table 28). The complete maintenance schedule and cost breakdowns can be found in Appendix J.

The total annual bridge cost in South Carolina was computed by adding the annual bridge fatigue damage cost and the annual bridge maintenance cost (Equation 5).

Equation 5: Total Annual Bridge Cost

$$\mathrm{C} = \mathrm{C_D} + \mathrm{C_M}$$

where,
C_D, annual bridge fatigue damage cost in South Carolina
$C_{M,}$ annual bridge maintenance cost in South Carolina

It was found that the total annual bridge cost in South Carolina is approximately $37 million dollars (2012 US $) (Table 28).

Table 28 Annual Bridge Damage Cost in South Carolina

Annual Fatigue Damage Cost (US $)	Annual Maintenance Cost (US $)	Total Annual Cost (US $)
30,445,947	6,554,992	37,000,939

7.5.2 Overweight Trucks Bridge Damage Cost

To identify the impact of overweight trucks on the bridge network, the annual bridge cost was allocated to overweight trucks in South Carolina based on the damage contribution of overweight trucks and the percentage of overweight trucks in the overall truck population. For the purpose of setting a fee structure for operating overweight trucks, the unit costs (cost per mile) of overweight trucks of different axle configurations and gross weights were also computed using the vehicle miles traveled (VMT) of individual truck models.

7.5.2.1 Annual Bridge Damage Cost Allocated to Overweight Trucks

Similar to the total annual bridge cost calculation, the annual bridge cost allocated to overweight trucks included two types of costs, namely the bridge fatigue and maintenance costs. The truck models with either gross vehicle weight levels 2 and 3 (GVW2 and GVW3) are considered to be overweight trucks.

The allocation of bridge damage cost was carried out using the damage contribution of the overweight trucks (Equation 6).

Equation 6: Annual Bridge Damage Cost Allocation

$$\mathbf{C_{D,O}} = \frac{\mathbf{D_{GVW2}} + \mathbf{D_{GVW3}}}{\mathbf{D}} \times \mathbf{C_D}$$

where,
$C_{D,O}$, annual bridge damage cost allocated to all overweight trucks
D_{GVW2}, annual bridge fatigue damage caused by all GVW2 trucks
D_{GVW3}, annual bridge fatigue damage caused by all GVW3 trucks
D, total annual bridge fatigue damage
C_D, annual bridge fatigue damage cost.

The allocation of the maintenance cost to the overweight trucks was carried out using the percent of the overweight truck in the total truck population (Equation 7).

Equation 7: Annual Bridge Maintenance Cost Allocation

$$\mathrm{C_{M,O}} = \frac{\mathrm{N_{GVW2}} + \mathrm{N_{GVW3}}}{\mathrm{N_{GVW1}} + \mathrm{N_{GVW2}} + \mathrm{N_{GVW3}}} \times \mathrm{C_M}$$

where,
$C_{M,O}$, annual bridge maintenance cost allocated to the overweight trucks
$N_{GVW1}, N_{GVW2}, N_{GVW3}$, number of trucks for gross vehicle weight levels GVW1, GVW2 and GVW3, respectively
C_M, total annual bridge maintenance cost

The total annual bridge cost allocated to the overweight trucks was calculated in Equation 8 and the results are summarized in Table 29. More details of the calculation can be found in Appendix H. The annual bridge cost caused by the overweight trucks is approximately $8.8 million dollars (2012 US $).

Equation 8: Total Annual Bridge Damage Cost Allocation

$$\mathbf{C_O = C_{D,O} + C_{M,O}}$$

where,
C_O, total annual bridge cost allocated to overweight trucks
$C_{D,O}$, annual bridge damage cost allocated to overweight trucks
$C_{M,O}$, annual bridge maintenance cost allocated to overweight trucks

Table 29 Annual Bridge Damage Cost Allocated to Overweight Trucks

Annual Bridge Fatigue Damage Cost Allocated to Overweight Trucks (US $)	Annual Bridge Maintenance Cost Allocated to Overweight Trucks (US $)	Annual Bridge Cost Allocated to Overweight Trucks (US $)
8,764,769	35,351	8,800,119

7.5.2.2 Overweight Trucks Bridge Damage Cost per Mile

Because the mileages travelled by overweight trucks included not only bridges but also pavements, unit costs associated with overweight trucks were calculated as per mile of road travelled, instead of per bridge length travelled. Because trucks with different weights and axle configurations cause different levels of damages, the overweight trucks bridge costs per mile in this research were computed by axle group. The overweight trucks bridge damage cost per mile for each axle group was computed using Equation 9.

Equation 9: Per Mile Bridge Damage Cost

$$C_{Pj,O} = \frac{C_{Oj}}{VMT_{j,O}}$$

where,

C_{Oj}, Daily bridge cost allocated to overweight trucks in each axle group

$VMT_{j,O}$, Daily VMT (vehicle miles travelled) by overweight trucks in the axle group being considered.

j, Axle group

The daily bridge cost allocated to overweight trucks in each axle group consisted of two parts: the daily fatigue damage cost and the daily maintenance cost. The estimated costs per mile by weight and axle group are shown in Table 30 and detailed calculations can be found in Appendix H. An example calculation for damage cost per trip is also provided in Table 30. Assuming a trip length of 100 miles, the corresponding cost for each truck type can be calculated by multiplying trip length by the cost per mile (Table 30). The results shown in Table 30 can be used for further analysis for establishing an overweight permit fee structure based on vehicle miles travelled.

Table 30 Overweight Trucks' Bridge Damage Cost per Mile in Each Axle Group (US $)

Axle Group	Overweight Trucks' Bridge Damage per Mile	Overweight Trucks' Bridge Damage per 100 Miles
2-Axle	0.0124	1.24
3-Axle	0.0153	1.53
4-Axle	0.0308	3.08
5-Axle	0.0306	3.06
6-Axle	0.0255	2.55
7-Axle	0.0617	6.17
8-Axle	0.0635	6.35

7.5.3 Bridge Damage Costs for Super-load Trucks

It has been observed that the relationship between damage and truck weight is highly nonlinear. The damages to bridges caused by trucks with extremely high loadings, referred herein as *super-load*, can be significantly higher than that of the trucks with their weights between the legal weight limit and the maximum weight limit. In this study, super-load means the truck gross vehicle weight is more than the maximum weight limit allowed by the South Carolina Department of Transportation (SCDOT, 2012a).

The first step in developing the functional relationship between bridge cost per mile and gross vehicle weight was to compute bridge costs per mile for each axle group for the three distinct weight levels, namely GVW1, GVW2, and GVW3. The methodology used to compute the super-load trucks bridge cost per mile for each gross vehicle weight level and axle group was the same as the one used to determine bridge damage cost per mile for the overweight trucks. The estimated costs per mile by weight and axle group are shown in Table 31 and detailed calculations can be found in Appendix I. Figure 13 shows the super-load trucks bridge cost per mile as a function of gross vehicle weight (GVW) and axle groups. A nonlinear exponential trend line was fitted to the three data points of each axle group, which corresponded to the three GVW levels (i.e. GVW1, GVW2 and GVW3).

Equation 10: Bridge Damage Model

$$C = c_1 e^{(c_2 \times GVW)}$$

where,
C, bridge cost per mile (in 2012 US $)
GVW, gross vehicle weight of the truck in kips
c_1 *and* c_2, coefficients determined through least-square regression
The fitted coefficients are shown in Figure 13.

Table 31 Bridge Cost per Mile by Axle Group and Gross Vehicle Weight (US $)

Axle Group	GVW1 Trucks Bridge Cost per Mile	GVW2 Trucks Bridge Cost per Mile	GVW3 Trucks Bridge Cost per Mile
2-Axle	0.0025	0.0042	0.0113
3-Axle	0.0045	0.0103	0.0188
4-Axle	0.0043	0.0088	0.0497
5-Axle	0.0050	0.0110	0.0682
6-Axle	0.0059	0.0228	0.0654
7-Axle	0.0076	0.0475	0.3512
8-Axle	0.0077	0.0507	0.1191

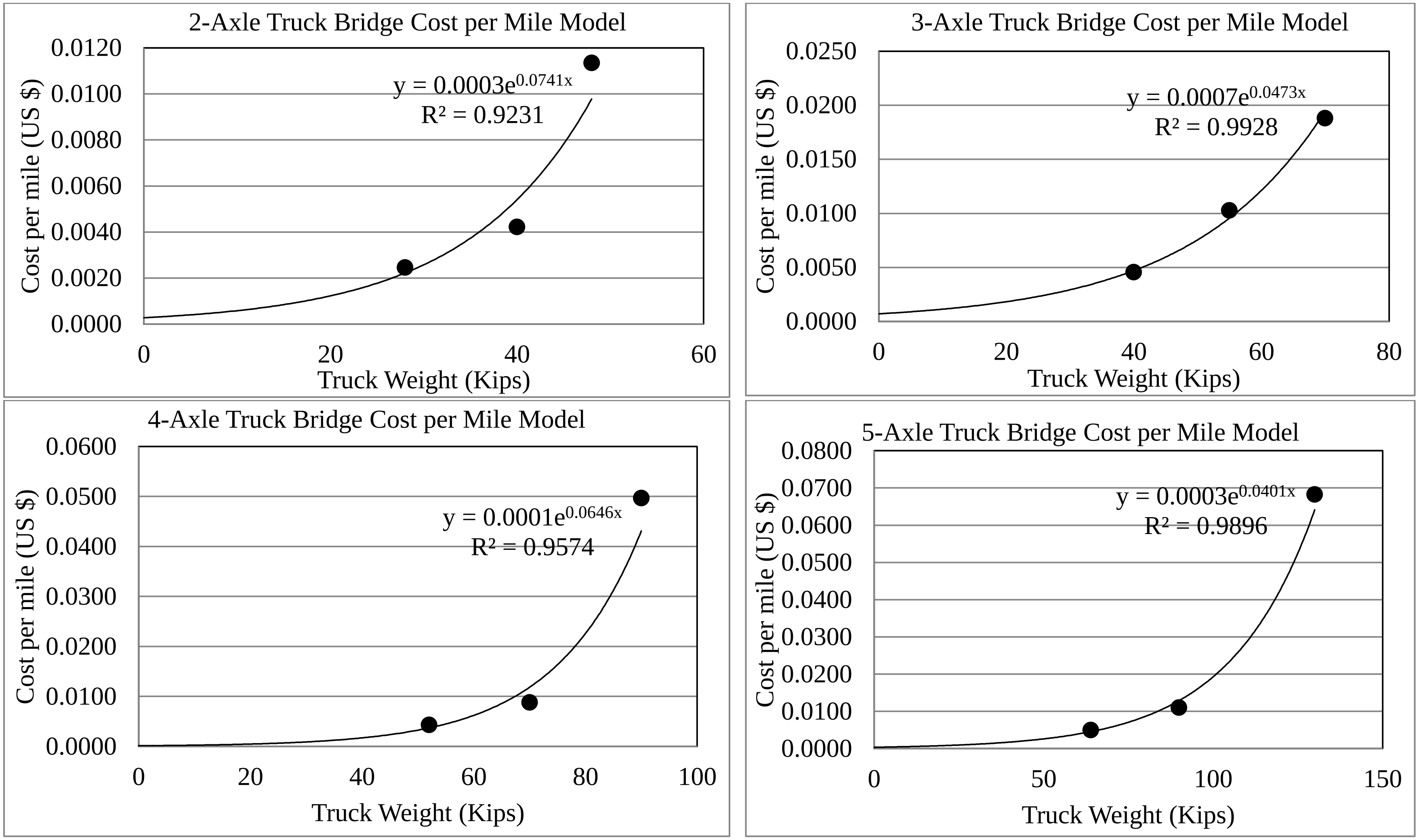


Figure 13 Bridge Damage Cost per Mile

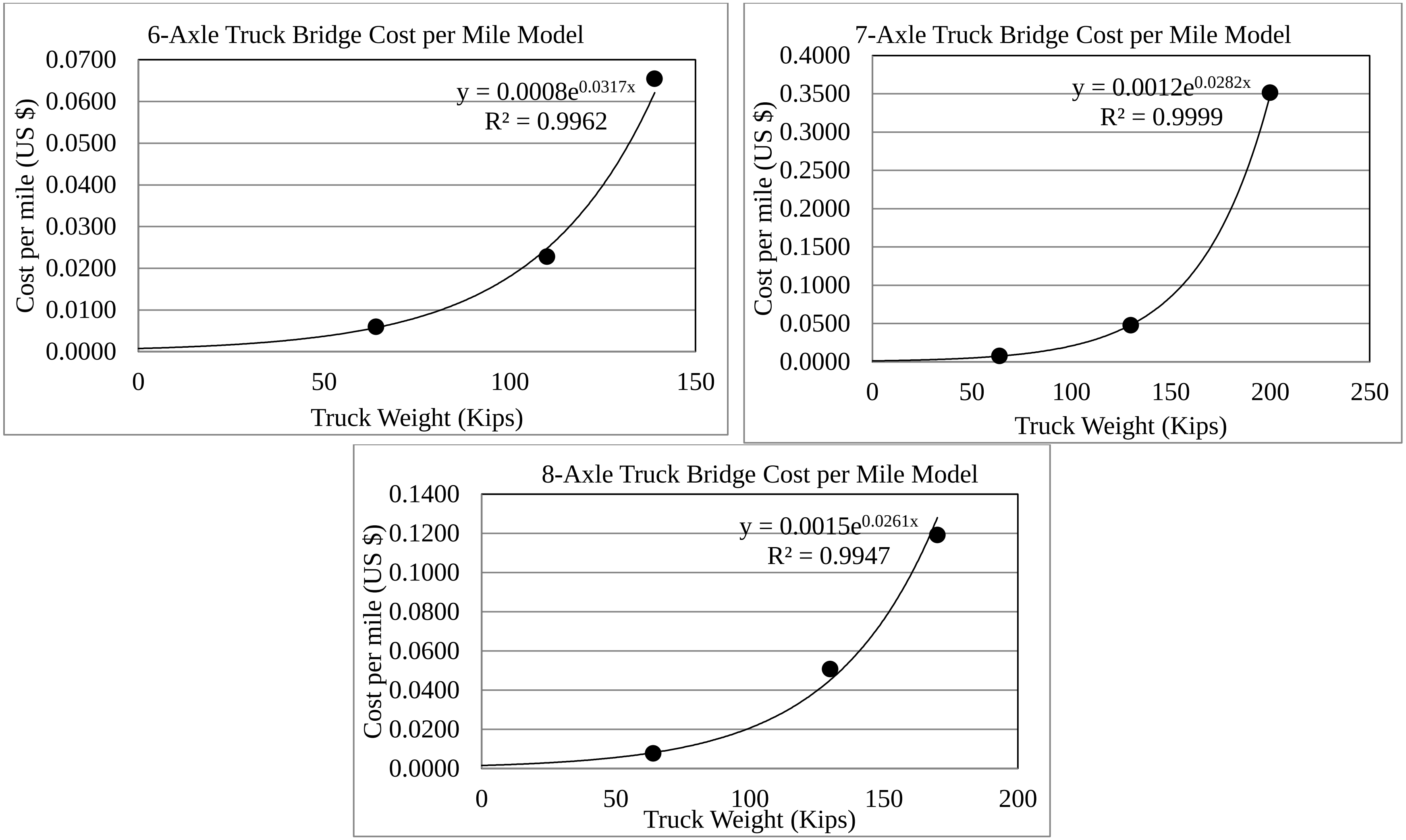


Figure 13 Bridge Damage Cost per Mile (Continued)

As can be seen, the relationship between cost per mile and truck weight is highly nonlinear. Using the cost per mile models developed for different axle groups, the cost of any arbitrary gross vehicle weight including that of the super-load trucks can be estimated. Due to the fact that the cost per mile and truck weigh relationships were derived from selected WIM data, these models must be used with caution.

The R^2 values of the fitted curves are very close to 1 which means the goodness-of-fit of the trend lines are extremely high. This is because only three data points were used to estimate two coefficients, which typically will yield good agreement. More accurate curves might be obtained if more data points were utilized. Based on the bridge damage cost equations (Figure 13), bridge damage cost per mile for trucks loaded at the legal weight limit and the maximum overweight limit are presented in Table 32.

Table 32 Unit Bridge Damage Cost Per mile for Different Truck Types (2012 $)

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

Because GVW1 and GVW3 are the lower and upper limits for each curve, respectively, application of the cost models for truck weights within these limits is considered to be accurate. However, great care in application of these models is necessary if the truck gross weight is outside of the limits (i.e., extrapolation).

The costs per mile of three levels of super-loading were computed in this study. These three super-loads are defined in Equation 11.

Equation 11: Super-load Classes

Super-load 1: GVW2 + 25% x (GVW3-GVW2)
Super-load 2: GVW2 + 50% x (GVW3-GVW2)
Super-load 3: GVW2 + 75% x (GVW3-GVW2)

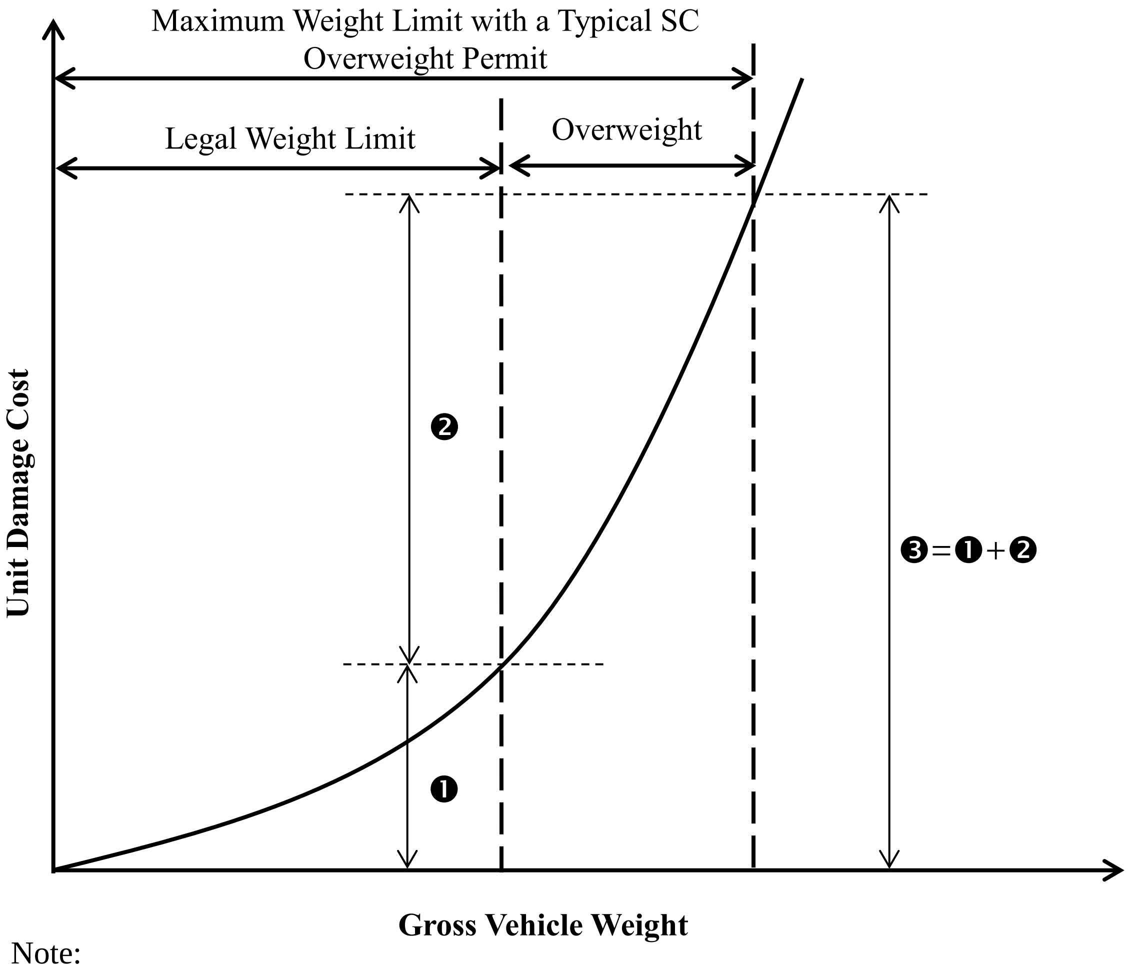
Note that GVW2 and GVW3 correspond to maximum weight limits and maximum considered weight for each axle group trucks, respectively. Using the bridge cost per mile models, the costs of these three super-loads for all axle groups were calculated (Table 33). The results presented here may be used by SCDOT to establish or adjust the fee structure for operating super-load trucks.

Table 33 Bridge Damage Due to Super-Load Trucks by Axle Group (2012 $)

Axle Group	Super-load	Vehicle Gross Weight (Kips)	Bridge Damage per Mile
2-Axle	1	42	0.0067
	2	44	0.0078
	3	46	0.0091
3-Axle	1	59	0.0114
	2	63	0.0138
	3	66	0.0159
4-Axle	1	75	0.0127
	2	80	0.0176
	3	85	0.0242
5-Axle	1	100	0.0165
	2	110	0.0247
	3	120	0.0369
6-Axle	1	117	0.0326
	2	125	0.0421
	3	132	0.0525
7-Axle	1	148	0.0779
	2	165	0.1259
	3	183	0.2091
8-Axle	1	140	0.0579
	2	150	0.0752
	3	160	0.0977

8.0 Combined Axle-Based Pavement and Bridge Damage Cost

Total damage cost due to overweight trucks can be broken down into two parts (Figure 14). Part 1 is the total damage imparted by a truck loaded at legal weight limits, and Part 2 represents additional damage cost due to additional weight allowed with typical overweight permits beyond the legal weight limit. In this study, damage costs were estimated for trucks loaded at legal weight limits and at corresponding maximum weight limits with typical overweight permits. Pavement and bridge unit damage costs were combined to estimate per-mile and per-trip damage costs for different overweight truck configurations.



Note:

❶Unit damage cost for a truck loaded at the legal weight limit

❷Additional unit damage cost due to additional weights above the legal weight limit to the maximum weight limit with typical SC overweight permits

❸Unit damage cost for a truck loaded at the maximum weight limit with typical SC overweight permits

Figure 14 Damage Contribution of Trucks at Different Gross Vehicle Weights

In Table 34, combined pavement and bridge damage cost per mile and per trip are presented considering estimated trip length for different truck types (Table 15 provides trip length by different truck types). As truck axle load and configurations were considered in the cost calculation, this damage cost can be interpreted as axle based damage cost. Additional damage cost due to additional weight of overweight trucks is shown in Table 34 (Column 6). As shown in Table 34, pavement and bridge damage increase substantially above legal weight limits. As an example, a 2-axle truck is loaded at the legal weight limit of 35,000 pounds incurs a damage cost of $26.42 per trip. Permitting 5,000 pounds above the legal weight limit increases the damage by $24.19 to a total of $50.61 of damage imparted for the trip, which indicates that overweight trucks cause accelerated damage to pavements and bridges above the legal weight limit.

Table 34 Combined Pavement and Bridge Damage Cost for Different Truck Types (2012 $)

Truck Type (See Figure 8 for details)	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	Per Trip Damage for a Truck Loaded at the Legal Weight Limit	Per Trip Damage for an Overweight Truck Loaded up to the Maximum Overweight Limit[5]	Additional per Trip Damage above the Legal Limit for an Overweight Truck Loaded up to the Maximum Overweight Limit
2-axle, 35-40 kips	$0.3523	$0.6748	$26.42	$50.61	24.19
3-axle, single unit, 46-50 kips	$0.2474	$0.3933	$24.74	$39.33	14.58
3-axle, combination, 50-55 kips	$0.4442	$0.7444	$55.53	$93.05	37.53
4-axle, single unit, 63.5-65 kips	$0.3585	$0.4600	$96.78	$124.21	27.42
4-axle, combination, 65-70 kips	$0.4884	$0.8247	$131.87	$222.68	90.80
5-axle, 80-90 kips	$0.4583	$0.8420	$73.33	$134.73	61.40
6-axle, 80-90 kips	$0.2585	$0.4407	$41.36	$70.52	29.16
6-axle, 90-100 kips	$0.2585	$0.6834	$41.36	$109.35	67.99
6-axle, 100-110 kips	$0.2585	$1.0123	$41.36	$161.97	120.61
7-axle, 80-90 kips	$0.1428	$0.2556	$22.84	$40.89	18.05
7-axle, 90-100 kips	$0.1428	$0.3956	$22.84	$63.29	40.45
7-axle, 100-110 kips	$0.1428	$0.5880	$22.84	$94.08	71.23
7-axle, 110-120 kips	$0.1428	$0.8440	$22.84	$135.04	112.20
7-axle, 120-130 kips	$0.1428	$1.1730	$22.84	$187.67	164.83
8-axle, 80-90 kips	$0.1140	$0.2005	$18.23	$32.08	13.84
8-axle, 90-100 kips	$0.1140	$0.3059	$18.23	$48.94	30.70
8-axle, 100-110 kips	$0.1140	$0.4668	$18.23	$74.69	56.46
8-axle, 110-120 kips	$0.1140	$0.6497	$18.23	$103.96	85.72
8-axle, 120-130 kips	$0.1140	$0.9030	$18.23	$144.47	126.24

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[5] Maximum weight allowed with typical SC overweight permits.

9.0 Summary of Heavy-Vehicle Impacts

Damage estimates of heavy trucks on pavements and bridges clearly indicate that compared to the legal limit trucks, overweight trucks are a primary cause of pavement and bridge damage. Current pavement and bridge design standards do not consider these heavy trucks that do reduce the structural service life. Designing bridges and pavements stronger than current standards would increase service life and reduce untimely maintenance needs. It would be economical to consider overweight trucks in the design phase of bridges and pavements as the relative damage imparted to them is disproportionately higher.

Estimates of the damage caused by overweight trucks in South Carolina show a major difference between the current damage fee charged by SCDOT and the estimated damage they cause. As SCDOT assets have been stretched to maintain the fourth largest state-maintained highway network, it is necessary to develop policy initiatives to generate sufficient revenue through rationale pricing comparable to the damage contribution of overweight trucks and other users. In addition, a revision of current design practices is expected to yield a more resilient highway system to support overweight truck traffic and reduce deterioration to pavements and bridges.

Part III: Cost Recovery

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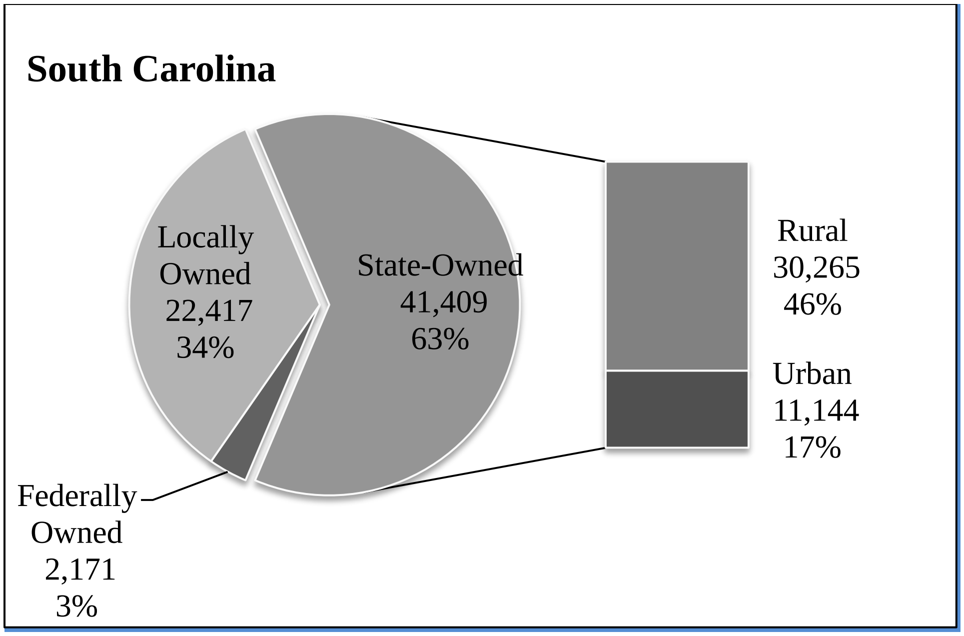
Truckers have traditionally contributed money toward public infrastructure via a few revenue mechanisms. Because truckers use large amounts of fuel, they pay proportionately higher gas taxes; they also pay more in registration fees and tire taxes. Many toll roads have traditionally charged variable rates according to the number of axles on vehicles (i.e., vehicles with more axles pay a higher toll). For large loads, all state departments of transportation in the United States have charged fees for permitting vehicles that are oversized, overweight, or both.

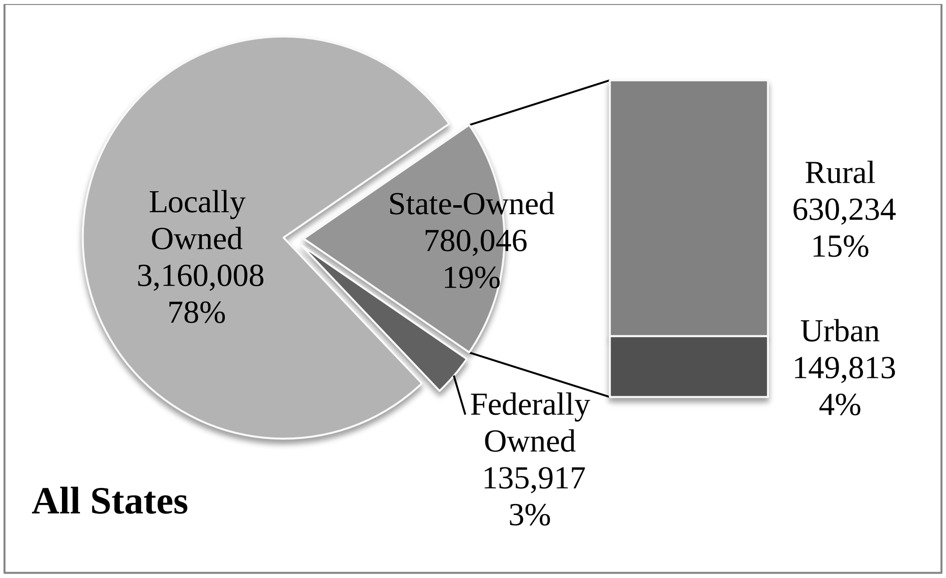
10.0 South Carolina Economy and Transportation Infrastructure

Like all states, South Carolina faces deficits for infrastructure repair and maintenance. In addition, South Carolina faces a unique situation in terms of infrastructure responsibility. In most states, counties hold responsibility for constructing and maintaining many public roads, but the State of South Carolina owns 63 percent of its public roads, compared to a national average of 19 percent (Figure 15).

South Carolina’s responsibilities and deficits are substantial; however, their significance must be interpreted in context before responsible policies can be designed. Trucking incurs financial costs, but no modern economy can survive without freight movement. In 2011, the State Department of Commerce declared (SCDC, 2011), “The [transportation, distribution, and logistics] sector in South Carolina includes over 2,500 business establishments and over 40,000 employees, paying nearly $1.6 billion in annual wages.” Interpreting the financial realities and responsibilities for the impact of trucking on road and bridge infrastructure requires recognition of infrastructure condition and consideration of freight stakeholders.

The economic importance of transportation systems is offered as justification for moving freight exceeding permitted loads. Stakeholders in South Carolina’s trucking industry indicated a range of need for overweight trucking from industries that declared they do not regularly run overweight vehicles to industries that consider overweight permits critical to their operations and commerce. Permits go to traditional agriculture to allow leeway for the imprecision of loading harvests in remote fields under quick turnaround (Quotation 1). In addition, new technologies such as self-propelled construction cranes and modern wind turbines have brought unprecedented single-unit loads that are hard to break down because factory assembly is necessary for precision laser tuning.





Data source: Federal Highway Administration 2012

Figure 15 Proportional Responsibility of State Agencies for Public Roads

Quotation 1: Accurately Weighing Trucks

November 14, 2008
Andrew W. Smith, Senior Assistant Director
Virginia Farm Bureau Governmental Relations

> *"In general these loaded trucks are during harvest season and the agricultural producer only hauls a few loads in a year's time. During harvest they are dealing with trying to get the crop to the market before it is lost in the field and are dealing with the varying moisture content of the crop being harvested. In each crop there is optimal % moisture they strive to harvest at, but Mother Nature doesn't always cooperate. When a crop is harvested that may be a few percent higher in moisture it can add significantly to the gross weight of the truck. Since they are not able to have a scale in each field [as] harvest is taking place they will have to estimate the loaded weight."* (VTRC, 2008)

In this study, state departments of transportation across the United States and Canada were surveyed to determine the state of the practice in managing truck weights. Trucking industry representatives and stakeholders in South Carolina's commercial trucking subsequently contributed their perspectives to this context through interviews. The following section's discussion of cost recovery has emerged from the results of the modeling study, survey, a multi-objective analysis applied to identify tradeoffs of fee types, and stakeholder interviews, as well as findings in previous studies and literature.

11.0 User Fees for Truck Freight

User fees have appeared since early civilizations implemented basic municipal services like water and sewage removal. Political, philosophical, and economic rationales have been used to justify user fees for public services (Bowlby et al., 2001).

Political rationales for user fees are characterized by user acceptance of the fees and the accountability of collected revenue. Conflicting objectives influence any financial decision made by elected bodies; they maintain special considerations to assure user fees represent actual use and ensure accountability by attributing the fee to a proposed use. Political action on transportation user fees has shifted in the United States, devolving from federal and state initiatives to local initiatives such as local taxes to build and maintain transportation infrastructure (Wachs, 2003).

Philosophical rationales of user fees justify that only people who benefit from a service should pay for that service; non-users should not have to subsidize what they do not use. In the context of transportation funding, localities increasing general sales taxes (e.g., a one-cent sales tax dedicated to funding public transit) do not qualify as user fees because non-transportation goods are also taxed. The general sales tax does not charge transportation users directly for benefitting from the system; hence the sales tax is less equitable and efficient than the fuel tax (Crabbe et al., 2005). Overweight permit fees do qualify as user fees because only users of the permits pay the tax; however, shippers might share the benefit indirectly. If that user fee improves infrastructure and passenger cars use the infrastructure in the future, those drivers should philosophically pay a fee.

Economic rationales seek economic efficiency. When truckers are willing to pay the same amount of money that the transportation department needs to receive to cover costs, the market achieves economic efficiency by reaching the equilibrium state. Economic evidence says the United States has not reached economic equilibrium in the market for freight infrastructure. The Engineering News-Record's cost index identified an 817% increase in major construction materials between 1957 and 2002 (McGraw Hill Construction, 2003) while the 50-state average fuel tax in inflation-adjusted dollars was 11 cents per gallon less in 2003 than in 1957 (Wachs, 2003). This acute revenue shortage has contributed to the current crisis of infrastructure deterioration while demand for new capacity is increasing at a rapid pace.

Construction and maintenance of the modern American transportation system has largely depended on user fees such as gas taxes, vehicle licensing fees, sales taxes on heavy trucks and trailers, tolls and other forms. Efficient and equitable user fees can lead to highway system provisions meeting a more demanding standard that reduces overall lifecycle costs (Small et al., 1989).

User fees for oversized and overweight vehicles fundamentally address the administrative costs of the permitting process. Some state departments of transportation have aimed for permit fees to contribute to funding maintenance and rehabilitation of infrastructure. State departments of transportation are examining the viability of assigning fees proportionate to the damage an overweight load inflicts. One South Carolina stakeholder adamantly argued the purpose of overweight permit fees is to generate revenue and should only support administrative costs for historical and regional continuity; in contrast, several other stakeholders felt equally strongly that permit fees should fund infrastructure.

This fundamental discrepancy in perceived purpose of the fee must be resolved before any methodology can revise and set permit fees for the future. How much influence should be attributed to engineering cost studies (economic and philosophical rationale) versus the political rationale of acceptability and conformance to current norms? Roughly three quarters of responding state departments of transportation indicated legislators and lobbyists set overweight fees and fines for their states or provinces.

Based on data from examination of web-posted policies of all states, overweight single-trip truck fees could be divided into four categories, as indicated in Table 35. While single-trip permits could be categorized into these four types, annual blanket permits were mostly flat with very limited consideration of distance or excess weight. One state had not engaged in issuing single trip permits.

Table 35 Prevalence of Single Trip Fee Categories

Type of Fee	States Administering in 2011
Flat	21
Axle based	5
Weight based	10
Distance based	2
Weight and distance based	11

Data source: J.J Keller & Associates, Inc, 2011

11.1 Basic Fee Types

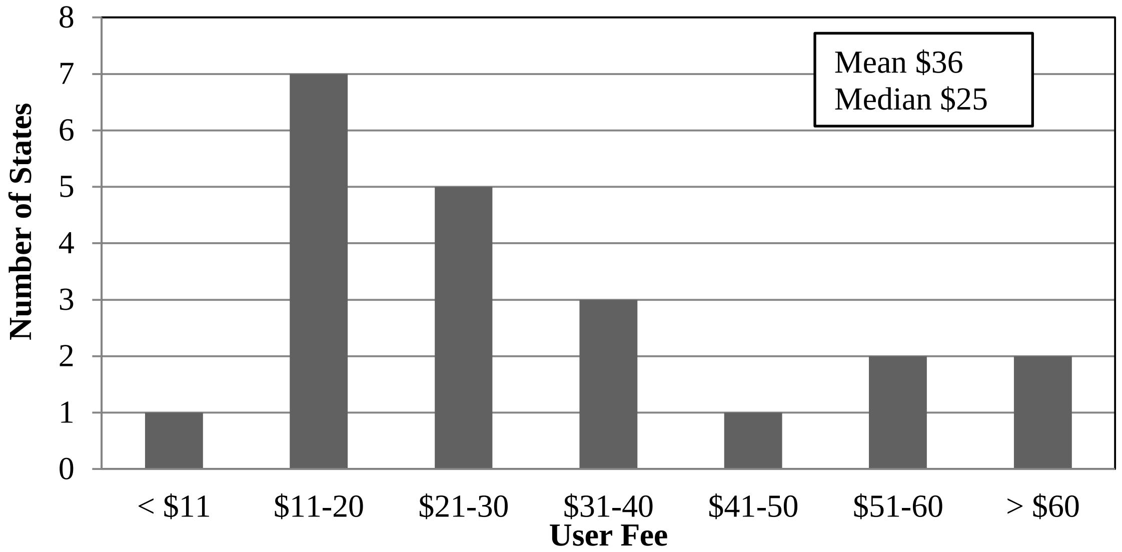
In Sections 11.1.1 through 11.1.4, current overweight permit practices among states in the US are elaborated on.

11.1.1 Flat Fees

The flat user fee is simplest to administer for both state permit offices and trucking companies. In 2011, 21 states issued flat-fee single-use permits with charges ranging from $5 to $135 with a median of $25 per single trip (Figure 16).

Flat fees commonly have addressed the administrative costs of issuing permits with contribution to highway maintenance. The permits have allowed state departments of transportation to track the extent of overweight shipping on roadways. This tracking can be useful for estimating acceleration of deterioration through awareness of general trends in heavy-vehicle activity, which facilitates maintenance scheduling and inventory tracking. As Figure 16 indicates, 19 states have set single-use permit fees between $5 and $60 to cover part or all of these administrative fees.

To date, South Carolina has issued flat-fee permits for oversized and overweight trips. Most stakeholders interviewed said they saw little advantage to this permit type beyond its simplicity. One indicated flat fees are the most unfair type of permit to the State if they are too low and the most unfair type of permit to carriers if they are set too high.

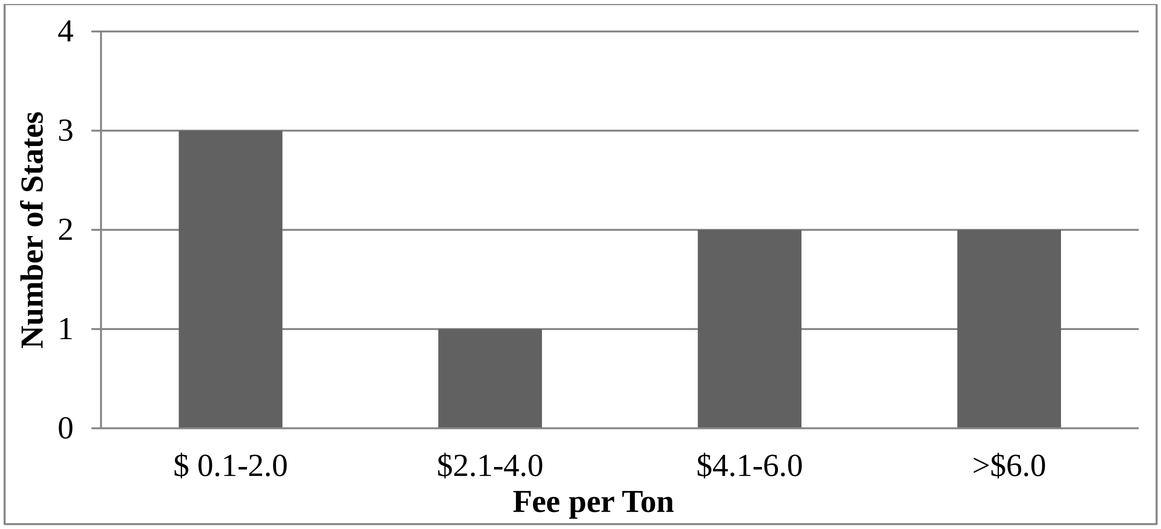


Data sources: J.J Keller & Associates, Inc, 2011, and state departments of transportation

Figure 16 States Issuing Single Trip Permits with a Flat User Fee

11.1.2 Weight Based Fees

Weight based fees charge for tons of load exceeding the legal limit, as indicated in Figure 17. States with low weight based fees inherently encourage heavy-weight industries while higher fees discourage them. States administering single-trip weight-based permits in 2011 charged from $0.1 to $20 for per ton of excess load (Figure 17).



Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

Figure 17 States Issuing Single Trip Permits with a Weight Based User Fee

Assigning the correct user fee for a truckload's trip weight requires modeling different traffic loads over specified infrastructure. How should fees increase as weight increases? A pavement deterioration model for a flexible pavement section in Iran considered pavement material properties, including asphalt layer thickness, pavement temperature, subgrade condition, and traffic speed. Upon determining relative damage due to several truck weights, the pavement damage increased exponentially, with significant amounts of damage experienced when weights exceeded the allowable weight limit (Sadeghi et al., 2007).

Although infrastructure engineers and many trucking industry stakeholders feel weight should serve as a factor for establishing fair user fees, some trucking stakeholders have expressed problems with using weight as a factor.

- One South Carolina trucking stakeholder declared skepticism over study results indicating that heavier loads create greater damage to infrastructure. This stakeholder would not willingly accept a weight-based fee without seeing convincing evidence that excess weight exacerbates damage. Such a discrepancy of underlying understanding among key figures can undermine the effectiveness of debate. Common understanding reflecting the wisdom of all perspectives can be developed through stakeholder engagement, as discussed in Section 16.2.1.
- Another stakeholder predicted difficulties for primary industries (agriculture, forestry, and so forth) if they must weigh shipments of raw materials originating in the field without the controlled environment of a warehouse. Large agribusiness will have an advantage over small producers if forced to buy scales because big business can amortize costs across greater volume.
- Perhaps because of such difficulties, another stakeholder indicated political processes typically have trumped weight-based calculations and should continue to do so. Many states' laws have allowed heavier weights for exempted industries, such as aggregate, farming, logging, waste hauling, and concrete mixing. If a large portion of excessive loads do not require permits, then the validity of assigning weight penalties to other trucks comes into question.
- A stakeholder participating in Virginia's study of freight stakeholders wanted to know how to account for return trips when trucks run empty (VTRC, 2009). However, if permits are issued for one-way trips, empty return trips will not require permits.

11.1.3 Distance Based Fees

While weight permits account for the stress placed on a piece of infrastructure, they do not account for the extent of exposure. Two trucks might have equal weight and pay equal amounts for permits while one traverses a local trip and the other crosses the entire state. Charging for distance offers consideration of how much length of roadway an overweight vehicle impacts.

Two states have issued distance-based single-use permits without considering the amount of excess weight shipped. Virginia set its distance rate at 10¢ per mile while Indiana set rate at 34¢ per mile up to 120,000 lbs. Just as many states have done with weight-based permitting, Virginia has not attempted to create a distance-based annual permit.

Most of South Carolina's trucking stakeholders indicated distance should be a factor used to set rates for overweight permits. They felt distance is a fair consideration and indicated no concern with tracking it. “Everyone has GPS.” They indicated distance fees will alter trucking prices, but distance fees can be passed on to customers.

If South Carolina chooses to implement a distance-based fee, some implementation issues will require resolution. Interviewed stakeholders raised the following questions.

- Distance is hard to administer and enforce. Law enforcement will have a difficult time identifying drivers without permits or violators of existing permits, particularly for non-super-load single trips. Will the inability to enforce distance permits systematically create a situation for abuse?
- Should the same distance price apply to trips over highly engineered interstates as to farm-to-market routes over old bridges and lighter duty pavements?

11.1.4 Axle Based Fees

Axle-based fees have commonly emerged for individual facilities, such as turnpikes and toll bridges. Evidence has shown the axle-based fee structures common to toll roads and overweight permitting fails to collect money proportionate to damage inflicted by loads on roads. A 2008 study among different truck classes used weigh-in-motion (WIM) data from two stations along Texas highway SH 130. Single-unit trucks caused more damage compared to semitrailers while paying less in fees (Conway et al., 2008). A truck with many axles can spread its weight across them, thus impacting pavement with less weight per axle, yet a higher number of axles is penalized in traditional axle-based fees.

Consideration of axles appears to be gaining favor. Five states have been setting overweight fees with number of axles and vehicle configurations in fee calculation for single trips. South Carolina’s stakeholders supported consideration of vehicle configuration in principle with recognition of demand for increasing weight per axle.

For a system based on axles and vehicle configuration, South Carolina stakeholders voiced regional consistency as their biggest concern. Some shipping companies have voiced resistance to reconfiguring their fleets to accommodate one state. One stakeholder suggested private companies will be more willing to invest in new equipment if South Carolina, North Carolina, and Georgia all recognize the same standards.

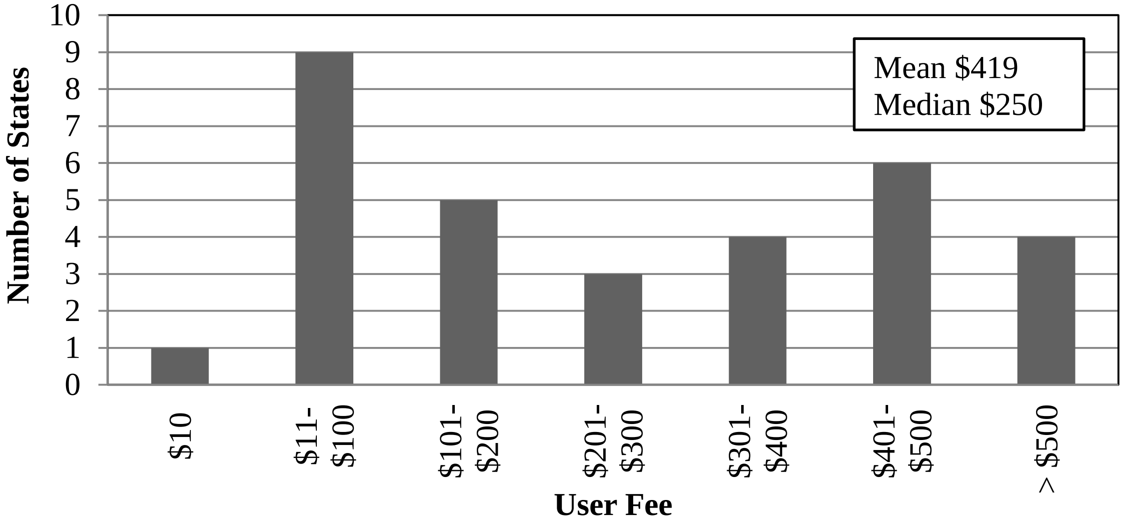
11.2 Combined Fee Types

Section 11.1 described the basic components of overweight fee structures, but many states combine those components into a more complex system. This section details some combined fee configurations currently in practice or proposed.

11.2.1 Annual Fees

Regardless of the type of single-use permit employed, most states have offered permits for unlimited overweight trips in a year. Most annual permits are in the form of flat-fee permit while some states include weight and distance in the annual fee calculation. Flat-fee annual permit rates of states varied from $10 to $2,500 with median at $250 (Figure 18).

The logic of annual fees is unclear. Presumably, states would offer a rational relationship between single-use and annual permits; however, the data have failed to reveal a strong connection. In 2011, one state charged $5 for a single use and $10 for an annual permit even though truckers with annual permits likely took more than two trips per year. An Ohio DOT study found that with annual permits 24.8 trips were made on average (ODOT, 2009). A survey among trucking companies or a log book survey of overweight trucks with annual permits could inform this imbalance between annual and single-trip permit rates.



Data sources: J.J Keller & Associates, Inc, 2011, and state departments of transportation

Figure 18 Flat User Fee- Annual Permit

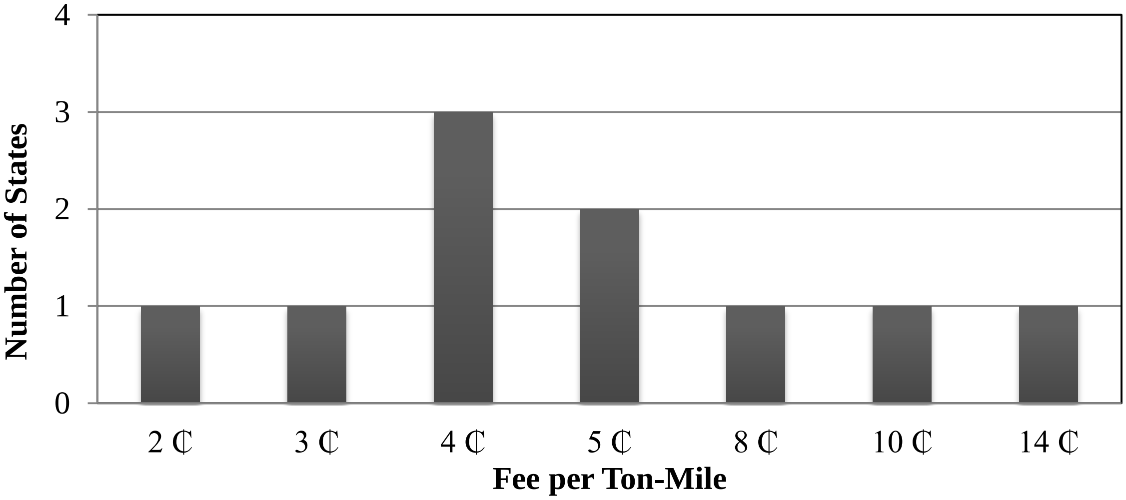
South Carolina's stakeholders held a range of opinions on annual permits:

- Some interviewees indicated annual permits should not exist because every fee should be based on individual loads to ensure fairness and precision.
- Other study participants saw annual fees as critically important to keeping businesses in South Carolina's trucking industry competitive due to the volume of freight and number of containers in large truck fleets.
- Multiple interviews revealed concern over the administrative burden and time commitment of handling permit requests and tracking every trip for trucks that are frequently used. Both trucking companies and SCDOT will feel that administrative burden, especially compared to the existing automated system for annual permits.
- One stakeholder suggested that if SCDOT could process a single-trip permit within 10-15 minutes, annual permits would not be necessary, but the permitting office would likely need to grow by 10 or 15 people to reach that level of service.
- Another interviewee suggested trucking companies could pay an up-front fee based on anticipated travel for a year, but this person recognized the difficulty with forecasting what will be carried for a year in advance.

Trucking companies and the state department of transportation in South Carolina all depend on annual fees, yet all interviewees recognized the system is flawed. The interview demonstrated that stakeholders have needs that can be articulated and ideas on how to improve the system.

11.2.2 Combined Consideration of Weight and Distance

Comprehensive fee structures used at the state level at the time of this study considered both the excess weight imposed on infrastructure and the length of infrastructure exposed to that weight. In 2011, 11 states offered single-use overweight permits based on weight and distance where five states accounted for axle overweight and number of axles to calculate the total fee. Figure 19 shows their fee structures ranging from 2 cents to 14 cents per ton-mile.



Data sources: J.J Keller & Associates, Inc, 2011, and state departments of transportation

Figure 19 Single Permit Fees per Ton-Mile

11.2.3 Base Annual Fee plus Trip Fee

One South Carolina stakeholder suggested combining a flat base annual fee with a per-trip fee. Under this system, each vehicle to be used in a year will need a permit to operate in the state, rather like a club membership. Each single trip would then also require a trip-based permit, akin to an activity fee for club members. This type of fee structure does not appear to be in use currently.

Such a system will favor in-state trucking companies and companies that frequently travel through South Carolina. If a truck makes only one overweight trip in the state in a year, that one trip must bear the burden of both the annual fee and the trip fee. As that truck makes more overweight trips in a year, the cost of the base annual fee is amortized more broadly. Out-of-state freight companies that rarely operate overweight loads in South Carolina will have the least opportunity to amortize the cost of the base fee, thus the combination of base annual fee and trip fee will export some of the cost of the infrastructure to out-of-state trucking companies.

11.3 Summary of Fee Types

Overweight vehicle permits are based on four components: flat, weight-based, distance-based, weight and distance-based, and axle configuration fees. Each of these fee types provides a different type of cost allocation and administrative burden, as indicated in Table 36. Across the nation, states have established permitting policies using a wide array of combinations of these types.

Table 36 Characteristics and Requirements of Permit Types

	Flat fee	Weight based	Distance based	Weight and distance based	Axle Configuration based
States administering in 2011	21	10	2	11	5
Collects based on scale of exposure	✗	✓	✗	✓	✓
Collects based on scope of exposure	✗	✗	✓	✓	✓
Requirements for administration	Declaration Enforcement	Scale Declaration Verification Enforcement	GPS Declaration Verification Enforcement	GPS Scale Declaration Verification Enforcement	Declaration Verification Enforcement

Legend: ✓- Yes, ✗- No

The most accurate and fair permit will consider weight, trip distance, and weight distribution on axles. This permit also presents the most invasion into trucking affairs and regional competitiveness, the most complexity to SCDOT administrators, and the most difficulty for law enforcement.

12.0 Economic Flows

When a user fee is established for a goods with robust demand, someone pays the fee and money starts to flow, but the success of the fee cannot be determined based only on the volume of money flowing. The impacts of who is paying for the fee and where the revenue goes must be gauged, and those impacts must be gauged against intended impacts.

These questions have underlying complexity that has remained unaddressed in the United States, as evidenced by the number of states with fee structures lacking a rational basis. As indicated in the discussion of fee types, trucking stakeholders have differing concepts of the objective of an overweight permit fees.

- Should overweight fees pay only for administration to track overweight loads as they currently do? If so, can South Carolina muster sufficient resources elsewhere to return its transportation infrastructure to competitive and safe standards? What is the purpose and value of administrative tracking?

- In contrast, can and should trucking companies pay for the full infrastructure damage incurred via overweight permits?
- Should permitting policies discourage trucking over standard weight limits for axles and gross vehicle weights, or should measures be taken to avoid discouraging growth of trucking and industries that rely on trucking?
- Will all industries that ship overweight freight bear the same burden of increased fees, or will some bear a greater burden?
- Whether the burden is equal across industries or not, will some industries suffer because they have insufficient economic resilience to adapt to increased transportation costs? If so, can South Carolina afford to lose those industries?
- If South Carolina raises the cost of overweight freight movement, will in-state industries dwindle relative to out-of-state competition?

Fundamentally, South Carolina stakeholders, legislators, and the state department of transportation must come to consensus on the objective of overweight permitting. Only when consensus develops on the ***intended*** impacts of overweight permitting, an effective system be designed and the success of that system ultimately can be evaluated. To provide a basis for forthcoming discussions, this section demonstrates how various fee structures create different economic flows and impacts.

12.1 Incidence of Fees in South Carolina

Trucking companies pay overweight fees on paper, but who ultimately pays a trucking fee? While trucking companies will pay increased fees for permitting, they might not bear the final burden of the increase. In some industries, shipping companies can pass on the cost of the increase to the producer, and the producer can sometimes pass the cost on to the consumer. In other industries, market demand will not sustain higher costs, which means that if suppliers or shipping companies do not reduce their profit margins, the industry will shrink.

The issue is the economic concept of elasticity, which Collins Dictionary defines as "a measure of the sensitivity of demand for goods or services to changes in price…." If the price of a good rises above consumer willingness to pay, consumers do not buy the goods. If consumers do not buy at existing prices, producers must reduce their prices or cease to offer the goods; in the long run, producers cannot sustainably reduce their prices below their breakeven points. The following subsections explore changes in incidence to trucking companies and industries with consideration of elasticity.

12.1.1 Comparison of Different Fee Structures for Complete Damage Recovery

How do various fee structures affect specific businesses? This question can stymie discussions as stakeholders struggle to comprehend how theories and ideas will appear in practice, as voiced in Quotation 2's letter regarding Virginia's examination of freight fee structures. The following sections address this difficulty with analysis comparing the performance of the four cost recovery structures. *Notably, the cost analyses in this section do not consider administrative costs of permitting systems.* The damage cost structures developed in this study also do not consider user fees paid through fuel tax, vehicle registration, or other fees due to lack of supporting information.

Quotation 2: Fitting Policy to Practice

Mark Singer
Virginia Utility & Heavy Contractors Council

"First, truck configuration examples need to [be] based on real-world vehicles, not magical ones created by bureaucrats to help them perform calculations for a bridge-weight formula."

"Second, it would be helpful to take a mega large, large, and mid-size overweight truck and apply the proposed [equivalent single-axle load] formula. Then determine all annual fees and taxes paid by each of these vehicles (fuel tax, license and registration fees, etc.). Finally, subtract the total of fees and taxes from the ESAL cost to determine the 'unfunded balance." (VTRC, 2008)

12.1.1.1 Flat Damage Fee

South Carolina currently collects a flat fee of $30 for single trip overweight permits and $100 for annual overweight permits. This study showed that trucks with identical loads but different axle configurations incur different damage costs. Flat fees assign average values and do not account for truck configurations and axle load distributions. Table 37 provides a comparison of axle-based damage cost (Column 2) and flat damage cost (Column 3) indicating that some truckers would pay more in flat cost structure than the damage they impart while other truckers would underpay. Based on the damage estimation, to recover additional pavement and bridge damage cost completely due to overweight trucks, a flat damage cost of $54.93 would need to be collected from each overweight trip. Flat cost was calculated as a weighted average of axle based damage costs (Column 2). Relative weight of each truck type was estimated through dividing the number of trips by each truck type with total number of trips by all truck types. Estimate of number of trips by different truck types can be found in Table O.1 in Appendix O. In a flat damage recovery structure, 2-axle overweight trucks would be paying $30.74 more compared to an axle based damage cost while 4-axle combination trucks would pay $35.88 less with a flat damage cost recovery structure compared to an axle based damage cost structure.

Table 37 Axle Based Damage Fee and Flat Damage Fee (per Trip)

Truck Type	**Additional Damage up to Maximum Overweight Limit**[6]	**Flat Additional Damage for Overweight Trucks**	**Difference between Axle Based Damage and Flat Additional Damage**
2-axle, 35-40 kips	$24.19	$54.93	$30.74
3-axle, single unit, 46-50 kips	$14.58	$54.93	$40.34
3-axle, combination, 50-55 kips	$37.53	$54.93	$17.40
4-axle, single unit, 63.5-65 kips	$27.42	$54.93	$27.50
4-axle, combination, 65-70 kips	$90.80	$54.93	-$35.88
5-axle, 80-90 kips	$61.40	$54.93	-$6.47
6-axle, 80-90 kips	$29.16	$54.93	$25.77
6-axle, 90-100 kips	$67.99	$54.93	-$13.06
6-axle, 100-110 kips	$120.61	$54.93	-$65.69
7-axle, 80-90 kips	$18.05	$54.93	$36.88
7-axle, 90-100 kips	$40.45	$54.93	$14.48
7-axle, 100-110 kips	$71.23	$54.93	-$16.30
7-axle, 110-120 kips	$112.20	$54.93	-$57.27
7-axle, 120-130 kips	$164.83	$54.93	-$109.90
8-axle, 80-90 kips	$13.84	$54.93	$41.09
8-axle, 90-100 kips	$30.70	$54.93	$24.22
8-axle, 100-110 kips	$56.46	$54.93	-$1.53
8-axle, 110-120 kips	$85.72	$54.93	-$30.79
8-axle, 120-130 kips	$126.24	$54.93	-$71.31

12.1.1.2 Weight Based Damage Fee

Based on pavement and bridge damage estimates, to recover additional damage completely above the legal weight limit by overweight trucks in a weight based damage cost recovery structure, a per ton damage cost between $2.77 to $36.57 (Column 3,Table 38) needs to be charged to different truck types. Additional per ton per trip damage cost (Column 3,Table 38) beyond the legal limit was estimated by dividing additional damage cost (Column 2, Table 37) by additional weight above the legal limit. A comparison between the additional damage cost in average per ton per trip cost structure (Column 4) and the truck type specific per ton per trip (Column 3) is presented in Column 5 of Table 38. Average of additional damage cost per ton was estimated by dividing the summation of the product of additional damage cost, number of trips and additional tonnage for each truck type by the summation of the product of number of trips and additional tonnage for

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[6] These additional damage cost accounts for additional damage due to additional weight above legal weight limit up to maximum weight limit allowed in typical SC overweight permit

each truck type. Analysis showed truckers with 3, 4, or 5 axles will pay less per trip under a simple average per ton per trip overweight permitting structure (Column 4) than under structures that account for how axles distribute the weight/ truck specific (Column 3). In essence, ignoring the axle distribution means that truckers with 3, 4, or 5 axles will be subsidized by other truck types that cause less damage comparatively.

12.1.1.3 Weight and Distance Based Fee

To recover additional overweight damage costs above legal limit with a cost recovery structure based on weight and distance, per ton-mile fee between $0.0173 and $0.1354 (Column 3, Table 39) would need to be assessed from different overweight trucks. Additional damage cost per ton-mile was calculated by dividing the additional damage cost per trip (Column 2, Table 37) by weight above the legal limit up to the maximum overweight limit and trip length (Column 3, Table 39). Average of additional damage cost per ton-mile was estimated by dividing the summation of the product of additional damage cost, number of trips, trip length and additional tonnage for each truck type by the summation of the product of number of trips, trip length and additional tonnage for each truck type. A comparison between average of additional damage costs (Column 4) and truck type specific per ton-mile damage cost (Column 3) is presented in Column 5 of Table 39. Similar to the findings from Table 38, Table 39 indicates a trucker carrying low weight with a low number of axles will benefit from permitting fees that consider average additional damage cost.

Table 38 Weight Based Damage Fee for Different Truck Types (per Ton per Trip)

Truck Type	Damage at the Legal Weight Limit	Additional Damage above the Legal Limit up to the Maximum Overweight Limit[7]	Average of Additional Damage above the Legal Limit up to the Maximum Overweight Limit	Difference between Truck Specific Damage and Average Additional Damage
2-axle, 35-40 kips	$1.51	$9.68	$11.95	$2.27
3-axle, single unit, 46-50 kips	$1.08	$7.29	$11.95	$4.65
3-axle, combination, 50-55 kips	$2.22	$15.01	$11.95	-$3.06
4-axle, single unit, 63.5-65 kips	$3.05	$36.57	$11.95	-$24.62
4-axle, combination, 65-70 kips	$4.06	$36.32	$11.95	-$24.38
5-axle, 80-90 kips	$1.83	$12.28	$11.95	-$0.33
6-axle, 80-90 kips	$1.03	$5.83	$11.95	$6.11
6-axle, 90-100 kips	$1.03	$6.80	$11.95	$5.15
6-axle, 100-110 kips	$1.03	$8.04	$11.95	$3.90
7-axle, 80-90 kips	$0.57	$3.61	$11.95	$8.34
7-axle, 90-100 kips	$0.57	$4.04	$11.95	$7.90
7-axle, 100-110 kips	$0.57	$4.75	$11.95	$7.20
7-axle, 110-120 kips	$0.57	$5.61	$11.95	$6.34
7-axle, 120-130 kips	$0.57	$6.59	$11.95	$5.35
8-axle, 80-90 kips	$0.46	$2.77	$11.95	$9.18
8-axle, 90-100 kips	$0.46	$3.07	$11.95	$8.88
8-axle, 100-110 kips	$0.46	$3.76	$11.95	$8.18
8-axle, 110-120 kips	$0.46	$4.29	$11.95	$7.66
8-axle, 120-130 kips	$0.46	$5.05	$11.95	$6.90

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[7] This per ton damage cost accounts for additional damage due to additional weight above legal weight limit up to maximum weight limit allowed in typical SC overweight permits.

Table 39 Weight Distance Based Damage Fee for Different Truck Types (per Ton-Mile)

Truck Type	Damage at the Legal Weight Limit	Additional Damage above the Legal Limit up to the Maximum Overweight Limit[8]	Average of Additional Damage above the Legal Limit up to the Maximum Overweight Limit	Difference between Truck Specific Damage and Average Additional Damage
2-axle, 35-40 kips	$0.0201	$0.1290	$0.0785	-$0.0505
3-axle, single unit, 46-50 kips	$0.0108	$0.0729	$0.0785	$0.0056
3-axle, combination, 50-55 kips	$0.0178	$0.1201	$0.0785	-$0.0416
4-axle, single unit, 63.5-65 kips	$0.0113	$0.1354	$0.0785	-$0.0569
4-axle, combination, 65-70 kips	$0.0150	$0.1345	$0.0785	-$0.0560
5-axle, 80-90 kips	$0.0115	$0.0767	$0.0785	$0.0018
6-axle, 80-90 kips	$0.0065	$0.0365	$0.0785	$0.0421
6-axle, 90-100 kips	$0.0065	$0.0425	$0.0785	$0.0360
6-axle, 100-110 kips	$0.0065	$0.0503	$0.0785	$0.0283
7-axle, 80-90 kips	$0.0036	$0.0226	$0.0785	$0.0560
7-axle, 90-100 kips	$0.0036	$0.0253	$0.0785	$0.0533
7-axle, 100-110 kips	$0.0036	$0.0297	$0.0785	$0.0489
7-axle, 110-120 kips	$0.0036	$0.0351	$0.0785	$0.0435
7-axle, 120-130 kips	$0.0036	$0.0412	$0.0785	$0.0373
8-axle, 80-90 kips	$0.0028	$0.0173	$0.0785	$0.0612
8-axle, 90-100 kips	$0.0028	$0.0192	$0.0785	$0.0593
8-axle, 100-110 kips	$0.0028	$0.0235	$0.0785	$0.0550
8-axle, 110-120 kips	$0.0028	$0.0268	$0.0785	$0.0517
8-axle, 120-130 kips	$0.0028	$0.0316	$0.0785	$0.0470

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[8] This per ton-mile damage cost accounts for additional damage due to additional weight above legal weight limit up to maximum weight limit allowed in typical SC overweight permits.

12.1.2 Differences in Incidence Based on Industry

After trucking companies pay for permits, the cost does not disappear. Producers, shipping companies, or consumers will bear part or all of the cost depending on the market and sensitivity of overweight permit demand to increase in permit fee.

If fees for overweight permits increase, shippers may first ask consumers to absorb the increase. If consumers are inelastic to the price change, they will be willing to pay for the increase. Consumers tend to be inelastic toward goods related to supporting their way of life or business. Consumers also tend to be inelastic about luxury goods and goods that have a less expensive but desirable substitute. For example, the heaviest loads in modern times frequently come in the form of machinery, such as wind turbines, that cannot be split into multiple loads without losing computer-refined calibration. If wind turbines incur greater shipping fees and people are not currently supporting their way of life with wind energy, consumers might decide against converting to wind energy and stay with the fossil fuel substitute.

Quotation 3: The Bearer of Burden

November 17, 2008
Philip F. Abraham, Director and General Counsel
The Vectre Corporation

"I represent […] mostly small and medium size highway contractors. Our members are struggling greatly under current economic conditions, repeated cuts in the [state transportation] construction and maintenance program and significant increases in materials costs. Many of our members have had to lay off employees and scale back their operations as a result of these economic conditions. Some are struggling to stay in business or are being forced to sell their operations to survive[….] I am also concerned that these increased costs will ultimately have to be passed back onto [the state department of transportation] by its contractors thereby putting even greater strain on ever-dwindling [state transportation] maintenance and construction revenues."(VTRC, 2008)

If consumers are inelastic and unwilling to pay higher prices due to increased shipping costs, producers will need to decide if they can absorb the cost increase. Industries with small profit margins have little room to absorb cost increases. Commodity industries with many competitive producers tend to have small profit margins. Agriculture is a classic example of a commodity industry with small profit margins. Many states do not charge sales tax on agricultural products such as milk because families are economically inelastic: they must buy these goods to survive, so consumers who can least afford the tax bear its burden. Specific to overweight fees, a stakeholder in Virginia's freight study wrote a letter (Quotation 3) that characterized how increased fees might have rippling negative repercussions due to the tenuous margins of the construction industry.

Strategic design of fees and taxes will consider incidence. For instance, a recreational community might levy a high sales tax and a low property tax, thus reducing housing costs for service-industry workers while paying for public infrastructure and services from the wealth of visitors. Strategies related to overweight fees might include:

- exporting costs out of state by placing high fees on trips that neither start nor end in the state,
- favoring or disfavoring trips that use non-interstate infrastructure, or
- favoring or disfavoring trips that serve target areas, such as rural poverty, the automotive industry cluster, and so forth.

All such strategies have implications on equity, industrial composition, and regional competitiveness. South Carolina decision makers will need to consider what strategies are desirable and feasible. The intent and likely outcomes must be considered thoroughly.

12.1.3 Comparison of Fee Structures with Different Level of Damage Recovery

Multiobjective analysis is useful in solving complex problems with conflicting objectives encountered in business, engineering, and planning. In a scenario with multiple conflicting objectives, there are infinitely many solutions, which are equally good. A decision stage naturally involves a decision maker (DM) with subjective preferences, priorities, expectations and personal aspirations about conflicting objectives. The differences between different efficient or Pareto optimal solutions, generated from solving optimization problems with multiple objectives, is that each solution is better in one objective but worse in another objective. The relative improvement of one objective over another is known as tradeoff (Ehrgott and Wiecek, 2005). In general, a tradeoff between two objective functions at a Pareto point is the ratio between increase of one function and decrease of the other assuming that all other objective functions remain constant. Tradeoffs quantification is useful to DMs in selecting an alternative after reviewing the trade-offs between alternatives and used in many multiobjective analysis applications.

This section demonstrates how fee structures for overweight permitting affect fee incidence. A bi-objective model was developed with the following two objective functions to demonstrate the trade-offs between different fee structures:

- minimizing unpaid pavements and bridges damage cost due to overweight truck trips (primary objective) and
- minimizing overweight permit fees to reduce freight transportation cost (secondary objective).

Generally, with an increase of transportation cost, freight demand tends to decrease. Freight demand and supply studies have indicated elasticity varying between -0.5 and -1.5 depending on type of freight goods[***] (Graham and Glaister, 2004). This elasticity

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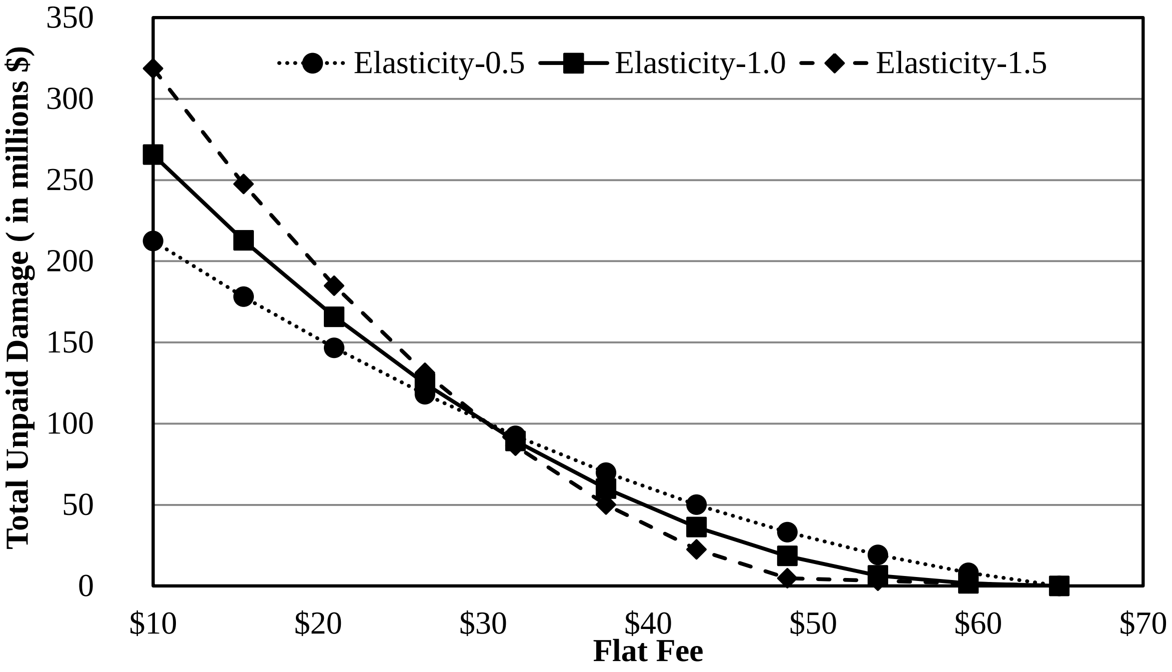
[***] Elasticity between -1 and 0 is considered inelastic, meaning consumers continue to buy despite changes in price; values less than -1 are deemed elastic, meaning small changes in price deter consumption.

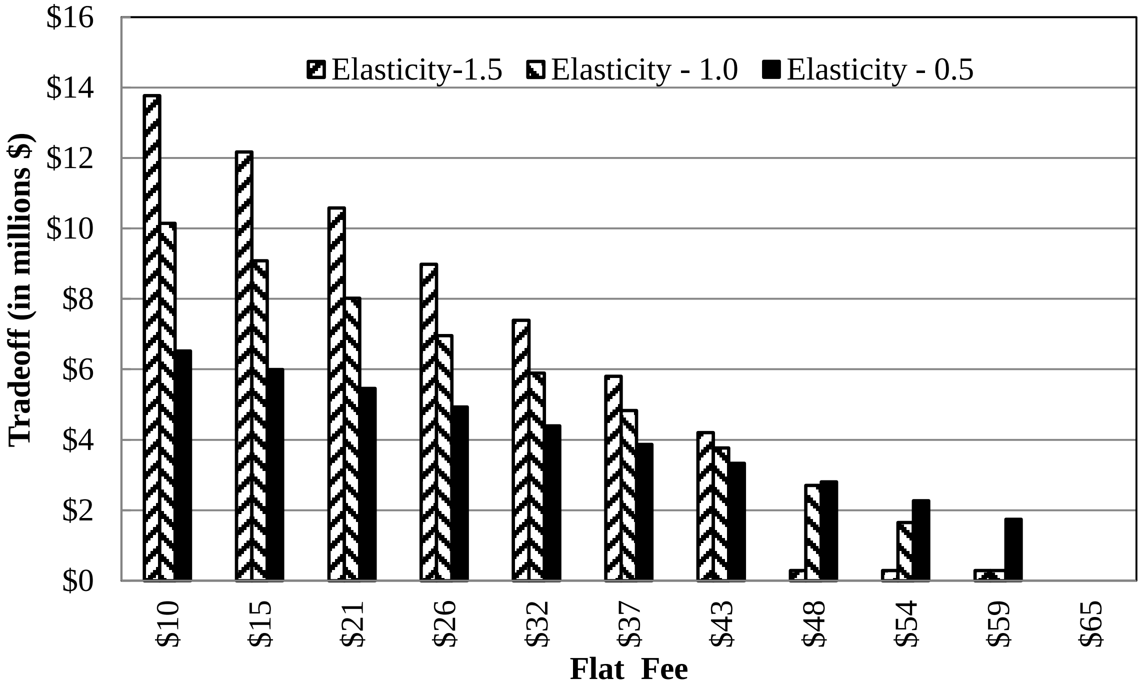
concept was applied in this study to relate permit fees and corresponding freight demand. In this study, elasticity values of high (-1.5), medium or inelastic (-1.0), and low (-0.5) were assumed to present sensitivity of overweight freight demand to permit fees. The description of tradeoff analysis method was presented in details in Appendix O.

Reduction in unpaid damage caused by increased permit fees is attributed to overall reduction in overweight freight demand and more revenue collection because of higher overweight fees. Such relationships were developed through a multi-objective analysis method to investigate how damage fee, and unpaid pavements and bridges damage costs interact. The analysis can help policy makers decide how to select fee structures to achieve a preferred performance target.

Figure 20 and Figure 21 present modeling results for two fee structures (flat and axle based fees) for a scenario in which overweight trucks will pay for the additional damage caused by their excess weight. Figure 20 and Figure 21 show the unpaid pavement and bridge damage corresponding to these two types of fee structures. Although raising the fees will generate more revenue per permit, it might simultaneously reduce demand by discouraging overweight freight trips. Scenarios with low, medium, and high elasticity represented the countervailing forces of fee increases and changes in trip demand.

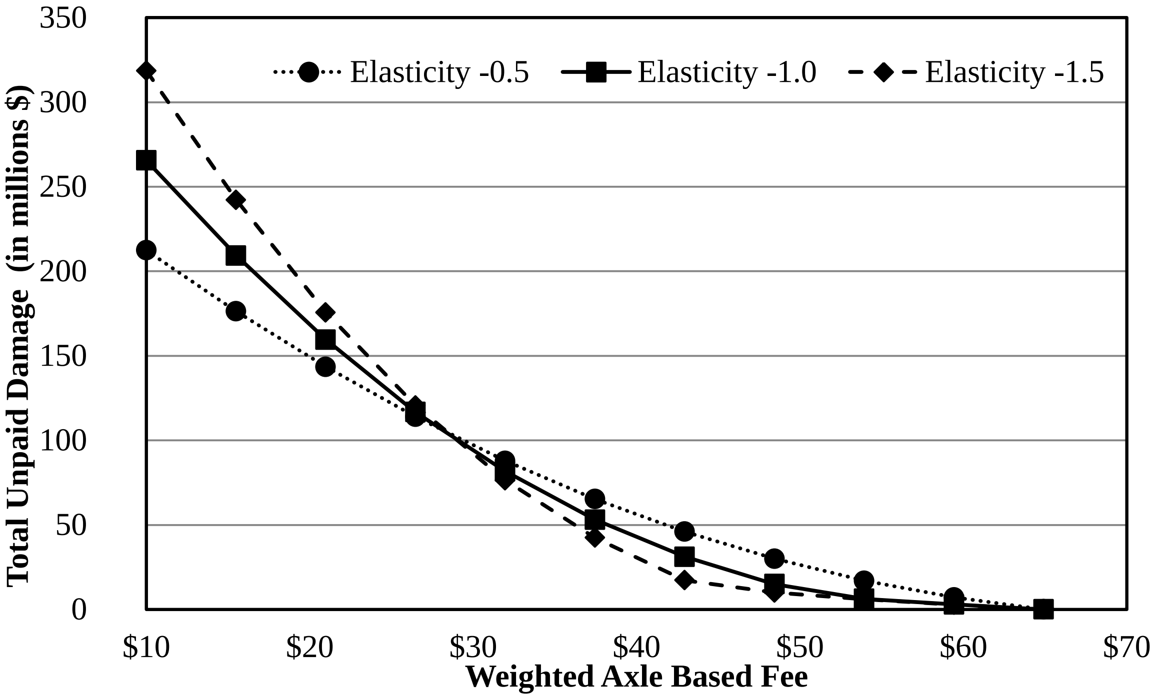


(a) Pareto optimal solutions

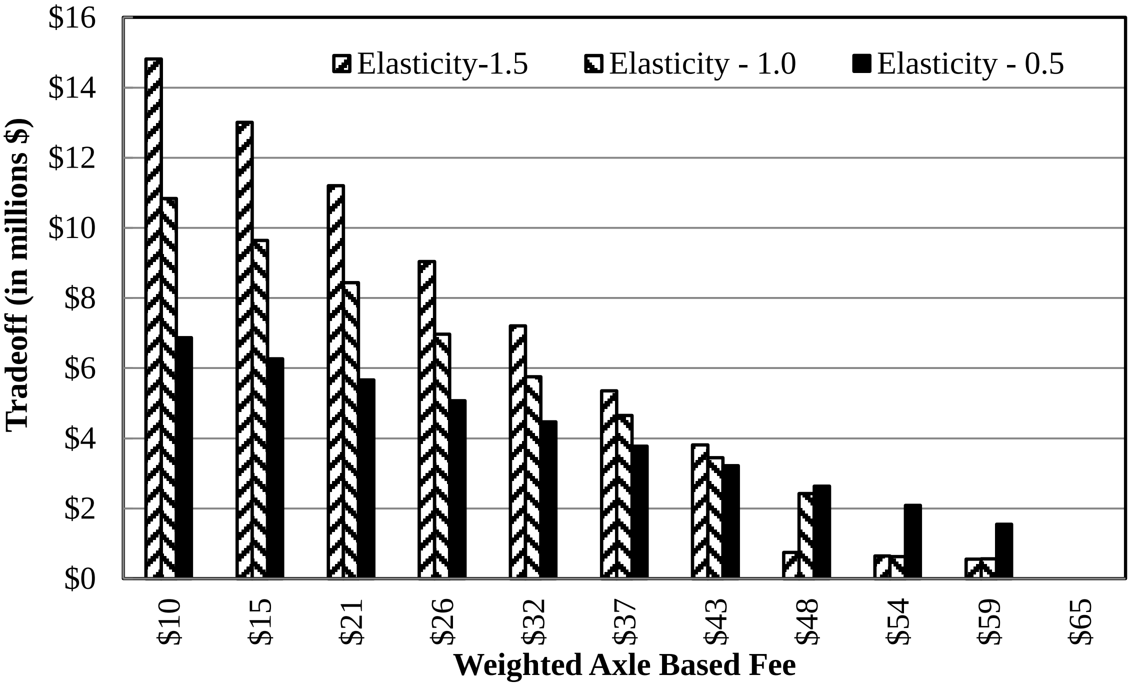


(b)Tradeoffs corresonding to Pareto optimal solutions

Figure 20 Flat Damage Fee and Unpaid Damage
($10 administrative cost included in flat damage fee)



(a) Pareto optimal solutions



(b) Tradeoffs corresonding to Pareto optimal solutions

Figure 21 Axle-Based Damage Fee and Unpaid Damage
($10 Administrative cost included in axle based damage fee)

The tradeoffs of the Pareto-optimal outcomes of two objective functions were calculated as the dual variables associated with the ε-constraint related to the original bi –objective problem (BOP). The tradeoff value indicated how much unpaid damage could be recovered by a unit increase in the corresponding damage fee. For example, when the flat damage fee was $43, the unpaid damage was $22.4 million in 2012 (for elasticity value of 1.5) (Figure 20). The tradeoff corresponding to a $43 flat damage fee was $4.2 million. The tradeoff of $4.2 million indicated that increasing the flat overweight damage fee by $1 to $44 from $43would reduce the unpaid damage equivalent to $4.2 million in year 2012. These tradeoffs at different fee levels show policy options to achieve the preferred performance tradeoff. This quantitative tradeoff estimate of each Pareto-optimal outcome provides data to DMs to make an informed choice among available policy options regarding fee rates to select the best alternative. Selection of appropriate fee rate depends on tradeoff analysis. If none of the generated solutions satisfies DM expectations, an interactive multiobjective analysis (IMA) strategy can be used to develop new solutions with the input from the DMs concerning their respective preferences (Chowdhury et al., 2000; Ehrgott and Wiecek, 2005).

As shown in Figure 21, in the axle based fee structure, the average axle based permit fee of $43 resulted in unpaid damages of $17.2 million in the year 2012 for elasticity value of -1.5. The corresponding tradeoff value of $3.8 million indicated that increasing the axle-based overweight damage fee by $1 to $44 from $43 would reduce the unpaid damage equivalent to $3.8 million in the year 2012 (Figure 21).

12.2 Indirect and Induced Benefits

“Trucking drives commerce.” Many stakeholders, legislators, and transportation advocates make this or similar declarations. Fundamentally, this notion indicates that the movement of goods benefits a larger economy than the simple transaction between shipper and shipping company. Consumers down the supply chain and producers all the way to extraction of raw resources depend on transportation links for their livelihoods and living. The fact that many states use general funds for transportation infrastructure rather than insisting all transportation pay for itself through user fees indicates a general belief that society benefits from facilitating transportation even if secondary benefits of a single trip are not obvious.

Economists use input-output analysis to quantify these secondary benefits. This method considers direct transactions of an industry (e.g., a shipper pays a trucking company), indirect transactions to support that industry (e.g., the trucking company buys tires to support the trip), and induced transactions through employee spending (e.g., the truck driver spends his or her salary at a restaurant). All of these transactions benefit state economies, yet the restaurateur does not necessarily pay a proportional amount of an overweight trip fee. As increased costs are passed through the supply chain, they might not be absorbed fairly or desirably. Quotation 3 posed a scenario of how increased overweight fees might take a shape undesirable to society.

Indirect and induced benefits offer a rationale for why America's transportation system has evolved away from user fees, but in the extreme, all transportation funding comes from a general fund to allocate costs across all of society. This system creates multiple difficulties. Legislators might allocate insufficient funding for infrastructure as it competes with other societal priorities such as education and law enforcement. Simultaneously, trucking companies have no incentive to develop fleets and operations with consideration of their impacts on infrastructure because infrastructure suffers from tragedy of the commons. In the economic theory of tragedy of the commons, a shared resource is depleted when many parties use it according to their rational individual interests even though everyone suffers from its depletion (Hardin, 1968).

In the United States, a movement toward direct economic accountability has been emerging for more than a decade, as evidenced by consideration across the nation of road pricing and sophisticated mechanisms for charging tolls. Conservative politicians have particularly encouraged user fees in many aspects of society. Policy makers' current consideration of overweight fees derived based on the damage a given vehicle creates on public infrastructure is commensurate with this movement. South Carolina's decision makers will need to decide how to balance the simplicity of a direct fee against societal consideration of indirect and induced transactions.

13.0 Considerations for Updating Fee Structures

Revising trucking fee structures takes place in a public context, which inherently brings for a number of stakeholder interests and considerations. This section discusses potential consumer reactions, fairness, and other issues related to updating fee structures.

13.1 Fairness

The consideration of any user fee should identify and analyze positive and negative impacts on different industries, business sizes, and socioeconomic groups. One South Carolina stakeholder declared that trucking is as diverse as any industry, requiring different trailers designed to accommodate a variety of loads. Axle requirements will have significant impacts on some industries and negligible impacts on others. High freight fees might cause disproportionate burden on small trucking companies and favor large companies that can afford the fees in their cost structures. Price structures might provide special considerations for low-income or special-needs groups to equalize the effect of increased or new fees. The structures should also be analyzed to identify how they will impact South Carolina businesses compared to interstate trucking.

All parties must start with a recognition that something needs to be done. All parties must agree on how much needs to be invested to accomplish what needs to be done.

Interviewees indicated that as requests for overweight movements have increased, SCDOT has looked closely at marginal bridges and increased restrictions. This action has the positive effects of removing service from declining infrastructure to prevent catastrophic damage during an overweight movement; however, local firms serving primary industries (agriculture, timber, and so forth) disproportionately bear the negative effects of detours and time lost.

The stakeholder interviews revealed an array of sentiment on what is fair. One respondent did not believe trucks damage infrastructure and did not consider it fair to charge truckers for infrastructure maintenance. One industry representative deemed South Carolina’s current flat fee of $30 per single trip to be the fairest structure of any neighboring Southern state, while another representative declared that trucking companies realize South Carolina’s fees are low and are willing to take on higher fees as long as they are implemented fairly. Another study participant considered distance driven an important variable for developing fair allocation.

Although consensus did not naturally exist on what fee structure is fair, the interview participants frequently cited the same considerations that should shape a fee structure. Interviewees most frequently indicated fee structures must not unfairly expect trucking fees to pay for the damage incurred from illegal trucking and past deferred maintenance, as discussed in the following subsections.

13.1.1 Fee Enforcement

Almost all trucking stakeholders participating in interviews expressed their primary fear of paying high fees while illegal trucking goes unpunished, and higher fees will incentivize more illegal operation. With weigh stations closed across the nation, law enforcement has lost a visible presence.

Transportation technology has revolutionized weight monitoring on highways in recent decades. In the early days of weight monitoring, every truck needed to pull off of highways at state borders and other critical junctures. They entered a queue to drive onto scales monitored by transportation officials and enforcers, and queuing could lead to significant delays. The advent of small computers led to computers monitoring scales, and intelligent transportation systems led to the ability to weigh trucks in motion. Trucks pull into weigh stations, and automatic detection signals weight problems (Cambridge Systematics, 2009).

The survey of state departments of transportation showed that states have been using combinations of enforcement techniques to achieve specific regional freight monitoring goals. Mobile enforcement teams or units and weigh-in-motion (WIM) are the most commonly used techniques (14 states out of 16 respondents). Traditional weigh stations (random and fixed schedule) with weight scales were also common; nine states (out of 16) were maintaining weigh stations 24 hours a day. Four states have implemented pre-pass check points and other strategies to reduce processing and traffic operations at checkpoints. One Canadian province reported using remote-controlled weigh stations. All types of monitoring for enforcement can also contribute data for system monitoring and traffic modeling.

What if the truck never pulls into the weigh station? Staffing for weight monitoring has decreased for a number of years. Without human monitoring, no state has a good estimate of the number of overweight trucks operating without a permit. The few caught through enforcement cannot be extrapolated to indicate the extent of the problem. Trucking companies avoiding permits can usually avoid routes that have permanent weigh stations. Mobile enforcement units are harder to predict, but they are sparse enough that the odds might be favorable to illegal trucking. It is also challenging for a mobile enforcement officer to suspect illegal overweight trucks visually for detail inspection. However, on non-interstate highways, finding a proper roadside location to conduct a weight check is a huge issue.

One stakeholder suggested that distance-based fees can pose a particular challenge to administration, verification, and enforcement. Law enforcement has few indicators to check permitted distances, particularly for single non super-load trips. A stakeholder suggested super-load movements are not likely to run without permits because the moves are isolated and operated by a limited number of companies with appropriate equipment. Highly competitive low-margin routine loads are most likely to tempt unpermitted travel.

13.1.2 Current Damage versus Deferred Maintenance

The current condition of South Carolina’s highway system reflects years of deferred maintenance. Trucking stakeholders recognized the need to catch up on that backlog but indicated competitive industries cannot afford to absorb the cost of catching up. Shipping clients would not be willing to pay those high transportation costs.

13.2 Difficulties of Increasing Fees

Finding funds to maintain existing infrastructure has always posed a challenge (Petroforte and Miller, 2002). The public will often endorse projects to build new infrastructure that will likely enhance their lives, but infrastructure maintenance carries a high cost just to maintain status quo. The public does not always grasp that status quo cannot be maintained without an infusion of resources for maintenance. Apart from the basic difficulty of convincing people to invest in something that already exists, macroeconomic forces such as economic cycles and regional competition affect the feasibility of changing fee structures.

13.2.1 No Time Is Good

Quotation 4: Timing Fee Increases

November 19, 2008
Dale Bennett
Virginia Trucking Association

"Current economic conditions preclude the trucking industry from being able to absorb any increases in the permit fees[….] In addition, current economic conditions preclude trucking companies from passing fee increases on to their customers. Industries such as home construction, road building, retail, etc. are struggling to keep their doors open. They can ill afford increases in their transportation costs and would likely be very resistant in any increases in transportation rates to offset increases in the permit fees." (VTRC, 2008)

Quotation 5: Not Now

November 17, 2008
Peter Easter
Virginia Ready-Mixed Concrete Association

"As you are well aware, the construction economy, both residential and commercial, is in a very serious recession, and the ready-mixed concrete suppliers are starving for business. Accordingly, it would be an imposition on these companies when their sales are very low, but it would be one more disincentive to getting the construction economy back on track." (VTRC, 2008)

As a general rule, no time is considered good for raising fees in the public sector, as indicated in selections from industry letters in Quotation 4 and Quotation 5. Economic cycles run from bad economies when businesses cannot afford increased fees, through growing economies, when fees should be avoided as encouragement of growth takes precedence, to good economies in which global competition and establishment of prominence is paramount, and back to lagging economies when people fear damaging delicate businesses and instigating recession. The rationale for keeping fees low always has a strong and loud voice.

Despite the general principle that no time is good, South Carolina might now have a rare window of opportunity: stakeholder interviews revealed general recognition that something must be done to maintain and improve infrastructure. One person said that state legal loads have outpaced design loads. Another indicated transportation infrastructure has an economic role, and the state's economy will decline without infrastructure maintenance and protection.

Countervailing opinions also came through the interviews. One stakeholder stated that South Carolina currently has a pro-business and anti-regulatory environment that will not likely support major revisions to trucking fee structures; this stakeholder recommended sustaining the current infrastructure finance structure and raising fuel taxes to support it.

Another stakeholder worried about developing a fee structure that accommodates current needs while locking into something that will not work in a decade. This respondent wanted to make sure South Carolina stays open to new processes and technologies.

13.2.2 Inter-jurisdictional Competition for Business

In the short run, inter-jurisdictional competition has inherently created downward pressure on trucking fees. Competition for South Carolina has emerged as close as adjacent states jockeying for manufacturing plants and as far as agribusiness which distributes its products around the globe.

A few interview contributors suggested that increased trucking fees will negatively impact the Port of Charleston, which brought South Carolina $44.8 billion of direct, indirect, and induced impact in 2008 (Wilbur Smith, 2008). Several states on the East Coast compete with neighboring states for cargo to originate and terminate at their ports, and land-based travel costs affect port competitiveness. One interviewee said customers sometimes buy from manufacturers located in states with low transportation costs to reduce total costs.

In the long run, a state establishes its competitiveness with solid infrastructure. One respondent said the Port of Charleston had lost refrigerated meat and poultry processing to Savannah's port because Georgia allowed heavier cargo. Heavier cargo requires sturdier infrastructure.

One stakeholder did not want to see changes to South Carolina's fee structure because the current system grants specific and competitive weight exceptions consistent with most states. He did not feel South Carolina should raise infrastructure funds through permit fees because no neighboring states do. Multiple interviewees indicated that agribusiness, in particular, look at competitive transportation costs in neighboring states and requires globally competitive prices.

13.3 Returns for Paying Increased Fees

South Carolina's trucking stakeholders had a few ideas for what they would like to see happen if they must pay higher fees for overweight permits. This section identifies what ideas emerged in the interviews. This account should be considered a launching point for continued discussion.

13.3.1 Balance of Precision, Simplicity, and Efficiency

South Carolina must decide where its fee structure should land on the spectrum from simplicity to precision (Figure 22). A system of user fees must establish a carefully determined balance between precision of impact and simplicity of execution and enforcement.

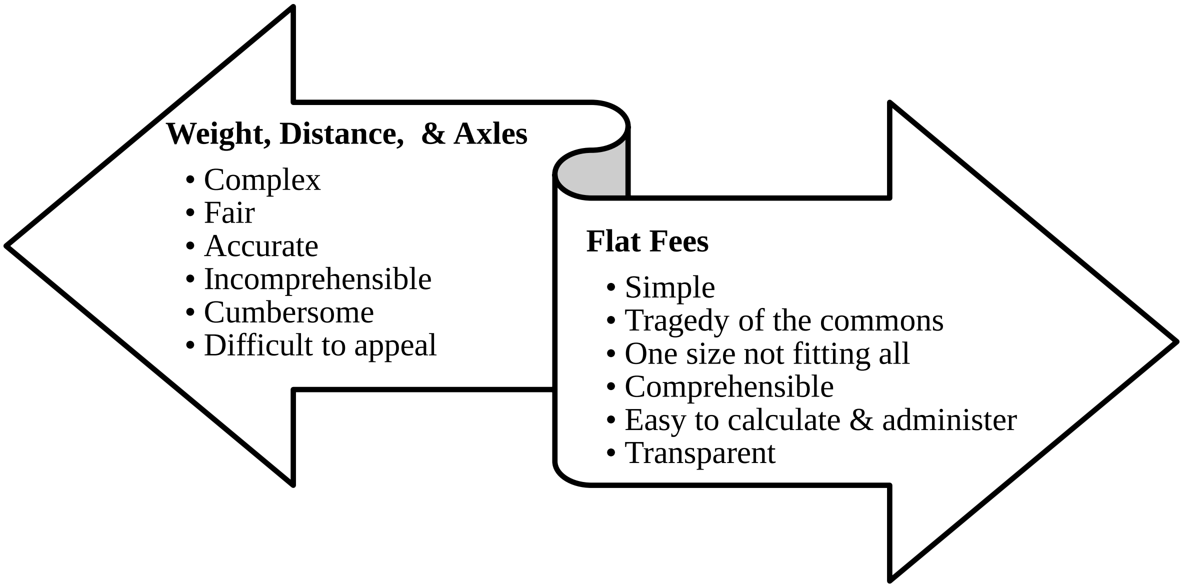


Figure 22 Spectrum from Complex to Simple Fee Structure

The most fair method of attributing road impacts to trucking movements will involve a detailed examination and inspection of each load, its balance within the vehicle, the vehicle’s weight and axle configuration, the route taken, and so forth. Such an approach is unpractical and impossible both in terms of private-sector time and public-sector resources.

Complex systems also lend themselves to problems with transparency and burden of proof. One stakeholder participating in interviews described a company that had incurred the trouble and cost of appealing a distance fee in another state. In this instance, the truck’s transponder recorded a $7,000 fee for traveling a turnpike. The burden of catching the error and pursuing the appeal fell upon the trucking company. The stakeholder indicated the system was either too complex or not automated enough to reduce human error. Another stakeholder indicated that Mississippi and Tennessee have been applying a formula to every ton over 80,000 pounds (36,287 kilograms), making it difficult for trucking companies to determine permitting fees up front when quoting to customers.

Flat fees are the simplest to administer for both the public and private sectors, but they encourage heavier loading as the damage amortizes unfairly across all carriers’ fees. Multiple trucking stakeholders indicated one size does not fit all.

13.3.2 Anticipated Infrastructure Improvements

When asked what infrastructure improvements should follow increased fees, interviewed stakeholders expressed broad-level consensus: infrastructure maintenance. Maintenance, repair, resurfacing, and fixing all were mentioned. Notably, these terms all relate to care of existing infrastructure rather than new construction. The one stakeholder who maintained the fee should be valued at the cost of permit administration stayed consistent in declaring that fees should only go to maintaining administrative services.

One interviewee indicated concern that the historically limited transportation funding in South Carolina has resulted in construction with short-lived materials and inexpensive subsurfaces, and materials with short life cycles incur greater costs in the long run. This stakeholder wanted to see greater consideration of life-cycle costing put into all infrastructure investments, particularly if trucking fees increase.

No one type of infrastructure emerged as the priority investment for immediate improvement. The stakeholders interviewed ranged from interstate trucking companies using major highways to agricultural interests accessing remote rural areas, and concrete trucks run on every type of infrastructure in all types of land use.

Although all infrastructure is needed, remote infrastructure was mentioned more than once as suffering the most from limited funding. Old low-demand rural bridges that were built to a historic standard have not received as much attention and funding as the modern Cooper River Bridge in Charleston. Many of these bridges cannot safely support overweight loads, forcing permitted vehicles to detour miles from their shortest routes, incurring private-sector costs and exposing more miles of pavement to the heavy vehicle.

13.3.3 Permit Processing Service

Given that South Carolina's existing flat fee structure is the simplest form of permit, any fee-structure changes will complicate administration well beyond the current level. Further, if a new fee structure eliminates flat fees for annual permits, trucks with the largest number of trips will instantly require processing for every individual trip. SCDOT's administrative burden will grow quickly and substantially, requiring additional staffing and systems.

Many trucking stakeholders indicated SCDOT administration of permitting services will need to increase along with fees. They were quick to praise the current service, indicating South Carolina typically turns around applications for overweight permits in a fraction of the time required in North Carolina. By policy, South Carolina offers permit processing in ten days, but all stakeholders reported the overweight permitting office typically has been responding in just two to three days. The turnaround time affects the competitive ability for trucking companies to respond promptly to requests for bids.

Some stakeholders were concerned about SCDOT's staffing for permit administration. Trucking companies have developed confidence in interactions with existing staff, but many staff members are now senior, which corresponds with a high number of vacation days and potential for retirement in upcoming years. The potential for turnover in this well-functioning office concerns trucking companies, especially in the context of changeover in the fee structure. One stakeholder commented that some states outsource permit administration to private contractors; this stakeholder neither endorsed nor condemned this practice. Another stakeholder requested greater automation with online self-service processing.

Inherent in the request for efficient and even automated permitting is the assumption that permits for weights beyond the legal limit should necessarily be authorized. The Interstate 5 bridge collapse over the Skagit River in Washington State on May 23rd, 2013, has illustrated the extreme implications of this mentality. In that collapse, a permitted oversized vehicle collided with functionally obsolete infrastructure on an approved route, resulting in structural failure and long-term highway closure, as depicted in Figure 23. This example has demonstrated that size and weight limitations exist for a reason, thus parameters should be established for what permits can be streamlined and what permits require greater scrutiny.

Source: Washington State Department of Transportation
http://www.wsdot.wa.gov/Projects/I5/SkagitRiverBridgeReplacement/

Figure 23 Skagit River I-5 Bridge Collapse from a Permitted Oversize Vehicle

13.4 Fee-Structure Development

The wide range of trucking configurations and overweight loads has contributed to the difficulty of setting permit fees rationally through scientific and financial analysis of infrastructure damage. Though recommendations based on engineering studies would offer rational basis for setting a comprehensive overweight user-fee structure, eleven of the sixteen states responding to the survey of state departments of transportation reported that legislature and lobbyists were the main contributors to decisions on adjusting fees. To improve the rationality of fee structures, this study has provided engineering and tradeoff analysis to initiate a fee policy discussion, as well as qualitative considerations of equity and economic flows. This section discusses what is necessary for developing a more rational system.

13.4.1 Consensus and Political Viability

Political viability is necessary for any successful economic plan. For instance, the major-investment concept of user-financed dedicated truck facilities has entered the national discussion on options. To accommodate growing demand in high-volume freight corridors, some state departments of transportation have considered constructing truck-only toll (TOT) lanes. This strategy has the advantage of targeting infrastructure for heavy use rather than upgrading all travel lanes, which would require substantial investment. The feasibility of financing TOTs depends on the willingness of trucking companies to pay for something they have thus far received for free. Proponents indicating a willingness to pay may emerge if operators are given opportunities to move heavier loads and long-combination vehicles (LCV). Beyond facilitating freight traffic, TOT lanes will potentially improve overall traffic operations by splitting slow truck traffic from other traffic; hazard exposure will also decrease by reducing conflicts between trucks and small vehicles (Korkut et al., 2010). The trucking industry has yet to embrace this idea, and without trucking associations and businesses reaching a consensus that TOT lanes are beneficial overall, the idea has rarely moved from the pages of feasibility studies to implementation on the ground. To develop political viability, consensus support from the trucking industry is a fundamental factor for initiatives that heavily affect shipping companies.

In the initiative to revise the overweight fee structure, South Carolina’s trucking stakeholders agree on some key points and hold differing opinions on others. Trucking industry representatives largely readily admit something needs to be done to improve South Carolina’s roadway infrastructure and SCDOT needs more funding. Consensus does not yet exist on the objective of overweight permitting. Perceptions of the objective ranged from administrative tracking and control, to cost recovery and revenue production.

13.4.2 Development of a Fee Structure

How is a fee structure developed? Stakeholders in South Carolina’s trucking industry expressed confusion on how to design a good fee structure.

> *“I can’t. I don’t know. I need to think about that and do some research on it.”*
>
> *“Get a grasp on what damage is happening.”*
>
> *“I don’t know the answer. I don’t know if it can ever be assessed. The best way is an administrative fee, engineering time, and damage to roads and bridges on a per ton-mile basis.”*

Coming from people who think about trucks on a daily basis, these statements of confusion indicate an intelligent desire to muster information on options and evaluate them. Information, analysis, and identification of repercussions need to be established before a system can be developed.

As indicated in the introduction to Section 11.0 , fee structures must follow from consensus recognition of the objective of the fees. The objective serves as the guiding principle from which the system will derive.

According to the survey of state departments of transportation, the most common objectives of overweight fees were:

- to recover costs for infrastructure damage incurred accurately and
- to increase revenue for infrastructure maintenance programs.

Permit structures did not match the latter declared reason because most of these states collected fees that are sufficient only to support the administration of permit processing. One state aimed to generate enough fee revenue to recover infrastructure damage from trucking without additional subsidy.

Secondary objectives also need to be determined. Fairness is an example. As another example, one stakeholder wanted to see simplicity and minimal negative impact on industry, saying, “We talk about overburdened regulations and reducing regulatory burdens.” A fee calculated from weight, distance, and axles will create a burden of reporting and complexity that might fail the secondary objective of simplicity.

Determining and establishing consensus on objectives will likely require lengthy public discussion, but time and effort invested up front in developing consensus on the objectives will facilitate every subsequent aspect of system development, implementation, performance monitoring, and review.

13.4.3 Consequences beyond the Objectives

As indicated in Section 12.1, the elasticity of demand and supply directly influence consumption of any kind of good or service, hence consumer behavior has a role. Changes in the price of a good or service (e.g., shipping freight) will naturally alter behavior as consumers respond to the change from economic equilibrium. Recognizing this economic principle, behavior can be artificially altered by intervening in the market through user fees. Levying a user fee will discourage use of that good or service if it is a normal good. User fees will also cascade through indirect and induced transactions spurred by the trucking industry.

High permit fees for overweight loads will reduce demand for overweight travel. A lower charge to smaller trucks might encourage breaking shipments into smaller goods if it is possible, which might be societally desirable. Alternatively, making shipment by large trucks difficult might encourage shippers to take a route through another state (Bowlby et al., 2001) or choose not to ship at all. Though all three outcomes benefit transportation infrastructure by decelerating deterioration, the overall economic impact might be undesirable. A 1997 federal study of highway cost recovery reported an unequal cost recovery from user fees among different vehicle classes, including trucks of different configurations and weights (March, 1998).

This discussion has raised a number of other considerations and potential consequences that should be debated in advance of system implementation. Negative side-effects can be avoided or mitigated if foreseen; likewise, positive side-effects might come to full fruition if steps are taken early to encourage their development. Too often, evaluations of policies and programs indicate “unforeseen consequences” that could and should have been predicted and addressed.

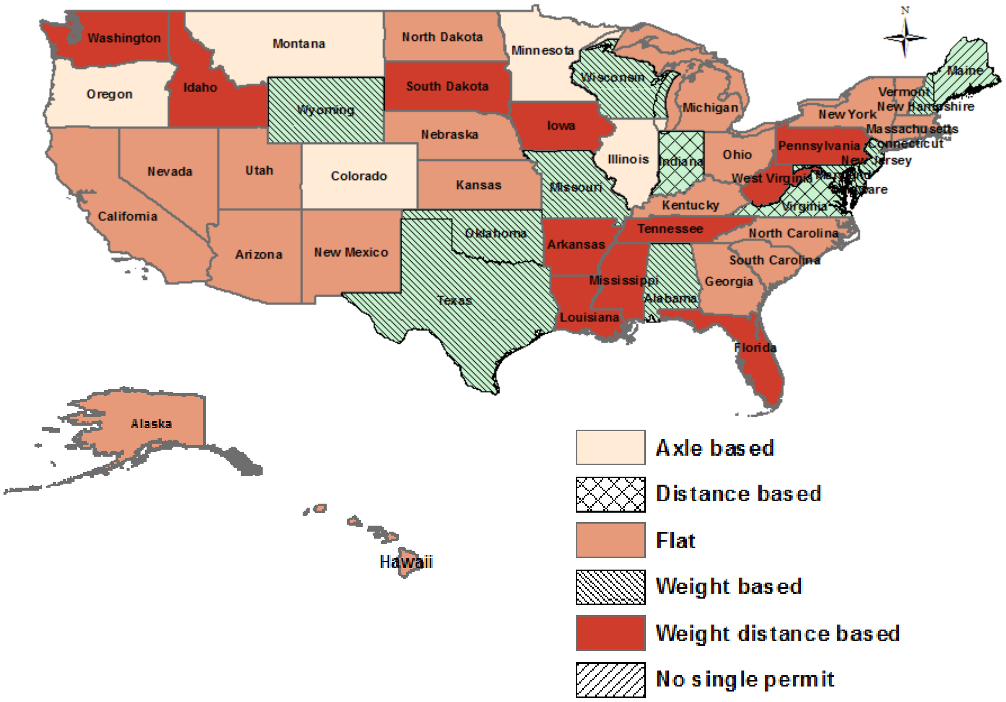
13.4.4 Fines for Overweight Violations

It is critical for DOTs to put forth sufficient effort to remove illegal overweight trucks from highways and charge a significant penalty to compensate for pavement damage as well as to discourage future illegal operations. As with permit fees, the survey of state departments of transportation showed legislators and lobbyists in most states have played the biggest role in determining how much should be charged for overweight violations. Besides legislators and lobbyists, state departments of transportation in four states took part in developing fine structures for infractions. One state reported using a specialized committee called the Uniform Fine and Bill Committee; another state relied on its judicial branch for the fine structure.

Given the emphasis that stakeholders of South Carolina’s trucking industry placed on enforcement (as discussed in Section 13.1.1), the structure and implementation of overweight fines needs strong consideration in terms of development and system monitoring. In the state survey, six states out of sixteen reported they had not performed any review of their fine structures since 2000. The most significant factor considered in determining overweight permit violation was to discourage illegal and overweight trucks on highways. Steep fines will likely serve as a strong deterrent.

13.4.5 Mega-regional Consistency of Fee Structures

A trucking company traveling an interstate can encounter a wide range of permitting structures. Figure 24 shows the geographic proximities of states with the five types of fee policies. Flat rates have appeared throughout the United States with particular prevalence in the southwest. Notably, the Port of Los Angeles/Long Beach conducts the highest container traffic in the nation (RITA, 2011), and the flat-rate policies of trucking in southwestern states create little economic disincentive to move heavy international containers onto rail to preserve road infrastructure. Weight-based policies have emerged in central states, which might make rail or marine modes attractive for heavy loads traveling long north-south routes. Shippers transporting heavy goods eastward from the ports in Seattle and Portland encounter a number of permitting structures that penalize for both weight and distance, which can make rail more attractive for heavy long-haul loads traveling between the coast and Chicago.



Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

Figure 24 Overweight Fee Structures Varying from State to State

Among South Carolina's neighbors, two other states have charged flat fees for regular overweight single trips. North Carolina has only charged $12 for a single overweight trip, compared to $30 in South Carolina and Georgia. Florida has developed a system considering trip length and gross vehicle weight ($0.27-$0.47 per mile). Tennessee has incorporated both distance and weight in its calculations. All of these southeastern states have offered annual permits for flat fees ranging from $100 to $1000 (Table 40).

Table 40 Overweight Permit Fees from South Carolina's Neighbors

State	Single Permit Fee	Annual Permit Fee
South Carolina	$30	$100
Florida	$3.33 + $0.27-$0.47 per mile	*$240-$500
Georgia	$30	$150
North Carolina	$12	**$100, $200
Tennessee	$15 + $0.05 per ton-mile	***$500, $1000

Data sources: J.J Keller & Associates, Inc, 2011 and state departments of transportation

*$240 for up to 95,000 pounds (43,091 kilograms) and $500 for up to 199,000 pounds (90,265 kilograms)

**$100 for general overweight vehicles, and $200 for mobile homes

***$500 for up to 120,000 pounds (54,431 kilograms), and $1000 for 120,000 to 150,000lbs (68,039 kilograms)

Many of South Carolina’s trucking representatives indicated fee structures in neighboring states should interact. Trucking moves along corridors, so a single trip might cross several state borders, and require compliance and permitting to several different standards. Stakeholders said mismatches, particularly in axle policies between states have led to business problems. One interviewee suggested axles should be considered in fee policies but must be coordinated among neighboring states to facilitate regional interstate commerce and economic health. He said if neighboring states will form consistent axle policies, companies will buy equipment accordingly. Another respondent said South Carolina should not establish itself as a barrier state although state policy on axle groupings already creates a barrier. Stakeholders largely indicated they would like to see coordination and collaboration among state departments of transportation across the Piedmont-Atlantic Mega-region (the Southeast region) for process, standardization, and operational consistency and uniformity.

14.0 Summary of Cost Recovery

User-fee structures to recover costs for overweight vehicles can have any or all of five basic fee structures: flat, distance-based, weight-based, weight-distance-based, and axle-based fees. Each structure commands unique characteristics related to fairness, precision of allocation, and implementation complexity. The incidence of each type of user fee will fall in various ways according to types of vehicles and industries. Economic elasticity determines who ultimately absorbs the cost of the fee.

South Carolina’s trucking stakeholders did not reveal consensus on how overweight fees in the state should evolve, but some points did emerge from multiple interviews. Fundamentally, representatives of well-intentioned shipping companies expressed concern that raising fees will encourage illegal trucking without permits, and the effectiveness of enforcement is nationally unclear since staffed weigh stations have given way to automated transponders. Enforcement planning must coincide with revision of South Carolina’s overweight fees. Other considerations included effects across jurisdictions and consistency of fee structures in the mega-region.

Part IV: Conclusions and Recommendations

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15.0 Conclusions

The largest loads on public road systems disproportionately inflict the largest damage on road and bridge infrastructure. Pavement models showed overweight trucks reduce pavement service life significantly, and current SCDOT pavement design standards do not include these heavy loads. Besides charging overweight trucks for associated damage, it might be economical to include heavy loads in pavement design to minimize premature pavement maintenance or rehabilitation.

Bridge model results indicated that bridge damage increase exponentially with an increase in gross vehicle weight. Preservation of bridges will require charging vehicles for associated damage or designing bridges to withstand higher weight trucks.

Traffic modeling has shown that South Carolina’s roads and bridges are exposed to overweight trucks that were not considered in the design process. Even though SCDOT issues permits for overweight trucks, current fees do not reflect the amount of imparted damage.

State departments of transportation address travel demand for loads in excess of federal and state standards. For state departments of transportation, the implications extend into the long term. Demand for truck freight is projected to increase by 72.3% by 2035, and truck configurations have grown in stature. The confluence of these trends has led to increased demand for the public highway system to support heavier loads, but the existing infrastructure was not designed to meet modern demand.

Five types of overweight permit fee have been implemented by state DOTs to recover pavement and bridge damage cost: flat, distance-based, weight-based, weight-distance-based and axle-based fee structures. Many states employ combinations of these types. Flat fees, which South Carolina has been administering, are most common but least fair in terms of collecting revenue. Comparative analysis of fee structures has shown relatively inconsistence performance of fee structures for different axle configurations.

To recover additional damage imparted by overweight trucks for additional load above legal limit in an axle based fee structure, the permit fee will vary between $24 and $175 per trip for different overweight truck types, while in a flat fee sturcture, all overweight trucks will pay $65 per trip (including $10 adminstrative permit processing fee). Consideration of axle load, axle configuration, and trip length in fee structures will more accurately reflect damage imparted by each truck type. Fee estimates provided in this study did not consider user fees paid through fuel tax, vehicle registration, or other fees.

Permitting rules allowing overweight trucks are inconsistent from state to state. Heterogeneous overweight permitting structures indicate a likely mismatch among permits, weight demand, and infrastructure capability. For shippers, this heterogeneous nature can confuse interstate overweight trucking operations over long corridors crossing several states, which suggests a need for coordination among neighboring states. Trucking industry representatives have indicated they would like to see coordination of fee structures among states in a region.

How to set a responsible fee structure for overweight permits eludes many informed people. State departments of transportation indicated that fee structures have often covered the administrative costs of tracking oversized and overweight loads rather than paying for damage to public infrastructure. Web survey responses have indicated that legislators and lobbyists, rather than engineering analysis of infrastructure damage costs, have played significant roles in setting overweight fees and fines in many states. Interviews showed that fundamentally, South Carolina's trucking stakeholders do not hold common ideas on the objective of overweight permits and fee structures. South Carolina will not likely find fee revisions and increases politically viable until a consensus develops around the objective of overweight permitting and fees. SCDOT and trucking industry representatives should work together in an ongoing focus group to develop common understanding of issues, consensus around objectives, and provisions for fairness that will address industry concerns.

16.0 Recommendations

The largest loads on the public road system disproportionately inflict the largest damage on public road and bridge infrastructure. Transportation policy makers need to match permitting structures and rates to the needs of public finance to attain the proper price equilibrium between supply and demand. Engineering and economic analyses need to set rates for permit fees and fines, removing or at least reducing the political influence and tying rates to infrastructure costs rather than administrative processes that represent a minor fraction of the true cost of overweight-load movement.

Based on the findings of this project, the research team proposes the following recommendations to improve South Carolina's current overweight permit practices.

16.1 Studies and Audits

This report has presented foundational analysis of engineering, infrastructure costs, and stakeholder issues, but supplemental information in other dimensions is still needed. The research team recommends the following studies.

16.1.1 An Enforcement Audit

Enforcement of unpermitted overweight travel stood as the most frequently identified concern among South Carolina's trucking stakeholders. To gain support for higher fees from the trucking industry, enforcement must be addressed. The research done on this topic will fill a gap in the nation's knowledge of illegal trucking activity since broad dissemination of weigh-in-motion and related intelligent transportation systems closed many staffed weigh stations.

South Carolina needs to determine the extent of the problem of unpermitted overweight loads. From this identification, a plan should emerge for targeting unpermitted activity.

16.1.2 An Economic Study

This study has produced findings on the costs of infrastructure deterioration from overweight trucking; the next step needs to identify the economic impact. To create a balanced discussion among stakeholders and decision makers, South Carolina should establish all facts of the economic situation surrounding the trucking industry and industries that ship overweight goods. This economic study should include a freight demand model and sensitivity analysis according to industries and business sizes. This study should also assess vulnerability of industries and businesses to shutting down due to an increased transportation cost structure.

16.1.3 A Finance Analysis

While the economic study will evaluate monetary issues of industries, a separate finance study is also needed to ensure the freight industry sees its fair returns on investment in infrastructure. This study needs to follow tax money as it travels from diesel pumps and registration forms through various government agencies and into general funds or funds dedicated to infrastructure. The research team attempted to follow this money trail in preparation for the stakeholder interviews, but found confusion amongst the agencies involved. A dedicated effort is necessary to track the path and quantity of money to determine how much trucking money goes to infrastructure and what is necessary to ensure that increased permit fees serve their intended purpose.

- How much federal diesel tax returns to South Carolina?
- Where does diesel tax revenue go?
- Even though indirect and induced benefits of trucking will be impossible to monitor and calculate on an ongoing basis, can at least direct sales-tax revenue from trucking businesses be dedicated to infrastructure maintenance?

16.1.4 Evaluation of Construction Standards

As mentioned in Section 13.3.2, there is some stakeholder concern that construction standards should be improved to reduce long-term maintenance and overall life-cycle costs. Because pavement and bridge damage increases exponentially, increasing design standards can increase service life. Subsurface and other standards of construction should be reviewed as South Carolina businesses agree to invest more in infrastructure through truck fees.

This study estimated pavement damage from default design parameters in the MEPDG. More localized calibration information will improve the accuracy of damage cost estimation by representing variation in pavement design parameters. The research team recommends this customized approach for locations where the SCDOT wants to focus attention.

16.1.5 An Audit of Service Efficiency

Several of South Carolina's trucking stakeholders expressed concern that a more complex system will require greater processing from SCDOT and decrease service efficiency. South Carolina should plan an audit of the permitting office's service efficiency both before and after making changes to the permitting system. Before making changes, an audit should identify and benchmark performance measures of efficiency and effectiveness in the office, including staff availability, processing times, processing accuracy, and other measures. Any observations that identify ways to streamline services while maintaining roadway safety should be documented, particularly in relation to automation and web-based options.

The process should be repeated six months or a year after making changes to the permitting process to monitor performance and make adjustments. Observations along new parameters might be relevant along with the baseline measures developed in the first service audit.

16.2 New Ongoing Processes

Studies by researchers and consultants provide information to support decision making, but facts on paper need to translate into actions by people and organizations. The following processes will facilitate communication, consensus, participation, and support for fee structures.

16.2.1 A Stakeholder Focus-Group Process

As mentioned in Section 13.4, the survey of state departments of transportation found that a strong majority of states have permit systems developed by politicians without a basis of engineering. South Carolina has already improved on this record by commissioning this study, but the process can become truly representative if stakeholders come together in a multi-meeting focus group to gain a common comprehensive understanding of how overweight vehicles affect infrastructure and what mechanisms can address the effect.

A common understanding does not exist naturally. Part III of this report on Cost Recovery has indicated subjects where consensus exists and other places where a system mandated by the legislature will likely develop dissention with possible negative economic repercussions for South Carolina. In these situations, consensus needs to be developed.

Given that South Carolina's trucking stakeholders rarely appear in one place to identify and discuss issues in depth, SCDOT will do well to begin an ongoing focus group of trucking-industry representatives, pavement and bridge engineers, permit administrators, and possibly legislators. All of these stakeholders need to listen to and learn from each other, gaining a common basis of understanding from which to develop and recommend a permitting system. A system developed in this manner will be more informed and functional than something developed through debate in the legislature, and all parties might well adapt day-to-day operations based on what they learn through the process. The focus group needs to involve the same people attending all meetings, allowing development of shared understanding and rapport from which informed decisions and actions can emerge.

Preliminary group sessions should include the following.

- Agreement on the purpose of the focus group and what should be accomplished.
- An industry-accessible explanation of the modeling processes and results in Part II of this report with an open session for questions and answers.
- Explanation and discussion of the state of South Carolina’s roadway infrastructure.
- Explanation and discussion of the issues raised in Part III of this report.
- Identification and fact-based presentation of other issues that need to be raised.
- Explanation and discussion of various fee systems and their economic ramifications.
- Best practices of how to make policies adaptable to inflation, fuel prices, and changes in various industries.
- Discussion of fee structures in the mega-region, possibly with participants invited from other states.

Only after these four (or more) sessions are held to develop common understanding and language should this focus group endeavor to make decisions. As discussions for stances of the group begin, the group should first and foremost discuss and decide the objective of the permitting system and fees as discussed in Section 13.4.1. Decisions of the group might include the following.

- Objective(s) of the permitting system (Section 13.4.2)
- Anticipated and accepted positive and negative side effects (Section 13.1 to 13.3)
- Permitting structure (Section 12.1)
- Whether annual permits should exist and how many trips they represent (Section 11.2.1)
- Allowable exceptions (Section 13.2.2)
- Level of service, staffing, and potential automation to establish for the future of the SCDOT permitting office (Section 13.3.3)
- Fines and enforcement (Sections 13.1.1 and 13.4.3)
- Benchmarks and performance monitoring

Each topic bullet point merits at least one full meeting’s discussion, thus this focus group will likely need to meet monthly over the course of one year. The group should also plan on meeting between six and twelve months after policy implementation to review results.

Stakeholder interviews generally indicated such a focus group will receive industry encouragement and participation. Different participants made the following statements.

> *"I recommend a small working group of people running trucking companies to discuss what we do well, what we do not do well, and how it is done in other states."*
>
> *"We want to be at the table when these decisions are made."*
>
> *"We are here as a partner."*
>
> *"Industry needs to be included and engaged. Give us a seat at the table. We need to be able to voice our concerns. It gives the State perspective. We are living it every day, and they are not."*

In contrast, one interviewee declared the trucking companies represented would leave the decision up to the legislature, and another stakeholder said industry representatives might not have the political perspective to feel comfortable talking. Presumably, stakeholders who want to participate in a focus group will participate and others will not.

16.2.2 Ongoing Monitoring of Overweight Vehicles

South Carolina can keep its fee structures representative and accurate by implementing technology to provide continuing characterization of overweight activity. Vehicle classification and the percentage of overweight trucks should be collected at all weigh-in-motion (WIM) locations to support damage determination. This study estimated overweight truck percentage based on data from one WIM station. This estimate might be improved if data from more WIM stations could be used.

An origin-destination and route study of trucking in the state can refine awareness of *what load configurations* are traveling *what distances* over *what roadway infrastructure*. Currently, permit holders declare their trip origins and destinations but not the number of miles travelled in each trip. As pavement and bridge damage is directly related to length of trip and truck load, it is recommended to keep track of routes and mileage travelled for each trip to readjust permit fees.

16.2.3 Mega-regional Collaboration on Trucking Fees

As the map in Figure 24 has indicated, state departments of transportation across the nation have adjusted their permitting schemes to consider factors of weight and distance. South Carolina should interact with neighboring states to learn their plans regarding oversize and overweight permitting. Especially if other states are planning revisions, state departments of transportation should communicate and possibly collaborate to work toward regional consistency that will benefit businesses throughout the Southeast and promote the region's ability to compete nationally and globally.

16.2.4 Periodic Review and Adjustment for Inflation

In the survey of state departments of transportation, 75% of respondents (12 out of 16) reported they had no set schedule for reviewing their overweight fee structures. Of the 2 states reporting their schedules, one state reviewed every 2-3 years and the other reviewed once a decade. Roughly one half of responding states had revised their fee structure in the last 10 years, and one-third had not done so in 15 or more years.

When South Carolina makes changes to state policy on overweight permitting, the new policy should incorporate a sunset clause. After a period of time, the policy should be reviewed for its applicability under the new normal economy. If the sunset clause is established at the time of writing the policy, the review can be more reliably anticipated and initiated in a reasonable time frame.

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APPENDICES

Appendix A SCDOT Overweight Trucks Permit Data

A-1 Overweight Truck Axle Distribution

2-Axle Trucks

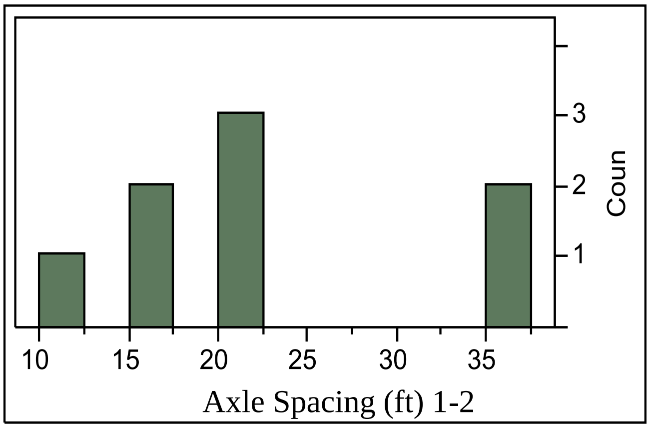


Figure A.1 2-Axle Truck Spacing Configuration

3-Axle Trucks

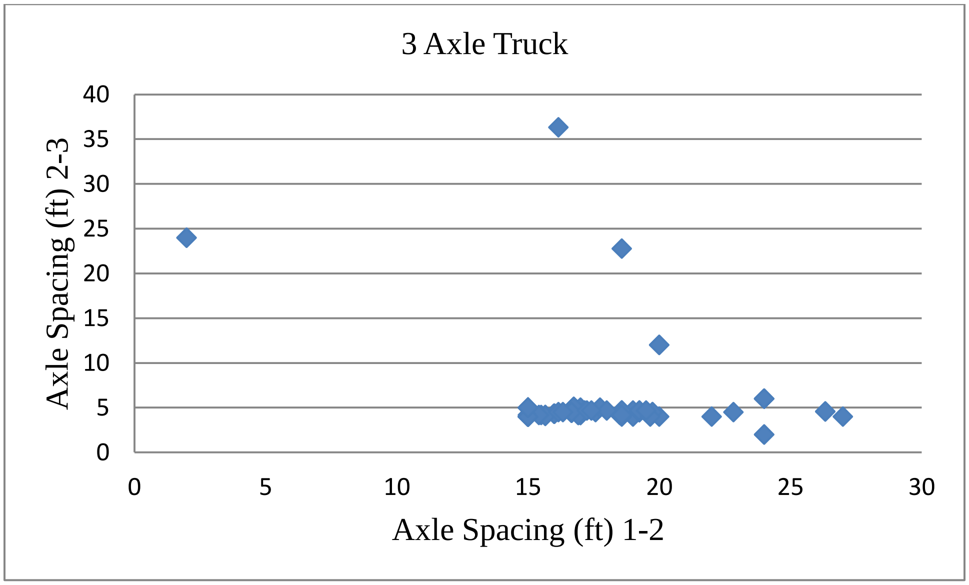


Figure A.2 3-Axle Truck Spacing Configuration

4-Axle Type A Trucks

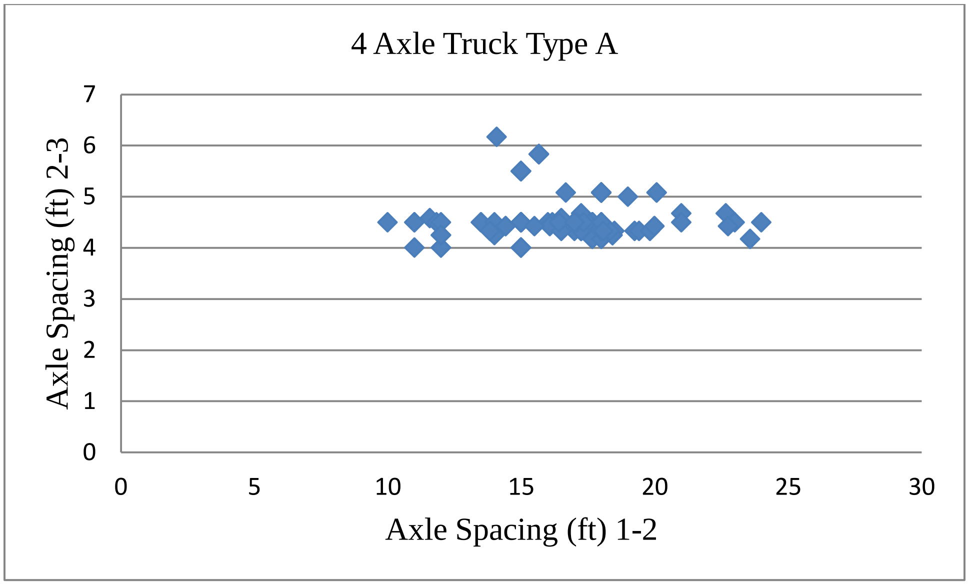


Figure A.3 4-Axle Type A Truck Spacing Configuration 1

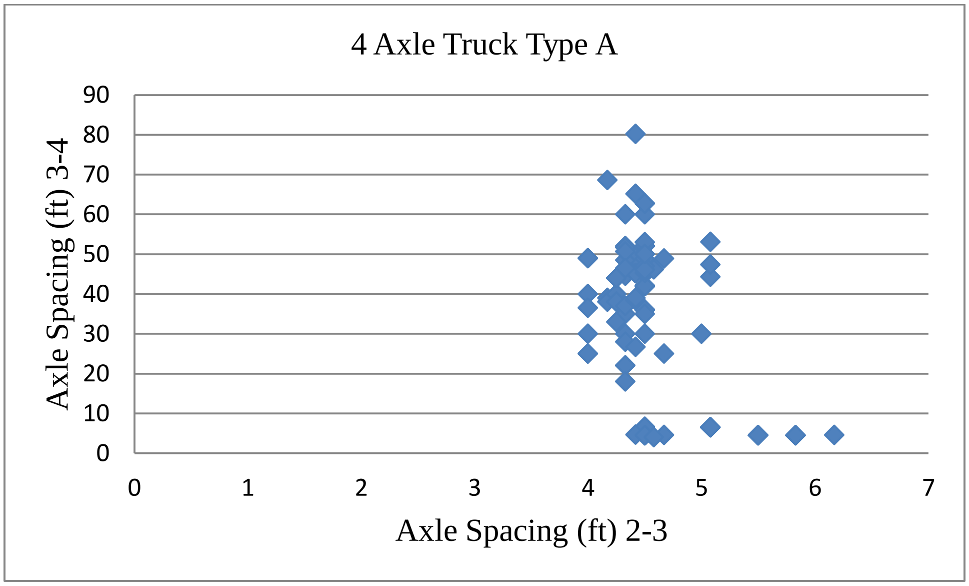


Figure A.4 4-Axle Type A Truck Spacing Configuration 2

4-Axle Type B Trucks

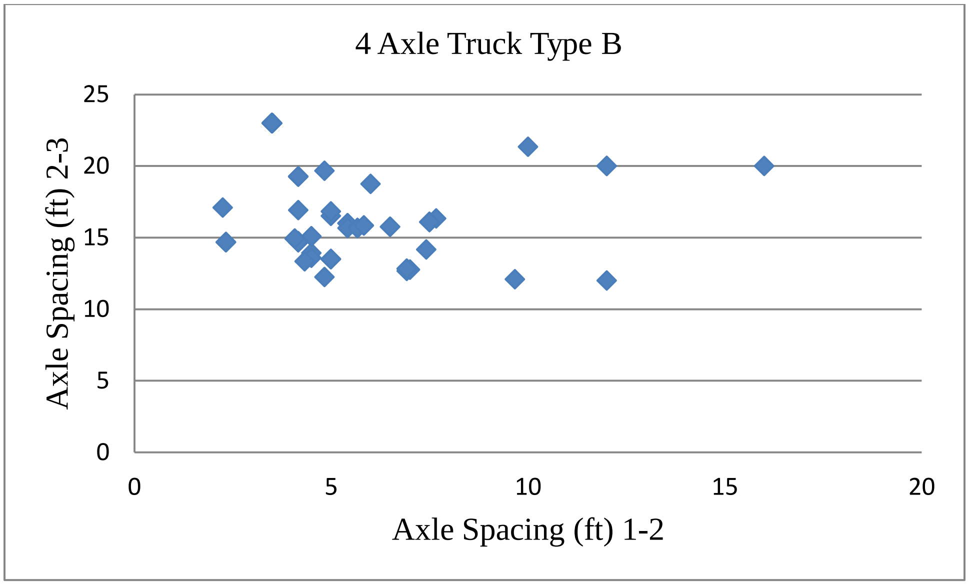


Figure A.5 4-Axle Type B Truck Spacing Configuration 1

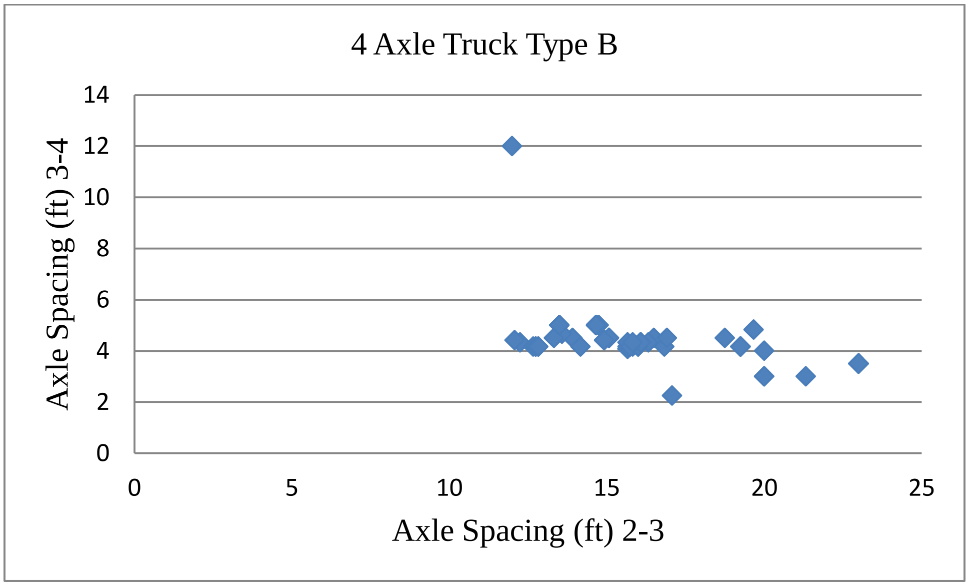


Figure A.6 4-Axle Type B Truck Spacing Configuration 2

4-Axle Type C Trucks

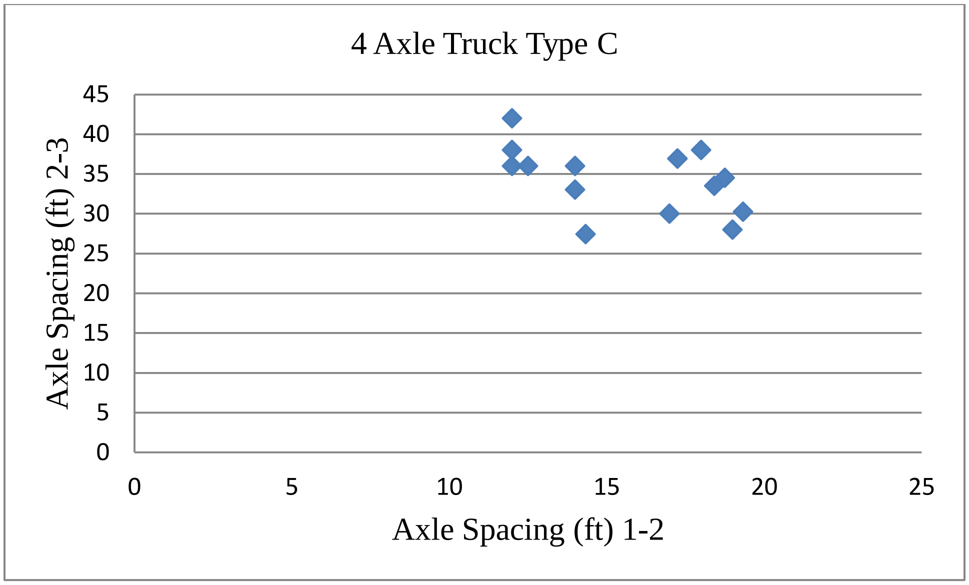


Figure A.7 4-Axle Type C Truck Spacing Configuration 1

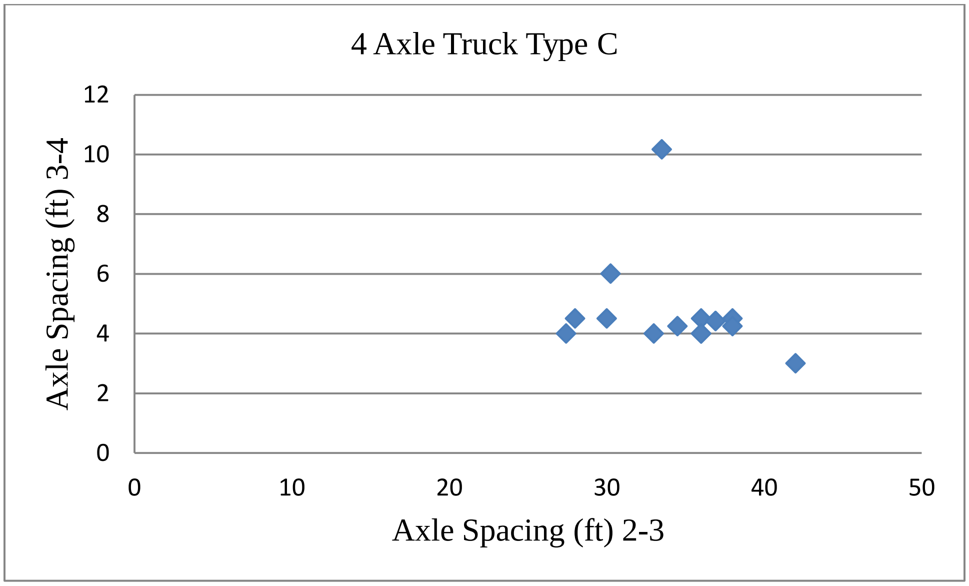


Figure A.8 4-Axle Type C Truck Spacing Configuration 2

5-Axle Trucks

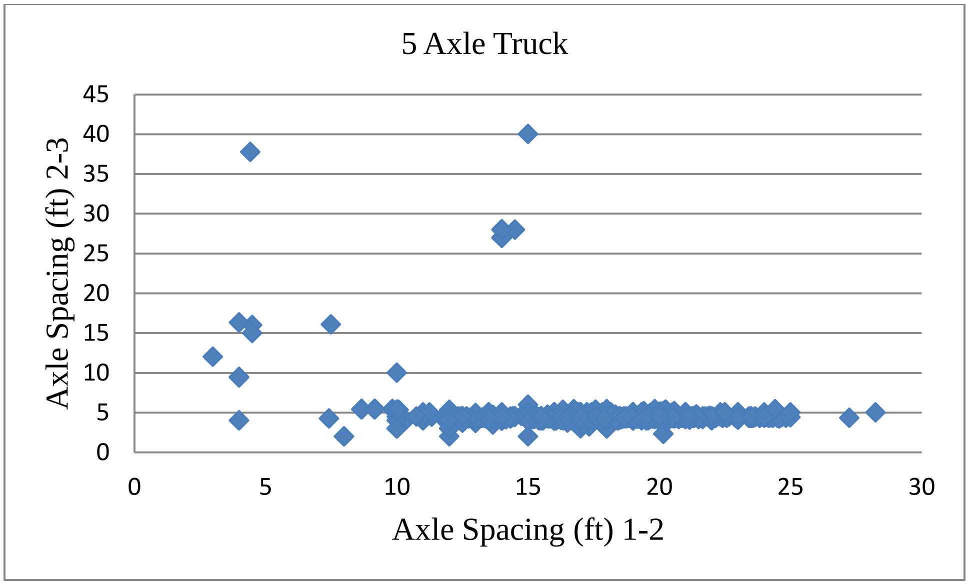


Figure A.9 5-Axle Truck Spacing Configuration 1

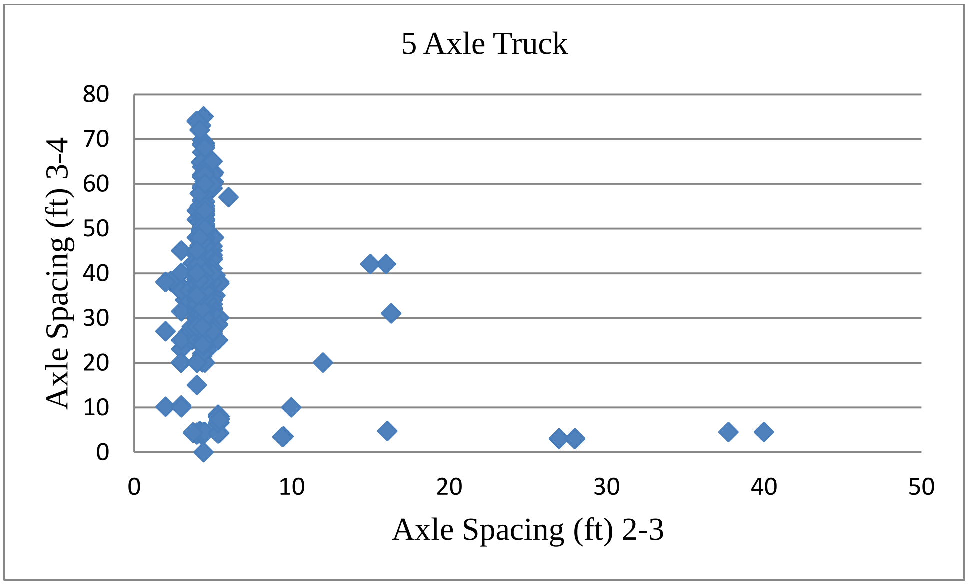


Figure A.10 5-Axle Truck Spacing Configuration 2

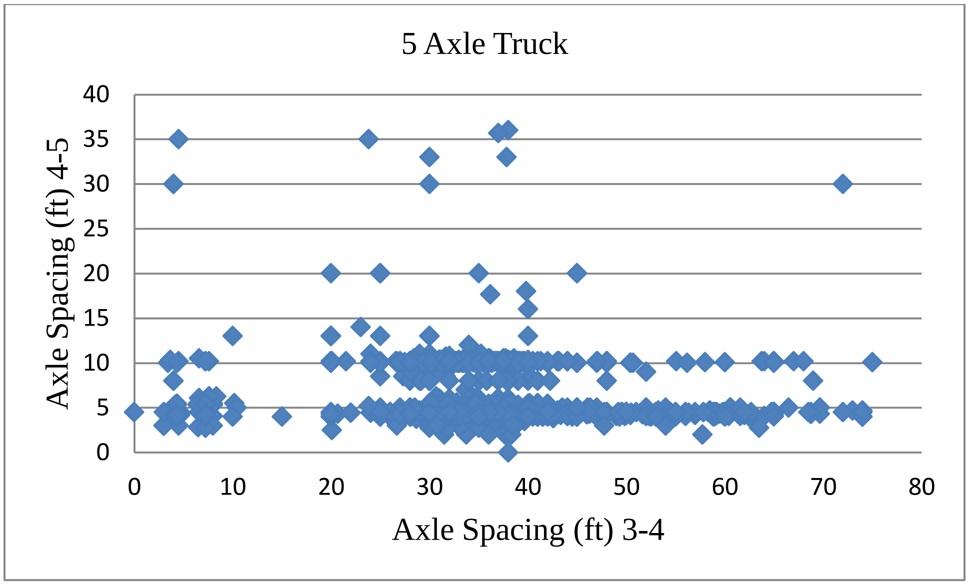


Figure A.11 5-Axle Truck Spacing Configuration 3

6-Axle Trucks

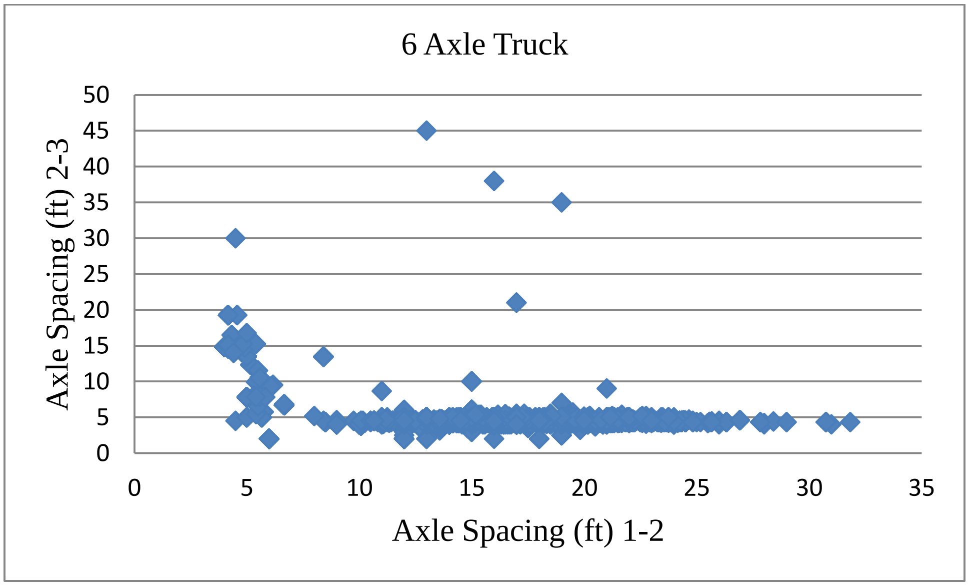


Figure A.12 6-Axle Truck Spacing Configuration 1

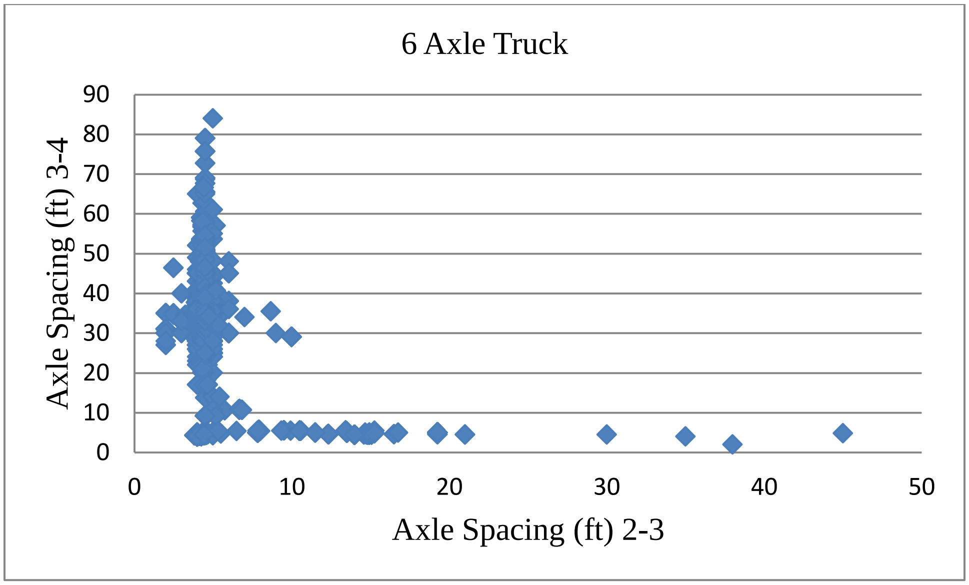


Figure A.13 6-Axle Truck Spacing Configuration 2

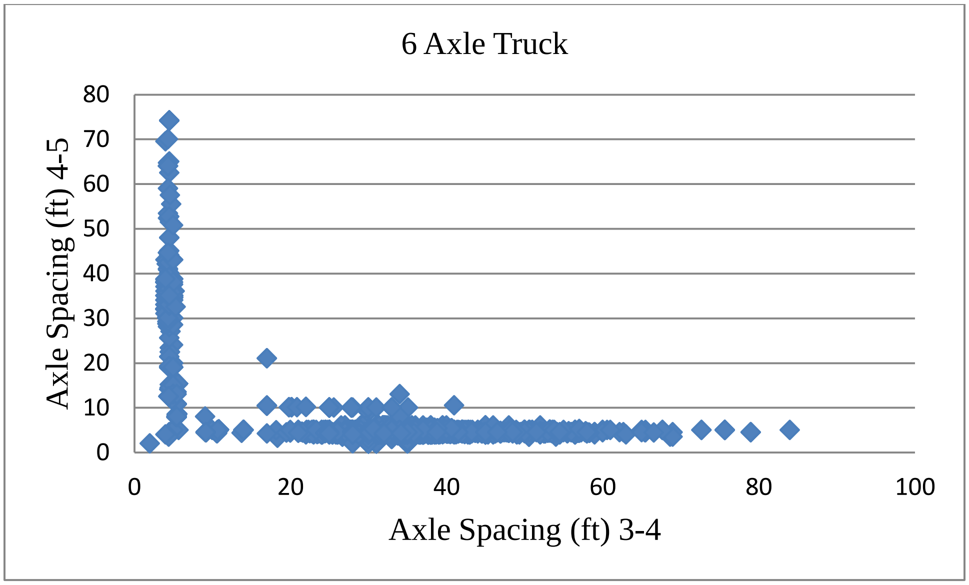


Figure A.14 6-Axle Truck Spacing Configuration 3

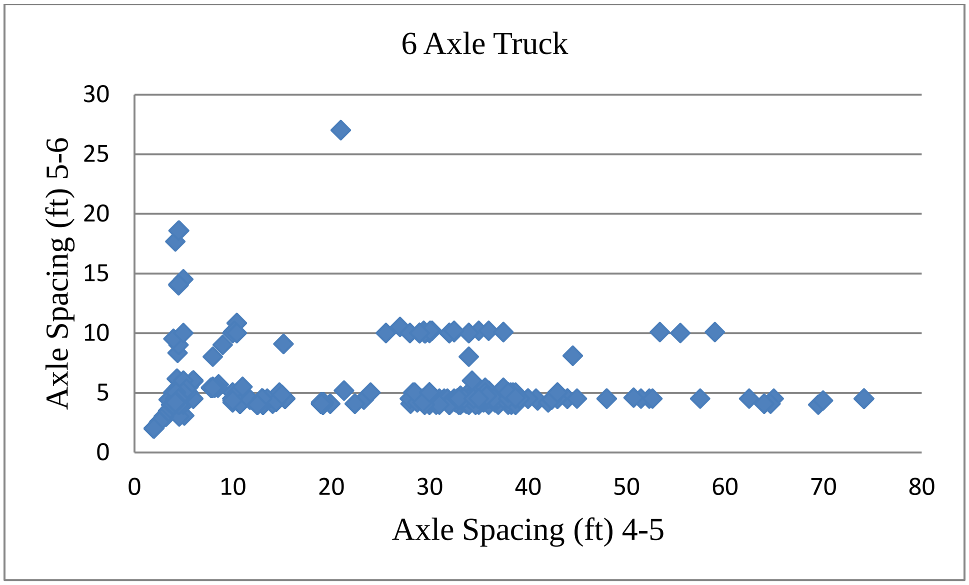


Figure A.15 6-Axle Truck Spacing Configuration 4

7-Axle Trucks

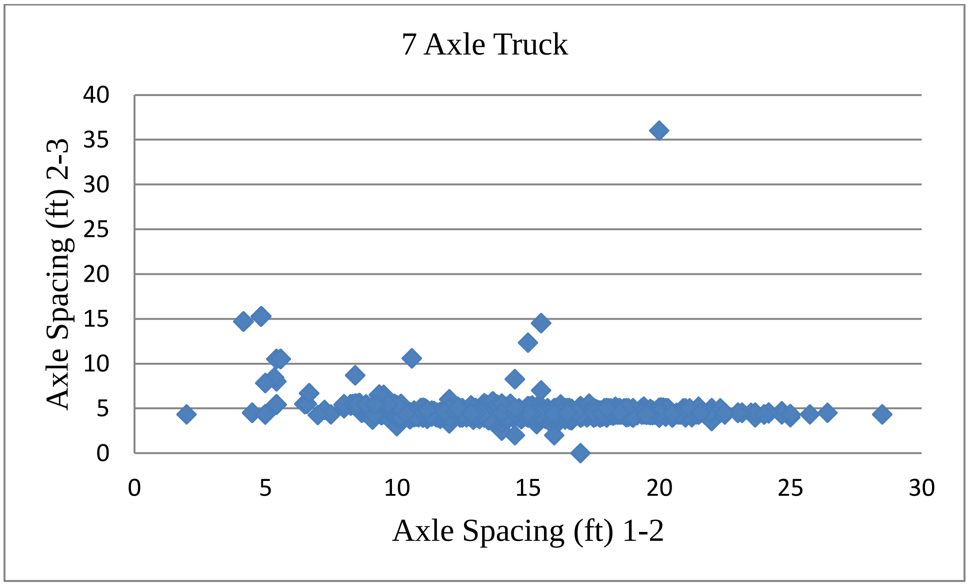


Figure A.16 7-Axle Truck Spacing Configuration 1

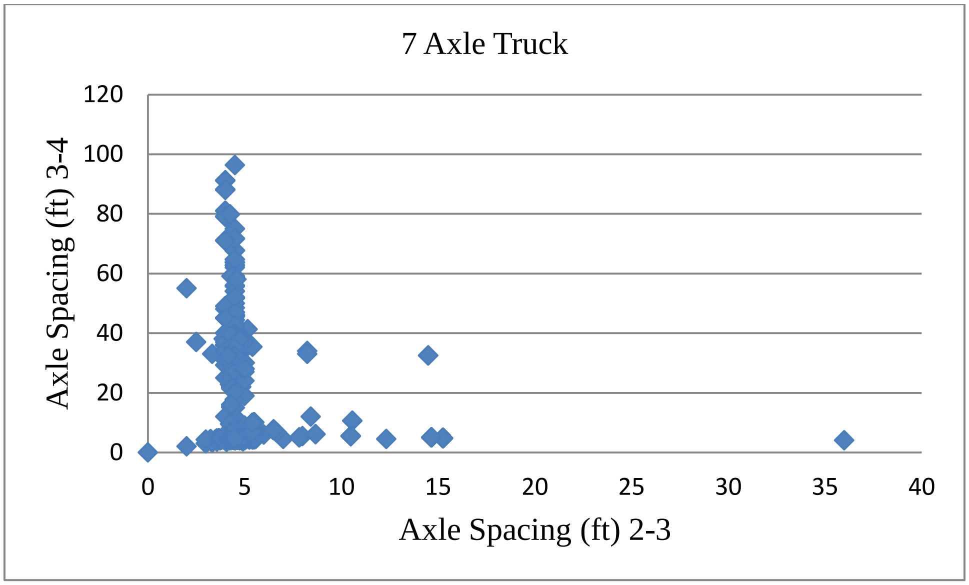


Figure A.17 7-Axle Truck Spacing Configuration 2

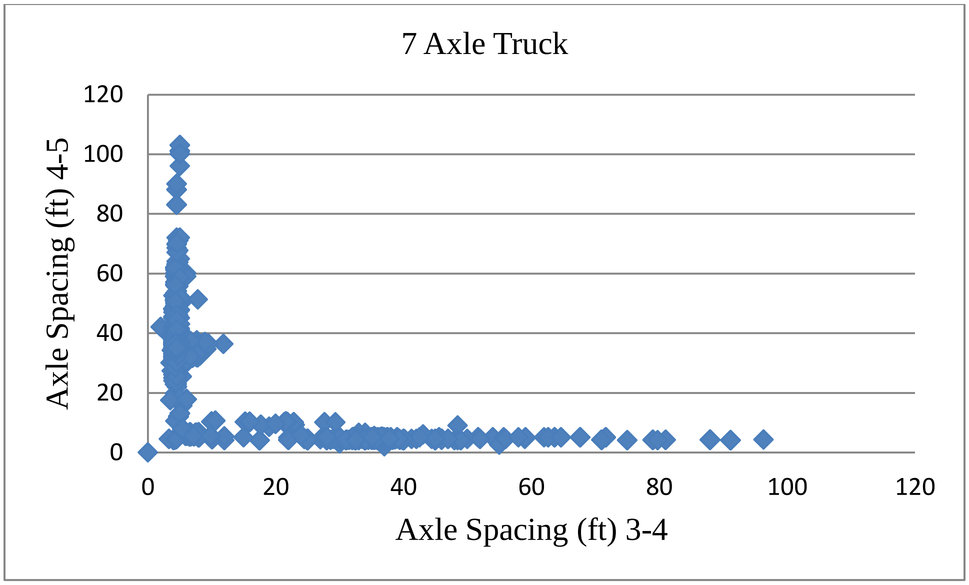


Figure A.18 7-Axle Truck Spacing Configuration 3

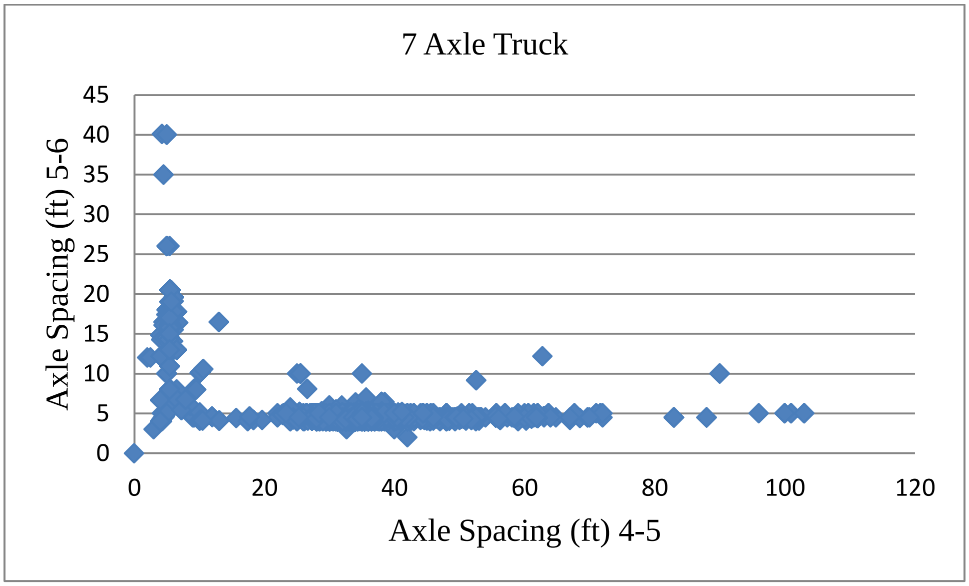


Figure A.19 7-Axle Truck Spacing Configuration 4

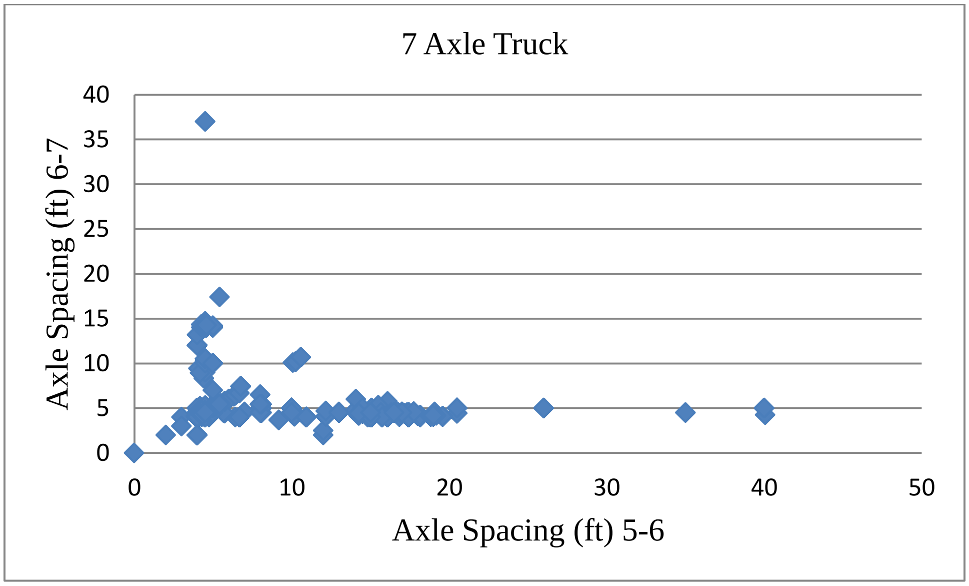


Figure A.20 7-Axle Truck Spacing Configuration 5

8-Axle Trucks

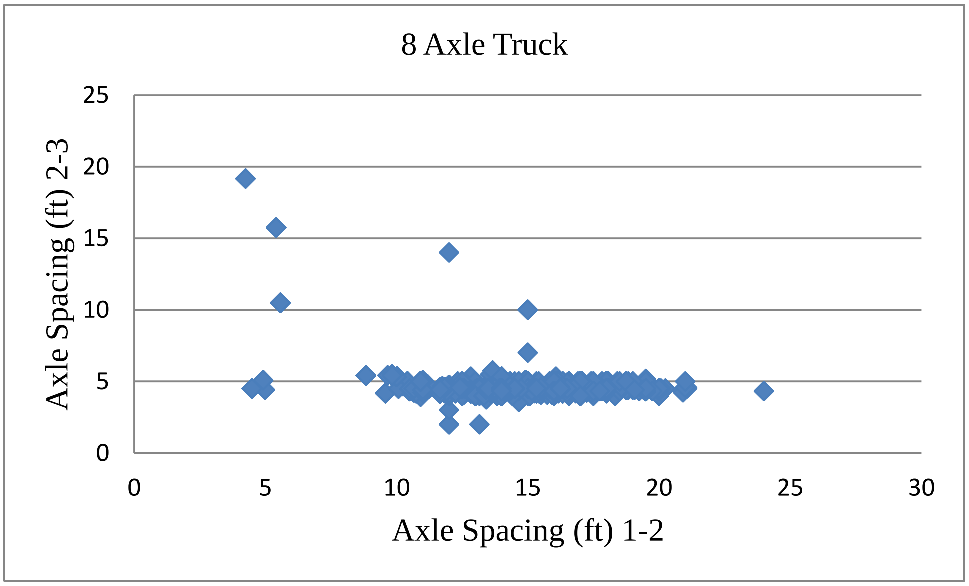


Figure A.21 8-Axle Truck Spacing Configuration 1

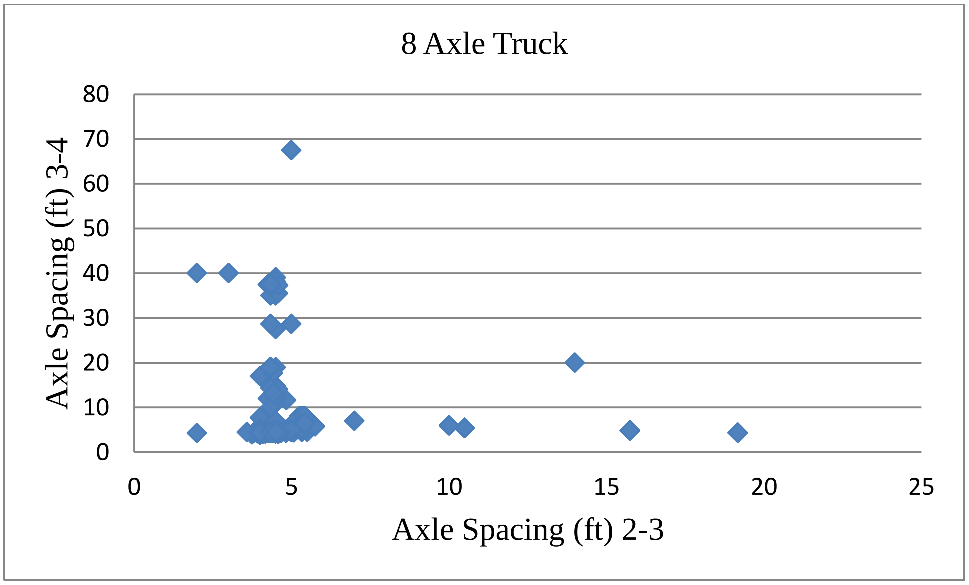


Figure A.22 8-Axle Truck Spacing Configuration 2

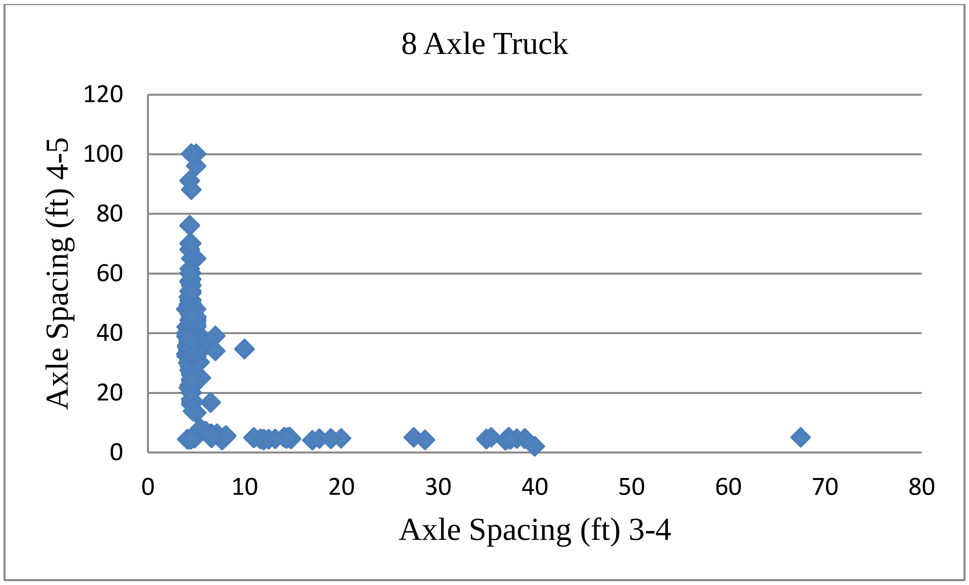


Figure A.23 8-Axle Truck Spacing Configuration 3

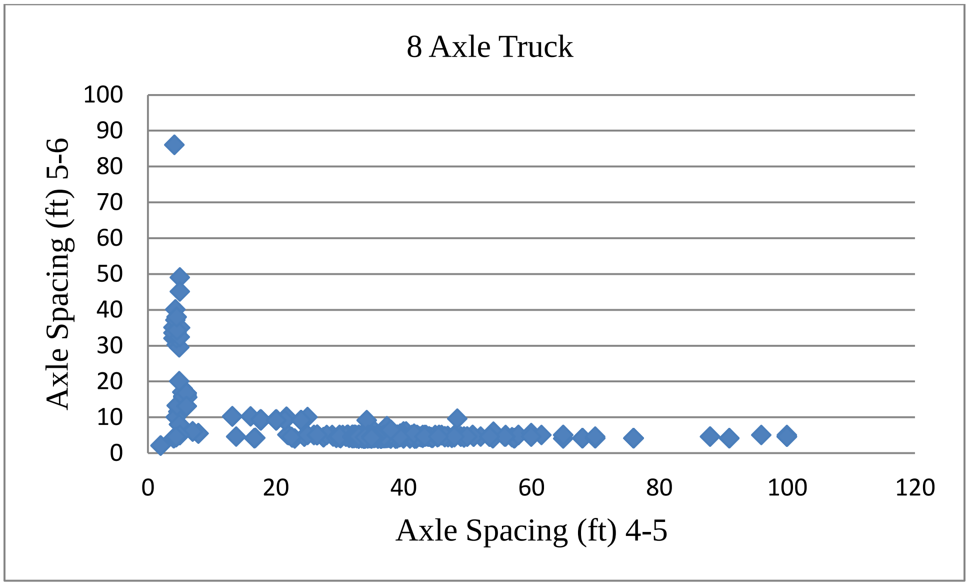


Figure A.24 8-Axle Truck Spacing Configuration 4

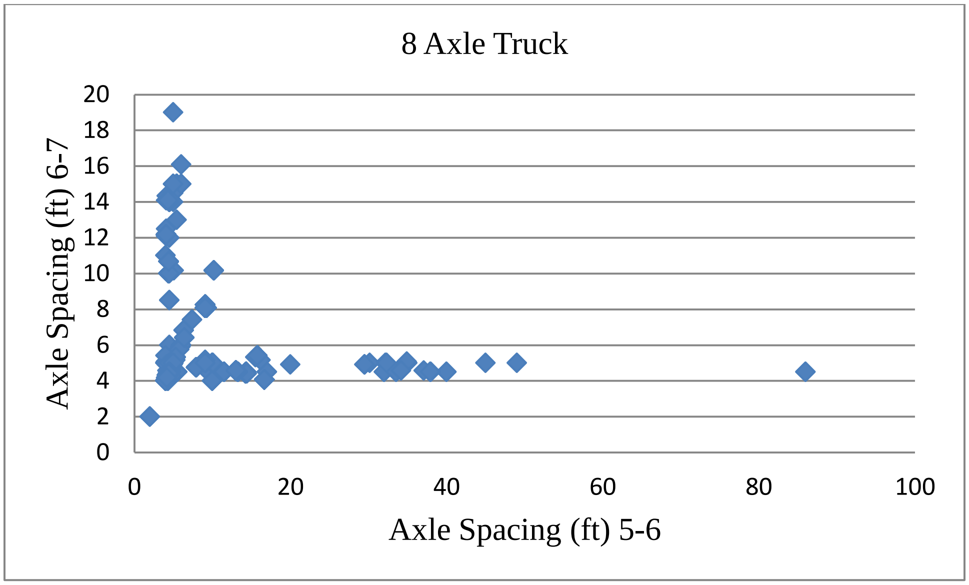


Figure A.25 8-Axle Truck Spacing Configuration 5

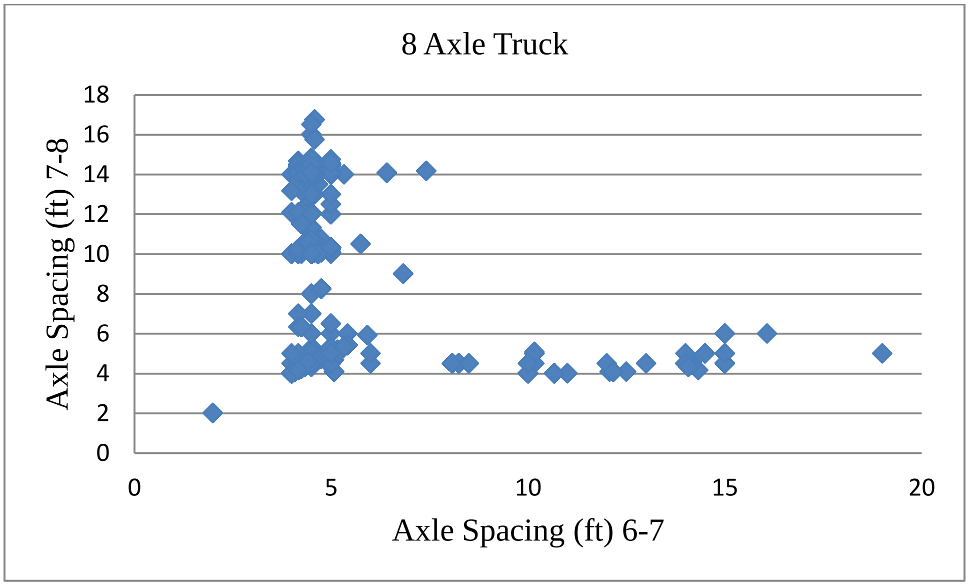


Figure A.26 8-Axle Truck Spacing Configuration 6

A-2 Overweight Truck Weight Distribution

The percent of truck associated with each GVW level and axle group shown in Table A.1 was determined using the weigh-in-motion data. From the weigh-in-motion data, the cumulative counts or numbers of trucks by gross weight for each vehicle class were used to fit the truck distribution to the 3-parameter Weibull distribution. The cumulative distribution function (CDF) for the 3-parameter Weibull distribution is:

$$F(x) = 1 - \exp\left[-\left(\frac{x-w}{u-w}\right)^{k}\right] \qquad (A.1)$$

Where,
x: truck weight
u: scale parameter (>0)
w: location parameter (lower limit of x, 10 kips was assumed as the base truck weight)
k: shape parameter (>0)

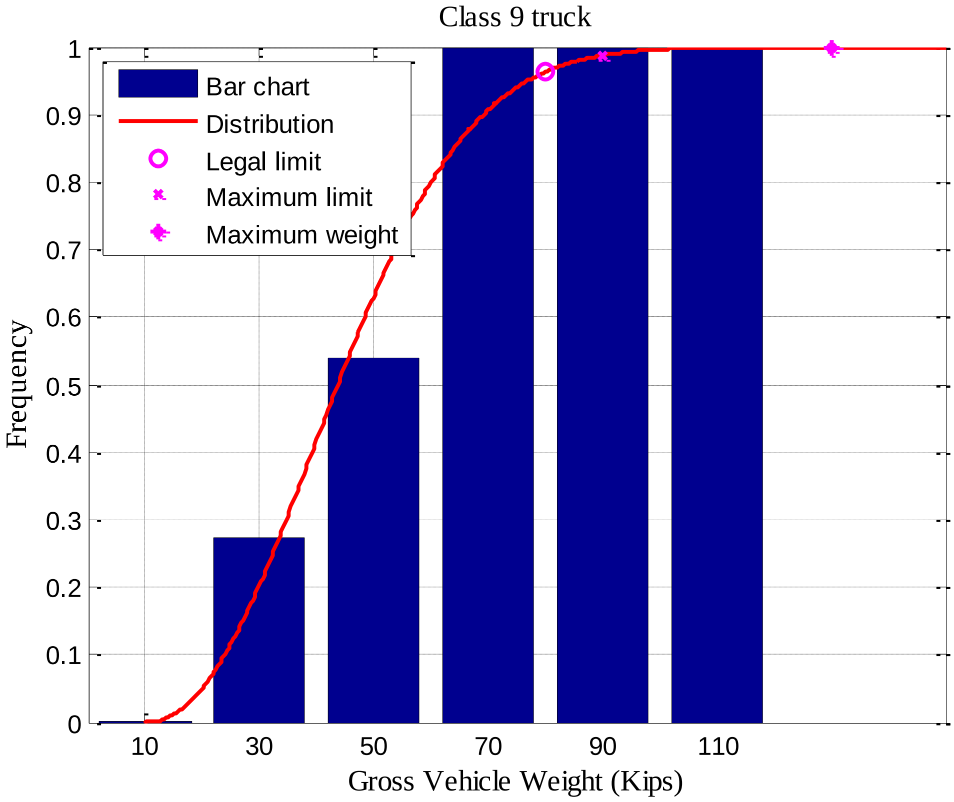


Figure A.27 Class 9 Truck Weight Distribution Model

Table A.1 Gross Vehicle Weight Distribution by Vehicle Class

FHWA Vehicle Class	Axle Group	Percentage of GVW1	Percentage of GVW2	Percentage of GVW3
5	2-Axle	99.98%	0.01%(a)	0.01%(a)
6	3-Axle	99.90%	0.08%	0.02%
7	4-Axle	99.91%	0.08%	0.01%(a)
8	3-Axle	99.92%	0.06%	0.02%
	4-Axle	99.98%	0.01%(a)	0.01%(a)
9	5-Axle	92.68%	4.82%	2.50%
10	6-Axle	95.86%	4.08%	0.06%
	7-Axle	95.85%	4.14%	0.01%(a)
11	5-Axle	99.95%	0.04%	0.01%(a)
12	6-Axle	75.00%	23.61%	1.40%
13	7-Axle	32.98%	54.20%	12.82%
	8-Axle	32.98%	54.20%	12.82%

(a) Note that some of the cells had zero observations. This is because the weigh-in-motion data were collected for one location (StGeorge1) over a six-month period. For those GVW2 and GVW3 cells with zero observations, a nominal percentage of 0.01% was assumed to consider the unaccounted overweight trucks due to the limited data.

Figure A.27 shows the cumulative distribution of the class 9 truck determined using the weigh-in-motion data (SCDPS 2012a). The blue bars represent the cumulative percentage of trucks with different gross weights and the red curve represents the fitted distribution model. With the CDF for each vehicle class determined, the probability density function (PDF) for the 3-parameter Weibull distribution was then obtained using the following equation:

$$f(x) = \frac{k}{u-w}\left(\frac{x-w}{u-w}\right)^{k-1} \exp\left[-\left(\frac{x-w}{u-w}\right)^{k}\right] \qquad (A.2)$$

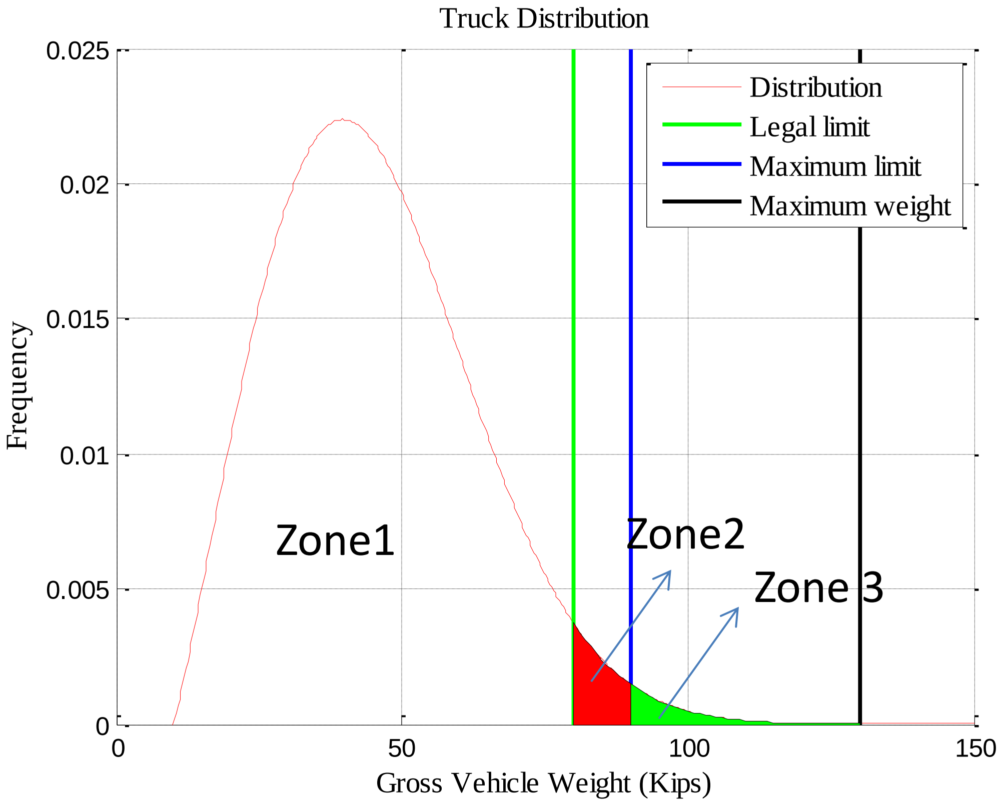


Figure A.28 Truck Gross Weight Distribution for Vehicle Class 9

Figure A.28 shows the PDF curve for the class 9 truck. Zone 1 includes those trucks with their gross vehicle weights less than the legal weight limit. For analysis purpose, the percentage of these trucks (i.e. area of Zone 1) was conservatively assigned to GVW1 (80% of the SCDOT legal weight limit). Zone 2 represents the percentage of trucks with gross vehicle weights between the legal limit and the maximum limit (see Table A.1). The area of Zone 2 was assigned to GVW2 (SCDOT maximum weight limit). Similarly, Zone 3 represents the trucks with gross vehicle weights larger than the maximum limit and this percentage was assigned to GVW3 (maximum considered truck weight). The percent distributions of GVW1 to GVW3 for all vehicle classes are given in Table A.2.

Using the mapping between the FWHA vehicle class and axle groups shown in Table A.2, the gross vehicle weight distribution by vehicle class (Table A.1) was then grouped by the number of axles and the results are shown in Table A.2.

.

Table A.2 Gross Vehicle Weight Distribution by Axle Group

Axle Group	Percentage of GVW1	Percentage of GVW2	Percentage of GVW3
2-Axle	99.98%	0.01%	0.01%
3-Axle	99.92%	0.06%	0.02%
4-Axle	99.98%	0.01%	0.01%
5-Axle	92.91%	4.66%	2.42%
6-Axle	95.54%	4.38%	0.08%
7-Axle	94.25%	5.41%	0.34%
8-Axle	32.98%	54.20%	12.82%

In order to account for the influence of axle configuration (i.e. axle spacing) on bridge damage, information on the axle spacing was incorporated into the surrogate truck models. The truck axle configuration information (axle spacing, axle weight) associated with each truck weight was determined from the SCDOT overweight truck permit data (SCDOT 2012). Since GVW1 and GVW2 trucks consisted of the majority of the trucks within each axle group, the most common truck axle configuration recorded in the SCDOT overweight truck permit data was assigned to GVW1 and GVW2 trucks. Since the GVW3 was derived using the maximum gross weight recorded in the SCDOT truck permit data (SCDOT 2012) and the size and weight inspection violations data (SCDPS 2012b), the axle configuration corresponded to the particular truck with the highest observed weight in the permit data was used for GVW3 truck. Therefore, the configuration (axle spacing) of the GVW3 truck model for each axle group might not be the same as that of GVW1 and GVW2. Table A.3 shows the axle spacing for each truck type and Table A.4 presents the weight of each truck axle for each truck type. A total of 27 truck models were developed to represent the whole truck population.

Table A.3 Truck Axle Spacing Configuration

Axle Group	Truck Type	Distance 1staxle-2ndaxle (ft)	Distance 2ndaxle-3rdaxle (ft)	Distance 3rdaxle-4thaxle (ft)	Distance 4thaxle-5thaxle (ft)	Distance 5thaxle-6thaxle (ft)	Distance 6thaxle-7thaxle (ft)	Distance 7thaxle-8thaxle (ft)
2-Axle	A21	20						
3-Axle	A31	20	5					
	A32	15	5					
4-Axle	A41	15	5	42				
	A42	4	15	5				
	A43	4	23	4				
	A44	17	30	5				
	A45	17	37	4				
5-Axle	A51	14	5	60	5			
	A52	17	4	37	5			
6-Axle	A61	11	5	25	4	4		
	A62	17	5	36	5	5		
7-Axle	A71	5	5	10	5	8	5	
	A72	12	4	4	36	5	5	
8-Axle	A81	16	5	5	24	9	8	5
	A82	12	4	4	35	5	5	11

Table A.4 Truck Axle Weight Configuration

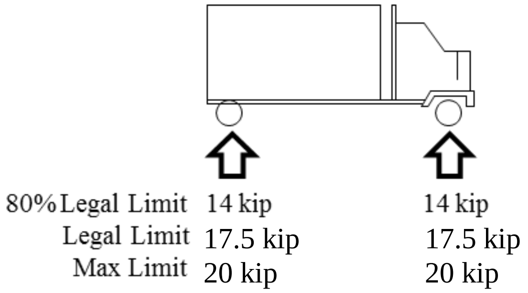
Axle Group	Truck Type	Axle Weight of GVW1 (kip)	Axle Weight of GVW2 (kip)	Axle Weight of GVW3 (kip)
2-Axle	A21	14+14	20+20	24+24
3-Axle	A31	N/A	N/A	20+25+25
	A32	12+14+14	17+19+19	N/A
4-Axle	A41	10+13+13+16	13+18+18+21	22+22+23+23
	A42	N/A	N/A	22+22+23+23
	A43	12+12+14+14	15+15+20+20	N/A
	A44	N/A	N/A	22+22+23+23
	A45	10+16+13+13	12+22+18+18	N/A
5-Axle	A51	N/A	N/A	12+17+17+42+42
	A52	8+14+14+14+14	14+19+19+19+19	N/A
6-Axle	A61	N/A	N/A	11+31+31+22+22+22
	A62	7+12+12+12+12+9	12+20+20+20+20+18	N/A
7-Axle	A71	N/A	N/A	26+29+29+29+29+29+29
	A72	4+10+10+10+10+10+10	10+20+20+20+20+20+20	N/A
8-Axle	A81	N/A	N/A	9+23+23+23+23+23+23+23
	A82	3+7+9+9+9+9+9+9	12+16+17+17+17+17+17+17	N/A

Appendix B Pavement Deterioration Modeling

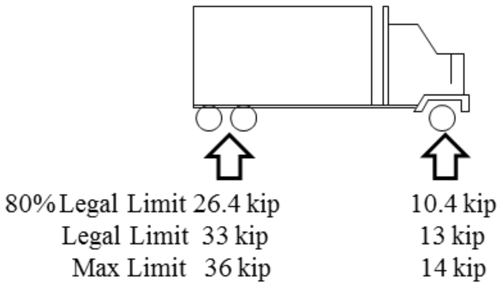
B.1 Pavement Design Methodology

The objective of this portion of the study was to determine the influence of overweight truck traffic on pavement performance. This analysis was performed for flexible pavements using the truck models summarized in Appendix A-2 . The truck models were categorized for this analysis as summarized in Figure B.1. The truck models were grouped in this manner because the axle spacing has less of an effect on pavement response compared to bridges, therefore, several of the models would result in a similar pavement response. The loading conditions of each truck model were established based on the axle spacing and axle loading data provided in Table A.3 and Table A.4.

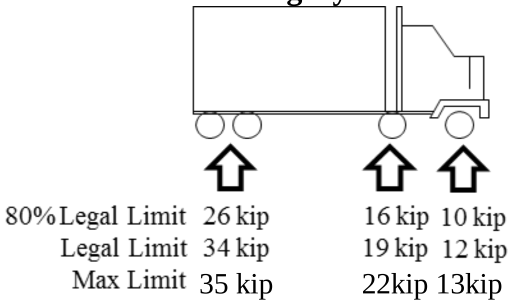
The analysis consisted of conducting a sensitivity analysis to assess the impact that each truck model classification had on the flexible pavement designs that were representative of pavement structures utilized for different roadway classes in South Carolina. The analysis was conducted on pavement structures that were designed to meet structural numbers (SN) ranging from 3 to 7 in accordance with the SCDOT Pavement Design Guidelines (SCDOT, 2008). The specifics about the pavement designs are included in Table B.1 and Table B.2. It should be noted that these designs were created to simplify the analysis by varying one pavement layer (HMA Base Course) and keeping the other layers constant. The thickness of the HMA Surface Course, HMA Intermediate Course, and Graded Aggregate Base Course were based on typical pavement designs provided by the SCDOT. The thickness of the HMA Base Course was calculated based on the desired SN using Equation B.1. The HMA Base Course was selected as the variable because it is the pavement layer that would most likely be increased in thickness in practice. However, the use of a 1-in. layer thickness as used for the pavement having SN = 3.136 is not recommended because it is less than the minimum thickness of this type of mixture. A SN of 3.136 was selected instead of a SN of 3.0 because the thickness of the HMA Base Course would be less than 1-in. for an SN equal to 3.0. These designs were used to limit the variables in the sensitivity analysis.



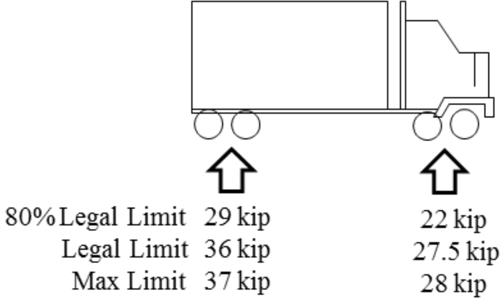
Truck Category A21



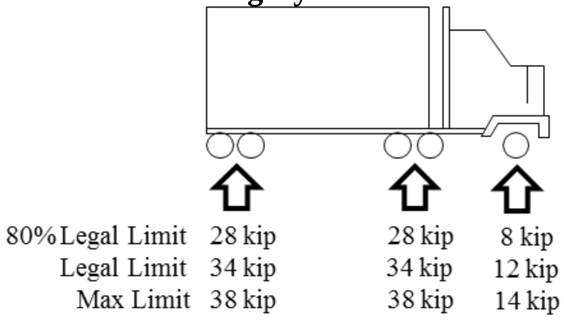
Truck Category A31/32



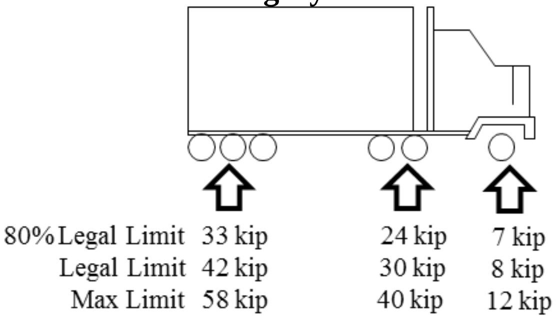
Truck Category A41/44/45



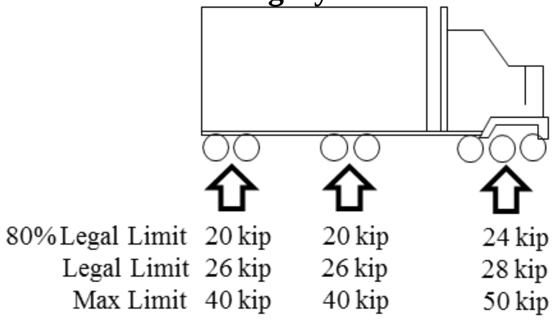
Truck Category A42/43



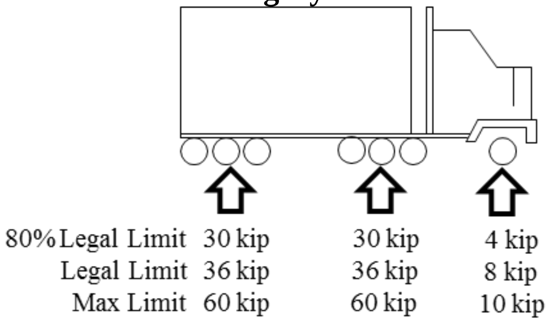
Truck Category A51/52



Truck Category A61/62



Truck Category A71



Truck Category A72

Figure B.1 Illustrative description of different truck categories and load distribution for each load scenario

Table B.1 Input parameters used for the pavement designs based on the SCDOT Pavement Design Guidelines

Variable	Value
Structural Layer Coefficients (a)	
HMA Surface Course (a_1)	0.44
HMA Intermediate Course (a_2)	0.44
HMA Based Course (a_3)	0.34
Graded Aggregate Base Course (a_4)	0.18
Soil Support Value (SSV)	1.5
Regional Factor (R)	1.0
Present Serviceability Index	
Initial serviceability (p_o)	4.2
Initial serviceability (p_t)	2.5

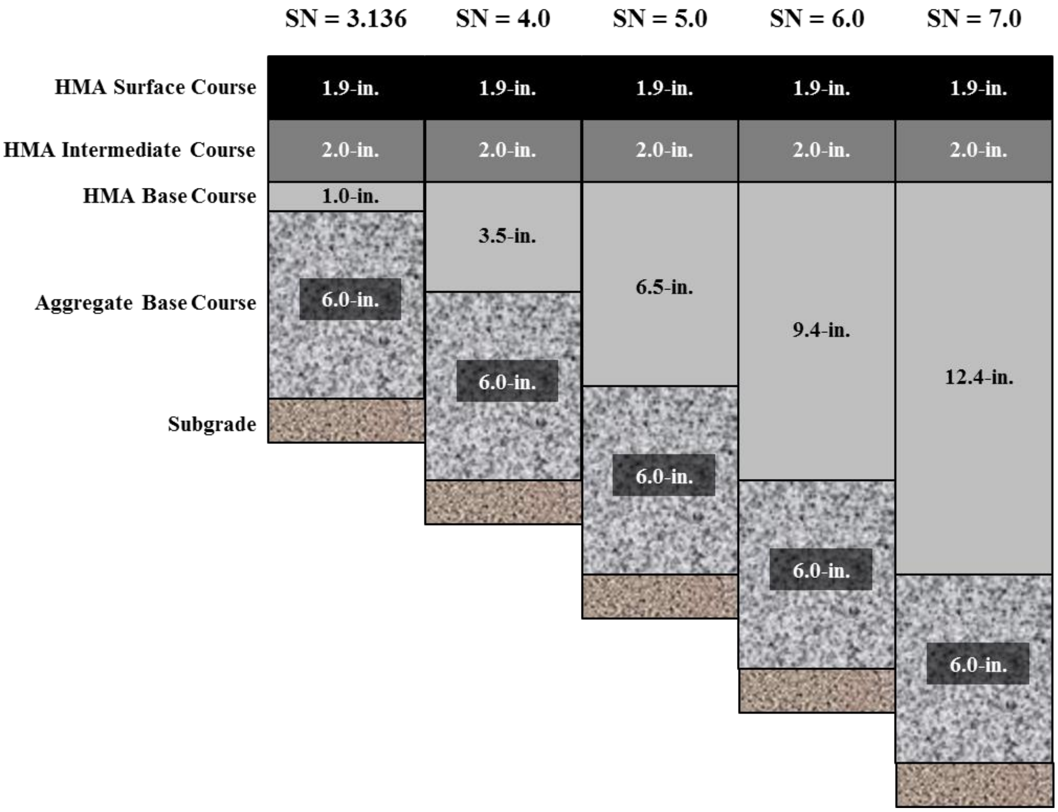


Figure B.2 Schematics of flexible pavement designs used for the analysis in this study

$$\mathrm{SN} = \sum_{i=1}^{n} a_i \times h_i \tag{B.1}$$

The analysis was conducted to determine the HMA Base Course thickness required to achieve the same performance as the target control pavement. This was done by determining the relative damage caused by each truck category and overweight condition. The analysis was conducted two ways: (1) based on ESALs in accordance with the SCDOT Pavement Design Guidelines and (2) based on DARWin-ME output.

B.2 ESAL Analysis

For this analysis, the total number of 18-kip ESALs for each pavement design in Figure B.2 was calculated using Equation B.2 from the SCDOT Pavement Design Guidelines (2008). The total number of design ESALs for each pavement design is included in Table B.2.

$$\log(\mathrm{ESALs}) = 9.36\log(\mathrm{SN}+1) - 0.20 + \frac{\log\left[\frac{(4.2-p_t)}{(4.2-1.5)}\right]}{0.40+\left[\frac{1094}{(\mathrm{SN}+1)^{5.19}}\right]} + \log\left(\frac{1}{R}\right) + 0.372(SSV-3.0) \tag{B.2}$$

Table B.2 Design ESALs for control pavement designs

Structural Number	Design ESALs
3.136	825,573
4.0	1,801,297
5.0	6,910,910
6.0	25,731,788
7.0	85,268,856

To quantify the relative damage of overweight trucks on each pavement design, the number of ESALs per truck category was determined using the equivalent axle load factor tables in the 1993 AASHTO Pavement Design Guide (AASHTO, 1993)for a design SN of 5 and a p_t of 2.5. The ESAL factor for each truck category was determined for a load that was 80% of the legal limit for a specific truck axle classification, the legal limit, and the maximum limit. The ESAL factors are included in Table B.3.

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Table B.3 ESAL factors for each truck category

	ESAL Factor		
Truck Category	80% of Legal Limit	Legal Limit	Maximum Limit
A21	0.720	1.812	3.020
A31/32	0.498	1.217	1.727
A41/44/45	1.075	2.534	3.690
A42/43	0.757	1.970	2.035
A51/52	1.024	2.369	3.760
A61/62	0.501	1.289	4.469
A71	0.299	0.837	5.380
A72	0.292	0.660	5.108

Using the number of total number of design ESALs from Table B.3 and the ESAL factors for each truck category and load category from Table B.4, the total number of passes of each truck category of each weight group was calculated by dividing the design ESALs by the ESAL factor. The total number of passes for a particular truck category are included in Table B.4 through Table B.11. The number of truck passes in these tables shows the influence of overweight trucks on the pavement life. These comparisons were made by conducting each analysis using only one specific truck type at a time. While this is a simplified method, it does isolate the effect of truck weight for a given axle configuration.

Table B.4 Total number of passes for truck category A21

	Total Number of Passes		
SN	80% of Legal Limit	Legal Limit	Maximum Limit
3.136	1,146,629	455,740	273,369
4.0	2,501,802	994,368	596,456
5.0	9,585,987	3,810,053	2,285,401
6.0	35,738,595	14,204,686	8,520,460
7.0	118,428,966	47,070,856	28,234,720

Table B.5 Total number of passes for truck category A31/32

	Total Number of Passes		
SN	80% of Legal Limit	Legal Limit	Maximum Limit
3.136	1,691,748	678,367	474,467
4.0	3,691,183	1,480,113	1,035,228
5.0	14,143,259	5,671,249	3,966,615
6.0	52,729,075	21,143,622	14,788,384
7.0	174,731,262	70,064,795	49,005,089

Table B.6 Total number of passes for truck category A41/44/45

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	767,975	325,798	215,301
4.0	1,675,625	710,851	469,761
5.0	6,420,382	2,723,722	1,799,951
6.0	23,936,547	10,154,613	6,710,598
7.0	79,319,866	33,649,904	22,237,281

Table B.7 Total number of passes for truck category A42/43

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	1,154,648	419,179	405,687
4.0	2,519,297	914,596	885,158
5.0	9,653,022	3,504,397	3,391,602
6.0	35,988,515	13,065,138	12,644,613
7.0	119,257,141	43,294,672	41,901,158

Table B.8 Total number of passes for truck category A51/52

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	806,224	348,490	219,567
4.0	1,759,079	760,362	479,068
5.0	6,740,147	2,913,428	1,835,614
6.0	25,128,700	10,861,878	6,843,561
7.0	83,270,367	35,993,607	22,677,887

Table B.9 Total number of passes for truck category A61/62

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	1,649,497	640,476	184,733
4.0	3,598,996	1,397,438	403,065
5.0	13,790,031	5,354,469	1,544,397
6.0	51,412,165	19,962,598	5,757,840
7.0	170,367,344	66,151,168	19,080,075

Table B.10 Total number of passes for truck category A71

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	2,761,114	986,348	153,452
4.0	6,024,406	2,152,088	334,814
5.0	23,083,313	8,246,010	1,282,883
6.0	86,059,493	30,742,878	4,782,860
7.0	285,180,119	101,874,379	15,849,230

Table B.11 Total number of passes for truck category A72

	Total Number of Passes		
SN	**80% of Legal Limit**	**Legal Limit**	**Maximum Limit**
3.136	2,827,305	1,250,868	161,624
4.0	6,168,827	2,729,238	352,642
5.0	23,636,680	10,457,440	1,351,196
6.0	88,122,563	38,987,558	5,037,547
7.0	292,016,629	129,195,236	16,693,198

The pavement life (number of truck passes) was used to calculate the relative damage for each truck category and each design structural number (SN_{des}) using equation B.3. The relative damage was calculated for the Maximum Limit load case using the Legal Limit load case as a reference and the results are included in Table B.12 and Figure B.3.

$$\text{Relative Damage} = \frac{\text{Passes of truck at reference load case}}{\text{Passes of truck at load case of interest}} \qquad \text{(B.3)}$$

Table B.12 Relative damage from ESAL analysis

Truck Category	HMA Base Thickness (in)	Relative Damage				
		SN_{des} = 3.136	SN_{des} = 4	SN_{des} = 5	SN_{des} = 6	SN_{des} = 7
A21	1.0	1.67	3.64	13.94	51.96	172.19
	3.5	0.76	1.67	6.39	23.82	78.92
	6.5	0.20	0.44	1.67	6.22	20.60
	9.4	0.05	0.12	0.45	1.67	5.52
	12.4	0.02	0.04	0.13	0.50	1.67
A31/32	1.0	1.43	3.12	11.95	44.56	147.67
	3.5	0.66	1.43	5.48	20.42	67.68
	6.5	0.17	0.37	1.43	5.33	17.66
	9.4	0.05	0.10	0.38	1.43	4.74
	12.4	0.01	0.03	0.12	0.43	1.43
A41/44/45	1.0	1.51	3.30	12.65	47.16	156.29
	3.5	0.69	1.51	5.80	21.62	71.63
	6.5	0.18	0.39	1.51	5.64	18.69
	9.4	0.05	0.11	0.41	1.51	5.01
	12.4	0.01	0.03	0.12	0.46	1.51
A42/43	1.0	1.03	2.25	8.64	32.20	106.72
	3.5	0.47	1.03	3.96	14.76	48.91
	6.5	0.12	0.27	1.03	3.85	12.77
	9.4	0.03	0.07	0.28	1.03	3.42
	12.4	0.01	0.02	0.08	0.31	1.03
A51/52	1.0	1.59	3.46	13.27	49.47	163.93
	3.5	0.73	1.59	6.08	22.67	75.13
	6.5	0.19	0.41	1.59	5.92	19.61
	9.4	0.05	0.11	0.43	1.59	5.26
	12.4	0.02	0.03	0.13	0.48	1.59
A61/62	1.0	3.47	7.56	28.98	108.06	358.09
	3.5	1.59	3.47	13.28	49.53	164.12
	6.5	0.41	0.90	3.47	12.93	42.83
	9.4	0.11	0.24	0.93	3.47	11.49
	12.4	0.03	0.07	0.28	1.05	3.47
A71	1.0	6.43	14.02	53.74	200.34	663.88
	3.5	2.95	6.43	24.63	91.82	304.27
	6.5	0.77	1.68	6.43	23.96	79.41
	9.4	0.21	0.45	1.72	6.43	21.30
	12.4	0.06	0.14	0.52	1.94	6.43
A72	1.0	7.74	16.89	64.70	241.22	799.36
	3.5	3.55	7.74	29.65	110.56	366.36
	6.5	0.93	2.02	7.74	28.85	95.62
	9.4	0.25	0.54	2.08	7.74	25.65
	12.4	0.07	0.16	0.63	2.34	7.74

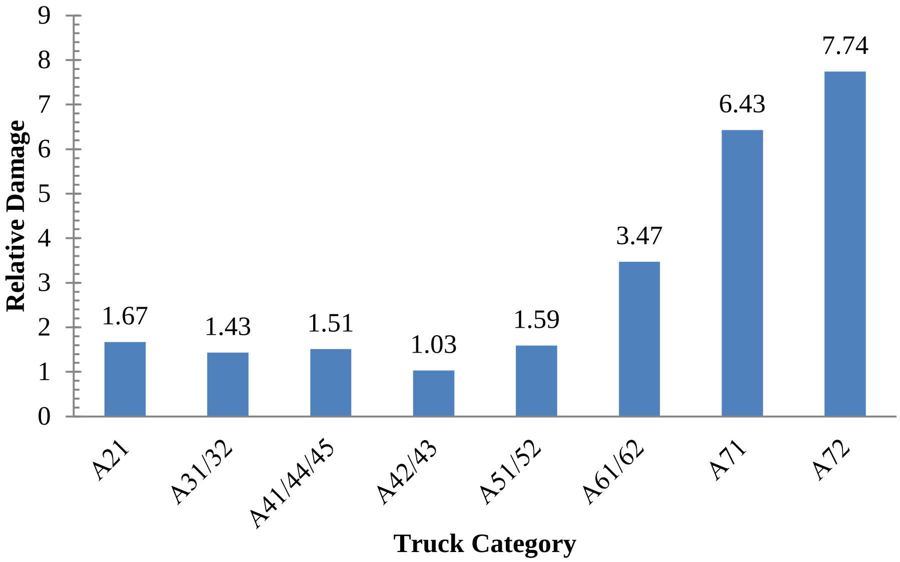


Figure B.3 Relative damage done by trucks loaded to maximum limit compared to legal limit based on ESAL analysis

Based on the results presented in Table B.12 and Figure B.3, it is evident that trucks loaded beyond the legal limit do impart additional damage to pavements based on the ESAL analysis. The amount of relative damage is fairly consistent for the truck models having two, three, four, and five axles. The slight reduction in relative damage for the A42/43 truck model compared to the A41/44/45 truck, both having four axles, can be attributed to two factors. The first is that the distribution of the load for the A42/43 truck is over two tandem axles compared to one tandem and two single axles for the A41/44/45 truck. Secondly, the difference between the legal limit and maximum limit for the A42/43 truck is only 1.5 kips compared to 5 kips for the A41/44/45 truck.

For trucks with number of axles more than five, the relative damage become more than doubles for each additional axle over five. This is most likely due to the fact that the maximum load for the two, three, four, and five axle trucks is no more than 10 kips greater than the respective legal limit, whereas the maximum limit for the six axle and seven axle trucks is 30 and 50 kips greater than the legal limit, respectively. This substantial increase in load will result is significant damage to pavements.

The relative damage factors from Table B.12 were then used to create models defining the relationship between the relative damage (LL/ML) and HMA Base Course thickness for each truck and SN_{des}. These relationships and developed models are included in Figure B.4 through Figure B.11.

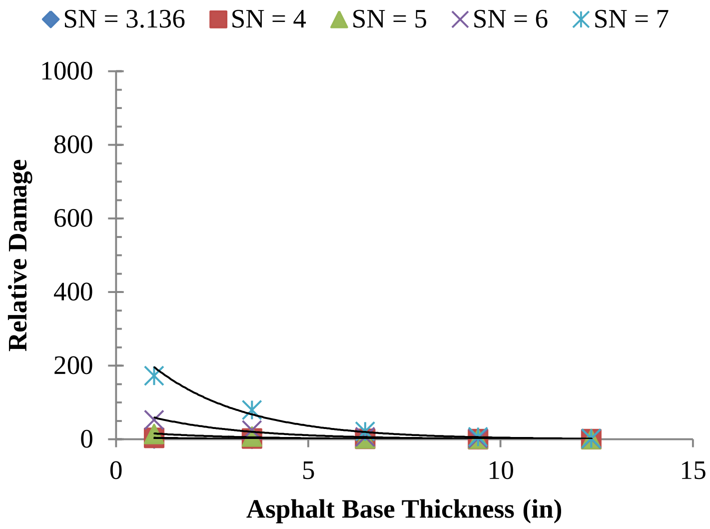


Figure B.4 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A21 for a given SN_{des}

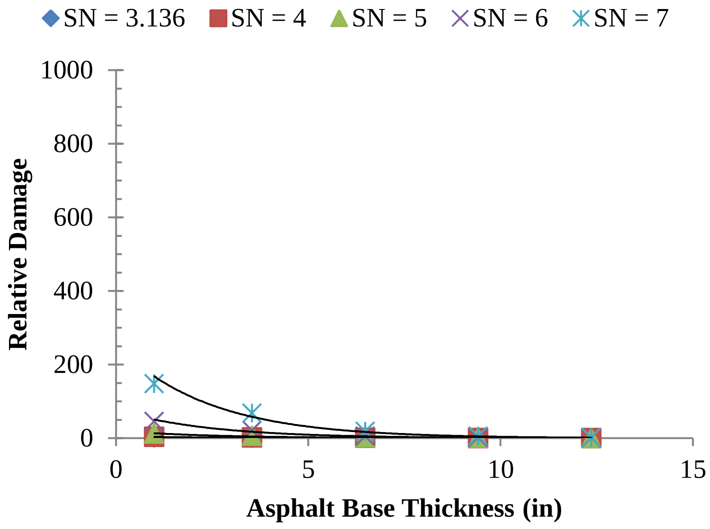


Figure B.5 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A31/32 for a given SN_{des}

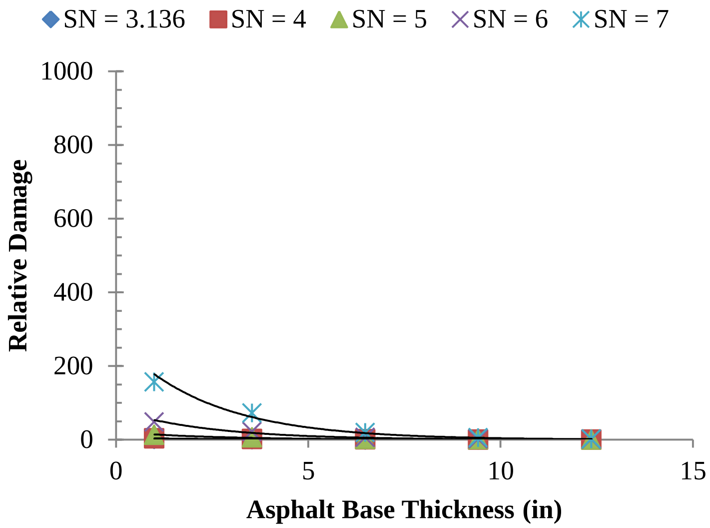


Figure B.6 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A41/44/45 for a given SN_{des}

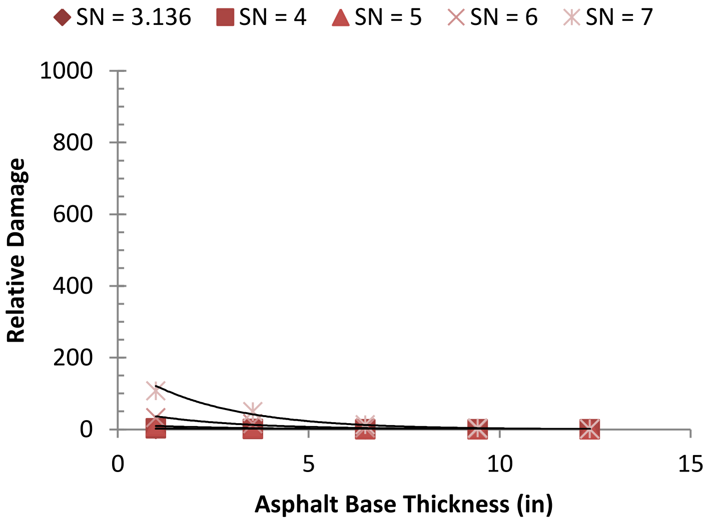


Figure B.7 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A42/43 for a given SN_{des}

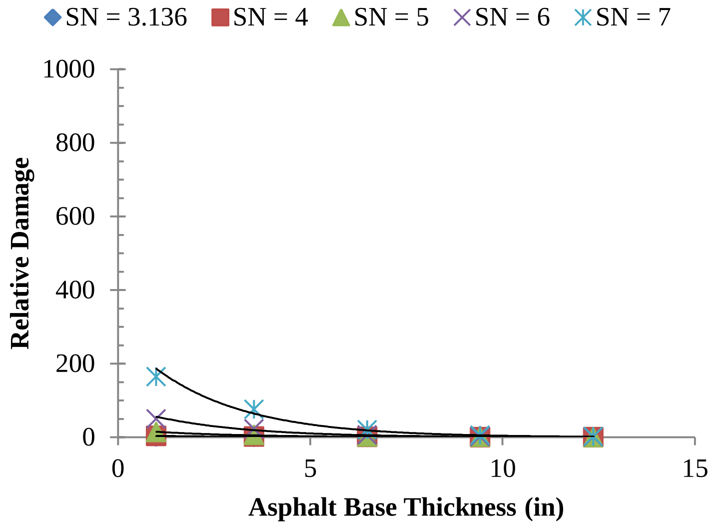


Figure B.8 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A51/52 for a given SN_{des}

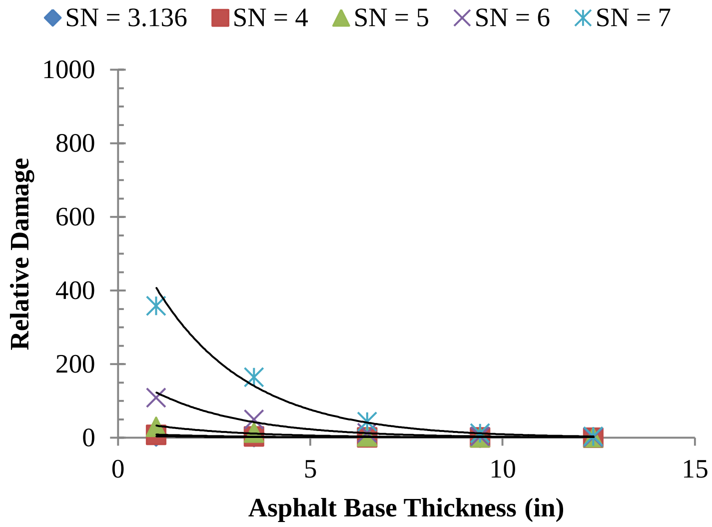


Figure B.9 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A61/62 for a given SN_{des}

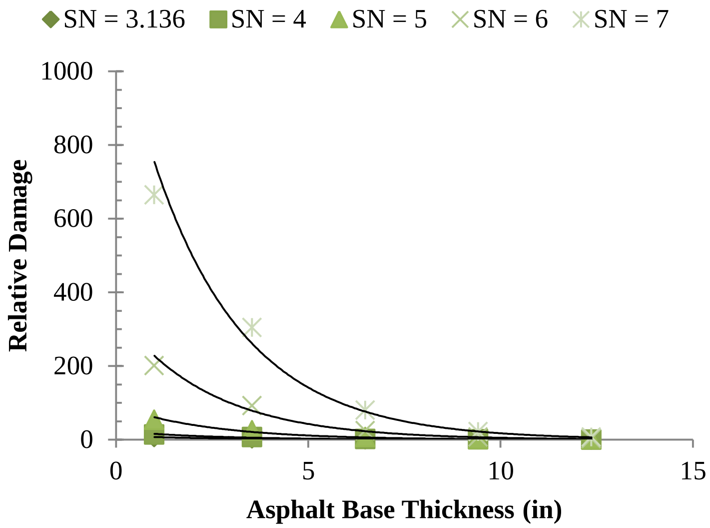


Figure B.10 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A71 for a given SN$_{des}$

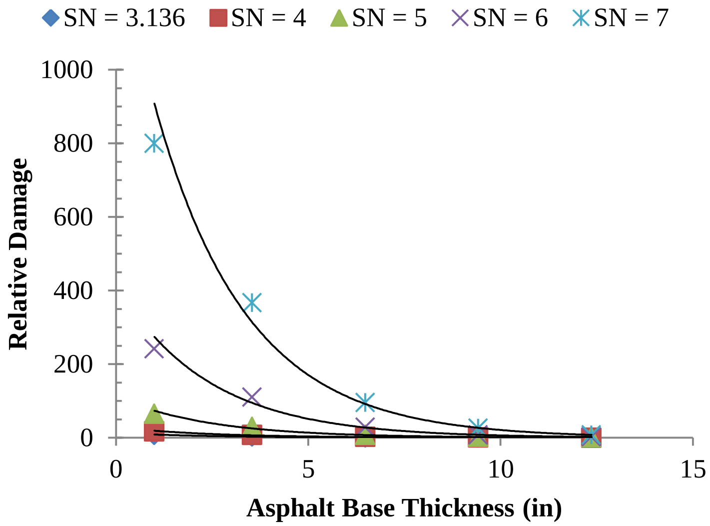


Figure B.11 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and HMA Base Course thickness for truck category A72 for a given SN$_{des}$

These models were then used to determine the additional pavement thickness required to accommodate the same number of passes of a given truck loaded at the maximum limit as that of the design truck used by the SCDOT. In other words, the increase in asphalt thickness required to reduce the relative damage factor to 1.0 can be determined. The additional pavement thickness was added to the HMA Base Course and the thickness of all other layers was kept constant. The results and models are included Figure B.12 through Figure B.19.

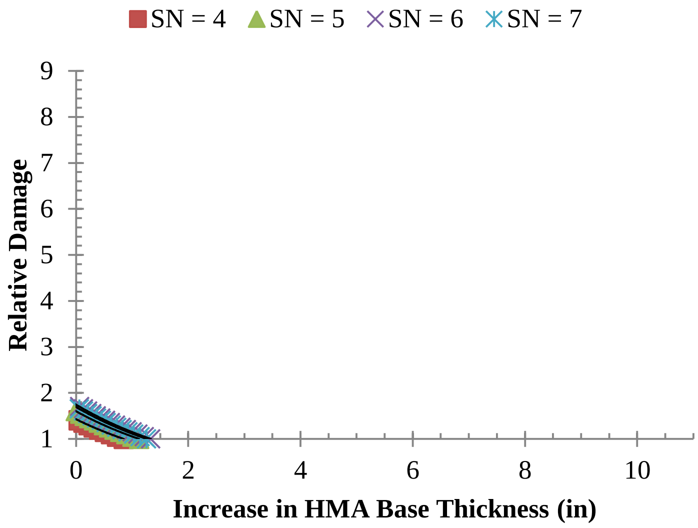


Figure B.12 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A21 for a given SN_{des}

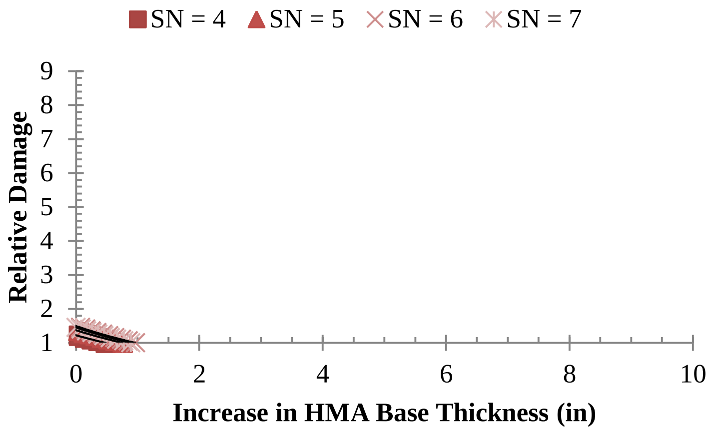


Figure B.13 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A31/32 for a given SN_{des}

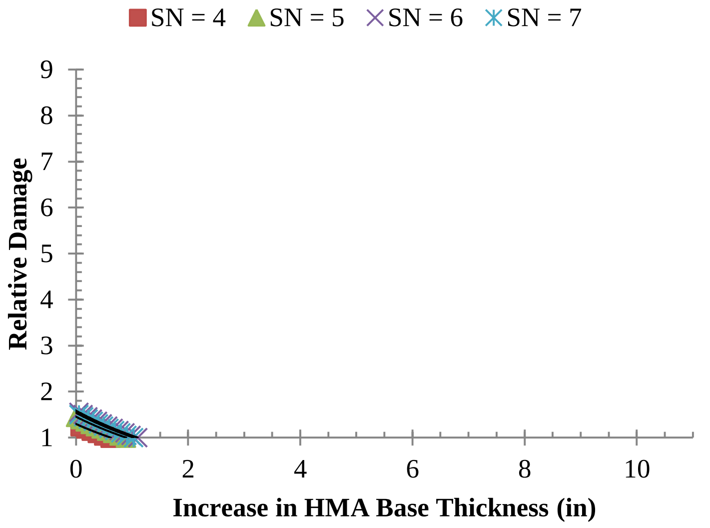


Figure B.14 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A41/44/45 for a given SN_{des}

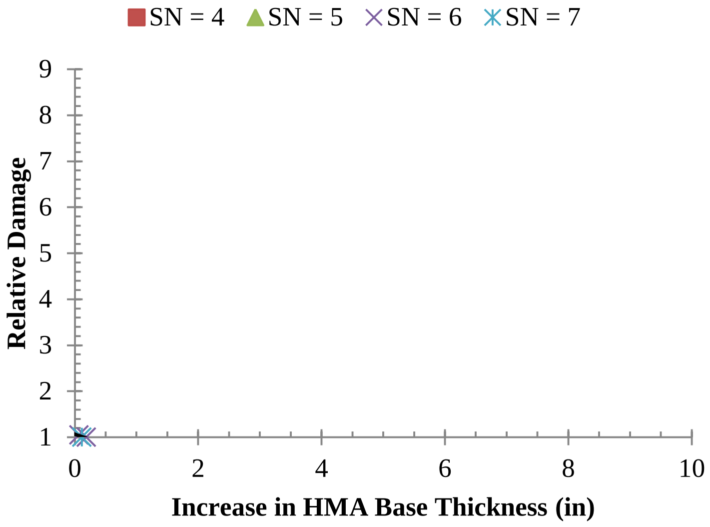


Figure B.15 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A42/43 for a given SN_{des}

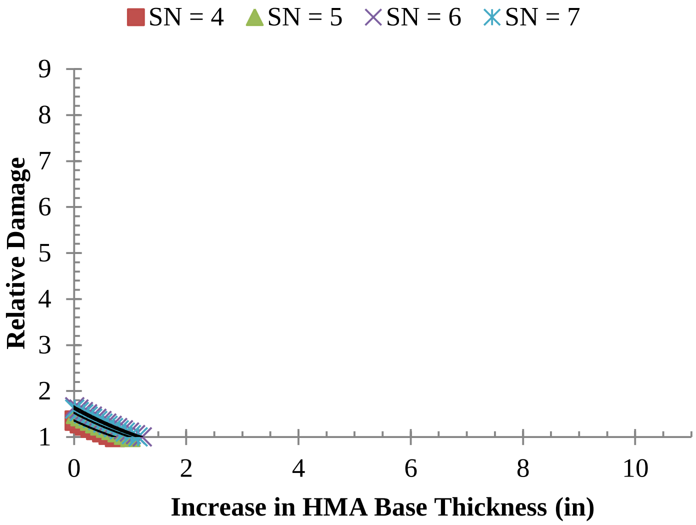


Figure B.16 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A51/52 for a given SN_{des}

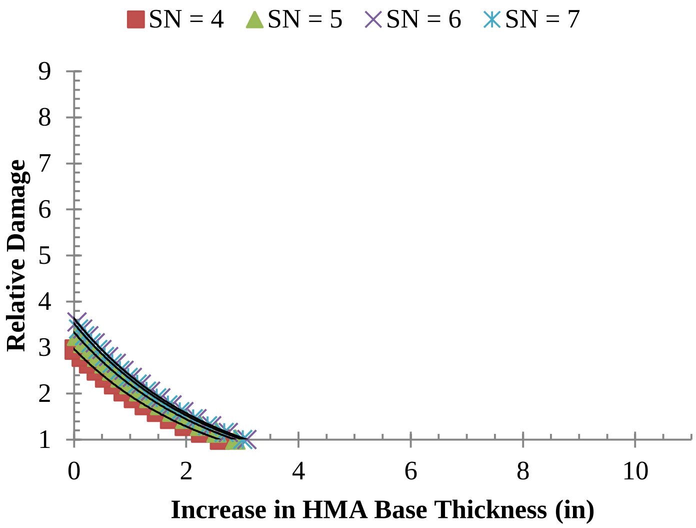


Figure B.17 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A61/62 for a given SN_{des}

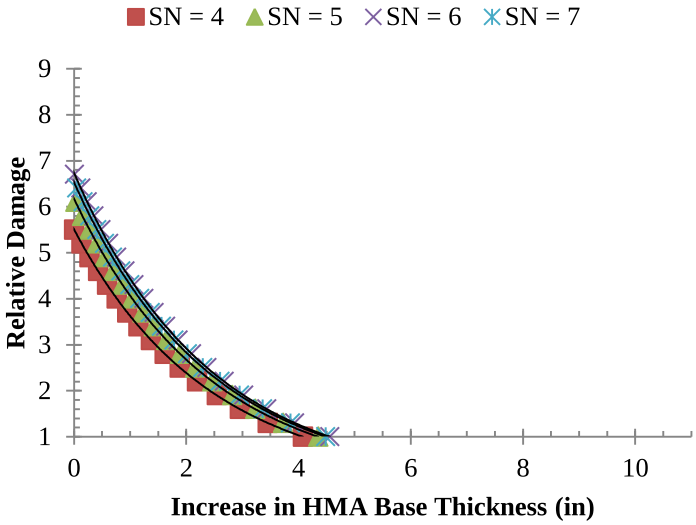


Figure B.18 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A71 for a given SN_{des}

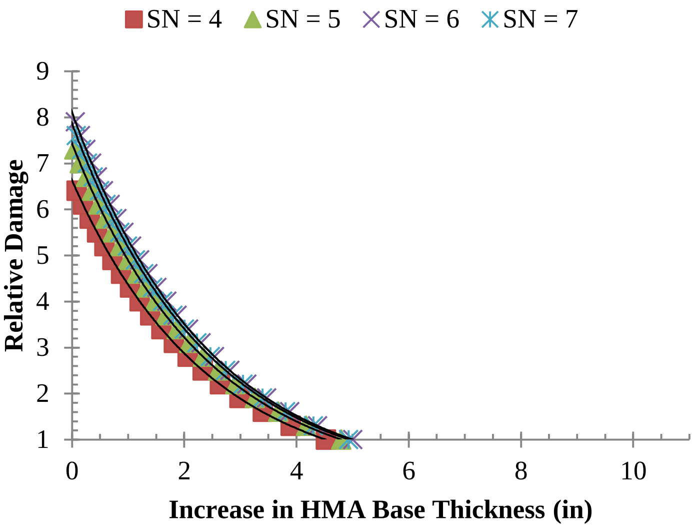


Figure B.19 Relationship between relative damage (passes at Legal Limit divided by passes at Max Limit) and increase in HMA Base Course thickness for truck category A72 for a given SN_{des}

The equations included in Table B.13 can be used to estimate the increased thickness of the HMA Base Course layer required to achieve a desired relative damage factor for each truck category for a given design structural number. Table B.14 and Figure B.20 summarize the additional thickness of the HMA Base Course needed to achieve a relative damage factor of 1.0 (number of passes at legal limit = number of passes at maximum limit) for each pavement design and truck category. The results indicate that for trucks having five or fewer axles require approximately an additional 1-in. of HMA Base Course to accommodate the increased loads. Beyond five axles, the necessary thickness increases to approximately 3-in. for the six axle trucks, and 4.4-in. and 4.8-in. for the trucks with seven axles, A71 and A72, respectively. It should be noted that the additional thickness included in these results are based on the hypothetical situation where 100% of the traffic is comprised of a single truck model with a gross vehicle weight equal to the respective maximum limit.

Table B.13 Summary of models to determine required increase in HMA Base Course thickness based on ESAL analysis. Note that RD = relative damage

Truck Category	Required Increase in HMA Base Thickness (in)			
	$SN_{des} = 4.0$	$SN_{des} = 5.0$	$SN_{des} = 6.0$	$SN_{des} = 7.0$
A21	$= \frac{\ln \frac{RD}{1.4285}}{-0.418}$	$= \frac{\ln \frac{RD}{1.6016}}{-0.418}$	$= \frac{\ln \frac{RD}{1.7472}}{-0.418}$	$= \frac{\ln \frac{RD}{1.6942}}{-0.418}$
A31/32	$= \frac{\ln \frac{RD}{1.2251}}{-0.418}$	$= \frac{\ln \frac{RD}{1.3736}}{-0.418}$	$= \frac{\ln \frac{RD}{1.4984}}{-0.418}$	$= \frac{\ln \frac{RD}{1.4529}}{-0.418}$
A41/44/45	$= \frac{\ln \frac{RD}{1.2966}}{-0.418}$	$= \frac{\ln \frac{RD}{1.4537}}{-0.418}$	$= \frac{\ln \frac{RD}{1.5859}}{-0.418}$	$= \frac{\ln \frac{RD}{1.5377}}{-0.418}$
A42/43	$= \frac{\ln \frac{RD}{0.8854}}{-0.418}$	$= \frac{\ln \frac{RD}{0.9927}}{-0.418}$	$= \frac{\ln \frac{RD}{1.0829}}{-0.418}$	$= \frac{\ln \frac{RD}{1.0500}}{-0.418}$
A51/52	$= \frac{\ln \frac{RD}{1.3600}}{-0.418}$	$= \frac{\ln \frac{RD}{1.5248}}{-0.418}$	$= \frac{\ln \frac{RD}{1.6634}}{-0.418}$	$= \frac{\ln \frac{RD}{1.6129}}{-0.418}$
A61/62	$= \frac{\ln \frac{RD}{2.9708}}{-0.418}$	$= \frac{\ln \frac{RD}{3.3308}}{-0.418}$	$= \frac{\ln \frac{RD}{3.6336}}{-0.418}$	$= \frac{\ln \frac{RD}{3.5232}}{-0.418}$
A71	$= \frac{\ln \frac{RD}{5.5076}}{-0.418}$	$= \frac{\ln \frac{RD}{6.1751}}{-0.418}$	$= \frac{\ln \frac{RD}{6.7366}}{-0.418}$	$= \frac{\ln \frac{RD}{6.5318}}{-0.418}$
A72	$= \frac{\ln \frac{RD}{6.6316}}{-0.418}$	$= \frac{\ln \frac{RD}{7.4349}}{-0.418}$	$= \frac{\ln \frac{RD}{7.8650}}{-0.418}$	$= \frac{\ln \frac{RD}{8.1112}}{-0.418}$

Table B.14 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for each truck category loaded to the maximum limit

Truck Category	Required Increase in HMA Base Thickness (in)			
	SN_{des} = 4.0	SN_{des} = 5.0	SN_{des} = 6.0	SN_{des} = 7.0
A21	0.85	1.13	1.33	1.26
A31/32	0.49	0.76	0.97	0.89
A41/44/45	0.62	0.90	1.10	1.03
A42/43	0.00	0.00	0.19	0.12
A51/52	0.74	1.01	1.22	1.14
A61/62	2.60	2.88	3.09	3.01
A71	4.08	4.36	4.56	4.49
A72	4.53	4.80	4.93	5.01

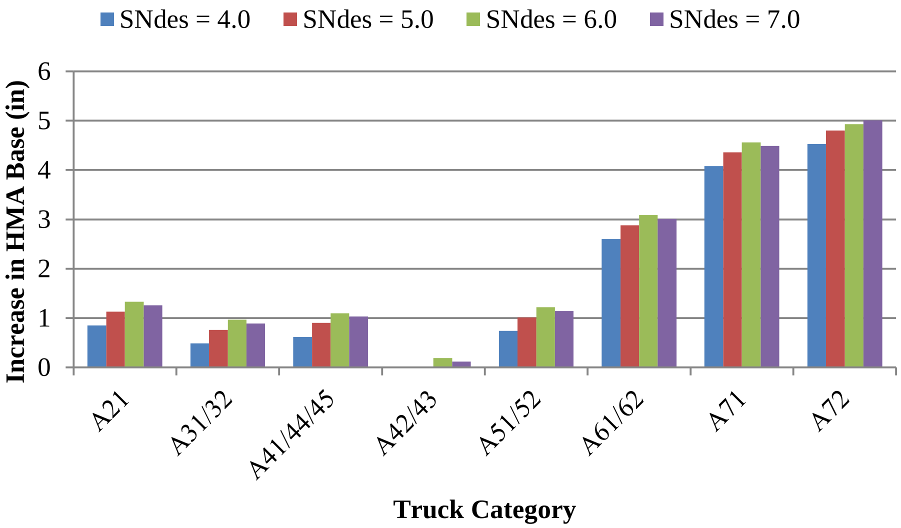


Figure B.20 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for each truck category loaded to the maximum limit

B.3 DARWin-ME Analysis

For this analysis, the total distress accumulation for a 20 year design life was estimated for each for each pavement design in Figure B.2 using DARWin-ME. The analysis was performed using many of the default values in DARWin-ME along with some Level 3 input data as summarized in Table B.15 through Table B.17. In addition to the material properties, the traffic information used in the analysis is included in Table B.18. As with the ESAL analysis, the load spectra only included the truck type and weight that being evaluated in each individual run.

Table B.15 Asphalt pavement layer properties input to DARWin-ME

		Gradation, % Passing	
Sieve Size	**Surface Course**	**Intermediate Course**	**Base Course**
¾-in.	100	99	90
⅜-in.	83	70	65
No. 4	53	42	49
No. 200	4	4	4
Binder Grade	PG 76-22	PG 64-22	PG 64-22
Effective Binder Content	11.6 %	11.6 %	11.6 %
Air Voids	7 %	7 %	7 %
Unit Weight	150 lb/ft^3	150 lb/ft^3	150 lb/ft^3

Table B.16 Crushed aggregate base layer properties used in DARWin-ME

Sieve Size	Gradation, % Passing
2-in.	100
1 ½-in.	97.9
1-in.	84.5
½-in.	62.1
No. 4	43.9
No. 8	36.2
No. 30	26.2
No. 200	6.9
Liquid Limit	6
Plasticity Index	1
Maximum Dry Unit Weight	129.5 lb/ft^3
Saturated Hydraulic Conductivity	1.04 in/hr
Specific Gravity	2.70
Optimum Moisture Content	6.9 %
Resilient Modulus	30 ksi

Table B.17 AASHTO A-6 subgrade soil layer properties used in DARWin-ME

Sieve Size	Gradation, % Passing
2-in.	99.8
1 ½-in.	99.5
1-in.	97.4
¾-in.	98.4
½-in.	97.4
⅜-in.	96.4
No. 4	93.5
No. 10	90.2
No. 40	82.4
No. 80	73.5
No. 200	63.2
Liquid Limit	33
Plasticity Index	16
Maximum Dry Unit Weight	107.8 lb/ft^3
Saturated Hydraulic Conductivity	7.68×10^{-4} in/hr
Specific Gravity	2.70
Optimum Moisture Content	17.1%
Resilient Modulus	14 ksi

Table B.18 Traffic input data used in DARWin-ME

Variable	**Input Value**
Initial two-way AADTT	15,000
Number of lanes in design direction	2
Percent trucks in design direction	50%
Percent trucks in design lane	95%
Operational speed	62 mph

The distress categories analyzed included total rutting, top-down cracking, bottom-up cracking, and International Roughness Index (IRI). All of the default calibration coefficients were utilized throughout the analysis. The default values were selected because the MEPDG has not been calibrated for South Carolina as of yet. Because of the global coefficients, some of the resulting values are not realistic. However, because the objective of this study was determine the relative damage caused by overweight trucks, the results should be reasonable because they are normalized values relating damage (or deterioration) caused by overweight trucks to that caused by trucks loaded below the legal limit. The distress quantities predicted by DARWin-ME over the 20 year design life are included in Table B.19 through Table B.26.

Table B.19 Distress prediction summary for truck category A21

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	62.5	71.3
	4.0	50.7	57.7
	5.0	42.0	47.8
	6.0	28.2	35.1
	7.0	24.2	27.6
Top-Down Cracking, in/mi	3.136	137,693	151,366
	4.0	69,539	93,725
	5.0	26,915	32,631
	6.0	26,600	32,255
	7.0	11,976	15,848
Bottom-Up Cracking, %	3.136	101.4	108.4
	4.0	55.4	69.7
	5.0	26.8	32.5
	6.0	8.7	20.9
	7.0	2.1	2.7
IRI, in/mi	3.136	275	293
	4.0	231	250
	5.0	201	213
	6.0	175	182
	7.0	167	173

Table B.20 Distress prediction summary for truck category A31/32

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	66.7	73.1
	4.0	54.8	60.1
	5.0	45.6	50.0
	6.0	30.9	33.9
	7.0	26.7	29.3
Top-Down Cracking, in/mi	3.136	163,161	164,392
	4.0	129,882	145,261
	5.0	21,394	24,646
	6.0	13,508	14,023
	7.0	6,560	7,188
Bottom-Up Cracking, %	3.136	94.6	101.3
	4.0	43.0	50.6
	5.0	22.3	24.2
	6.0	2.6	3.5
	7.0	1.8	2.0
IRI, in/mi	3.136	280	293
	4.0	235	248
	5.0	205	213
	6.0	179	184
	7.0	172	176

Table B.21 Distress prediction summary for truck category A41/44/45

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	80.1	75.3
	4.0	65.6	61.3
	5.0	54.6	50.8
	6.0	36.8	34.0
	7.0	31.8	29.3
Top-Down Cracking, in/mi	3.136	164,379	160,663
	4.0	138,668	91,254
	5.0	29,215	29,944
	6.0	24,800	28,446
	7.0	11,566	13,391
Bottom-Up Cracking, %	3.136	106.4	106.2
	4.0	62.1	61.3
	5.0	28.5	29.5
	6.0	13.8	16.7
	7.0	2.3	2.4
IRI, in/mi	3.136	307	298
	4.0	262	252
	5.0	222	217
	6.0	189	185
	7.0	180	176

Table B.22 Distress prediction summary for truck category A42/43

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	79.2	80.0
	4.0	64.9	65.6
	5.0	54.0	54.6
	6.0	36.5	36.9
	7.0	31.5	31.8
Top-Down Cracking, in/mi	3.136	164,375	164,379
	4.0	137,083	139,037
	5.0	29,038	29,258
	6.0	24,798	24,802
	7.0	11,525	11,580
Bottom-Up Cracking, %	3.136	106.2	106.5
	4.0	61.6	62.2
	5.0	28.3	28.5
	6.0	13.3	13.9
	7.0	2.3	2.3
IRI, in/mi	3.136	305	307
	4.0	260	262
	5.0	221	222
	6.0	189	189
	7.0	180	180

Table B.23 Distress prediction summary for truck category A51/52

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	85.9	96.2
	4.0	70.6	79.2
	5.0	58.8	65.9
	6.0	39.5	44.3
	7.0	34.1	38.2
Top-Down Cracking, in/mi	3.136	164,411	164,423
	4.0	154,422	159,447
	5.0	27,480	32,521
	6.0	11,743	15,798
	7.0	7,245	9,359
Bottom-Up Cracking, %	3.136	105.8	110.6
	4.0	57.7	70.3
	5.0	26.0	30.6
	6.0	6.1	18.4
	7.0	2.2	2.7
IRI, in/mi	3.136	315	333
	4.0	269	288
	5.0	227	241
	6.0	193	202
	7.0	184	191

Table B.24 Distress prediction summary for truck category A61/62

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	80.0	106.8
	4.0	66.2	88.4
	5.0	55.2	73.6
	6.0	37.3	49.8
	7.0	32.2	42.9
Top-Down Cracking, in/mi	3.136	164,402	165,633
	4.0	153,566	163,144
	5.0	32,047	52,881
	6.0	7,387	11,763
	7.0	4,798	7,330
Bottom-Up Cracking, %	3.136	96.0	111.3
	4.0	42.8	72.0
	5.0	23.0	33.8
	6.0	4.1	23.6
	7.0	2.1	10.1
IRI, in/mi	3.136	302	350
	4.0	255	304
	5.0	220	257
	6.0	189	212
	7.0	181	200

Table B.25 Distress prediction summary for truck category A71

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	70.4	112.2
	4.0	58.1	94.7
	5.0	48.3	78.7
	6.0	32.4	52.7
	7.0	27.9	45.5
Top-Down Cracking, in/mi	3.136	163,165	165,634
	4.0	134,154	163,149
	5.0	20,230	48,306
	6.0	4,680	10,160
	7.0	4,279	8,635
Bottom-Up Cracking, %	3.136	85.8	113.0
	4.0	34.8	78.9
	5.0	15.5	36.0
	6.0	2.2	23.7
	7.0	1.7	9.8
IRI, in/mi	3.136	281	359
	4.0	236	317
	5.0	208	265
	6.0	181	217
	7.0	174	203

Table B.26 Distress prediction summary for truck category A72

	SN	Legal Limit	Maximum Limit
Rut Depth, mm	3.136	70.1	112.2
	4.0	58.0	95.3
	5.0	48.8	80.2
	6.0	33.0	54.1
	7.0	28.6	46.8
Top-Down Cracking, in/mi	3.136	90,763	165,634
	4.0	35,436	95,696
	5.0	9,432	24,623
	6.0	6,868	17,599
	7.0	4,645	11,248
Bottom-Up Cracking, %	3.136	87.4	113.0
	4.0	34.2	81.9
	5.0	9.5	34.4
	6.0	2.0	22.4
	7.0	1.7	6.0
IRI, in/mi	3.136	278	359
	4.0	231	315
	5.0	208	265
	6.0	182	219
	7.0	174	205

Based on the distress prediction summaries, the relative damage caused by trucks loaded to the maximum limit (ML) compared to legal limit (LL) are included in Table B.27 through Table B.34 and Figure B.21 through Figure B.24.

Table B.27 Relative damage for rutting based on the DARWin-ME analysis

Truck Category	HMA Base Thickness (in)	Relative Damage (Rutting)				
		SN_{des} = 3.136	SN_{des} = 4	SN_{des} = 5	SN_{des} = 6	SN_{des} = 7
A21	1.0	1.14	1.41	1.70	2.53	2.94
	3.5	0.92	1.14	1.38	2.05	2.38
	6.5	0.76	0.94	1.14	1.70	1.97
	9.4	0.56	0.69	0.84	1.25	1.45
	12.4	0.44	0.54	0.66	0.98	1.14
A31/32	1.0	1.10	1.34	1.60	2.37	2.74
	3.5	0.90	1.10	1.32	1.94	2.25
	6.5	0.75	0.91	1.10	1.62	1.87
	9.4	0.51	0.62	0.74	1.10	1.27
	12.4	0.44	0.53	0.64	0.95	1.10
A41/44/45	1.0	0.94	1.15	1.38	2.05	2.37
	3.5	0.76	0.93	1.12	1.67	1.93
	6.5	0.63	0.77	0.93	1.38	1.60
	9.4	0.42	0.52	0.62	0.93	1.07
	12.4	0.37	0.45	0.54	0.80	0.92
A42/43	1.0	1.01	1.23	1.48	2.19	2.54
	3.5	0.83	1.01	1.21	1.80	2.08
	6.5	0.69	0.84	1.01	1.50	1.73
	9.4	0.47	0.57	0.68	1.01	1.17
	12.4	0.40	0.49	0.59	0.87	1.01
A51/52	1.0	1.12	1.36	1.64	2.44	2.82
	3.5	0.92	1.12	1.35	2.00	2.32
	6.5	0.77	0.93	1.12	1.67	1.93
	9.4	0.52	0.63	0.75	1.12	1.30
	12.4	0.44	0.54	0.65	0.97	1.12
A61/62	1.0	1.34	1.61	1.93	2.86	3.32
	3.5	1.11	1.33	1.60	2.37	2.75
	6.5	0.92	1.11	1.33	1.97	2.29
	9.4	0.62	0.75	0.90	1.33	1.55
	12.4	0.54	0.65	0.78	1.15	1.33
A71	1.0	1.59	1.93	2.32	3.47	4.02
	3.5	1.34	1.63	1.96	2.93	3.39
	6.5	1.12	1.36	1.63	2.43	2.82
	9.4	0.75	0.91	1.09	1.63	1.89
	12.4	0.65	0.78	0.94	1.41	1.63
A72	1.0	1.60	1.93	2.30	3.40	3.92
	3.5	1.36	1.64	1.95	2.89	3.33
	6.5	1.14	1.38	1.64	2.43	2.80
	9.4	0.77	0.93	1.11	1.64	1.89
	12.4	0.67	0.81	0.96	1.42	1.64

Table B.28 Relative damage for top-down cracking based on the DARWin-ME analysis

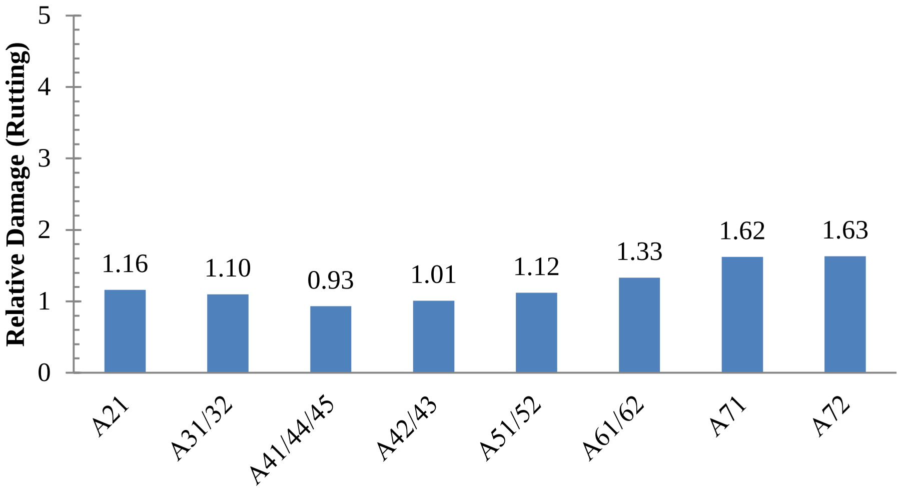
Truck Category	HMA Base Thickness (in)	Relative Damage (Top-Down Cracking)				
		SN_{des} = 3.136	SN_{des} = 4	SN_{des} = 5	SN_{des} = 6	SN_{des} = 7
A21	1.0	1.10	2.18	5.62	5.69	12.64
	3.5	0.68	1.35	3.48	3.52	7.83
	6.5	0.24	0.47	1.21	1.23	2.72
	9.4	0.23	0.46	1.20	1.21	2.69
	12.4	0.12	0.23	0.59	0.60	1.32
A31/32	1.0	1.01	1.27	7.68	12.17	25.06
	3.5	0.89	1.12	6.79	10.75	22.14
	6.5	0.15	0.19	1.15	1.82	3.76
	9.4	0.09	0.11	0.66	1.04	2.14
	12.4	0.04	0.06	0.34	0.53	1.10
A41/44/45	1.0	0.98	1.16	5.50	6.48	13.89
	3.5	0.56	0.66	3.12	3.68	7.89
	6.5	0.18	0.22	1.02	1.21	2.59
	9.4	0.17	0.21	0.97	1.15	2.46
	12.4	0.08	0.10	0.46	0.54	1.16
A42/43	1.0	1.00	1.20	5.66	6.63	14.26
	3.5	0.85	1.01	4.79	5.61	12.06
	6.5	0.18	0.21	1.01	1.18	2.54
	9.4	0.15	0.18	0.85	1.00	2.15
	12.4	0.07	0.08	0.40	0.47	1.00
A51/52	1.0	1.00	1.06	5.98	14.00	22.69
	3.5	0.97	1.03	5.80	13.58	22.01
	6.5	0.20	0.21	1.18	2.77	4.49
	9.4	0.10	0.10	0.57	1.35	2.18
	12.4	0.06	0.06	0.34	0.80	1.29
A61/62	1.0	1.01	1.08	5.17	22.42	34.52
	3.5	0.99	1.06	5.09	22.08	34.00
	6.5	0.32	0.34	1.65	7.16	11.02
	9.4	0.07	0.08	0.37	1.59	2.45
	12.4	0.04	0.05	0.23	0.99	1.53
A71	1.0	1.02	1.23	8.19	35.39	38.71
	3.5	1.00	1.22	8.06	34.86	38.13
	6.5	0.30	0.36	2.39	10.32	11.29
	9.4	0.06	0.08	0.50	2.17	2.37
	12.4	0.05	0.06	0.43	1.84	2.02
A72	1.0	1.82	4.67	17.56	24.12	35.66
	3.5	1.05	2.70	10.15	13.93	20.60
	6.5	0.27	0.69	2.61	3.59	5.30
	9.4	0.19	0.50	1.87	2.56	3.79
	12.4	0.12	0.32	1.19	1.64	2.42

Table B.29 Relative damage for bottom-up cracking based on the DARWin-ME analysis

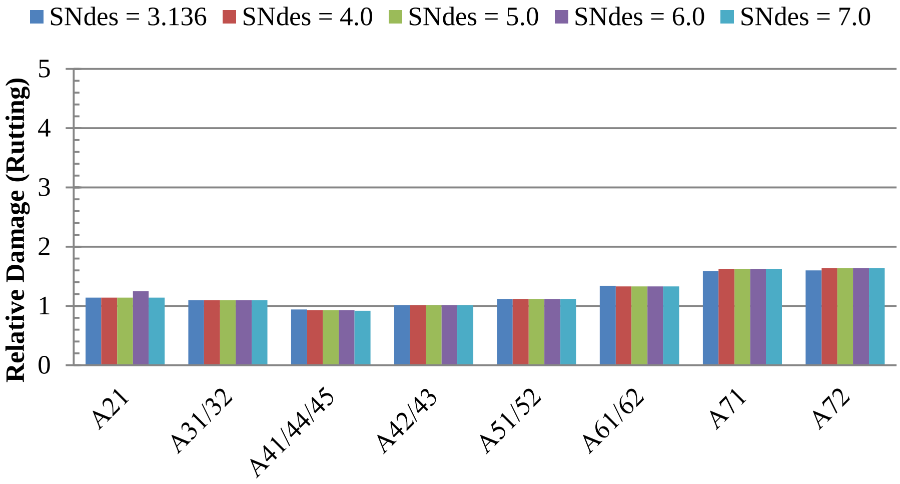
Truck Category	HMA Base Thickness (in)	Relative Damage (Bottom-Up Cracking)				
		SN_{des} = 3.136	SN_{des} = 4	SN_{des} = 5	SN_{des} = 6	SN_{des} = 7
A21	1.0	1.07	1.96	4.05	12.50	51.62
	3.5	0.69	1.26	2.60	8.04	33.20
	6.5	0.32	0.59	1.21	3.75	15.48
	9.4	0.21	0.38	0.78	2.41	9.96
	12.4	0.03	0.05	0.10	0.31	1.27
A31/32	1.0	1.07	2.36	4.54	38.97	55.97
	3.5	0.53	1.18	2.27	19.47	27.96
	6.5	0.26	0.56	1.09	9.32	13.39
	9.4	0.04	0.08	0.16	1.35	1.94
	12.4	0.02	0.05	0.09	0.76	1.09
A41/44/45	1.0	1.00	1.71	3.73	7.69	46.18
	3.5	0.58	0.99	2.15	4.43	26.63
	6.5	0.28	0.48	1.04	2.14	12.83
	9.4	0.16	0.27	0.58	1.20	7.24
	12.4	0.02	0.04	0.08	0.17	1.02
A42/43	1.0	1.00	1.73	3.76	7.98	46.51
	3.5	0.59	1.01	2.20	4.66	27.17
	6.5	0.27	0.46	1.01	2.14	12.45
	9.4	0.13	0.23	0.49	1.04	6.07
	12.4	0.02	0.04	0.08	0.17	1.01
A51/52	1.0	1.05	1.92	4.25	18.22	51.45
	3.5	0.66	1.22	2.70	11.58	32.70
	6.5	0.29	0.53	1.18	5.04	14.24
	9.4	0.17	0.32	0.71	3.02	8.54
	12.4	0.03	0.05	0.10	0.44	1.25
A61/62	1.0	1.16	2.60	4.84	27.22	52.50
	3.5	0.75	1.68	3.13	17.61	33.97
	6.5	0.35	0.79	1.47	8.27	15.95
	9.4	0.25	0.55	1.02	5.76	11.11
	12.4	0.10	0.24	0.44	2.46	4.75
A71	1.0	1.32	3.25	7.31	52.32	65.70
	3.5	0.92	2.27	5.10	36.53	45.88
	6.5	0.42	1.03	2.33	16.67	20.94
	9.4	0.28	0.68	1.53	10.97	13.77
	12.4	0.11	0.28	0.63	4.53	5.69
A72	1.0	1.29	3.30	11.90	56.22	67.27
	3.5	0.94	2.39	8.62	40.75	48.76
	6.5	0.39	1.01	3.62	17.12	20.48
	9.4	0.26	0.66	2.36	11.16	13.35
	12.4	0.07	0.18	0.63	3.00	3.58

Table B.30 Relative damage for IRI based on the DARWin-ME analysis

Truck Category	HMA Base Thickness (in)	Relative Damage (IRI)				
		SN_{des} = 3.136	SN_{des} = 4	SN_{des} = 5	SN_{des} = 6	SN_{des} = 7
A21	1.0	1.06	1.27	1.46	1.67	1.75
	3.5	0.91	1.09	1.25	1.43	1.50
	6.5	0.77	0.92	1.06	1.22	1.27
	9.4	0.66	0.79	0.91	1.04	1.09
	12.4	0.63	0.75	0.86	0.99	1.03
A31/32	1.0	1.05	1.25	1.43	1.64	1.71
	3.5	0.89	1.06	1.21	1.39	1.45
	6.5	0.76	0.91	1.04	1.19	1.24
	9.4	0.66	0.78	0.90	1.03	1.07
	12.4	0.63	0.75	0.86	0.99	1.03
A41/44/45	1.0	0.97	1.14	1.34	1.58	1.66
	3.5	0.82	0.96	1.13	1.33	1.40
	6.5	0.71	0.83	0.97	1.14	1.20
	9.4	0.60	0.71	0.83	0.98	1.03
	12.4	0.57	0.67	0.79	0.93	0.98
A42/43	1.0	1.01	1.18	1.39	1.62	1.70
	3.5	0.86	1.00	1.18	1.39	1.45
	6.5	0.73	0.85	1.01	1.18	1.24
	9.4	0.62	0.73	0.86	1.00	1.05
	12.4	0.59	0.69	0.81	0.95	1.00
A51/52	1.0	1.06	1.24	1.47	1.72	1.81
	3.5	0.92	1.07	1.27	1.49	1.57
	6.5	0.77	0.90	1.06	1.25	1.31
	9.4	0.64	0.75	0.89	1.05	1.10
	12.4	0.61	0.71	0.84	0.99	1.04
A61/62	1.0	1.16	1.38	1.59	1.85	1.94
	3.5	1.01	1.19	1.38	1.61	1.68
	6.5	0.85	1.01	1.16	1.35	1.42
	9.4	0.70	0.83	0.96	1.12	1.18
	12.4	0.66	0.78	0.91	1.05	1.11
A71	1.0	1.28	1.52	1.73	1.99	2.07
	3.5	1.13	1.34	1.52	1.75	1.82
	6.5	0.94	1.12	1.27	1.47	1.53
	9.4	0.77	0.92	1.05	1.20	1.25
	12.4	0.72	0.86	0.98	1.13	1.17
A72	1.0	1.29	1.56	1.72	1.98	2.06
	3.5	1.13	1.37	1.51	1.73	1.81
	6.5	0.96	1.15	1.27	1.46	1.52
	9.4	0.79	0.95	1.05	1.20	1.25
	12.4	0.74	0.89	0.98	1.13	1.18

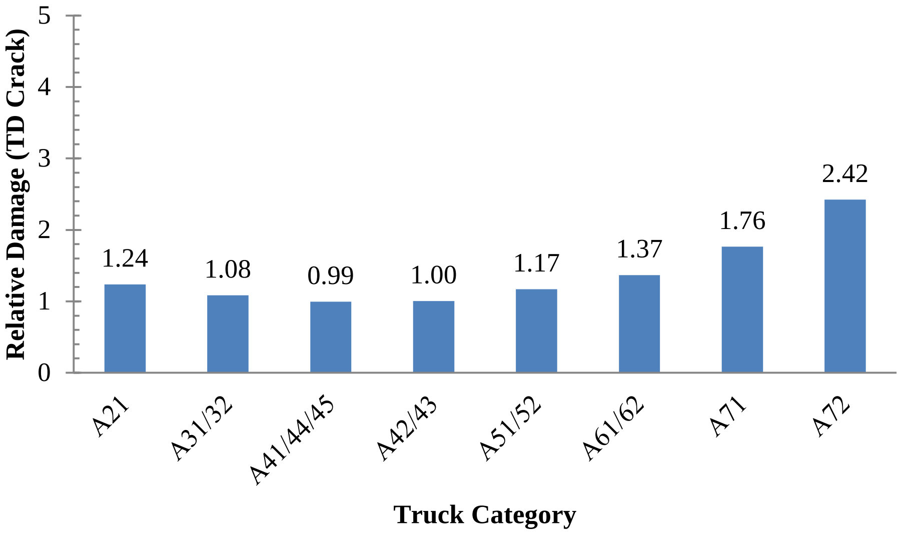


(a)

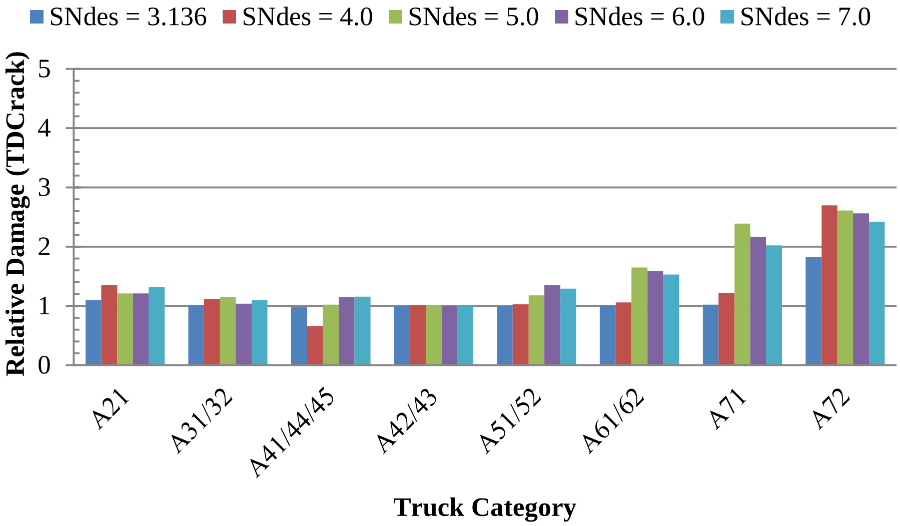


(b)

Figure B.21 Relative damage related to rutting done by trucks loaded to maximum limit compared to legal limit based on the DARWin-ME analysis: (a) average relative damage and (b) relative damage factors for each SN_{des}

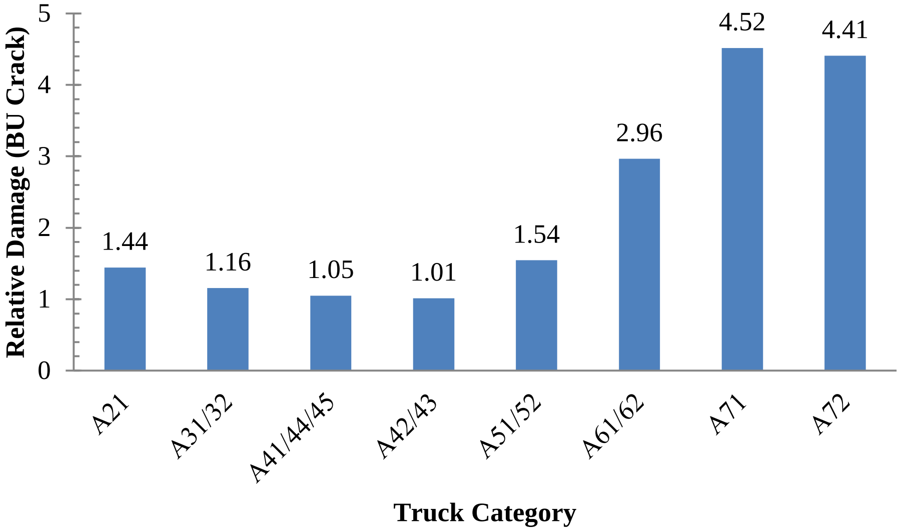


(a)

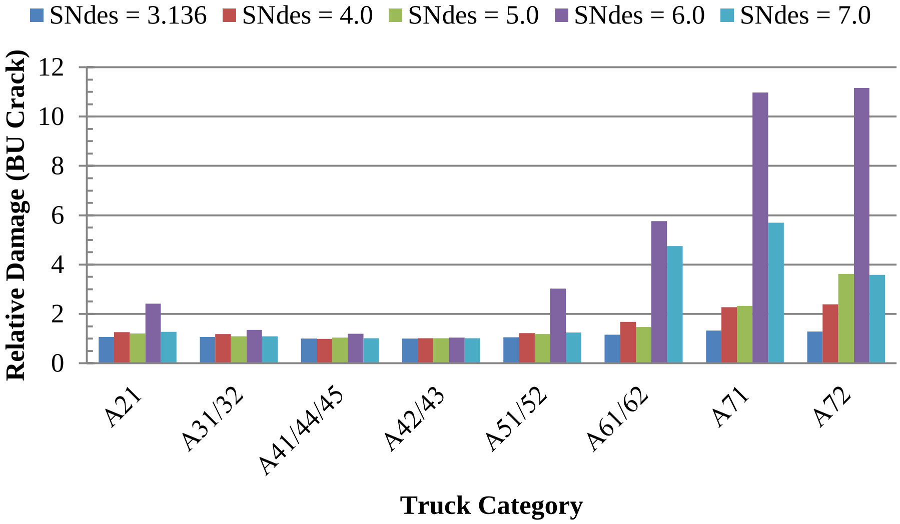


(b)

Figure B.22 Relative damage related to top-down cracking done by trucks loaded to maximum limit compared to legal limit based on the DARWin-ME analysis: (a) average relative damage and (b) relative damage factors for each SNdes

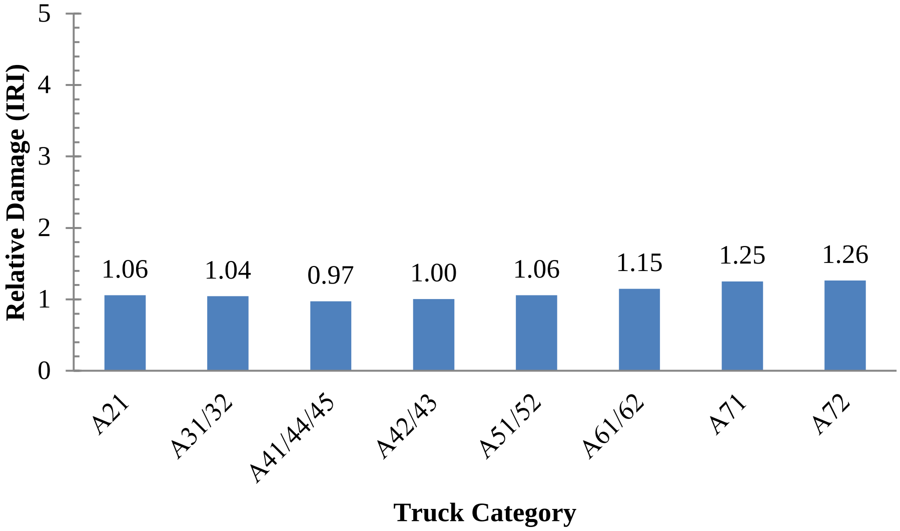


(a)

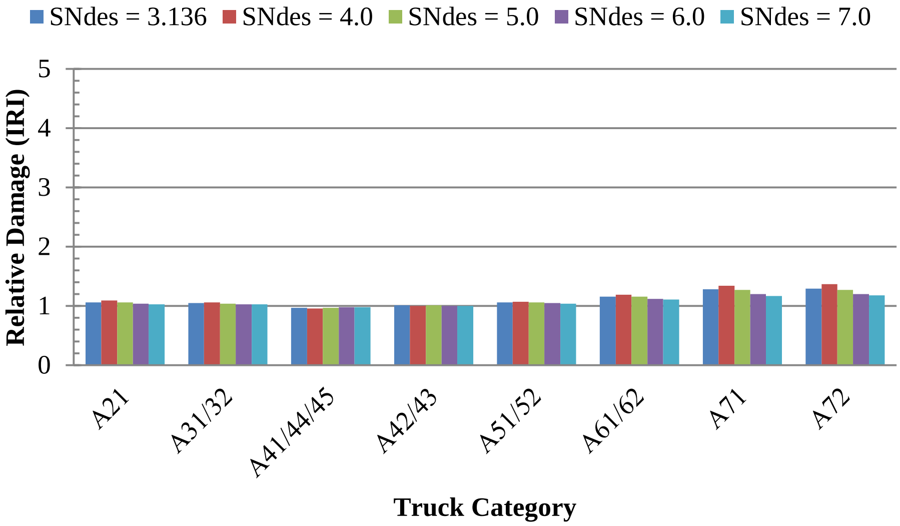


(b)

Figure B.23 Relative damage related to bottom-up cracking done by trucks loaded to maximum limit compared to legal limit based on the DARWin-ME analysis: (a) average relative damage and (b) relative damage factors for each SN_{des}



(a)



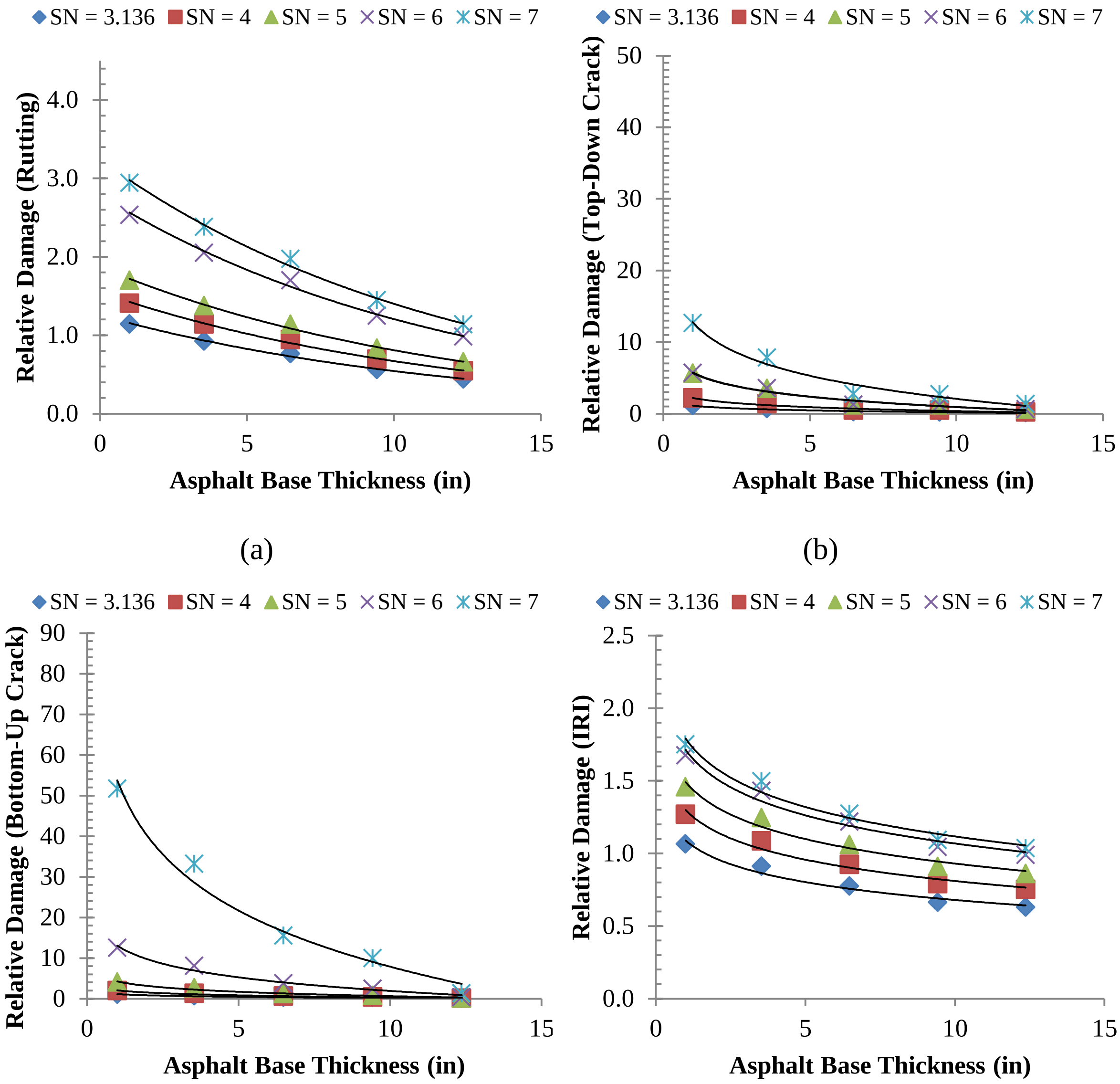
(b)

Figure B.24 Relative damage related to IRI done by trucks loaded to maximum limit compared to legal limit based on the DARWin-ME analysis: (a) average relative damage and (b) relative damage factors for each SN$_{des}$

Based on the results presented in Table B.27 through Table B.30 and Figure B.21 through Figure B.24, it is evident that trucks loaded beyond the legal limit do impart additional damage to pavements based on the DARWin-ME analysis. The amount of relative damage is fairly consistent for the truck models having two, three, four, and five axles. In this analysis, the relative damage for the A42/43 truck model was slightly greater than that of the A41/44/45 truck. Both of these trucks have four axles, but with different configurations as the A41/44/45 truck has one tandem and two single axles compared to the two tandem axles on the A42/43 truck. This comparison indicates that for this load range and number of axles, the configuration may not be a major factor on pavement damage. The relative damage significantly increases for each additional axle over five (i.e. six and seven axles). This is most likely due to the fact that the maximum load for the two, three, four, and five axle trucks is no more than 10 kips greater than the respective legal limit, whereas the maximum limit for the six axle and seven axle trucks is 30 and 50 kips greater than the legal limit, respectively. This substantial increase in load will result is significant damage to pavements. As with the four axle trucks, the relative damage of the two seven axle configurations (A71 and A72) is generally comparable to each other with respect to rutting, IRI, and even bottom-up cracking, indicating that axle configuration may not be a major factor for these two distress category. However, the relative damage for the top-down cracking was significantly greater for truck model A72 (one single axle and two tridem axles) compared to A71 (two tandem axles and one tridem axle). This suggests that the higher load concentration on the triple axles may accelerate the development of top-down cracking in flexible pavements.

The results also indicate that the relative damage for certain distresses is sensitive to the pavement design. For top-down and bottom-up cracking, the relative damage was relatively insensitive to structural design for the trucks having two, three, and four axles. However, when the number of axles increased to five, six, and seven, the relative damage was more sensitive to pavement thickness. This was evident by the higher relative damage factors for thicker pavement sections and the sensitivity increased as the number of axles and load increased. For the bottom-up cracking, the SN_{des} of 6.0 was especially sensitive as the relative damage factors were much greater than the next closest design having a SN_{des} of 7.0. This sensitivity was not evident in the ESAL analysis. It should be noted that use of a fatigue resistant asphalt base layer typically used in the design of perpetual pavements may mitigate this sensitivity with respect to fatigue cracking, especially bottom-up cracking.

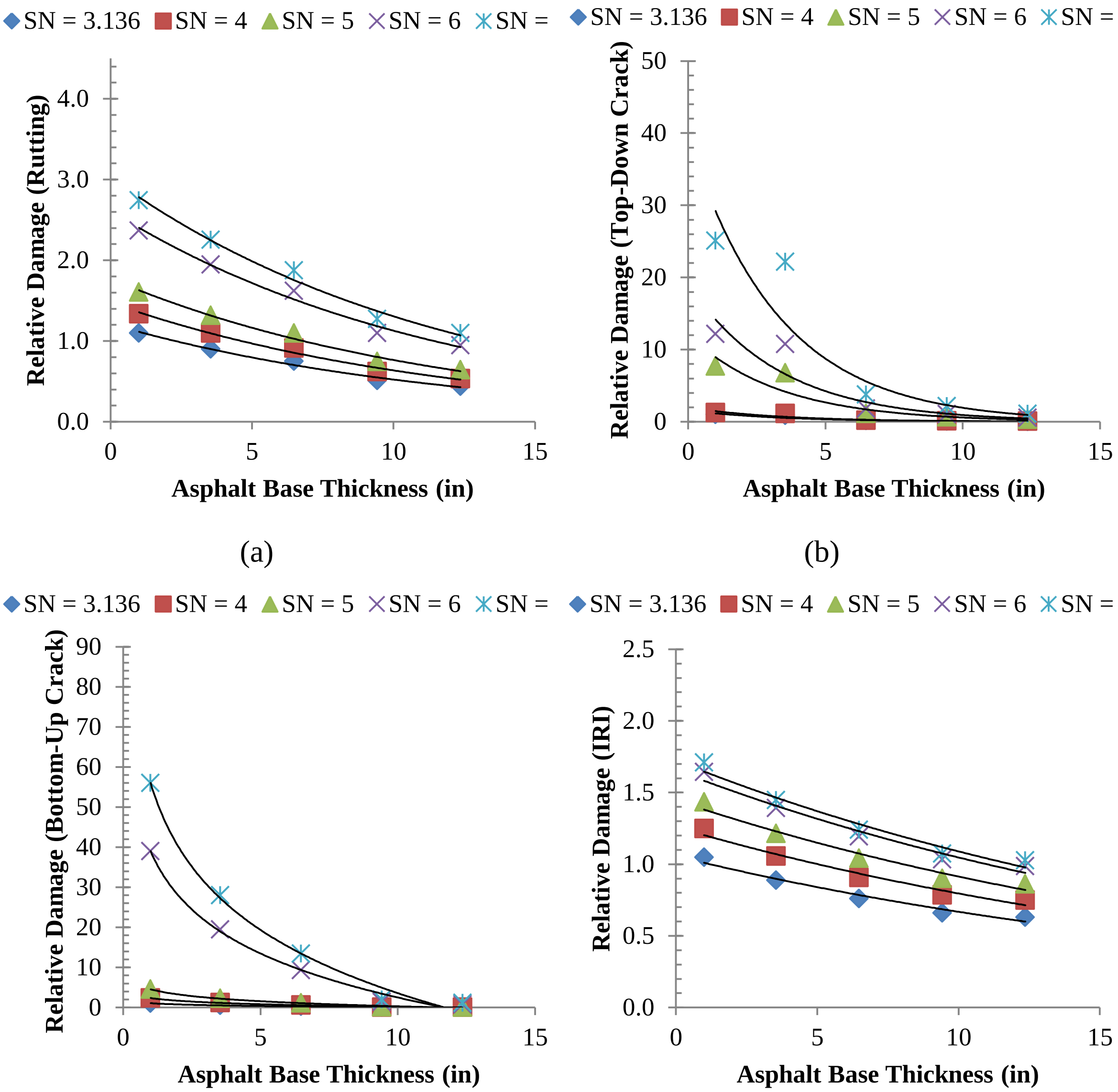
The relative damage factors from Table B.27 through Table B.30 were then used to create models defining the relationship between the relative damage (ML/LL) and HMA Base Course thickness for each truck and SN_{des}. These relationships and developed models are included in Figure B.25 through Figure B.32. It should be noted that the additional thickness included in these results are based on the hypothetical situation where 100% of the traffic is comprised of a single truck model with a gross vehicle weight equal to the respective maximum limit.



(a) (b)

(c) (d)

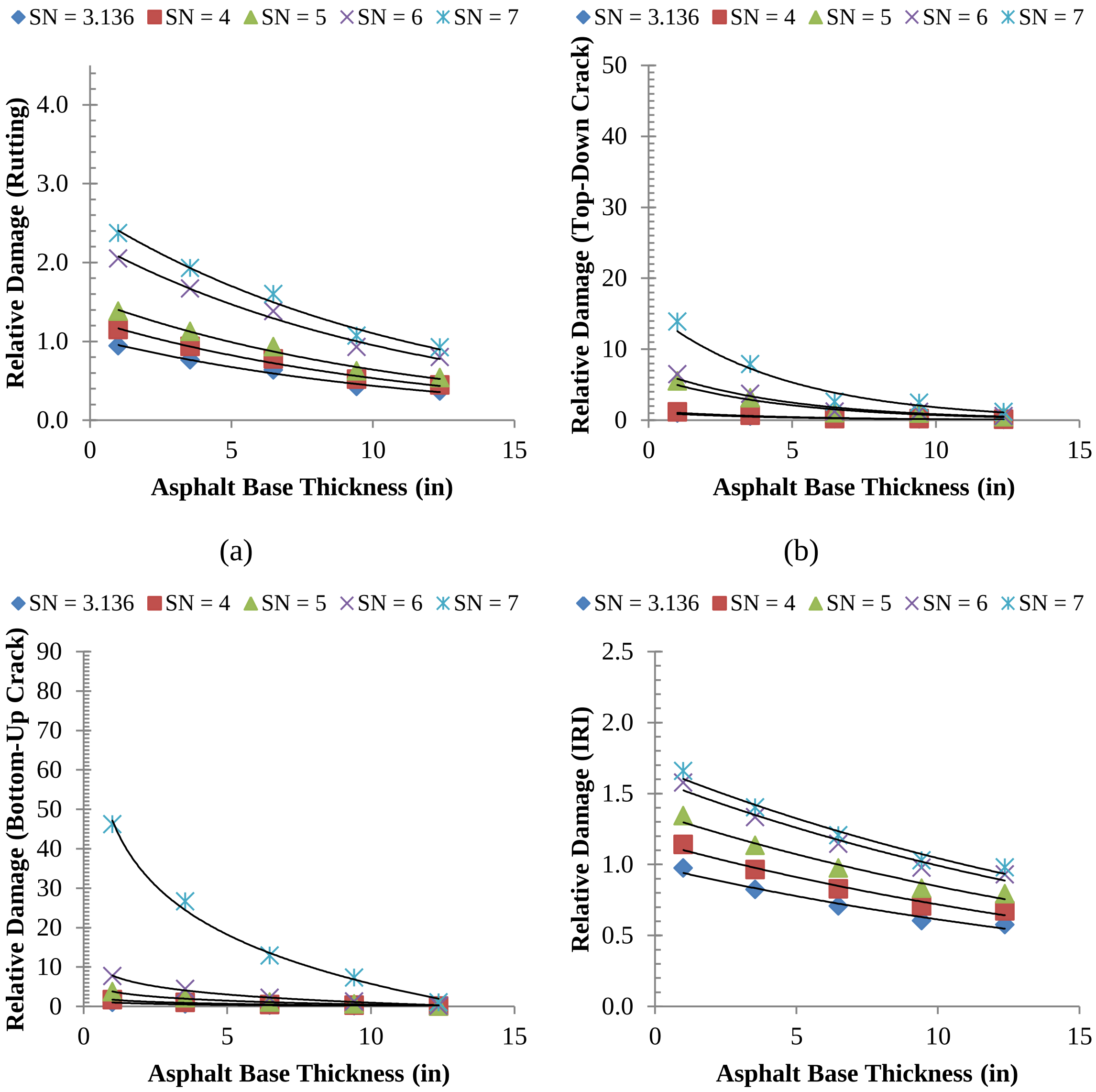
Figure B.25 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A21 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

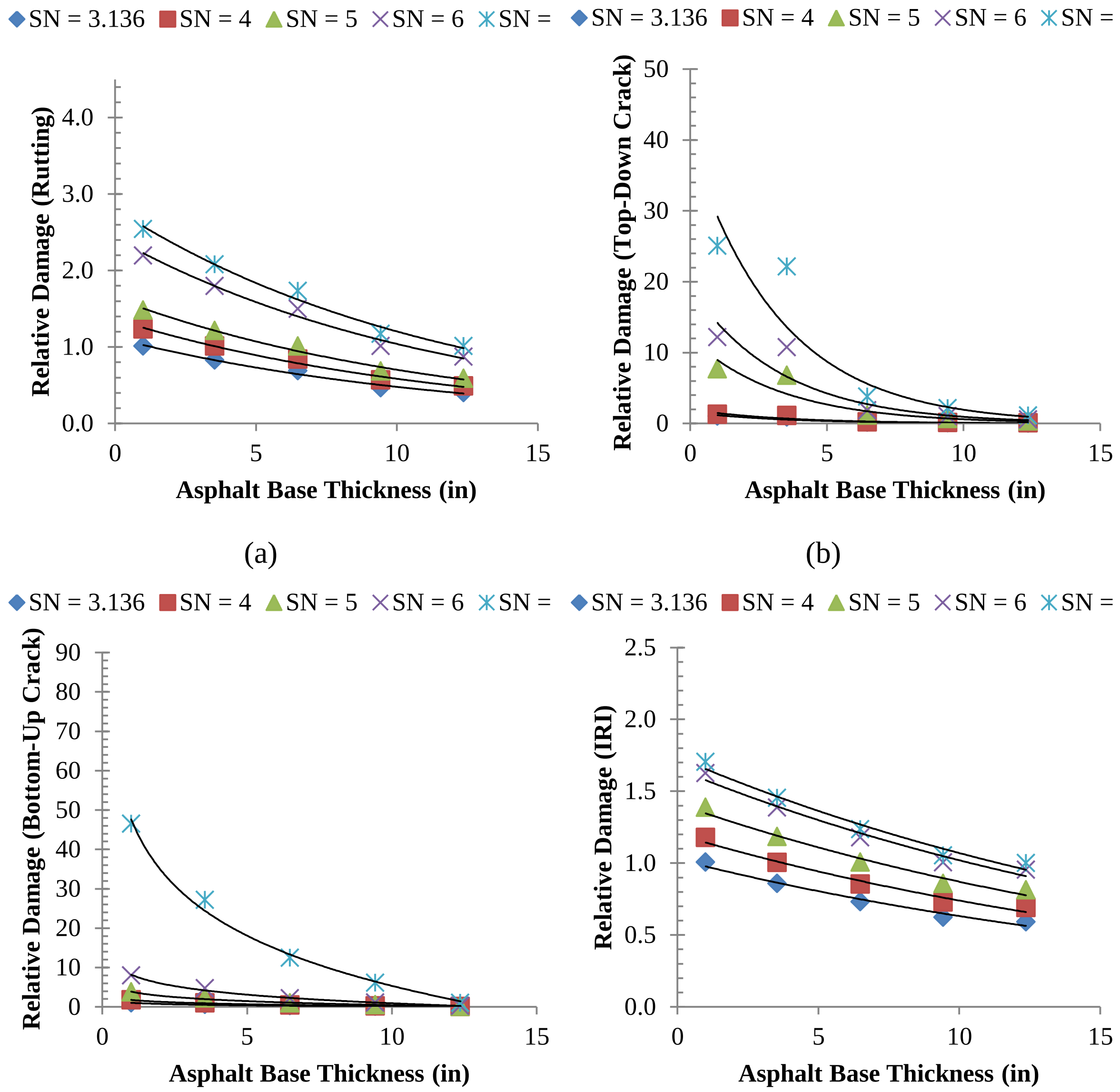
Figure B.26 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A31/32 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

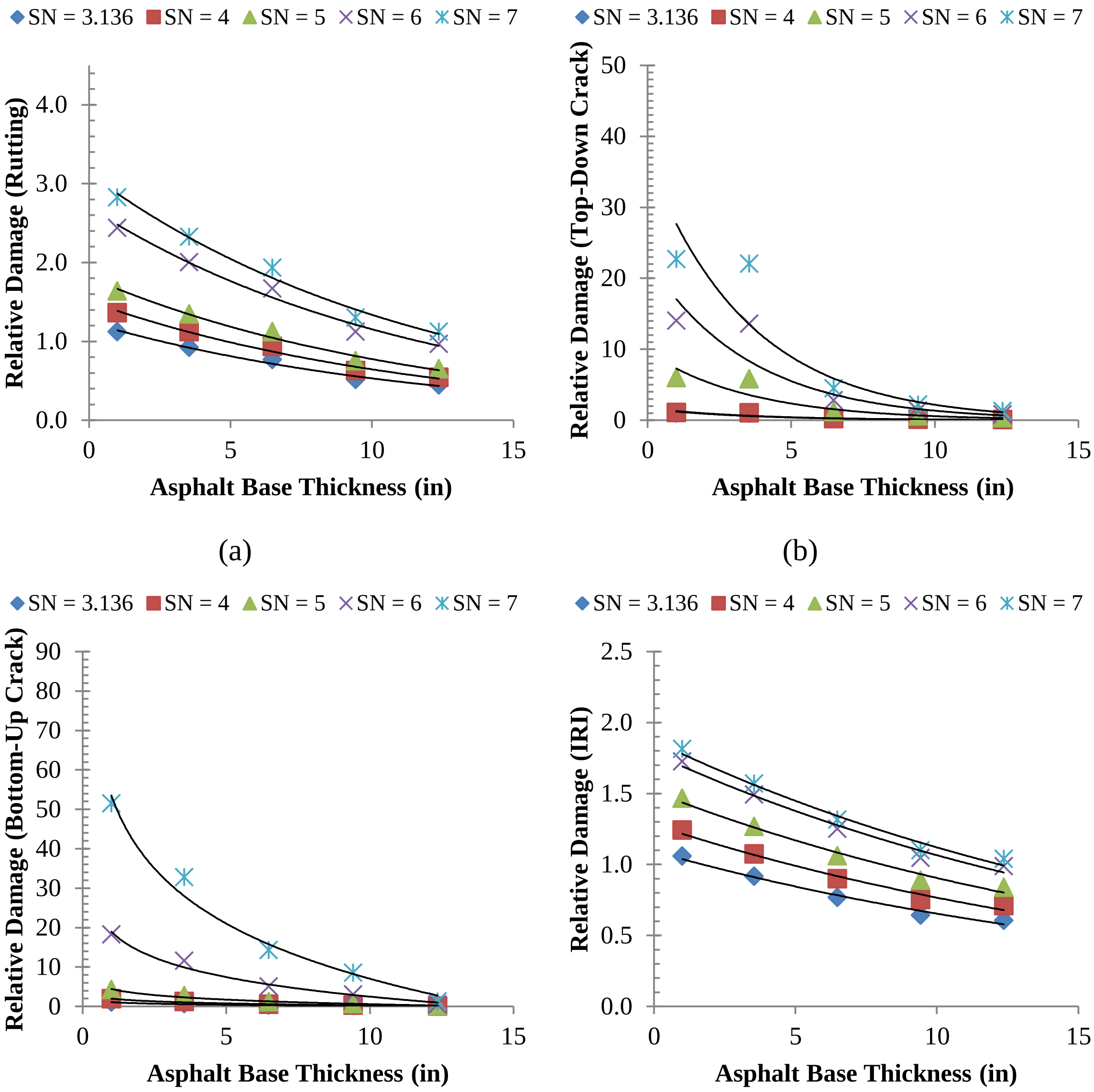
Figure B.27 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A41/44/45 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

Figure B.28 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A42/43 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



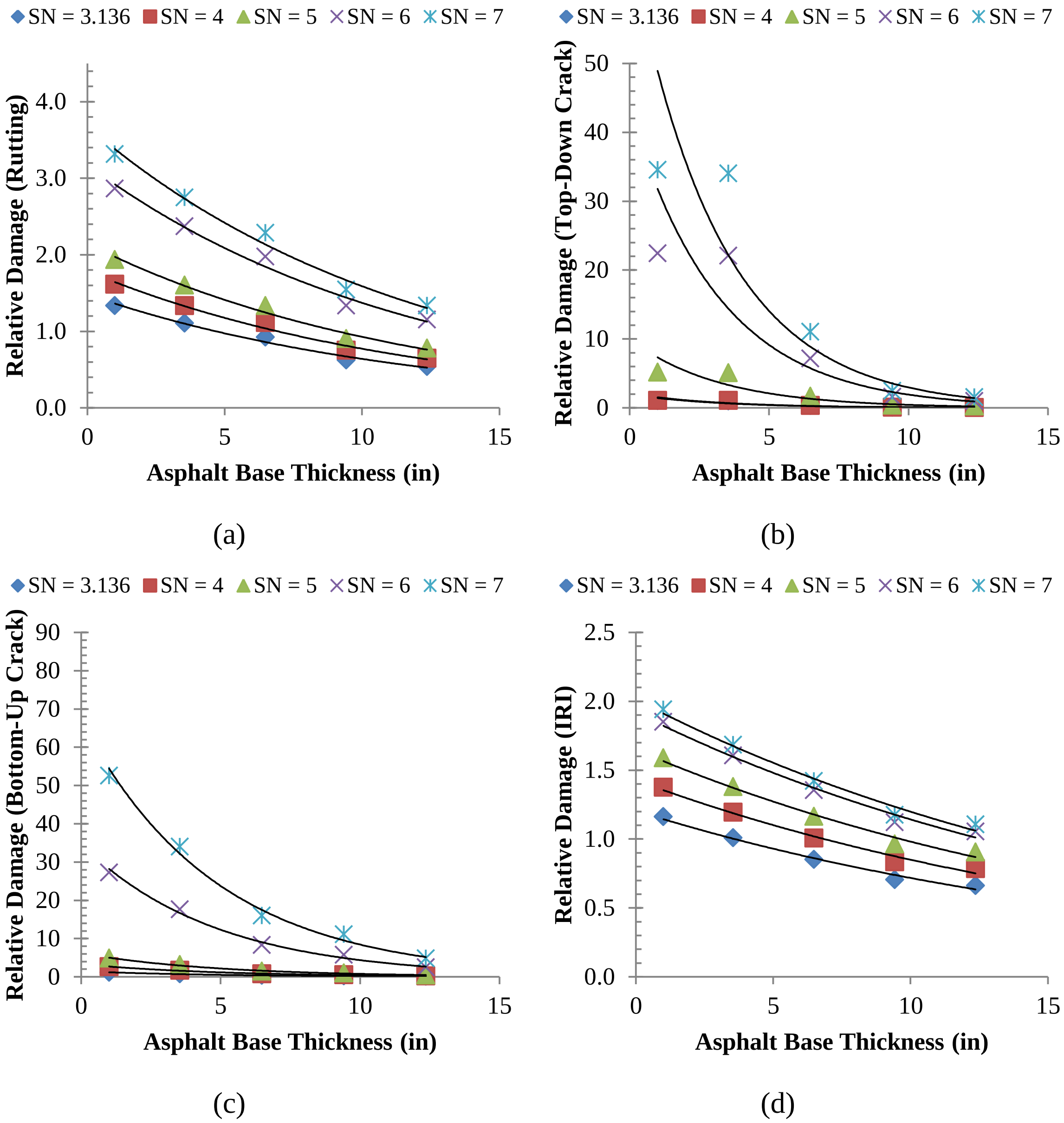
(a)

(b)

(c)

(d)

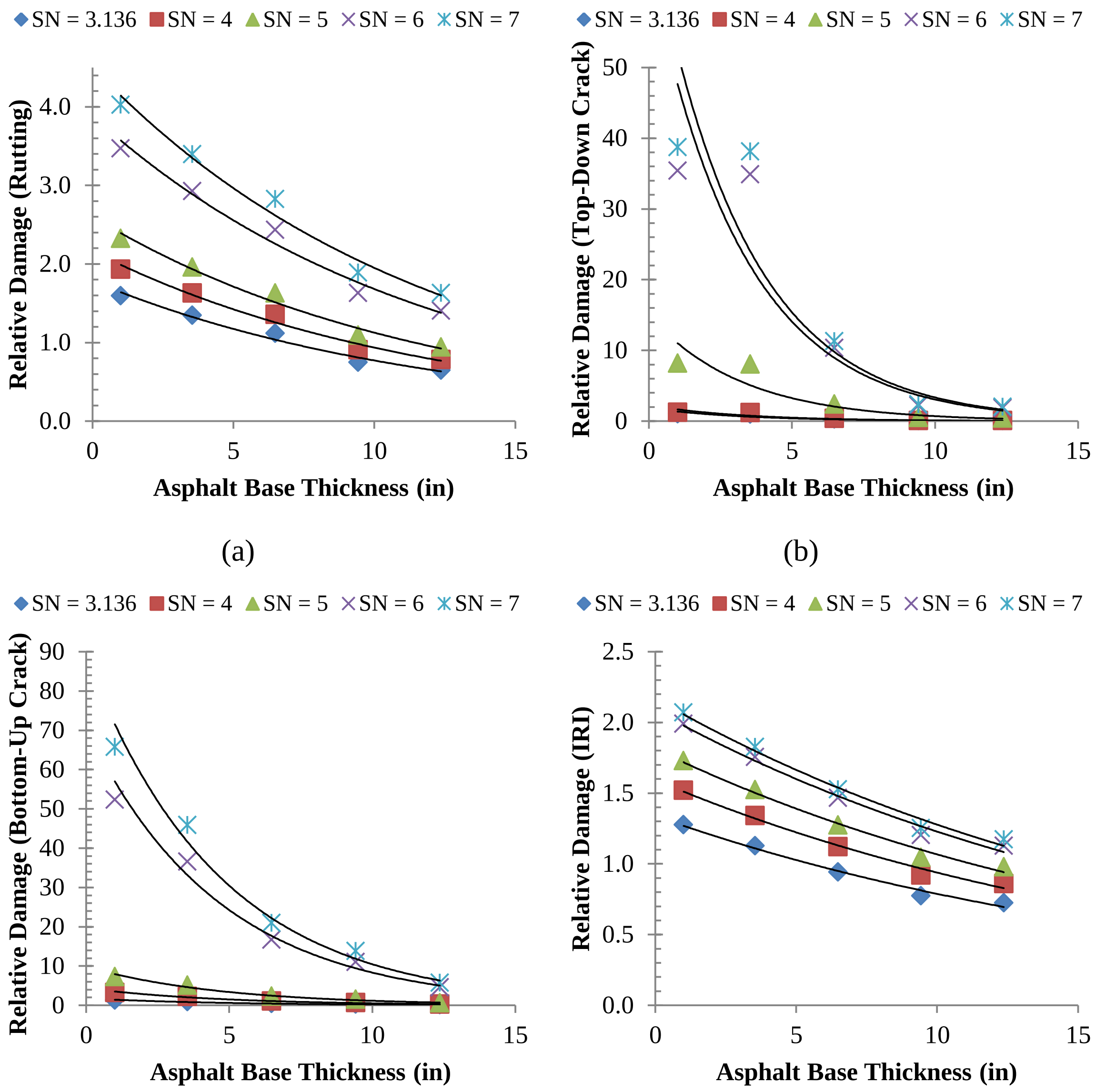
Figure B.29 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A51/52 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

Figure B.30 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A61/62 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



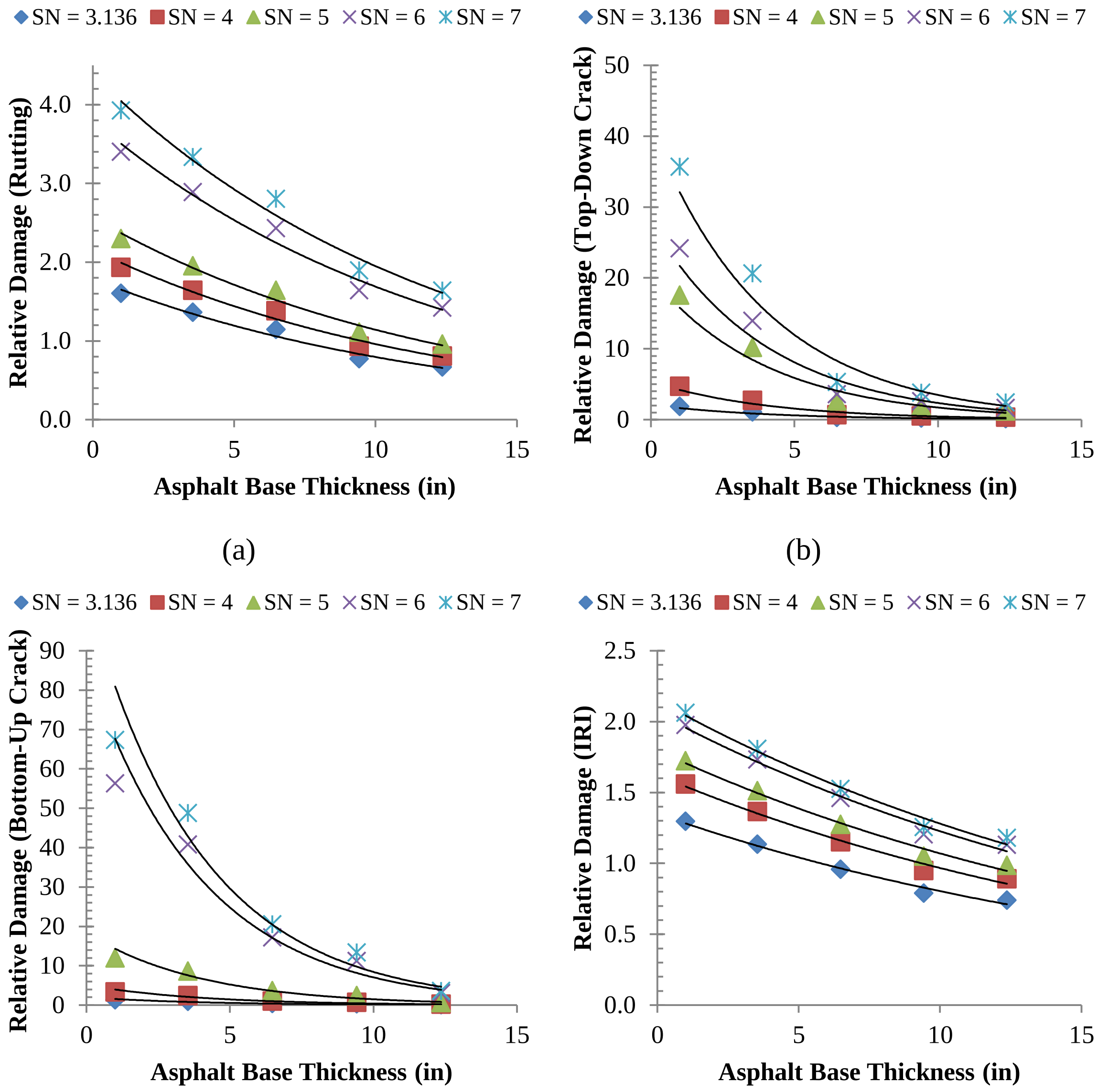
(a)

(b)

(c)

(d)

Figure B.31 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A71 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a)

(b)

(c)

(d)

Figure B.32 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and HMA Base Course thickness for truck category A72 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI

These models were then used to determine the additional pavement thickness required that would yield the same value for each distress for a given truck loaded at the maximum limit as that of the same truck loaded to the legal limit. In other words, the increase in asphalt thickness required to reduce the relative damage factor to 1.0 can be determined for each distress type. The additional pavement thickness was added to the HMA Base Course and the thickness of all other layers was kept constant. The results and models are included Figure B.33 through Figure B.39.

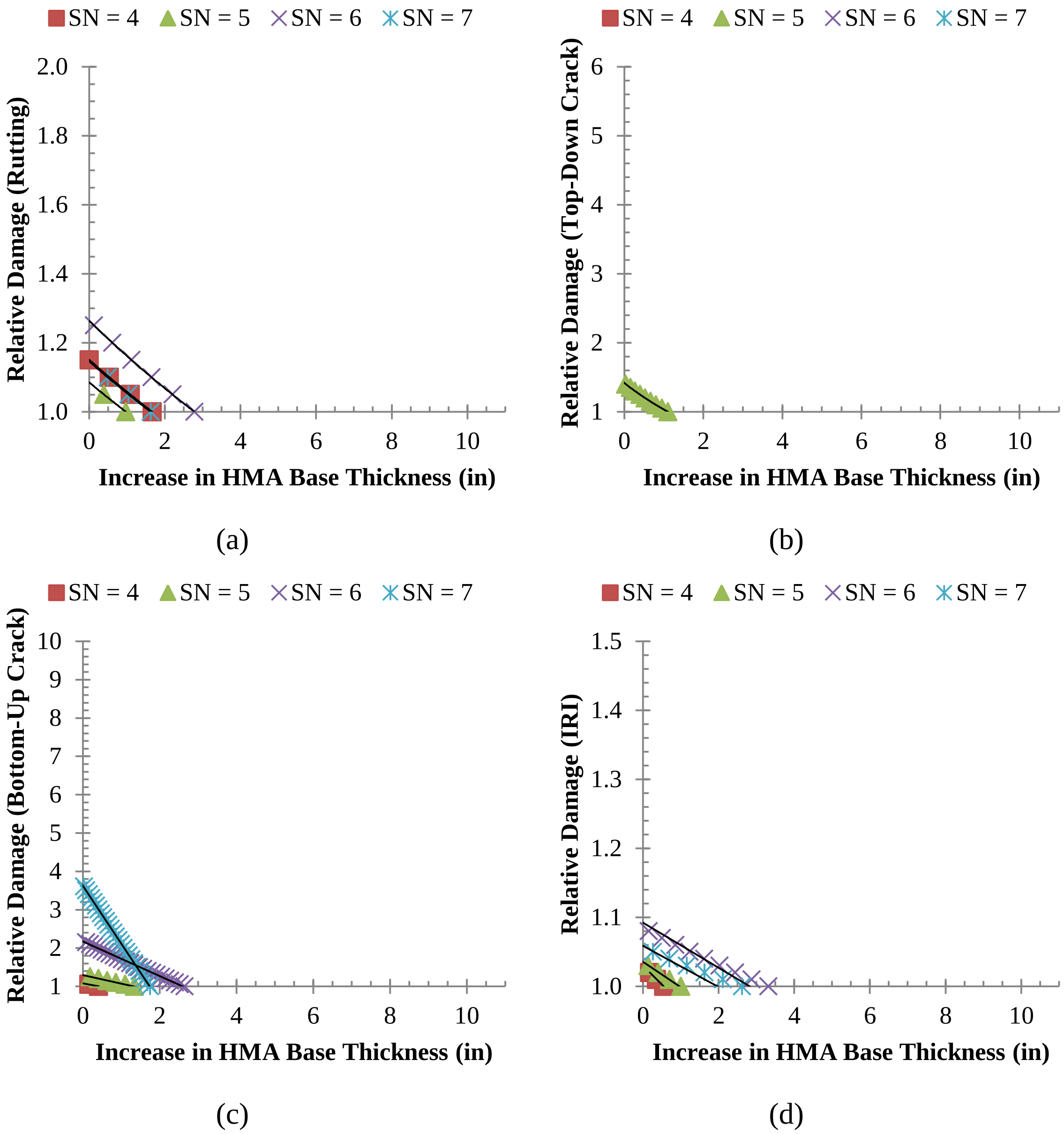
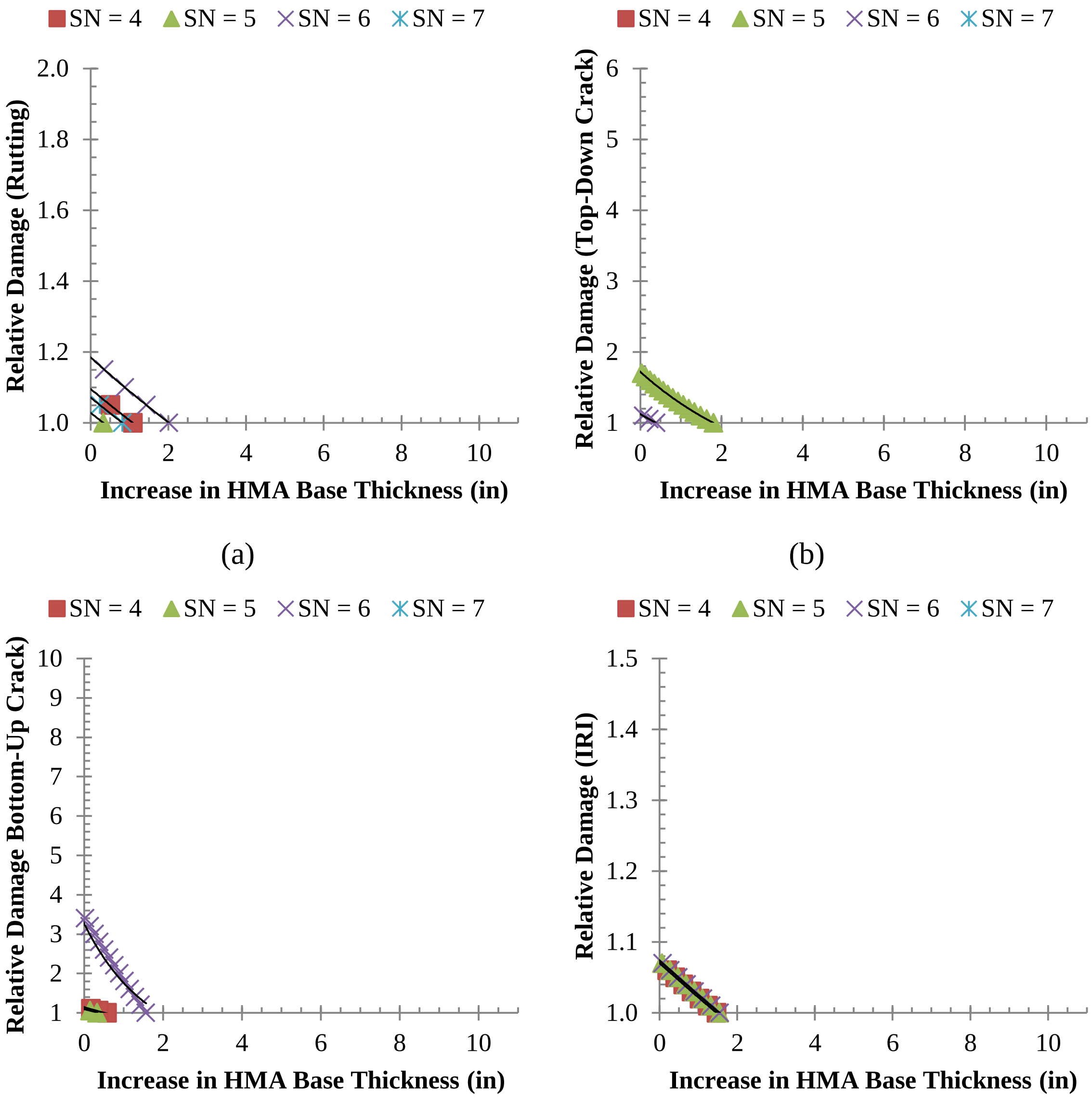


Figure B.33 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A21 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a)

(b)

(c)

(d)

Figure B.34 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A31/32 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI

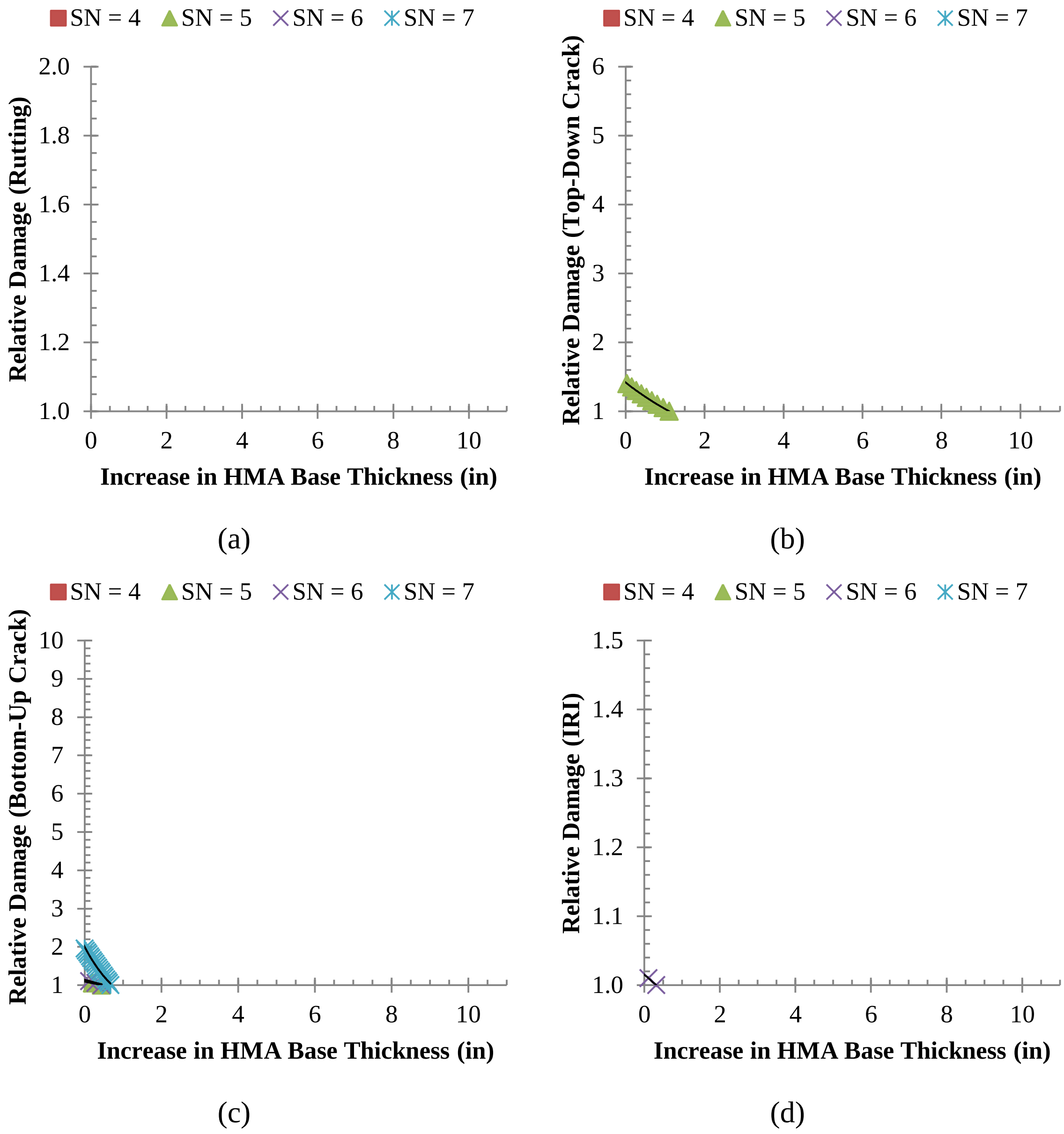


Figure B.35 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A41/44/45 for a given SNdes for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI

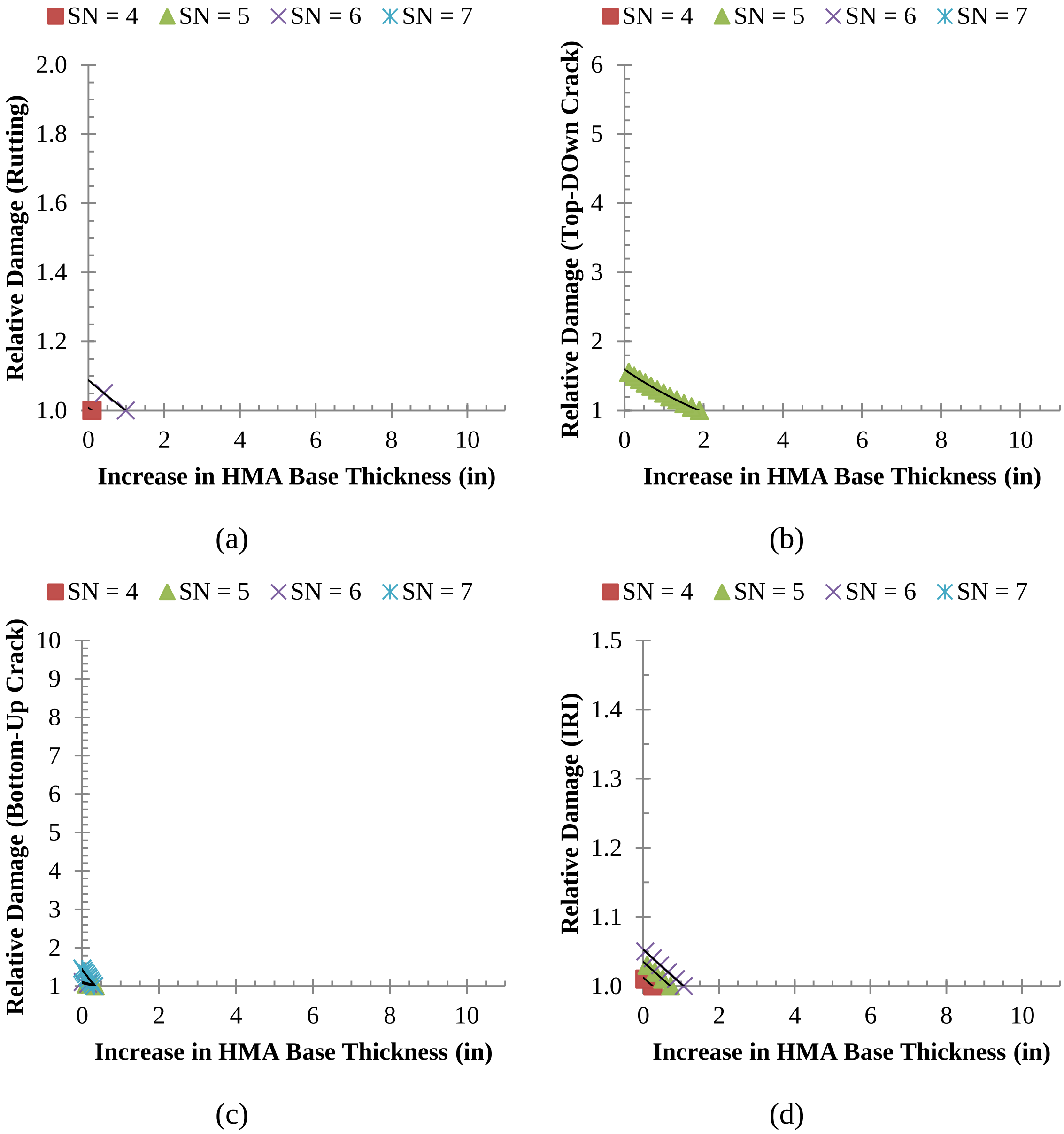
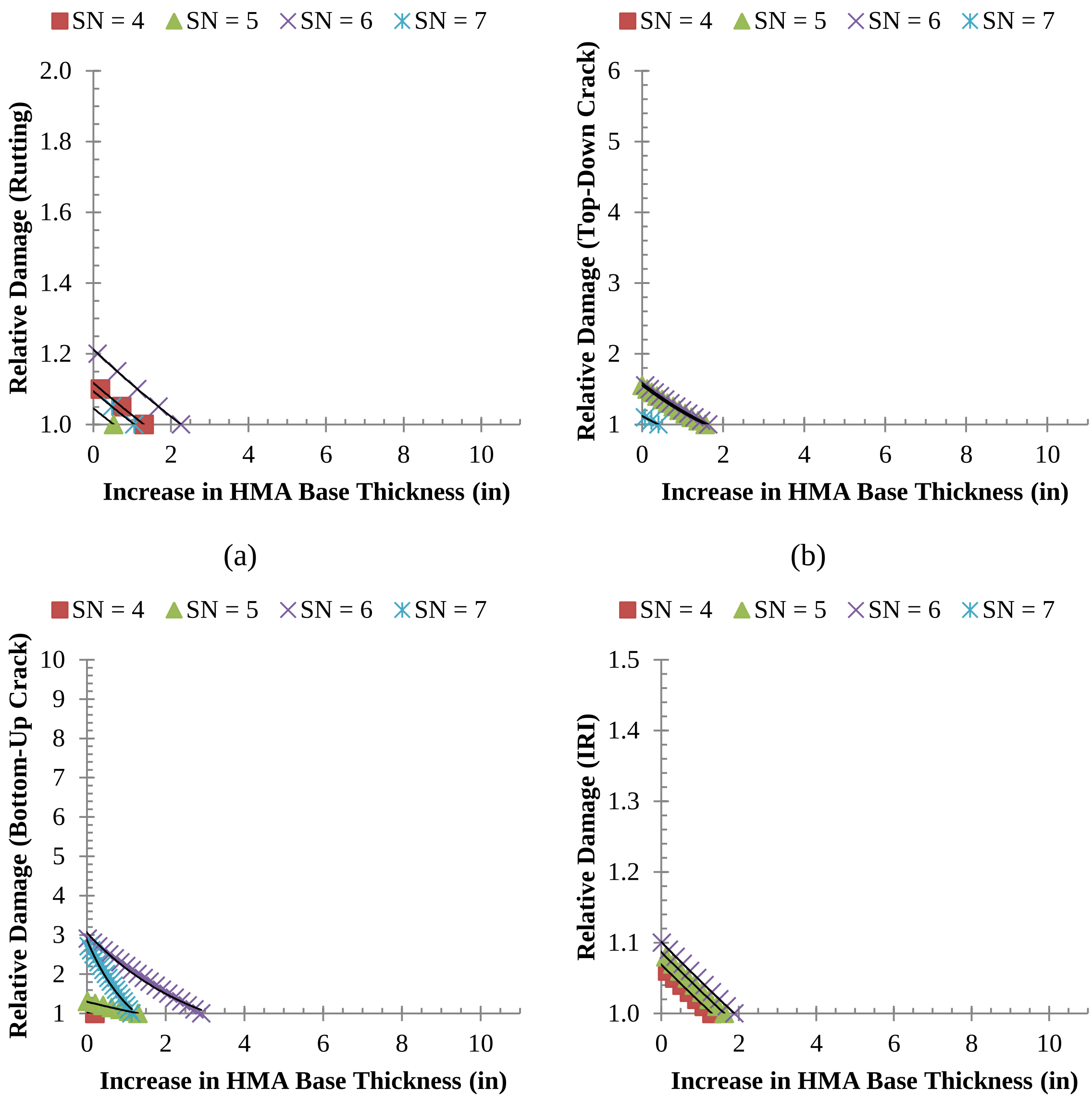


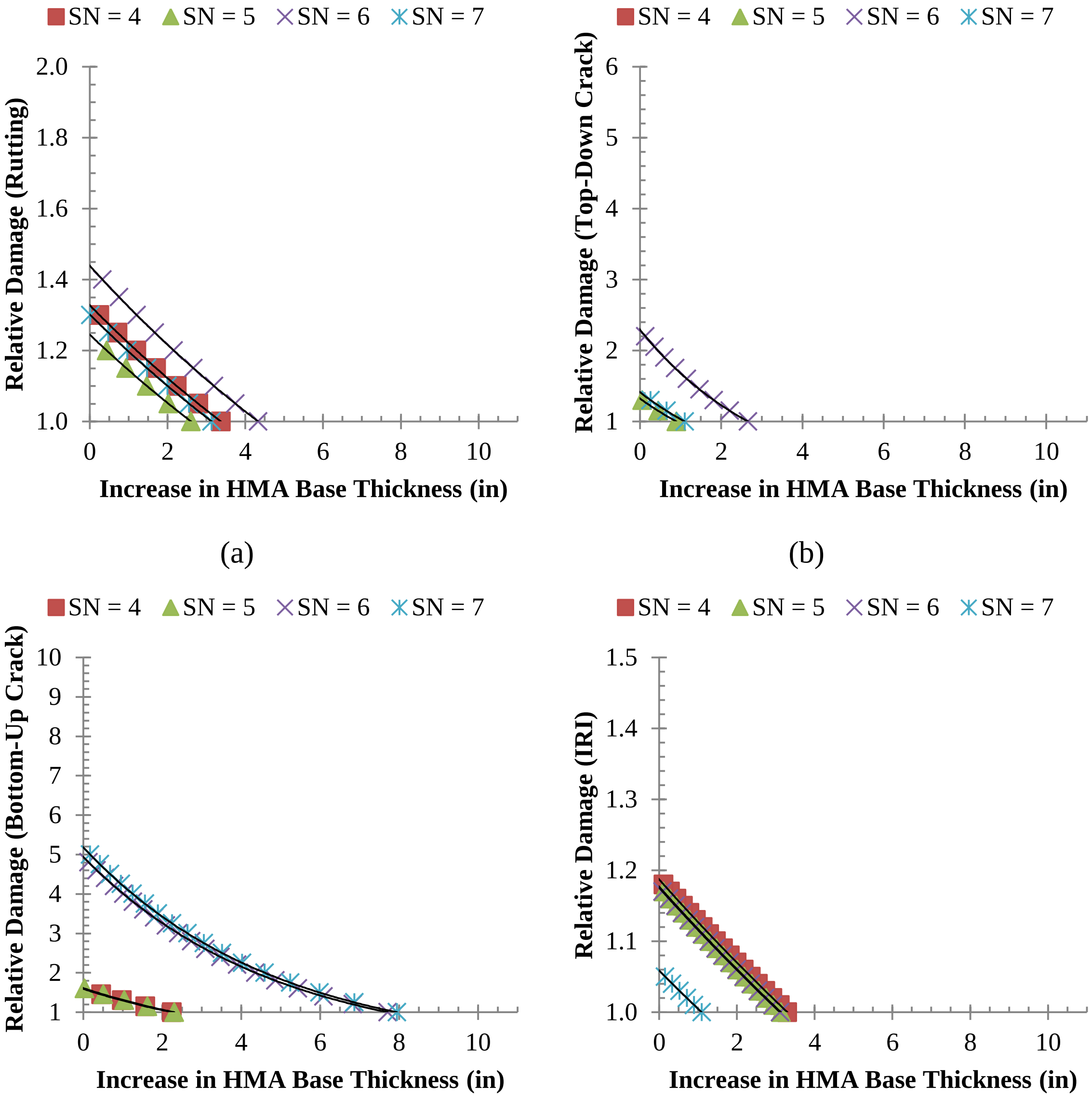
Figure B.36 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A42/43 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

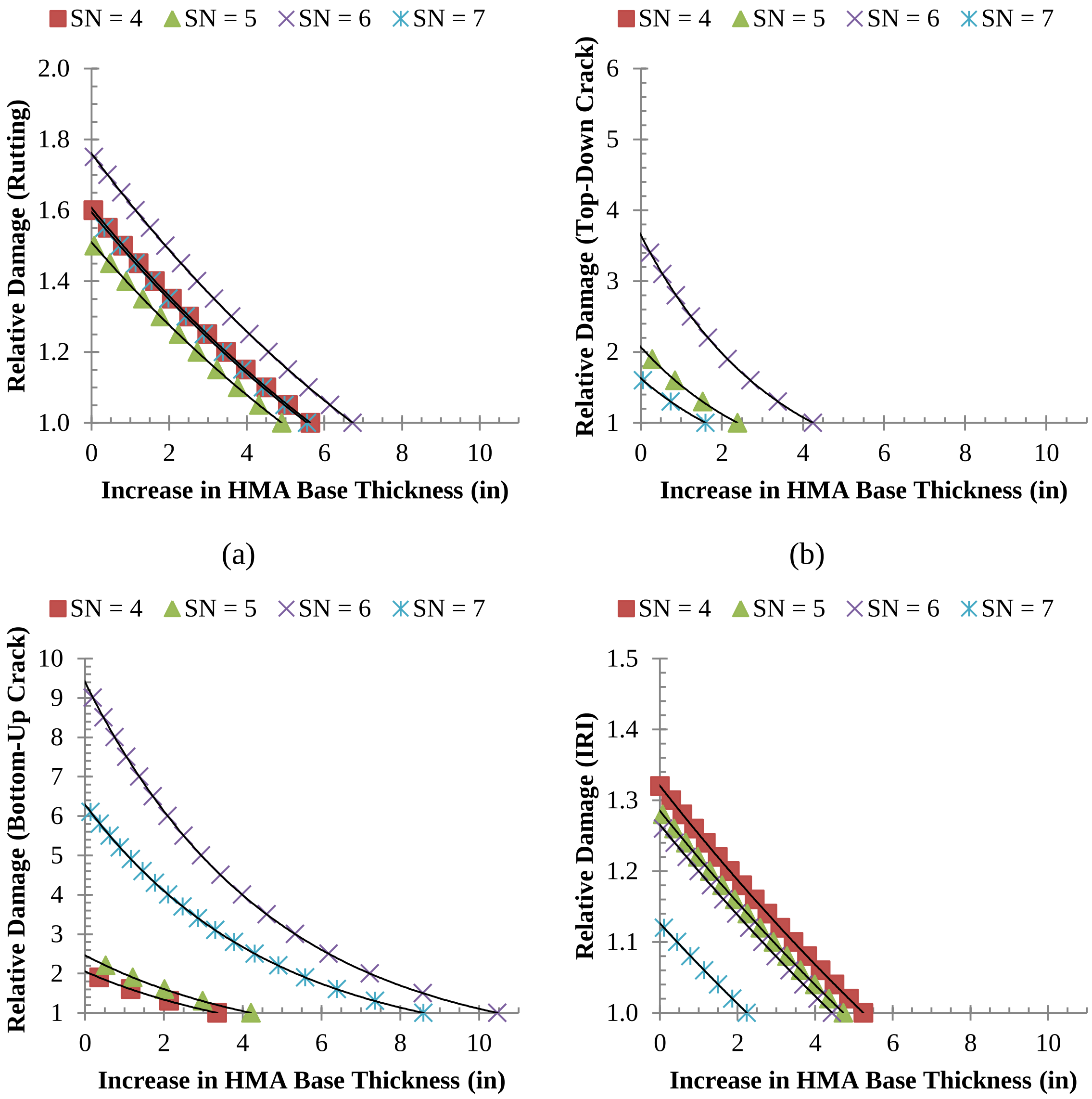
Figure B.37 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A51/52 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

Figure B.38 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A61/62 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



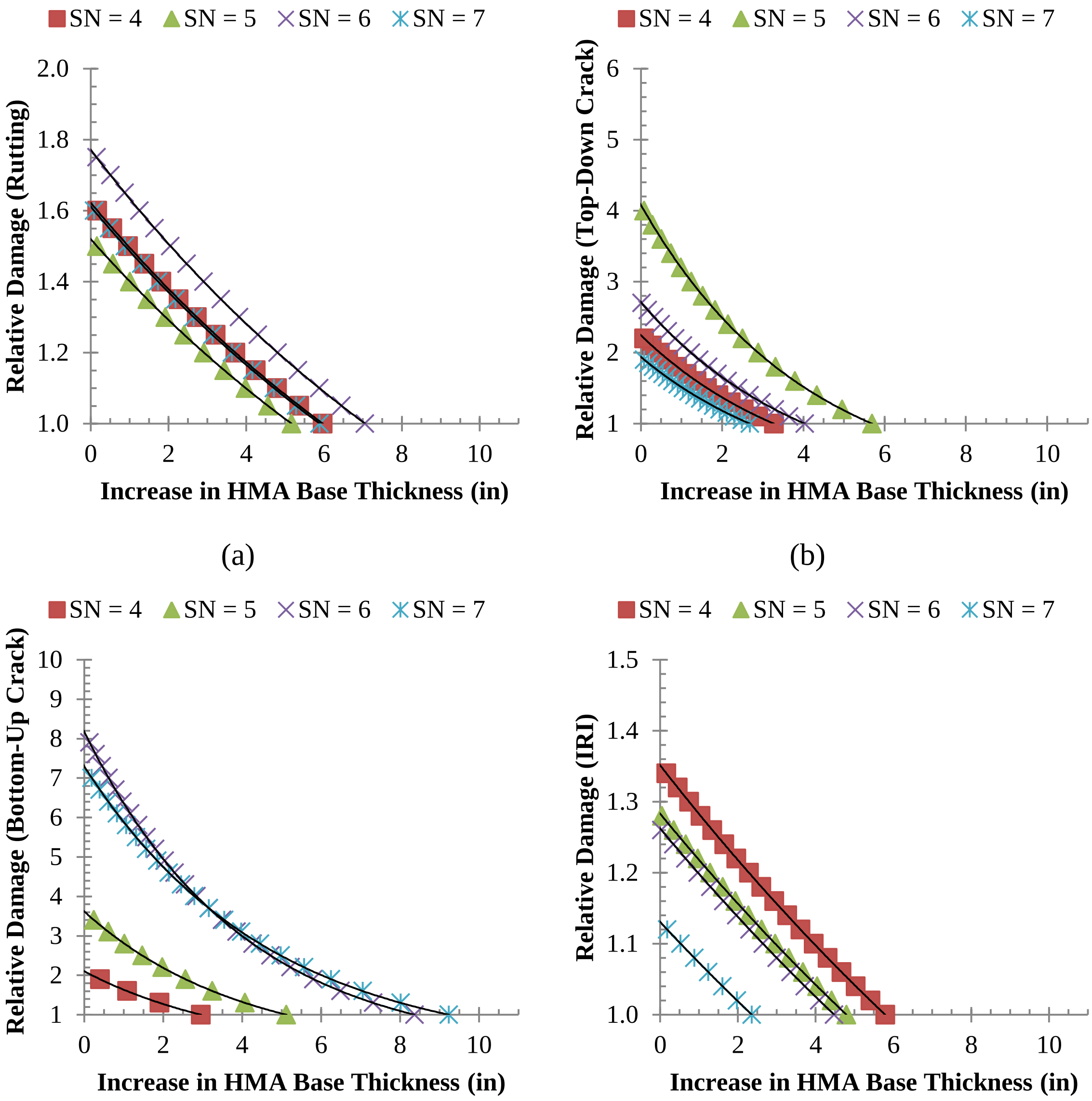
(a)

(b)

(c)

(d)

Figure B.39 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A71 for a given SN_{des} for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI



(a) (b)

(c) (d)

Figure B.40 Relationship between relative damage (distress at Max Limit divided by distress at Legal Limit) and increase in HMA Base Course thickness for truck category A72 for a given SN$_{des}$ for (a) rutting, (b) top-down cracking, (c) bottom-up cracking, and (d) IRI

The equations included in Table B.31, Table B.33, Table B.35, and Table B.37 are based on the results presented in Figure B.33 through Figure B.39 and can be used to estimate the increased thickness of the HMA Base Course layer required to achieve a desired relative damage factor for each truck category for a given design structural number. Table B.32, Table B.34, Table B.36, and Table B.38 and Figure B.40 through Figure B.43 summarize the additional thickness of the HMA Base Course needed to achieve a relative damage factor of 1.0 (number of passes at legal limit = number of passes at maximum limit) for each pavement design and truck category based on each distress, respectively.

Table B.31 Summary of models to determine required increase in HMA Base Course thickness based rutting using the DARWin-ME analysis. Note that RD = relative damage

	Required Increase in HMA Base Thickness (in)			
Truck Category	**SN_{des} = 4.0**	**SN_{des} = 5.0**	**SN_{des} = 6.0**	**SN_{des} = 7.0**
A21	$= \frac{\ln \frac{RD}{1.5492}}{-0.084}$	$= \frac{\ln \frac{RD}{1.8704}}{-0.084}$	$= \frac{\ln \frac{RD}{2.7880}}{-0.084}$	$= \frac{\ln \frac{RD}{3.2377}}{-0.084}$
A31/32	$= \frac{\ln \frac{RD}{1.4752}}{-0.084}$	$= \frac{\ln \frac{RD}{1.7720}}{-0.084}$	$= \frac{\ln \frac{RD}{2.6139}}{-0.084}$	$= \frac{\ln \frac{RD}{3.0262}}{-0.084}$
A41/44/45	$= \frac{\ln \frac{RD}{1.2694}}{-0.087}$	$= \frac{\ln \frac{RD}{1.5265}}{-0.087}$	$= \frac{\ln \frac{RD}{2.2651}}{-0.087}$	$= \frac{\ln \frac{RD}{2.6224}}{-0.087}$
A42/43	$= \frac{\ln \frac{RD}{1.3623}}{-0.085}$	$= \frac{\ln \frac{RD}{1.6371}}{-0.085}$	$= \frac{\ln \frac{RD}{2.4229}}{-0.085}$	$= \frac{\ln \frac{RD}{2.8041}}{-0.085}$
A51/52	$= \frac{\ln \frac{RD}{1.5101}}{-0.085}$	$= \frac{\ln \frac{RD}{1.8142}}{-0.085}$	$= \frac{\ln \frac{RD}{2.6995}}{-0.085}$	$= \frac{\ln \frac{RD}{3.1287}}{-0.085}$
A61/62	$= \frac{\ln \frac{RD}{1.7874}}{-0.084}$	$= \frac{\ln \frac{RD}{2.1454}}{-0.084}$	$= \frac{\ln \frac{RD}{3.1746}}{-0.084}$	$= \frac{\ln \frac{RD}{3.6764}}{-0.084}$
A71	$= \frac{\ln \frac{RD}{2.1627}}{-0.084}$	$= \frac{\ln \frac{RD}{2.6016}}{-0.084}$	$= \frac{\ln \frac{RD}{3.8835}}{-0.084}$	$= \frac{\ln \frac{RD}{4.5045}}{-0.084}$
A72	$= \frac{\ln \frac{RD}{2.1608}}{-0.081}$	$= \frac{\ln \frac{RD}{2.5684}}{-0.081}$	$= \frac{\ln \frac{RD}{3.7993}}{-0.081}$	$= \frac{\ln \frac{RD}{4.3851}}{-0.081}$

Table B.32 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for rutting based on the DARWin-ME analysis for each truck category loaded to the maximum limit

	Required Increase in HMA Base Thickness (in)			
Truck Category	SN_{des} = 4.0	SN_{des} = 5.0	SN_{des} = 6.0	SN_{des} = 7.0
A21	5.21	7.45	12.21	13.99
A31/32	4.63	6.81	11.44	13.18
A41/44/45	2.74	4.86	9.40	11.08
A42/43	3.64	5.80	10.41	12.13
A51/52	4.85	7.01	11.68	13.42
A61/62	6.91	9.09	13.75	15.50
A71	9.18	11.38	16.15	17.92
A72	9.51	11.65	16.48	18.25

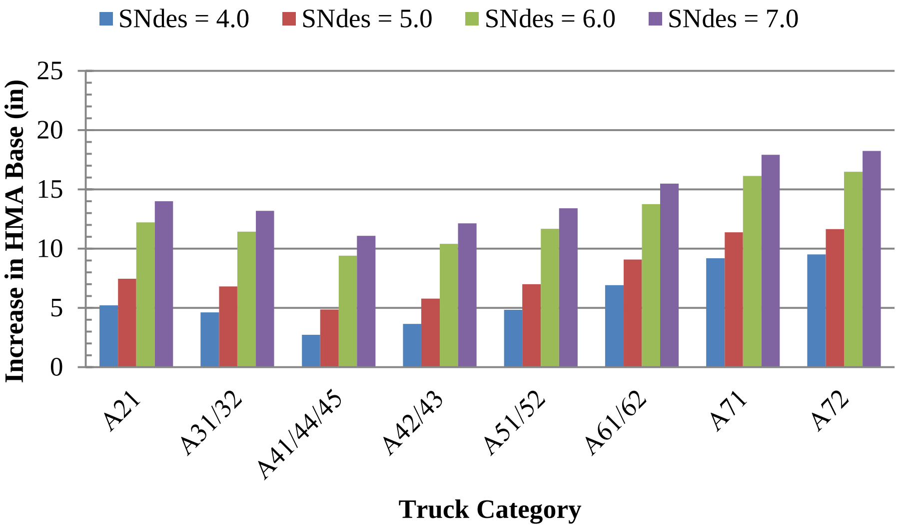


Figure B.41 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for rutting based on DARWin-ME analysis for each truck category loaded to the maximum limit

Table B.33 Summary of models to determine required increase in HMA Base Course thickness based top-down cracking using the DARWin-ME analysis. Note that RD = relative damage

Truck Category	Required Increase in HMA Base Thickness (in)			
	$\mathrm{SN_{des}} = 4.0$	$\mathrm{SN_{des}} = 5.0$	$\mathrm{SN_{des}} = 6.0$	$\mathrm{SN_{des}} = 7.0$
A21	$= e^{\left(\frac{RD-2.202}{-0.801}\right)}$	$= e^{\left(\frac{RD-5.6891}{-2.071}\right)}$	$= e^{\left(\frac{RD-5.7566}{-2.095}\right)}$	$= e^{\left(\frac{RD-12.786}{-4.653}\right)}$
A31/32	$= \frac{\ln \frac{RD}{1.9933}}{-0.301}$	$= \frac{\ln \frac{RD}{12.101}}{-0.301}$	$= \frac{\ln \frac{RD}{19.166}}{-0.301}$	$= \frac{\ln \frac{RD}{39.467}}{-0.301}$
A41/44/45	$= \frac{\ln \frac{RD}{1.2954}}{-0.214}$	$= \frac{\ln \frac{RD}{6.1488}}{-0.214}$	$= \frac{\ln \frac{RD}{7.2432}}{-0.214}$	$= \frac{\ln \frac{RD}{15.531}}{-0.214}$
A42/43	$= \frac{\ln \frac{RD}{1.6635}}{-0.246}$	$= \frac{\ln \frac{RD}{7.8530}}{-0.246}$	$= \frac{\ln \frac{RD}{9.1955}}{-0.246}$	$= \frac{\ln \frac{RD}{19.786}}{-0.246}$
A51/52	$= \frac{\ln \frac{RD}{1.7192}}{-0.282}$	$= \frac{\ln \frac{RD}{9.6610}}{-0.282}$	$= \frac{\ln \frac{RD}{22.609}}{-0.282}$	$= \frac{\ln \frac{RD}{36.643}}{-0.282}$
A61/62	$= \frac{\ln \frac{RD}{2.0875}}{-0.312}$	$= \frac{\ln \frac{RD}{10.003}}{-0.312}$	$= \frac{\ln \frac{RD}{43.395}}{-0.312}$	$= \frac{\ln \frac{RD}{66.808}}{-0.312}$
A71	$= \frac{\ln \frac{RD}{2.2554}}{-0.305}$	$= \frac{\ln \frac{RD}{14.957}}{-0.305}$	$= \frac{\ln \frac{RD}{64.647}}{-0.305}$	$= \frac{\ln \frac{RD}{70.716}}{-0.305}$
A72	$= \frac{\ln \frac{RD}{5.3853}}{-0.247}$	$= \frac{\ln \frac{RD}{20.233}}{-0.247}$	$= \frac{\ln \frac{RD}{27.788}}{-0.247}$	$= \frac{\ln \frac{RD}{41.085}}{-0.247}$

Table B.34 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for top-down cracking based on the DARWin-ME analysis for each truck category loaded to the maximum limit

Truck Category	Required Increase in HMA Base Thickness (in)			
	SN_{des} = 4.0	SN_{des} = 5.0	SN_{des} = 6.0	SN_{des} = 7.0
A21	4.48	9.62	9.68	12.59
A31/32	2.29	8.28	9.81	12.21
A41/44/45	1.21	8.49	9.25	12.82
A42/43	2.07	8.38	9.02	12.13
A51/52	1.92	8.04	11.06	12.77
A61/62	2.36	7.38	12.08	13.47
A71	2.67	8.87	13.67	13.96
A72	6.82	12.18	13.46	15.04

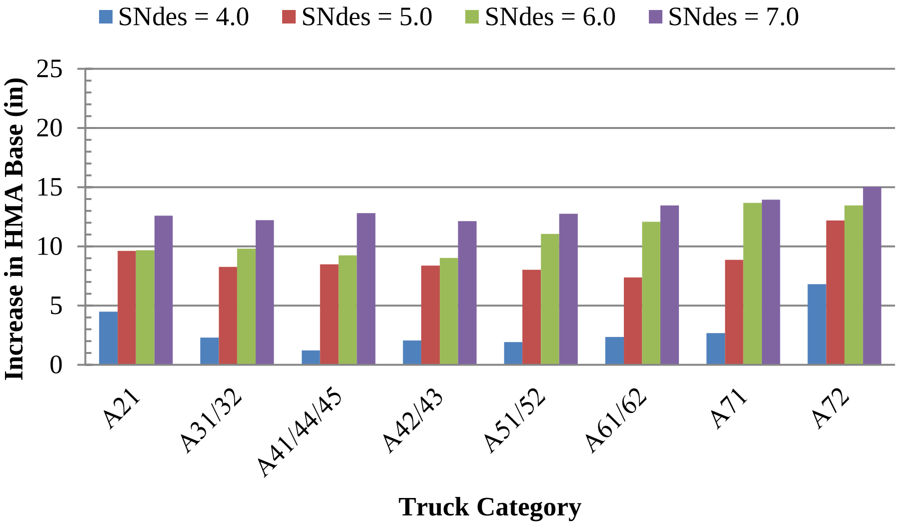


Figure B.42 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for top-down cracking based on DARWin-ME analysis for each truck category loaded to the maximum limit

Table B.35 Summary of models to determine required increase in HMA Base Course thickness based bottom-up cracking using the DARWin-ME analysis. Note that RD = relative damage

Truck Category	Required Increase in HMA Base Thickness (in)			
	$SN_{des} = 4.0$	$SN_{des} = 5.0$	$SN_{des} = 6.0$	$SN_{des} = 7.0$
A21	$= e^{\left(\frac{RD-2.0375}{-0.755}\right)}$	$= e^{\left(\frac{RD-4.2142}{-1.562}\right)}$	$= e^{\left(\frac{RD-13.022}{-4.827}\right)}$	$= e^{\left(\frac{RD-53.761}{-19.93}\right)}$
A31/32	$= e^{\left(\frac{RD-2.3568}{-0.958}\right)}$	$= e^{\left(\frac{RD-4.5456}{-1.848}\right)}$	$= e^{\left(\frac{RD-38.987}{-15.85}\right)}$	$= e^{\left(\frac{RD-56.004}{-22.77}\right)}$
A41/44/45	$= e^{\left(\frac{RD-1.7455}{-0.665}\right)}$	$= e^{\left(\frac{RD-3.8027}{-1.449}\right)}$	$= e^{\left(\frac{RD-7.8447}{-2.990}\right)}$	$= e^{\left(\frac{RD-47.137}{-17.97}\right)}$
A42/43	$= e^{\left(\frac{RD-1.7702}{-0.683}\right)}$	$= e^{\left(\frac{RD-3.8525}{-1.485}\right)}$	$= e^{\left(\frac{RD-8.1756}{-3.152}\right)}$	$= e^{\left(\frac{RD-47.626}{-18.36}\right)}$
A51/52	$= e^{\left(\frac{RD-1.9910}{-0.751}\right)}$	$= e^{\left(\frac{RD-4.4176}{-1.666}\right)}$	$= e^{\left(\frac{RD-18.929}{-7.138}\right)}$	$= e^{\left(\frac{RD-53.443}{-20.15}\right)}$
A61/62	$= \frac{\ln\frac{RD}{3.3146}}{-0.207}$	$= \frac{\ln\frac{RD}{6.1641}}{-0.207}$	$= \frac{\ln\frac{RD}{34.694}}{-0.207}$	$= \frac{\ln\frac{RD}{66.933}}{-0.207}$
A71	$= \frac{\ln\frac{RD}{4.3766}}{-0.214}$	$= \frac{\ln\frac{RD}{9.8544}}{-0.214}$	$= \frac{\ln\frac{RD}{70.532}}{-0.214}$	$= \frac{\ln\frac{RD}{88.575}}{-0.214}$
A72	$= \frac{\ln\frac{RD}{5.1082}}{-0.251}$	$= \frac{\ln\frac{RD}{18.395}}{-0.251}$	$= \frac{\ln\frac{RD}{86.940}}{-0.251}$	$= \frac{\ln\frac{RD}{104.02}}{-0.251}$

Table B.36 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for bottom-up cracking based on the DARWin-ME analysis for each truck category loaded to the maximum limit

	Required Increase in HMA Base Thickness (in)			
Truck Category	**SN_{des} = 4.0**	**SN_{des} = 5.0**	**SN_{des} = 6.0**	**SN_{des} = 7.0**
A21	3.95	7.83	12.07	14.12
A31/32	4.12	6.81	10.99	11.20
A41/44/45	3.07	6.92	9.87	13.03
A42/43	3.09	6.83	9.74	12.67
A51/52	3.74	7.78	12.33	13.50
A61/62	5.79	8.79	17.13	20.31
A71	6.90	10.69	19.89	20.95
A72	6.50	11.60	17.79	18.50

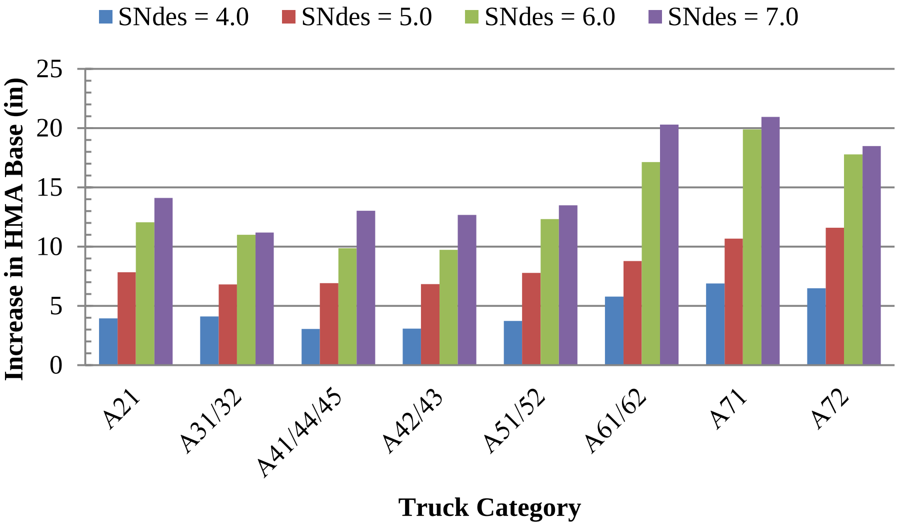


Figure B.43 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for bottom-up cracking based on DARWin-ME analysis for each truck category loaded to the maximum limit

Table B.37 Summary of models to determine required increase in HMA Base Course thickness based IRI using the DARWin-ME analysis. Note that RD = relative damage

Truck Category	Required Increase in HMA Base Thickness (in)			
	SN_{des} = 4.0	SN_{des} = 5.0	SN_{des} = 6.0	SN_{des} = 7.0
A21	$= e^{\left(\frac{RD-1.2985}{-0.212}\right)}$	$= e^{\left(\frac{RD-1.491}{-0.244}\right)}$	$= e^{\left(\frac{RD-1.7125}{-0.280}\right)}$	$= e^{\left(\frac{RD-1.7904}{-0.292}\right)}$
A31/32	$= \frac{\ln \frac{RD}{1.2591}}{-0.046}$	$= \frac{\ln \frac{RD}{1.4462}}{-0.046}$	$= \frac{\ln \frac{RD}{1.6564}}{-0.046}$	$= \frac{\ln \frac{RD}{1.7237}}{-0.046}$
A41/44/45	$= \frac{\ln \frac{RD}{1.1554}}{-0.048}$	$= \frac{\ln \frac{RD}{1.3595}}{-0.048}$	$= \frac{\ln \frac{RD}{1.5959}}{-0.048}$	$= \frac{\ln \frac{RD}{1.6802}}{-0.048}$
A42/43	$= \frac{\ln \frac{RD}{1.1999}}{-0.048}$	$= \frac{\ln \frac{RD}{1.4131}}{-0.048}$	$= \frac{\ln \frac{RD}{1.6549}}{-0.048}$	$= \frac{\ln \frac{RD}{1.7365}}{-0.048}$
A51/52	$= \frac{\ln \frac{RD}{1.2806}}{-0.051}$	$= \frac{\ln \frac{RD}{1.5124}}{-0.051}$	$= \frac{\ln \frac{RD}{1.7802}}{-0.051}$	$= \frac{\ln \frac{RD}{1.8723}}{-0.051}$
A61/62	$= \frac{\ln \frac{RD}{1.4271}}{-0.052}$	$= \frac{\ln \frac{RD}{1.6486}}{-0.052}$	$= \frac{\ln \frac{RD}{1.9188}}{-0.052}$	$= \frac{\ln \frac{RD}{2.0130}}{-0.052}$
A71	$= \frac{\ln \frac{RD}{1.5929}}{-0.053}$	$= \frac{\ln \frac{RD}{1.8115}}{-0.053}$	$= \frac{\ln \frac{RD}{2.0848}}{-0.053}$	$= \frac{\ln \frac{RD}{2.1685}}{-0.053}$
A72	$= \frac{\ln \frac{RD}{1.6245}}{-0.052}$	$= \frac{\ln \frac{RD}{1.7973}}{-0.052}$	$= \frac{\ln \frac{RD}{2.0603}}{-0.052}$	$= \frac{\ln \frac{RD}{2.1502}}{-0.052}$

Table B.38 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for IRI based on the DARWin-ME analysis for each truck category loaded to the maximum limit

Truck Category	Required Increase in HMA Base Thickness (in)			
	SN_{des} = 4.0	SN_{des} = 5.0	SN_{des} = 6.0	SN_{des} = 7.0
A21	4.09	7.48	12.74	14.98
A31/32	5.01	8.02	10.97	11.84
A41/44/45	3.01	6.40	9.74	10.81
A42/43	3.80	7.20	10.49	11.50
A51/52	4.85	8.11	11.31	11.66
A61/62	6.84	9.61	12.53	13.45
A71	8.78	11.21	13.86	14.60
A72	9.33	11.27	13.90	14.72

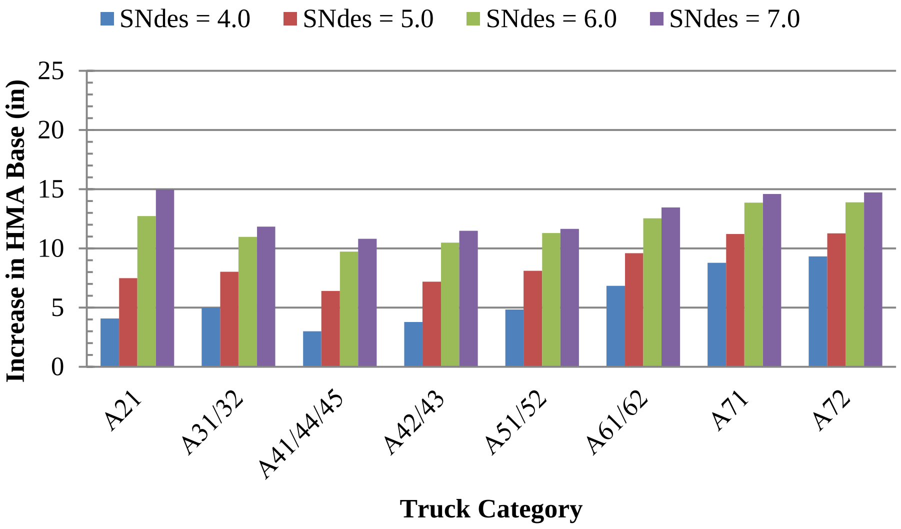


Figure B.44 Required increase in HMA Base Course thickness to achieve a relative damage factor of 1.0 for IRI based on DARWin-ME analysis for each truck category loaded to the maximum limit

The results indicate that the necessary increase in HMA Base Course thickness is fairly consistent for trucks having five or fewer axles to accommodate the increased loads. Beyond five axles, the necessary thickness increases for both the six axle and seven axle trucks. The trends follow those of the relative damage. As with the relative damage results, bottom-up cracking appears to the be controlling distress type as more thickness is required to address the damaged caused by overweight trucks compared to rutting, top-down cracking, and IRI.

B.4 Conclusion

Based on the results of this analysis of the effect of heavy trucks on pavement damage, it is evident that overweight trucks do result in increased damage to pavements compared to legal limit trucks. The relative damage is relatively consistent for trucks having two, three, four, or five axles, but increases for every additional axle greater than five. This increase in relative damage could, however, be due to the fact that the difference in the gross vehicle weight between the maximum limit and legal limit is greater than the difference for the trucks having five or fewer axles.

Based on the analysis using DARWin-ME, fatigue cracking was the most dominant distress for comparison of overweight trucks in that the relative damage with respect to bottom-up and top-down cracking was affected to a greater degree than rutting and IRI. The relative damage was also sensitive to pavement design for trucks having five or more axles. This sensitivity was evident as the relative damage for bottom-up and top-down cracking increased for thicker pavements as the number of axles and maximum load limit increased.

In summary, the results of this analysis indicate that increasing the frequency of overweight trucks without consideration in design will render the pavements structurally deficient.

This analysis was conducted using two different methods to determine the relative damage factors for trucks loaded to the maximum limit compared to the legal limit trucks. The first method was based on calculation of ESALs using the SCDOT Pavement Design Guidelines (2008) and the second was based on the distress prediction models using DARWin-ME. A comparison of these two analysis methods indicates that the ESAL prediction equation and/or ESAL load factors appears to overestimate the relative damage especially for larger trucks carrying heavier loads. This could potentially be due to the fact that this method is built on empirical relationships developed from the original AASHO Road Test and that truck configurations and loads have changed significantly in the decades since the original design guide was developed.

Appendix C Archetype Bridges

There are 9,271 bridges in the state of South Carolina (SC) (NBI, 2012). Due to the large number of bridges and diverse bridge structure types, it was not feasible to create a finite element model for each bridge. For modeling purpose, these bridges were grouped into Archetypes. Each Archetype bridge model was used to represent a group of bridges sharing common features and structural characteristics. To facilitate the development of Archetype models, bridge information such as the material, span length, count, location and etc. was obtained from the NBI database. Table C.1 to Table C.4 show the distribution of bridges in SC categorized by construction materials, structural systems, number of span, and maximum span length, respectively.

Table C.1: Distribution of SC bridges Based on Construction Materials

Description	Count	Percentage
1 Concrete	5,028	54.23%
2 Concrete continuous	533	5.75%
3 Steel	948	10.23%
4 Steel continuous	389	4.20%
5 Prestressed concrete	2,014	21.72%
6 Prestressed concrete continuous	261	2.82%
7 Wood or Timber	82	0.88%
8 Masonry	4	0.04%
9 Aluminum, Wrought Iron, or Cast Iron	10	0.11%
0 Other	2	0.02%
Total	9,271	

Table C.2: Distribution of SC bridges Based on Structure Systems

Description	Count	Percentage
01 Slab	4,297	46.35%
02 Stringer/Multi-beam or Girder	2,847	30.71%
03 Girder and Floorbeam System	17	0.18%
04 Tee Beam	850	9.17%
05 Box Beam or Girders - Multiple	30	0.32%
06 Box Beam or Girders - Single or Spread	9	0.10%
07 Frame (except frame culverts)	5	0.05%
08 Orthotropic	0	0.00%
09 Truss - Deck	0	0.00%
10 Truss - Thru	37	0.40%
11 Arch - Deck	48	0.52%
12 Arch - Thru	0	0.00%
13 Suspension	0	0.00%
14 Stayed Girder	1	0.01%
15 Movable - Lift	0	0.00%
16 Movable - Bascule	3	0.03%
17 Movable - Swing	5	0.05%
18 Tunnel	2	0.02%
19 Culvert (includes frame culverts)	1,086	11.71%
20 * Mixed types	0	0.00%
21 Segmental Box Girder	2	0.02%
22 Channel Beam	20	0.22%
00 Other	12	0.13%
Sum	9,271	

Table C.3: Distribution of SC bridges Based on Number of Spans

Description	Count	Percentage
1	1,625	17.53%
2	1,638	17.67%
3	2,549	27.49%
4	1,347	14.53%
5	825	8.90%
6	384	4.14%
7	212	2.29%
8	210	2.27%
9	76	0.82%
10	90	0.97%
11	49	0.53%
12	43	0.46%
13	35	0.38%
14	20	0.22%
15	25	0.27%
16	19	0.20%
17	17	0.18%
18	11	0.12%
Else	96	1.04%
Sum	9,271	

Table C.4: Distribution of SC bridges Based on Maximum Span

Description	Count	Percentage
<5m	3,696	39.87%
5m-10m	2,447	26.39%
10-15m	828	8.93%
15m-20m	960	10.35%
20m-25m	494	5.33%
25m-30m	270	2.91%
Else	576	6.21%
Sum	9,271	

As can be seen from Table C.1, reinforced concrete, prestressed concrete and steel are the three main construction materials which account for more than 98% of all bridges in SC. Table C.2 shows that slab and stringer/multi-beam or multi-girder are the two most commonly used structure systems for the superstructure. From Table C.3 and Table C.4, one can observe that approximately 77% of all the bridges are with four or less spans (Table C.3) and the maximum span length for most of the bridges are less than 20 meters (66 ft) (Table C.4). Considering all the above information and due to time constraint, four Archetype bridges were selected as surrogate bridge models and analyzed in this study (Table C.5).

Table C.5: Archetype Bridges

Archetype	Description
1	Reinforcement concrete slab bridge, span of 10m (33ft)
2	Prestressed concrete girder bridge, span less than 20m (66ft)
3	Prestressed concrete girder bridge, span 20m (66ft) to 35m (115ft)
4	Prestressed concrete girder bridge, span 35m (115ft) to 45m (148ft)

Detailed drawings for selected as-built bridges suitable for the four Archetype bridges were obtained from the SCDOT and used to develop the FE bridge models. Discussion of these drawings can be found in the following sections

A set of standard structural drawings for Archetype 1 bridge was obtained from the SCDOT website (SCDOT 2011). SCDOT provides standard drawings for slab bridges of span length of 30ft, 60ft, and up to 120ft. The structural drawings for the 30ft span superstructure with 34ft roadway were used to develop the finite element model for Archetype 1 bridge (Figure C.1 and Figure C.2).

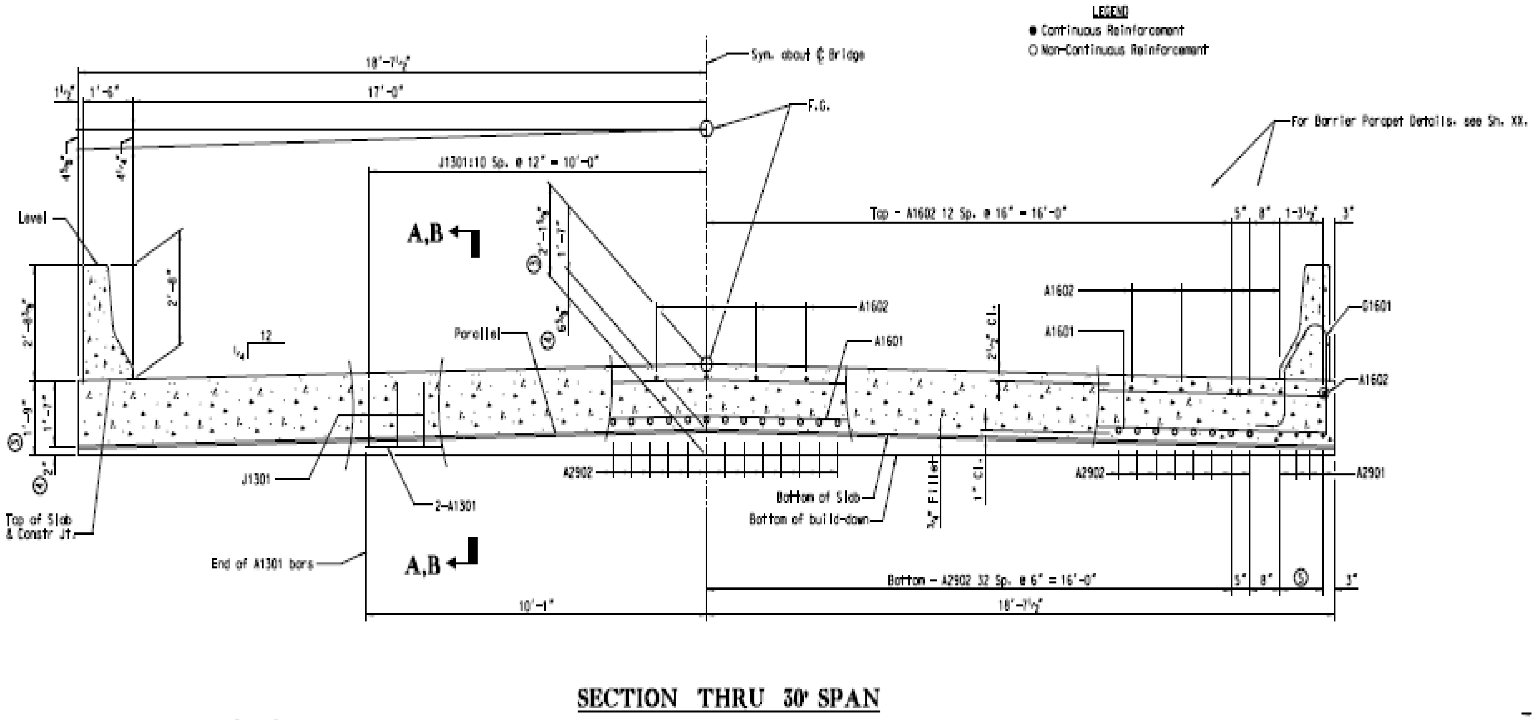


Figure C.1 Cross-Sectional View of Archetype 1 Bridge (SCDOT 2011)

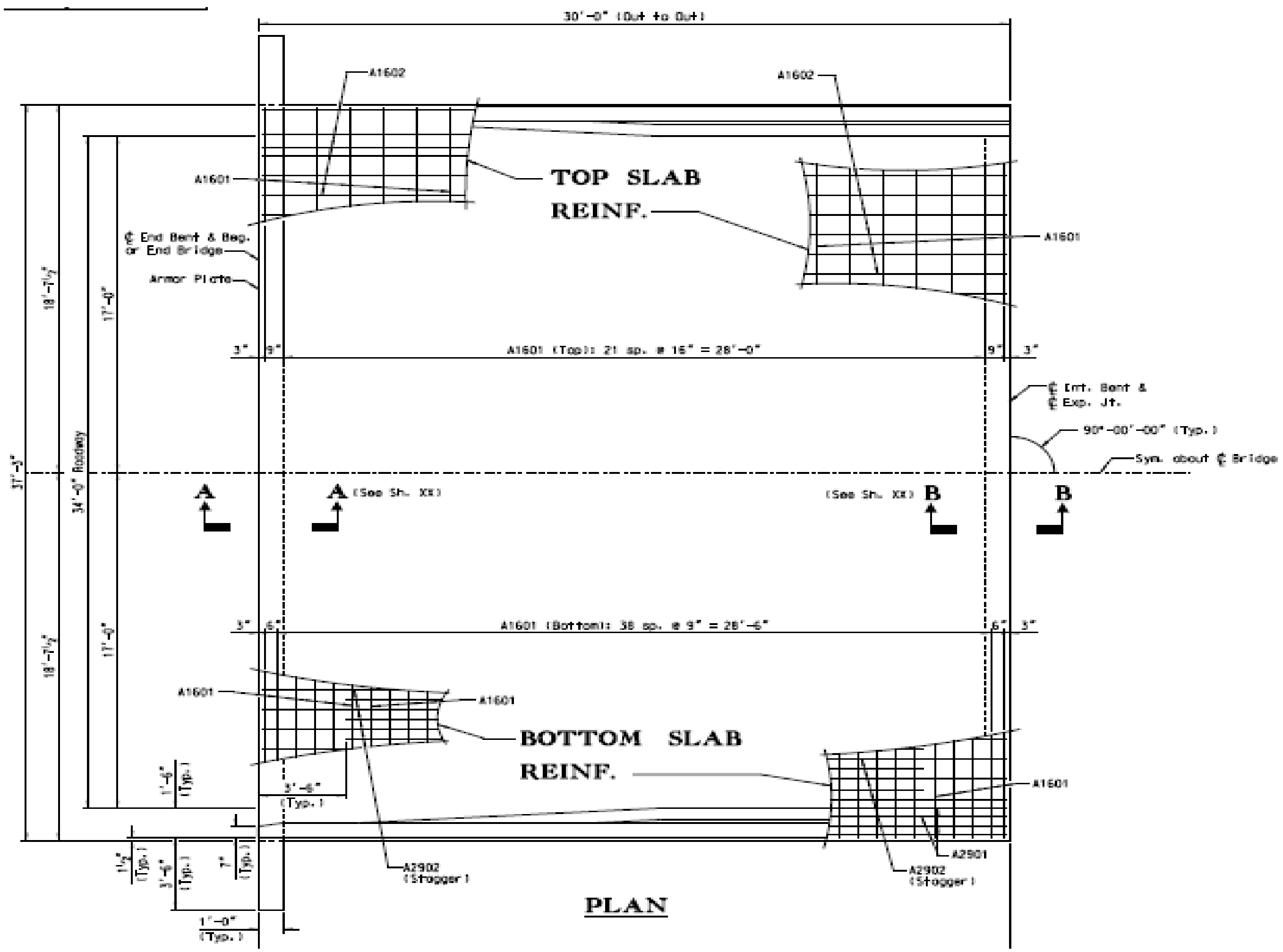


Figure C.2 Plan View of Archetype 1 Bridge (SCDOT 2011)

For Archetype 2 and Archetype 3 bridges, the structural drawings of a simply supported prestressed concrete dual overpass girder bridge located at the Marshland Road, Beaufort County were selected as the reference drawings. The as-built bridge drawings (SCDOT bridge reference number 7.581.3) were obtained from the SCDOT (Barrett, 2011). This bridge has three spans. On the southbound, the middle span length is 84 ft and 6 in. long and the side span length is 45 ft. On the northbound, the middle span length is 84 ft 6 in long and the side span length is 41 ft and 3 in. Bridge width is 40 feet 10 in. and roadway width is 38 ft. The structural configuration of the bridge side span on the southbound, which is the 45 feet span, was adopted to develop the finite element model for Archetype 2 bridge. The structural configuration of the bridge middle span on the southbound, which is the 84 ft 6 in span, was adopted for modeling Archetype 3 bridge. Figure C.3 to Figure C.5 show the details.

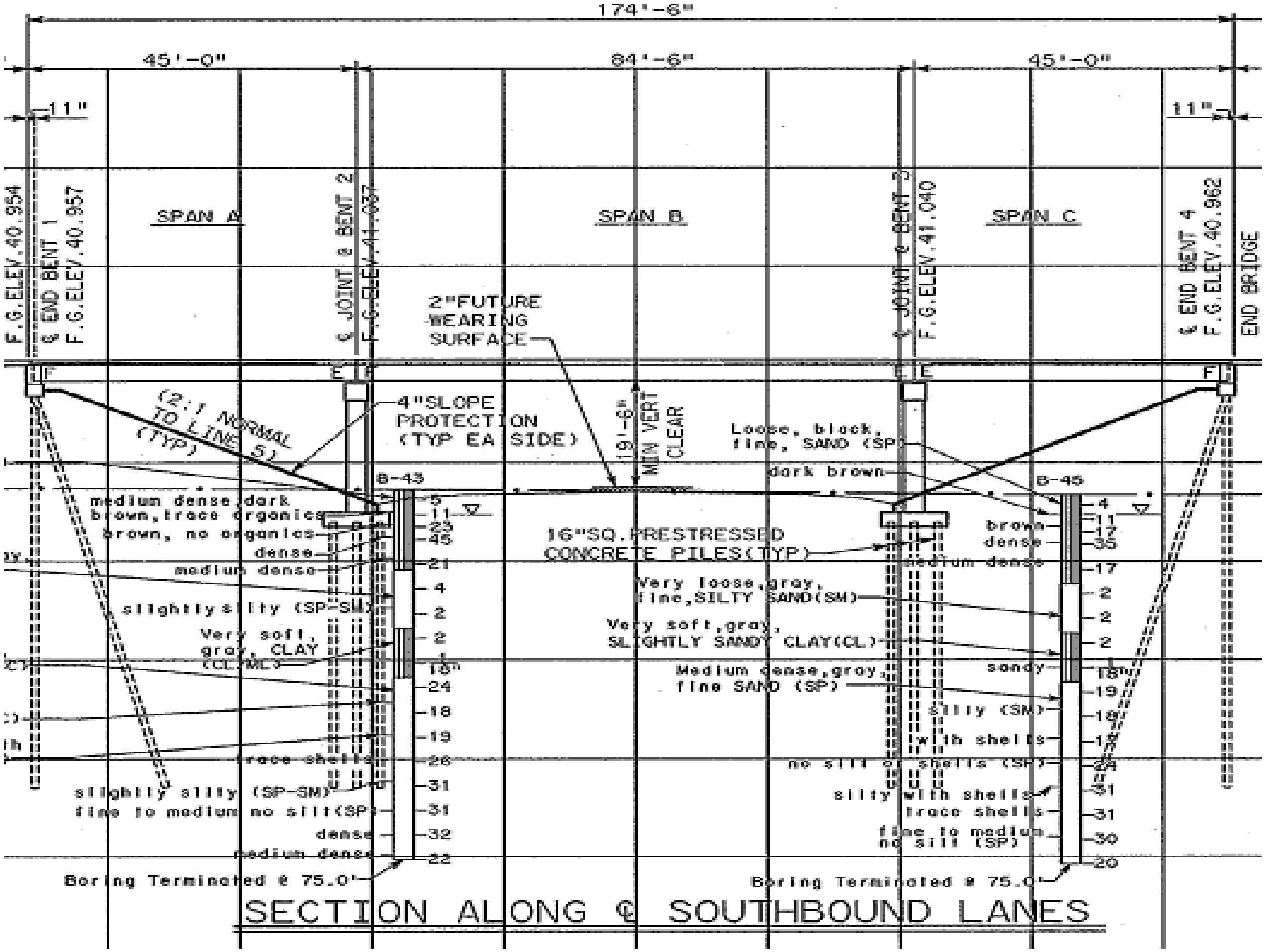


Figure C.3 Elevation View of Archetype 2 and 3 Bridges

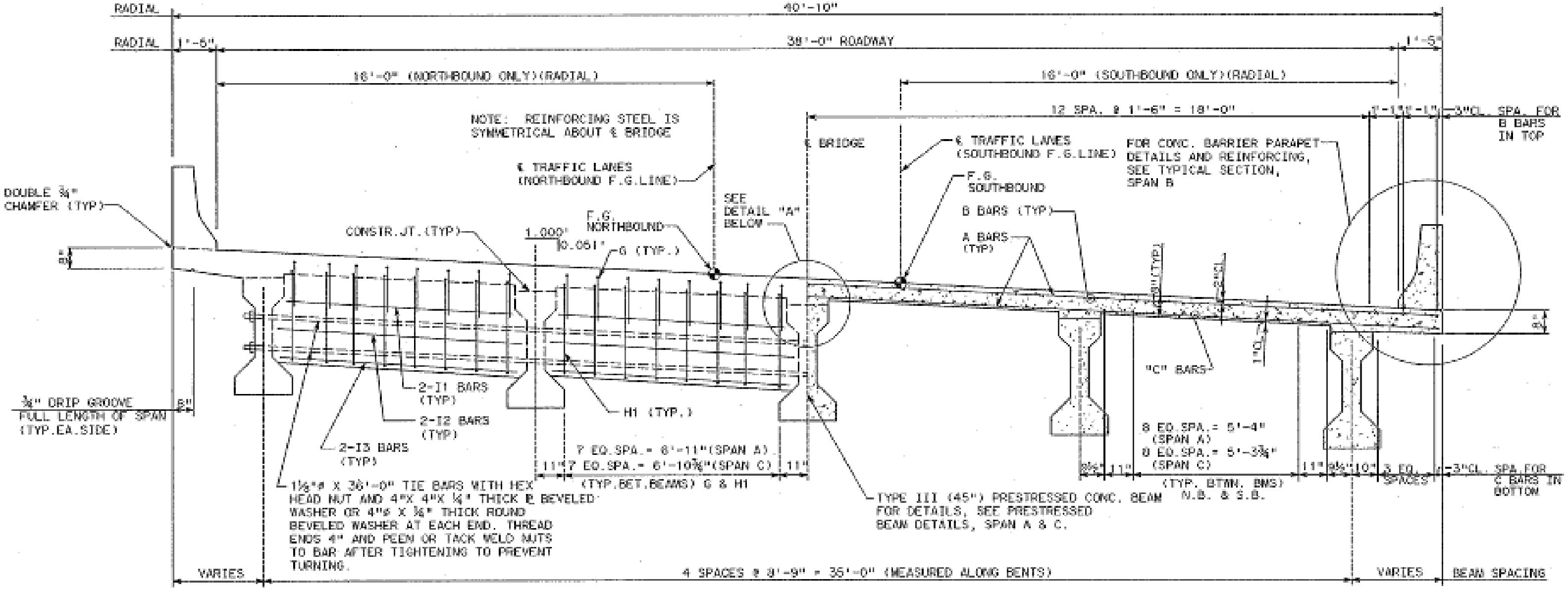


Figure C.4 Cross-Sectional View of Archetype 2 Bridge

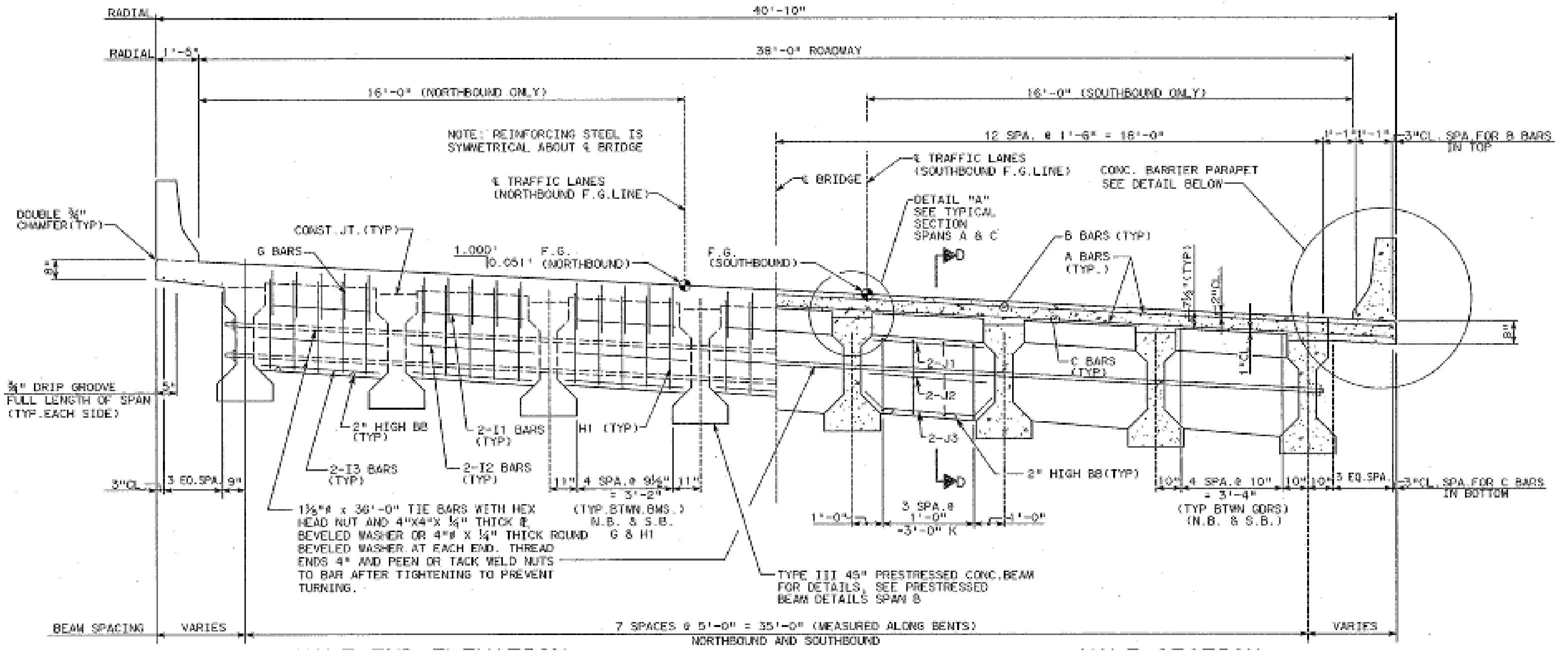


Figure C.5 Cross-Sectional View of Archetype 3 Bridge

For Archetype 4 bridge, the structural drawings (SCDOT bridge reference number 19.103B) of a simply supported prestressed concrete girder bridge over the Horne Creek, at Edgefield county were used to develop the FE model. These drawings were obtained from SCDOT (Barrett 2012). This bridge has two spans. Each span is 120 ft. The bridge width is 46 ft 10 in. and the roadway width is 44 ft (see Figure C.6 and Figure C.7).

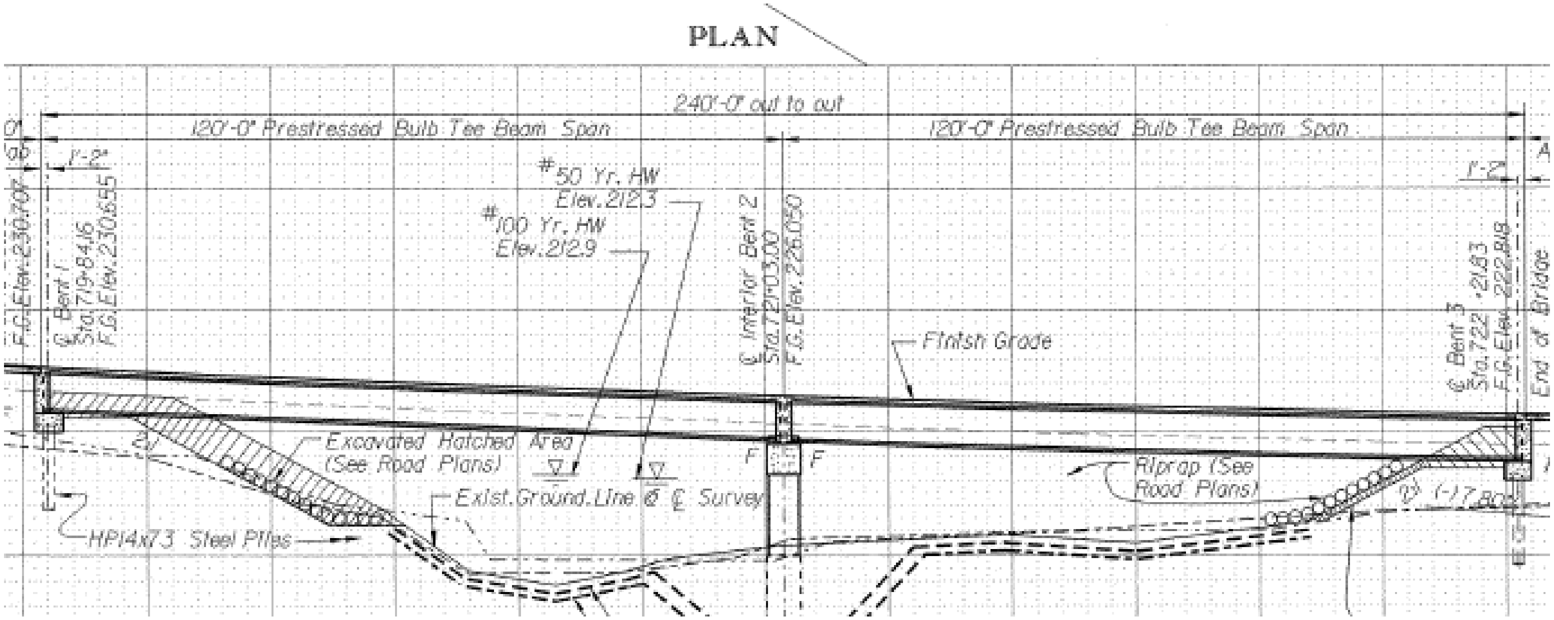


Figure C.6 Elevation View of Archetype 4 Bridge Drawing

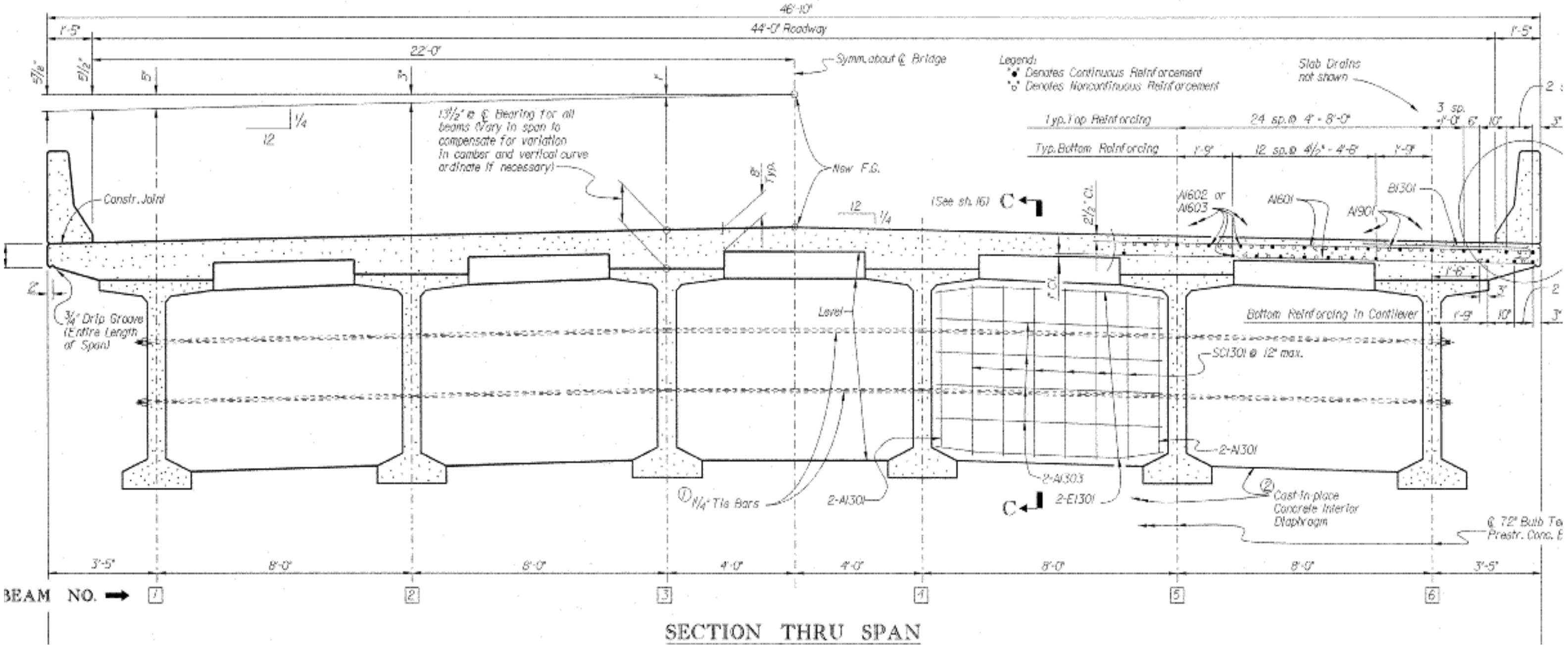


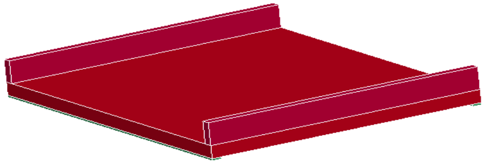
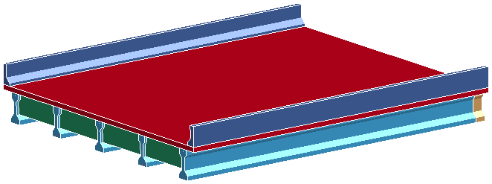
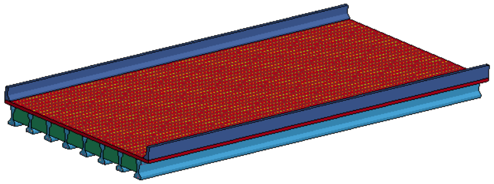
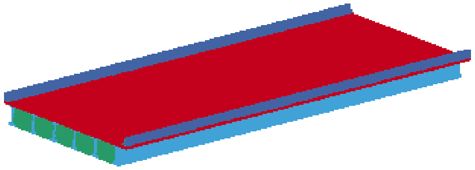
Figure C.7 Cross-Sectional View of Archetype 4 Bridge Drawing

Appendix D Archetype Bridge Element Models and Analysis Results

Finite Element Models

The structural behavior of Archetype bridges was analyzed using the LS-DYNA finite element (FE) analysis program. Due to high computational demand of the FE bridge models, the finite element analyses were performed using the Argonne National Laboratory supercomputer. Four Archetype bridges with truck models were first modeled using the LS-PREPOST software and then solved using the LS-DYNA program. The four Archetype bridges are shown in Table D.1. The details of the four Archetype bridge models are discussed in following sections.

Table D.1 Archetype Bridge Models Summary

Archetype	Description	Models
1	Reinforcement concrete slab bridge with span of 10m (33ft)	
2	Prestressed concrete beam bridge with span less than 20m (66ft)	
3	Prestressed concrete beam bridge with span 20m (66ft) to 35m (115ft)	
4	Prestressed concrete beam bridge with span 35m (115ft) to 45m (148ft)	

Finite Element Model Results

For each of the Archetype bridge models, individual truck model was utilized to apply loading to the bridge and the maximum stress range endured by prestressing strands or steel rebar at the mid span was recorded for each truck model. For Archetype 1 bridge, the stress ranges of all longitudinal reinforcement rebars at the mid span were recorded and the maximum value was selected as the stress range for the fatigue analysis. Similarly, for Archetype 2, 3 and 4 bridges, the stress ranges of the bottom prestressing strands at the mid span were recorded and the maximum values were selected as the stress range for the fatigue analysis. Figure D.1 shows a typical element strain time-history output from LS-DYNA analysis. In Figure D.1, the maximum strain and minimum strain during the analysis were recorded and the stress range was determined as the strain range multiplied by the elastic modulus of the strand.

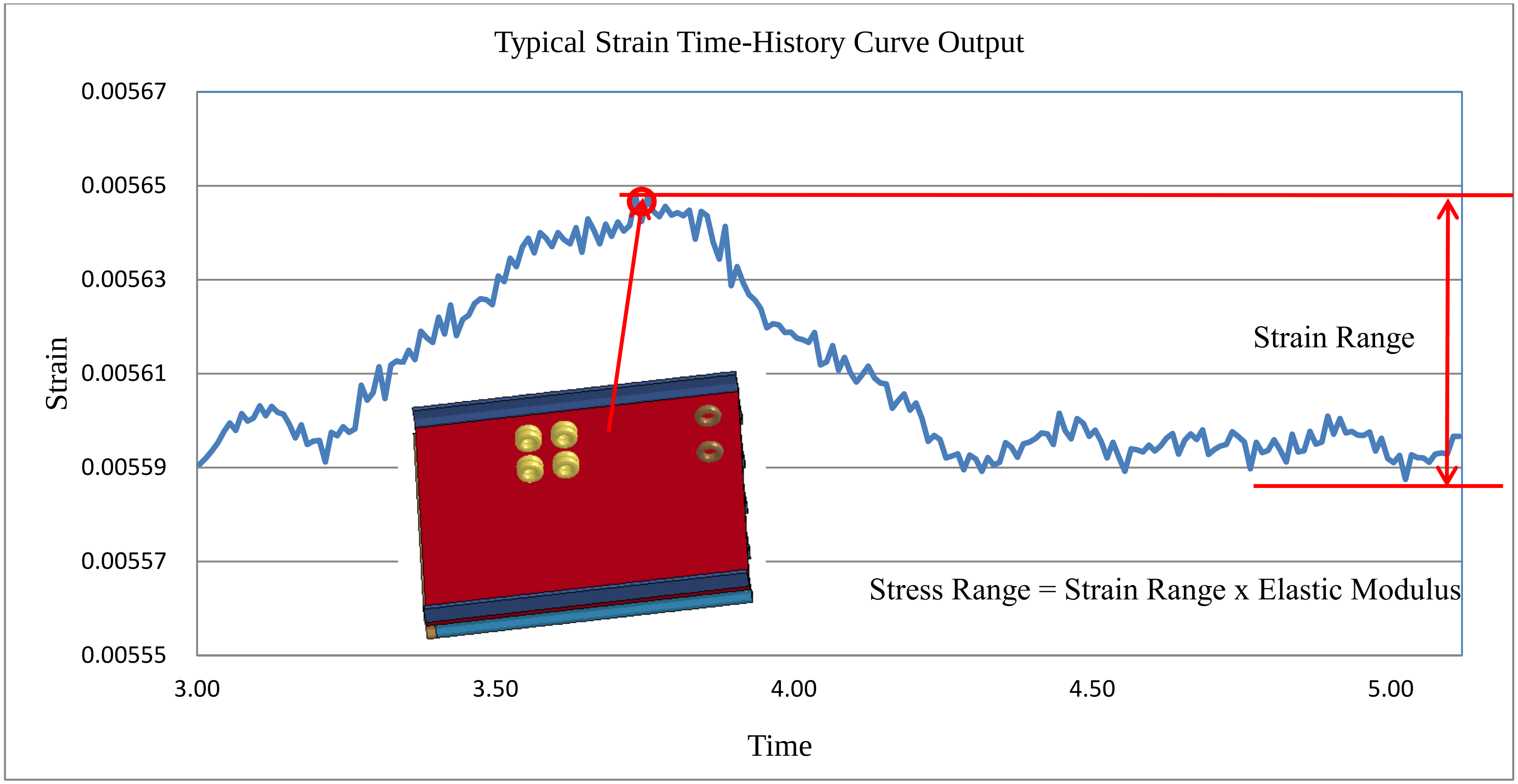


Figure D.1: Typical Strain Time-History Results Curve

Archetype 1 Bridge

Figure D.2 to Figure D.4 show the finite element model of the Archetype 1 bridge. The concrete slab was modeled using the fully integrated 3-D 8-node solid elements. For the concrete slab, the concrete strength was 4000 psi; elastic modulus was 3.605e+006 psi and Poisson's ratio was 0.3. The "Mat_Plastic_Kinematic" material model (elastic modulus = 2.900e+007 psi, tangent modulus 2.900e+006 psi, yield stress = 60ksi and Poisson's ratio = 0.3) was used in conjunction with the 1-D beam element to model the rebars (LS-DYNA, 2010). The actual rebar sizes were determined from the SCDOT drawings. In the finite element models, the 1-D beam elements (rebars) and the 3D 8-node solid elements (concrete) shared the same nodes (i.e. assumed not slip between the rebars and concrete).

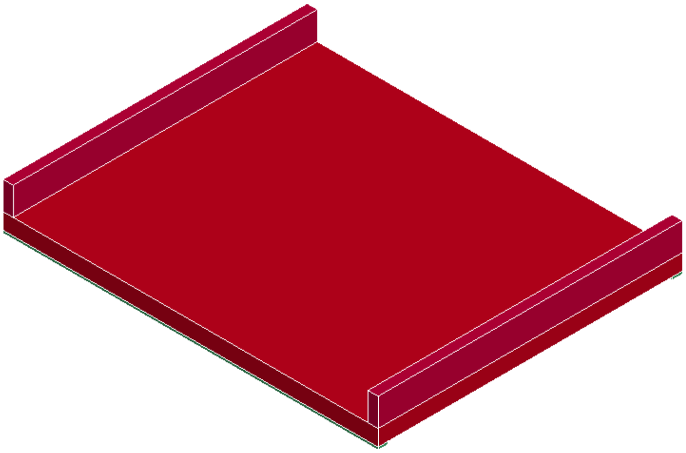


Figure D.2 3-D View of Archetype 1 Bridge Model

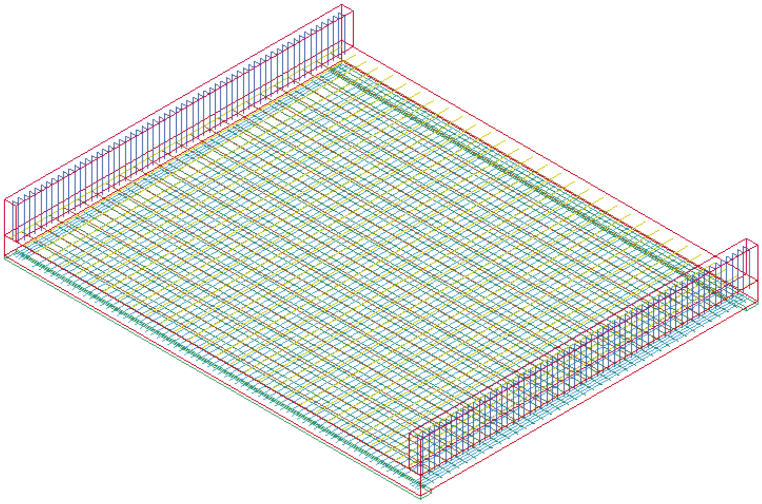


Figure D.3 3-D View of Rebars in the Archetype 1 Bridge Model

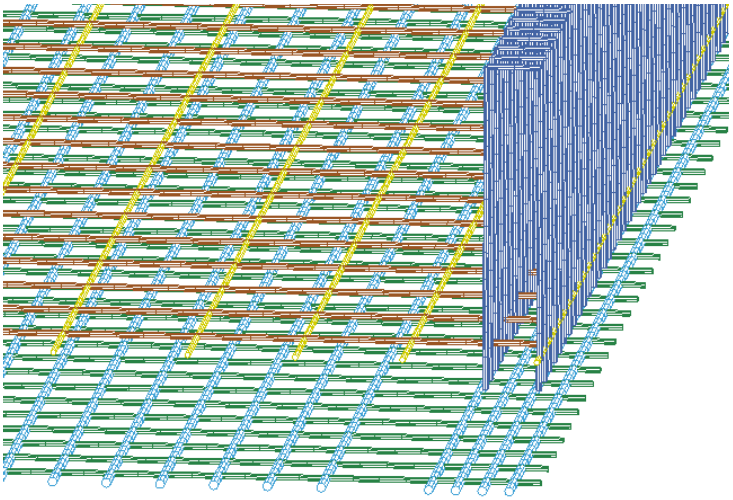


Figure D.4 Zoom-In View of Rebars in the Archetype 1 Bridge Model

Archetype Bridge 2, 3 and 4

Similar to the Archetype 1 bridge, the concrete slab for Archetypes 2, 3 and 4 bridges was modeled using the fully integrated 3-D 8-node solid elements. The actual bridge dimensions and girder sizes for each Archetype bridge were determined from their respective structural drawings. Both rebar and prestressing strands were modeled using the 1-D beam element. For the rebar element, the “Mat_Plastic_Kinematic” material model with the same material properties as the Archetype 1 bridge was utilized (LS-DYNA, 2010). For the prestressing strands, the “Mat_Cable_Discrete_Beam” material model (elastic modulus = 2.900e+007 psi) was utilized to introduce prestressing force into the strands elements (LS-DYNA, 2010).

Figure D.5 to Figure D.10 show the 3-D views and cross-sectional views of the Archetypes 2, 3 and 4 models.

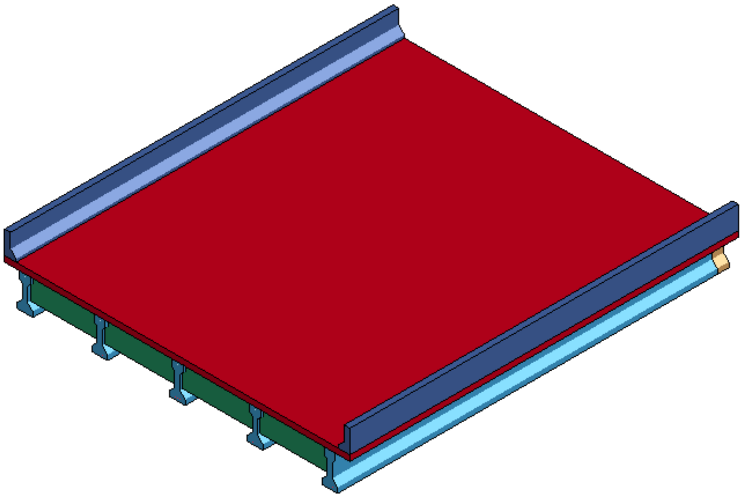


Figure D.5 3-D View of Archetype 2 Bridge Model

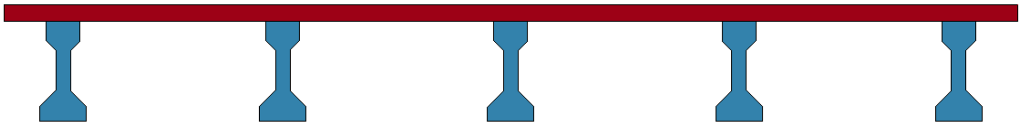


Figure D.6 Cross-Sectional View of Archetype 2 Bridge Model

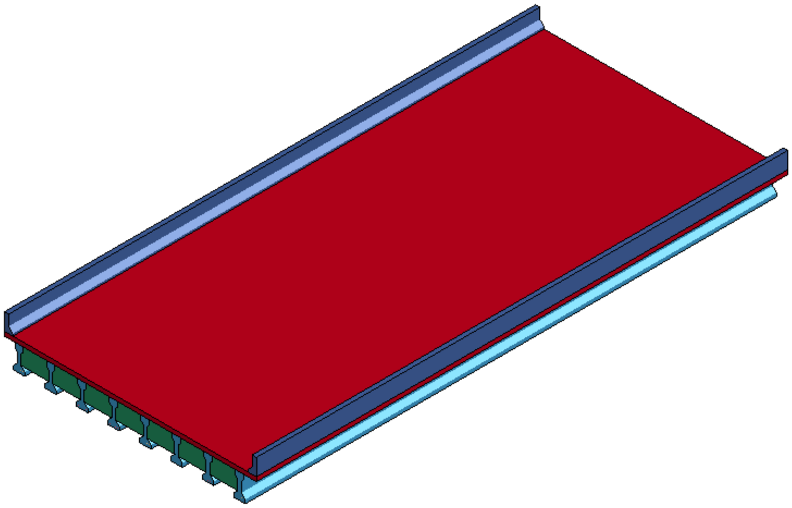


Figure D.7 3-D View of Archetype 3 Bridge Model

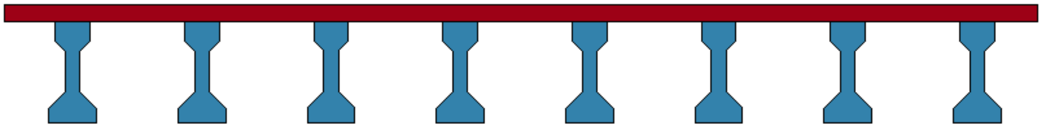


Figure D.8 Cross-Sectional View of Archetype 3 Bridge Model

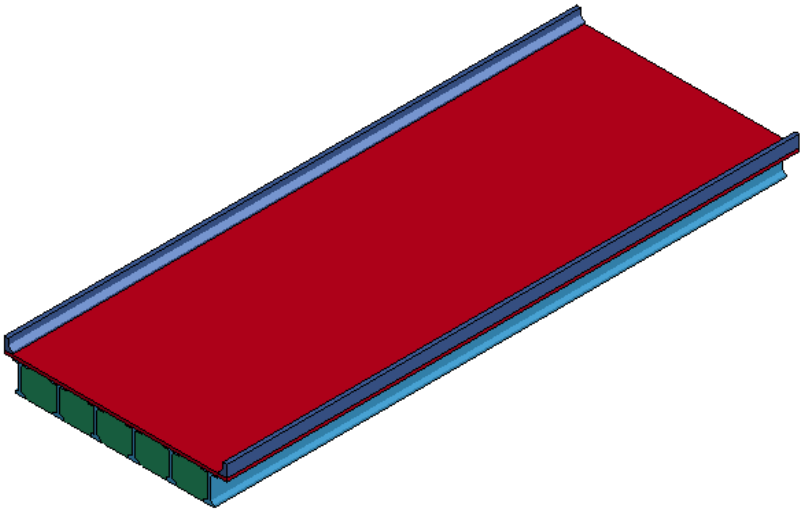


Figure D.9 3-D View of Archetype 4 Bridge Model

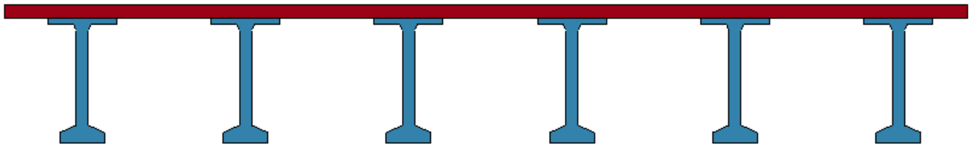


Figure D.10 Cross-Sectional View of Archetype 4 Bridge Model

Similar to the slab model, FE meshes for the girders of the Archetypes 2, 3 and 4 models were constructed using the 3-D solid and 1-D beam elements to represent the concrete and prestressing strands, respectively. Using a mesh with smaller elements generally produces better results but it also needs more computation time (LS-DYNA, 2010). In order to keep the mesh size and the computation time at a reasonable level, it was deemed not feasible to model each prestressing strand in the girder as a separate element. In this study, several prestressing strands were lumped together in girder meshes.

Figure D.11 (left) shows the actual strands arrangement at the mid span of the Archetype 2 girder. As can be seen, there were 2 top strands and 12 bottom strands in the girder (Barrett, 2011). The corresponding FE mesh for the girder is shown in Figure D.11 (right) where one line of strand elements in the top of the girder and five lines of strand elements in the bottom of the girder were utilized to represent the actual distribution of the strands. In the Archetype 2 FE model, one top strand element represented 2 prestressing strands while one bottom strand element represented 2.4 prestressing strands. Figure D.12 shows the cross-sectional and isometric views of the LS-DYNA model for the girders of Archetype 2 bridge.

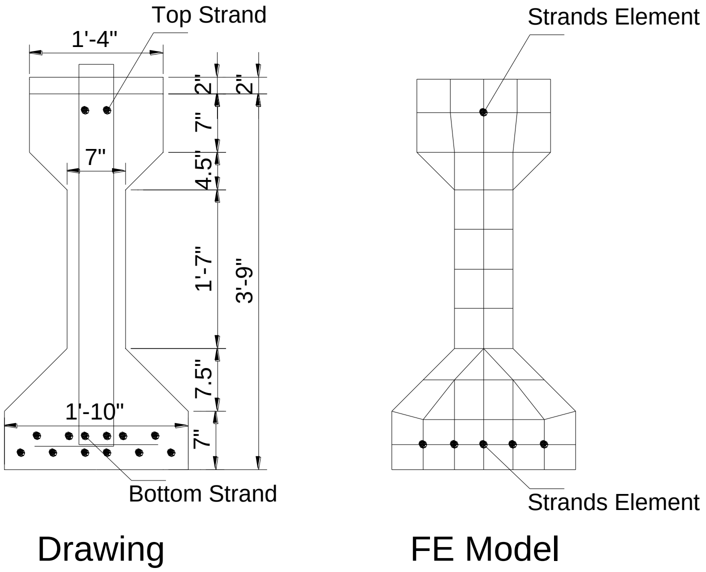


Figure D.11 Cross-Sectional View of Archetype 2 Bridge Girder at Mid-Span: (Left) Actual Strands Distribution and (Right) Strand Elements in FE Model

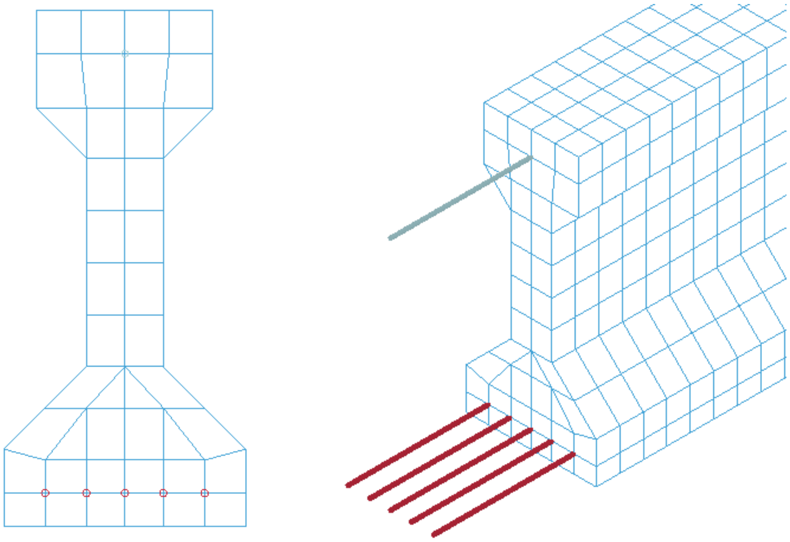


Figure D.12 Zoom-In View of Strands at the Mid-Span of The Girder of Archetype 2 Bridge

The same modeling technique was utilized in the FE models for the Archetypes 3 and 4 bridges.

Figure D.**13** (left) and (right) shows the actual strands arrangement and the FE model strand layout at the mid span of the Archetype 3 bridge girder, respectively. The actual girder had 2 top strands and 30 bottom strands while in the FE model, one and ten lines of strand elements were utilized in the top and bottom of the girder, respectively. Figure D.14 shows the cross-sectional and isometric views of strands in the LS-DYNA model for the girders of Archetype 3 Bridge.

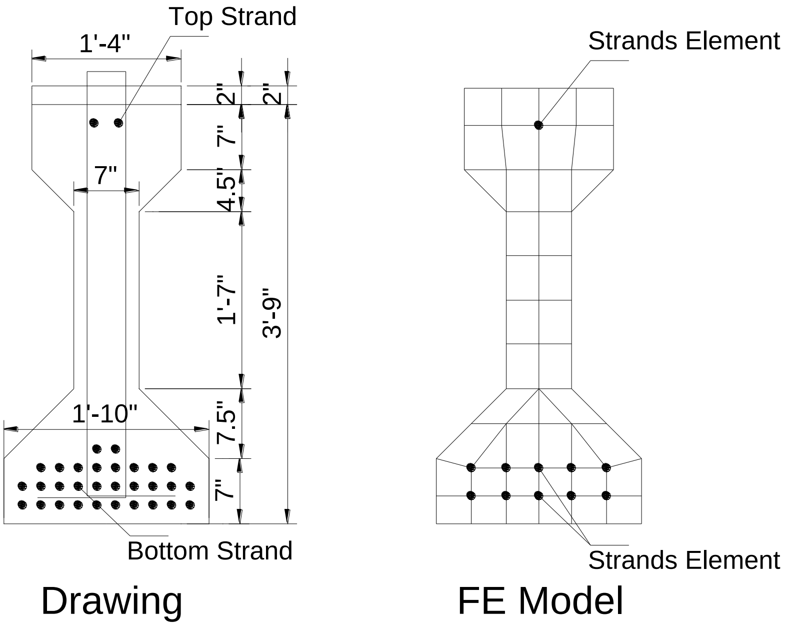


Figure D.13 Cross-Sectional View of Archetype 3 Bridge Girder at Mid-Span: (Left) Actual Strands Distribution and (Right) Strand Elements in FE Model

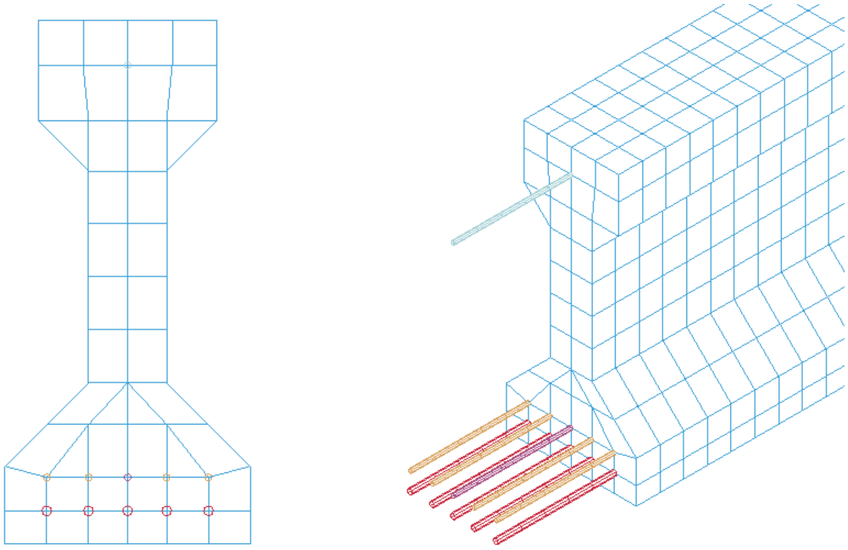


Figure D.14 Zoom-In View of Strands at the Mid-Span of The Girder of Archetype 3 Bridge

The cross-sectional views at the mid-span of Archetype 4 bridge girder were obtained from the actual structural drawings (Figure D.15). As can be seen, there are 4 top strands and 42 bottom strands. For modeling purpose, the four top strands were lumped into one line of strand element and the 42 bottom strands were modeled using 12 lines of strand elements. So for Archetype 4 bridge model, one top strand element represented four prestressing strands and one bottom strand element represented 1.6 to 6 prestressing strands, depending on its location. Figure D.16 shows the LS-DYNA FE mesh for the girder and strands for Archetype 4 bridge.

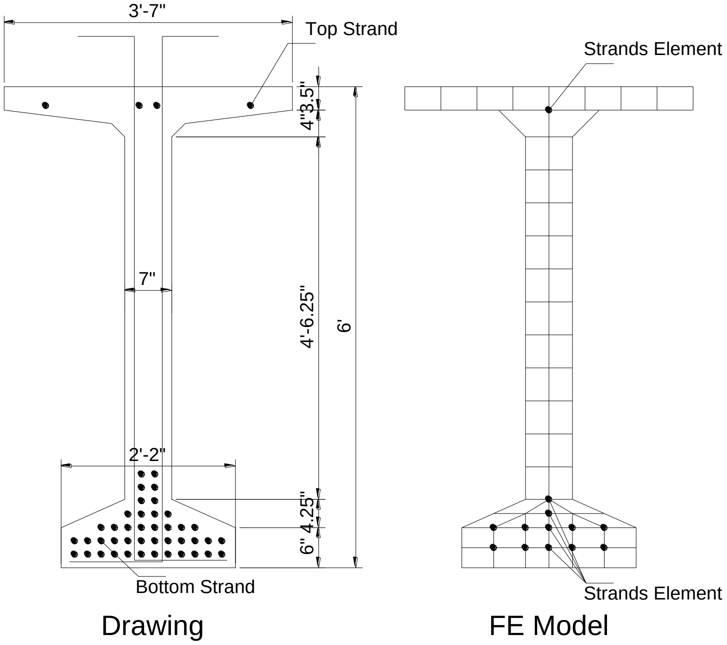


Figure D.15 Cross-Sectional View of Archetype 4 Bridge Girder at Mid-Span: (Left) Actual Strands Distribution and (Right) Strand Elements in FE Model

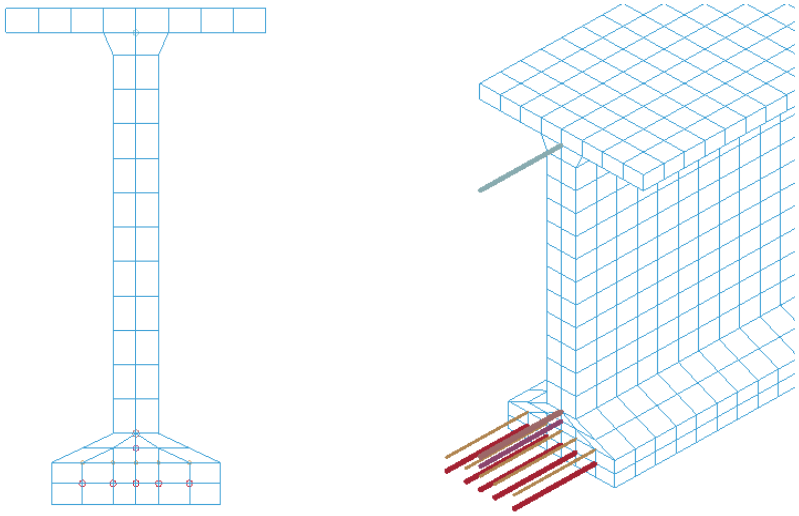


Figure D.16 Zoom-In View of Strands at the Mid-Span of The Girder of Archetype 4 Bridge

Finite element model analysis results are given in Table D.2 to Table D.5.

Table D.2 Stress Range of Archetype 1 Bridge

Axle Group	Truck Type	Stress Range of GVW1 (ksi)	Stress Range of GVW2 (ksi)	Stress Range of GVW3 (ksi)
2-Axle	A21	0.453	1.147	1.494
3-Axle	A31	N/A	N/A	1.338
	A32	0.633	0.755	N/A
4-Axle	A41	0.667	0.688	1.665
	A42	N/A	N/A	2.015
	A43	0.710	0.818	N/A
	A44	N/A	N/A	1.572
	A45	0.518	0.755	N/A
5-Axle	A51	N/A	N/A	2.099
	A52	0.744	0.913	N/A
6-Axle	A61	N/A	N/A	1.575
	A62	0.841	1.122	N/A
7-Axle	A71	N/A	N/A	2.561
	A72	0.736	1.220	N/A
8-Axle	A81	N/A	N/A	2.287
	A82	0.992	1.229	N/A

Table D.3 Stress Range of Archetype 2 Bridge

Axle Group	Truck Type	Stress Range of GVW1 (ksi)	Stress Range of GVW2 (ksi)	Stress Range of GVW3 (ksi)
2-Axle	A21	0.718	1.044	1.835
3-Axle	A31	N/A	N/A	2.082
	A32	1.163	1.650	N/A
4-Axle	A41	1.143	1.462	2.327
	A42	N/A	N/A	2.824
	A43	1.098	1.516	N/A
	A44	N/A	N/A	3.235
	A45	1.123	1.466	N/A
5-Axle	A51	N/A	N/A	3.206
	A52	1.098	1.579	N/A
6-Axle	A61	N/A	N/A	2.697
	A62	1.314	2.156	N/A
7-Axle	A71	N/A	N/A	4.244
	A72	1.439	2.762	N/A
8-Axle	A81	N/A	N/A	3.206
	A82	1.383	2.636	N/A

Table D.4 Stress Range of Archetype 3 Bridge

Axle Group	Truck Type	Stress Range of GVW1 (ksi)	Stress Range of GVW2 (ksi)	Stress Range of GVW3 (ksi)
2-Axle	A21	1.051	1.379	1.715
3-Axle	A31	N/A	N/A	2.129
	A32	1.421	1.939	N/A
4-Axle	A41	1.356	1.811	2.613
	A42	N/A	N/A	3.241
	A43	1.577	2.116	N/A
	A44	N/A	N/A	2.671
	A45	1.291	1.661	N/A
5-Axle	A51	N/A	N/A	3.136
	A52	1.540	1.968	N/A
6-Axle	A61	N/A	N/A	3.534
	A62	1.472	2.204	N/A
7-Axle	A71	N/A	N/A	5.802
	A72	1.607	2.684	N/A
8-Axle	A81	N/A	N/A	3.723
	A82	1.530	2.934	N/A

Table D.5 Stress Range of Archetype 4 Bridge

Axle Group	Truck Type	Stress Range of GVW1 (ksi)	Stress Range of GVW2 (ksi)	Stress Range of GVW3 (ksi)
2-Axle	A21	1.063	1.571	1.808
3-Axle	A31	N/A	N/A	2.378
	A32	1.493	1.904	N/A
4-Axle	A41	1.394	1.816	2.589
	A42	N/A	N/A	3.346
	A43	1.586	2.154	N/A
	A44	N/A	N/A	2.776
	A45	1.354	1.864	N/A
5-Axle	A51	N/A	N/A	2.842
	A52	1.733	2.282	N/A
6-Axle	A61	N/A	N/A	3.918
	A62	1.790	2.773	N/A
7-Axle	A71	N/A	N/A	5.614
	A72	1.998	3.143	N/A
8-Axle	A81	N/A	N/A	4.516
	A82	1.848	3.067	N/A

Appendix E Archetype Bridge Fatigue Life

Bridge Fatigue Life

The bridge fatigue life is defined as the number of allowable stress cycles under a given stress range, referred herein as the N value. The N value can be computed using Equation (E.1) and Equation (E.2) for concrete slab (Archetype 1) and prestresstred concrete (Archetypes 2 to 4) bridges, respectively. It should be noted that Equations (E.1) and (E.2) are for the strength-level fatigue limit state (i.e. fatigue fracture of rebars or prestressing strands). The endurance limit for both the rebars and the prestressing strands is 20 ksi. Based on the FE analysis results (see Table D.2 to Table D.5), it can be concluded that all stress ranges are less than the endurance limit, which indicates that the bridges have unlimited number of stress cycles (or infinite fatigue life). Per AASTHO design specification (AASHTO, 2007), bridges are designed with a limited service life of 75 years. So while the strength-level limit state Equations (E.1) and (E.2) suggest that fatigue fracture of rebars or prestressing strands will not occur over the design lifetime (i.e. 75 years), it is not realistic to expect the bridges to have infinite service life under repetitive fatigue loading, in particular with heavy overweight trucks. A recent study (Bathias and Paris, 2005) shows that under extreme large number of stress cycles (in Giga-Cycle range), the N value (i.e. fatigue life) will further decrease. Based on the study by Bathias and Paris (2005) and the target design life of 75 years, a service-level fatigue limit state is defined to estimate the bridge fatigue damage. This service-level fatigue limit state is derived from the strength-level fatigue limit state curve and calibrated using the target design bridge life (i.e. 75 years).

The allowable bridge fatigue cycles (N values) for all truck models (different axle configurations and gross vehicle weights) and for all four Archetype bridges were calculated using the above equations.

Service-Level Fatigue Limit State for Archetype 1 Bridge

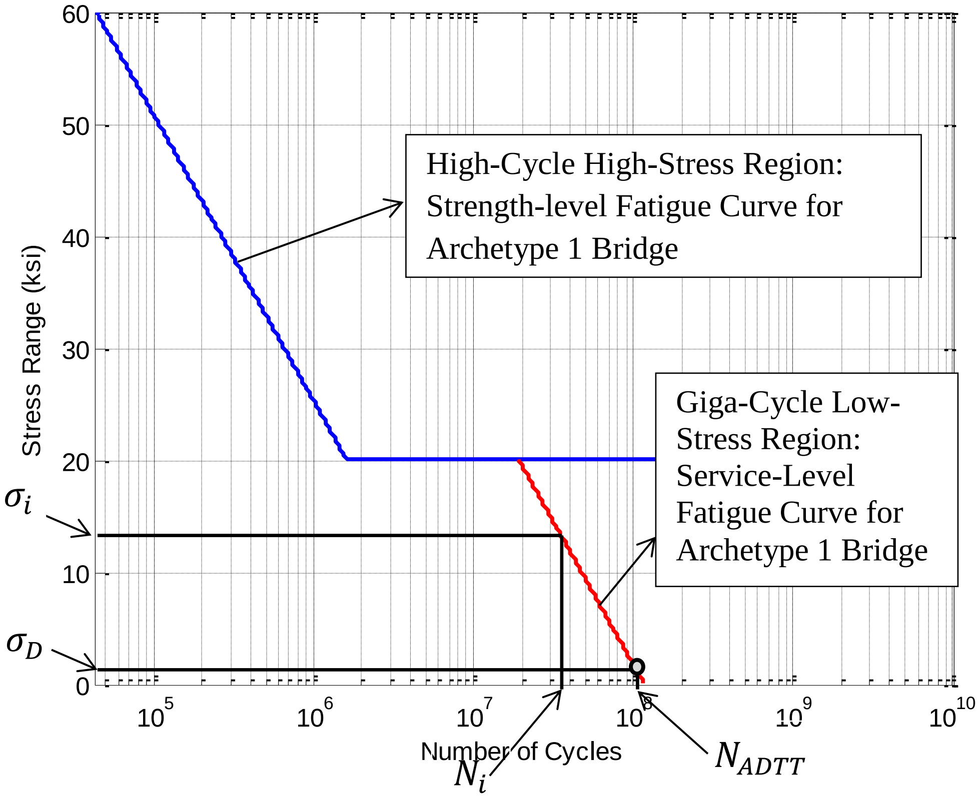


Figure E.1 Strength-Level and Service-Level Fatigue Curves for Archetype 1 Bridge

Figure E.1 shows both the strength-level fatigue limit state curve and service-level fatigue limit state curve for Archetype 1 bridge. In this figure, the vertical axis represents the stress ranges and the horizontal axis represents the N number, which is the number of cycles the bridge can sustain for a stress range. In this study, when the stress range was more than 20ksi (i.e. in the high-cycle high-stress region), the strength-level fatigue limit state (Equation (E.2)) is used to calculate the N number. In the Giga-Cycle region where stress range is less than 20ksi, a service-level fatigue limit state was derived and was used to calculate the N number.

The AASTHO fatigue design truck and target bridge life (i.e. 75 years) were used to derive the service-level fatigue limit state equation. Table E.1 shows the stress ranges caused by the AASHTO fatigue design truck (σ_D) on the four Archetype bridges.

Table E.1 LRFD Fatigue Design Truck Stress Range

	Archetype 1	Archetype 2	Archetype 3	Archetype 4
LRFD Fatigue Design Truck Stress Range (ksi)	0.708	1.086	1.772	1.834

The corresponding N number (N_{ADTT}) for the stress ranges caused by the fatigue design truck (σ_D) can be calculated using the following equation:

$$N_{ADTT} = 4000 \text{ x } 365 \text{ x } 75 \tag{E.1}$$

where 4000 is the design average daily truck traffic (ADTT), which was determined from the AASHTO LRFD specification (AASHTO, 2007) assuming the maximum average daily traffic (ADT) of 20,000 per lane and rural interstate truck traffic fraction of 0.2 (AASHTO, 2007). The design ADTT computed using Equation (E.1) is given in Table E.2.

Table E.2 LRFD Fatigue Design Truck Allowable Number of Passing

ADTT	Days	Years	LRFD Fatigue Design Truck Allowable Number of Passing
4000	365	75	1.10E+08

The stress ranges caused by the AASHTO fatigue truck and the design ADTT yield the Giga-cycle region (see Figure E.1). According to Bathias and Paris (2005), the slope of the fatigue curve corresponds to the low-stress and extreme high-cycle region is similar to that of the high-stress region (i.e. Equation (E.2)).

$$\text{Log N} = 4.419 - 0.0392 \times \sigma - 0.013 \times \sigma_{\text{min}} + 0.0079 \times \text{G} + 7.8059 \times \text{D}_{\text{nom}} - 8.4155 \times \text{D}_{\text{nom}}{}^{2} + 2.799 \times \text{D}_{\text{nom}}{}^{3} \tag{E.2}$$

where

N: fatigue life in number of stress cycles for fatigue design truck, from Table E.2

σ_{min}: minimum stress during stress cycle, (1.34ksi under self-weight)

G: rebar yield strength 60 ksi

D_{nom}: nominal rebar diameter 1.128 inch

σ: fatigue design truck stress range from Table E.1

Substitute (N_{ADTT}) and the stress range of the design fatigue truck for Archetype 1 bridge into Equation (G.3) while keeping the slope of Equation E.3 constant (i.e. 0.0392) yields the following equation for Archetype 1 bridge:

$$\text{Log N} = 8.0672 - 0.0392 \times \sigma \tag{E.3}$$

Equation (E.3), service-level fatigue limit state equation, was used to determine fatigue life and fatigue damage cost of Archetype 1 bridge.

The combined fatigue limit state curve (i.e. including the strength-level fatigue limit state and service-level fatigue limit state) is shown in Figure E.1, where σ_D represents the fatigue design truck stress range and σ_i represents the stress range caused by an arbitrary truck model. N_{ADTT} is the number of expected cycles under the fatigue design truck while N_i is the allowable number of cycles under the stress range caused by an arbitrary truck (with a given axle configuration and weight).

Service-Level Fatigue Limit State for Archetype 2, 3 and 4 Bridges

The same concept and procedure used to determine the service-level fatigue limit state equation for Archetype 1 bridge were adopted and applied to Archetype 2, 3 and 4 bridges. The strength-level fatigue limit state Equation (E.4) for prestressing strands:

$$\text{Log N} = 11 - 3.5 \times \text{Log}\,\sigma \tag{E.4}$$

where

N: fatigue life in number of stress cycles for fatigue design truck, from Table E.2.

σ: fatigue design truck stress range from Table E.1

Substitute N_{ADTT} and the stress ranges caused by the AASHTO fatigue design truck on Archetype 2, 3 and 4 bridges into Equation (E.4) while maintaining the slope of Equation (E.4) yields the following set of three service-level fatigue limit state equations for Archetype 2, 3 and 4 bridges, respectively:

Archetype 2 Bridge:

$$\text{Log N} = 8.1648 - 3.5 \times \text{Log}\sigma \tag{E.6}$$

Archetype 3 Bridge:

$$\text{Log N} = 8.909 - 3.5 \times \text{Log}\sigma \tag{E.7}$$

Archetype 4 Bridge:

$$\text{Log N} = 8.9613 - 3.5 \times \text{Log}\sigma \tag{E.8}$$

The strength-level and service-level fatigue limit state equations for all Archetype bridges are shown in Figure E.2.

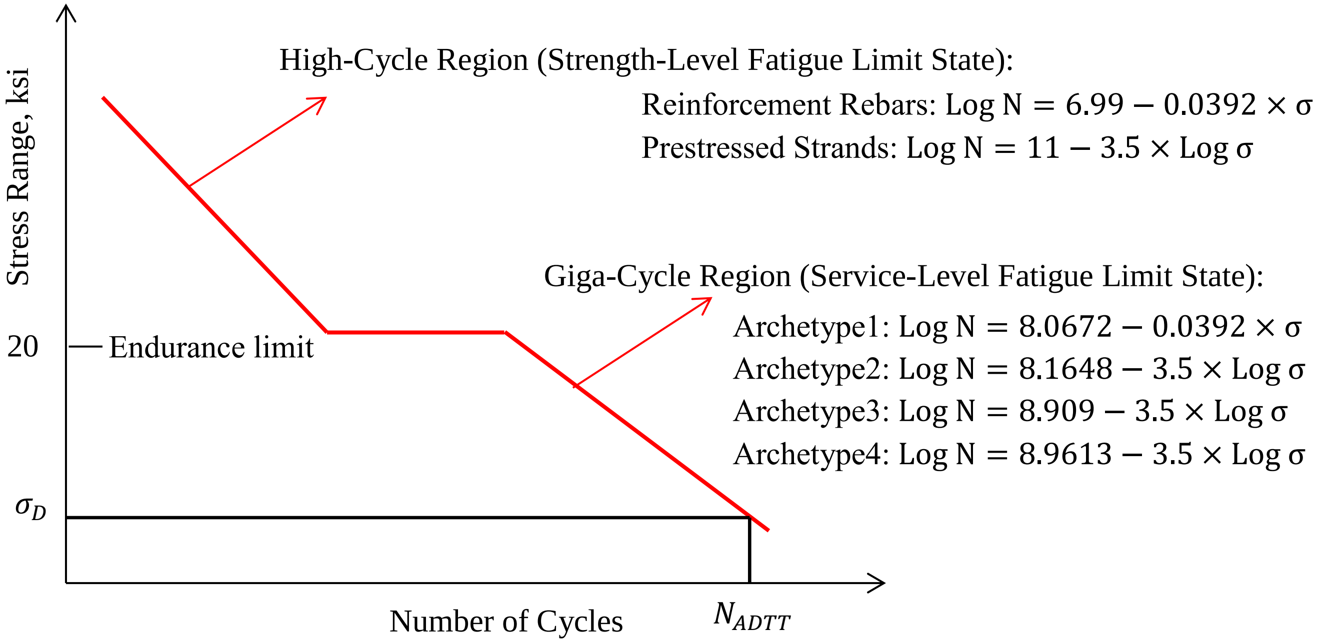


Figure E.2 Strength-Level and Service-Level Fatigue Curves and Equations

The allowable bridge fatigue cycles (N values) for all truck models (different axle configurations and gross vehicle weights) and for all four Archetype bridges were calculated using the above equations.

Table E.3 Bridge Fatigue Life of Archetype 1 Bridge

Axle Group	Truck Type	Allowable Number of Passing for GVW1	Allowable Number of Passing for GVW2	Allowable Number of Passing for GVW3
2-Axle	A21	1.12E+08	1.05E+08	1.02E+08
3-Axle	A31	N/A	N/A	1.03E+08
	A32	1.10E+08	1.09E+08	N/A
4-Axle	A41	1.10E+08	1.10E+08	1.00E+08
	A42	N/A	N/A	9.73E+07
	A43	1.09E+08	1.08E+08	N/A
	A44	N/A	N/A	1.01E+08
	A45	1.11E+08	1.09E+08	N/A
5-Axle	A51	N/A	N/A	9.66E+07
	A52	1.09E+08	1.07E+08	N/A
6-Axle	A61	N/A	N/A	1.01E+08
	A62	1.08E+08	1.05E+08	N/A
7-Axle	A71	N/A	N/A	9.26E+07
	A72	1.09E+08	1.05E+08	N/A
8-Axle	A81	N/A	N/A	9.50E+07
	A82	1.07E+08	1.04E+08	N/A

Table E.4 Bridge Fatigue Life of Archetype 2 Bridge

Axle Group	Truck Type	Allowable Number of Passing for GVW1	Allowable Number of Passing for GVW2	Allowable Number of Passing for GVW3
2-Axle	A21	4.66E+08	1.26E+08	1.75E+07
3-Axle	A31	N/A	N/A	1.12E+07
	A32	8.62E+07	2.53E+07	N/A
4-Axle	A41	9.15E+07	3.87E+07	7.60E+06
	A42	N/A	N/A	3.86E+06
	A43	1.05E+08	3.41E+07	N/A
	A44	N/A	N/A	2.40E+06
	A45	9.74E+07	3.83E+07	N/A
5-Axle	A51	N/A	N/A	2.48E+06
	A52	1.05E+08	2.95E+07	N/A
6-Axle	A61	N/A	N/A	4.54E+06
	A62	5.62E+07	9.93E+06	N/A
7-Axle	A71	N/A	N/A	9.28E+05
	A72	4.09E+07	4.17E+06	N/A
8-Axle	A81	N/A	N/A	2.48E+06
	A82	4.70E+07	4.91E+06	N/A

Table E.5 Bridge Fatigue Life of Archetype 3 Bridge

Axle Group	Truck Type	Allowable Number of Passing for GVW1	Allowable Number of Passing for GVW2	Allowable Number of Passing for GVW3
2-Axle	A21	6.81E+08	2.63E+08	1.23E+08
3-Axle	A31	N/A	N/A	5.76E+07
	A32	2.37E+08	7.99E+07	N/A
4-Axle	A41	2.79E+08	1.01E+08	2.81E+07
	A42	N/A	N/A	1.32E+07
	A43	1.65E+08	5.88E+07	N/A
	A44	N/A	N/A	2.60E+07
	A45	3.32E+08	1.37E+08	N/A
5-Axle	A51	N/A	N/A	1.48E+07
	A52	1.79E+08	7.58E+07	N/A
6-Axle	A61	N/A	N/A	9.77E+06
	A62	2.10E+08	5.10E+07	N/A
7-Axle	A71	N/A	N/A	1.72E+06
	A72	1.54E+08	2.56E+07	N/A
8-Axle	A81	N/A	N/A	8.15E+06
	A82	1.83E+08	1.87E+07	N/A

Table E.6 Bridge Fatigue Life of Archetype 4 Bridge

Axle Group	Truck Type	Allowable Number of Passing for GVW1	Allowable Number of Passing for GVW2	Allowable Number of Passing for GVW3
2-Axle	A21	7.39E+08	1.88E+08	1.15E+08
3-Axle	A31	N/A	N/A	4.41E+07
	A32	2.25E+08	9.60E+07	N/A
4-Axle	A41	2.86E+08	1.13E+08	3.28E+07
	A42	N/A	N/A	1.33E+07
	A43	1.82E+08	6.24E+07	N/A
	A44	N/A	N/A	2.57E+07
	A45	3.17E+08	1.03E+08	N/A
5-Axle	A51	N/A	N/A	2.36E+07
	A52	1.34E+08	5.10E+07	N/A
6-Axle	A61	N/A	N/A	7.68E+06
	A62	1.19E+08	2.58E+07	N/A
7-Axle	A71	N/A	N/A	2.18E+06
	A72	8.11E+07	1.66E+07	N/A
8-Axle	A81	N/A	N/A	4.67E+06
	A82	1.07E+08	1.81E+07	N/A

Appendix F Annual Bridge Fatigue Damage Cost Sample Calculation

The annual bridge damage cost is bridge type and site specific (i.e. it depends on the truck traffic). For discussion purpose, a bridge site with daily average truck traffic (ADTT) of 4000 is assumed for the following sample calculations.

Step 1: Compute the allowable bridge fatigue life (N) for each truck model using the FE analysis results (see Appendix D)

The allowable bridge fatigue life (i.e., number of passages allowed for each truck model (N)) was computed using the methodology discussed in Appendix D. The results for all four Archetype bridges and truck models are shown in Table E.3 to Table E.6.

Step 2: Compute the annual consumed bridge fatigue life (N_C) for each truck model

The annual consumed bridge fatigue life for a particular truck model (axle configuration and weight) was determined using the expected truck traffic for this particular truck model in a year. The annual truck traffic (including all truck models) for a given bridge site can be estimated using the ADTT in NBI database (NBI 2012). The annual truck traffic for a given bridge site was then distributed to each truck model by the truck axle group distribution (Table 2.3) and the truck GVWs distribution (Table A.2). For the sample calculation here, a 4000 ADTT value was used. Results for the sample calculation are shown in Table F.1.

Table F.1 Sample Calculation for Annual Consumed Bridge Fatigue Life

Axle Group	Truck Type	ADTT	Percentage of Axle Group	Percentage of GVW1	Percentage of GVW2	Percentage of GVW3	Count for GVW1	Count for GVW2	Count for GVW3
2-Axle	A21	4000	8.84%	99.98%	0.01%	0.01%	128979	13	13
3-Axle	A31		5.70%	99.92%	0.06%	0.02%	N/A	N/A	17
	A32						83147	53	N/A
4-Axle	A41		4.60%	99.98%	0.01%	0.01%	22371	2	2
	A42						N/A	N/A	2
	A43						22371	2	N/A
	A44						N/A	N/A	2
	A45						22371	2	N/A
5-Axle	A51		78.49%	92.91%	4.66%	2.42%	N/A	N/A	27778
	A52						1064686	53439	N/A
6-Axle	A61		1.17%	95.54%	4.38%	0.08%	N/A	N/A	14
	A62						16265	746	N/A
7-Axle	A71		1.18%	94.25%	5.41%	0.34%	N/A	N/A	58
	A72						16209	931	N/A
8-Axle	A81		0.03%	32.98%	54.20%	12.82%	N/A	N/A	56
	A82						144	237	N/A

Step 3: Compute the annual bridge fatigue damage (D)

The annual bridge damage caused by a truck model is defined as the annual consumed fatigue life by this truck model (N_{Ci}) divided by the bridge fatigue life of this truck model (N_i). The total bridge fatigue damage (D) is the sum of fatigue damages from all truck models, as shown in Equation (F.1).

$$\text{Fatigue Damage (D)} = \frac{\text{Consumed Fatigue Life}}{\text{Bridge Fatigue Life}}$$

$$= \sum \left(\frac{N_{Ci,1}}{N_{i,1}} + \frac{N_{Ci,2}}{N_{i,2}} + \frac{N_{Ci,3}}{N_{i,3}} \right) \qquad (F.1)$$

where

$N_{Ci,1}$, $N_{Ci,2}$, $N_{Ci,3}$: number of loading cycles consumed for the i-th truck model with gross vehicle weight levels 1 to 3 (GVW1, GVW2, GVW3), respectively

$N_{i,1}$, $N_{i,2}$,, $N_{i,3}$: allowable number of loading cycles for the i-th truck model with gross vehicle weight levels 1 to 3 (GVW1, GVW2, GVW3), respectively

i: Truck type

Note that the bridge fatigue damage (D) is a unitless quantity, where D equal to zero means no damage and D equal to unity means the particular bridge has used up its fatigue life (i.e. complete damage under repetitive fatigue loading). The results for all four Archetype bridges are listed in Table F.2 to Table F.5.

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Table F.2 Sample Calculation for Annual Fatigue Damage of Archetype 1 Bridge

Axle Group	Truck Type	Annual Fatigue Damage of GVW1	Annual Fatigue Damage of GVW2	Annual Fatigue Damage of GVW3	Annual Bridge Fatigue Damage
2-Axle	A21	1.15E-03	1.23E-07	1.26E-07	1.34%
3-Axle	A31	N/A	N/A	1.61E-07	
	A32	7.54E-04	4.89E-07	N/A	
4-Axle	A41	2.04E-04	2.19E-08	2.23E-08	
	A42	N/A	N/A	2.30E-08	
	A43	2.04E-04	2.21E-08	N/A	
	A44	N/A	N/A	2.21E-08	
	A45	2.01E-04	2.20E-08	N/A	
5-Axle	A51	N/A	N/A	2.88E-04	
	A52	9.75E-03	4.97E-04	N/A	
6-Axle	A61	N/A	N/A	1.36E-07	
	A62	1.50E-04	7.07E-06	N/A	
7-Axle	A71	N/A	N/A	6.24E-07	
	A72	1.48E-04	8.90E-06	N/A	
8-Axle	A81	N/A	N/A	5.91E-07	
	A82	1.35E-06	2.27E-06	N/A	

Table F.3 Sample Calculation for Annual Fatigue Damage of Archetype 2 Bridge

Axle Group	Truck Type	Annual Fatigue Damage of GVW1	Annual Fatigue Damage of GVW2	Annual Fatigue Damage of GVW3	Annual Bridge Fatigue Damage
2-Axle	A21	2.77E-04	1.03E-07	7.39E-07	2.62%
3-Axle	A31	N/A	N/A	1.48E-06	
	A32	9.65E-04	2.10E-06	N/A	
4-Axle	A41	2.44E-04	6.20E-08	2.94E-07	
	A42	N/A	N/A	5.79E-07	
	A43	2.12E-04	7.04E-08	N/A	
	A44	N/A	N/A	9.32E-07	
	A45	2.30E-04	6.26E-08	N/A	
5-Axle	A51	N/A	N/A	1.12E-02	
	A52	1.01E-02	1.81E-03	N/A	
6-Axle	A61	N/A	N/A	3.03E-06	
	A62	2.89E-04	7.51E-05	N/A	
7-Axle	A71	N/A	N/A	6.23E-05	
	A72	3.96E-04	2.23E-04	N/A	
8-Axle	A81	N/A	N/A	2.27E-05	
	A82	3.07E-06	4.83E-05	N/A	

Table F.4: Sample Calculation for Annual Fatigue Damage of Archetype 3 Bridge

Axle Group	Truck Type	Annual Fatigue Damage of GVW1	Annual Fatigue Damage of GVW2	Annual Fatigue Damage of GVW3	Annual Bridge Fatigue Damage
2-Axle	A21	1.89E-04	4.90E-08	1.05E-07	0.96%
3-Axle	A31	N/A	N/A	2.89E-07	
	A32	3.51E-04	6.67E-07	N/A	
4-Axle	A41	8.01E-05	2.36E-08	7.96E-08	
	A42	N/A	N/A	1.69E-07	
	A43	1.36E-04	4.07E-08	N/A	
	A44	N/A	N/A	8.59E-08	
	A45	6.74E-05	1.75E-08	N/A	
5-Axle	A51	N/A	N/A	1.87E-03	
	A52	5.95E-03	7.05E-04	N/A	
6-Axle	A61	N/A	N/A	1.41E-06	
	A62	7.76E-05	1.46E-05	N/A	
7-Axle	A71	N/A	N/A	3.35E-05	
	A72	1.05E-04	3.63E-05	N/A	
8-Axle	A81	N/A	N/A	6.89E-06	
	A82	7.89E-07	1.27E-05	N/A	

Table F.5: Sample Calculation for Annual Fatigue Damage of Archetype 4 Bridge

Axle Group	Truck Type	Annual Fatigue Damage of GVW1	Annual Fatigue Damage of GVW2	Annual Fatigue Damage of GVW3	Annual Bridge Fatigue Damage
2-Axle	A21	1.75E-04	6.85E-08	1.12E-07	1.15%
3-Axle	A31	N/A	N/A	3.77E-07	
	A32	3.70E-04	5.55E-07	N/A	
4-Axle	A41	7.82E-05	2.12E-08	6.83E-08	
	A42	N/A	N/A	1.68E-07	
	A43	1.23E-04	3.84E-08	N/A	
	A44	N/A	N/A	8.72E-08	
	A45	7.06E-05	2.32E-08	N/A	
5-Axle	A51	N/A	N/A	1.18E-03	
	A52	7.97E-03	1.05E-03	N/A	
6-Axle	A61	N/A	N/A	1.79E-06	
	A62	1.36E-04	2.89E-05	N/A	
7-Axle	A71	N/A	N/A	2.65E-05	
	A72	2.00E-04	5.60E-05	N/A	
8-Axle	A81	N/A	N/A	1.20E-05	
	A82	1.35E-06	1.31E-05	N/A	

Step 4: Determine the bridge replacement cost (C_R)

In this sample calculation, a replacement cost of $1 million dollars was assumed for all four Archetype bridges. The determination of the actual replacement cost for individual bridges in South Carolina is discussed in Appendix G.

Step 5: Compute the annual bridge fatigue damage cost (C_D)

The annual bridge fatigue damage cost for a given bridge can be calculated by multiplying the annual bridge fatigue damage, D (computed in step 3) with the bridge replacement cost C_R (step 4).

$$\text{Damage Cost } (C_D) = C_R \times D \qquad \text{(F.2)}$$

The results for this sample calculation, assuming a bridge replacement value of $1 million dollars, are shown in Table F.6.

Table F.6: Sample Calculation for Annual Bridge Fatigue Damage Cost.

Archetype Bridge	Bridge Replacement Cost (Dollar)	Annual Bridge Fatigue Damage	Annual Bridge Fatigue Damage Cost (Dollar)
A1	1,000,000	1.34%	13,374
A2	1,000,000	2.62%	26,185
A3	1,000,000	0.96%	9,639
A4	1,000,000	1.15%	11,492

Appendix G Bridge Replacement Cost Models

Bridge Replacement Cost Models Development

In order to estimate the damage costs caused by truck traffic on bridges, the replacement costs of individual bridges must first be determined. The bridge replacement costs used in this study were derived from the bridge replacement cost database in the HAZUS-MH program (HAZUS, 2003). The HAZUS-MH is developed for loss estimation under extreme natural hazard events (e.g. earthquakes); hence not all the bridges are accounted for in the HAZUS-MH program. The HAZUS-MH database contains the replacement costs for a proximately half of the bridges in South Carolina (4,096 bridges). The total number of bridges in South Carolina is 9,271. For those bridges that are not in the HAZUS-MH database, their replacement costs were estimated using the bridge cost models, developed as part of this study using the replacement costs of the 4,096 bridges available in the HAZUS-MH database.

The first step in developing the bridge cost model was to match the longitude and latitude coordinates of the 4,096 bridges with known replacement costs in the HAZUS program to that in the NBI database. Next, the 9,271 bridges in NBI database were grouped together according to their material type and structural type (Table G.1).

Table G.1: Bridge Cost Group.

Cost Model Number	Material Type	Structure Type
1	Concrete	Slab
2	Concrete	Stringer/Multi-Beam or Girder
3	Concrete	Girder and Floor Beam System
4	Concrete	Tee Beam
5	Concrete	Box Beam or Girders - Multiple
6	Concrete	Frame (except frame culverts)
7	Concrete	Arch - Deck
8	Concrete	Tunnel
9	Concrete	Culvert (includes frame culverts)
10	Concrete	Channel Beam
11	Concrete	Other
12	Concrete Continuous	Slab
13	Concrete Continuous	Stringer/Multi-Beam or Girder
14	Concrete Continuous	Tee Beam
15	Concrete Continuous	Box Beam or Girders - Multiple
16	Concrete Continuous	Box Beam or Girders - Single or Spread
17	Steel	Slab
18	Steel	Stringer/Multi-Beam or Girder
19	Steel	Girder and Floor Beam System
20	Steel	Frame (except frame culverts)
21	Steel	Truss - Thru
22	Steel	Arch - Deck
23	Steel	Movable - Bascule
24	Steel	Movable - Swing
25	Steel	Culvert (includes frame culverts)
26	Steel	Other
27	Steel Continuous	Slab
28	Steel Continuous	Stringer/Multi-Beam or Girder
29	Steel Continuous	Girder and Floor Beam System

Table G.1: Bridge Cost Group (continued)

Cost Model Number	Material Type	Structure Type
30	Steel Continuous	Frame (except frame culverts)
31	Steel Continuous	Truss - Thru
32	Steel Continuous	Stayed Girder
33	Steel Continuous	Movable - Swing
34	Prestressed Concrete	Slab
35	Prestressed Concrete	Stringer/Multi-Beam or Girder
36	Prestressed Concrete	Girder and Floor Beam System
37	Prestressed Concrete	Tee Beam
38	Prestressed Concrete	Box Beam or Girders - Multiple
39	Prestressed Concrete	Channel Beam
40	Prestressed Concrete	Other
41	Prestressed Concrete Continuous	Slab
42	Prestressed Concrete Continuous	Stringer/Multi-Beam or Girder
43	Prestressed Concrete Continuous	Segmental Box Girder
44	Wood or Timber	Slab
45	Wood or Timber	Stringer/Multi-Beam or Girder
46	Masonry	Arch - Deck
47	Masonry	Culvert (includes frame culverts)
48	Aluminum, Wrought Iron, or Cast Iron	Culvert (includes frame culverts)
49	Other	Slab
50	Other	Other

For those bridge cost groups that have more than five known bridge replacement costs (obtained from the HAZUS-MH database), the bridge replacement costs were fitted to two power equations, one as a function of the total structure length (Equation G.1) , and the other as a function of the total structure area (Equation G.2).

$$C_{R1} = a_1 L^{b_1} \tag{G.1}$$

where

C_{R1} : is the bridge replacement cost as a function of the total structure length

L : is the total structure length

a_1 and b_1 : are fitted distribution parameters for Equation (G.1)

$$C_{R2} = a_2 A^{b_2} \tag{G.2}$$

where

C_{R2} : is the bridge replacement cost as a function of the total structure area

A : is the total structure area

a_2 and b_2 : are fitted distribution parameters for Equation (G.2)

Figure G.1 and Figure G.2 give two example replacement cost models for the prestressed concrete girder. The data points shown in Figure G.1 and Figure G.2 represent the known bridge replacement cost values obtained from the HAZUS-MH database. For each bridge cost group, the RMS (root mean square) errors of the fitted power equation curves for both the total structure length and total area models (i.e. Equations G.1 and G.2) were calculated. The model with the smaller RMS value was selected as the cost model for the bridge cost group. The selected model or equation was then used to compute the replacement costs of those bridges that were not accounted for in the HAZUS-MH database.

For the bridge cost groups that have less than five known bridge replacement costs, an average unit area cost was determined and used as the replacement cost to compute the replacement costs for the rest of the bridges in the same cost group. For bridge cost groups that were unable to establish a cost model or unit area cost, a cost model or unit area cost from a similar bridge cost group was assigned to this cost group.

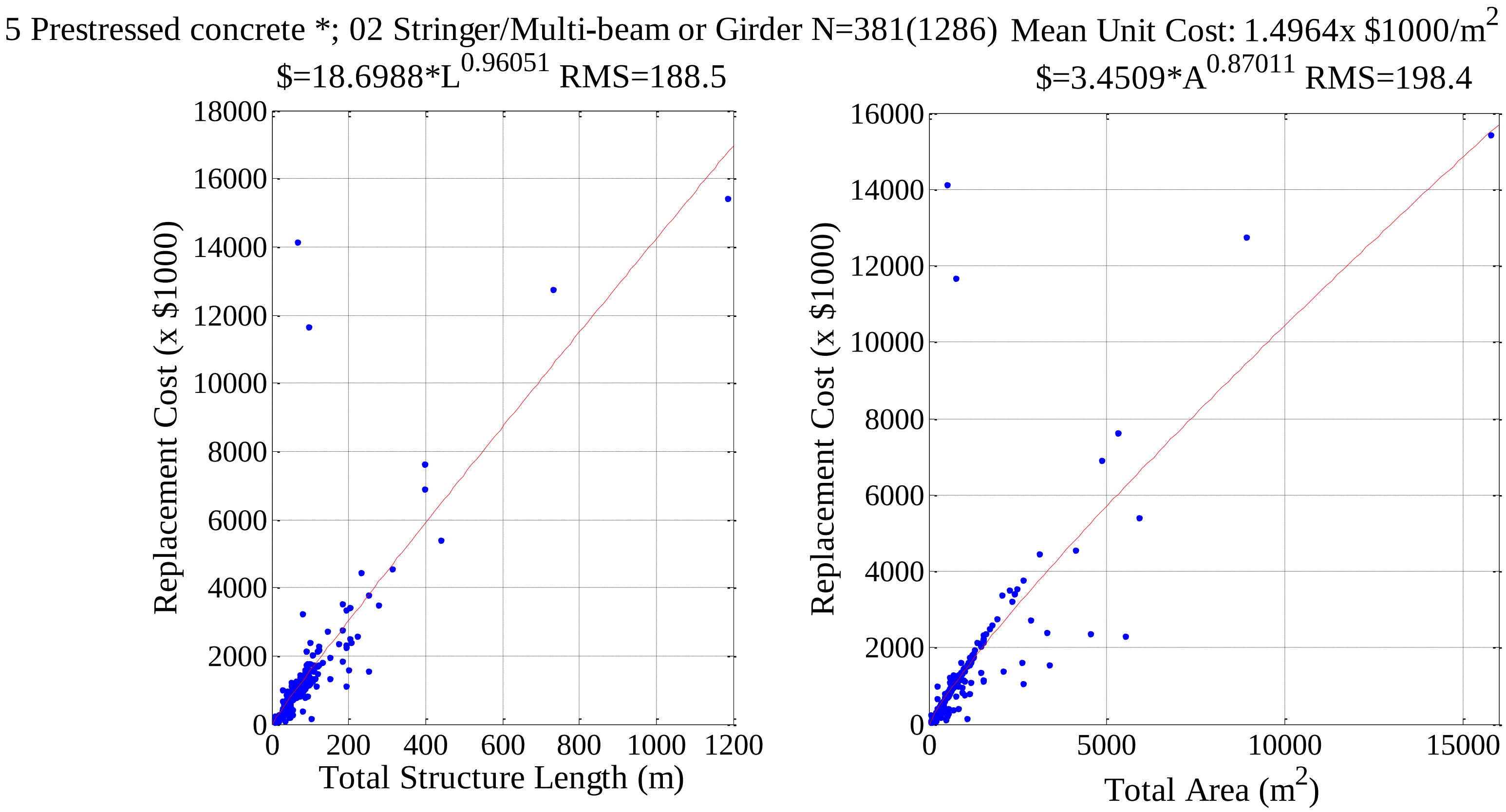
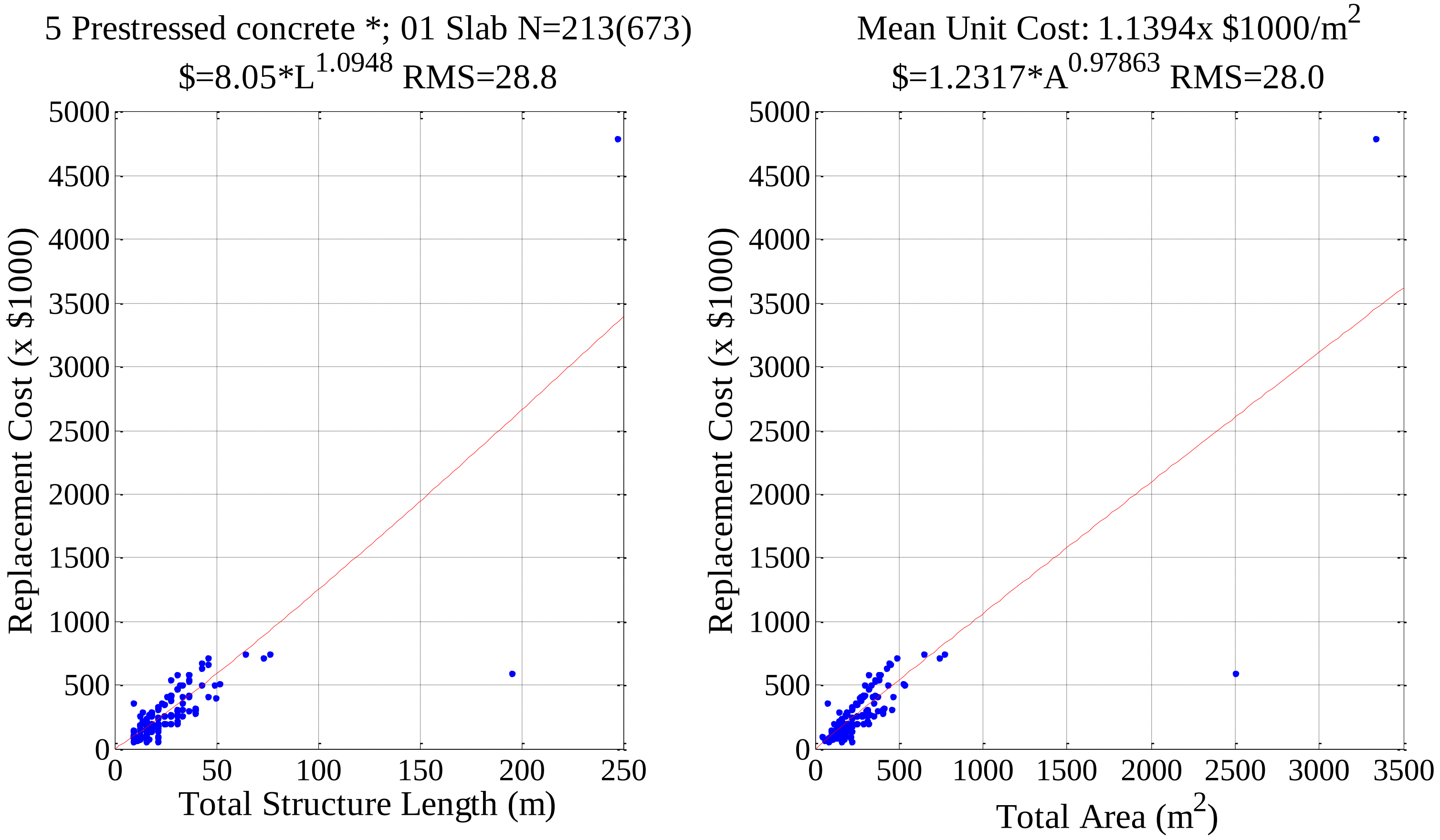


Figure G.1: Replacement Cost Model for Cost Model 35

Figure G.1shows the replacement cost model for multi-girder prestressed concrete bridges. The data points are the known replacement costs from the HAZUS-MH program and the red curves are the least-squares fits of the replacement costs using Equations G.1 and G.2. The left figure is the replacement cost model as a function of the structure length and the right figure is the replacement cost model as function of total bridge area. The fitted equations for both models are also shown in the figure. The model with the total length as the predictor had a smaller RMS (188.5) than the model using the total area as the predictor (198.4); therefore, the total structure length model was selected to estimate the replacement cost for all bridges in this bridge cost group.



5 Prestressed concrete *; 01 Slab N=213(673)
$\$=8.05*L^{1.0948}$ RMS=28.8

Mean Unit Cost: 1.1394x $1000/m^2
$\$=1.2317*A^{0.97863}$ RMS=28.0

Figure G.2: Replacement Cost Model for Cost Model 34

Figure G.2 shows the two candidate replacement cost models prestressed concrete slab bridges. For prestressed concrete slab bridges, the fitted cost model using the total length had a larger RMS (28.8) than that of the total area model (28); In this case, the cost model with the total structure area as the predictor was utilized to estimate the replacement costs of the remaining prestressed slab bridges that were without cost information.

Once the bridge cost models for different bridge types were developed, the replacement cost for each bridge in the NBI database was able to be determined. The histogram in

Figure G.3 shows the distribution of bridge replacement costs in South Carolina. The replacement costs for the majority of the bridges are less than $3 million dollars (2003 US Dollar). Figure G.4 shows the geographical distribution of the bridge replacement costs. As expected, the majority of bridges with replacement cost of greater than $1 million dollars (2003 US Dollar) are along the main highway routes. These bridge replacement costs were used in conjunction with the fatigue analysis results to determine the annual damage costs for individual bridges.

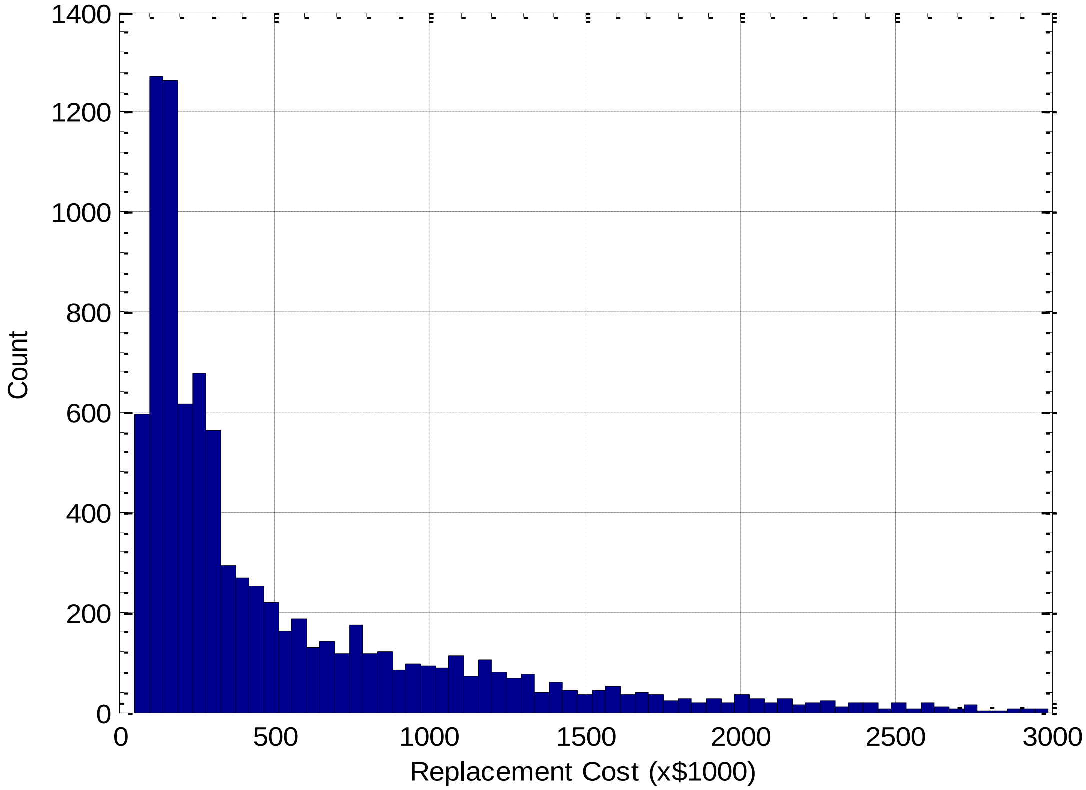


Figure G.3: Distribution of South Carolina Bridge Replacement Costs

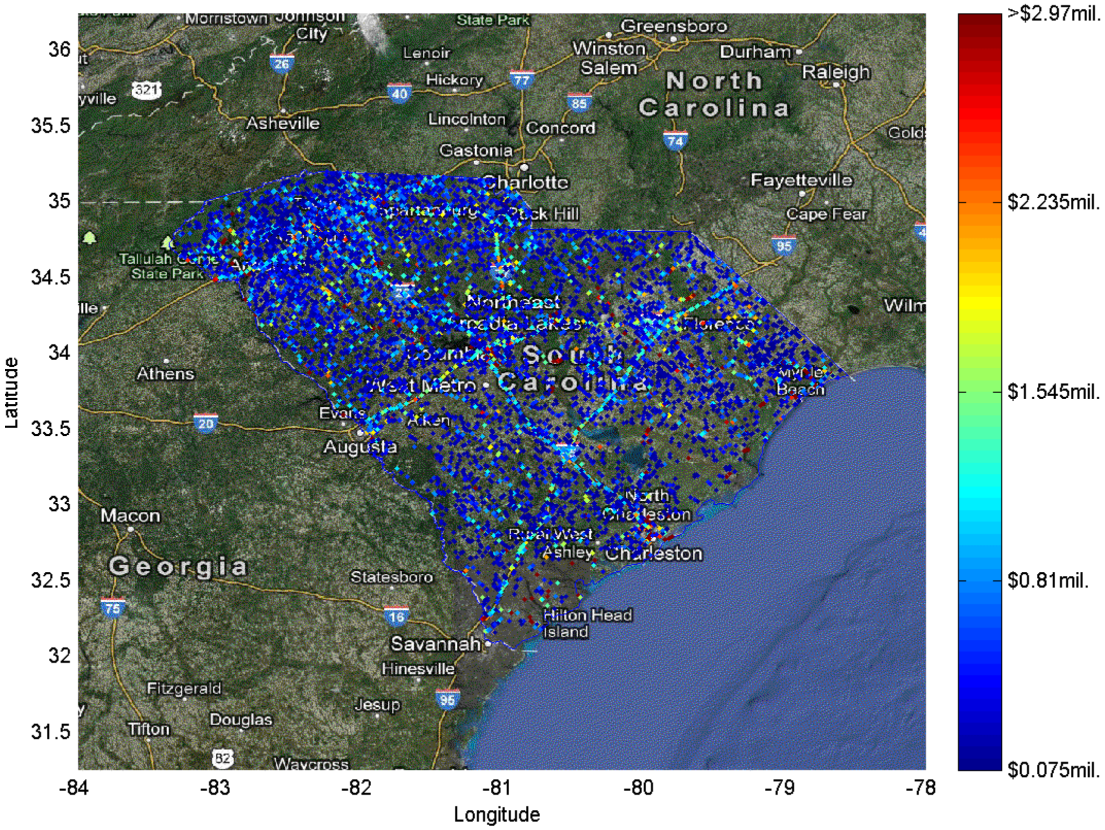


Figure G.4: Geographical Distribution of South Carolina Bridge Replacement Costs

The total replacement cost for all bridges in South Carolina was determined to be approximately $7.615 billion dollars (2003 US Dollar). Note that the estimated total bridge asset value was derived from the bridge replacement cost database in the HAZUS-MH program, which was based on the 2003 US dollar. Using consumer price index (CPI) these costs were converted from 2003 to 2012 and the total bridge replacement cost in 2012 US dollar was found to be $9.491 billion dollars. Details of cost models are presented in following sections.

Table G.2 Bridge Cost Models Parameters

Cost Model Number	a_1	b_1	RMS_1	a_2	b_2	RMS_2	Average Unit Area Cost (x$1000/$m^2$)
1	2.649	1.445	413.5	1.944	0.990	492.6	1.422
2	75.307	0.688	16.8	0.835	1.071	5.0	1.338
4	22.128	0.926	81.0	1.856	0.966	49.1	1.549
7	67.174	0.580	3.2	0.583	1.159	0.8	1.428
9	29.225	0.868	36.3	9.380	0.638	35.4	1.679
12	9.814	1.080	53.1	4.219	0.798	69.7	1.002
13	48.238	0.608	3.9	41.035	0.352	4.0	0.694
14	0.000	0.000	0.0	0.000	0.000	0.0	1.323
16	1068.053	0.171	31.0	1033.993	0.126	32.0	1.943
18	0.930	1.490	300.7	1.559	0.989	118.7	1.532
19	0.000	0.000	0.0	0.000	0.000	0.0	1.554
21	5.879	1.078	1.2	1.286	1.013	3.6	1.425
22	0.000	0.000	0.0	0.000	0.000	0.0	1.585
23	0.000	0.000	0.0	0.000	0.000	0.0	1.565
24	0.000	0.000	0.0	0.000	0.000	0.0	1.446
25	0.000	0.000	0.0	0.000	0.000	0.0	2.295
27	0.000	0.000	0.0	0.000	0.000	0.0	0.833
28	65.277	0.775	593.8	12.888	0.731	608.9	1.268
29	0.000	0.000	0.0	0.000	0.000	0.0	1.594
30	0.000	0.000	0.0	0.000	0.000	0.0	1.427
31	0.000	0.000	0.0	0.000	0.000	0.0	1.116
32	0.000	0.000	0.0	0.000	0.000	0.0	0.560
34	8.050	1.095	28.8	1.232	0.979	28.0	1.139
35	18.699	0.961	188.5	3.451	0.870	198.4	1.496
38	3.567	1.311	3.6	0.377	1.159	2.6	0.870
41	0.000	0.000	0.0	0.000	0.000	0.0	0.805
42	6.034	1.158	299.8	0.002	1.617	318.8	1.209
43	0.000	0.000	0.0	0.000	0.000	0.0	1.428
44	0.000	0.000	0.0	0.000	0.000	0.0	1.791
45	10.674	0.942	1.8	4.100	0.790	1.0	1.813
46	0.000	0.000	0.0	0.000	0.000	0.0	1.501
47	0.000	0.000	0.0	0.000	0.000	0.0	1.451
48	0.000	0.000	0.0	0.000	0.000	0.0	2.573

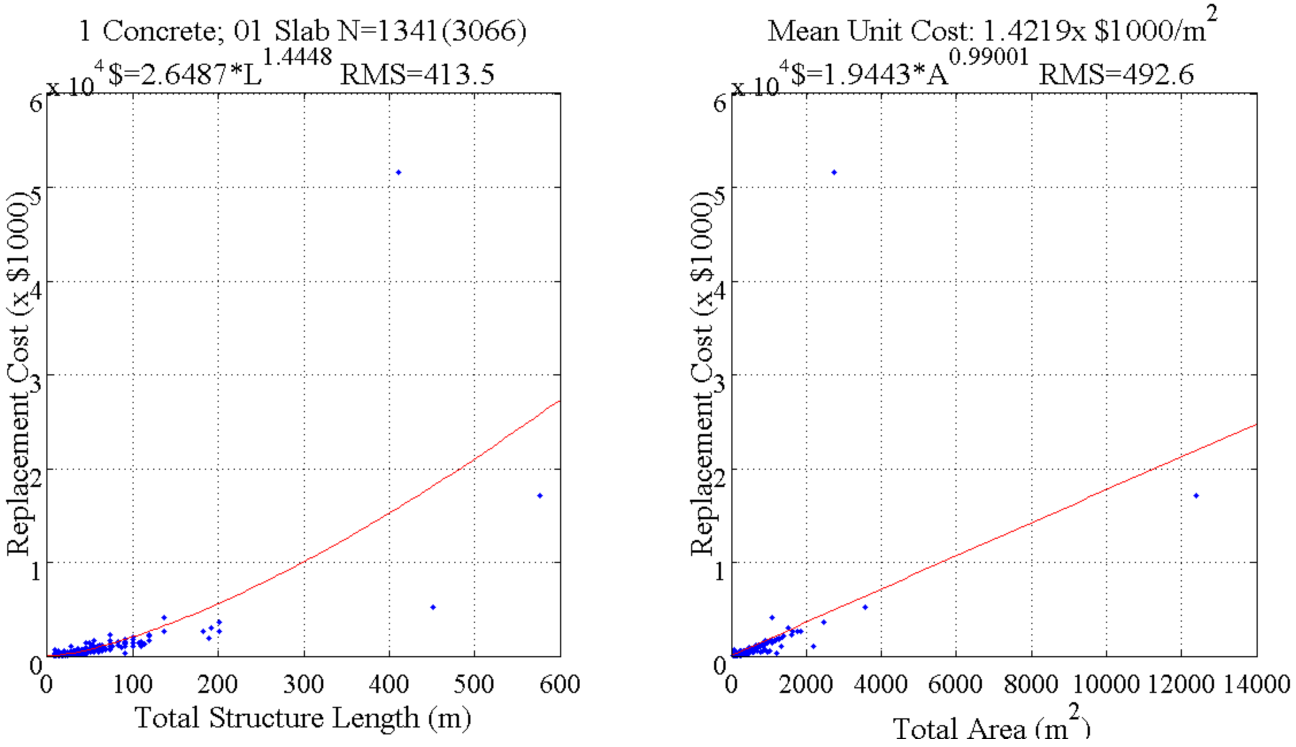


Figure G.5 Cost Model 1

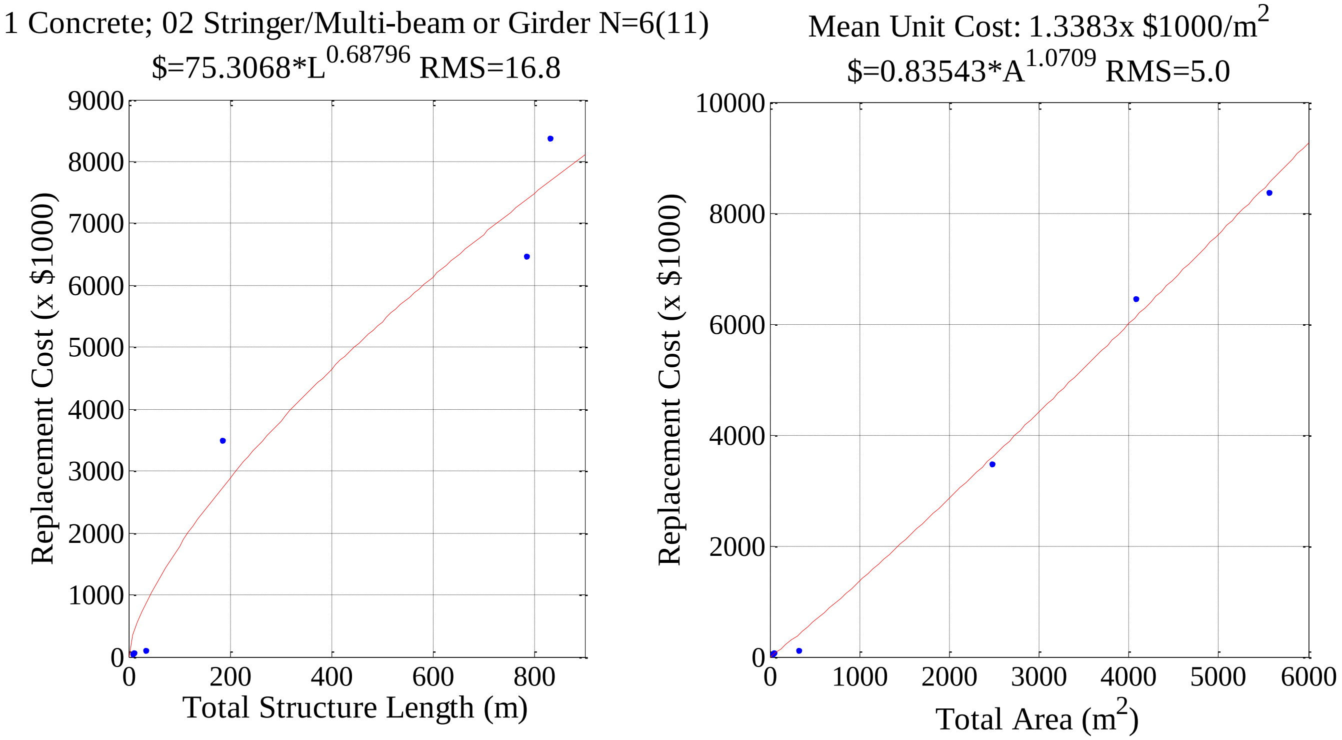


Figure G.6 Cost Model 2

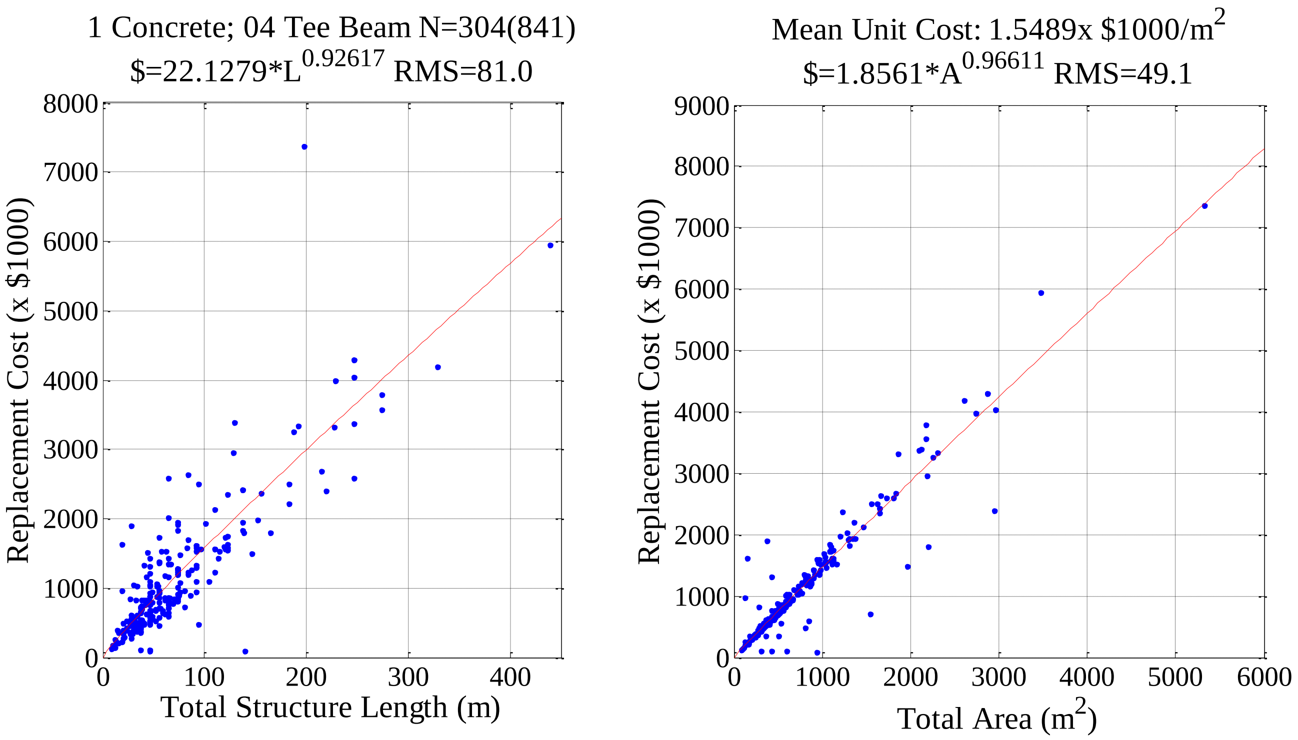


Figure G.7 Cost Model 4

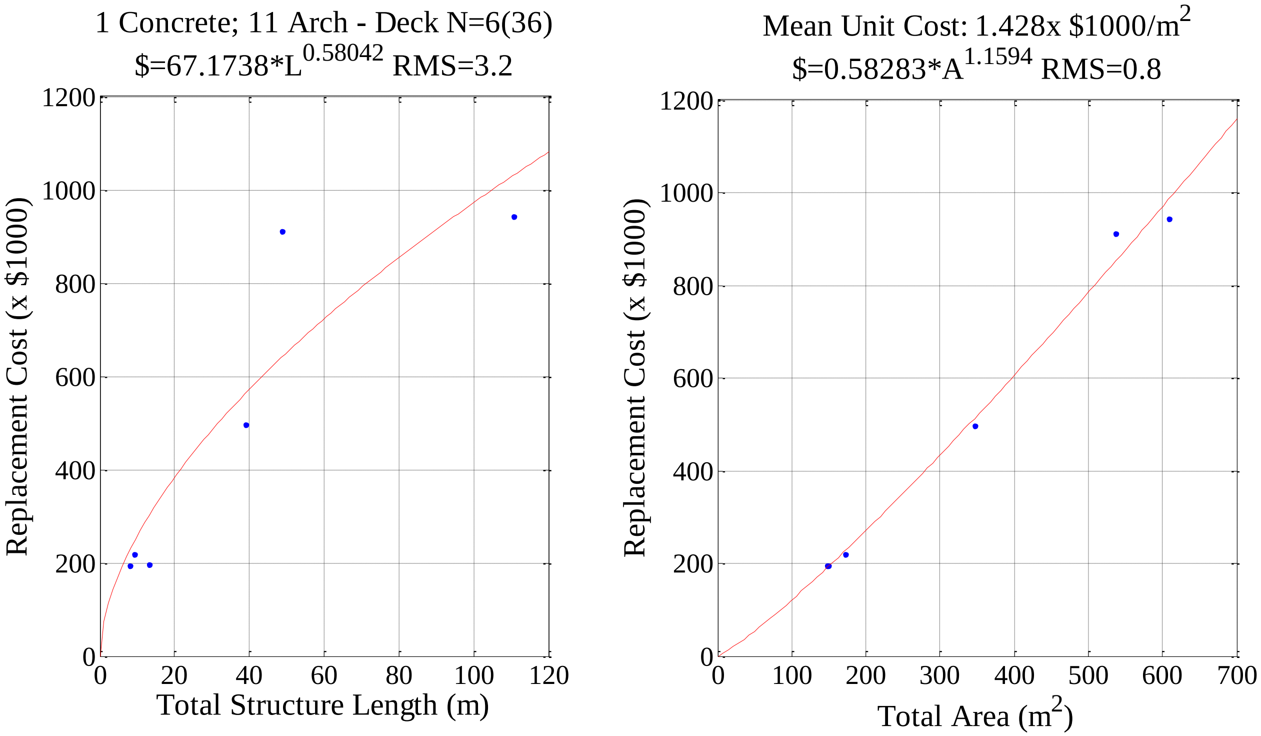


Figure G.8 Cost Model 7

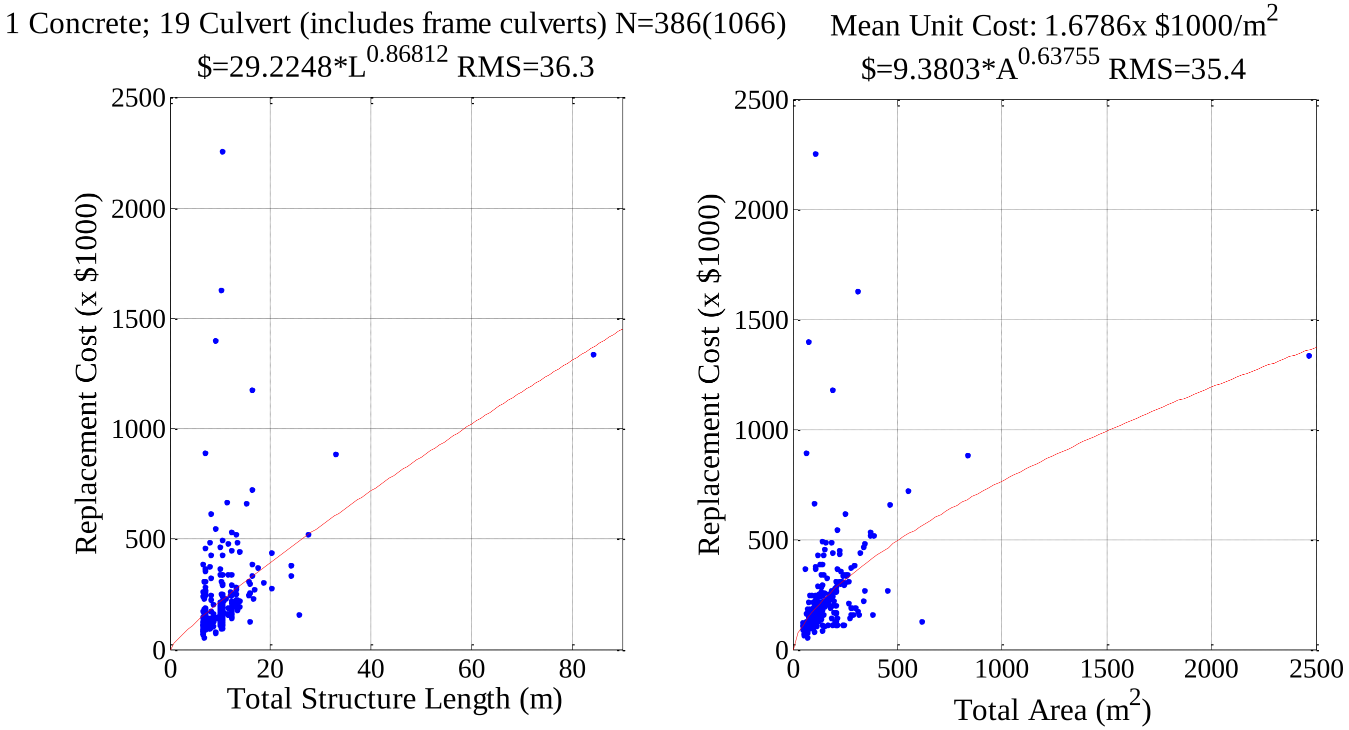
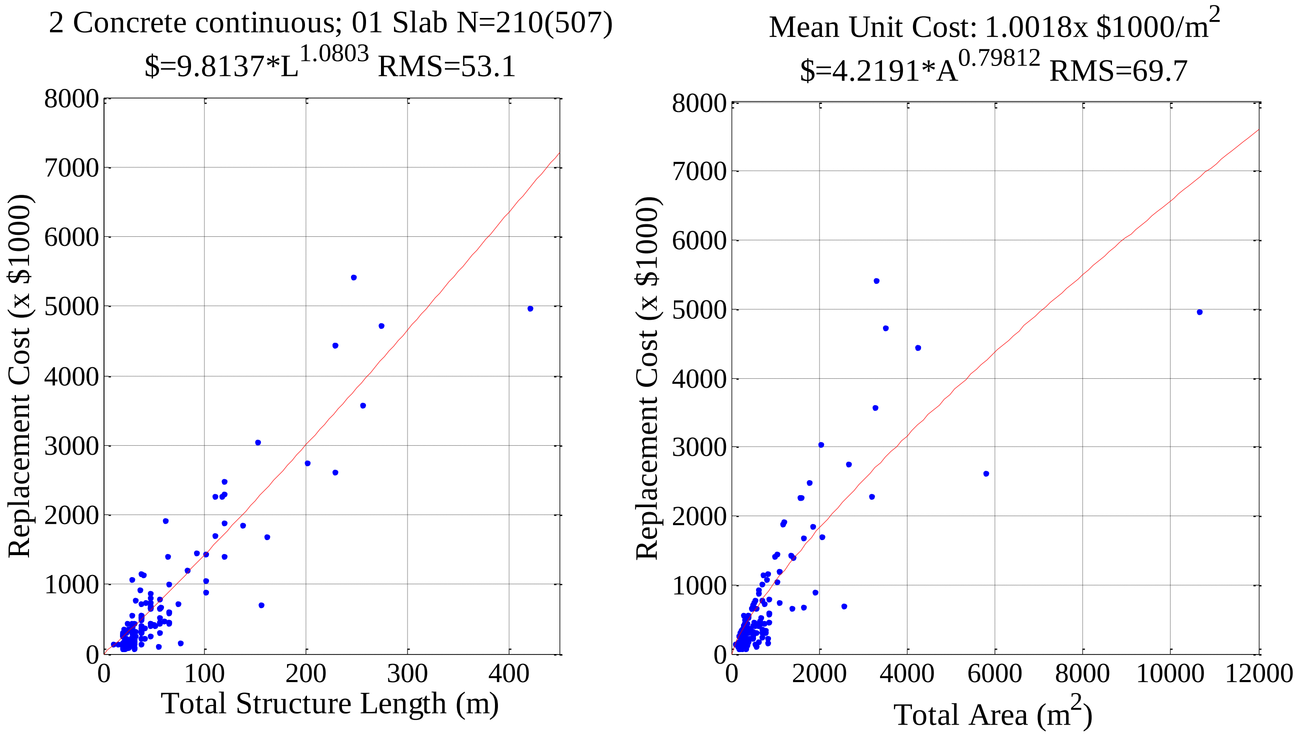


Figure G.9 Cost Model 9



2 Concrete continuous; 01 Slab N=210(507)

$\$=9.8137*L^{1.0803}$ RMS=53.1

Mean Unit Cost: 1.0018x $\$1000/m^2$

$\$=4.2191*A^{0.79812}$ RMS=69.7

Figure G.10 Cost Model 12

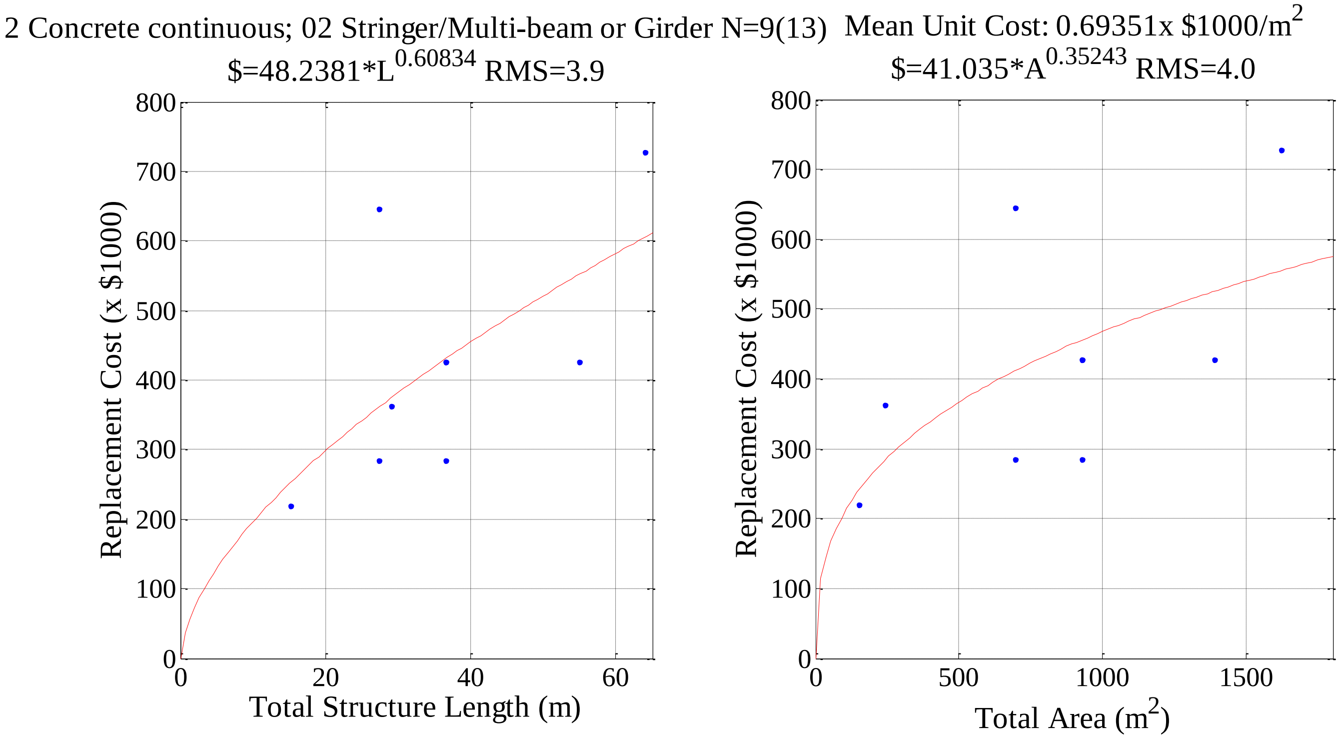


Figure G.11 Cost Model 13

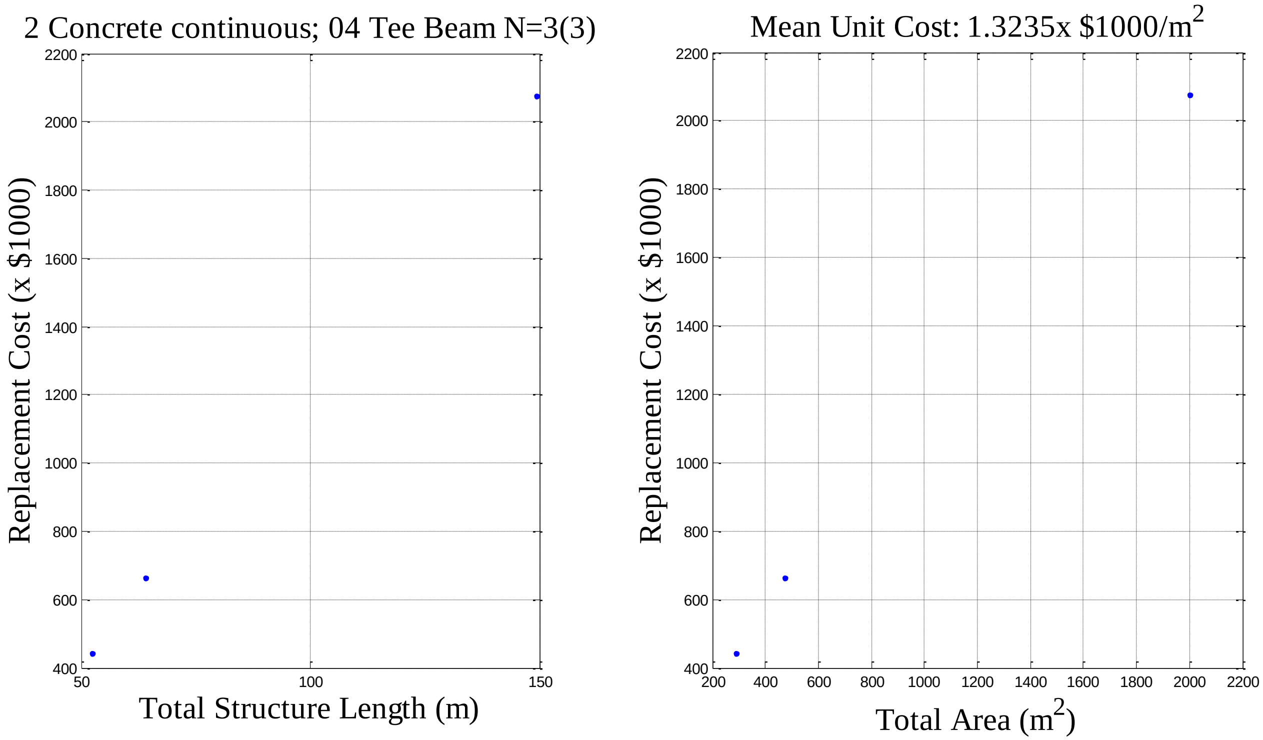


Figure G.12 Cost Model 14

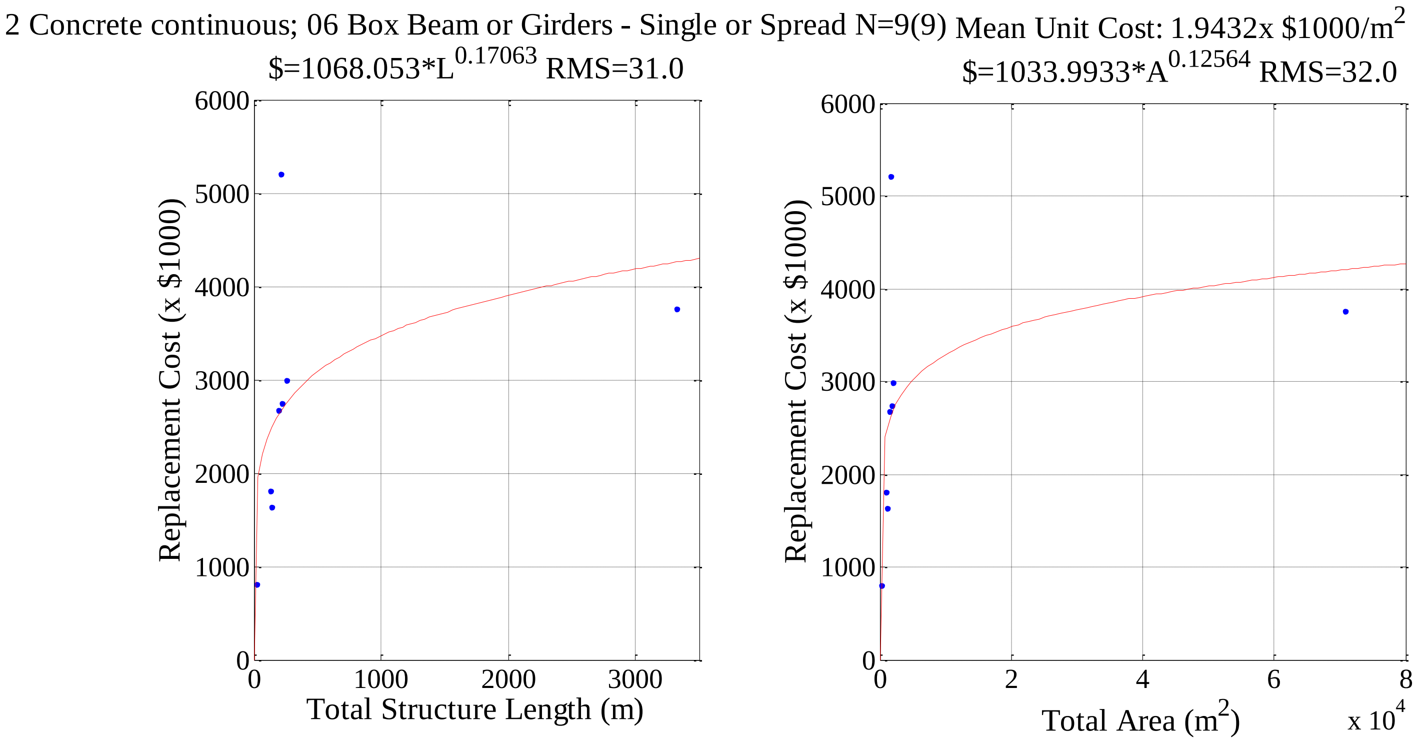
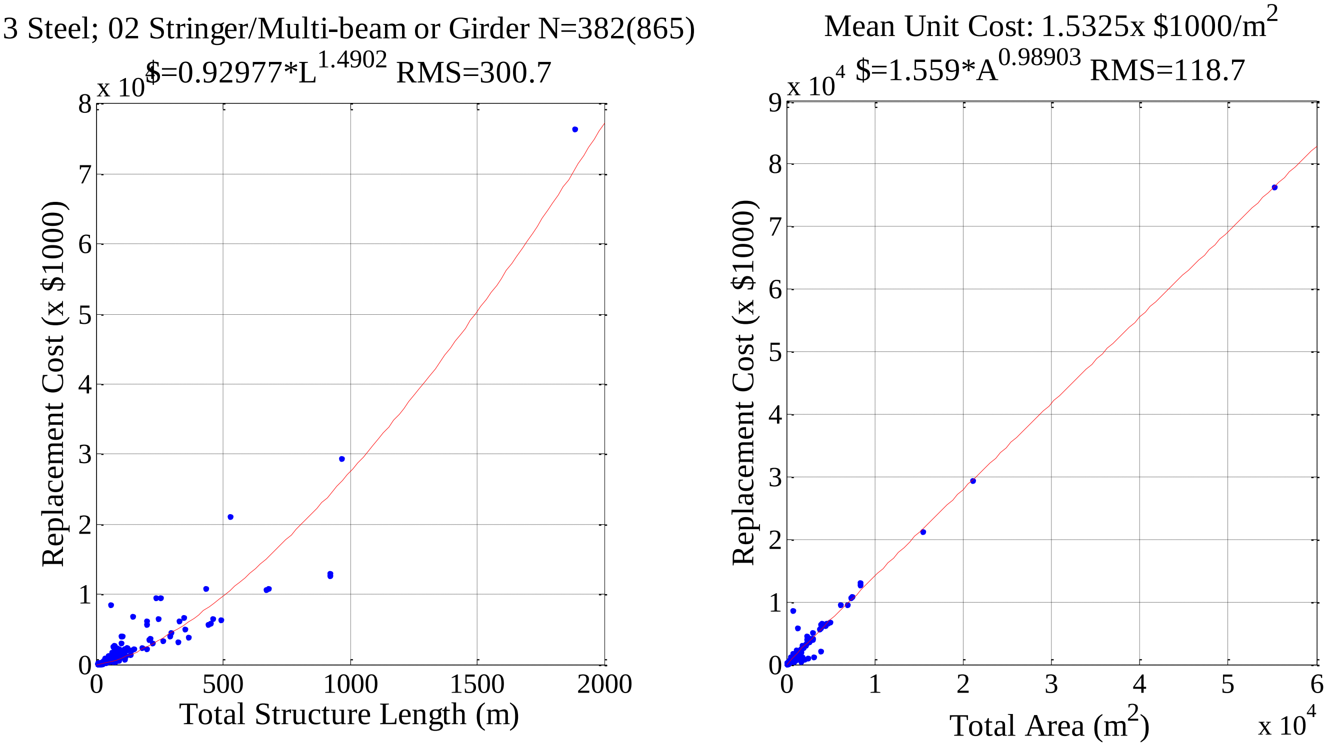


Figure G.13 Cost Model 16


3 Steel; 02 Stringer/Multi-beam or Girder N=382(865)

$\$=0.92977*L^{1.4902}$ RMS=300.7

Mean Unit Cost: 1.5325x $1000/m^2

$\$=1.559*A^{0.98903}$ RMS=118.7

Figure G.14 Cost Model 18

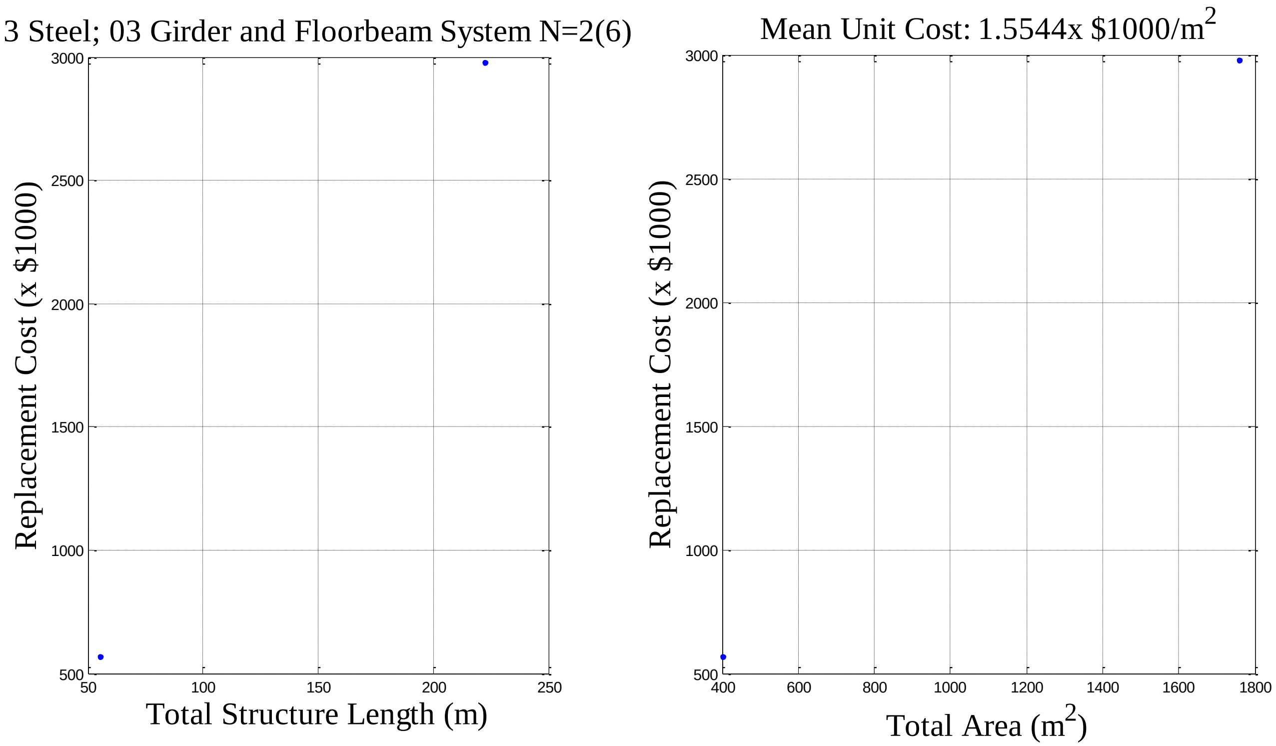


Figure G.15 Cost Model 19

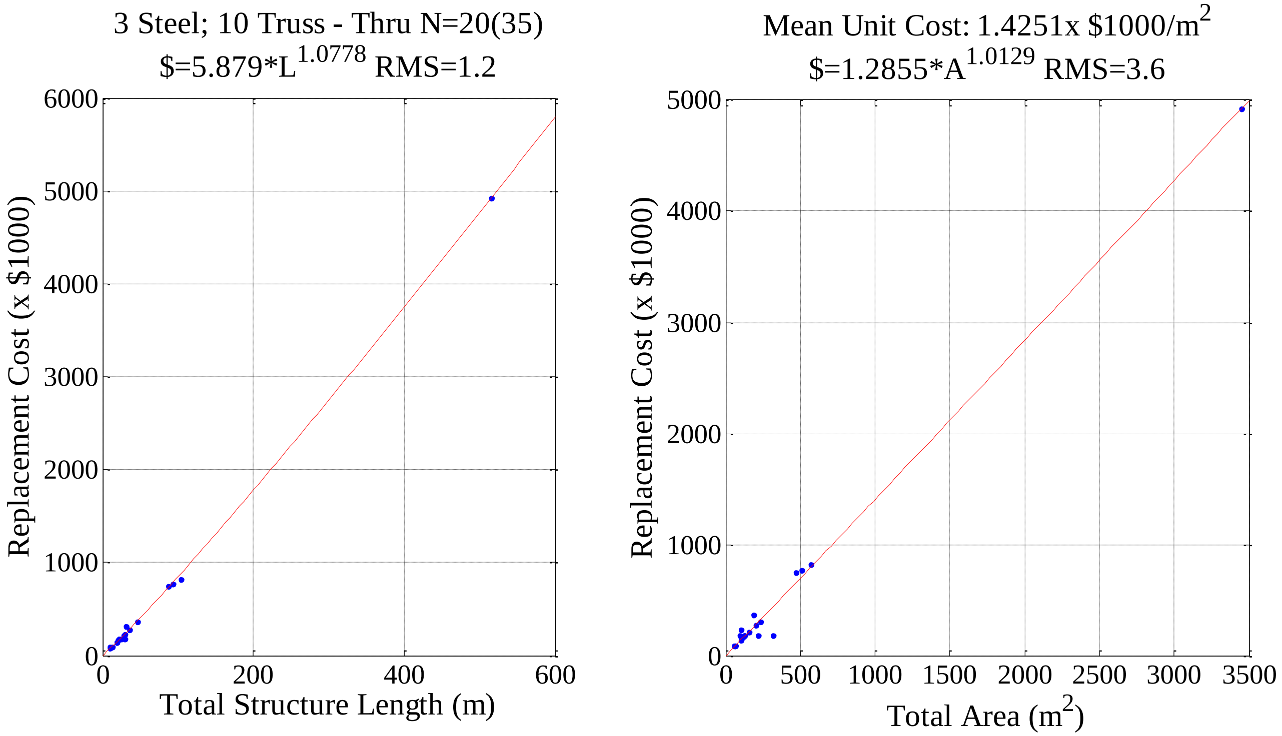


Figure G.16 Cost Model 21

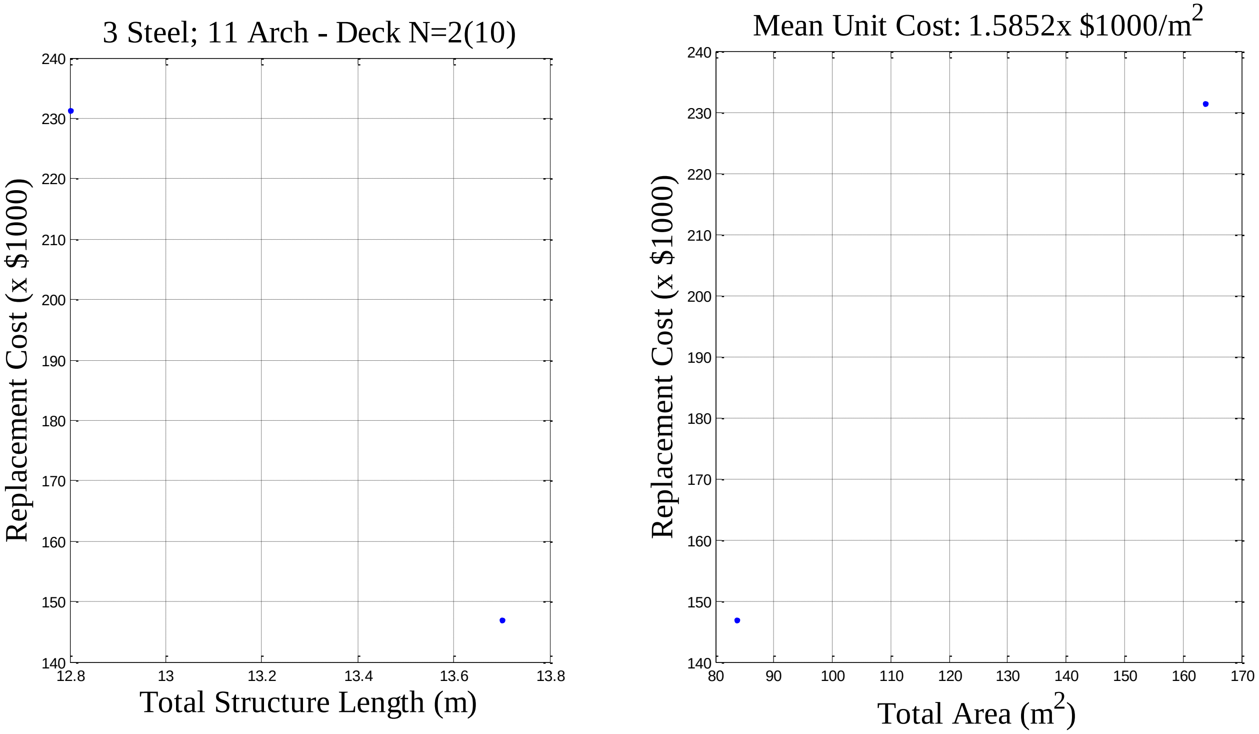


Figure G.17 Cost Model 22

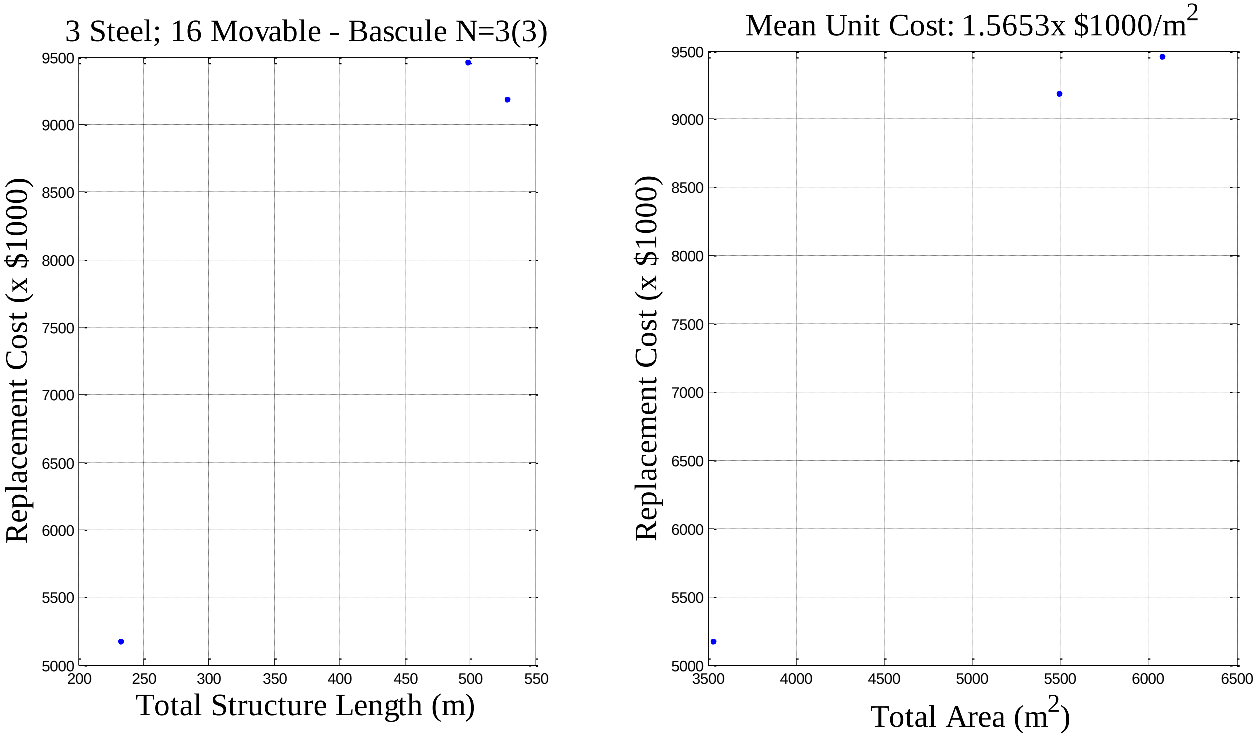


Figure G.18 Cost Model 23

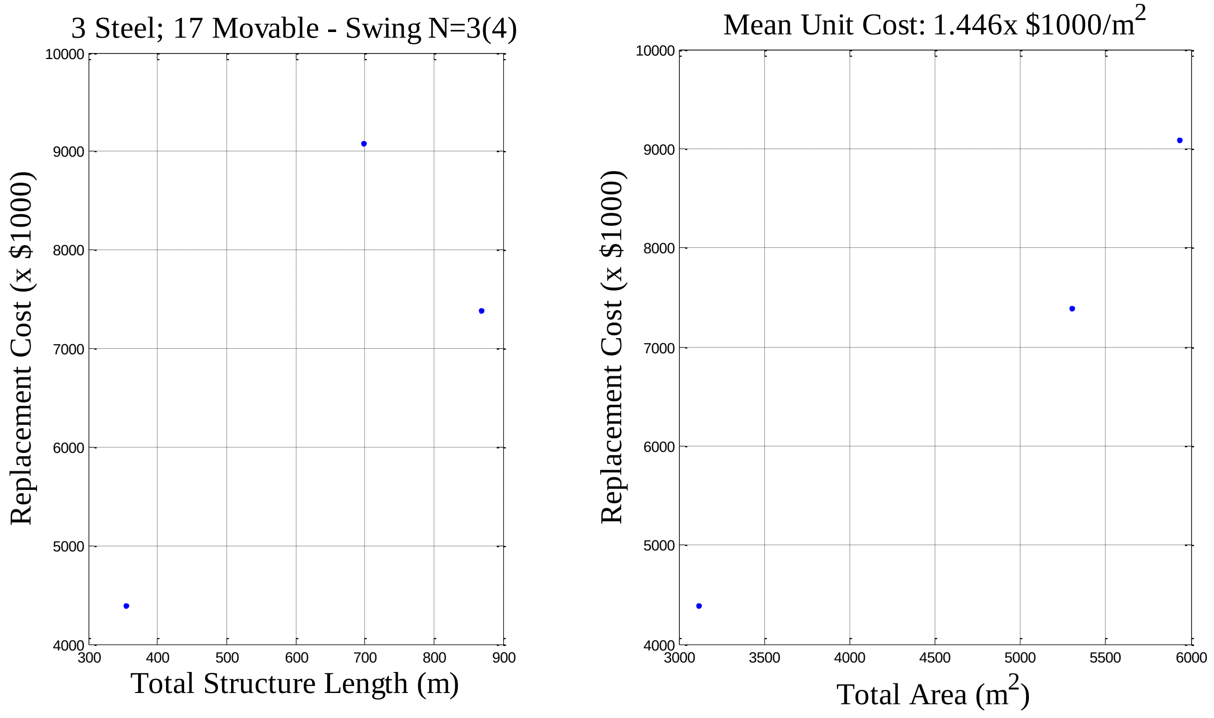


Figure G.19 Cost Model 24

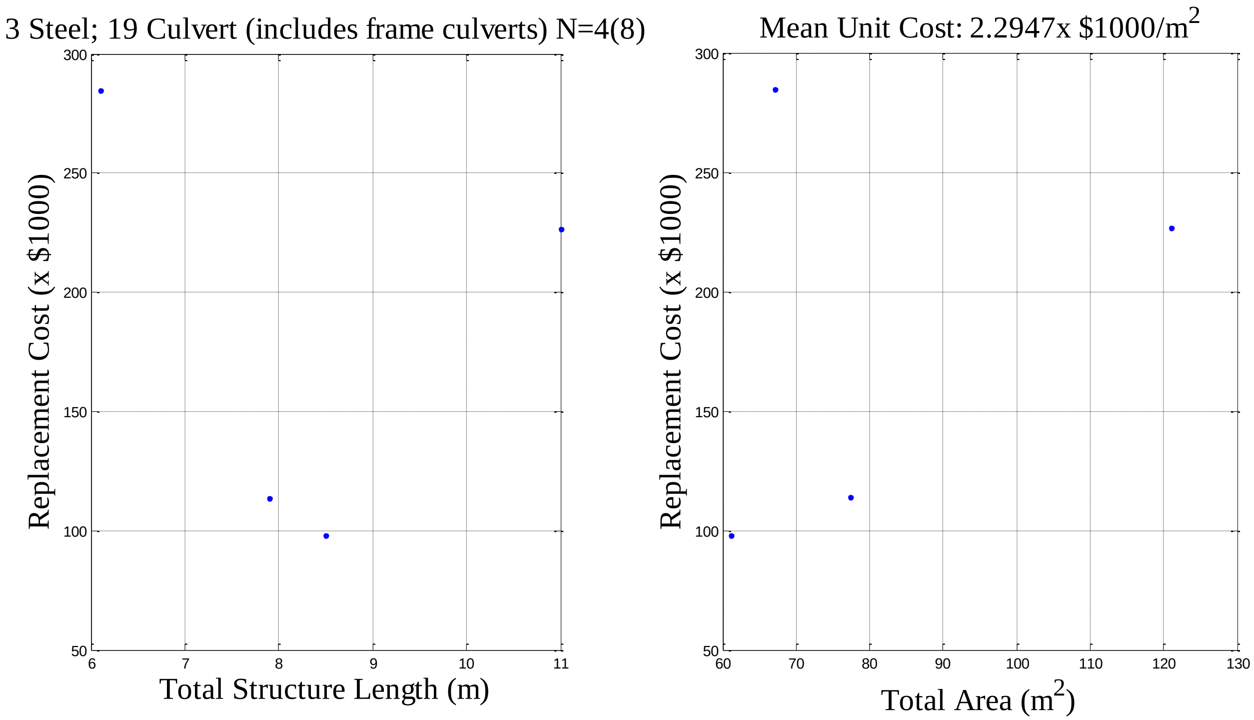


Figure G.20 Cost Model 25

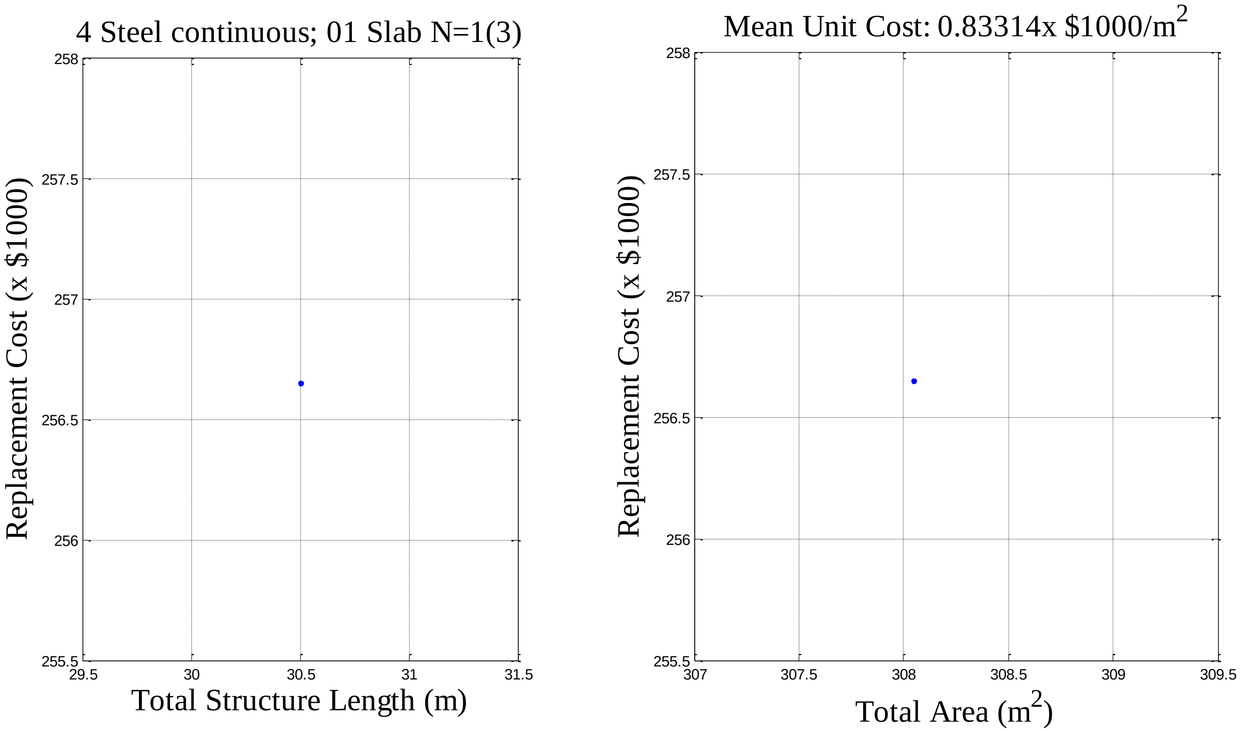


Figure G.21 Cost Model 27

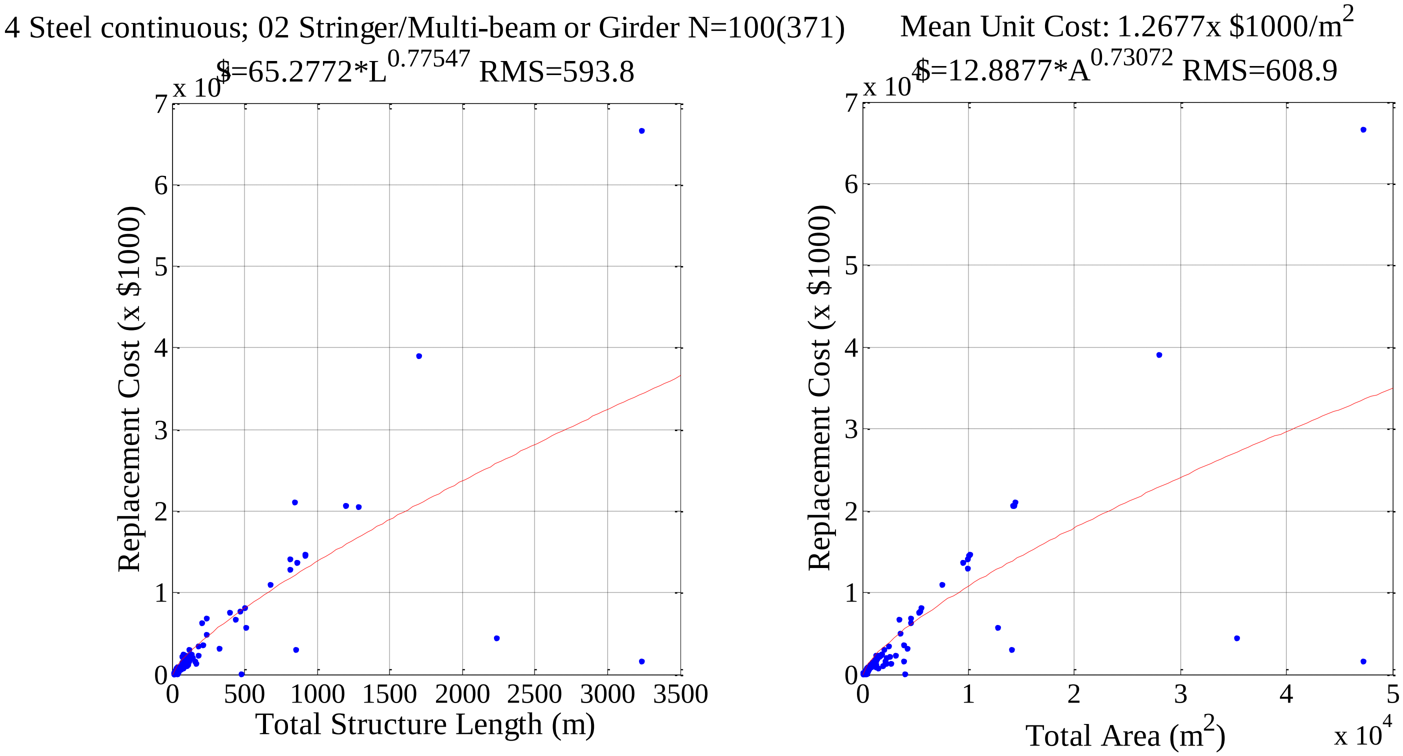


Figure G.22 Cost Model 28

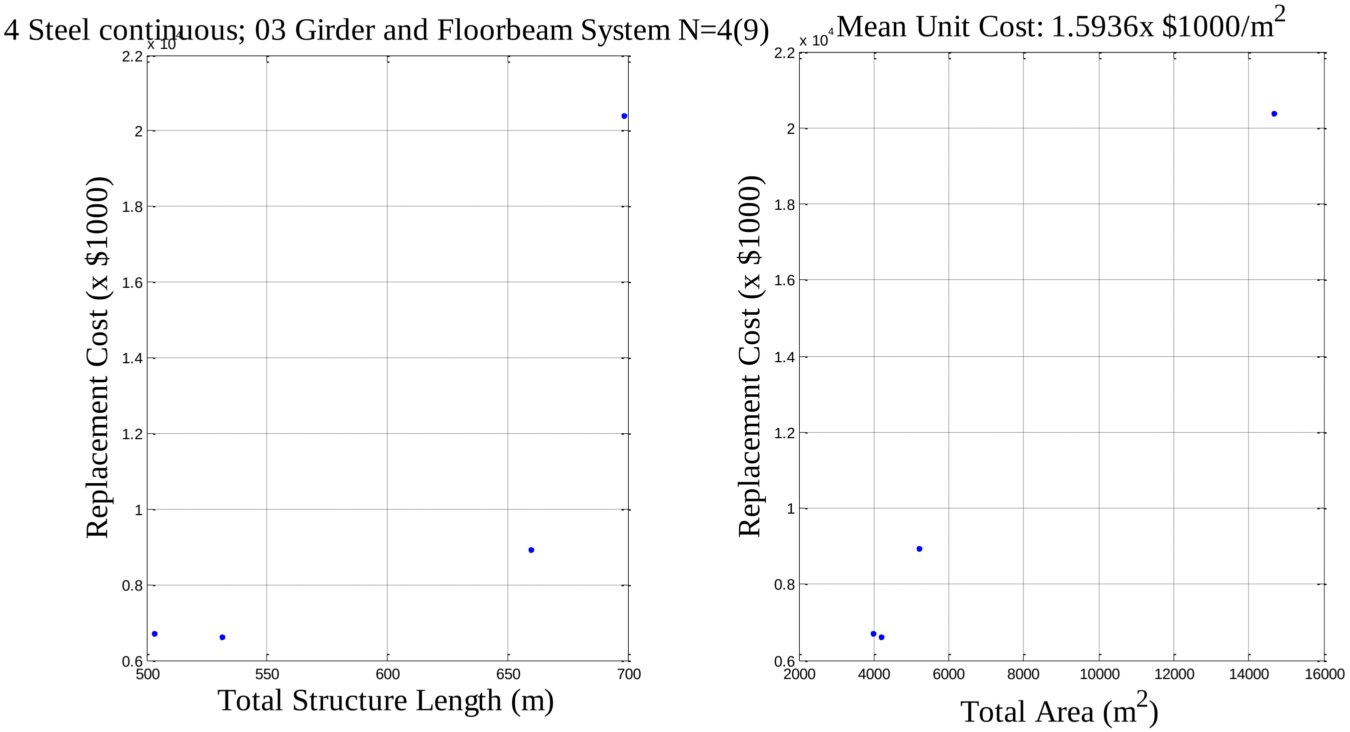


Figure G.23 Cost Model 29

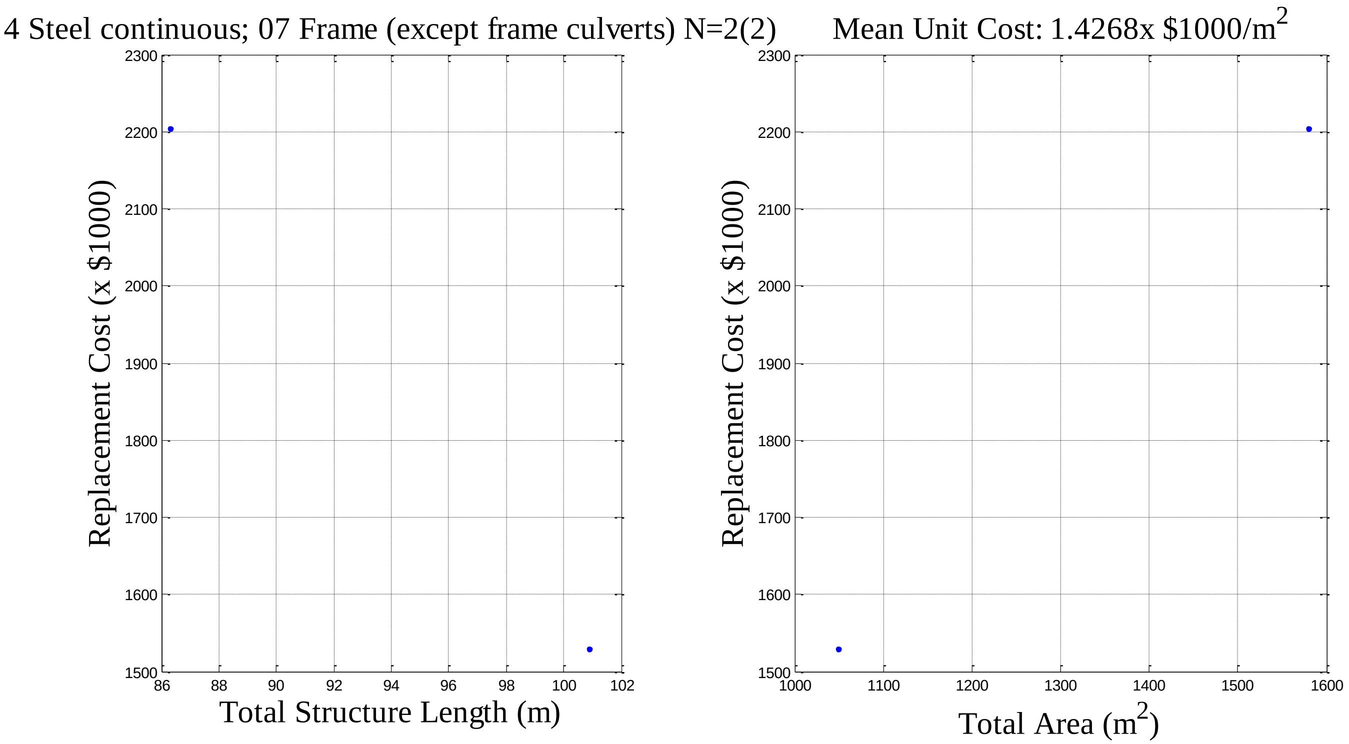


Figure G.24 Cost Model 30

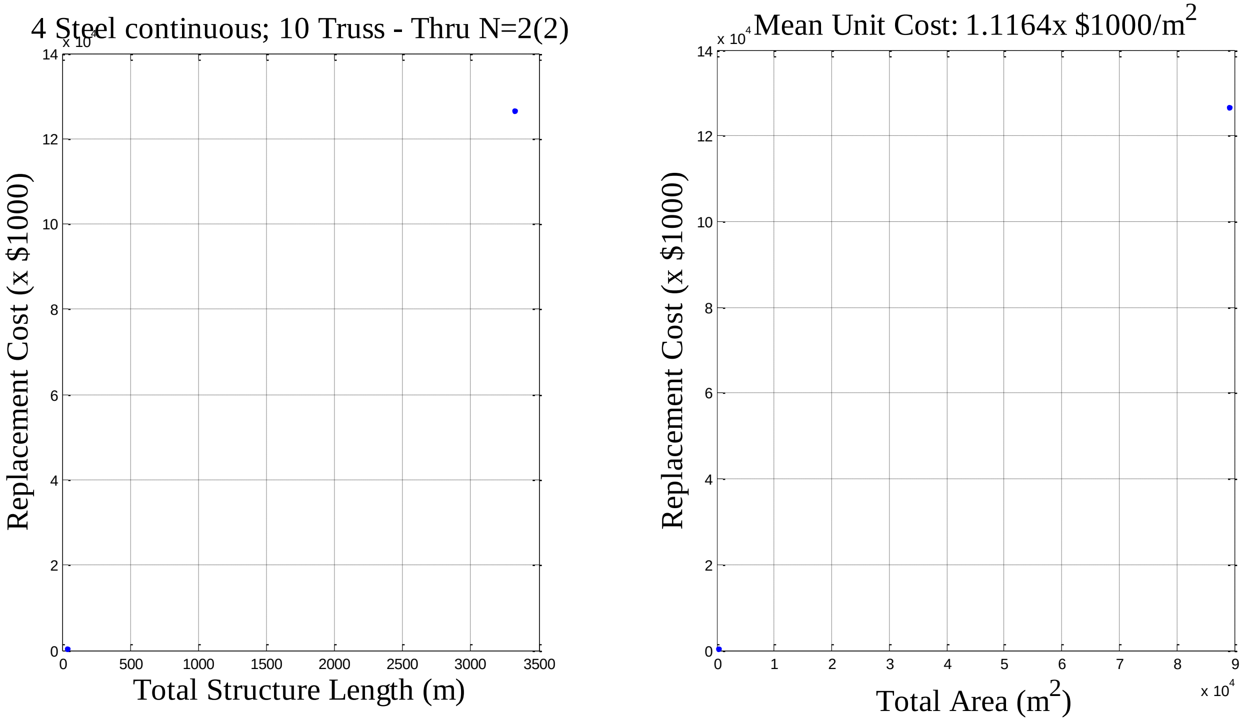


Figure G.25 Cost Model 31

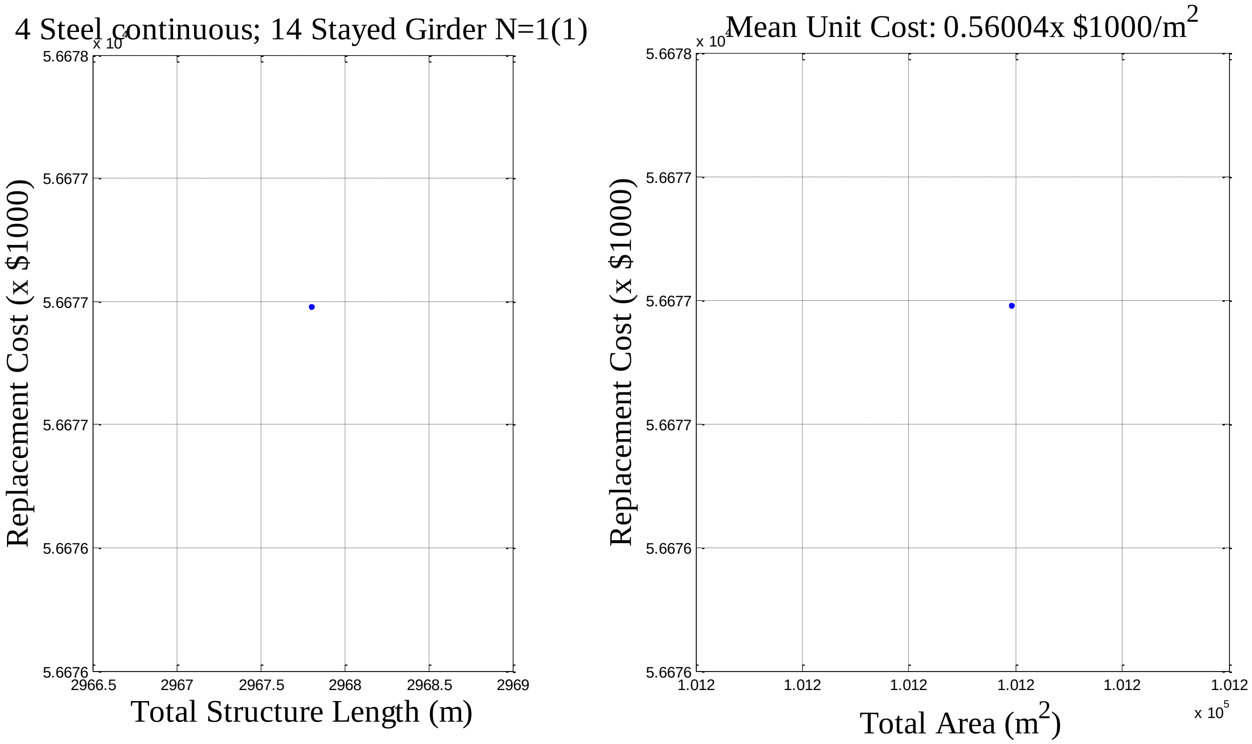
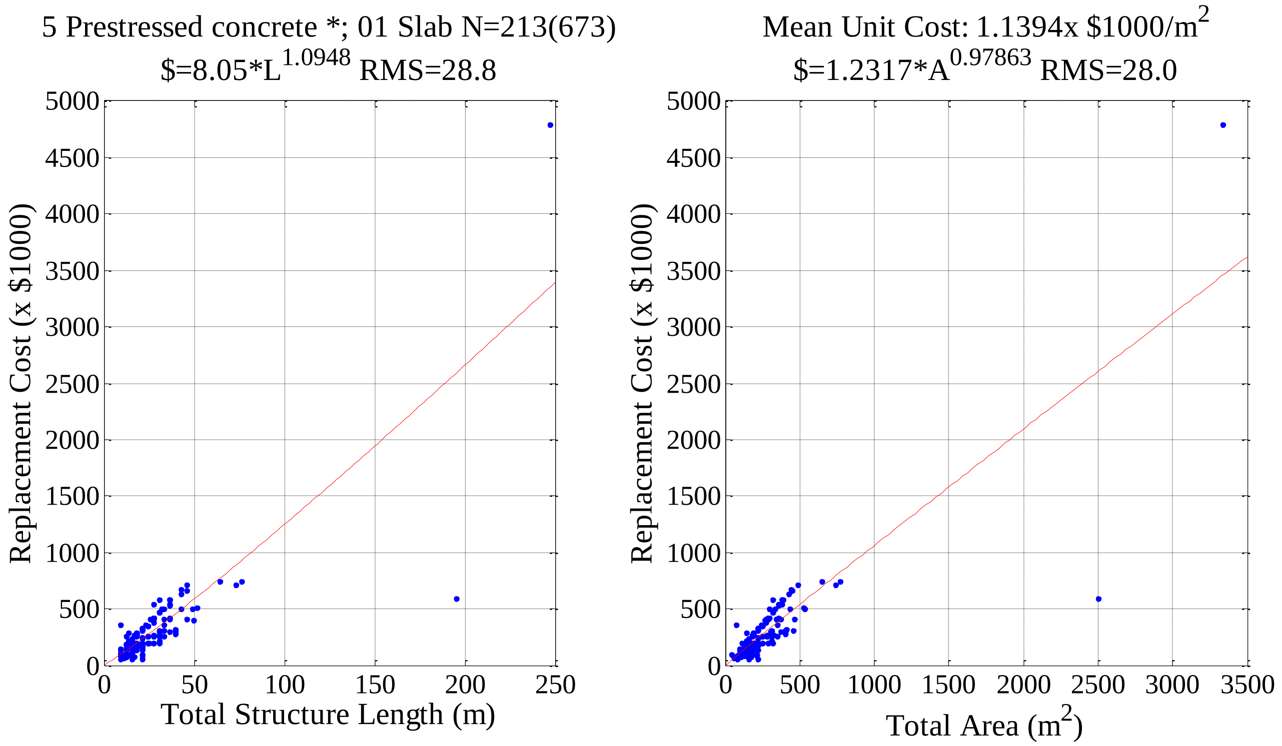


Figure G.26 Cost Model 32



5 Prestressed concrete *; 01 Slab N=213(673)

$\$=8.05*L^{1.0948}$ RMS=28.8

Mean Unit Cost: 1.1394x \$1000/m^2

$\$=1.2317*A^{0.97863}$ RMS=28.0

Figure G.27 Cost Model 34

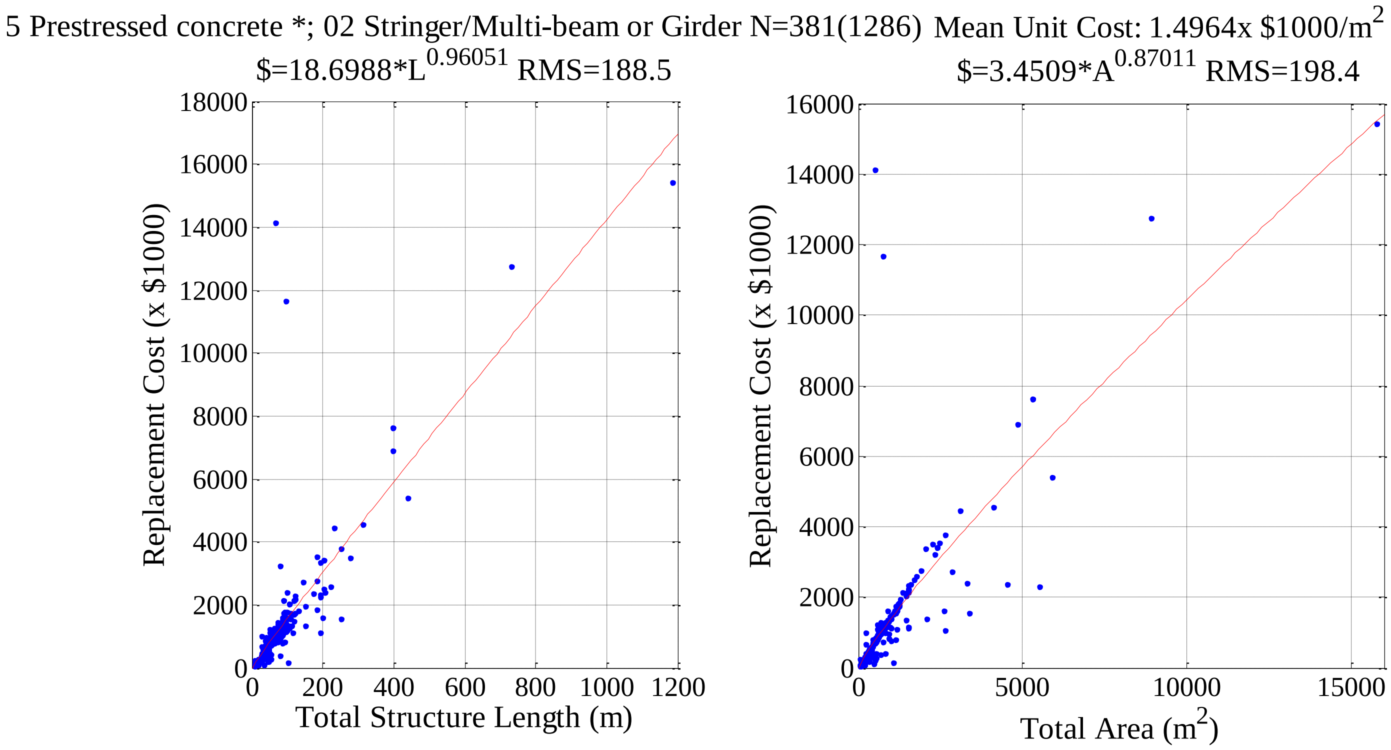


Figure G.28 Cost Model 35

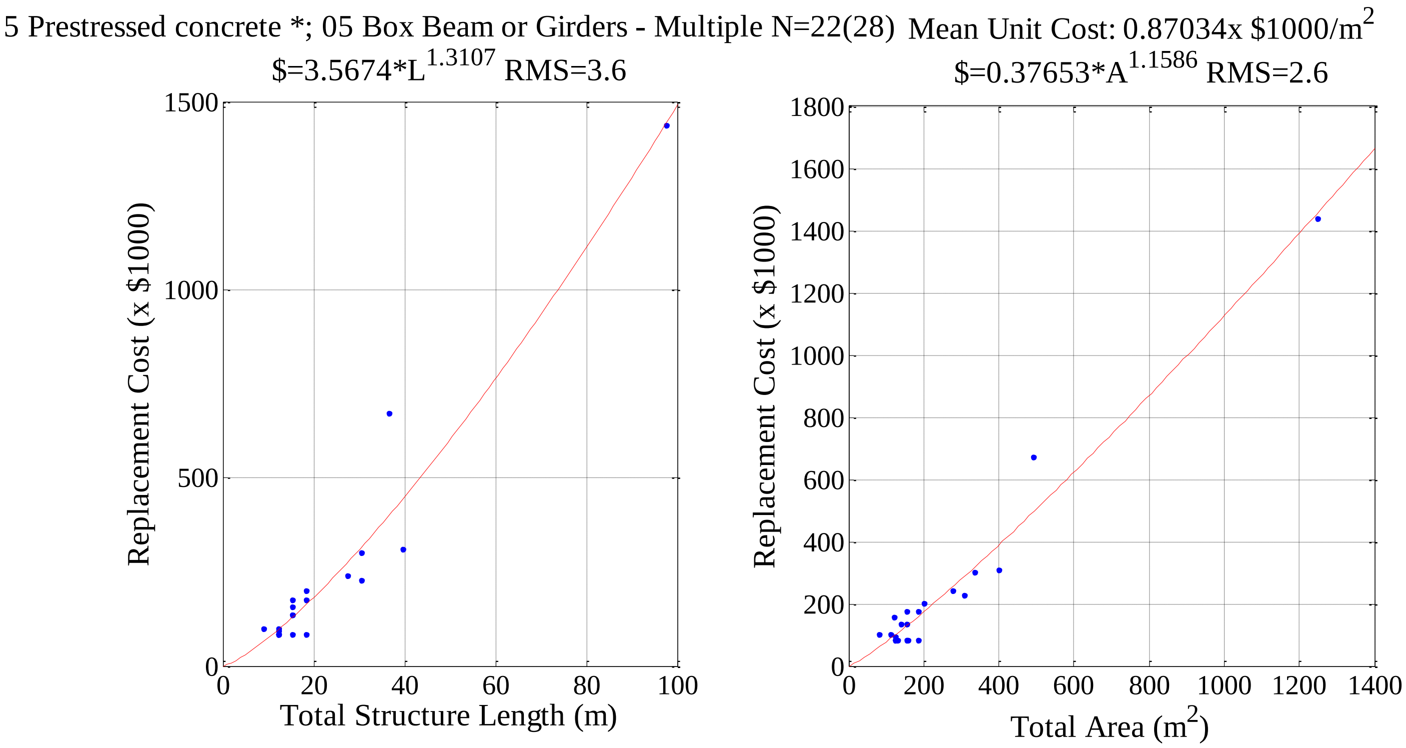


Figure G.29 Cost Model 38

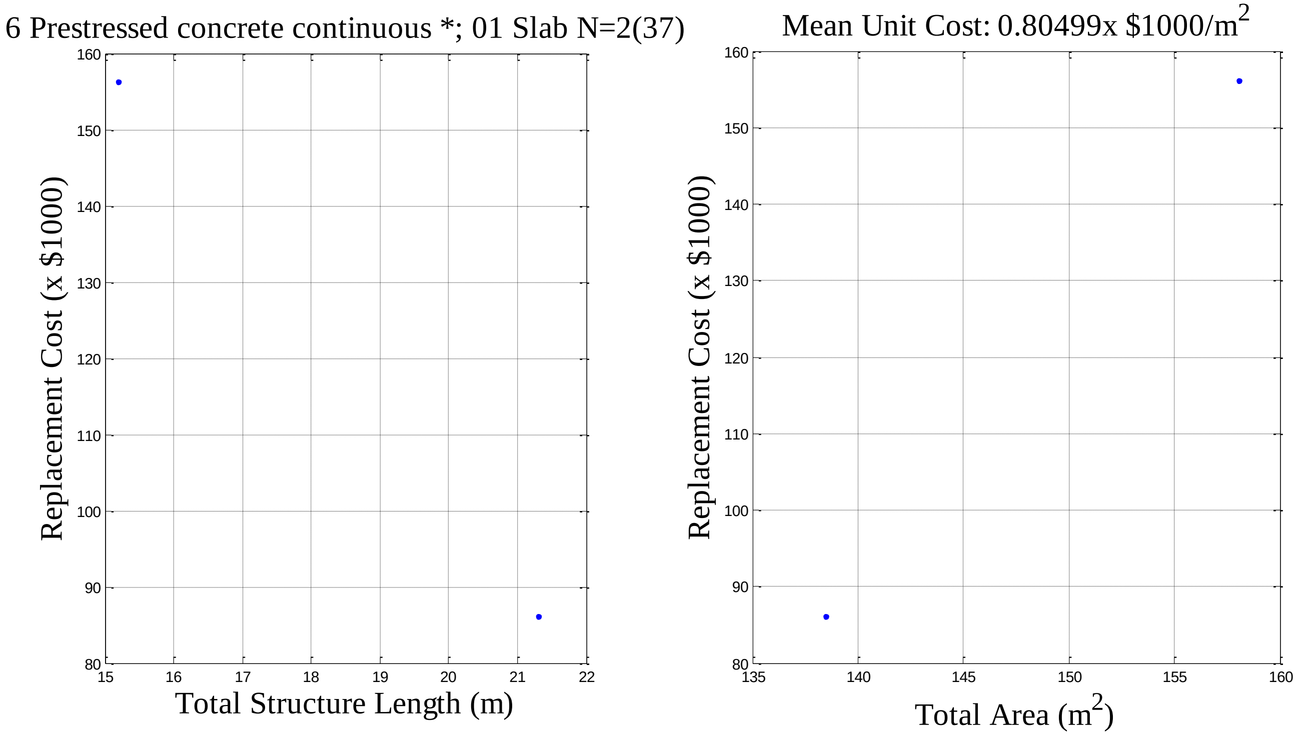


Figure G.30 Cost Model 41

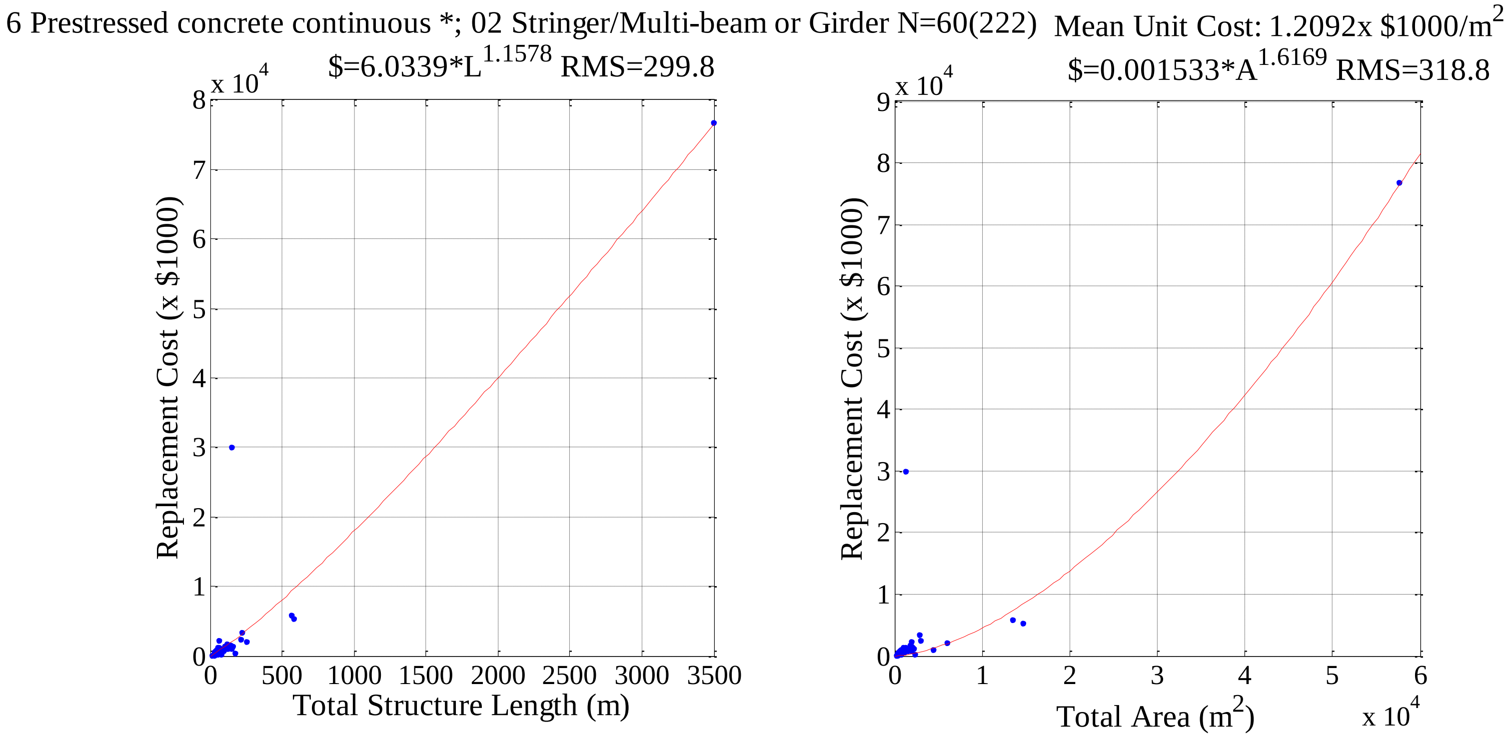


Figure G.31 Cost Model 42

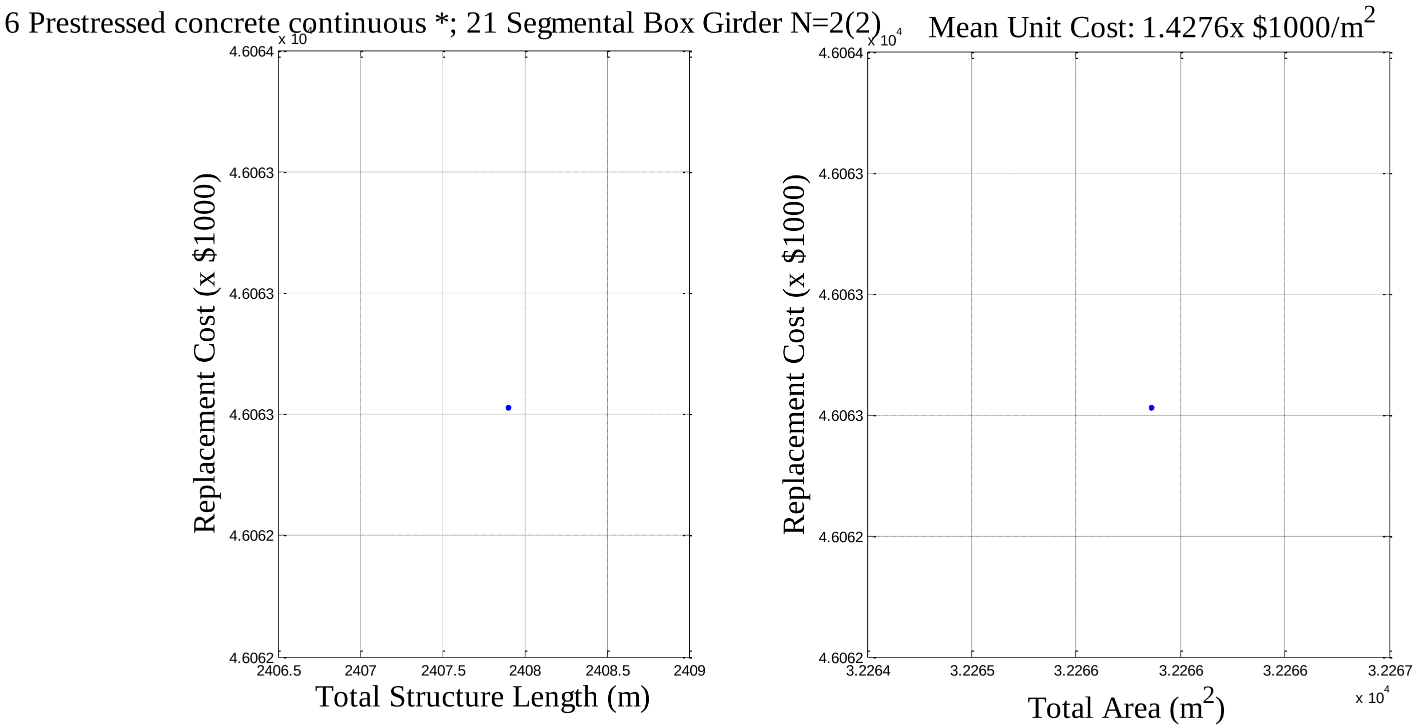


Figure G.32 Cost Model 43

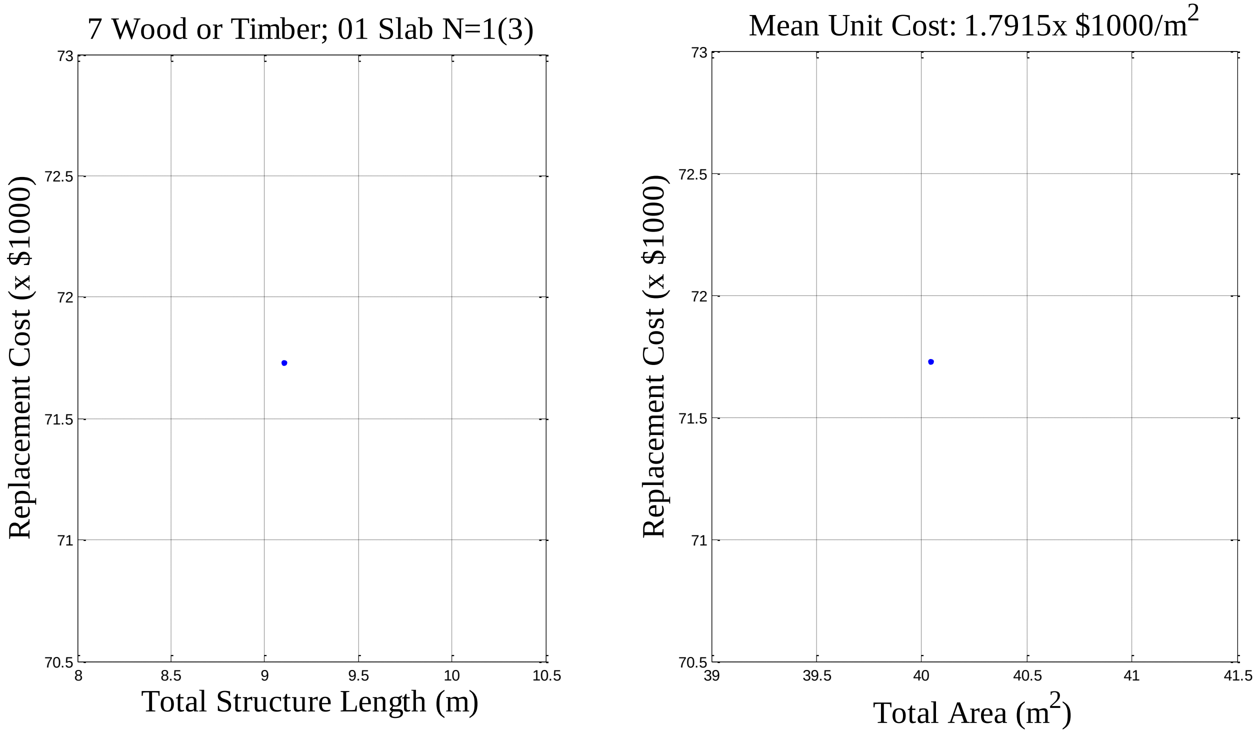


Figure G.33 Cost Model 44

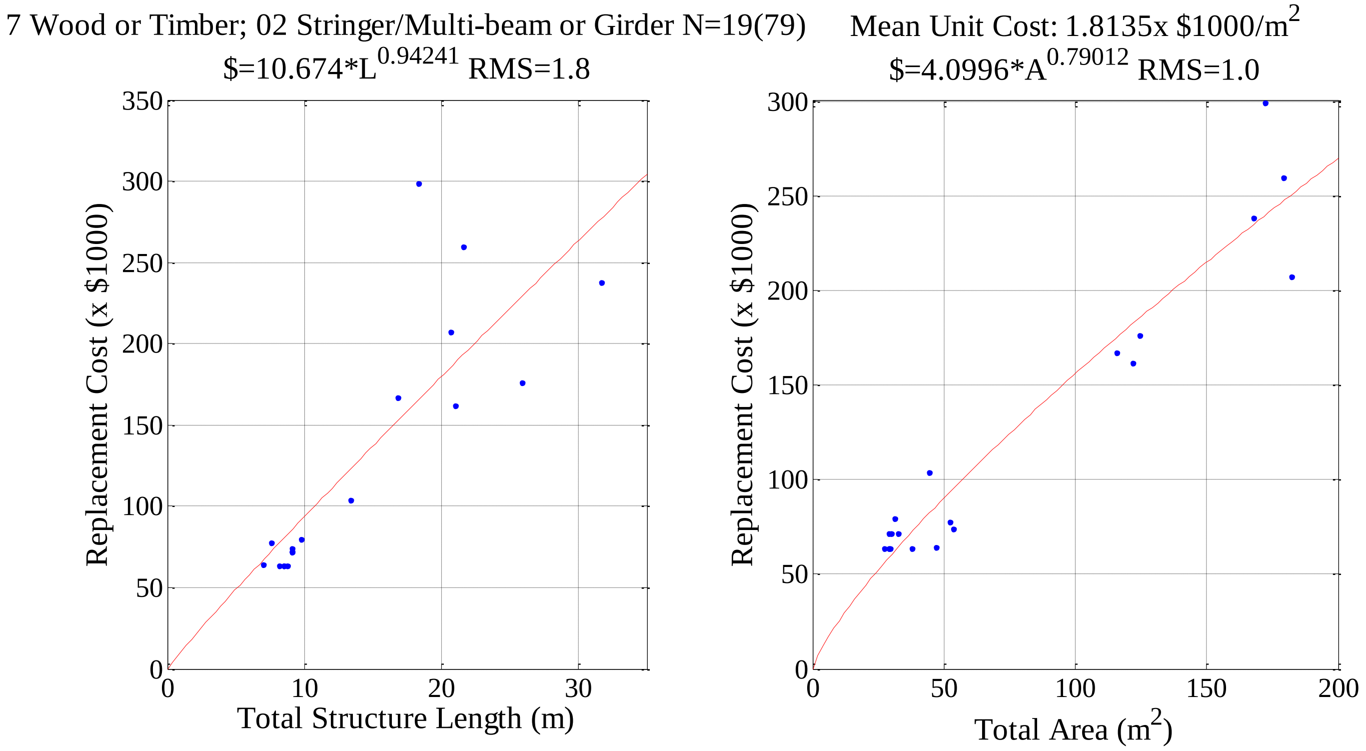


Figure G.34 Cost Model 45

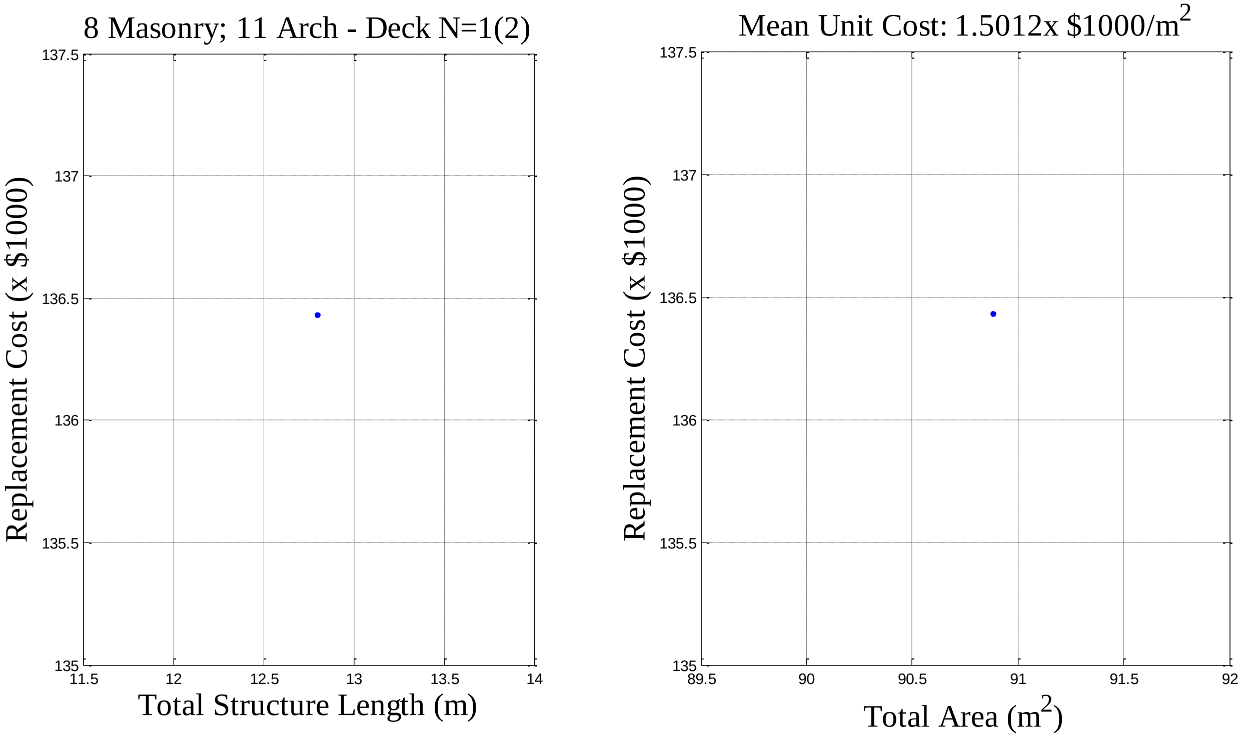


Figure G.35 Cost Model 46

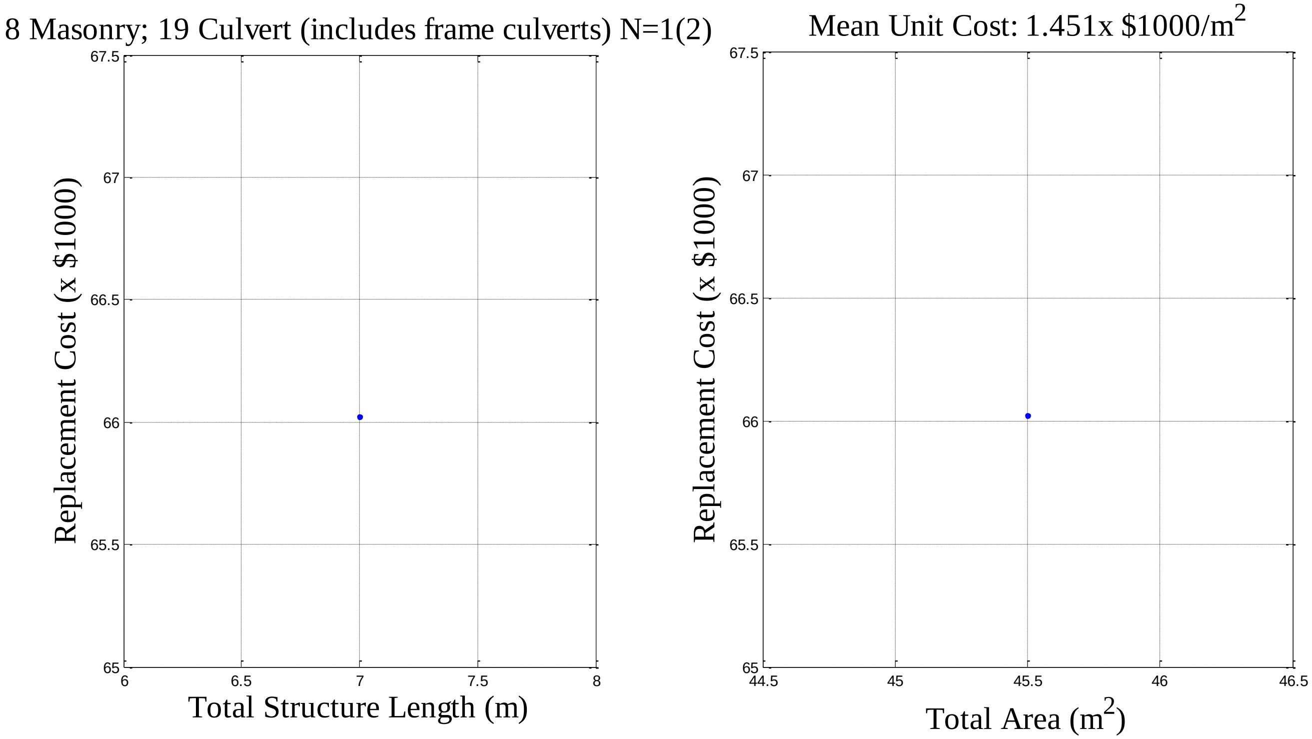


Figure G.36 Cost Model 47

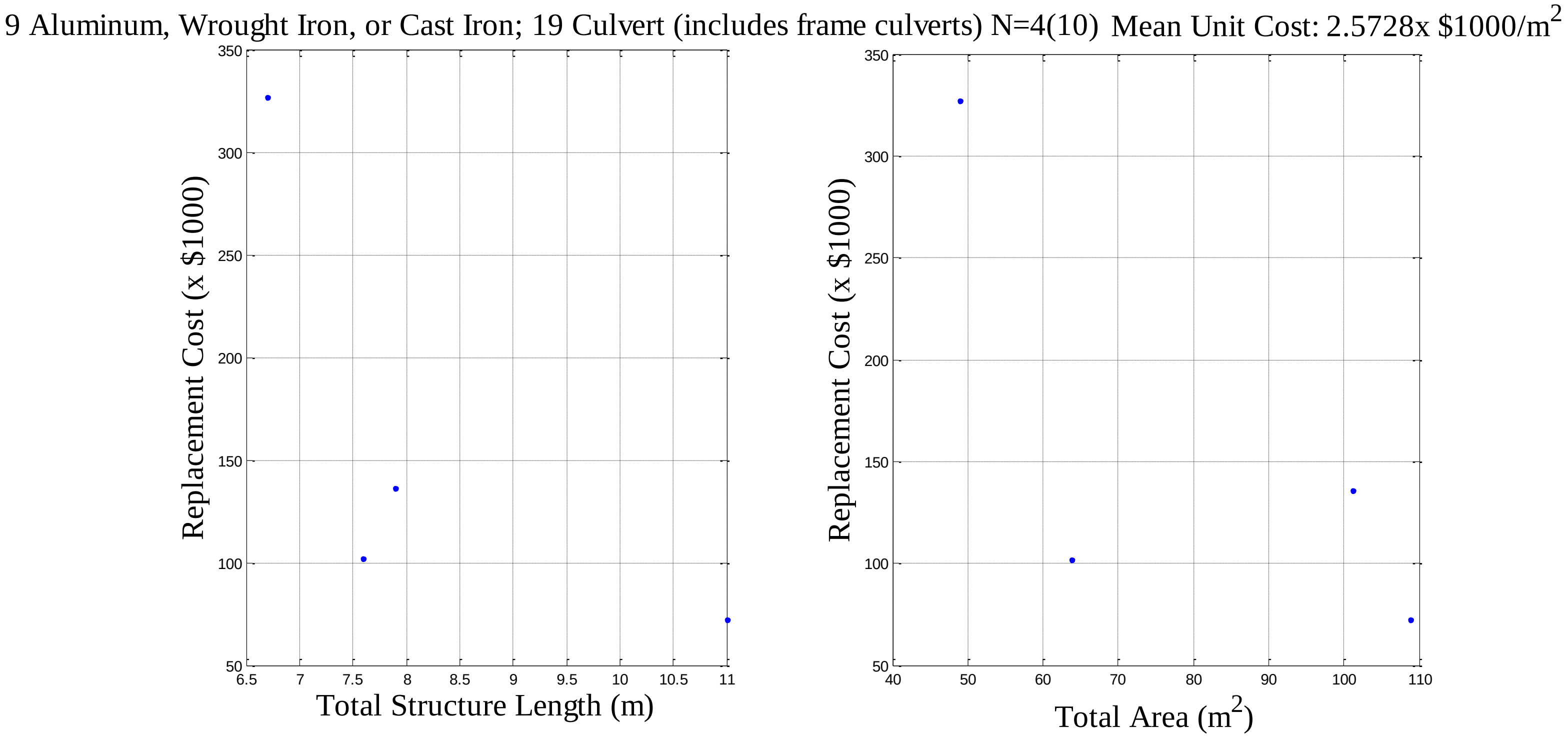


Figure G.37 Cost Model 48

Bridge Replacement Cost Models Assignments

For bridge groups that were unable to establish a cost model or unit area cost, a cost model or unit area cost from a similar bridge group was assigned to this group.

Table G.3 Bridge Cost Models Assignment

Bridge Groups Without A Cost Model or Unit Area Cost			Assigned Cost Model(b)
Cost Model Number	Material Type	Structure Type	Cost Model Number
3	Concrete	Girder and Floor Beam System	4
5	Concrete	Box Beam or Girders - Multiple	
6	Concrete	Frame (except Frame Culverts)	
8	Concrete	Tunnel	
10	Concrete	Channel Beam	
11	Concrete	Other	
15	Concrete Continuous	Box Beam or Girders - Multiple	16
17	Steel	Slab	18
20	Steel	Frame (except Frame Culverts)	
26	Steel	Other	
33	Steel Continuous	Movable - Swing	31
36	Prestressed Concrete	Girder and Floor Beam System	35
37	Prestressed Concrete	Tee Beam	
39	Prestressed Concrete	Channel Beam	
40	Prestressed Concrete	Other	

(a) For cost model details refer to Table G.2.

Appendix H Overweight Trucks Bridge Cost Calculation

Annual Bridge Cost Allocated to Overweight Trucks

Similar to the total annual bridge cost calculation, the annual bridge cost allocated to overweight trucks include two types of costs, namely the bridge fatigue and maintenance costs. The truck models with either gross vehicle weight levels 2 and 3 (GVW2 and GVW3) are considered to be overweight trucks.

The allocation of bridge damage cost was carried out using the damage contribution of the overweight trucks:

$$\mathrm{C_{D,O}} = \frac{\mathrm{D_{GVW2}} + \mathrm{D_{GVW3}}}{\mathrm{D}} \times \mathrm{C_D} \qquad (\mathrm{H.1})$$

where

$\mathrm{C_{D,O}}$: is the annual bridge damage cost allocated to all overweight trucks

$\mathrm{D_{GVW2}}$: is the annual bridge fatigue damage caused by all GVW2 trucks

$\mathrm{D_{GVW3}}$: is the annual bridge fatigue damage caused by all GVW3 trucks

D: is the total annual bridge fatigue damage

$\mathrm{C_D}$: is the annual bridge fatigue damage cost.

In the sample fatigue damage calculation for Archetype 1 to 4 bridges shown in Table F.2 to Table F.5, the overweight trucks are the GVW2 and GVW3 trucks and the normal or non-overweight weight trucks are the GVW1 truck. Table H.1 to Table H.4 present the breakdowns of the damage contributions of normal and overweight trucks for Archetypes 1 to 4 bridges, respectively. The annual fatigue damages caused by the normal weight trucks (Table H.1 to Table H.4) were the same as the annual fatigue damages of the GVW1 trucks in Table F.2 to Table F.5. The annual bridge fatigue damage by overweight trucks was obtained by summing up the annual fatigue damage caused by the GVW2 and GVW3 trucks in Table F.2 to Table F.5. The percent contribution of overweight trucks to the total annual fatigue damage was computed by dividing the damage caused by overweight trucks (GVW2 and GVW3) by the total annual bridge fatigue damage.

Table H.1 Percentage of Damage by Overweight Trucks for Archetype 1 Bridge

Axle Group	Annual Fatigue Damage by Normal Weight Trucks	Annual Fatigue Damage by Overweight Trucks	Total Annual Bridge Fatigue Damage	Percentage Damage by Overweight Trucks
2-Axle	1.15E-03	2.49E-07	1.34%	6.02%
3-Axle	7.54E-04	6.49E-07		
4-Axle	6.09E-04	1.33E-07		
5-Axle	9.75E-03	7.85E-04		
6-Axle	1.50E-04	7.20E-06		
7-Axle	1.48E-04	9.53E-06		
8-Axle	1.35E-06	2.86E-06		

Table H.2 Percentage of Damage by Overweight Trucks for Archetype 2 Bridge

Axle Group	Annual Fatigue Damage by Normal Weight Trucks	Annual Fatigue Damage by Overweight Trucks	Total Annual Bridge Fatigue Damage	Percentage Damage by Overweight Trucks
2-Axle	2.77E-04	8.41E-07	2.62%	51.42%
3-Axle	9.65E-04	3.59E-06		
4-Axle	6.86E-04	2.00E-06		
5-Axle	1.01E-02	1.30E-02		
6-Axle	2.89E-04	7.81E-05		
7-Axle	3.96E-04	2.85E-04		
8-Axle	3.07E-06	7.10E-05		

Table H.3 Percentage of Damage by Overweight Trucks for Archetype 3 Bridge

Axle Group	Annual Fatigue Damage by Normal Weight Trucks	Annual Fatigue Damage by Overweight Trucks	Total Annual Bridge Fatigue Damage	Percentage Damage by Overweight Trucks
2-Axle	1.89E-04	1.54E-07	0.96%	27.83%
3-Axle	3.51E-04	9.56E-07		
4-Axle	2.83E-04	4.16E-07		
5-Axle	5.95E-03	2.58E-03		
6-Axle	7.76E-05	1.60E-05		
7-Axle	1.05E-04	6.99E-05		
8-Axle	7.89E-07	1.96E-05		

Table H.4 Percentage of Damage by Overweight Trucks for Archetype 4 Bridge

Axle Group	Annual Fatigue Damage by Normal Weight Trucks	Annual Fatigue Damage by Overweight Trucks	Total Annual Bridge Fatigue Damage	Percentage Damage by Overweight Trucks
2-Axle	1.75E-04	1.81E-07	1.15%	20.57%
3-Axle	3.70E-04	9.32E-07		
4-Axle	2.72E-04	4.06E-07		
5-Axle	7.97E-03	2.22E-03		
6-Axle	1.36E-04	3.07E-05		
7-Axle	2.00E-04	8.25E-05		
8-Axle	1.35E-06	2.51E-05		

The annual bridge fatigue damage costs allocated to overweight trucks are summarized in Table H.5. It was found that the total annual fatigue damage cost due to overweight trucks is approximately \$8.765 million dollars which is 28.8% of the estimated total annual bridge fatigue damage cost (\$30.446 million dollars, 2012 US Dollar) in South Carolina. While overweight trucks consist of approximately 5.7% of the truck population, they are responsible for 28.8% of the bridge damage cost.

Table H.5 Annual Bridge Fatigue Damage Cost Allocated to Overweight Trucks

Archetype Bridge	Annual Bridge Fatigue Damage Cost (Dollar)	Percentage of Damage by Overweight Trucks	Annual Bridge Fatigue Damage Cost Allocated to Overweight Trucks (Dollar)
A1	3,491,516	6.02%	210,253
A2	5,761,460	51.42%	2,962,326
A3	1,701,961	27.83%	473,591
A4	651,344	20.57%	133,971
Others	18,839,665	26.46%	4,984,628
Total	30,445,947		8,764,769

The allocation of the maintenance cost to the overweight trucks was carried out by percentage of the overweight truck in the total truck population (Equation H.2).

$$\mathrm{C_{M,O}} = \frac{\mathrm{N_{GVW2}} + \mathrm{N_{GVW3}}}{\mathrm{N_{GVW1}} + \mathrm{N_{GVW2}} + \mathrm{N_{GVW3}}} \times \mathrm{C_M} \qquad (\mathrm{H.2})$$

where:

$\mathrm{C_{M,O}}$: is the annual bridge maintenance cost allocated to the overweight trucks

$\mathrm{N_{GVW1}}, \mathrm{N_{GVW2}}, \mathrm{N_{GVW3}}$: are the number of trucks for gross vehicle weight levels GVW1, GVW2 and GVW3, respectively

$\mathrm{C_M}$: is the total annual bridge maintenance cost

According to the NBI database, the total ADT for all bridges in South Carolina was 45,706,454 and the total ADTT for all bridges was 4,316,773 (i.e. 9.44% of traffic was truck). Using the overweight trucks distribution data shown in Table F.17, it was found that around 246,491 of the total ADTT were from the overweight trucks (GVW2 truck and GVW3 truck). Therefore, using Equation (H.3), the annual bridge maintenance cost allocated to the overweight trucks was determined to be (Table H.6).

$$\mathrm{C_{M,O}} = \frac{246{,}491}{45{,}706{,}454} \times 6{,}554{,}992 = 35{,}351\ \mathrm{Dollars} \qquad (\mathrm{H.3})$$

Table H.6: Annual Bridge Maintenance Cost Allocated to Overweight Trucks.

Annual Bridge Maintenance Cost (Dollar)	Annual Bridge Maintenance Cost by Overweight Trucks (Dollar)
6,554,992	35,351

The total annual bridge cost allocated to the overweight trucks was calculated in Equation (H.4) and the results are summarized in Table H.7. The annual bridge cost caused by the overweight trucks is approximately $8.8 million dollars (2012 US Dollar).

$$\mathrm{C_O} = \mathrm{C_{D,O}} + \mathrm{C_{M,O}} \tag{H.4}$$

where

$\mathrm{C_O}$: is the total annual bridge cost allocated to overweight trucks

$\mathrm{C_{D,O}}$: is the annual bridge damage cost allocated to overweight trucks

$\mathrm{C_{M,O}}$: is the annual bridge maintenance cost allocated to overweight trucks

Table H.7: Annual Bridge Cost Allocated to Overweight Trucks.

Annual Bridge Fatigue Damage Cost Allocated to Overweight Trucks (Dollar)	Annual Bridge Maintenance Cost Allocated to Overweight Trucks (Dollar)	Annual Bridge Cost Allocated to Overweight Trucks(Dollar)
8,764,769	35,351	8,800,119

<u>Overweight Trucks Bridge Cost per Mile</u>

There are multiple ways to set the fee structure for overweight permits. A rational method would be to base it on the overweight trucks' unit cost (cost per mile) and then use the mileages travelled of overweight trucks to determine their overweight fee. Because the mileages travelled by overweight trucks include not only bridges but also other infrastructures such as pavement, the overweight trucks' unit cost was calculated as per mile of road travelled, instead of per bridge length travelled. Since trucks with different weights and axle configurations cause different levels of damages, the overweight trucks bridge costs per mile in this research were computed by axle group.

The overweight trucks bridge cost per mile for each axle group was computed as follow:

$$C_{Pj,O} = \frac{C_{Oj}}{VMT_{j,O}} \qquad (H.5)$$

where

C_{Oj}: Daily bridge cost allocated to overweight trucks in each axle group

$VMT_{j,O}$: Daily VMT (vehicle miles travelled) by overweight trucks in the axle group being considered.

j: Axle group

The daily bridge cost allocated to overweight trucks in each axle group consisted of two parts: the daily fatigue damage cost and the daily maintenance cost. The allocation of daily fatigue damage cost to each axle group was carried out using the fatigue damage of overweight trucks in each axle group divided by the total fatigue damage of overweight trucks.

Firstly, the daily bridge fatigue damage cost allocated to overweight trucks was calculated by dividing the annual fatigue costs of overweight trucks (Table H.5) by 365 days. The daily bridge fatigue damage costs caused by overweight trucks are grouped by bridge Archetype and are summarized in Table H.8.

Table H.8 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks

Archetype Bridge	Annual Bridge Fatigue Damage Cost Allocated to Overweight Trucks (Dollar)	Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks (Dollar)
A1	210,253	576
A2	2,962,326	8,116
A3	473,591	1,298
A4	133,971	367
Others	4,984,628	13,657
Total	8,764,769	24,013

Secondly, the above daily costs were then distributed to each axle group based on the percentage of overweight trucks fatigue damage of each axle group in the total overweight trucks fatigue damage as shown in Table H.9 to Table H.12. As seen in these tables, because the 5-axle trucks are the most common trucks, the collective fatigue damages caused by the 5-axle overweight trucks are the highest for all four Archetype bridges.

Table H.9 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks in Each Axle Group for Archetype 1 Bridge

Axle Group	Annual Fatigue Damage by Overweight Trucks	Total Annual Fatigue Damage by Overweight Trucks	Overweight Damage Distribution	Overweight Damage Cost (Dollar)
2-Axle	2.49E-07	0.08%	0.03%	0.18
3-Axle	6.49E-07		0.08%	0.46
4-Axle	1.33E-07		0.02%	0.10
5-Axle	7.85E-04		97.44%	561.28
6-Axle	7.20E-06		0.89%	5.15
7-Axle	9.53E-06		1.18%	6.81
8-Axle	2.86E-06		0.36%	2.05

Table H.10 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks in Each Axle Group for Archetype 2 Bridge

Axle Group	Annual Fatigue Damage by Overweight Trucks	Total Annual Fatigue Damage by Overweight Trucks	Overweight Damage Distribution	Overweight Damage Cost (Dollar)
2-Axle	8.41E-07	1.35%	0.01%	0.51
3-Axle	3.59E-06		0.03%	2.16
4-Axle	2.00E-06		0.01%	1.21
5-Axle	1.30E-02		96.73%	7850.25
6-Axle	7.81E-05		0.58%	47.08
7-Axle	2.85E-04		2.12%	171.97
8-Axle	7.10E-05		0.53%	42.79

Table H.11 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks in Each Axle Group for Archetype 3 Bridge

Axle Group	Annual Fatigue Damage by Overweight Trucks	Total Annual Fatigue Damage by Overweight Trucks	Overweight Damage Distribution	Overweight Damage Cost (Dollar)
2-Axle	1.54E-07	0.27%	0.01%	0.07
3-Axle	9.56E-07		0.04%	0.46
4-Axle	4.16E-07		0.02%	0.20
5-Axle	2.58E-03		96.01%	1245.75
6-Axle	1.60E-05		0.60%	7.75
7-Axle	6.99E-05		2.61%	33.81
8-Axle	1.96E-05		0.73%	9.46

Table H.12 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks in Each Axle Group for Archetype 4 Bridge

Axle Group	Annual Fatigue Damage by Overweight Trucks	Total Annual Fatigue Damage by Overweight Trucks	Overweight Damage Distribution	Overweight Damage Cost (Dollar)
2-Axle	1.81E-07	0.24%	0.01%	0.03
3-Axle	9.32E-07		0.04%	0.14
4-Axle	4.06E-07		0.02%	0.06
5-Axle	2.22E-03		94.08%	345.32
6-Axle	3.07E-05		1.30%	4.77
7-Axle	8.25E-05		3.49%	12.81
8-Axle	2.51E-05		1.06%	3.90

In the above tables, the total annual fatigue damages by overweight trucks were computed using the results shown in Table H.1 to Table H.4 for the four Archetype bridges. For example, the annual fatigue damage to Archetype 1 bridges by all truck traffic was estimated to be 1.34% and overweight trucks responsible for 6.02% of the 1.34% damage (Table H.1). Hence, the annual fatigue damage to Archetype 1 bridges by only the overweight trucks was 0.08% (1.34% x 6.02%) (see Table H.9). The overweight damage distribution for each axle group was computed by dividing the overweight damage of respective axle group by the total overweight damage. Using the overweight damage distribution of axle groups, the daily bridge fatigue damage cost allocated to overweight trucks in each axle group was then computed (Table H.13). For the other bridges (i.e. other than Archetypes 1 to 4), an average ratio from the four Archetype bridges for each axle group was used to compute the daily damage cost contribution of each axle group. Table H.13 summarizes the total daily overweight damage cost for all bridges by axle group.

Table H.13 Daily Bridge Fatigue Damage Cost Allocated to Overweight Trucks in Each Axle Group

Axle Group	A1 Overweight Damage Cost (Dollar)	A2 Overweight Damage Cost (Dollar)	A3 Overweight Damage Cost (Dollar)	A4 Overweight Damage Cost (Dollar)	Other Overweight Damage Cost (Dollar)	Total Overweight Damage Cost (Dollar)
2-Axle	0.18	0.51	0.07	0.03	1.73	2.51
3-Axle	0.46	2.16	0.46	0.14	6.23	9.46
4-Axle	0.10	1.21	0.20	0.06	2.19	3.75
5-Axle	561.28	7850.25	1245.75	345.32	13119.06	23121.67
6-Axle	5.15	47.08	7.75	4.77	115.11	179.86
7-Axle	6.81	171.97	33.81	12.81	320.85	546.26
8-Axle	2.05	42.79	9.46	3.90	91.34	149.55

Recall that the annual bridge maintenance cost allocated to overweight trucks was estimated to be 35,351 dollars (Table H.6), so, the daily bridge maintenance cost allocated to overweight trucks was 97 dollars (35,351/365). This daily maintenance cost was then allocated to each axle group based on the overweight truck proportion of each axle group. In Table H.14, the axle group percentages were determined from weigh-in-motion data (see Table 7) and the percentages of GVW2+GVW3 (i.e. overweight trucks) were calculated from Table A.2. The percentage of overweight trucks for each axle group was calculated as the axle group percentage multiplied by the percentage of GVW2 and GVW3. The relative distribution of overweight trucks for each axle group was obtained using the percentage of overweight trucks for each axle group (column 4 in Table H.14) divided by the total percentage of overweight trucks (5.71%). The daily bridge maintenance costs of overweight trucks by axle group are presented in Table H.15. Because the 5-axle trucks are the most recorded trucks in weigh-in-motion data, the daily bridge maintenance costs of 5-axle overweight trucks is the highest.

Table H.14 Overweight Trucks Relative Distribution

Axle Group	Axle Group Percentage	Percentage of GVW2+GVW3	Percentage of Overweight Trucks	Total Percentage for Overweight Trucks	Overweight Trucks Relative Distribution
2	8.84%	0.02%	0.002%	5.71%	0.03%
3	5.70%	0.08%	0.005%		0.08%
4	4.60%	0.02%	0.001%		0.02%
5	78.49%	7.09%	5.563%		97.42%
6	1.17%	4.46%	0.052%		0.91%
7	1.18%	5.75%	0.068%		1.19%
8	0.03%	67.02%	0.020%		0.35%

Table H.15 Daily Bridge Maintenance Cost Allocated to Overweight Trucks in Each Axle Group

Axle Group	Daily Bridge Maintenance Cost Allocated to Overweight Trucks (Dollar)	Overweight Trucks Relative Distribution	Daily Bridge Maintenance Cost Allocated to Overweight Trucks in Each Axle Group (Dollar)
2-Axle	97	0.03%	0.03
3-Axle		0.08%	0.08
4-Axle		0.02%	0.02
5-Axle		97.42%	94.35
6-Axle		0.91%	0.88
7-Axle		1.19%	1.15
8-Axle		0.35%	0.34

Table H.16 shows the daily bridge cost allocated to overweight trucks in each axle group (C_{Oj}) which is calculated by adding up the daily bridge fatigue damage cost and the daily bridge maintenance cost allocated to overweight trucks in each axle group.

Table H.16 Daily Bridge Cost Allocated to Overweight trucks in Each Axle Group

Axle Group	Daily Bridge Cost Allocated to Overweight Trucks in Each Axle Group (Dollar)
2-Axle	3
3-Axle	10
4-Axle	4
5-Axle	23216
6-Axle	181
7-Axle	547
8-Axle	150

Table H.17 shows the daily vehicle miles travelled (VMT) of overweight trucks in South Carolina categorized by axle group ($VMT_{j,O}$). The VMT for each road was calculated using the ADTT (average daily truck traffic) of the respective road multiplied by the road length. Then the total VMT was computed by adding up the VMT of the road network. The total VMT was further divided into the VMT of overweight truck by axle group (Table H.17).

Table H.17 Overweight VMT Distribution in Each Axle Group

Axle Group	Daily Overweight VMT
2-Axle	241
3-Axle	653
4-Axle	130
5-Axle	759,024
6-Axle	7,096
7-Axle	8,859
8-Axle	2,364

Finally, the overweight truck bridge cost per mile by each axle group was calculated using Equation (H.5), by dividing the daily cost (Table H.16) by the daily

VMT (Table H.17). The overweight truck bridge costs per mile by axle group are shown in Table H.18. It can be seen that the overweight trucks bridge cost per mile increases as the number of axles increases. Trucks with more axles are generally heavier than trucks with fewer axles. Unlike pavement where the damage is mainly governed by the load of axles, for bridges, gross vehicle weight has a more significant impact on the bridge damage than the axle load alone. An example calculation for damage cost per trip is also provided in Table H.18. Assuming a trip length of 100 miles, the corresponding cost for each truck type can easily be calculated by multiplying trip length by the cost per mile (see Table H.18). The results shown in Table H.18 can be used for further analysis for establishing an overweight permit fee structure based on vehicle mile travelled.

Table H.18: Overweight Trucks Bridge Cost per Mile in Each Axle Group

Axle Group	Overweight Trucks Bridge Cost per Mile (Dollar)	Overweight Trucks Bridge Cost per Trip (100 miles)
2-Axle	0.0124	1.24
3-Axle	0.0153	1.53
4-Axle	0.0308	3.08
5-Axle	0.0306	3.06
6-Axle	0.0255	2.55
7-Axle	0.0617	6.17
8-Axle	0.0635	6.35

Appendix I GVW1, GVW2 and GVW3 Trucks Bridge Cost per Mile Calculation

The bridge cost per mile for GVW1, GVW2, GVW3 trucks in each axle group was computed as follow:

For GVW1:

$$\mathrm{C_{Pj,1}} = \frac{\mathrm{C_{1j}}}{\mathrm{VMT_{j,1}}} \tag{I.1}$$

For GVW2:

$$\mathrm{C_{Pj,2}} = \frac{\mathrm{C_{2j}}}{\mathrm{VMT_{j,2}}} \tag{I.2}$$

For GVW3:

$$\mathrm{C_{Pj,3}} = \frac{\mathrm{C_{3j}}}{\mathrm{VMT_{j,3}}} \tag{I.3}$$

where,

$\mathrm{C_{Pj,1}}, \mathrm{C_{Pj,2}}, \mathrm{C_{Pj,3}}$: GVW1, GVW2 and GVW3 truck bridge cost per mile in each axle group, respectively

$\mathrm{C_{1j}}, \mathrm{C_{2j}}, \mathrm{C_{3j}}$: Daily bridge cost allocated to the GVW1, GVW2 and GVW3 trucks in each axle group, respectively

$\mathrm{VMT_{j,1}}, \mathrm{VMT_{j,2}}, \mathrm{VMT_{j,3}}$: Daily VMT (vehicle miles travelled) by the GVW1, GVW2 and GVW3 trucks in the axle group being considered, respectively

j: Axle group

The daily bridge cost allocated to the GVW1, GVW2 and GVW3 trucks in each axle group has two parts: daily fatigue damage cost and daily maintenance cost. The allocation of daily fatigue damage cost was carried out using the fatigue damage contribution of the GVW1, GVW2 and GVW3 trucks in each axle group divided by the total GVW1, GVW2 and GVW3 fatigue damage, respectively.

The daily bridge fatigue damage cost for all bridges in South Carolina is shown in Table I.1.

Table I.1 Daily Bridge Fatigue Damage Cost in South Carolina

Archetype Bridge	Annual Bridge Fatigue Damage Cost (Dollar)	Daily Bridge Fatigue Damage Cost (Dollar)
A1	3,491,516	9,566
A2	5,761,460	15,785
A3	1,701,961	4,663
A4	651,344	1,785
Others	18,839,665	51,616
All	30,445,947	83,414

The daily bridge fatigue damage for GVW1, GVW2 and GVW3 of each axle group which can be found in Table F.2 to Table F.5 for the four Archetype bridges are shown in Table I.2 to Table I.4.

Using the daily cost in Table I.1 multiplied by the respective daily bridge fatigue damage, the daily bridge fatigue damage cost for GVW1, GVW2 and GVW3 of each axle group were calculated and presented in Table I.5 to Table I.7.

Table I.2 Bridge Fatigue Damage Percentage of GVW1 Trucks in Each Axle Group

Axle Group	A1 GVW1 Damage Percentage	A2 GVW1 Damage Percentage	A3 GVW1 Damage Percentage	A4 GVW1 Damage Percentage	Others GVW1 Damage Percentage
2-Axle	8.607%	1.057%	1.964%	1.519%	3.287%
3-Axle	5.639%	3.686%	3.638%	3.216%	4.045%
4-Axle	4.551%	2.621%	2.940%	2.364%	3.119%
5-Axle	72.937%	38.589%	61.728%	69.394%	60.662%
6-Axle	1.124%	1.105%	0.805%	1.187%	1.055%
7-Axle	1.110%	1.514%	1.091%	1.738%	1.363%
8-Axle	0.010%	0.012%	0.008%	0.012%	0.010%

Table I.3 Bridge Fatigue Damage Percentage of GVW2 Trucks in Each Axle Group

Axle Group	A1 GVW2 Damage Percentage	A2 GVW2 Damage Percentage	A3 GVW2 Damage Percentage	A4 GVW2 Damage Percentage	Others GVW2 Damage Percentage
2-Axle	0.0009%	0.0004%	0.0005%	0.0006%	0.0006%
3-Axle	0.0037%	0.0080%	0.0069%	0.0048%	0.0059%
4-Axle	0.0005%	0.0007%	0.0008%	0.0007%	0.0007%
5-Axle	3.7171%	6.9076%	7.3094%	9.1257%	6.7649%
6-Axle	0.0528%	0.2867%	0.1516%	0.2518%	0.1857%
7-Axle	0.0666%	0.8515%	0.3771%	0.4873%	0.4456%
8-Axle	0.0170%	0.1845%	0.1314%	0.1142%	0.1118%

Table I.4 Bridge Fatigue Damage Percentage of GVW3 Trucks in Each Axle Group

Axle Group	A1 GVW3 Damage Percentage	A2 GVW3 Damage Percentage	A3 GVW3 Damage Percentage	A4 GVW3 Damage Percentage	Others GVW3 Damage Percentage
2-Axle	0.0009%	0.0028%	0.0011%	0.0010%	0.0015%
3-Axle	0.0012%	0.0057%	0.0030%	0.0033%	0.0033%
4-Axle	0.0005%	0.0069%	0.0035%	0.0028%	0.0034%
5-Axle	2.1505%	42.8253%	19.4067%	10.2255%	18.6520%
6-Axle	0.0010%	0.0116%	0.0146%	0.0156%	0.0107%
7-Axle	0.0047%	0.2380%	0.3480%	0.2306%	0.2053%
8-Axle	0.0044%	0.0866%	0.0715%	0.1045%	0.0668%

Table I.5 Daily Bridge Fatigue Damage Cost Allocated to GVW1 Trucks in Each Axle Group

Axle Group	A1 GVW1 Damage Cost (Dollar)	A2 GVW1 Damage Cost (Dollar)	A3 GVW1 Damage Cost (Dollar)	A4 GVW1 Damage Cost (Dollar)	Others GVW1 Damage Cost (Dollar)	Total GVW1 Damage Cost (Dollar)
2-Axle	823	167	92	27	1,696	2,805
3-Axle	539	582	170	57	2,088	3,436
4-Axle	435	414	137	42	1,610	2,638
5-Axle	6,977	6,091	2,878	1,238	31,311	48,496
6-Axle	108	174	38	21	545	885
7-Axle	106	239	51	31	704	1,131
8-Axle	1	2	0.38	0.21	5	9

Table I.6 Daily Bridge Fatigue Damage Cost Allocated to GVW2 Trucks in Each Axle Group

Axle Group	A1 GVW2 Damage Cost (Dollar)	A2 GVW2 Damage Cost (Dollar)	A3 GVW2 Damage Cost (Dollar)	A4 GVW2 Damage Cost (Dollar)	Others GVW2 Damage Cost (Dollar)	Total GVW2 Damage Cost (Dollar)
2-Axle	0.09	0.06	0.02	0.01	0.31	0.50
3-Axle	0.35	1.27	0.32	0.09	3.02	5.05
4-Axle	0.05	0.12	0.04	0.01	0.36	0.58
5-Axle	355.57	1,090.35	340.83	162.85	3,491.76	5,441.37
6-Axle	5.06	45.25	7.07	4.49	95.87	157.74
7-Axle	6.37	134.41	17.58	8.70	230.00	397.06
8-Axle	1.63	29.13	6.13	2.04	57.69	96.61

Table I.7 Daily Bridge Fatigue Damage Cost Allocated to GVW3 Trucks in Each Axle Group

Axle Group	A1 GVW3 Damage Cost (Dollar)	A2 GVW3 Damage Cost (Dollar)	A3 GVW3 Damage Cost (Dollar)	A4 GVW3 Damage Cost (Dollar)	Others GVW3 Damage Cost (Dollar)	Total GVW3 Damage Cost (Dollar)
2-Axle	0.09	0.45	0.05	0.02	0.75	1.36
3-Axle	0.12	0.89	0.14	0.06	1.70	2.90
4-Axle	0.05	1.09	0.16	0.05	1.77	3.11
5-Axle	205.71	6,759.90	904.91	182.47	9,627.32	17,680.33
6-Axle	0.10	1.83	0.68	0.28	5.51	8.39
7-Axle	0.45	37.56	16.23	4.12	105.98	164.33
8-Axle	0.42	13.67	3.34	1.87	34.46	53.75

The daily bridge maintenance cost allocated to GVW1, GVW2 and GVW3 of each axle group were calculated in Table I.8 using the percentage of GVW1, GVW2 and GVW3 trucks in each axle group in the total truck population. In Table I.8, the numbers of GVW1, GVW2 and GVW3 trucks in each axle group were calculated using the total ADTT in South Carolina multiplied by their corresponding percentage (see Table A.1 and Table A.2). Then the daily bridge maintenance cost was found by using the numbers of GVW1, GVW2 and GVW3 trucks divided by the total ADT in South Carolina and then multiplied them by the daily bridge total maintenance cost in South Carolina (Table I.8).

Table I.8 Daily Bridge Maintenance Cost Allocated to GVW1, GVW2 and GVW3 Trucks in Each Axle Group

Axle Group	Total ADTT in SC	Total ADT in SC	Daily Bridge Total Maintenance Cost in SC (Dollar)	Number of GVW1 Trucks	Daily Bridge Maintenance for GVW1 Trucks	Number of GVW2 Trucks	Daily Bridge Maintenance for GVW2 Trucks	Number of GVW3 Trucks	Daily Bridge Maintenance for GVW3 Trucks
2-Axle	4,316,773	45,706,454	17,959	381,351	149.84	38	0.01	38	0.01
3-Axle				245,841	96.60	158	0.06	49	0.02
4-Axle				198,429	77.97	21	0.01	20	0.01
5-Axle				3,147,951	1,236.89	158,002	62.08	82,130	32.27
6-Axle				48,089	18.90	2,204	0.87	41	0.02
7-Axle				47,926	18.83	2,752	1.08	171	0.07
8-Axle				427	0.17	702	0.28	166	0.07

The total daily bridge costs for GVW1, GVW2 and GVW3 trucks of each axle group were computed by adding up their corresponding allocated daily bridge fatigue damage cost and allocated daily bridge maintenance cost (Table I.9).

Table I.9 Daily Bridge Cost Allocated to GVW1, GVW2 and GVW3 Trucks in Each Axle Group

Axle Group	Daily Bridge Cost Allocated to GVW1 Trucks in Each Axle Group (Dollar)	Daily Bridge Cost Allocated to GVW2 Trucks in Each Axle Group (Dollar)	Daily Bridge Cost Allocated to GVW3 Trucks in Each Axle Group (Dollar)
2-Axle	2,955.13	0.51	1.37
3-Axle	3,532.59	5.11	2.92
4-Axle	2,716.37	0.59	3.12
5-Axle	49,732.77	5,503.45	17,712.60
6-Axle	904.36	158.60	8.41
7-Axle	1,149.46	398.14	164.39
8-Axle	8.98	96.88	53.82

Finally, using the daily VMT for GVW1, GVW2 and GVW3 trucks of each axle group shown in Table I.10, the bridge costs per mile for GVW1, GVW2 and GVW3 trucks of each axle group were calculated in Table I.11.

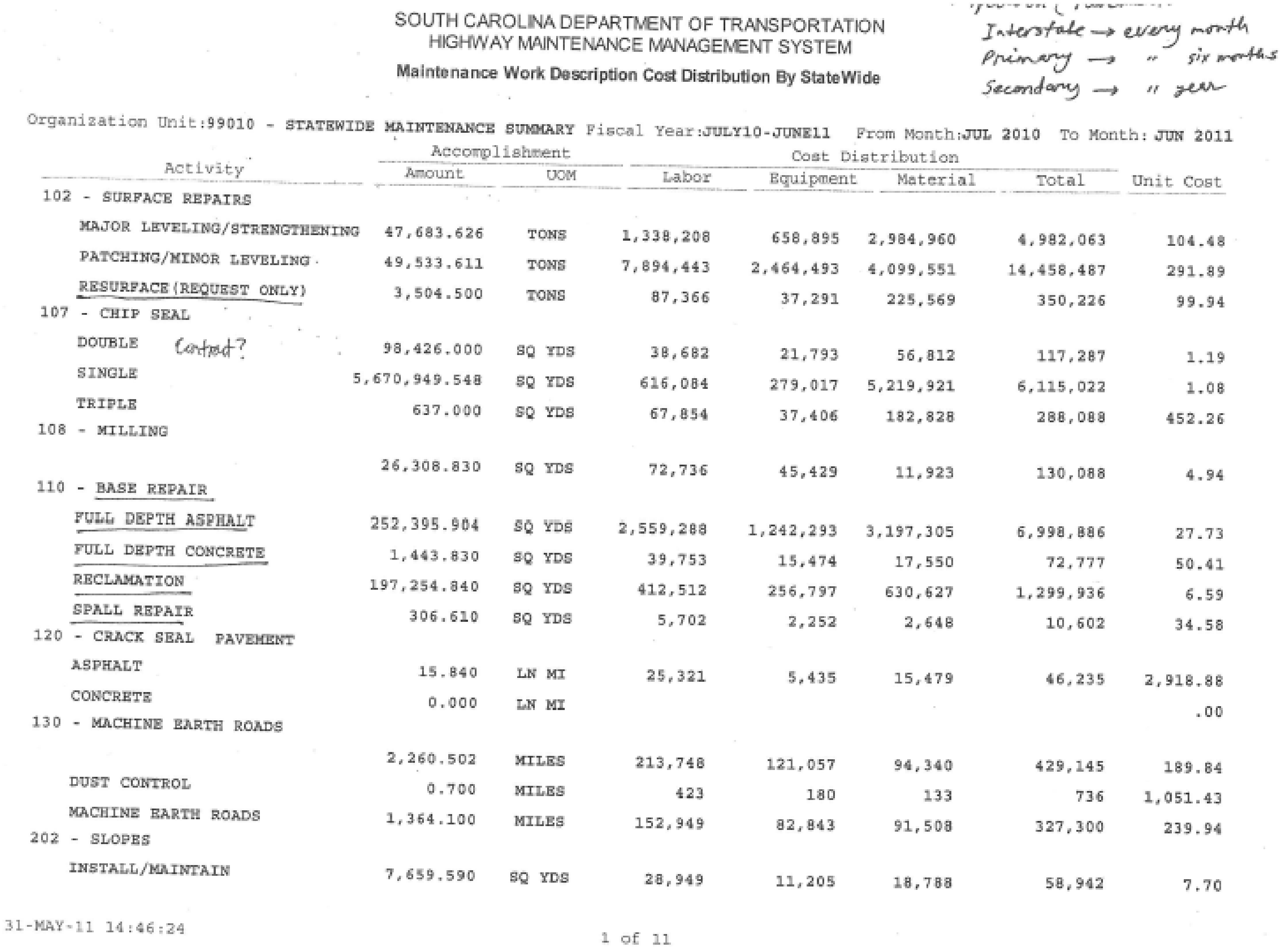
Table I.10 GVW1, GVW2 and GVW3 VMT Distribution in Each Axle Group

Axle Group	VMT for GVW1	VMT for GVW2	VMT for GVW3
2-Axle	1,205,400	121	121
3-Axle	777,070	498	155
4-Axle	627,207	67	63
5-Axle	9,950,246	499,422	259,602
6-Axle	152,004	6,968	129
7-Axle	151,300	8,391	468
8-Axle	1,164	1,912	452

Table I.11 GVW1, GVW2 and GVW3 Trucks Bridge Cost per Mile in Each Axle Group

Axle Group	GVW1 Trucks Bridge Cost per Mile (Dollar)	GVW2 Trucks Bridge Cost per Mile (Dollar)	GVW3 Trucks Bridge Cost per Mile (Dollar)
2-Axle	0.0025	0.0042	0.0113
3-Axle	0.0045	0.0103	0.0188
4-Axle	0.0043	0.0088	0.0497
5-Axle	0.0050	0.0110	0.0682
6-Axle	0.0059	0.0228	0.0654
7-Axle	0.0076	0.0475	0.3512
8-Axle	0.0077	0.0507	0.1191

Appendix J SCDOT Maintenance Cost Schedule from Jul 2010 to June 2011



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Maintenance Work Description Cost Distribution By StateWide

Interstate → every month
Primary → " six months
Secondary → " year

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
102 - SURFACE REPAIRS							
MAJOR LEVELING/STRENGTHENING	47,683.626	TONS	1,338,208	658,895	2,984,960	4,982,063	104.48
PATCHING/MINOR LEVELING	49,533.611	TONS	7,894,443	2,464,493	4,099,551	14,458,487	291.89
RESURFACE(REQUEST ONLY)	3,504.500	TONS	87,366	37,291	225,569	350,226	99.94
107 - CHIP SEAL							
DOUBLE Contract?	98,426.000	SQ YDS	38,682	21,793	56,812	117,287	1.19
SINGLE	5,670,949.548	SQ YDS	616,084	279,017	5,219,921	6,115,022	1.08
TRIPLE	637.000	SQ YDS	67,854	37,406	182,828	288,088	452.26
108 - MILLING							
	26,308.830	SQ YDS	72,736	45,429	11,923	130,088	4.94
110 - BASE REPAIR							
FULL DEPTH ASPHALT	252,395.904	SQ YDS	2,559,288	1,242,293	3,197,305	6,998,886	27.73
FULL DEPTH CONCRETE	1,443.830	SQ YDS	39,753	15,474	17,550	72,777	50.41
RECLAMATION	197,254.840	SQ YDS	412,512	256,797	630,627	1,299,936	6.59
SPALL REPAIR	306.610	SQ YDS	5,702	2,252	2,648	10,602	34.58
120 - CRACK SEAL PAVEMENT							
ASPHALT	15.840	LN MI	25,321	5,435	15,479	46,235	2,918.88
CONCRETE	0.000	LN MI					.00
130 - MACHINE EARTH ROADS							
	2,260.502	MILES	213,748	121,057	94,340	429,145	189.84
DUST CONTROL	0.700	MILES	423	180	133	736	1,051.43
MACHINE EARTH ROADS	1,364.100	MILES	152,949	82,843	91,508	327,300	239.94
202 - SLOPES							
INSTALL/MAINTAIN	7,659.590	SQ YDS	28,949	11,205	18,788	58,942	7.70

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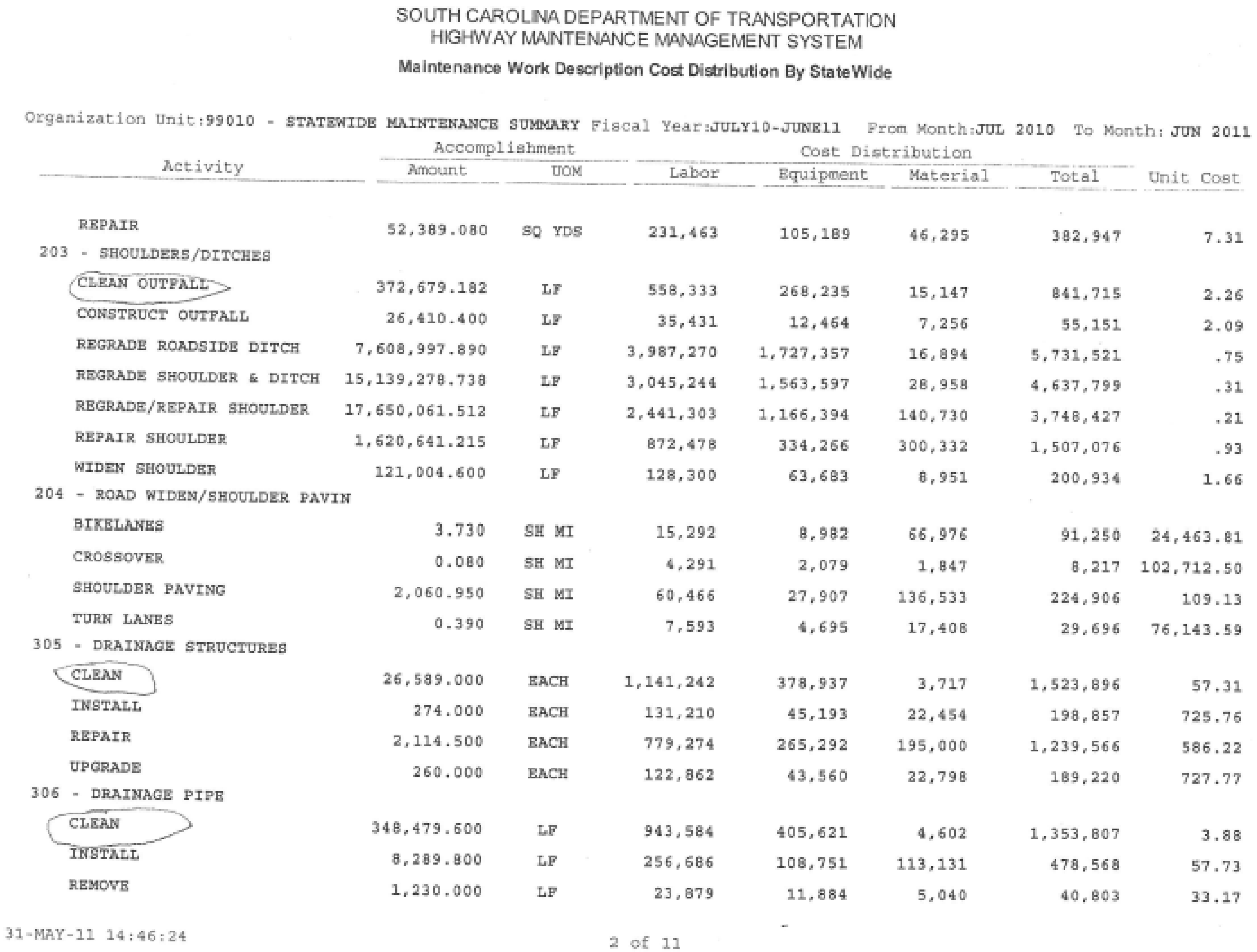
Figure J.1 SCDOT Maintenance Cost Schedule 1



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
REPAIR	52,389.080	SQ YDS	231,463	105,189	46,295	382,947	7.31
203 - SHOULDERS/DITCHES							
CLEAN OUTFALL	372,679.182	LF	558,333	268,235	15,147	841,715	2.26
CONSTRUCT OUTFALL	26,410.400	LF	35,431	12,464	7,256	55,151	2.09
REGRADE ROADSIDE DITCH	7,608,997.890	LF	3,987,270	1,727,357	16,894	5,731,521	.75
REGRADE SHOULDER & DITCH	15,139,278.738	LF	3,045,244	1,563,597	28,958	4,637,799	.31
REGRADE/REPAIR SHOULDER	17,650,061.512	LF	2,441,303	1,166,394	140,730	3,748,427	.21
REPAIR SHOULDER	1,620,641.215	LF	872,478	334,266	300,332	1,507,076	.93
WIDEN SHOULDER	121,004.600	LF	128,300	63,683	8,951	200,934	1.66
204 - ROAD WIDEN/SHOULDER PAVIN							
BIKELANES	3.730	SH MI	15,292	8,982	66,976	91,250	24,463.81
CROSSOVER	0.080	SH MI	4,291	2,079	1,847	8,217	102,712.50
SHOULDER PAVING	2,060.950	SH MI	60,466	27,907	136,533	224,906	109.13
TURN LANES	0.390	SH MI	7,593	4,695	17,408	29,696	76,143.59
305 - DRAINAGE STRUCTURES							
CLEAN	26,589.000	EACH	1,141,242	378,937	3,717	1,523,896	57.31
INSTALL	274.000	EACH	131,210	45,193	22,454	198,857	725.76
REPAIR	2,114.500	EACH	779,274	265,292	195,000	1,239,566	586.22
UPGRADE	260.000	EACH	122,862	43,560	22,798	189,220	727.77
306 - DRAINAGE PIPE							
CLEAN	348,479.600	LF	943,584	405,621	4,602	1,353,807	3.88
INSTALL	8,289.800	LF	256,686	108,751	113,131	478,568	57.73
REMOVE	1,230.000	LF	23,879	11,884	5,040	40,803	33.17

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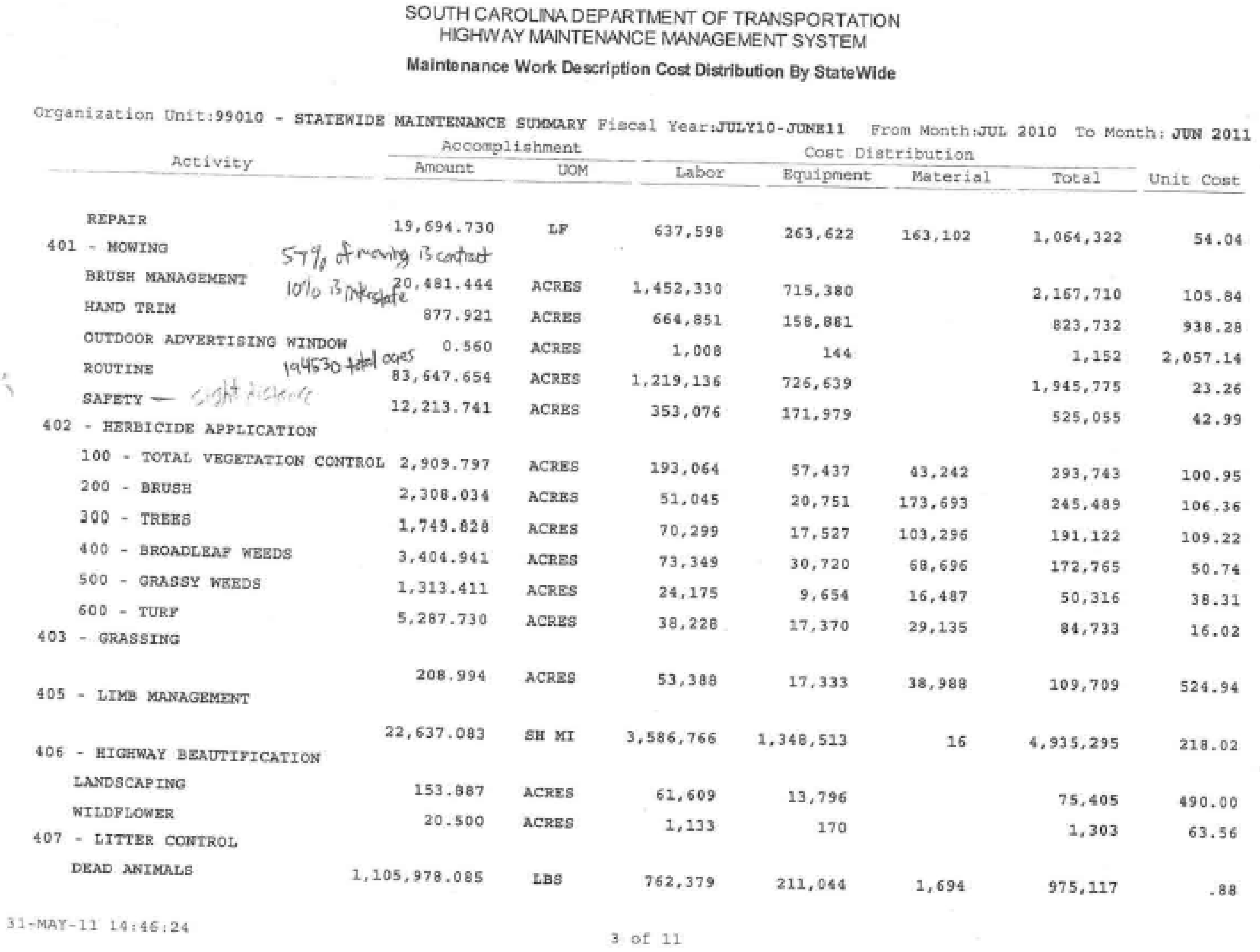
Figure J.2 SCDOT Maintenance Cost Schedule 2



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
REPAIR	19,694.730	LF	637,598	263,622	163,102	1,064,322	54.04
401 - MOWING 57% of mowing is contract							
BRUSH MANAGEMENT 10% is interstate	20,481.444	ACRES	1,452,330	715,380		2,167,710	105.84
HAND TRIM	877.921	ACRES	664,851	158,881		823,732	938.28
OUTDOOR ADVERTISING WINDOW	0.560	ACRES	1,008	144		1,152	2,057.14
ROUTINE 194530 total acres	83,647.654	ACRES	1,219,136	726,639		1,945,775	23.26
SAFETY — sight distance	12,213.741	ACRES	353,076	171,979		525,055	42.99
402 - HERBICIDE APPLICATION							
100 - TOTAL VEGETATION CONTROL	2,909.797	ACRES	193,064	57,437	43,242	293,743	100.95
200 - BRUSH	2,308.034	ACRES	51,045	20,751	173,693	245,489	106.36
300 - TREES	1,749.828	ACRES	70,299	17,527	103,296	191,122	109.22
400 - BROADLEAF WEEDS	3,404.941	ACRES	73,349	30,720	68,696	172,765	50.74
500 - GRASSY WEEDS	1,313.411	ACRES	24,175	9,654	16,487	50,316	38.31
600 - TURF	5,287.730	ACRES	38,228	17,370	29,135	84,733	16.02
403 - GRASSING	208.994	ACRES	53,388	17,333	38,988	109,709	524.94
405 - LIMB MANAGEMENT	22,637.083	SH MI	3,586,766	1,348,513	16	4,935,295	218.02
406 - HIGHWAY BEAUTIFICATION							
LANDSCAPING	153.887	ACRES	61,609	13,796		75,405	490.00
WILDFLOWER	20.500	ACRES	1,133	170		1,303	63.56
407 - LITTER CONTROL							
DEAD ANIMALS	1,105,978.085	LBS	762,379	211,044	1,694	975,117	.88

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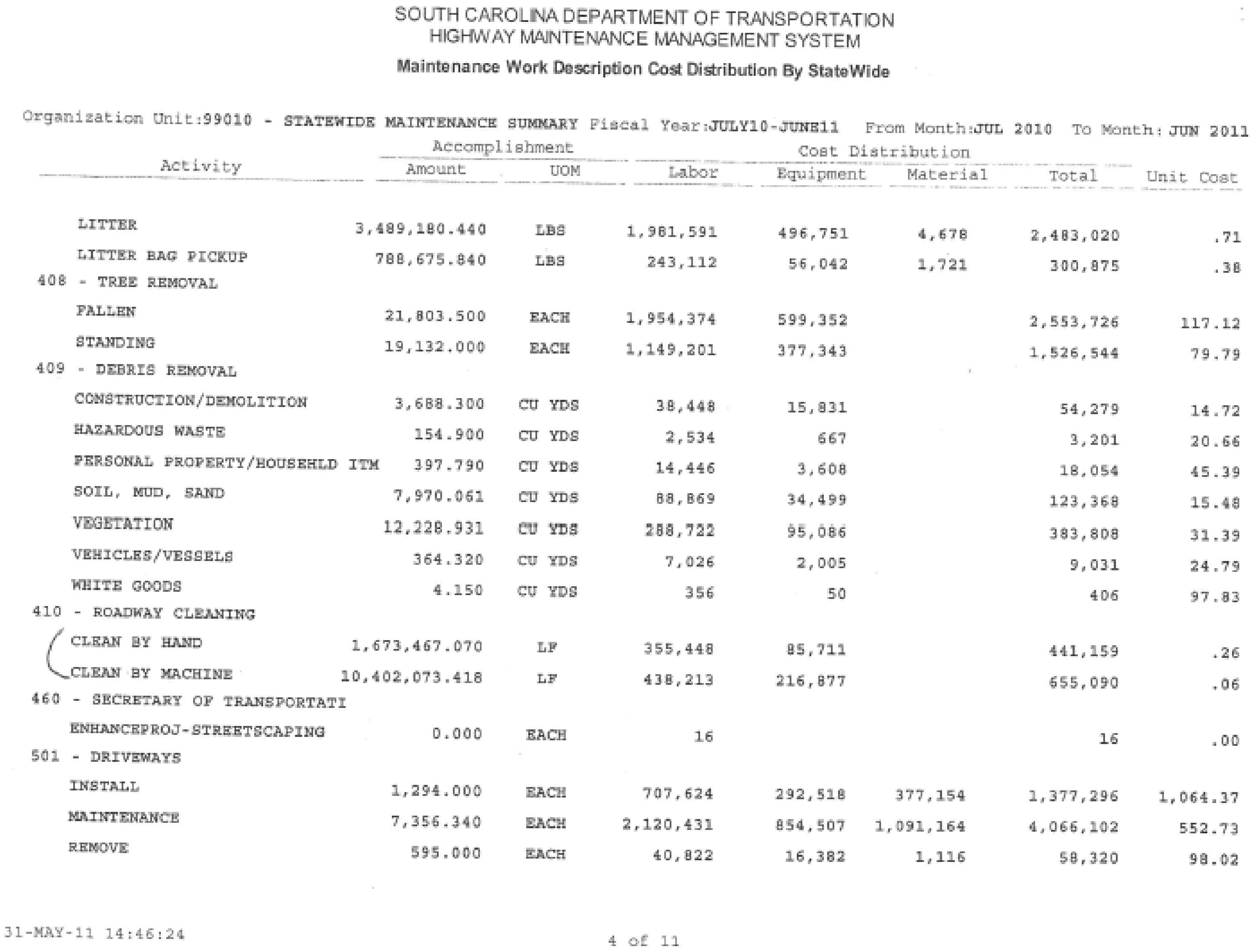
Figure J.3 SCDOT Maintenance Cost Schedule 3



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
LITTER	3,489,180.440	LBS	1,981,591	496,751	4,678	2,483,020	.71
LITTER BAG PICKUP	788,675.840	LBS	243,112	56,042	1,721	300,875	.38
408 - TREE REMOVAL							
FALLEN	21,803.500	EACH	1,954,374	599,352		2,553,726	117.12
STANDING	19,132.000	EACH	1,149,201	377,343		1,526,544	79.79
409 - DEBRIS REMOVAL							
CONSTRUCTION/DEMOLITION	3,688.300	CU YDS	38,448	15,831		54,279	14.72
HAZARDOUS WASTE	154.900	CU YDS	2,534	667		3,201	20.66
PERSONAL PROPERTY/HOUSEHLD ITM	397.790	CU YDS	14,446	3,608		18,054	45.39
SOIL, MUD, SAND	7,970.061	CU YDS	88,869	34,499		123,368	15.48
VEGETATION	12,228.931	CU YDS	288,722	95,086		383,808	31.39
VEHICLES/VESSELS	364.320	CU YDS	7,026	2,005		9,031	24.79
WHITE GOODS	4.150	CU YDS	356	50		406	97.83
410 - ROADWAY CLEANING							
CLEAN BY HAND	1,673,467.070	LF	355,448	85,711		441,159	.26
CLEAN BY MACHINE	10,402,073.418	LF	438,213	216,877		655,090	.06
460 - SECRETARY OF TRANSPORTATI							
ENHANCEPROJ-STREETSCAPING	0.000	EACH	16			16	.00
501 - DRIVEWAYS							
INSTALL	1,294.000	EACH	707,624	292,518	377,154	1,377,296	1,064.37
MAINTENANCE	7,356.340	EACH	2,120,431	854,507	1,091,164	4,066,102	552.73
REMOVE	595.000	EACH	40,822	16,382	1,116	58,320	98.02

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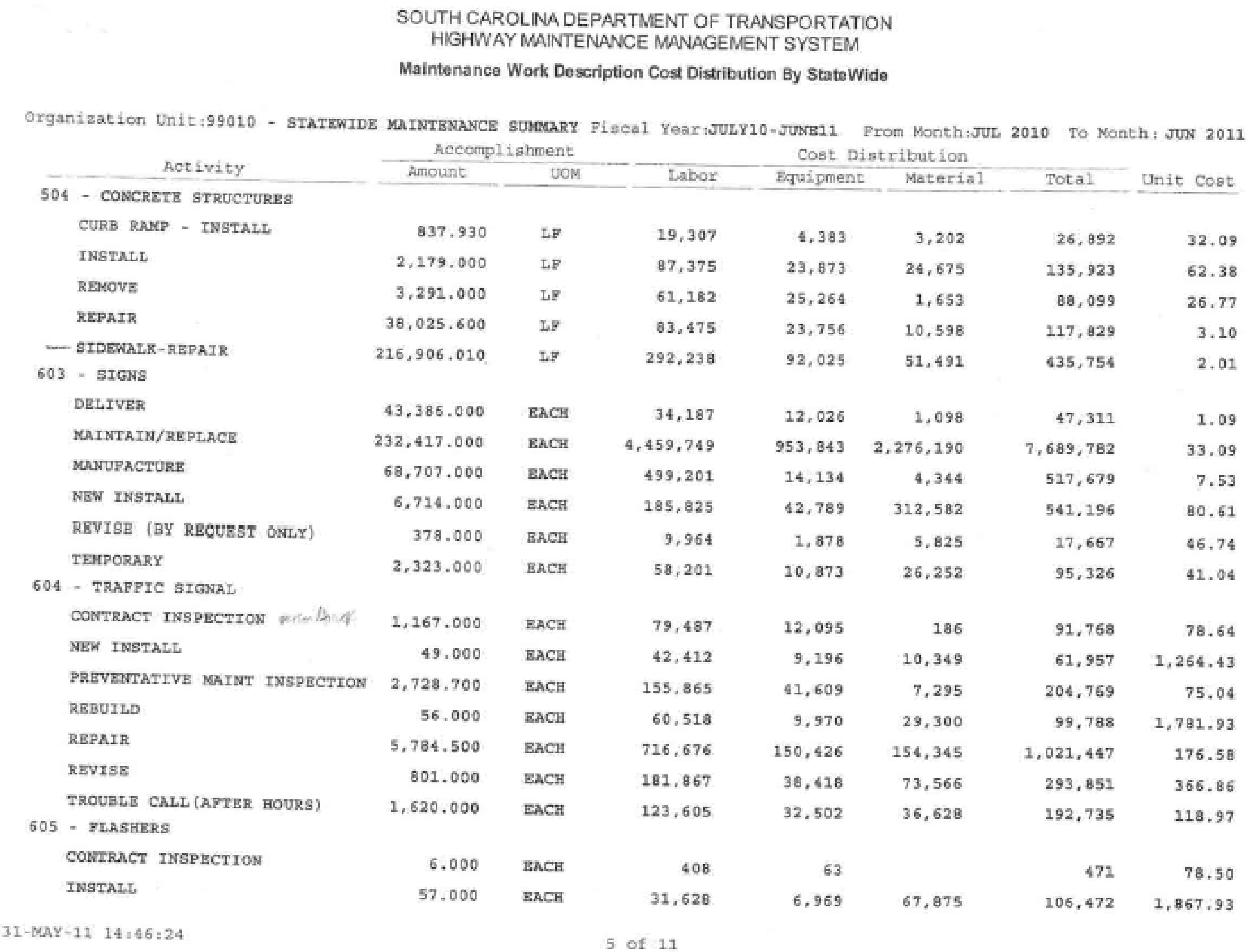
Figure J.4 SCDOT Maintenance Cost Schedule 4



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - **STATEWIDE MAINTENANCE SUMMARY** Fiscal Year:**JULY10-JUNE11** From Month:**JUL 2010** To Month: **JUN 2011**

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
504 - CONCRETE STRUCTURES							
CURB RAMP - INSTALL	837.930	LF	19,307	4,383	3,202	26,892	32.09
INSTALL	2,179.000	LF	87,375	23,873	24,675	135,923	62.38
REMOVE	3,291.000	LF	61,182	25,264	1,653	88,099	26.77
REPAIR	38,025.600	LF	83,475	23,756	10,598	117,829	3.10
SIDEWALK-REPAIR	216,906.010	LF	292,238	92,025	51,491	435,754	2.01
603 - SIGNS							
DELIVER	43,386.000	EACH	34,187	12,026	1,098	47,311	1.09
MAINTAIN/REPLACE	232,417.000	EACH	4,459,749	953,843	2,276,190	7,689,782	33.09
MANUFACTURE	68,707.000	EACH	499,201	14,134	4,344	517,679	7.53
NEW INSTALL	6,714.000	EACH	185,825	42,789	312,582	541,196	80.61
REVISE (BY REQUEST ONLY)	378.000	EACH	9,964	1,878	5,825	17,667	46.74
TEMPORARY	2,323.000	EACH	58,201	10,873	26,252	95,326	41.04
604 - TRAFFIC SIGNAL							
CONTRACT INSPECTION	1,167.000	EACH	79,487	12,095	186	91,768	78.64
NEW INSTALL	49.000	EACH	42,412	9,196	10,349	61,957	1,264.43
PREVENTATIVE MAINT INSPECTION	2,728.700	EACH	155,865	41,609	7,295	204,769	75.04
REBUILD	56.000	EACH	60,518	9,970	29,300	99,788	1,781.93
REPAIR	5,784.500	EACH	716,676	150,426	154,345	1,021,447	176.58
REVISE	801.000	EACH	181,867	38,418	73,566	293,851	366.86
TROUBLE CALL(AFTER HOURS)	1,620.000	EACH	123,605	32,502	36,628	192,735	118.97
605 - FLASHERS							
CONTRACT INSPECTION	6.000	EACH	408	63		471	78.50
INSTALL	57.000	EACH	31,628	6,969	67,875	106,472	1,867.93

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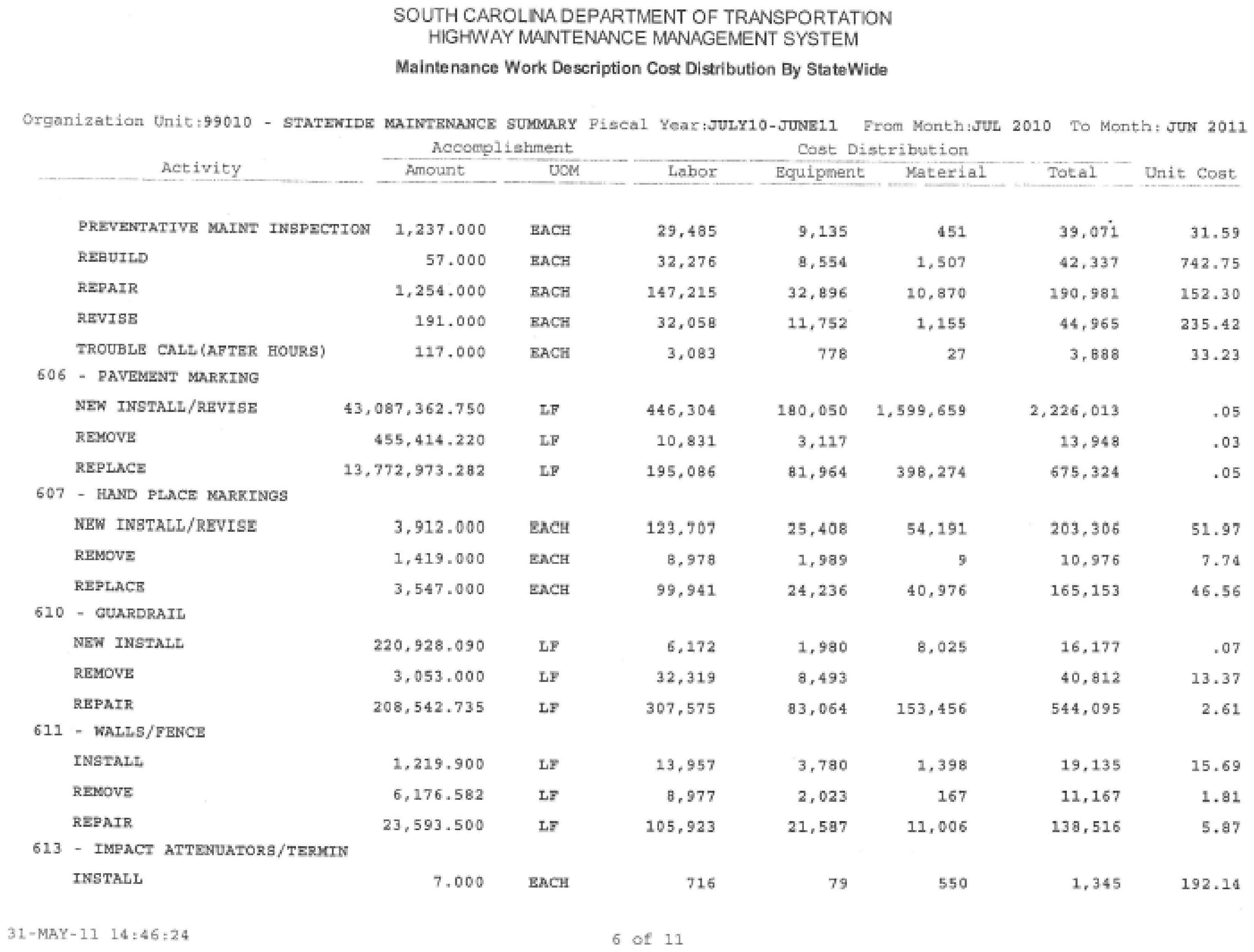
Figure J.5 SCDOT Maintenance Cost Schedule 5



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

	Accomplishment		Cost Distribution				
Activity	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
PREVENTATIVE MAINT INSPECTION	1,237.000	EACH	29,485	9,135	451	39,071	31.59
REBUILD	57.000	EACH	32,276	8,554	1,507	42,337	742.75
REPAIR	1,254.000	EACH	147,215	32,896	10,870	190,981	152.30
REVISE	191.000	EACH	32,058	11,752	1,155	44,965	235.42
TROUBLE CALL(AFTER HOURS)	117.000	EACH	3,083	778	27	3,888	33.23
606 - PAVEMENT MARKING							
NEW INSTALL/REVISE	43,087,362.750	LF	446,304	180,050	1,599,659	2,226,013	.05
REMOVE	455,414.220	LF	10,831	3,117		13,948	.03
REPLACE	13,772,973.282	LF	195,086	81,964	398,274	675,324	.05
607 - HAND PLACE MARKINGS							
NEW INSTALL/REVISE	3,912.000	EACH	123,707	25,408	54,191	203,306	51.97
REMOVE	1,419.000	EACH	8,978	1,989	9	10,976	7.74
REPLACE	3,547.000	EACH	99,941	24,236	40,976	165,153	46.56
610 - GUARDRAIL							
NEW INSTALL	220,928.090	LF	6,172	1,980	8,025	16,177	.07
REMOVE	3,053.000	LF	32,319	8,493		40,812	13.37
REPAIR	208,542.735	LF	307,575	83,064	153,456	544,095	2.61
611 - WALLS/FENCE							
INSTALL	1,219.900	LF	13,957	3,780	1,398	19,135	15.69
REMOVE	6,176.582	LF	8,977	2,023	167	11,167	1.81
REPAIR	23,593.500	LF	105,923	21,587	11,006	138,516	5.87
613 - IMPACT ATTENUATORS/TERMIN							
INSTALL	7.000	EACH	716	79	550	1,345	192.14

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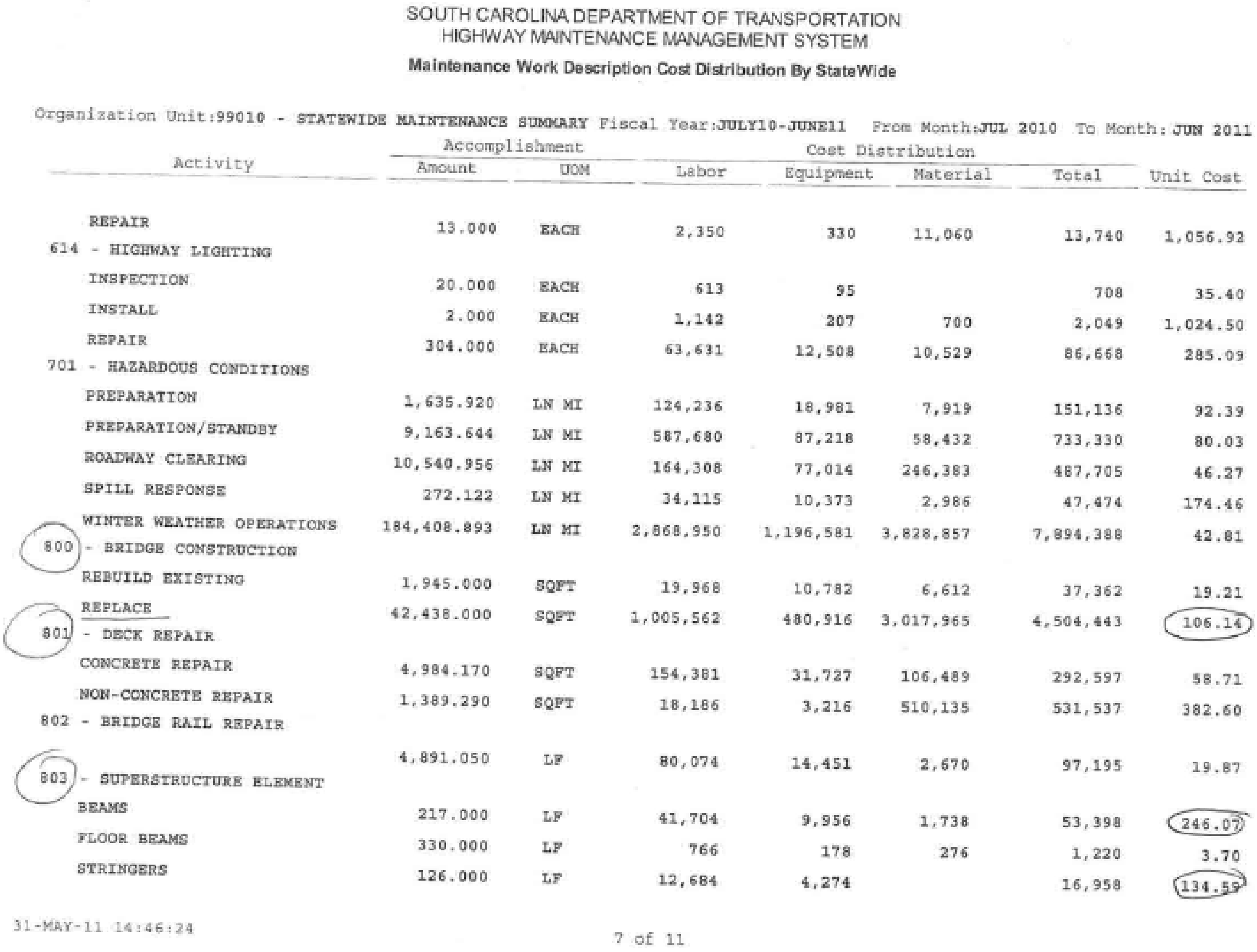
Figure J.6 SCDOT Maintenance Cost Schedule 6



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
REPAIR	13.000	EACH	2,350	330	11,060	13,740	1,056.92
614 - HIGHWAY LIGHTING							
INSPECTION	20.000	EACH	613	95		708	35.40
INSTALL	2.000	EACH	1,142	207	700	2,049	1,024.50
REPAIR	304.000	EACH	63,631	12,508	10,529	86,668	285.09
701 - HAZARDOUS CONDITIONS							
PREPARATION	1,635.920	LN MI	124,236	18,981	7,919	151,136	92.39
PREPARATION/STANDBY	9,163.644	LN MI	587,680	87,218	58,432	733,330	80.03
ROADWAY CLEARING	10,540.956	LN MI	164,308	77,014	246,383	487,705	46.27
SPILL RESPONSE	272.122	LN MI	34,115	10,373	2,986	47,474	174.46
WINTER WEATHER OPERATIONS	184,408.893	LN MI	2,868,950	1,196,581	3,828,857	7,894,388	42.81
800 - BRIDGE CONSTRUCTION							
REBUILD EXISTING	1,945.000	SQFT	19,968	10,782	6,612	37,362	19.21
REPLACE	42,438.000	SQFT	1,005,562	480,916	3,017,965	4,504,443	106.14
801 - DECK REPAIR							
CONCRETE REPAIR	4,984.170	SQFT	154,381	31,727	106,489	292,597	58.71
NON-CONCRETE REPAIR	1,389.290	SQFT	18,186	3,216	510,135	531,537	382.60
802 - BRIDGE RAIL REPAIR							
	4,891.050	LF	80,074	14,451	2,670	97,195	19.87
803 - SUPERSTRUCTURE ELEMENT							
BEAMS	217.000	LF	41,704	9,956	1,738	53,398	246.07
FLOOR BEAMS	330.000	LF	766	178	276	1,220	3.70
STRINGERS	126.000	LF	12,684	4,274		16,958	134.59

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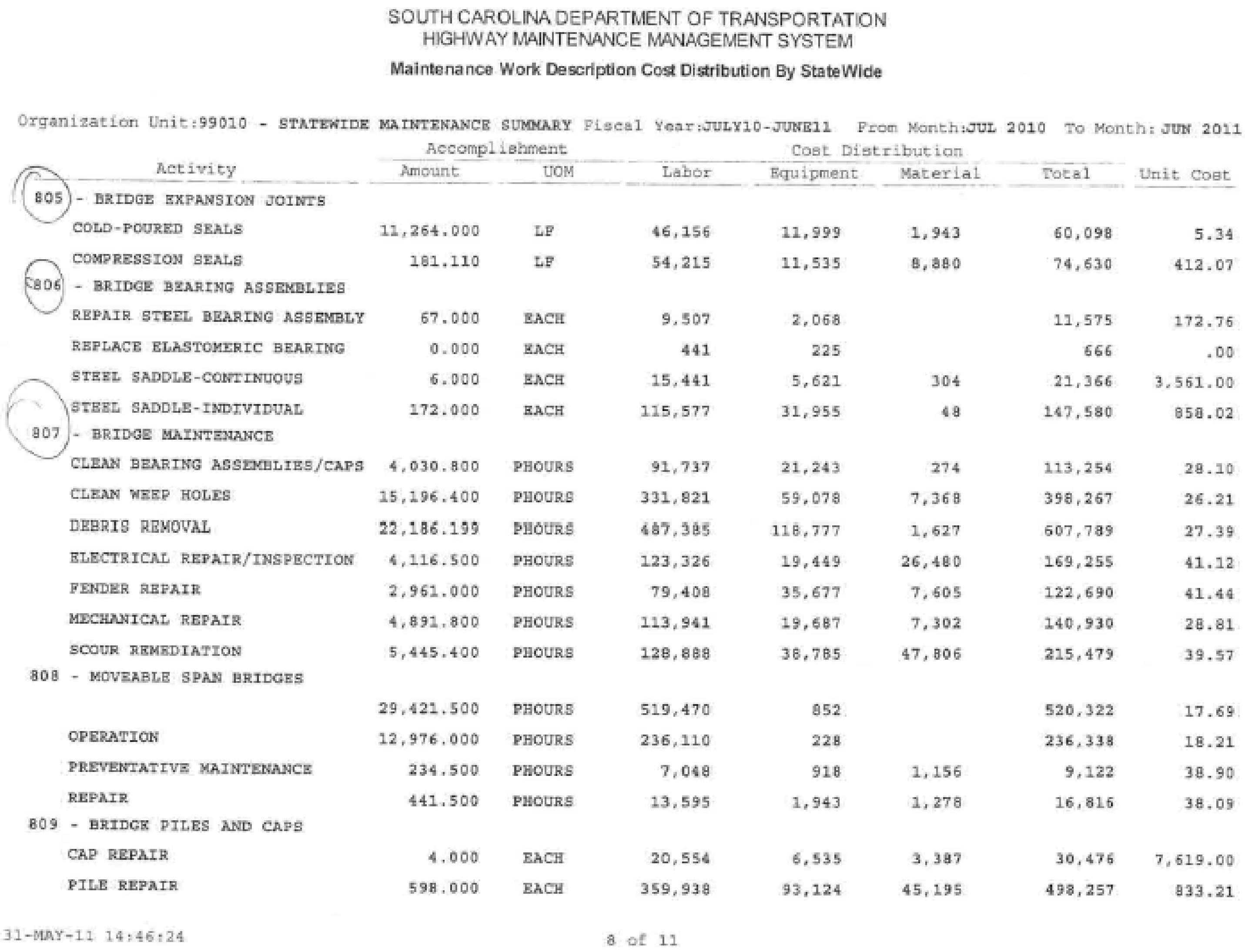
Figure J.7 SCDOT Maintenance Cost Schedule 7



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - **STATEWIDE MAINTENANCE SUMMARY** Fiscal Year:JULY10-JUNE11 From Month:**JUL 2010** To Month: **JUN 2011**

	Accomplishment		Cost Distribution				
Activity	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
805 - BRIDGE EXPANSION JOINTS							
COLD-POURED SEALS	11,264.000	LF	46,156	11,999	1,943	60,098	5.34
COMPRESSION SEALS	181.110	LF	54,215	11,535	8,880	74,630	412.07
806 - BRIDGE BEARING ASSEMBLIES							
REPAIR STEEL BEARING ASSEMBLY	67.000	EACH	9,507	2,068		11,575	172.76
REPLACE ELASTOMERIC BEARING	0.000	EACH	441	225		666	.00
STEEL SADDLE-CONTINUOUS	6.000	EACH	15,441	5,621	304	21,366	3,561.00
STEEL SADDLE-INDIVIDUAL	172.000	EACH	115,577	31,955	48	147,580	858.02
807 - BRIDGE MAINTENANCE							
CLEAN BEARING ASSEMBLIES/CAPS	4,030.800	PHOURS	91,737	21,243	274	113,254	28.10
CLEAN WEEP HOLES	15,196.400	PHOURS	331,821	59,078	7,368	398,267	26.21
DEBRIS REMOVAL	22,186.199	PHOURS	487,385	118,777	1,627	607,789	27.39
ELECTRICAL REPAIR/INSPECTION	4,116.500	PHOURS	123,326	19,449	26,480	169,255	41.12
FENDER REPAIR	2,961.000	PHOURS	79,408	35,677	7,605	122,690	41.44
MECHANICAL REPAIR	4,891.800	PHOURS	113,941	19,687	7,302	140,930	28.81
SCOUR REMEDIATION	5,445.400	PHOURS	128,888	38,785	47,806	215,479	39.57
808 - MOVEABLE SPAN BRIDGES							
	29,421.500	PHOURS	519,470	852		520,322	17.69
OPERATION	12,976.000	PHOURS	236,110	228		236,338	18.21
PREVENTATIVE MAINTENANCE	234.500	PHOURS	7,048	918	1,156	9,122	38.90
REPAIR	441.500	PHOURS	13,595	1,943	1,278	16,816	38.09
809 - BRIDGE PILES AND CAPS							
CAP REPAIR	4.000	EACH	20,554	6,535	3,387	30,476	7,619.00
PILE REPAIR	598.000	EACH	359,938	93,124	45,195	498,257	833.21

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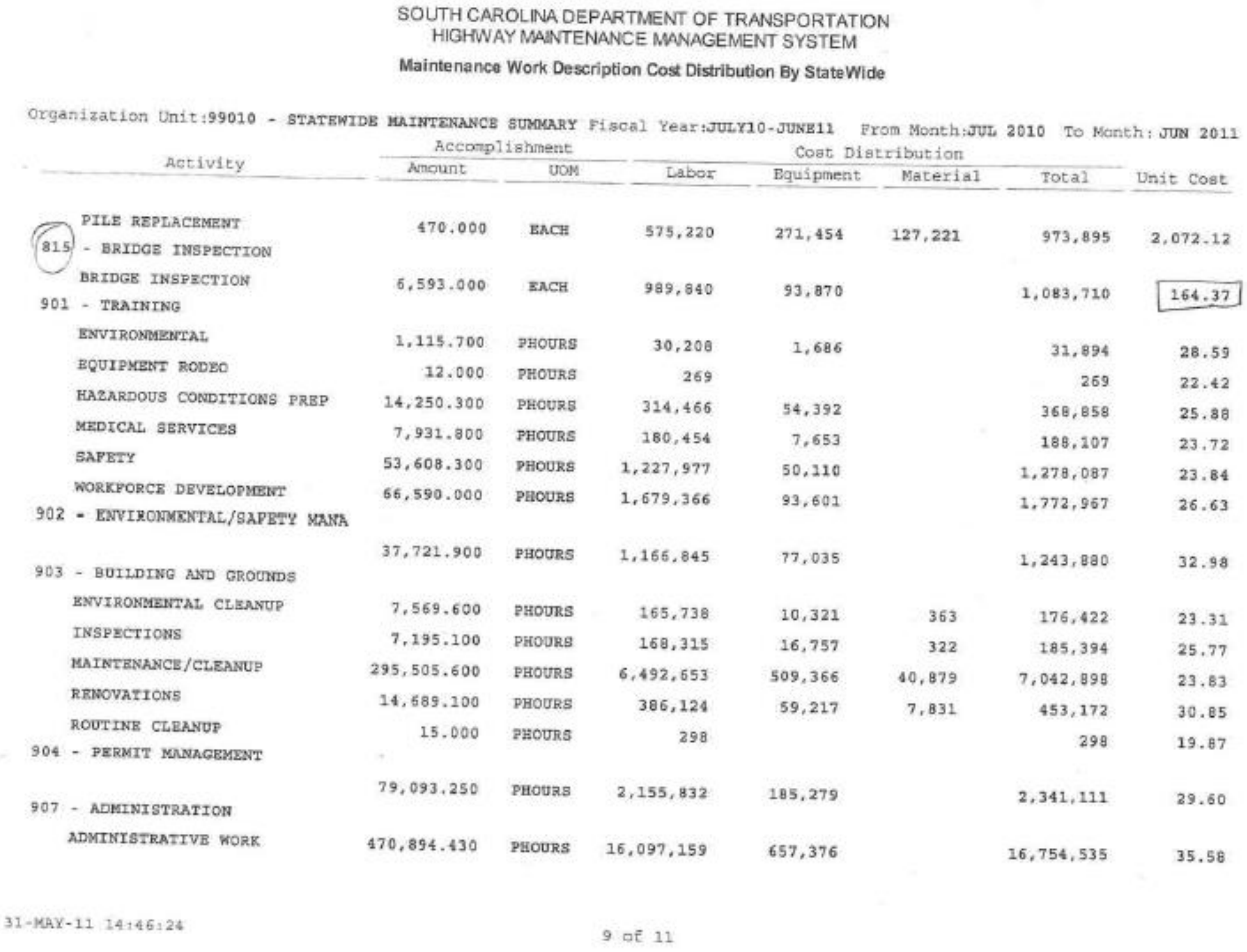
Figure J.8 SCDOT Maintenance Cost Schedule 8



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
PILE REPLACEMENT	470.000	EACH	575,220	271,454	127,221	973,895	2,072.12
815 - BRIDGE INSPECTION							
BRIDGE INSPECTION	6,593.000	EACH	989,840	93,870		1,083,710	164.37
901 - TRAINING							
ENVIRONMENTAL	1,115.700	PHOURS	30,208	1,686		31,894	28.59
EQUIPMENT RODEO	12.000	PHOURS	269			269	22.42
HAZARDOUS CONDITIONS PREP	14,250.300	PHOURS	314,466	54,392		368,858	25.88
MEDICAL SERVICES	7,931.800	PHOURS	180,454	7,653		188,107	23.72
SAFETY	53,608.300	PHOURS	1,227,977	50,110		1,278,087	23.84
WORKFORCE DEVELOPMENT	66,590.000	PHOURS	1,679,366	93,601		1,772,967	26.63
902 - ENVIRONMENTAL/SAFETY MANA							
	37,721.900	PHOURS	1,166,845	77,035		1,243,880	32.98
903 - BUILDING AND GROUNDS							
ENVIRONMENTAL CLEANUP	7,569.600	PHOURS	165,738	10,321	363	176,422	23.31
INSPECTIONS	7,195.100	PHOURS	168,315	16,757	322	185,394	25.77
MAINTENANCE/CLEANUP	295,505.600	PHOURS	6,492,653	509,366	40,879	7,042,898	23.83
RENOVATIONS	14,689.100	PHOURS	386,124	59,217	7,831	453,172	30.85
ROUTINE CLEANUP	15.000	PHOURS	298			298	19.87
904 - PERMIT MANAGEMENT							
	79,093.250	PHOURS	2,155,832	185,279		2,341,111	29.60
907 - ADMINISTRATION							
ADMINISTRATIVE WORK	470,894.430	PHOURS	16,097,159	657,376		16,754,535	35.58

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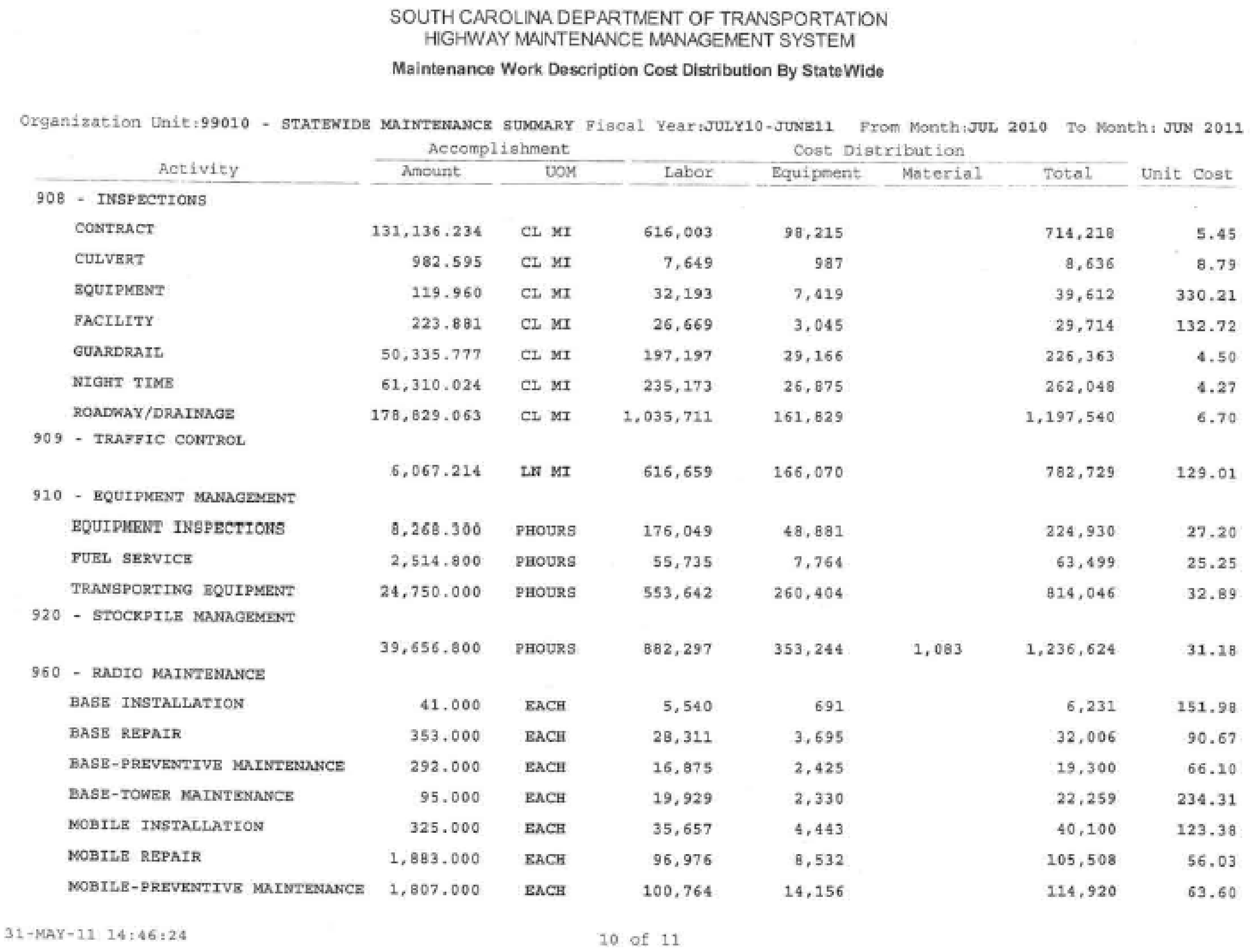
Figure J.9 SCDOT Maintenance Cost Schedule 9



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - STATEWIDE MAINTENANCE SUMMARY Fiscal Year:JULY10-JUNE11 From Month:JUL 2010 To Month: JUN 2011

Activity	Accomplishment		Cost Distribution				
	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
908 - INSPECTIONS							
CONTRACT	131,136.234	CL MI	616,003	98,215		714,218	5.45
CULVERT	982.595	CL MI	7,649	987		8,636	8.79
EQUIPMENT	119.960	CL MI	32,193	7,419		39,612	330.21
FACILITY	223.881	CL MI	26,669	3,045		29,714	132.72
GUARDRAIL	50,335.777	CL MI	197,197	29,166		226,363	4.50
NIGHT TIME	61,310.024	CL MI	235,173	26,875		262,048	4.27
ROADWAY/DRAINAGE	178,829.063	CL MI	1,035,711	161,829		1,197,540	6.70
909 - TRAFFIC CONTROL							
	6,067.214	LN MI	616,659	166,070		782,729	129.01
910 - EQUIPMENT MANAGEMENT							
EQUIPMENT INSPECTIONS	8,268.300	PHOURS	176,049	48,881		224,930	27.20
FUEL SERVICE	2,514.800	PHOURS	55,735	7,764		63,499	25.25
TRANSPORTING EQUIPMENT	24,750.000	PHOURS	553,642	260,404		814,046	32.89
920 - STOCKPILE MANAGEMENT							
	39,656.800	PHOURS	882,297	353,244	1,083	1,236,624	31.18
960 - RADIO MAINTENANCE							
BASE INSTALLATION	41.000	EACH	5,540	691		6,231	151.98
BASE REPAIR	353.000	EACH	28,311	3,695		32,006	90.67
BASE-PREVENTIVE MAINTENANCE	292.000	EACH	16,875	2,425		19,300	66.10
BASE-TOWER MAINTENANCE	95.000	EACH	19,929	2,330		22,259	234.31
MOBILE INSTALLATION	325.000	EACH	35,657	4,443		40,100	123.38
MOBILE REPAIR	1,883.000	EACH	96,976	8,532		105,508	56.03
MOBILE-PREVENTIVE MAINTENANCE	1,807.000	EACH	100,764	14,156		114,920	63.60

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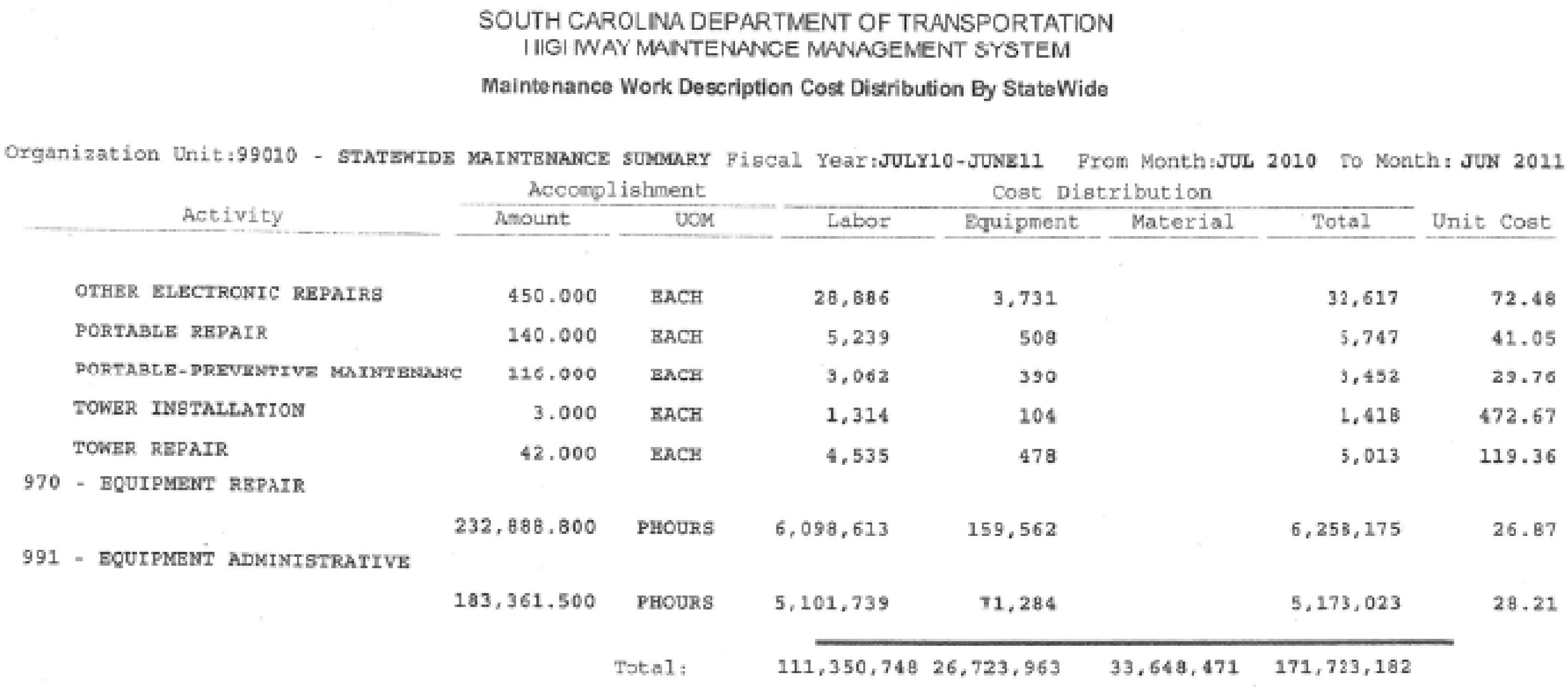
Figure J.10 SCDOT Maintenance Cost Schedule 10



SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM
Maintenance Work Description Cost Distribution By StateWide

Organization Unit:99010 - **STATEWIDE MAINTENANCE SUMMARY** Fiscal Year:**JULY10-JUNE11** From Month:**JUL 2010** To Month: **JUN 2011**

	Accomplishment		Cost Distribution				
Activity	Amount	UOM	Labor	Equipment	Material	Total	Unit Cost
OTHER ELECTRONIC REPAIRS	450.000	EACH	28,886	3,731		32,617	72.48
PORTABLE REPAIR	140.000	EACH	5,239	508		5,747	41.05
PORTABLE-PREVENTIVE MAINTENANC	116.000	EACH	3,062	390		3,452	29.76
TOWER INSTALLATION	3.000	EACH	1,314	104		1,418	472.67
TOWER REPAIR	42.000	EACH	4,535	478		5,013	119.36
970 - EQUIPMENT REPAIR							
	232,888.800	PHOURS	6,098,613	159,562		6,258,175	26.87
991 - EQUIPMENT ADMINISTRATIVE							
	183,361.500	PHOURS	5,101,739	71,284		5,173,023	28.21
		Total:	111,350,748	26,723,963	33,648,471	171,723,182	

Figure J.11 SCDOT Maintenance Cost Schedule 11

Appendix K Research Design

This study sought to provide perspective on South Carolina's trucking and infrastructure policies through two mechanisms: comparison to standards across the nation and consideration of the freight stakeholders within South Carolina. An online survey of state and provincial departments of transportation in the United States and Canada provided assessment of common practices, and interviews with trucking stakeholders developed context for interpreting practices and identifying considerations perhaps specific to South Carolina.

K-1 Comparison of Common Practices

This research captured the current state of the practice by bringing together public records and a survey of state and provincial departments of transportation in the United States and Canada. Primary data collection came from U.S. states and Canadian provinces.

Public records provided general truckload limits and information on overweight-permit programs from the 50 states. Web data gathered in October and November 2011 validated and supplemented data and information on truckload management practices from the *Vehicle Sizes and Weights Manual* (J.J Keller & Associates Inc., 2011).

For the invited survey, transportation departments in all 50 states of the United States and 10 Canadian provinces received invitations to participate in the fall of 2011. Investigators received 16 responses, amounting to 27 percent of the total population of 60. Investigators attempted to raise the response rate by sending email reminders twice and extending the time allowed for responses. Still facing low response and a small sample size, this report only presents data from questions where respondent answers generally matched, thus providing higher confidence in the representativeness of the results.

K-2 Interviews with Trucking Stakeholders

The primary goal of this interview process was to communicate with different stakeholders of overweight-freight transportation in South Carolina about ways to tackle infrastructure deterioration issues. The objectives of these interviews were to:

- characterize the framework in which South Carolina freight, and pavement and bridge infrastructure relate,
- elucidate the issues faced and educate stakeholders on each other's needs,
- familiarize the research team with the business process requirements and any logistical issues that exist in the permit or data collection process, and
- establish knowledge on the acceptability of policy initiatives in South Carolina.

This interview methodology built upon the methodology of a 2008 review of Virginia study (Virginia Transportation Research Council, 2008). In that study, researchers asked stakeholders to comment on the potential for trucking user fees to address infrastructure damage. Feedback came from industry representatives for concrete, excavated materials, agriculture, forestry, oil, coal, manufactured housing, heavy contracting, and trucking. Respondents indicated they were paying sufficiently with truck registrations and diesel taxes. They also indicated slim profit margins in industrial sectors related to primary industries (farming, mining, and so forth) made fee increases impossible to afford.

In light of Virginia's findings, Clemson's researchers designed the interview methodology with multiple considerations. As with Virginia, Clemson wanted interview respondents to have time to consider their responses, thus participants received the question list in advance. The advance information also included data on South Carolina's shortfall discrepancy between infrastructure costs and revenue generated from fuel taxes, registration fees, and overweight permits.

Contributing Organizations

The research team developed a list of organizations and agencies expected to have a stake in trucking and the infrastructure that supports it in South Carolina. The list focused on state organizations, but some national organizations were contacted because they might have perspective of national viewpoints and stances.

The following organizations participated in the study, and they were asked if they recommended researchers contact any other organizations that might have viewpoints to contribute.

- Greenville Chamber of Commerce Transportation and Infrastructure Committee representing business and shippers
- South Carolina Trucking Association representing shipping companies
- South Carolina State Transport Police representing law enforcement
- South Carolina Department of Transportation representing interests of infrastructure maintenance
- South Carolina Farm Bureau representing the agricultural industry
- Carolinas Ready-Mixed Concrete Association representing heavy construction materials

Several stakeholders chose not to participate in the study. The Federal Motor Carrier Safety Administration said the subject matter more closely resembled the activities of the Federal Highway Administration; the Federal Highway Administration indicated it could not participate in a study supported with funding from the United States Department of Transportation. The American Trucking Association deferred to the South Carolina Trucking Association for its state-specific knowledge. The South Carolina Department of Commerce declined to participate but offered to support the study if other means were available. The South Carolina Timber Producers' Association received multiple inquiries by telephone and email but did not respond. The office of South Carolina State Senate Transportation Committee Chairman Larry Grooms indicated willingness to participate but was unavailable.

Interview Process

Each organization received an initial telephone contact in mid-February 2013, which was followed up with an email and attached document. The document, which is included in a subsequent appendix, introduced the study objectives, preliminary findings, information on fee structures in other states, the interview questions, and the list of organizations contacted to participate in the study. The document was intended to give interview participants time to think about the subject matter and their responses, thus providing thorough description of how they see the issues and giving them confidence that nothing about the interview would catch them off guard. Almost all of the interviewees took the opportunity to talk with colleagues to solidify how to present their viewpoints before scheduling the interviews; this process took several weeks. Interviews concluded in early April 2013.

Most interviewees initially demonstrated uneasiness or uncertainty with the interview process and their participation. Each conversation began with two assurances.

- The intent of the interview was to create accurate representation of stakeholder perspectives on issues, and no one was to be portrayed as a hero or villain.
- No one would be quoted in the research report without explicit confirmation of the quotation and the interviewee's desire to receive attribution.

Because stakeholders received the questions in advance and generally prepared concise answers, telephone interviews lasted only between 15 and 45 minutes.

Interview Content

The interviews covered the following nine questions.

1) Regarding the information provided, what comments or questions do you have?
2) What are the primary issues to consider when balancing the needs of freight movement and infrastructure maintenance?
3) Equity can be viewed in many ways. What are the primary considerations for ensuring fairness in setting permitting policies and fees?
4) How should overweight permitting fees be set relative to the calculated amount of damage overweight vehicles inflict? If you recommend a difference from the exact amount of damage, how do you justify it? How should that difference be calculated?
5) What are the strengths, weaknesses, opportunities, and threats of implementing the following potential fee structures in South Carolina?

- Flat fees
- Weight-based fees
- Fees based on weight and distance
- Fees considering axle configurations

6) Annual permitting practices in the United States have ranged from charging less than the cost of 2 single permits to the equivalent cost of 52 single permits. South Carolina currently sets an annual permit fee equivalent to 3 ⅓ single trips. Should South Carolina offer flat fees for annual permits, and if so, what frequency of usage should be assumed in setting the value for the permit? Why that frequency?
7) Setting permitting structures must consider permit value. If South Carolina increases fees for overweight vehicles, what transportation-system improvements should emerge to serve operators of heavy and overweight vehicles and related stakeholders?
8) Beyond the numbers, what considerations need to be evaluated for weight and infrastructure policies? Examples might include but not be limited to administrative processes, logistics, legal frameworks, state or global competitiveness, and so forth.
9) What other issues would you like to raise; what remaining comments do you have?

These questions intentionally did not request response to the engineering study's findings. Modelers were still finalizing their results at the time of the interviews, and full documentation of the study and its methodology was not yet available for interviewees to examine. Rather than recording responses to the study, the interviews captured relevant perspectives and issues that should be addressed in future public discussions.

Appendix L Survey of State Departments of Transportation

1) What state do you represent? We will use this information to complement your responses to data we are gathering from state web sites.

____

Freight Monitoring

2) What types of enforcement strategies does your state use to enforce truck weight limits on the road system?

a. 24-hour weigh stations ☐
b. Part-time weigh stations (regular operating schedule) ☐
c. Part-time weigh stations (random operating schedule) ☐
d. Mobile weigh equipment units or teams ☐
e. Weigh-in-motion (WIM) ☐
f. Pre-pass checkpoints ☐
g. Other: ____

3) How many teams or stations of the following does your state use to enforce truck weight limits on the road system? Enter a number for each line.

a. 24-hour weigh stations _____
b. Part-time weigh stations _____
c. Mobile weigh equipment units or teams _____
d. Weigh-in-motion (WIM) _____
(Standalone-not located near weigh stations)
e. Pre-pass checkpoints _____
(Standalone-not located near weigh stations)
f. Other: ___________________________ ________________

4) What type of truck information does your state check at weigh stations?

Checked
a. Vehicle classification ☐
b. Number of axles ☐
c. Axle loads ☐
d. Axle spacing ☐
e. Gross vehicle weight ☐
f. Trip origin ☐
g. Trip destination ☐

5) Are data on the number of trucks checked for weight categorized by axle limits and gross vehicle weight limits? (ie. Is the number of trucks whose axle weights were checked recorded as well as the number of trucks whose gross vehicle weights were checked recorded?)

☐ Yes ☐ No

6) Are data on the number or percentage of trucks exceeding weight limits categorized by axle limits and gross vehicle weight limits?

☐ Yes ☐ No

If the answer to question 5) or 6) is no, skip to question 8).

7) How many trucks in calendar year 2010 fit in the following categories? Please enter either the absolute number of trucks or the percentage of all trucks. If the data are not readily available, who may we contact to obtain these data?

Percentage or Number Contact name Contact email or phone
a. Trucks checked for axle loads ___________ _____________ ____
b. Trucks at or under legal axle weight ______ _____ _____________
c. Permitted trucks with axle(s) overweight ______ ______ ________
d. Trucks with axle(s) overweight (no permit) ______ ______ ________
e. Gross vehicle weights checked ______ ___________ _____________
f. Trucks at or under legal gross vehicle weight ______ _____ _____
g. Permitted trucks over the gross vehicle weight limit ______ ______ ________
h. Trucks over gross vehicle weight limit (no permit) ______ ______ _____

8) What is the percentage or number of trucks in calendar year 2010 for each of the following? If the data are not readily available, who may we contact to obtain these data?

Percentage or Number Contact name Contact email or phone
a. Trucks checked for gross vehicle or axle weight ___________ ______ ______
b. Trucks at or under weight limits ______ _____ _____
c. Trucks over gross vehicle or axle weight limit (no permit) _____ ______ ______
d. Permitted trucks over gross vehicle or axle weight limit _____ ______ ______

9) What, if any other vehicle information does your state check and/or keep records of at weigh stations? ____

10) Does your state keep records on fines issued for overweight violations?
☐ Yes ☐ No

If the answer to question 10) is no, skip to question 12).

11) Is the severity of the overweight violations included in records on fines issued for overweight violations?
☐ Yes ☐ No ☐ Do not know
12) Who may we contact about records on fines issued for overweight violations?
a. Name
b. Email or phone

Overweight Vehicles

13) How does your state handle trucks with overweight permits? Check all that apply.
○ Checked for declared weight at weigh stations
○ Checked for declared weight by weigh-in-motion units
○ Checked for declared weight by mobile units
○ Not checked by enforcement efforts

- Other _______________

14) Does your state keep records on permits issued for overweight vehicles?
☐ Yes ☐ No

If the answer to question 14) is no, skip to question 16).

15) How many overweight permits were issued in calendar year 2010? _____

16) Does your state estimate how many overweight trucks (exceeding axle or gross vehicle weight) without permits are **not** caught by enforcement efforts?

☐ Yes ☐ No ☐ Do not know

If the answer to question 16) is "do not know," skip to question 19).
If the answer to question 16) is no, skip to question 20).

17) How many overweight trucks (exceeding axle or gross vehicle weight) without permits does your state estimate are **not** caught by enforcement efforts?
____

____

____

18) How does your state derive these estimates?

____

____

19) Who can we contact to learn about these estimates of overweight trucks not caught by enforcement efforts?
a. Name
b. Email or phone

Trucking Fee Structures

20) Who participates in determining the structure for overweight fees?
☐ Advisory committee
☐ Focus group
☐ Legislature and lobbyists
☐ Dedicated DOT department
☐ Maintenance or engineering department of DOT
☐ Business stakeholders
☐ Other:____

21) Have the fee structures been reviewed on a set schedule?

☐ Yes ☐ No

If the answer to question 21) is no, skip to question 23).

22) How frequently has the fee structure been reviewed?
☐ ≤ 1 year
☐ 2-3 years
☐ 4-5 years
☐ 6-7 years
☐ 8-9 years
☐ ≥ 10 years

23) When was the last revision of overweight fee structures performed?
Year:____________________________

24) Based on the last change in the overweight fee structure, what were the main factors in the decision? Check all that apply.
☐ Reduce freight costs to encourage freight activity
☐ Increase freight costs to discourage freight activity
☐ Accurately recover costs for infrastructure damage incurred
☐ Increase revenue for infrastructure maintenance program
☐ Other:____
☐ I do not know.

If the answer to question 24) is "I don't know," skip to question 27).

25) Has your state conducted an economic or engineering study for developing or reviewing the fee structure?

☐ Yes ☐ No

If the answer to question 25) is no, skip to question 27).

26) How can we find this study or who can we contact about it?

____
____
____

27) Who can we contact to inquire about changes in the overweight fee structure?
a. Name ______________________________
b. Email or phone ______________________________

Trucking Fine Structures

28) Who participates in determining the structure for illegal and overweight fines?
☐ Advisory committee
☐ Focus group
☐ Legislature and lobbyists

☐ Dedicated DOT department
☐ Maintenance or engineering department of DOT
☐ Business stakeholders
☐ Other:____

29) Have the fine structures been reviewed on a set schedule?

☐ Yes ☐ No

If the answer to question 29) is no, skip to question 31).

30) How frequently has the fine structure been reviewed?
☐ ≤ 1 year
☐ 2-3 years
☐ 4-5 years
☐ 6-7 years
☐ 8-9 years
☐ ≥ 10 years

31) When was the last revision of illegal and overweight fine structures performed?
Year:____________________________

32) Based on the last change in the illegal and overweight fine structure, what were the main factors in the decision? Check all that apply.
☐ Discourage illegal and overweight freight activity
☐ Accurately recover costs for infrastructure damage incurred
☐ Increase revenue for infrastructure maintenance program
☐ Other:____
☐ I do not know.

If the answer to question 32) is "I don't know," skip to question 35).

33) Has your state conducted an economic or engineering study for developing or reviewing the fine structure?

☐ Yes ☐ No

If the answer to question 33) is no, skip to question 35).
34) How can we find this study or who can we contact about it?

____
____
____

35) Who can we contact to inquire about changes in the illegal and overweight fine structure?
a. Name ____________________________
b. Email or phone ____________________________

Surface freight in the next 10 years

36) How does your state expect its magnitude and distribution of freight volume by mode to change in the next 10 years?

____

____

37) How does your state expect demand for designated trucking routes in your state to change in the next 10 years? Include changes due to generators such as ports, airports, distribution centers or specific industries, as well as any other changes your state foresees.

____

____

38) How is changing demand affecting freight and infrastructure planning in your state? For example, will your state make changes to designated trucking routes, implement highway technologies, facilitate mode shift, or take other measures?

____

____

39) What is your state doing to increase freight capacity? (check box options will be: not considered, considered but no implemented, implemented, implemented but since ceased)

a. Creating/extending highway corridors or routes	☐	☐	☐	☐
b. Adding capacity to existing highway corridors	☐	☐	☐	☐
c. Adding truck-only lanes	☐	☐	☐	☐
d. Adding truck-only toll lanes (TOT)	☐	☐	☐	☐
e. Improving highway access or capacity to ports	☐	☐	☐	☐
f. Improving highway access or capacity to airports	☐	☐	☐	☐
g. Improving highway access to rail	☐	☐	☐	☐
h. Improving rail access or capacity to ports	☐	☐	☐	☐
i. Improving rail access or capacity to airports	☐	☐	☐	☐
j. Upgrading functionally obsolete infrastructure (e.g., weight-restricted bridges)	☐	☐	☐	☐
k. Easing freight-related restrictions (e.g. increasing weight limits)	☐	☐	☐	☐
l. Improving regulation efficiency (e.g. implementing weigh-in-motion technology)	☐	☐	☐	☐
m. Introducing mandatory freight-traffic bypasses	☐	☐	☐	☐

n. Other: ____

Contact Details

40) Name:

41) Organization name:

42) Department:

43) Title:

44) Email:

45) If you have any further comments about freight planning in your state, this survey, or this study, please include them here.

Thank you for your time completing this survey. If there is anyone else who might contribute further to this study please forward the survey to them.

Appendix M Survey Response Summary Tables

Table M.1 Types of Enforcement strategies

Enforcement Strategies	**States/Provinces**
Mobile weigh equipment units or teams	14
Weigh-in-motion (WIM)	14
Part-time weigh stations (random operating schedule)	11
Part-time weigh stations (regular operating schedule)	7
24-hour weigh stations	9
Pre-pass checkpoints	4

Table M.2 Number of Enforcement stations/ Teams

Enforcement type	**Number of stations/teams**				
	Minimum	**Mean**	**Median**	**Maximum**	**Standard Deviation**
24-hour weigh stations	0	2	1	8	3
Part-time weigh stations	1	16	9	80	19
Mobile weigh equipment units or teams	0	36	27	140	40
Weigh-in-motion (WIM) (Standalone-not located near weigh stations)	0	12	4	100	25
Pre-pass checkpoints (Standalone-not located near weigh stations)	0	1	0	8	2

Table M.3 Type of information collected by Enforcement

Type of information collected	**States/ Provinces**
Axle loads	16
Axle spacing	16
Gross vehicle weight	16
Number of axles	15
Vehicle classification	13
Trip origin	11
Trip destination	11
Other information: Tax, Registration, Safety compliance, Driver hours of service, dangerous goods, permit conditions, load securement, safety equipment, mechanical condition, insurance, Equipment, log books, equipment, DOT number etc.	

Table M.4 Participants involved in determining overweight permit fee and violation fine

Participants	Overweight fee	Illegal Overweight fine
Legislature and lobbyists	11	12
Dedicated DOT department	5	4
Maintenance or engineering department of DOT	4	2
Business stakeholders	4	1
Advisory committee	2	4
Focus group	1	0
Other		*4

* State Police, Judicial branch, Special Committee

Table M.5 Last revision of Overweight Permit fee and Violation fine structure

Last revision	Overweight fee	Illegal Overweight fine
Last Year	1	0
1-5 Years ago	5	2
6-10 Years ago	3	2
11-15 Years ago	2	2
More than 15 Years ago	5	4

Table M.6 Factors considered in Overweight fee and violation fine setting

Factors	Overweight fee	Illegal Overweight fine
Discourage illegal and overweight freight activity	-	6
Do not know	7	4
Accurately recover costs for infrastructure damage incurred	4	1
Increase revenue for infrastructure maintenance program	2	1
Other	*5	**2
*To cover increased administrative costs, Ensure that the overweight permit program is not subsidized by taxpayers, To bring fees closer to surrounding states ,Deter the operation of overweight vehicles		
** Public safety, Allowing 80,000 lbs on part of other highways		

Strategies to improve freight capacity:

1 Creating/extending highway corridors or routes
2 Adding capacity to existing highway corridors
3 Adding truck-only lanes
4 Adding truck-only toll lanes (TOT)
5 Improving highway access or capacity to ports
6 Improving highway access or capacity to airports
7 Improving highway access to rail
8 Improving rail access or capacity to ports
9 Improving rail access or capacity to airports
10 Upgrading functionally obsolete infrastructure (e.g., weight-restricted bridges)
11 Easing freight-related restrictions (e.g. increasing weight limits)
12 Improving regulation efficiency (e.g. implementing weigh-in-motion technology)
13 Introducing mandatory freight-traffic bypasses

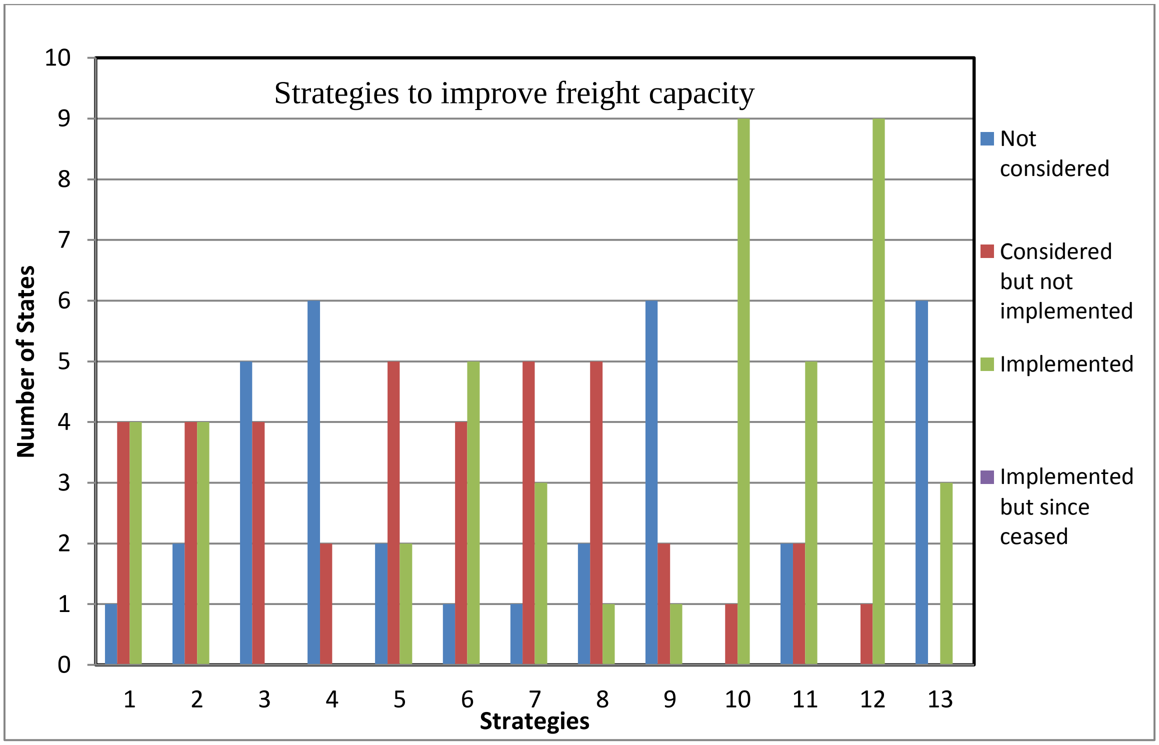


Figure M.1 Strategies to improve freight capacity

Appendix N Background and Questions Distributed to Participants before Stakeholder Interviews

Introduction to the Interview Process

With sponsorship from the South Carolina Department of Transportation (SCDOT), Clemson University is studying how overweight vehicles affect deterioration of South Carolina pavements and bridges. This project addresses the dichotomy of shrinking revenue and growing need for funding to maintain transportation infrastructure at a safe and competitive level. The objectives of this project are to represent the impact of heavy vehicle traffic on pavements and bridges in South Carolina and to create policy recommendations informed by both technical analysis and the modern political and institutional environment in South Carolina.

To date, this project has:

- synthesized past research efforts and current policy practices for attributing infrastructure deterioration and recovering associated costs across the United States,
- compiled freight demand from forecasting model of South Carolina truck traffic,
- modeled weight impacts on deterioration of South Carolina roads and bridges, and
- developed a multi-objective analysis tool to assist in making decisions.

The final phase of this project will develop policy recommendations based on these results. ***We are seeking input from key stakeholders representing different freight interests in South Carolina***. The primary goal of this interview process is to communicate with different stakeholders of overweight-freight transportation in South Carolina about ways to tackle infrastructure deterioration issues.

The objectives of these interviews are to:

- characterize the framework in which South Carolina freight, and pavements and bridge infrastructure relate,
- elucidate the issues faced and educate stakeholders on each other’s needs,
- familiarize the research team with the business process requirements and any logistical issues that exist in the permit or data collection process, and
- establish knowledge on the acceptability of policy initiatives in South Carolina.

Findings from interviews will figure in development of policy recommendations.

Background Information

South Carolina's Department of Transportation is looking for ways to recover funds necessary to maintain infrastructure in good condition. Particular attention is going toward updating the user-fee structure for overweight permitting to capture the impact of weight on roads and bridges in the state.

In South Carolina, overweight trucks pay $30 for a single trip and $100 for an annual permit. These flat fees cover the cost of administering the permitting program, but they do not consider the relative damage due to incremental increases in vehicle weights and trip distances. As a result, SCDOT's current overweight permit fee rate for overweight trucks does not generate sufficient revenue to mitigate damage caused by overweight vehicles.

Research has shown that overweight vehicles create disproportionate damage to infrastructure with damage increasing fastest for additional weight on the heaviest trucks (see Figure N.1), but many states have flat fees for all weights in excess of the legal limit. States are evolving overweight fee structures to consider the magnitude of impact various vehicles impose. Several states have adopted fee structures to charge according to weight of vehicles and distance traveled (see Figure N.2).

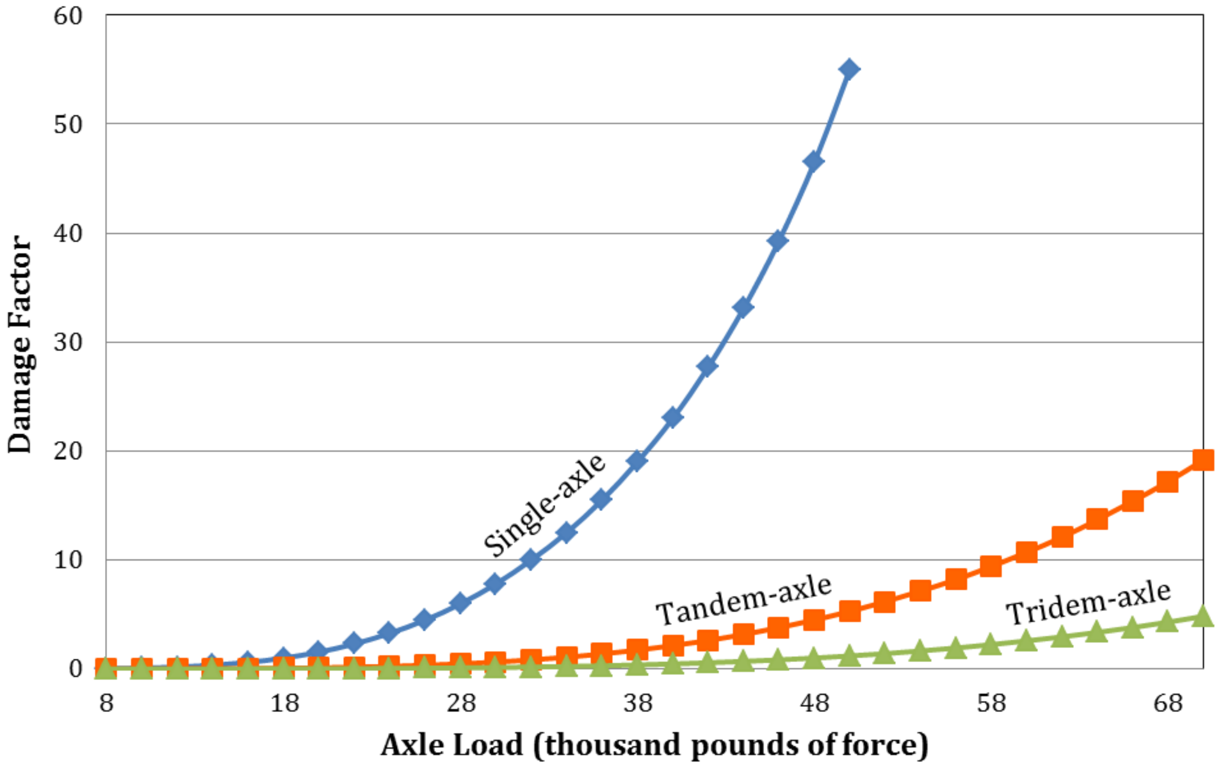


Figure N.1: Modeled Impact of Weight on South Carolina Pavements

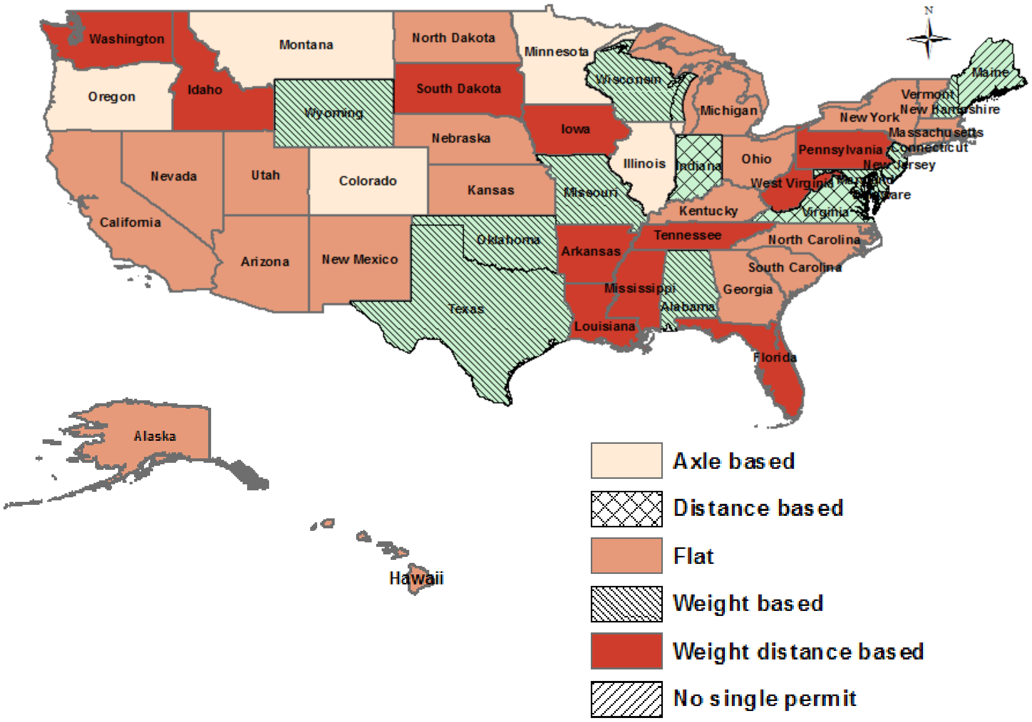


Figure N.2: Geographic Distribution of Various fee Structures

States near South Carolina have a variety of overweight permitting structures that capture a range of infrastructure impacts, as indicated in Table N.1. North Carolina and Georgia have continued to charge flat fees; Florida and Tennessee have adopted overweight permitting structures that consider vehicle weights and the distances vehicles travel.

Table N.1: Overweight Permitting Structures of Neighboring States

State	Single permit fee	Annual permit fee
South Carolina	$30	$100
Florida	$3.33+ $0.27-$0.47 per mile	*$240-$500
Georgia	$30	$150
North Carolina	$12	**$100, $200
Tennessee	$15+ $0.05 per ton-mile	***$500, $1000

* $240 covers up to 95,000lbs, $500 covers up to 199,000lbs

** $100 for general overweight, $200 for mobile homes

*** $500 covers up to 120,000lbs, $1000 covers 120,000 to 150,000lbs

How can South Carolina fairly recover funds commensurate with the impact of overweight vehicles to re-invest in highway infrastructure, thereby maintaining safe and competitive roads and bridges?

Questions for Telephone Discussion

1) Regarding the information provided, what comments or questions do you have?
2) What are the primary issues to consider when balancing the needs of freight movement and infrastructure maintenance?
3) Equity can be viewed in many ways. What are the primary considerations for ensuring fairness in setting permitting policies and fees?
4) How should overweight permitting fees be set relative to the calculated amount of damage overweight vehicles inflict? If you recommend a difference from the exact amount of damage, how do you justify it? How should that difference be calculated?
5) What are the strengths, weaknesses, opportunities, and threats of implementing the following potential fee structures in South Carolina?

Fee Basis	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
a) Flat fee	i)	ii)	iii)	iv)
b) Weight	i)	ii)	iii)	iv)
c) Weight and distance	i)	ii)	iii)	iv)
d) Axle, configuration, and weight	i)	ii)	iii)	iv)
e) Axle, configuration, weight, and distance	i)	ii)	iii)	iv)
f) Other*	i)	ii)	iii)	iv)

*If you have an alternative model to recommend, please explain it and likewise identify its strengths, weaknesses, opportunities, and threats.

6) Annual permitting practices in the United States have ranged from charging less than the cost of 2 single permits to the equivalent cost of 52 single permits. South Carolina currently sets an annual permit fee equivalent to 3 ⅓ single trips. Should South Carolina offer flat fees for annual permits, and if so, what frequency of usage should be assumed in setting the value for the permit? Why that frequency?
7) Setting permitting structures must consider permit value. If South Carolina increases fees for overweight vehicles, what transportation-system improvements should emerge to serve operators of heavy and overweight vehicles and related stakeholders?
8) Beyond the numbers, what considerations need to be evaluated for weight and infrastructure policies? Examples might include but not be limited to administrative processes, logistics, legal frameworks, state or global competitiveness, and so forth.
9) What other issues would you like to raise; what remaining comments do you have?

Additional Perspectives

The following people are receiving invitations to contribute to this interview study. *If you know of someone else who should receive an invitation, please let us know.*

Stakeholder	**Organization**
Business/shippers	Greenville Chamber of Commerce
	South Carolina Department of Commerce
Shipping Companies	American Trucking Association
	South Carolina Trucking Association
USDOT	Federal Highway Administration, South Carolina Division
	Federal Motor Carrier Safety Administration
Law enforcement	State Transport Police
Legislators	State Senate Transportation Committee
Infrastructure maintenance	South Carolina Department of Transportation
Other stakeholders	South Carolina Farm Bureau
	The Carolinas Ready-Mixed Concrete Association
	South Carolina Timber Producers' Association

Appendix O Multiobjective analysis

Multiobjective analysis in transportation decision making

Multiobjective analysis has been applied in transportation decision making endeavors such as resource allocation, asset management, investment decision making, and network optimization to address the conflicting multiobjective nature of each research problem (Chowdhury et. al, 2002). Fwa et al. demonstrated the superiority of multiobjective optimization over traditional single objective optimization in pavement maintenance programming (Fwa et. al, 2000), the efficiency of which has been achieved by simultaneously considering minimization of cost, the maximization of network condition, and maximization of maintenance work.

In the context of freight transportation, most of the research entailing multiple objectives has been conducted in freight transportation supply chain management to develop optimal solutions to minimize freight truck fleet size, environmental impact, and inventory and transportation costs (Hwang, 2009; Sabria and Beamon, 2000; Ho and Dey, 2010). No significant effort has been made to examine the impact of overweight truck policies that considers both the damage to aging transportation infrastructure service life while considering freight operators' objectives or interests in the context of multiple conflicting objectives. The deterioration of transportation infrastructure from freight traffic is a complex problem, and the evaluation of alternatives for handling this problem can be overwhelming in the face of seemingly incomparable objectives.

Multiobjective Strategy

In the context of freight transportation, conflicting objective criteria may include freight traffic flow, transportation cost, damage of infrastructure (e.g., pavement, bridge), and freight truck pollution. Multiobjective analysis consists of two paired stages: mathematics-based optimization stage and decision maker-driven decision stage (Ehrgott, 2005; Miettinen, 1999).

The goal of the optimization stage is to formulate multiobjective optimization problems (MOPs), i.e., mathematical programs with multiple objective functions, and find their solution sets (Ehrgott, 2005; Ehrgott and Wiecek, 2005). In multiple conflicting objectives scenario, there are infinitely many solutions which are equally good. While the solution set in the optimization sense can be clearly defined based on rigorous mathematical concepts (such as the Pareto optimality), the decision stage naturally involves a DM with subjective preferences, priorities, expectations and personal aspirations which are often not easily described. The differences between different efficient or Pareto optimal solutions or options, generated from solving optimization problems with multiple objectives, is that each solution is better in one objective but worse in another objective. The relative improvement of one objective over another objective is known as tradeoff. In general, a tradeoff between two objective functions at a Pareto point is the ratio between increase of one function and decrease of the other assuming that all other objective functions remain constant

From the perspective of a DM, the optimization stage of multiobjective analysis is only a preliminary step to select a final preferred decision which then constitutes the overall solution to the multiobjective model and, after translation into the real-life problem context, to the original decision-making problem (Miettinen, 1999). While the solution set in the optimization sense can be clearly defined based on rigorous mathematical concepts (such as the Pareto optimality), the decision stage naturally involves a DM with subjective preferences, priorities, expectations and personal aspirations which are often not easily described or readily articulated in terms of the chosen mathematical model. Hence, finding a final solution can still be quite difficult if DM's preferences are not completely modeled or known and if the numbers of potential candidates and objectives are too large to make use of existing enumeration or visualization techniques.

Of special interest to DMs performing the decision stage are tradeoffs associated with each Pareto-optimal outcome and a corresponding efficient decision. In general, a tradeoff between two objective functions at a Pareto point is the ratio between increase of one function and decrease of the other when moving from this Pareto point to a point in a small neighborhood assuming that all other objective functions remain constant. Additionally, if the size of the neighborhood approaches zero, the definition of the tradeoff is supplemented with a limit of the ratio. In any case, tradeoffs quantification is of great value to DMs and used in many multiobjective analysis procedures supporting decision making with multiple criteria.

There are two general classes of approaches to generating efficient solutions of MOPs: (a) scalarization, and (b) nonscalarizing methods (Ehrgott and Wiecek, 2005). Scalarization methods are used to transform the MOP to a single objective optimization problem (SOP). Among the nonscalarizing methods other optimality concepts than Pareto are used, a class of set-oriented methods including a variety of metaheuristics, in particular, genetic algorithms (Deb, 2001).

The ε-constraint method, one of the most often applied scalarization techniques, was selected to carry out the optimization stage of the multiobjective analysis, because of its relative simplicity in controlling the objective functions while converting the MOP into an SOP. Epsilon (ε)-constraint method can be used in both linear and non-linear multiobjective optimization scenarios. The advantage of the ε-constraint method is that if the analyst can determine upper and lower bounds for the objective functions values, then the original MOP can be converted into an SOP by moving all objective functions but one to the constraints.

As pareto-optimal points along a Pareto-optimal frontier are inexact indicators of optimal outcomes, tradeoff analysis is then used to yield ordered Pareto-optimal points based on a tradeoff measure. A tradeoff between two objective functions can be calculated following the mathematical relationship (Chankong and Haimes, 1983). Tradeoff represents the amount of improvement of the primary objective function, due to a unit deterioration in objective function while all other objective functions remain constant. When the ε-constraint method is applied to MOPs, tradeoffs can be calculated as the dual variables (prices) associated with the ε constraints.

Bi-objective model for overweight truck permit Management

Overweight truck operators are required to secure a permit by paying a fee to DOTs stating the amount of excess weight above legal limits. This permit fee covers the administrative costs of the dedicated DOT permit program, and a damage fee to recover excessive damage to pavements and bridges. However, there are several types of overweight permit fee structures implemented by DOTs nationwide. Different fee structures place a different cost burden on different truck types, favoring some types over others. Such as flat permit fee would favor heavy overweight trucks as they pay less for much higher damage than light overweight trucks.

A multiobjective model was developed with two objective functions to demonstrate the tradeoffs between the variations in the fee structures. The most challenging aspect of any optimization model is the selection of appropriate decision variables, and the development of functional relationships among constraints and multiple objectives as described in previous section. An overweight freight operation scenario with two objectives (bi-objective) is formulated and solved to examine the applicability of a multiobjective strategy approach to overweight permit fee and policy analysis. Two objective functions are considered: (1) the minimization of unpaid damage associated with overweight freight truck operations and (2) the minimization of overweight truck damage fee to reduce the transportation cost of trucking companies in the context of overweight trucking operations on the South Carolina state highway system.

Currently, South Carolina DOT issues permits to overweight trucks and charges a flat $30 for single trips. The damage quantification shows that the damage imparted by overweight trucks is much higher than the current fee. A multiobjective analysis is applied to examine the impacts of different levels of fee implementation on damage recovery and overweight permit demand. Freight demand is influenced by changes in transportation cost. Understanding and determining users' reaction to any policy change (such as increasing permit fee) will assist DMs to estimate the impacts of policy changes to both the economy and users. It is known that freight demand is comparatively less sensitive to increases in transportation cost (i.e., inelastic), and in the existing literature, though limited, there are wide variations in the elasticity estimates of freight demand, primarily due to distinctions in the estimation models (Graham and Glaister, 2004). Generally, an increase of transportation cost (i.e., permit fee), tends to decrease the demand for freight shipped. It has also been observed in various supply and demand studies on freight that the elasticity of the freight demand varies between -0.5 and -1.5 depending upon the type of freight goods (Graham and Glaister, 2004). In this study, we assume elasticity values of high (-1.5), medium (-1.0), and low (-0.5) to present the sensitivity of the overweight freight demand to transportation cost. In response to demand sensitivity, the number of overweight permits demand decreases with an increase in permit fees. The generalized model leads to the following bi-objective optimization problem (BOP) with axle based fee structure in the second objective:

Subscripts and Superscripts	
i	$1, \ldots \ldots ., \mathrm{n}$ denotes truck class (2 axle, 3 axle etc,)
j	$1, \ldots \ldots . ., \mathrm{m}$ denotes GVW category in each truck class
Parameters	
$\mathrm{f_o}$	Current single trip permit fee in SC ($30)
$\mathrm{f_{ij}}$	New proposed permit fee
$\mathrm{F_{ij}}$	Estimated pavement and bridge damage due to one trip by $\mathrm{i} - \mathrm{th}$ truck class and $\mathrm{j} - \mathrm{th}$ GVW category
$\mathrm{N_{ij}}$	Number of trips in $\mathrm{i} - \mathrm{th}$ truck class and $\mathrm{j} - \mathrm{th}$ GVW category
$\mathrm{N_{ij}}'$	Fee adjusted number of trips in $\mathrm{i} - \mathrm{th}$ truck class and $\mathrm{j} - \mathrm{th}$ GVW category
c	Fixed administrative cost

r_{ij}	Perecentage of truck trips in $i - th$ truck class and $j - th$ GVW category
e	Overweight freight trip demand elasticity $(-0.5, -1.0, -1.5)$
E_{ij}	Change in permit deamnd
d_{ij}	Additional per trip damage cost by an overweight truck due to differences in imparted damages by the truck loaded at the legal limit, and maximum limit permitted for the truck with a typical overweight permit
Decision Variables	
x	Damage recovery percentage
Objectives	
Primary Objective (Minimize unpaid damage)	$\sum_{i=1}^{i=n} \sum_{j=1}^{j=m} (F_{ij} - f_{ij}) N_{ij}'$
Second objective (Minimize damage/permit fee)	$\sum_{i=1}^{i=n} \sum_{j=1}^{j=m} r_{ij} f_{ij}$
Constraints	
1) $N_{ij}' = N_{ij} E_{ij}$	Change in permit demand due to change in permit fee
2) $E_{ij} = \left(1 + e \frac{f_o - f_{ij}}{f_o}\right)$	Change in trip demand due to demand elasticity
3) $F_{ij} = d_{ij} + c$	Permit fee at 100% damage recovery scenario
4) $f_{ij} = d_{ij} * x + c$	Permit fee at x% damage recovery scenario
5) $N_{ij}' \geq 0.1 N_{ij}$	At least 10% of trips will exist irrespect of demand elasticity
6) $0 \leq x \leq 1$	Damage recovery percentage

In this multiobjective model, these two fee structures are considered in the second objective while minimizing permit fee:

1) The flat damage fee (where all overweight trucks pay the identical permit fee without any consideration to the amount of overweight load and the distance traveled in each trip)
2) The axle based damage fee (where the overweight amount, the truck configuration, the axle loads and the trip distance are considered in determining the damage fee)

Estimation of Model Parameters

To find solutions to assist DMs in developing overweight truck management strategies using the bi-objective scenario, an estimation of model parameters was critical. In the following subsections, the estimation of model parameters is described.

Estimation of number of overweight trips

Though state DOTs have been issuing overweight permits for decades, there are no reliable statistics on the percentage of overweight trucks currently using state highway systems. In this research, the weigh-in-motion (WIM) data was collected from the St. George WIM station on I-95 in South Carolina to estimate the percentage of overweight trucks. This data was also used to estimate the truck traffic composition. The WIM data revealed that 8.3% trucks were either axle load or gross vehicle weight overweight.

To estimate relative damage caused by overweight trucks, vehicle miles traveled (VMT) were estimated for South Carolina Department of Transportation (SCDOT) maintained highways utilizing overweight truck percentages and truck distribution observed at WIM station. More details on the VMT calculation and truck models can be found in Section 4.4.

Currently SCDOT overweight truck permit applications require that truckers provide information on both the origin and destination of trips. As trip lengths were not reported explicitly in current applications, a typical trip length was estimated using 2002 South Carolina Economic Census data (US Census, 2004). It has been assumed that trucks operate a regular five day work week, with an average of one trip per day. The total number of trips for a year (2012) was estimated using the estimated trip length and the annual VMT for each truck class.

Table O.1 Estimated Annual Overweight Trips in South Carolina in 2012

Truck Type	Trip Length (miles) (t_{ij})*	Number of Trips (N_{ij})*	Distribution of Trips(r_{ij})*
2 axle	75	496,667	17.12%
3 axle, single unit	100	48,448	1.67%
3 axle, combination	125	153,473	5.29%
4 axle, single unit	270	735	0.03%
4 axle, combination	270	71,052	2.45%
5 axle semitrailer	160	2,067,989	71.29%
6 axle semitrailer	160	30,723	1.06%
7 axle semitrailer	160	30,927	1.07%
8-axle semitrailer	160	681	0.02%

*tij, Nij and rij are model parameters

Estimation of pavement and bridge damage cost parameter (d_{ij})

Estimated pavement and bridge damage costs per trip by different truck types are presented in Table O.2. More details can be found in Sections 6 to 8 of the main report.

Table O.2 Additional per trip damage cost by an overweight truck loaded at the maximum limit above the legal weight limit (2012 $)

Truck Type	Per trip damage cost
2-axle, 35-40 kips	24.19
3-axle, single unit, 46-50 kips	14.58
3-axle, combination, 50-55 kips	37.53
4-axle, single unit, 63.5-65 kips	27.42
4-axle, combination, 65-70 kips	90.80
5-axle, 80-90 kips	61.40
6-axle, 80-90 kips	29.16
6-axle, 90-100 kips	67.99
6-axle, 100-110 kips	120.61
7-axle, 80-90 kips	18.05
7-axle, 90-100 kips	40.45
7-axle, 100-110 kips	71.23
7-axle, 110-120 kips	112.20
7-axle, 120-130 kips	164.83
8-axle, 80-90 kips	13.84
8-axle, 90-100 kips	30.70
8-axle, 100-110 kips	56.46
8-axle, 110-120 kips	85.72
8-axle, 120-130 kips	126.24

**Model parameters,* d_{ij}

To apply the ε- constraint method and compute Pareto-optimal outcomes of this BOP (Chankong and Haimes, 1983), the upper and lower bound of the secondary objective function is calculated by maximizing (f_{max}) and minimizing (f_{min}) this objective function subject to general constraints without considering pavement damage objective as a constraint.

The values f_{min} and f_{max} create an interval of feasible values of the ε parameter. The ε-constraint problem is solved for several values of ε which generate Pareto-optimal points of the bi-objective problem (BOP) based on type of fee structure considered in objective function. The ε-constraint single objective problem (SOP) is solved using a multiobjective optimization problem solver. Performances of both objective functions and tradeoffs are presented in Figures 20 to 21 of the main report for flat damage fee, axle based damage fee, weight-based damage fee, and weigh- distance-based damage fee, respectively. Each model is solved for elasticity value of -0.5, -1.0 and -1.5. Figures 20 and 21 show unpaid pavement and bridge damage corresponding to each fee category and their associated tradeoff.

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