DEVELOPMENT OF OVERWEIGHT PERMIT FEE USING MECHANISTIC-EMPIRICAL PAVEMENT DESIGN AND LIFE-CYCLE COST ANALYSIS

By

JINGNAN ZHAO

A Thesis submitted to the

Graduate School-New Brunswick

Rutgers, the State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate Program in Civil and Environmental Engineering

Written under the direction of

Dr. Hao Wang

and approved by

____

____

____

New Brunswick, New Jersey

January 2015

ABSTRACT OF THE THESIS

DEVELOPMENT OF OVERWEIGHT PERMIT FEE USING MECHANISTIC-EMPIRICAL PAVEMENT DESIGN AND LIFE-CYCLE COST ANALYSIS

By JINGNAN ZHAO

Thesis Director: Dr. Hao Wang

This study is conducted to investigate a framework to develop permit fee for overweight trucks using mechanistic-empirical (M-E) pavement design and life-cycle cost analysis (LCCA).

Mechanistic-Empirical Pavement Design Guide (MEPDG) is used to predict pavement performance and service life. The weight-in-motion (WIM) data of Interstate Highway 78 and New Jersey state highway 55 is processed and used for traffic input of typical major road and minor road. Empirical approach and Mechanistic-Empirical approach are utilized to estimate road usage expressed as equivalent single axle loads (ESALs).

Pavement life-cycle cost analysis using rehabilitation strategy with 2% discount rate during a 60-year analysis period is conducted to calculate equivalent uniform annual cost (EUAC). Regression models are developed to study the relationship between EUAC and average annual ESALs. According to EUAC regression models, marginal pavement damage costs for different pavement structures are estimated. Moreover, sensitivity analysis is performed to evaluate the impacts of LCCA parameters on marginal pavement damage cost (MPDC). In reference to EUAC and

MPDC estimation, a conceptual framework is established to calculate distance based, weight based, weight & distance based, and flat permit fee for overweight trucks.

It should be noted that, according to mechanistic-empirical pavement design, thin flexible pavement fails due to fatigue cracking, while thick flexible pavement and composite pavement fail due to asphalt concrete rutting. Exponential MPDC functions were developed. The sensitivity analysis revealed that repair strategy, analysis period, and load equivalency factor estimates have a significant impact on MPDC. Slight changes of MPDC were resulted from discount rate. The permit structure comparison indicated that overweight permit fee was not likely to be fair to all the overweight trucks.

ACKNOWLEDGEMENTS

Foremost, I would like to express my deepest gratitude to my advisor, Dr. Hao Wang, for his excellent technique guidance, enthusiasm, and patience. Without his endless help, it was impossible to accomplish my thesis. Besides my advisor, I would like to pay my regards to the rest of my thesis committee: Dr. Hani Nassif and Dr. Xiang Liu for their variable time, encouragement, and insightful comments. Finally, I would also like to present my special thanks to my parents for supporting me, both financially and emotionally, throughout my life.

TABLE OF CONTENTS

ABSTRACT OF THE THESIS .... **ii**
ACKNOWLEDGEMENTS .... **iv**
TABLE OF CONTENTS .... **v**
LIST OF FIGURES .... **vii**
LIST OF TABLES .... **ix**
CHAPTER 1 .... **1**
INTRODUCTION **1**
1.1 Problem of Statement 1
1.2 Objective and Study Scope 2
1.3 Organization of Thesis 4
CHAPTER 2 .... **5**
LITERATURE REVIEW **5**
2.1 State-of-Practice on Permit Fee Structure 5
2.1.1 Overview of Permit Fee Structure 5
2.1.2 Illustration of Permit Fee Structure at Different States 8
2.2 Effect of Overweight Truck on Pavement Damage Cost 11
2.3 Overweight Permit Fee Regulation Studies 24
CHAPTER 3 .... **33**
MARGINAL PAVEMENT DAMAGE COST **33**
3.1 Mechanistic Empirical Pavement Analysis 33
3.2 WIM Data Analysis 36
3.2.1 Selection of Representative WIM Data 36
3.2.2 Comparison between Overweight and Non-overweight Traffic 37
3.3 Pavement Life at Different Traffic Scenarios 42
3.4 Life-Cycle Cost Analysis 46
3.4.1 General Methodology of LCCA 46
3.4.2 Pavement Rehabilitation Strategy and Cost 48
3.5 Load Equivalency Factor 51
3.5.1 LEF Derived from M-E Analysis 51
3.5.2 AASHTO LEF 52

3.6 Marginal Pavement Damage Cost ... 57
3.7 Effects of LCCA Parameters on MPDC ... 62
3.7.1 Effects of Maintenance Method on MPDC Estimates ... 63
3.7.2 Effects of Analysis Period on MPDC Estimates ... 66
3.7.3 Effects of Discount Rate on MPDC Estimates ... 69
3.7.4 Effects of AASHTO LEFs on MPDC Estimates ... 72
CHAPTER 4 ... 74
DETERMINATION OF PERMIT FEE FOR OVERWEIGHT TRUCK ... 74
4.1 Conceptual Framework ... 74
4.2 Pavement Damage Cost Caused by Excessive Weight ... 78
4.2.1 Truck Traffic Composition ... 78
4.2.2 Pavement Cost Estimation Caused by Overweigh Tonnage ... 79
4.3 Permit Fee based on Individual Truck ... 85
4.3.1 Distance based Permit Fee ... 85
4.3.2 Weight & Distance based Permit Fee ... 86
4.3.3 Weight based Permit Fee ... 86
4.3.4 Flat Permit Fee ... 88
4.4 Comparison of Permit Fee Structures ... 89
CHAPTER 5 ... 93
CONCLUSIONS AND RECOMMONDATIONS ... 93
5.1 Conclusions ... 93
5.2 Recommendations for Future Research ... 94
REFERENCES ... 95

LIST OF FIGURES

FIGURE 2.1 Geographic Proximities of States Different Permit Fee Structures..........8
FIGURE 2.2 Research Flow Chart Used by Roberts and Djakfar (1999)...................12
FIGURE 2.3 Weights per Axle vs. Unit Pavement Cost, Urban and Rural Interstates for 134,000 lb GVW Truck..16
FIGURE 2.4 Unit Pavement Cost vs. Truck Miles Travelled for Urban Interstate Highways 16
FIGURE 2.5 Unit Pavement Cost vs. Number of Axles for Urban Interstate Highways 17
FIGURE 2.6 All Analyzed Cases in Agency Study 19
FIGURE 3.1 Vehicle Class Distributions at the Selected WIM Sites...........................38
FIGURE 3.2 Hourly Distributions at the Selected WIM Sites....................................39
FIGURE 3.3 Monthly Distributions at the Selected WIM Sites:.................................40
FIGURE 3.4 Axle Load Spectrum of Class 9-Non-overweight at 41
FIGURE 3.5 Axle Load Spectrum of Class 9-Overweight Trucks at (a) Interstate Highway 78 (b) New Jersey State Highway 55..42
FIGURE 3.6 Pavement Life Comparisons between Flexible Pavement and Composite Pavement of (a) Major Road (b) Minor Road..45
FIGURE 3.7 Activity Flow in a 60-year Analysis Period for (a) Thick Flexible Pavement (b) Thin Flexible Pavement...50
FIGURE 3.8 Load Equivalency Factors for (a) Fatigue Cracking and (b) AC Rutting 52
FIGURE 3.9 AASHTO and M-E LEFs of (a) Thick Flexible Pavement (b) Thin Flexible Pavement...55
FIGURE 3.10 Variation of EUAC with ESALs for (a) Thick Flexible Pavement (b) Composite Pavement 59
FIGURE 3.11 Variation of EUAC with ESALs for (a) Thin Flexible Pavement (b) Composite Pavement 60
FIGURE 3.12 Variation of MPDC with ESALs for Major Road: (a) Thick Flexible Pavement (b) Composite Pavement...61

FIGURE 3.13 Variation of MPDC with ESALs for Minor Road: (a) Thin Flexible Pavement (b) Composite Pavement 62
FIGURE 3.14 Activity Flow in a 60-year Analysis Period for (a) Thick Flexible Pavement (b) Thin Flexible Pavement 64
FIGURE 3.15 MPDC Comparison of Major Road between Rehabilitation and Full Reconstruction for (a) Thick Flexible Pavement (b) Composite Pavement 65
FIGURE 3.16 MPDC Comparison of Minor Road between Rehabilitation and Full Reconstruction (a) Thick Flexible Pavement (b) Composite Pavement 66
FIGURE 3.17 MPDC Comparison of Major Road during 30 and 60 years (a) Thick Flexible Pavement (b) Composite Pavement 68
FIGURE 3.18 MPDC Comparison of Minor Road during 30 and 60 years (a) Thin Flexible Pavement (b) Composite Pavement 69
FIGURE 3.19 MPDC Comparison of Major Road with 2% and 5% Discount Rate for (a) Thick Flexible Pavement (b) Composite Pavement 71
FIGURE 3.20 MPDC Comparison of Minor Road with 2% and 5% Discount Rate for (a) Thin Flexible Pavement (b) Composite Pavement 72
FIGURE 3.21 MPDC Comparison between using M-E and AASHTO for (a) Thick Flexible Pavement (b) Thin Flexible Pavement 73
FIGURE 4.1 Framework of Determination of Permit Fee for Overweight Trucks using Marginal Pavement Damage Cost 77
FIGURE 4.2 Annual ESALs Comparison between Original and Modified Traffic 83
FIGURE 4.3 EUAC Differences between Original Traffic and Modified Traffic for (a) Major Road (b) Minor Road 84
FIGURE 4.4 Variation of MPDC with ESALs for Thick Flexible Pavement 90

LIST OF TABLES

TABLE 2.1 Distribution of Permit Types 6
TABLE 2.2 Characteristics and Requirements of Permit Types 7
TABLE 2.3 Overweight Permit Fee from Illinois's Neighbors 9
TABLE 2.4 Overweight Permit Fee from New Jersey's Neighbors 10
TABLE 2.5 Overweight Permit Fee from California's Neighbors 11
TABLE 2.6 Weight per Axle vs. Unit Pavement Cost, Urban and Rural Interstates Used by Bilal et al. (2010) 15
TABLE 3.1 MEPDG Traffic Inputs 34
TABLE 3.2 MEPDG Level 3 Material Property Inputs 35
TABLE 3.3 Climate Input and Failure Criteria 35
TABLE 3.4 WIM Data at the Selected Sites 36
TABLE 3.5 Representative Pavement Structures Used for (a) Major Road (b) Minor Road 43
TABLE 3.6 Traffic Volume Assumption Matrixes 44
TABLE 3.7 Comparison of ESAL Factors Using AASHTO and M-E LEFs for Thick Flexible Pavement 56
TABLE 3.8 Comparison of ESAL Factor Using AASHTO and M-E LEFs for Thin Flexible Pavement 56
TABLE 3.9 Model Estimates for MPDC Estimation 58
TABLE 3.10 Model Estimates for MPDC Estimation Using Full Reconstruction 64
TABLE 3.11 Model Estimates over Different Analysis Period 67
TABLE 3.12 Model Estimates for MPDC Estimation Using 3% to 5% Discount Rate 70
TABLE 3.13 Model Estimates for MPDC Estimation Using AASHTO LEFs 72
TABLE 4.1 Characteristics of I-78 and NJ-55 78
TABLE 4.2 Overweight Truck Distribution in Each Truck Classification on Major and Minor Road 79
TABLE 4.3 Examples of Modifying Overweight Truck Traffic (Major Road) 81
TABLE 4.4 Examples of Modifying Overweight Truck Traffic (Minor Road) 82
TABLE 4.5 Annual ESALs and ESAL Factor Comparison between Original Traffic and Modified Traffic of (a) Major Road (b) Minor Road 83

TABLE 4.6 EUAC Difference between Original and Modified Traffic 85
TABLE 4.7 Estimated Truck Trip Length Using US Census Data 88
TABLE 4.8 Comparison of Permit Fee Structures (Major Road) 91
TABLE 4.9 Comparison of Permit Fee Structures (Minor Road) 92

CHAPTER 1

INTRODUCTION

1.1 Problem of Statement

Truck weight limits were first set in 1913 for the purpose of protecting highway pavements and bridges. On the basis of truck weight limits placed by Federal Highway Administration (FHWA) and state Departments of Transportation (DOTs), overweight permit fee is implemented to recover infrastructure maintenance expenditure, for which infrastructure users are supposed to be responsible. Using overweight trucks to transport commodity on highways is an available freight choice, because user fees, including vehicle fees and fuel taxes, can be reduced through operating overweight trucks in fewer trips.

According to data from J.J. Keller & Associate, Inc 2011 and state department of transportation, it is suggested that only 16 of the 49 states have charged weight & distance based or axle configuration based permit fee, which provide detailed and reasonable fees to recover pavement damage costs accounting for the impact caused by overweight trucks.

The overweight permit fee schedule applied in New Jersey is a weight based permit fee. New Jersey Department of Transportation legislates 80,000 pound as the legal gross vehicle weight (GVW). Federal Bridge Formula applies on GVW, steer, single, tandem, tridem and other successive-axle. The legal axle weight on a single axle is 22,400lbs, and the legal tandem axle weight is 34,000lbs. For a single permit, five US dollar per ton is charged once GVW or axle weight exceeds their legal weight limits. Besides the excess weight fee, 10 US dollar base fee, 12 US dollar transaction fee and 5% service fee are included in the permit fee. Basically, this policy is based on an assumed linear relationship between pavement damage and overweight tonnage.

However, the additional pavement damage costs caused by overload are not assured to be equal to permit fees paid by overweight truck fleet. The impacts of overweight tonnage above legal limits on pavement damage are difficult to quantify. Empirical and Mechanistic-Empirical approach are two typical methodologies to predict pavement performance. Mechanistic-Empirical Pavement Design Guide (MEPDG) is the trend to design new or rehabilitated pavements. In the MEPDG, pavement responses (strain and stress) to traffic loading are predicted based on mechanistic theory and then empirical models are used to link pavement responses and the performance of pavement structures.

The overweight permit fee schedules were established decades ago by state agencies. As truck freight demand has increased recently, overload trucking has been frequently observed. Researchers have investigated whether the existing permit fees can compensate the annual expenditures for pavement maintenance. In order to test and verify if legal weight limits could be increased, the impacts of regulation changes related to truck weights were studied. How to develop a methodology to determine overweight permit fee to balance the needs for preserving transportation infrastructure and encouraging economic development has become a challenge for future study.

1.2 Objective and Study Scope

The objective this study is to develop a framework to develop rational permit fee for overweight truck using mechanistic-empirical pavement design and life-cycle cost analysis. To achieve this objective, the following research tasks were conducted:

- Develop marginal pavement damage cost functions for typical pavement structure in New Jersey;

- Evaluate impacts of overweight trucks on pavement life and life-cycle cost; and
- Determine permit fee for overweight trucks using weight and/or distance criteria.

Mechanistic-Empirical Pavement Design Guide (MEPDG) is a new tool to design new and rehabilitated pavements. The axle load spectrums of the two selected WIM sites were utilized as required traffic input in the DARWin-ME software. According to the traffic volume, pavements are grouped into major roads and minor roads. One flexible pavement and one composite pavement are designated for each road type. Road usage is measured by ESALs calculated using load equivalency factors (LEFs) determined from AASHO road test and M-E analysis.

For the four designated pavement structures (thick flexible and composite pavement for major road, and thin flexible and composite pavement for minor road), pavement life-cycle cost analysis (LCCA) is performed. The marginal pavement damage cost (MPDC) is defined as a unit cost of providing pavement structure for one extra passage of a unit road usage expressed as equivalent single axle load (ESAL). Based on equivalent uniform annual cost (EUAC) and annual ESALs, models for MPDC estimation are developed for each pavement structure. Sensitivity analysis is conducted to evaluate impacts of LCCA parameters, such as discount rate, analysis period, maintenance strategy, and load equivalency factors, on MPDC estimation.

Total traffic and traffic without overweight trucks are the basic traffic scenarios to estimate the pavement damage cost difference. Flat permit, distance based permit, weight & distance based permit, and weight based permit are considered to compare the difference between permit fees charged by individual truck at each truck classification.

1.3 Organization of Thesis

There are five chapters in this thesis.

Chapter 1

A brief description of permit fee, which could be charged to compensate extra infrastructure damage cost, is presented.

Chapter 2

A comprehensive literature review of the current practice of permit fee for overweight trucks is conducted. Besides, prior works related to effects of overweight trucks on pavement damage cost are included.

Chapter 3

Mechanistic-Empirical approach is utilized to predict pavement performance. EUAC and average annual ESALs are computed to develop models to estimate marginal pavement damage cost.

Chapter 4

A conceptual framework of developing overweight permit fee using marginal pavement damage cost is presented. The elements of this framework are explained in detail. In reference to this framework and obtained WIM data, a case study is performed.

Chapter 5

Conclusions and recommendations for future study are presented.

CHAPTER 2

LITERATURE REVIEW

As trucking is the most flexible freight transportation tool, overweight trucking is a common phenomenon on the United States highways. In recent years, overweight permit fee has been used to preserve and manage infrastructure by state highway agencies. A number of researches have been conducted to develop a reasonable but simple-operated fee schedule to recover the extra costs caused by overloaded vehicles. The conclusions from the previous work vary depending on data source, methodologies, and policy purpose. The determination of overweight permit fee is related to infrastructure deterioration due to overloading and the level of balance encouraging commerce and protecting infrastructure. Pavements and bridges comprise transportation system involved in infrastructure damage costs caused by overloading issues. This Chapter provides a review on the current state-of-practice on permit fee structure and permit fee studies related to pavement damage cost.

2.1 State-of-Practice on Permit Fee Structure

2.1.1 Overview of Permit Fee Structure

Administrative costs of permit process are the basic component of the user fee charged by overweight/oversize trucks. Some state DOTs agree that the purpose of over-dimensional permits is not only to fund permitting processing, but also to recover the incremental pavement damage costs caused by overloading. State departments of transportation are aligning a series of scientific regulations to make over-dimensional permit fees proportionate to additional pavement damage.

Based on the period of validity, overweight permits could be sorted into single use, multiple use, monthly use, seasonal use, and annual use. The data collected from the Truck and Weights Manual (J.J. Keller & Associate, 2011) and the web sites of state DOTs indicated that 21 states issued single-trip permits, of which the validity is only three to five days, with fees flowing from $5 to $135, which were not related to either weight or total distance traveled.

Annual permits “assist” in reducing related administrative costs of the permit processing for state DOTs and simplifying permit applications for truck companies. As shown in Table 2.1, a faster growing trend of annual permits increasing for divisible loads was observed. Annual permits with a flat fee, which allow unlimited uses within one year, have positive influence on saving time spent in permit applications for each trip and reducing overall costs of trucking company.

TABLE 2.1 Distribution of Permit Types (thousands)

Permit Type	Year 2005	Year 2009	Increase
Non-divisible single trip permits	2712	3286	21.17%
Non-divisible annual permits	233	299	28.33%
Divisible single trip permits	288	370	28.47%
Divisible annual permits	393	574	46.06%
Total permits	3626	4529	24.90%

Source: Federal Highway Administration, 2010

Pavement deterioration is based on traffic volume and vehicular loading that depends on gross vehicle weight (GVW) and weight distributions on axles. These three critical factors provide states a direction to determine permit structures to fund pavement maintenance and rehabilitation. Due to the technological monitoring systems' potential challenging, in 2011 only 11(Table 2.2) states take trip length into consideration to compute the permit fee for excessive weight beyond legal limit. For instance, Oregon applied the weight & distanced-based policy to the overall commercial traffic (Oregon DOT, 2008).

TABLE 2.2 Characteristics and Requirements of Permit Types (Chowdhury et al., 2013)

	Flat fee	Weight-based	Distance-based	Weight & distance -based	Axle-based
States administering in 2011	21	10	2	11	5
Collects based on scale of exposure	No	Yes	No	Yes	Yes
Collects based on scope of exposure	No	No	Yes	Yes	Yes
Requirements for administration	Declaration Enforcement	Scale Declaration Verification Enforcement	GPS Declaration Verification Enforcement	GPS Scale Declaration Verification Enforcement	Declaration Verification Enforcement

Data source: Chowdhury et al. (2013)

According to the contributing factors above, the overweight vehicle permits are fundamentally grouped into five categories: flat, weight-based, distance-based, weight and distance-based, and axle-based. **Figure 2.1** shows the distribution of these five permit types in the United States. Each of the permit fee structure has its unique advantages and challenging in the aspects of fairness, precision allocation, and implement of complexity. Besides, their performance is various in different commerce and truck configurations.

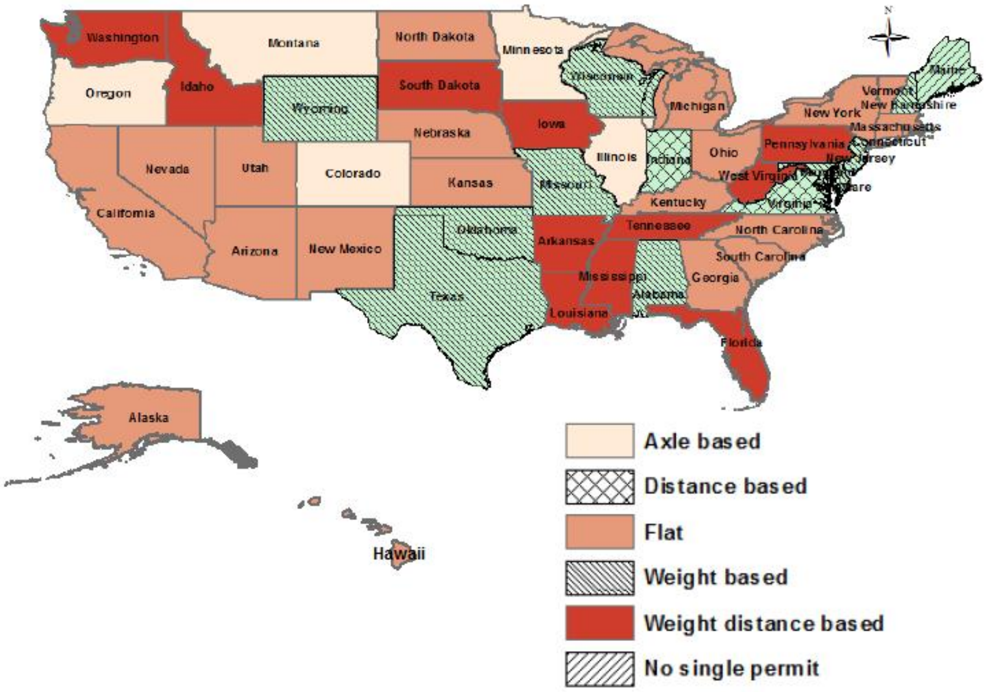


FIGURE 2.1 Geographic Proximities of States Different Permit Fee Structures

(Data source: J.J.Keller & Associate, Inc, 2011)

2.1.2 Illustration of Permit Fee Structure at Different States

Illinois Department of Transportation has established a relatively comprehensive overweight permit fees system considering gross vehicle weight (GVW), axle weight, and distance. Like many other states, Illinois's maximum legal weight limits are based on the federal bridge formulas. For the vehicle with both dimension and gross vehicle weight under the legal limits, axle overweight fees for each 45 mile increment are charged from \$5 to \$11. The fees are sorted into single, tandem, and tridem type. If the vehicle dimension exceeds the legal limits, extra oversize fee will be added to the axle overweight fees. For the vehicle dimension up to 15' high, 145' long and 12' wide or more, depending on the number of axle, gross vehicle weight and axle weight, overweight fees are grouped into 12 categories. The fees for each 45 mile increment of these categories range from $2.5 to $25, while in a certain category the relationship between trip length and permit fees is linear.

Two states of Illinois's neighbors have charged flat fees for regular overweight single trips. Iowa has only charged $10 for a single overweight trip, compared to $60 in Kentucky. Indiana has developed a system considering both trip length and gross vehicle weight ($0.35-1.0 per mile) in permit fee. Missouri and Wisconsin established the permitting system on the basis of gross vehicle weight. Not all of Illinois's neighbors offer a specific regulation for annual permit fee. Iowa, Kentucky, and Missouri have offered annual permits for flat fees ranging from $300 to $624; while Wisconsin has considered gross vehicle weight into annual permit fee calculations.

TABLE 2.3 Overweight Permit Fee from Illinois's Neighbors

State	Single Trip Permit Fee	Annual Permit Fee
Illinois	$10-$280[1]	---
Iowa	$10	$300
Indiana	$20+$0.35-$1.0/mile[2]	---
Kentucky	$60	$500
Missouri	$15+$20 per each 10kips	$300-$624[3]
Wisconsin	$20-$105[4]	$200-$850[5]

Data source: SC&RA oversize/overweight permit manual

1. $10 for up to 88,000 pounds (45 miles) and $280 for up to 100,000 pounds (495 miles)

2. $0.35 per mile for GVW 80,001–108,000; $ 0.60 per mile for GVW 108,001–150,000; $1.00 per mile for GVW 150,001 and over

3. $300 for overweight well drillers or concrete pump truck permit and $624 for emergency overweight permit

4. $20 for 90,000 pounds or less and $105+10 per 1,000 pounds for 150,001 pounds or more

5. $200 for 90,000 pounds or less and $850 for up to 150,000

At east region, only one state of New Jersey's neighbors has charged flat fees for regular overweight single trips. New York has charged $40-$360 per single trip, which depends on commodity. Pennsylvania has developed a system considering both trip length and gross vehicle weight ($0.03 per ton per mile). New Jersey and Delaware established the permitting system on the basis of weight. Virginia's permit fee is based on distance. New York and Pennsylvania have offered annual permits for flat fees which have a wide range from $200 to several thousand dollars. The annual permits of New York and Pennsylvania depend on commodity. Moreover, New York also has offered divisible load overweight permits, and the divisible load annual permits are based on the number of axles and minimum wheelbase. Delaware has charged annual crane permit fee for self-propelled cranes.

TABLE 2.4 Overweight Permit Fee from New Jersey's Neighbors

State	Single Trip Permit Fee	Annual Permit Fee
New Jersey	$10+$5 per ton[1]	---
New York	$40 - $360[2]	$360-$750[6]
Pennsylvania	$25/$50+$0.03/ton-mile	$200 to several thousand dollars[2]
Virginia	$20+$0.10 per mile[4]	---
Delaware	$10+$8 per each 8000lbs	$1500-$2500[5]

Data source: SC&RA oversize/overweight permit manual

1. $5 per ton for the maximum excessive weight of GVW and axle load
2. Depend on commodity
3. $25 if under or equal to 14' wide, and if over 14' wide the fee is $50
4. A mileage fee of $0.10/mile is added if overweight or if the vehicle configuration cannot be licensed in Virginia
5. Annual crane: $1,500 (plus a weight fee) for self-propelled cranes up to and including 24,000 pounds, and $2,500 (plus a weight fee) for self-propelled cranes over 24,000 pounds.
6. Varies from $360 to $1,000 and plus trailer fees up to $20 each for divisible load.

At west region, Arizona has developed a permitting system considering both axle and trip length ($1.00 per axle per 50 miles). Besides California, Nevada and Oregon have charged flat permit fees for overweight trucks. Washington established its permit fee on the basis of weight exceeding 100,000 lbs. California and Nevada have flat annual permit fees ranging from $60 to $90.

TABLE 2.5 Overweight Permit Fee from California's Neighbors

State	Single Trip Permit Fee	Annual Permit Fee
California	$16	$90
Arizona	$1.00 per axle per 50 miles[1]	---
Nevada	$25	$60
Oregon	$8	---
Washington	$25[2]	---

Data source: SC&RA oversize/overweight permit manual

1.Motor carrier fees are $48.00 per trip for over 50 miles, and $12.00 per trip of 50 miles or less. The fee for use fuel is $65.00 per trip for over 50 miles traveled, and $16.00 per trip for 50 miles or less.

2. The fee for weights in excess of 100,000 pounds is $4.25 plus $0.50 for each 5,000 pounds increment or portion thereof exceeding 100,000 pounds.

2.2 Effect of Overweight Truck on Pavement Damage Cost

Roberts and Djakfar (1999) conducted a preliminary assessment of impacts of increasing the GVW from the existing legal limit to 100kips on trucks hauling sugarcane, rice, timber, and cotton. The agronomic/horticultural permit, the cotton module permit, and the harvest season or natural forest products permit were the permits issued by Louisiana Department of Transportation and Development (LaDOTD) and included in the study. From the flow chart (**Figure 2.2**) below, it was found that researchers spent amount of time communicating with the related departments to determine roadways for each commodity, because the additional pavement damage depends on the trip-length which were determined by locations of each crop and their transportation routes. The truck weight scenario and payload per truck would affect pavement costs. Researchers found that smaller impacts were resulted from increasing of GVW on vehicles if the pavement was designated to haul larger sum of ESALs.

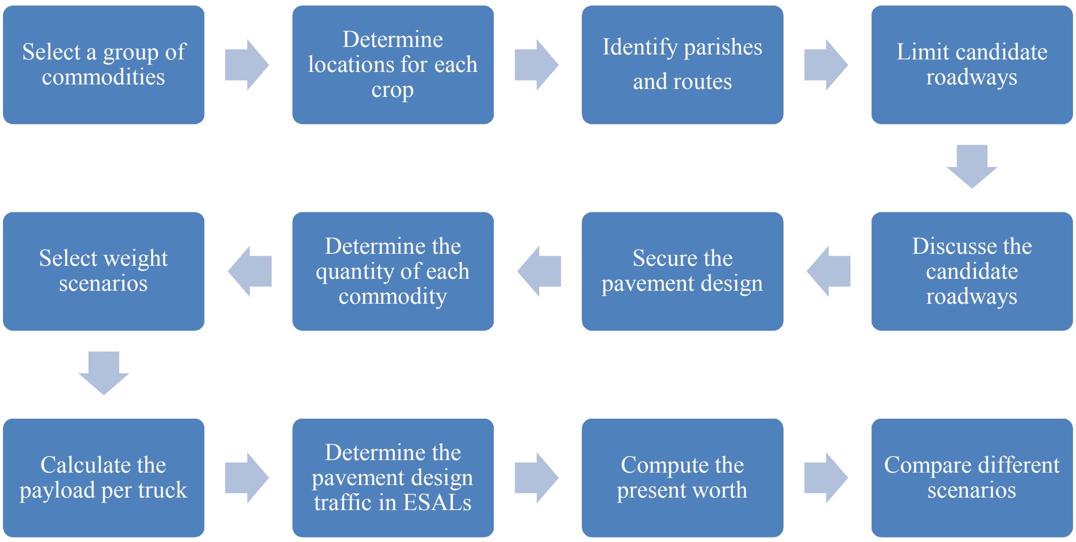


FIGURE 2.2 Research Flow Chart Used by Roberts and Djakfar (1999)

Boilé et al. (2003) performed a study on impacts of buses on New Jersey highway infrastructure. The proposed approach and data requirements applied in this study were similar to what were utilized in the truck study. However, buses stopped frequently at bus stops, which was a unique characteristic. Bus axle loads were supplied by vehicle manufacturers for crash load condition, which stand for fully loaded buses. Base on AASHTO procedure, the load of individual axle was estimated to calculate the total equivalent single axle loads (ESALs) of a whole bus for one pass.

It was noted that on New Jersey highways buses could result in comparable pavement damage to the damage caused by trucks. Researchers were able to compare and figure out which bus type have more negative influence on pavement. 70% of the New Jersey highways were assumed flexible pavements, and vehicle miles traveled (VMT) was the indicator of how much of the infrastructure was used by buses. It was found that buses were responsible for 2.4% of pavement maintenance and rehabilitation costs. A regression model was developed to study the relationship between the asphalt layer coefficient and resilient modulus of asphalt. The modulus in stop and go, slow and normal conditions traffic loading is 300,000psi, 500,000psi, and 700,000psi, respectively. The stop and go condition had the greater effect on pavement deterioration than the other two conditions. Based on the AASHTO design method, DARWin computer program was used to conduct sensitivity analysis for the hypothetical pavement sections.

Straus and Semmens (2006) conducted a study to estimate the costs of overweight vehicles traveling on Arizona highway. The researchers listed specific questions to survey several states in order to gather the information about overweight permit schedules. Unlike the other studies, the comparisons were made within the states by percentage, because the additional weight exceeding legal weight was the vital factor to estimate the costs of overweight trucks. The researchers identified the inadequacy of WIM data to estimate the pavement damage cost, because usually the WIM date was spare and not consistent. Instead, the researchers estimated the percentage of overweight vehicles on the basis of existing reports. They recommended a useful study for the future researchers: which types of vehicles were subject to the most overweight violations.

27 states were involved in the questionnaires survey conducted by Timm et al. (2007). The permit fee criteria, infrastructure damage assessment techniques and legal weight limits for these states were summarized and grouped on the basis of the survey results. The researchers emphasized the methodology, including Mechanistic-Empirical Pavement Design Guide (MEPDG) framework, Life-Cycle Cost Analysis (LCCA) framework and the three loading scenarios. Shifting entire loading spectra towards heavier loads, specific overloaded axle, which included constant volume-increased weight (CV-IW) and decreased volume-constant weight (DV-CW), and altering the axle configuration on trucks with specific axle weights were the three main scenarios simulated in the research. Through MEPDG, the researchers obtained the baseline and plots after shifting these three load spectrums.

In pavement damage analysis, pavement thicknesses and pavement life were re-evaluated using the increased load spectra after the baseline was determined for both flexible and rigid pavements. WESLEA, a layered elastic pavement analysis software, was used to find the maximum horizontal tensile strain at the bottom of the HMA layer for each loading case in flexible pavements. In the cost analysis, a 60-year period with at least two rehabilitation cycles could be considered for every baseline case. An interest rate of 4% was assumed in the life-cycle cost analysis (LCCA). The analysis compared the cost difference between entire load shifting and specific overloaded axle shifting. Different percentages of the four traffic levels were assumed to transfer tandem axles to tridem axles.

Bilal et al. (2010) gathered and summarized the detailed permitting fee structures in Indiana and its seven neighboring states. Multiple-trip permit expenditures summed up over one year and single-trip permit expenditure summed up over one year were evaluated. A company with 200 trucks in various dimensions was assumed for the evaluation. The third case study was to calculate the total annual permit fee to be paid by another hypothetical company on the basis of current single-trip fee structure. The fourth case was about determining how much a hypothetical trucker should pay in each given year on the basis of damage done to pavement. Researchers assumed a hypothetical truck with gross vehicle weight (GVW) of 134,000 lbs, which would travel 10,000 times per year. In order to find a relationship between weight per axle and unit pavement cost, the cost data in **Table 2.6** was used to plot nomographs and establish models for urban interstate and rural interstate highways.

TABLE 2.6 Weight per Axle vs. Unit Pavement Cost, Urban and Rural Interstates Used by Bilal et al. (2010)

Number of Axles	GVW (lbs)	Weight Per Axle (lbs)	Unit Pavement Cost ($/1000 Miles)	
			Rural	Urban
(a)	*(b)*	*(b)÷(a)*		
4	40,000	10000	10.0	31.0
4	60,000	15000	56.0	181.0
5	60,000	12000	33.0	105.0
5	80,000	16000	127.0	409.0

Researchers explored the relationship between unit pavement cost and weight per axle as shown in **Figure 2.3**. Using the formula, the researchers estimated the unit pavement cost per 1,000 miles for each set of axle number from six to ten and for urban and rural interstate highways. Then the pavement cost could be computed for different millage. From the processed data, pavement cost nomographs (**Figure 2.4** and **Figure 2.5**), which reflected the relationship between mileage and unit pavement cost and the relationship between mileage and the number of axle, were plotted. Finally, they got three conclusions from this research. First of all, increasing the number of axles led to a decrease in load per axle. Secondly, if mileage increased, pavement cost for a given number of axles increased linearly. Thirdly, the increasing of the number of axles for a given traveled distance decreased drastically pavement damage cost.

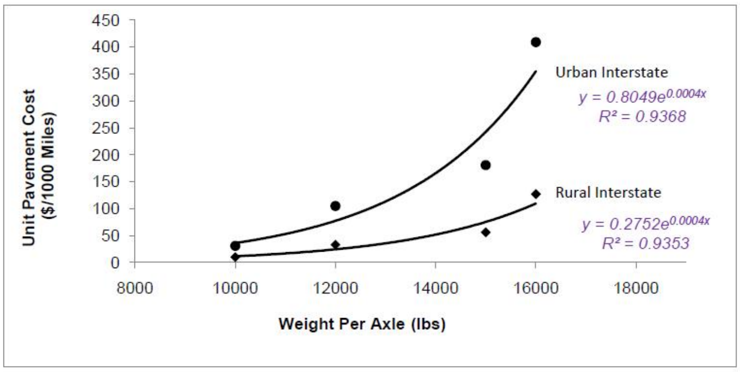


FIGURE 2.3 Weights per Axle vs. Unit Pavement Cost, Urban and Rural Interstates for 134,000 lb GVW Truck Developed by Bilal et al. (2010)

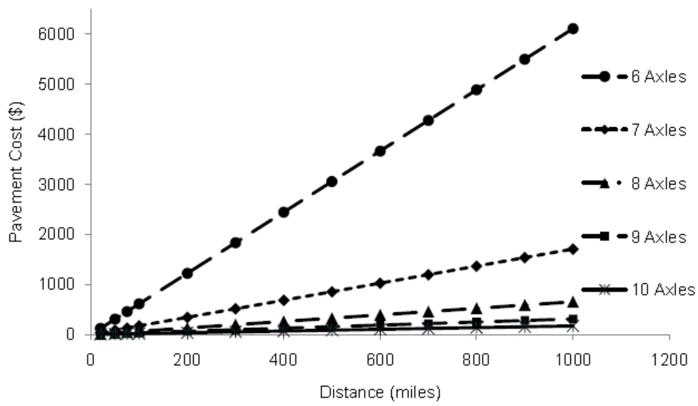


FIGURE 2.4 Unit Pavement Cost vs. Truck Miles Travelled for Urban Interstate Highways Developed by Bilal et al. (2010)

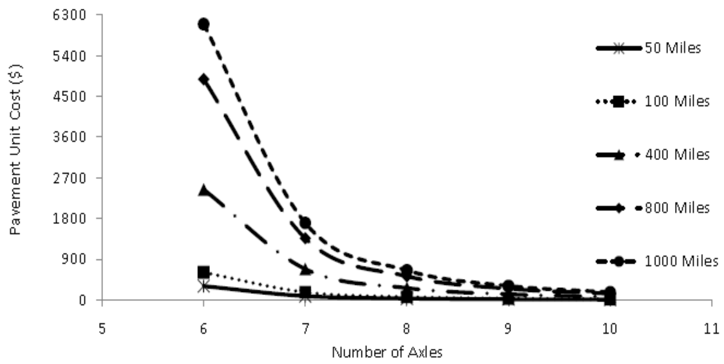


FIGURE 2.5 Unit Pavement Cost vs. Number of Axles for Urban Interstate Highways Developed by Bilal et al. (2010)

Martin (2002) estimated heavy vehicle road wear cost, which was an approximation for the marginal cost of road wear, based on two approaches. One of them was utilizing statistical relationship between maintenance cost and road use. Martin established a simple linear regression of the maintenance expenditure in terms of annual average cost including the parameter of road use variable, which was in form of ESALs-km. The second approach was to use pavement deterioration models. Road roughness was selected to predict pavement condition degradation. Attributable road wear cost was assumed to be related to environmental factors: average of the annual mean maximum and minimum air temperature, mean monthly precipitation, and Thornthwaite index (Thornthwaite 1948) based on soil and climatic conditions.

Barnes and Langworthy (2004) discussed the typical disadvantages of the existing methodologies or models currently used for estimating operating costs, which was of significance and related to various factors. Researchers intended to establish a baseline cost applicable to local condition and capable to compute special situation through adjustment factors. The baselines for costs of operating personal vehicles and trucks were considered and calculated separately. The costs of operating trucks depended on six different sources from review, of which fuel, vehicle maintenance, and tires costs were the three major factors. Besides, depreciation and adjustment factors were supposed to be considered. The researchers built the baseline (pavement serviceability index=3.5) and compared it with the other two situations: city driving condition (extreme congestion level) and poor pavement quality driving condition (pavement serviceability index=2). They selected $1.5 per gallon for fuel, 10.4 cents per mile for vehicle maintenance, 3.5 cents per mile for tires, and $8 per mile for depreciation costs (2003 US dollars). The variable cost of 43 cents took around 33% of the non-driver total cost of $1.30, while the driver cost was 50 cents per mile. This number increased to 52.9 cents in city driving condition and increased to 48.9 cents in poor pavement driving condition.

Fortowsky and Humphreys (2006) concluded two methodologies to estimate freight changes and pavement impacts from freight truck diversion caused by changes of truck weight limits on interstate highways. The purpose of the first methodology was to evaluate the changes in truck freight if Interstate Highway 95 was open to heavy weight trucks. The current case and exemption case, where truck traffic rerouted on interstate highways, were assumed in the study. The subtraction of the current case cost from the exemption case cost was the total safety, pavement and bridge cost difference. In order to estimate truck vehicle mile travelled (VMT) and ESALs, a representative ratio of five-axle and six-axle trucks were developed to convert freight tonnage to counts of five-axle and six-axle trucks. Through multiplying ESAL factors by truck VMT for each truck type and summation, ESAL-mile was calculated for each pavement segment. Since rerouting trucks on interstate highways, mapping and routing traffic network by TransCAD model was an important step in the study. The second methodology was to calculate road cost per ESAL by road type. The historical annual costs paid for pavement maintenance for each functional system were provided by Maine Department of Transportation (MDOT). Dividing expenditure by ESALs calculated in the first methodology, the researchers obtained road cost per ESAL. It was found that pavement cost savings were underestimated if state GVW limits were allowed on all of I-95.

Nie (2013) studied the impact of overweight truck on pavement damage cost using Mechanistic Empirical Pavement Design Guide (MEPDG). Four types of pavement structures and two sets of interstate highway traffic data from NJDOT were used in his study (**Figure 2.6**). Pavement life was predicted through MEPDG. LEF fitting functions were utilized to estimated the total ESALs caused by road use. Two variables were considered when the author calculated agency costs. A different maintenance strategy means that it uses the different pavement service life for total traffic and traffic with GVW under 80kips. A same maintenance strategy means that it uses the same pavement service life for total traffic and traffic with GVW under 80kips.

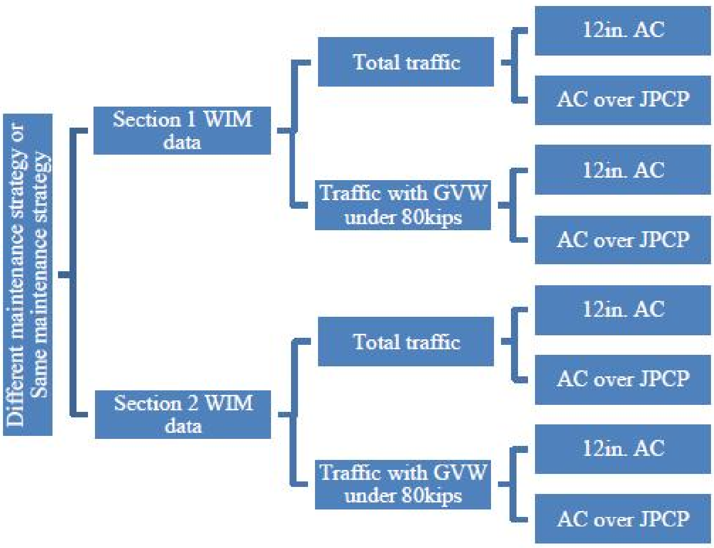


FIGURE 2.6 All Analyzed Cases in Agency Study

Jawad and Ozbay (2006) developed a compound model (LCCOM) for optimizing life cycle cost in transportation infrastructure, especially for flexible pavement projects. A study of diverse components indicated interrelations of these components should be taken into consideration once economic evaluation was conducted. A primer discussing all the key elements and principals of life-cycle cost analysis (LCCA) was presented as an introduction to the probabilistic approach towards leading to the interacting of the input parameters. The concept of utilizing various discount rates on the basis of governmental and academic guidance was explored meticulously. It was found that probability distribution constructed by best-fitting the real treasury discount rates were the most appropriate. Intelligent transportation systems (ITS) projects were concluded to be evaluated at higher discount rates than other traditional projects. The key of LCCOM, a mixed-integer nonlinear problem, was to minimize the net present economic worth through specifying pavement facilities according to targeted life cycle strategy. In LCCOM, the genetic algorithm was used as a search tool, and a risk analysis tool (monte carlo simulation) that took the interacting uncertainty into consideration were incorporated. After testing and improvement, LCCOM has proved its efficiency as a long-term decision-making management tool.

Ohio Department of Transportation (2009) performed a simplified highway cost allocation study (HCAS) to study the impacts of overweight trucks. In their study, a 20-year design life was assumed for new pavement construction and a 12-year life for pavement overlays. First, in order to get the total annual costs, they calculated expenditures for multi-lane and 2-lane system separately for typical pavement cross sections designated based on highway functional classes. Then they removed the overweight trucks from the total traffic and did the same expenditure calculations. The cost allocators depended on the two widely used allocators: vehicle miles traveled (VMT) and ESALs. Utilizing the total annual costs and cost allocators, they compared the costs between including and excluding overweight traffic. It was noted that over 14,500 lane miles of pavement would be designed thinner if no overweight trucks existed and the overweight weight trucks were supposed to responsible for about 122 million dollars per year.

Ahmed (2012) conducted marginal pavement damage cost estimation and found it in the range of \$0.0033 per ESAL-mile on interstate highways to \$0.1157 per ESAL-mile on non-national highway systems (NNHS). Unlike the methodology utilized in the previous researches, various overlay materials types and thicknesses applied in fixed intervals were considered for flexible and rigid pavements, which was more practical and realistic. There were three different highway types: Interstate highways, non-interstate highway system (NIS or NHS), and non-national highway system. To make the study more comprehensive, truck traffic volumes at four sub-categories (very high, high, medium, and low) for each highway type, separately. The compound annual traffic growth rates were estimated by formulation or assigned by Indiana Department of Transportation (INDOT).

The researcher used ordinary least square (OLS) regression to explore pavement performance models, which had been widely utilized in other researches. However due to heterogeneity which might be caused by unobserved factors, the random parameter regression model was confirmed to be a better option than OLS regression model. Over an infinite analysis period, five pavement age groups, including new and old pavements, were considered in pavement life-cycle MR&R (maintenance, rehabilitation and reconstruction) profile. The present worth of MR&R cost for partial-cycle and full-cycle was converted to equivalent uniform annual cost (EUAC). The MR&R EUAC was related to road use (ESALs), pavement types, and pavement age. Four scenarios were simulated to study the impacts of non-consideration of reconstruction or maintenance costs on marginal pavement damage costs. It was found that the only realistic manner was to incorporate highway agency MR&R strategy into marginal pavement damage cost estimation and consider all pavement repair costs. The pavement life cycle length and the interest rate utilized in the analysis were two main contributing factors which had significant influence on marginal pavement damage costs. Besides, the length of rest period and effectiveness of rehabilitation treatments could affect the accuracy of marginal pavement damage cost estimates.

Hajek et al. (1998) developed a methodology to evaluate the changes of pavement cost due to the regulation changes related to truck weights and dimensions. The ESAL-based cost functions, which were determined under 6% discount rate under 60-year analysis period for new pavements and in-service pavements, respectively, indicated that life-cycle pavement costs were in an exponential relationship with logarithmic increase in truck volumes. The authors assumed that 10% of ESAL changes produced by new pavements and 90% were produced by in-service pavements. Marginal cost functions were obtained through deducting one year ESAL cost function from its continuous year ESAL cost function. An exponential increase in marginal costs for low-volume roads was noted. After quantifying damage costs of proportionally rearranged traffic steams in Ontario pavement network, it was found that highway type is the main factor accounting for marginal pavement damage costs.

Bruzelius (2004) summarized four different approaches to measure the marginal costs of road use: direct approach, indirect approach, full cost allocation approach (also known as club and equity approach), and econometric approach. The HDM-4 Model was the most common, which was utilized in the direct approach. This method was not new but seldom applied in reality. Both indirect approach and full cost allocation approach were established on the foundation of Newbery's 'fundamental theorem' (1988b and 1989). In this theory, the marginal cost was in proportional relationship with the average maintenance cost of road use. The Road User Charges version 3.00 (RUC30) Model was developed by World Bank and widely used to quantify marginal pavement costs. Due to difficulties of generating required data and obtaining historic data, the example of econometric approach, such as the methodology developed by Hajek (1998), was few. Using one or two approaches above, the estimates of Swedish, US federal, British, EU and German studies were included in an international survey report.

According to Burmister's elastic layered theory (Burmister 1958), Sadeghi et al (2007) established a modeling procedure to discuss flexible pavement deterioration due to overweight traffic. KENLAYER computer program was utilized to simulate the elastic multilayer pavement system. Fatigue cracking based on the horizontal tensile strain at the bottom of hot mixed asphalt (HMA) and rutting based on vertical compressive strain on the top of subgrade were taken into consideration to calculate the number of allowable number of load repetitions. It was found that in most cases tensile strain was the critical factor. On the basis of a group of reference values, sensitivity analysis was conducted including four contributing factors related to pavement damage: asphalt layer thickness, pavements temperature, subgrade condition, and vehicle speed. The final deterioration formula was assumed in linear relationship with the deterioration formula of reference case, and affected by the changes of four sensitivity parameters. Pavement deterioration was expressed in term of the original load repetitions and load cycles after increasing axle loads. Through multiplying calculating operational life reduction factors from pavement deterioration by pavement length and total pavement costs per meter, overweight ticketing was determined. The operational life reduction was related to track loads. A software program was used for ticking calculation. The parameters of the average asphalt layer thickness, the pavements temperature, and the subgrade CBR could be imported as defaults. The vehicle speed, the vehicle type, and the length of the road passed by a truck were record by a digital truck scale, which was linked to the software. The comparison between the existing fine policy used in Iran and the overweight ticketing modeled in their study indicated that the revenue collected through fines was not inadequate.

On the basis of life cycle cost (LCC), Liedtke et al. (2009) presented a forward-looking approach for infrastructure cost calculation. The road infrastructure network was subdivided based on individual structures and its asset value was computed separately. Each policy decision was undertaken with a view toward minimizing LCC through considering traffic forecasts and technological development. In terms of increasing replacement cost over time, economic depreciation distributes the cost fairly between user generations.

2.3 Overweight Permit Fee Regulation Studies

Whitford and Moffett (1995) cited the existing annual permit system in Indiana and indicated that the existing permit process to an annual permit was supposed to be remained. A system was in need to simplify the work by permit staff. The overweight permitting was supposed to be reviewed more precisely. The researchers studied the permits for Michigan Truck-Trains, which were non-conforming vehicles using the “extra heavy duty highways”, and discussed the feasibility of implying annual permits. A serious loss of revenue caused by Michigan Train annual permits was noticed.

Meyburget al. (1998) used truck usage data gathered from truck operators in 1990-1991 through three seasonal mail surveys, assuming three weight scenarios: 125%, 135%, and 145% of the federal weight limits, and focused on the extra pavement damage caused by overloaded trucks issued with overweight permits. The federal legal weight limit is based on the so-called “bridge formula”. The research team chose $0.02, $0.06, and $0.40 (1987 US Dollar) per ESAL per mile for interstate, state, and local highways, respectively, during three selected seasons. To compare pavement damage cost caused by overweight trucks, the primary economic benefits were estimated in terms of labor cost, vehicle cost, operation cost and, operating time. The researchers found that the economic benefits exceeded the incremental pavement damage cost caused by overload trucks in all three scenarios.

Hewitt et al. (1999) explored a procedure to quantify pavement damage and economic impacts due to regulation changes related to truck weights in Montana. Instead of existing vehicle fleet, based on several sources of information from Montana Motor Carries Associations (MMCA), a new traffic stream was created to estimate the changes of truck traffic volume and vehicle miles traveled (VMT) for Montana highway network. The AASHTO design method and equivalent uniform annual cost (EUAC) were utilized to calculate pavement performance and costs, and the ESAL and cost changes were plotted in term of percentage. The transportation costs of the 12 selected commercial industries were evaluated under the assumption of hauling the same amount of freight, which provided a truck productivity comparison between various sectors. A major purpose of this study was to run input-output (I-O) models of Montana economy, in which infrastructure and productivity costs were input and gross state product was the output. The system developed by Regional Economic Modeling, Inc (REMI) could be applied to all regions in the U.S. to determine board economic trends. Since the result was based on selected commercial industries, it was not able to stand for general cases.

Luskin et al. (2002) discussed the economic inefficiency of fee structure for 2060 permits, which is an annual divisible-load permit legislated by the Texas government in 1989 for trucks to operate above the general weight limits. Due to the lack of detailed data on travel information, extreme-case scenarios for pavement damage, the worst-case and the best-case scenarios, were confined in the analysis. A truck traveling only on relatively light-duty roads was the subject in the worst-case scenario, while a truck traveling only on the relatively heavy-duty roads was the subject in the best-case scenario. Five-axle truck-trailer combinations were the predominant configuration among the trucks with the 2060 permit. The researchers selected a typical road for each traveling type and endeavored to maximize the difference of GVW between with permit and without permit for the worst-case scenario, while minimize the difference for the best-case scenario.

The authors considered the facts that heavier trucks need fewer trips to transport the same amount, which could save some pavement consumptions for the users. In the best-case scenario, the average permit fee of $234 is much less than the net of saving $500, and even less in the other scenario. This comparison between the permit fees and pavement consumption costs indicates that the HB 2060 permit is underpriced. Collection of additional data for investments to ensure and support the conclusion, expended role of counties on regulating the permit fee structures, and comprehensive overhaul of over-dimensional vehicles permitting system were required in future study. It was found that the combination of certified wide-area road-use monitoring (CWARUM) and GPS-based system was the trend in determining permitting regulations in the future study.

Fekpe et al. (2006) provided a conceptual framework for a federally supervised, but state-administered, performance-based oversize and overweight permitting program. Performance standards and framework, which were the two essential elements of a performance-based system suitable for application in the United States, were emphasized in the study. They illustrated the three major building blocks: administrative, enforcement, and evaluation, and defined the components of each building block for performance-based program. The evaluation played a unique role in this framework, because the performance could be continuously detected and the results could be used for revising performance measures. An overall assessment of the performance of the system is allowed to be committed by the feedback from the evaluation system and enforcement system in order to improve the highway safety. However, periodic reassessments of permitted vehicles were in need to make enforcement system more comprehensive.

Conway and Walton (2008) conducted a research to develop a methodology for testing whether the existing class-based toll structures was “fair” between various commercial truck classes and for optimizing toll rates in each truck class in order to fully recover the total cost of pavement consumed by trucks. They found that due to the disproportionality of the cost-recovery optimization strategy, a majority of vehicles would overpay for their actual pavement cost. The calculation of toll rates was supposed to be based on actual load equivalency factor (LEF) values, instead of vehicle classes, because the “fairness” within vehicle classes could not be achieved by the calculation of toll rates on the basis of optimal LEFs. Direction, bridge impacts, and space consumption were the additional factors which should be considered to improve the methodology. Besides, the study results indicated that real weight data were useless for testing and improving toll equity.

Sathaye (2009) explored an analysis methodology, which might be used for future policy assessments, to evaluate impacts on emissions under a variety of freight logistics policies aimed at load factors, influencing load consolidation, and increasing maximum truck weight limits. Load consolidation was defined as shifting of cargo between vehicles to increase laden load factor and decrease the number of trips. It was found that this shifting may cause increasing or decreasing total ESALs. Estimates of vehicle trips and ESALs were conducted using processed data from "Economic Census: Vehicle Inventory & Use Survey". Pavement design and deterioration models were simulated to estimate the effects of freight traffic changes on initial pavement structure design and pavement maintenance strategies. Finally, they concluded the resulting tailpipe and pavement supply-chain emissions to explore weather unintended environmental impacts are likely to be a significant concern or not. It was noted that the load increase policies aimed at large trucks would not result in unintended emissions.

Before conducting the phone interviews with Delaware, Maryland, New York, Pennsylvania and Virginia State Department of Transportation, Titze and Feese (2011) presented comprehensive review on overweight/oversize (OS/OW) permit fee. The final interview was about the organization of oversize and overweight permitting in these states, permit types and detailed regulation, permit fees and numbers, automation, performance measures and legislation. The interview results provided a robust foundation for further investigation to improve the New Jersey over-dimensional permitting system.

Titze et al. (2013) gathered, examined and analyzed the detailed state-practice of seven states including Connecticut, Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia. An extensive principle review and comprehensive analysis for each of the states in Mid-Atlantic Region were committed. In the study, permit fee structure, fine structure, routing considerations, escort policy and non-interstate road jurisdiction were defined and compared among these states. Through the comparison with New Jersey's neighboring states, New Jersey Department of Transportation learned lessons and summarized a series of recommendations to have the regulations and operations aligned. New Jersey was recommended to explore and add the creation of a non-divisible load blanket permit type to their list in order to allow more flexible overweight/oversize travel and directly reduce the work on agencies related to single trip permit reviews, while New Jersey Department of Justice did not support this suggestion. Due to the significant potential benefits to motor carrier industry, New Jersey may wish to have enforcement practices and carrier liability in local municipality permitting reviewed. New Jersey could take the relationship between infrastructure damage freight movements into consideration. Seeking permitting approaches which address recouping pavement or bridge damage through overweight/oversize permit fees was the next object. Exploring automated routing functionality in the future and sharing "Best Practices" with other automated states were recommended to New Jersey. New Jersey was also recommended to expand the need for an escort certification policy that could align with previously advanced best practices and review the origins of its existing escort dimensional limits to make sure the safety of the motoring public. It is recommended that NASTO should utilize existing regional permit models as a baseline and modify the permitting if necessary.

Six scenarios were created by Adams et al. (2013) to reflect a series of dimensional characteristics and essential information, which had influence on carrier fee, agency fee and escort fee of Mid America Association of State Transportation

Officials (MAASTO) states. In each scenario, the trucker was assumed to travel a 300-mile single trip on the highway in eight hours. At least one state Department of Transportation (DOT) representative from every MAASTO state was required to receive the survey and specify the applicable permit fee and the amount for each type of fee. Agency fee only covered the direct and marginal costs. Carrier fee depended on the permit fee schedule. Carrier fee and agency cost discrepancies were analyzed and calculated in the research. The comparison indicated that permit fee could not recover the costs of issuance, because the permit fee schedule was not developed on the basis of cost-recovery mechanism. DOT should take the high infrastructure impacts caused by the overweight/oversize loads into account.

Chowdhury et al. (2013) performed a research to estimate pavement deterioration caused by overweight trucks and study the adequacy of standard permitting practices in state agencies. The additional pavement damage costs due to overweight trucks comprised two main sections: truck freight on South Carolina highways and the sum of ESALs produced by each individual truck. Researchers obtained AADTT estimates for roads at different functional classes in South Carolina through TRANSEARCH database and studied the truck type distribution (from 2-axle to 8-axle) through WIM data from the St. George weigh station on I-95. The average trip length of each truck class was estimated on the basis of annual mileage reported in the 2002 South Carolina Economic Census data. The trucks were assumed to be operated five days per week and travel once a day. An analysis was performed for flexible pavements in three different GVW groups: 80% of the SCDOT legal weight limits, SCDOT maximum weight limits, and Maximum considered truck weight. Three traffic scenarios were created: no trucks in the traffic (minimum design scenario), traffic includes trucks but no weights exceeding legal weight limits, and traffic includes trucks where 8.3% of trucks were overweight. The researchers created truck configuration and calculated the ESAL factors for each individual truck. Then the replacement costs for each pavement design scenario were estimated to investigate the additional pavement damage costs in order to calculate permit fees Four basic types (flat fees, weight based fees, distance based fees and axle based fees) and two combined types (annual permit and combined consideration of weight and distance) of overweight permit fee were involved in the study.

Hjelle (2003) established the FAMAROW-Model (factual marginal road wear) to perform regression analysis using time series of factual road wear based on roughness (IRI) and rutting (rut-depth) against traffic data obtained from weight-in-motion (WIM) and Automatic Traffic Control (ATC). The object of this model was to convert factual road wear into marginal costs and calculate marginal road wear costs. Another model defined in this study was CATERU-model for the purpose of calculating tax relevant external costs of road use. It was combined with a application of the proper economic principles.

Dey et al. (2013) discussed a multi-objective analysis approach applied to satisfy overweight freight truck mobility and select the optimal permit fee simultaneously. The objectives in the bi-objective model were the minimization of unpaid damage associated with overweight trucks and the minimization of overweight damage fee. A series of parameters and formulas were given to develop the relationship between the two objectives. The flat damage fee, the axle based damage fee, the weight based damage fee, and the weight and distance based damage fee were the four fee structures considered in the analysis. Overweight freight trip demand elasticity of -0.5, -1.0, and -1.5 were assumed to study the sensitivity of overweight demand to the permit fee. Representative truck models for different truck configurations were based on 2011 SCDOT overweight permit database. The ESALs was estimated based on the assumption for a standard flexible pavement section with structural number (SN) of 5 and terminal serviceability index (Pt) of 2.5. Minimum damage cost to all vehicles, additional damage cost due to all truck traffic, and additional damage cost due to overweight trucks only were the three scenarios used to estimate pavement costs. The elasticity value reflected the sensitivity of overweight demand to the permit fee.

CHAPTER 3

MARGINAL PAVEMENT DAMAGE COST

3.1 Mechanistic Empirical Pavement Analysis

Mechanistic-empirical (M-E) approach is a compound method. Empirical model is used to make the appropriate correlation between mechanistic theory and the performance of pavement structures. Mechanistic Empirical Pavement Design Guideline (MEPDG), which is based on M-E approach, is a new tool to design new construction and rehabilitation pavement structures. Hierarchical approach for the design inputs is applied to MEPDG. There are three levels of design input in MEPDG. Laboratory measured material properties and project-specific traffic data are required in Level 1 input. Level 2 input is obtained through empirical correlations with other parameters. The Level 3 input was used in this study. Compared to Level 1 and Level 2 input, Level 3 input supplies the lowest accurate analysis results, because default values with minimal material testing and data collection are used in DARWin-ME software program.

MEPDG inputs are comprised of traffic, material property, pavement structure, and climate input. **Table 3.1** summarized traffic inputs required in the software. In this study, traffic information was obtained through processing weigh-in-motion (WIM) data. Pavement structures, including layer type, material type and layer thickness, were designated according to traffic volume. Default material property inputs are included in **Table 3.2**. In MEPDG software, there is a library of weather data for about 800 weather stations all over the U.S. If climate site is selected, environmental conditions will be inputted automatically. The enhanced Integrated Climatic Model (EICM) is utilized to predict environmental conditions. EICM is a mechanistic model which reflects the daily and seasonal variations of temperature and moisture in the pavement structures induced by environmental factors at the project site. **Table 3.3** shows the climate information input in DARWin-ME and failure criteria applied in the software.

TABLE 3.1 MEPDG Traffic Inputs (Baus and Stires, 2010)

Site Specific Traffic Inputs
• Initial Two Way Average Annual Daily Truck Traffic (AADTT) • Percent Trucks in Design Lane • Percent Trucks in Design Direction • Operational Speed • Truck Traffic Growth
WIM Traffic Data
• Axle Load Distribution • Normalized Truck Volume Distribution • Axle Load Configurations • Monthly Distribution Factors • Hourly Distribution Factors
Other Inputs
• Dual Tire Spacing • Tire Pressure • Lateral Wander of Axle Loads

TABLE 3.2 MEPDG Level 3 Material Property Inputs (Baus and Stires, 2010)

HMA	PCC
• Aggregate Gradation	• Elastic Modulus and/or Flexural Strength
• Air Voids	
• Effective Asphalt Binder Content	• Poisson's Ratio
• Total Unit Weight	• Unit Weight
• Poisson's Ratio	• Coefficient of Thermal Expansion
• Dynamic Modulus	• Surface Shortwave Absorptivity
• Surface Shortwave Absorptivity	• Thermal Conductivity
• Reference Temperature	• Heat Capacity
• Thermal Conductivity of Asphalt	• PCC Zero-Stress Temperature
	• Cement Type
• Heat Capacity of Asphalt	• Compendious Material Content
Unbound Materials	• Water to Cement Ratio
• Gradation	• Aggregate Type
• Resilient Modulus	• Curing Method
• Poisson's Ratio	• Ultimate Shrinkage
• Moisture Content	• Reversible Shrinkage
• Dry Density	• Time to Develop 50% of Ultimate Shrinkage
• Atterberg Limits	

TABLE 3.3 Climate Input and Failure Criteria

Spectra	Minor roads	Major roads
Basic Information		
Design Life	40 years	
Climate Data Sources (Lat/Lon)	40.683,-74.169 (Newark, NJ)	
Design Criteria		
Reliability	90%	90%
Target for Terminal IRI	172 in./mile	172 in./mile
Permanent Deformation-Total Pavement	0.75 in.	0.75 in.
AC Bottom-up Fatigue Cracking	10%	10%
AC Thermal Fracture	1000 ft./mile	1000 ft./mile
AC Top-down Fatigue Cracking	2000 ft./mile	2000 ft./mile
Permanent Deformation-AC only	0.25 in.	0.25 in.

3.2 WIM Data Analysis

3.2.1 Selection of Representative WIM Data

Weigh-in-motion devices can continuously capture and record axle load, gross vehicle load (GVW) and axle spacing with supplementary data such as date, time, speed, lane of travel, vehicle type, etc, over a measurement site. **Table 3.4** shows the average annual daily truck traffic (AADTT) and the percentage of overweight trucks after analysis of WIM data in 10 selected sites. As expected, the AADTT in the interstate highway is much greater the AADTT in the minor road. However, the percentage of overweight trucks varies in a wide range from 3% to 25%. Total truck traffic and overweight trucks are recorded at the WIM sites. Non-overweight truck traffic was obtained by subtracting the number of overweight trucks from the number of total trucks at each truck classification for single, tandem, tridem and quad axle.

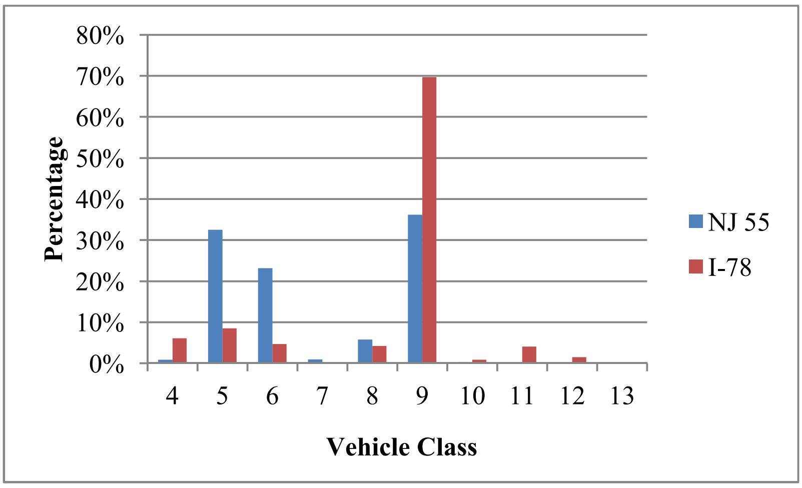
TABLE 3.4 WIM Data at the Selected Sites

Route #	Average Annual Daily Truck Traffic (AADTT)		Percentage of Overweight Trucks
	Total	Overweight	
I-78	11,739	1,970	17%
I-80	14,131	1,567	11%
I-195	3,572	686	19%
U.S. 1	8,337	558	7%
I-287	10,747	275	3%
I-295	13,607	899	7%
NJ 202	928	230	25%
NJ 34	2,710	239	9%
NJ 55	1,348	143	11%
NJ 138	485	26	5%

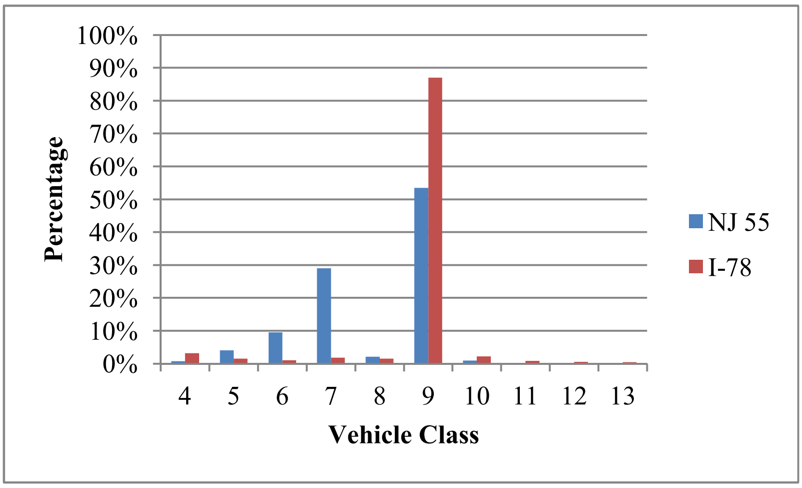
Among the six interstate highways in **Table 3.4**, the AADTT of four highways exceeds 10,000, and the AADTT of U.S. 1 is almost 10,000. For two of the four minor roads, the AADTT is approximately 1000. Thus WIM data at Interstate Highway 78 (I-78) and data at New Jersey state highway 55 (NJ-55) were selected for traffic input of typical major road and minor road. A linear growth rate of 3% was assumed for traffic increase. Other traffic input including axles per truck, monthly adjustment factors, and hourly distribution factors were obtained through the post-processing of WIM data at the selected two sites.

3.2.2 Comparison between Overweight and Non-overweight Traffic

The non-overweight and overweight percentages of each truck class at the Interstate Highway 78 and state highway 55 are shown in **Figure 3.1**. It is found that for non-overweight traffic at both sites the truck traffic composition manly includes class 9 (five-axle, single trailer), class 5 (two-axle, six-tire, single unit), class 6 (three-axle, single unit) and class 8 (four-axle or less, single trailer). Class 9 and class 5 cover nearly 80% of the total traffic. However, for overweight truck traffic, class 9 and class 7 are the main comprising vehicle classes.



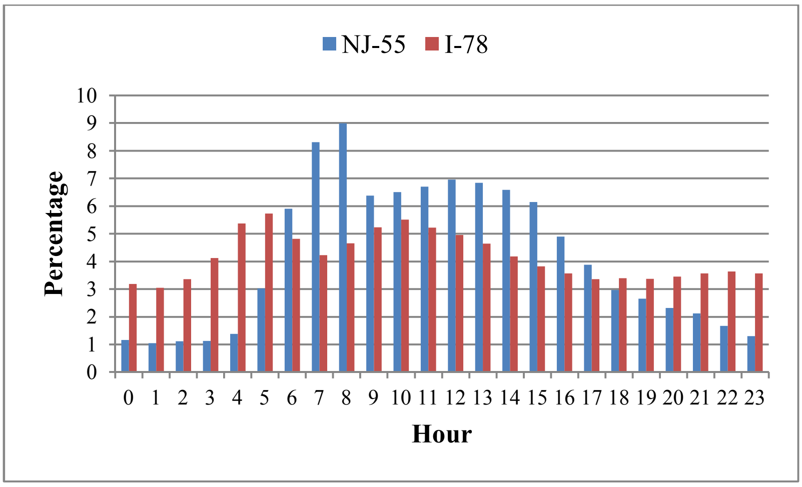
(a)



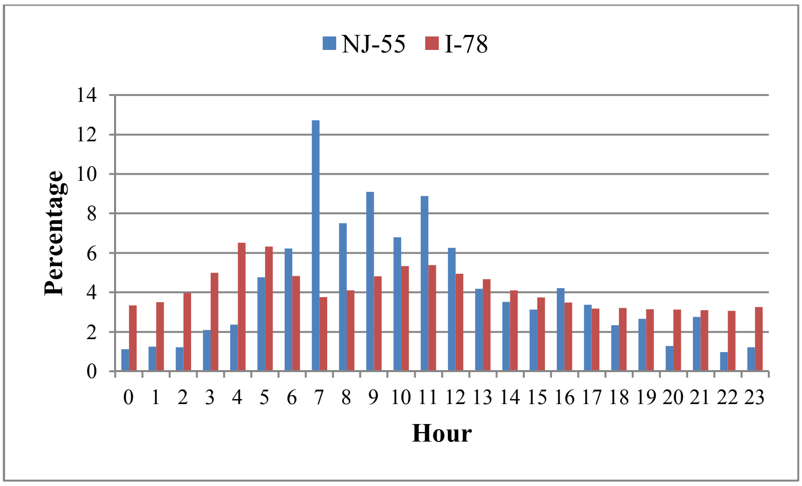
(b)

FIGURE 3.1 Vehicle Class Distributions at the Selected WIM Sites (a) Traffic without Overweight Trucks (b) Overweight Trucks

Figure 3.2 shows hourly distributions at Interstate Highway 78 and state highway 55. The rush hour appears at 10 am on Interstate Highway 78, and at 8 am on state highway 55. Traffic without overweight trucks and overweight truck traffic has the similar hourly distribution patterns.



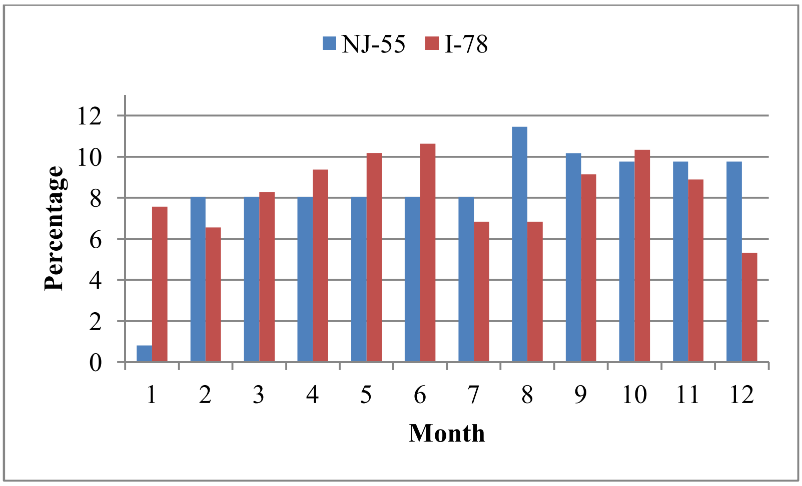
(a)



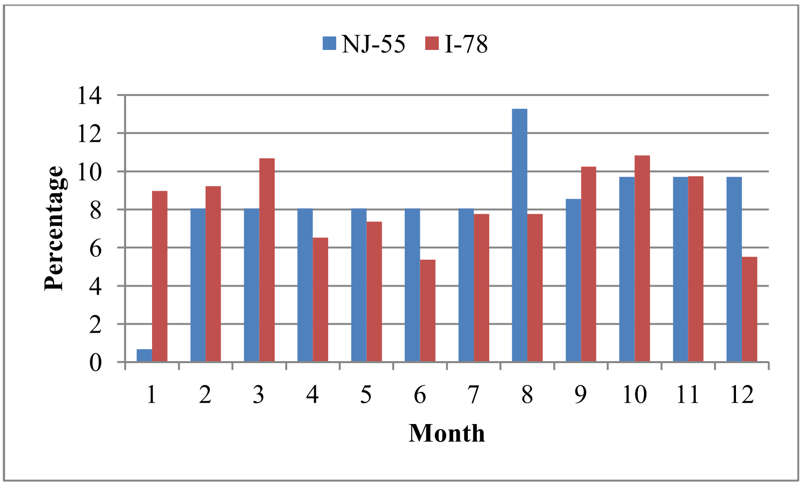
(b)

FIGURE 3.2 Hourly Distributions at the Selected WIM Sites (a) Traffic without Overweight Trucks (b) Overweight Trucks

Figure 3.3 shows monthly distributions at Interstate Highway 78 and state highway 55. Temperature and moisture are various in different months. Material properties, structure response, pavement distress and drainage are affected by changes of temperature and moisture. Therefore monthly distribution is a critical factor affecting pavement performance.



(a)

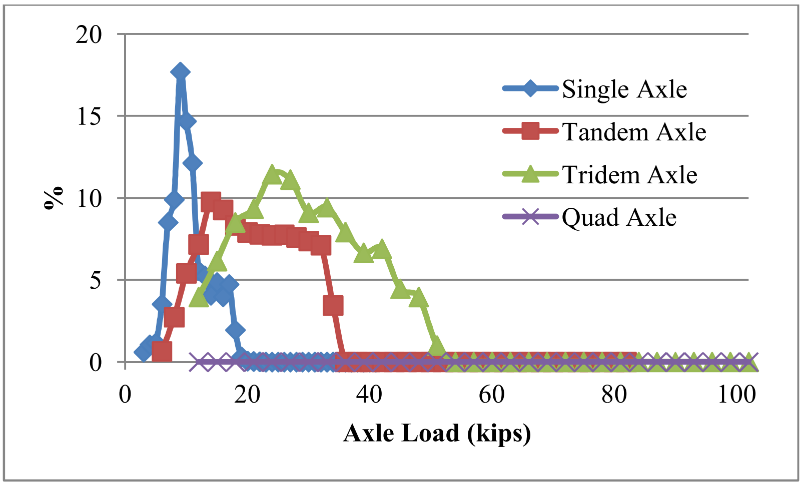


(b)

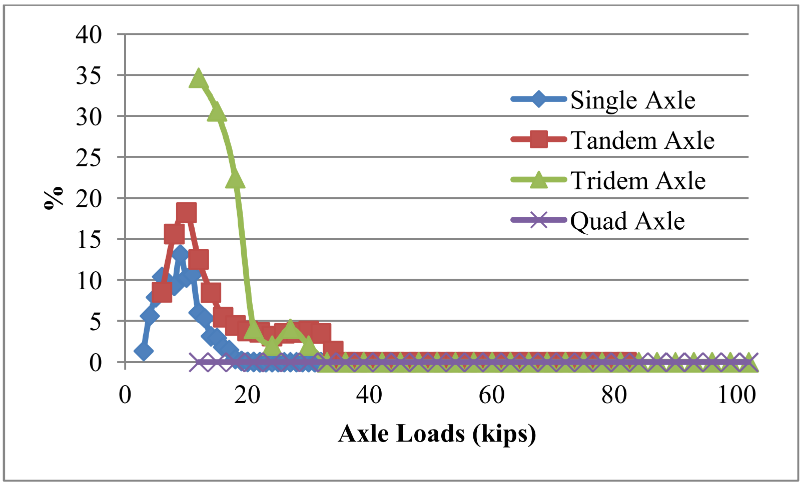
FIGURE 3.3 Monthly Distributions at the Selected WIM Sites: (a) Traffic without Overweight Trucks (b) Overweight Trucks

The selected WIM data provides axle load spectrum input of typical major and minor road. The axle load spectrum of overweight truck traffic and traffic without overweight trucks are the foundation of recalculating new axle load spectrum for designated pavement structures. Significant differences between traffic without overweight trucks and overweight truck traffic were found.

Figure 3.4 shows the axle load spectrum of class 9 vehicles excluding overweight trucks averaged for 12 months. The results show that at Interstate Highway 78 the single axle loads concentrate in the range of 10-12 kips. The tandem axle loads have a wide distribution range of 15-35 kips, and tridem axle loads range from 20 kips to 40 kips. At New Jersey state highway 55, the single axle loads concentrate in the range of 8-10 kips, and the tandem axle loads concentrate in the range of 8-20 kips. However, tridem axle loads have a wide distribution range of 20-40 kips.



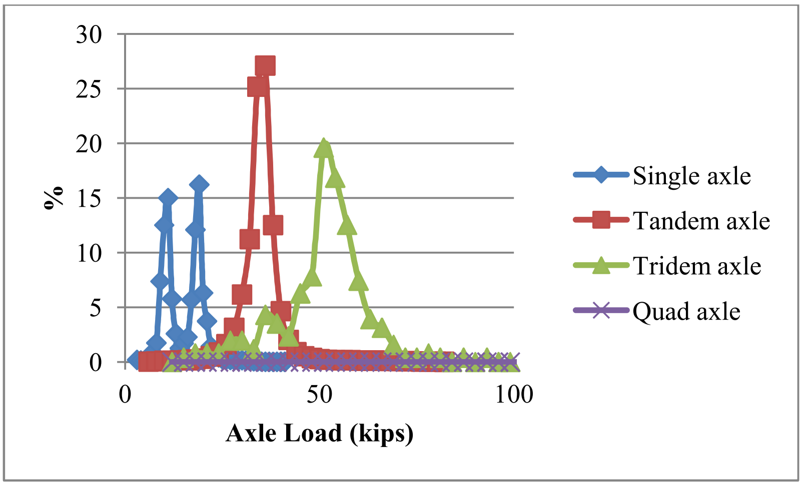
(a)



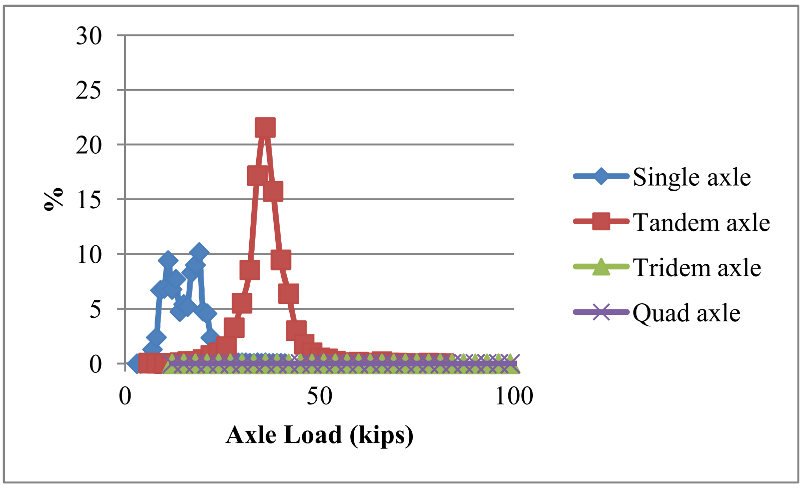
(b)

FIGURE 3.4 Axle Load Spectrum of Class 9-Non-overweight at (a) Interstate Highway 78 (b) New Jersey State Highway 55

Figure 3.5 shows the axle load spectrum of class 9 vehicles for overweight trucks for 12 months at the two WIM sites. The results show that the single axle loads concentrate in the range of 5-20 kips and the tandem axle loads concentrate in the range of 35-40 kips. Besides, two significant peaks in single axle loads and one peak in tandem axle loads are found. For major roads, the tridem axle loads have a distribution range of 50-60 kips.



(a)



(b)

FIGURE 3.5 Axle Load Spectrum of Class 9-Overweight Trucks at (a) Interstate Highway 78 (b) New Jersey State Highway 55

3.3 Pavement Life at Different Traffic Scenarios

Based on practical pavement structures applied in New Jersey, flexible pavement and composite pavement were selected for analysis. Due to traffic volume difference, thicker pavement structures using better asphalt were designated for major road. The layer type, material type, and thickness of flexible and composite pavements for each road type are summarized in **Table 3.5**.

TABLE 3.5 Representative Pavement Structures Used for (a) Major Road (b) Minor Road

(a)

Pavement Type	Layer Type	Material	Thickness (in.)
Thick Flexible Pavement	Flexible	Asphalt concrete (PG 76-22)	6
	Flexible	Asphalt concrete (PG 64-22)	6
	Non-stabilized	Crushed gravel	20
	Subgrade	A-1 soil	Semi-infinite
Composite Pavement	Flexible	Asphalt concrete (PG 76-22)	6
	Rigid	Cement concrete	9
	Non-stabilized	Crushed gravel	12
	Subgrade	A-1 soil	Semi-infinite

(b)

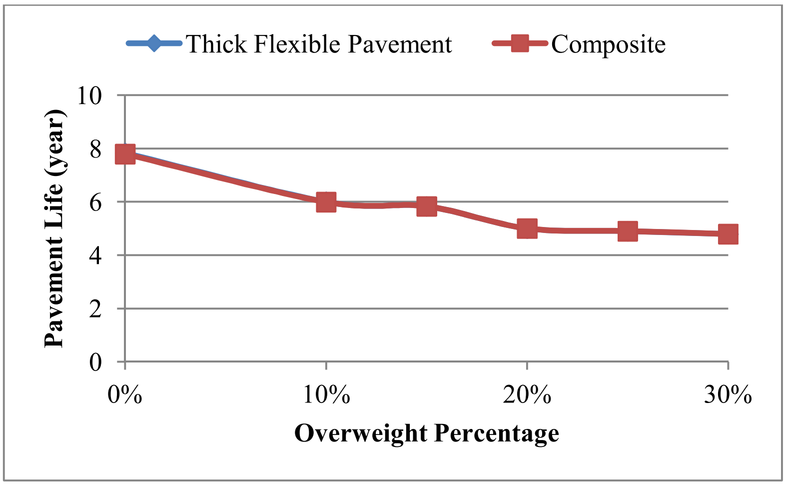
Pavement Type	Layer Type	Material	Thickness (in.)
Thin Flexible Pavement	Flexible	Asphalt concrete (PG 64-22)	2
	Flexible	Asphalt concrete (PG 64-22)	2
	Non-stabilized	Crushed gravel	20
	Subgrade	A-1 soil	Semi-infinite
Composite Pavement	Flexible	Asphalt concrete (PG 64-22)	4
	Rigid	Cement concrete	7
	Non-stabilized	Crushed gravel	12
	Subgrade	A-1 soil	Semi-infinite

Table 3.6 includes the truck traffic volume combinations for software input. Non-overweight AADTT and overweight truck percentage as of non-overweight AADTT are two factors which have influence on pavement service life. Based on traffic volume assumptions, the axle load spectra of non-overweight and overweight truck traffic in **Figure 3.4** and **Figure 3.5**, the new axle load spectra for traffic inputs was recalculated. 30 cases were conducted for each pavement structure.

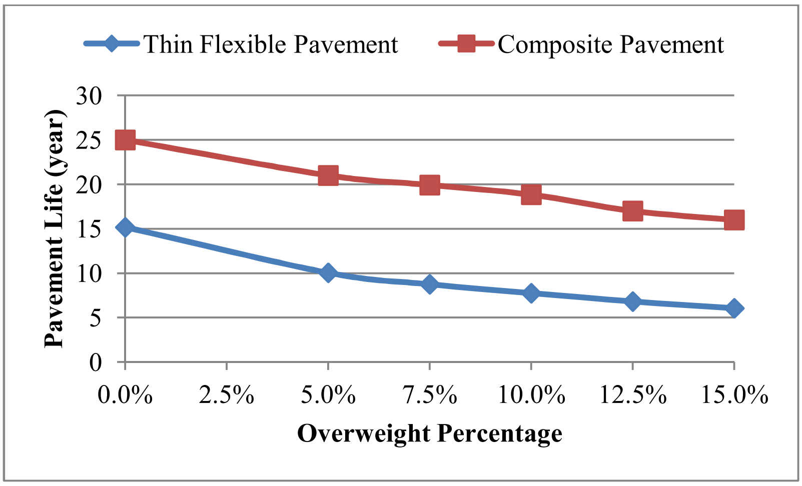
TABLE 3.6 Traffic Volume Assumption Matrixes

Axle Load Spectrum Used	AADTT without Overload	Overweight Truck Percent as of AADTT without Overload
Major Road	4000, 6000, 8000, 10000,12000	0%,10%,20%,30%, 25%,25%
Minor Road	500, 1000, 1500, 2000,3000	0%,5%,7.5%,10%, 12.5%,15%

The criteria for maximum bottom-up cracking is 10% (thin flexible pavement only) and for maximum subtotal AC rutting is 0.25in (thick flexible pavement and composite pavement). According to pavement life prediction, it is found that thick flexible pavement and composite pavement fail due to AC rutting, while thin flexible pavement fail due to fatigue cracking. The typical flexible pavement and composite pavement life at 90% reliability were predicted. Pavement life with 2000 AADTT for minor road and 8000 AADTT for major road is presented in **Figure 3.6**.



(a)



(b)

FIGURE 3.6 Pavement Life Comparisons between Flexible Pavement and Composite Pavement of (a) Major Road (b) Minor Road

It is expected that pavement life decreases as overweight percentage increases. For major road, the pavement life difference between thick flexible pavement and composite pavement is tiny as presented in **Figure 3.6(a)**. However, it is shown that the plots of pavement life for minor roads in **Figure 3.6(b)** are parallel. Compared pavement life difference due to the changes of overweight percentage from 0% to 15%, overweight percentage has more influence on minor road than major road.

3.4 Life-Cycle Cost Analysis

3.4.1 General Methodology of LCCA

Life-cycle cost analysis (LCCA) is a process for evaluating the over-all-long-term economic worth of a project segment by calculating initial costs and discounted future costs, which are including maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs. Agency costs and user costs are two major parts in life-cycle cost analysis. Agency costs are defined all the costs related to the owning organizations over the life of the project segment, such as initial construction costs and maintenance costs etc. User costs are including travel time, vehicle operation, accidents and discomfort costs paid by the use of facility. In this study, road users were assumed not charged user costs, and only agency costs were considered in the pavement life-cycle cost analysis.

Analysis period and discount rate are the two most significant parameters affecting pavement life-cycle cost. The analysis period should be chosen to be long enough to include major future rehabilitation treatments but not so long that it becomes unreasonable (Walls and Smith 1998). Pavement life-cycle cost analysis with different analysis periods, discount rates and repair strategies were considered in the sensitivity analysis part.

According to National Cooperative Highway Research Program (NCHRP) Guide for Pavement-Type Selection, an analysis period of at least 40 years was suggested for new construction or reconstruction of pavements, while an analysis period of at least 30 years was suggested for rehabilitation of pavements. A respectively longer analysis period should be selected for long-life pavements. Discount rate is used to convert future costs to present year costs. Historically discount rates are in the range of 3% to

5%. The long-term real discount rate values supplied in the lately updated edition of the Office of Management and Budget (OMB) Circular A-94, Appendix C, was suggested to use in life-cycle cost analysis. The current long-term real discount rate is approximately 2%. Thus, an analysis period of 60 years and 2% discount rate were used in the life-cycle cost analysis.

There are several economic indicators available to the analyst such as Benefit/Cost (B/C) Ratios, Internal Rate of Return (IRR), Net Present Value (NPV), and Equivalent Uniform Annual Costs (EUAC). IRR is a return rate which makes net present value of all cash flows from a certain project investment equal to zero. NPV converts all costs to a single base year costs; while converts all projects to a recurring yearly cost. After converting to NPV or EUAC, the costs of various investment options can be compared.

The NPV is defined as the sum of the present values of the individual cash flows of the same entity and has wide application in pavement life cycle cost analysis. The NPV of agency cost during the analysis period is computed using the discounted monetary value of future costs and salvages by transforming costs occurring in different time periods and salvages at the end of analysis period to a common unit of measurement. NPV is a common economic calculation and, for highways, which is expressed by the following equation:

$$NPV = C + M_i\left(\frac{1}{1+r}\right)^{n_i} + \ldots + M_j\left(\frac{1}{1+r}\right)^{n_j} - S\left(\frac{1}{1+r}\right)^{N} \quad (4\text{-}1)$$

Where, NPV=Net present value or present worth;

C= Present cost of initial rehabilitation activity;

M_i= Cost of the ith maintenance & rehabilitation (M&R) alternative in terms of constant dollars;

r=Discount rate;

n_i= Number of years from the present to the ith M & R activity;

N= Length of the analysis period in years;

S= Salvage value at the end of the analysis period.

$$S = \left(1 - \frac{L_A}{L_E}\right)C \tag{4-2}$$

Where, S=Salvage value (or residual value) of rehabilitation alternative;

L_A=Analysis life of rehabilitation alternative in years;

L_E=Expected life of the rehabilitation alternative; and

C= Cost of the rehabilitation alternative.

EUAC represents the NPV of a particular investment option assuming that they were to occur uniformly over the entire analysis period. After figuring NPV by **Equation 4-1**, the following formula was used for EUAC calculation:

$$EUAC = NPV\left[\frac{r(1+r)^N}{(1+r)^N - 1}\right] \tag{4-3}$$

Where, EUAC= Equivalent uniform annual costs;

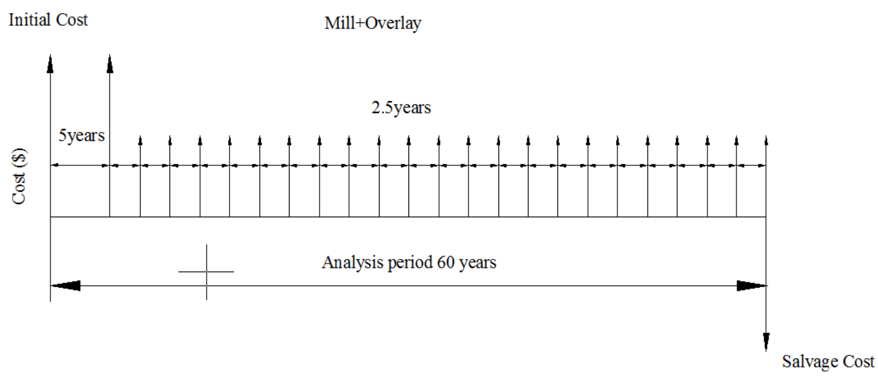
r= Discount rate; and

N= Analysis period.

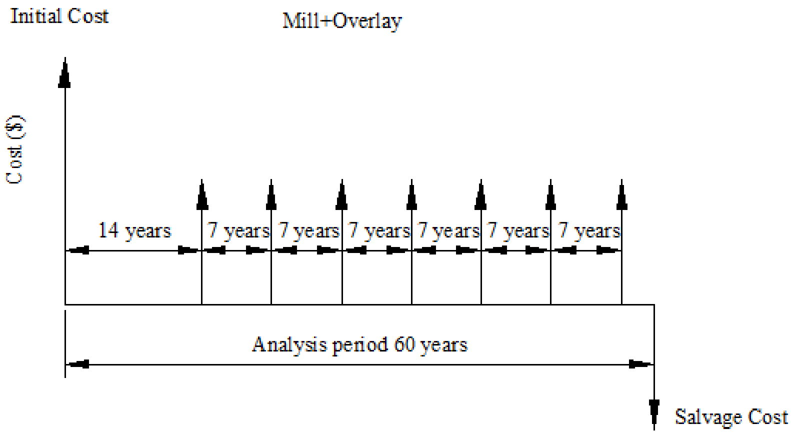
3.4.2 Pavement Rehabilitation Strategy and Cost

In addition to analysis period and discount rate, pavement repair strategy is an essential factor affecting life-cycle costs. Rehabilitation strategy was considered and the cost was accumulated for 60-year life-cycle with 2% discount rate. A typical rehabilitation strategy of milling to a depth of 2 in. and overlaying with 2 in. of new asphalt concrete was used by state DOTs, such as NJDOT. For 2-in. milling and overlay, it is assumed that after the initial overlay successive overlays will be placed and the service life of each overlay equals to half of the service life of the initial construction. In the sensitivity analysis, reconstruction strategy was considered. Either preventive maintenance or annual maintenance was not considered. Rehabilitation strategy may underestimate the total pavement life-cycle cost, but it can still reflect the influence of overweight trucks on pavement damage cost.

Figure 3.7 illustrates the activity flow in a 60-year analysis period for thick flexible pavement and thin flexible pavement, respectively. For thick flexible pavement, the non-overweight AADTT is 10000, and the overweight percentage is 15%. The pavement life predicted using M-E approach is 5 years. For thin flexible pavement, the non-overweight AADTT is 1000, and the overweight percentage is 10%. The pavement life predicted using M-E approach is 14 years.



(a)



(b)

FIGURE 3.7 Activity Flow in a 60-year Analysis Period for (a) Thick Flexible Pavement (b) Thin Flexible Pavement

Maintenance costs for different treatments were calculated using the formulas in a previous study conducted by Zaghloul et al. (2006) for the NJDOT. The unit cost ($ per square yard) equations used for flexible pavements and composite pavements are shown in **Equations 4-4** to **4-7**.

Flexible pavements:

Mill + overlay: $3.98M + 7.0T_{ac}$ (4-4)

Full reconstruction: $65.71 + 7.0T_{ac}$ (4-5)

Composite pavements:

Mill + overlay: $3.98M + 7.01T_{ac}$ (4-6)

Full reconstruction: $163.6 + 7.0T_{ac} + 23.38D$ (4-7)

Where, M= thickness of milling in inches;

T_{ac}= thickness of AC overlay in inches; and

D= thickness of concrete slab in inches.

3.5 Load Equivalency Factor

3.5.1 LEF Derived from M-E Analysis

Pavement damage is determined by road use resulted from axle loads and GVW of individual truck configuration. Load equivalency factors (LEFs) are commonly utilized to measure road usage.

The LEF is defined as the ratio between pavement damage caused by one single pass of the axle in consideration and pavement damage caused by one single pass of the standard 18-kip single axle load with dual tires (one ESAL), as shown in **Equation 4-8**. The calculated LEFs can be used to determine the equivalent number of ESALs for each specific axle that will provide the basis for allocation of pavement damage cost.

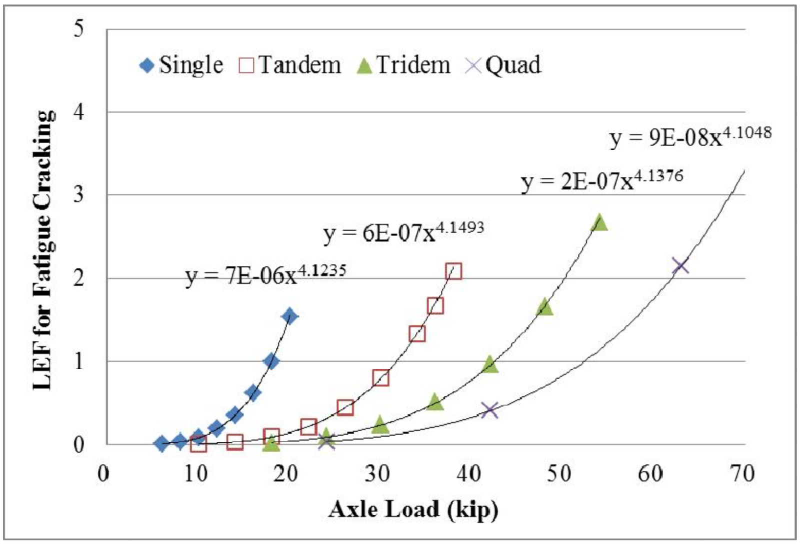
$$LEF = \frac{1/N}{1/N_{ESAL}} = \frac{N_{ESAL}}{N} \qquad (4\text{-}8)$$

Where, LEF = Load Equivalency Factor;

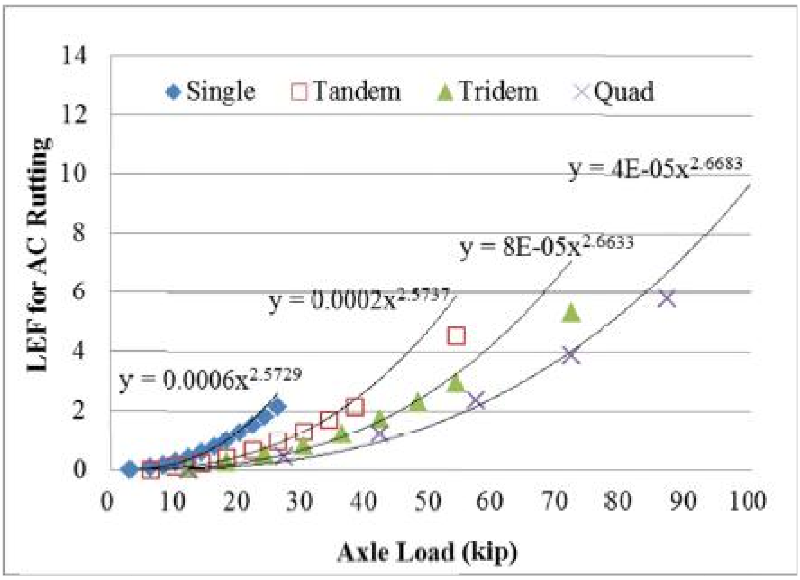
N_{ESAL}=Allowable number of load repetitions to failure under the loading of the standard 18-kip single axle load with dual tires; and

N=Allowable number of load repetitions to failure under the loading of the axle with different load magnitudes and configurations.

LEF fitting functions estimated through mechanistic-empirical (M-E) approach in a previous study (Wang et al. 2014) were used to accurately calculate and compare pavement deterioration caused by different axle types: single, tandem, tridem and quad. **Figure 3.8** presents the LEF fitting functions for fatigue cracking and AC rutting.



(a)



(b)

FIGURE 3.8 Load Equivalency Factors for (a) Fatigue Cracking and (b) AC Rutting

3.5.2 AASHTO LEF

AASHTO guide provides the traditional LEFs calculation method through empirical approach. However, AASHTO LEFs can only be applied to the flexible pavement structures. First, structural number (SN) of the designed pavement structures was computed as follows:

$$SN=a_1D_1+a_2D_2m_2+a_3D_3m_3 \quad (4\text{-}9)$$

Where, a_1, a_2, a_3=Layer coefficients for the surface, base, and subbase;

D_1, D_2, D_3=The thickness of the surface, base and subbase; and

m_2, m_3=The drainage coefficients for the surface, base and subbase course.

Layer coefficients used in AASHTO Road Tests were utilized for SN computation in this study. The layer coefficient a_1 is 0.44, which corresponds to a resilient modulus of 45,000 psi. The layer coefficient a_2 for the granular base material is 0.14, which corresponds to a resilient modulus of 30,000 psi. The layer coefficient a_3 for the granular subbase is 0.11, which corresponds to a resilient modulus of 15,000 psi. The thickness of the surface, base and subbase are included in **Table 3.5**. The drainage coefficients for untreated base and subbase materials in flexible pavements equal to 1.0. Thus, the SN of thick flexible pavement is 5.68, and the SN of thin flexible pavement is 3.36. Terminal serviceability index P_t is assumed 2.5. The AASHTO equations (**Equations 4-10** to **4-12**) from Huang (2004) were used to calculate the AASHTO LEFs for each axle load type. The AASHTO LEFs of thick and thin flexible pavement are presented in **Figure 3.9,** and compared with M-E LEFs.

$$\log_{10}\left(\frac{W_{tx}}{W_{t18}}\right)=4.79\log_{10}(18+1)-4.79\log_{10}(L_x+L_2)+4.33\log_{10}L_2+\frac{G_t}{\beta_x}-\frac{G_t}{\beta_{18}} \quad (4\text{-}10)$$

$$G_t=\log_{10}\left(\frac{4.2-p_t}{4.2-1.5}\right) \quad (4\text{-}11)$$

$$\beta_x = 0.40 + \frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19} L_2^{3.23}} \tag{4-12}$$

Where, W_{tx} =Number of applications of given axle;

W_{t18} =Number of standard axle passes (single 18 kip axle);

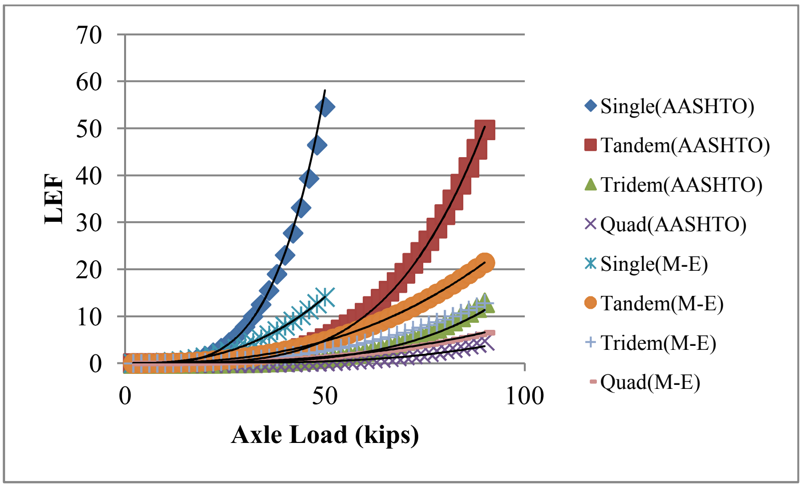
L_x =Load in kips of axle group;

L_2 =Axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles);

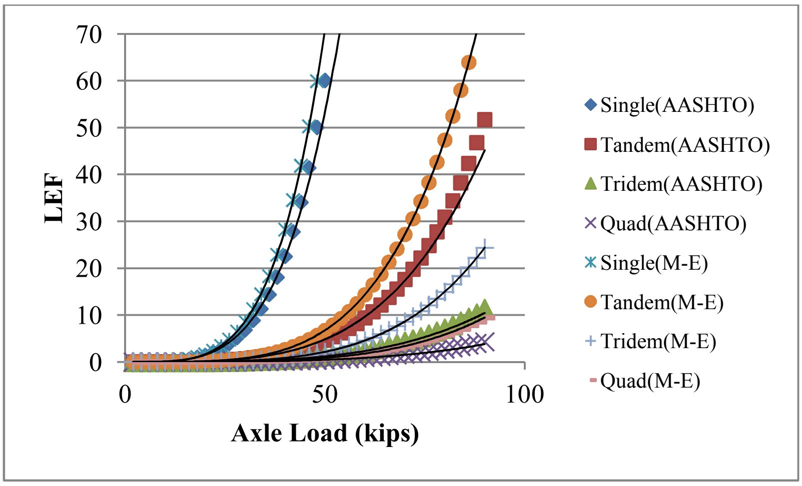
β_{18} =Value of β_x when L_x = 18 and L_2 = 1;

p_t =Terminal serviceability; and

SN =Structural number.



(a)



(b)

FIGURE 3.9 AASHTO and M-E LEFs of (a) Thick Flexible Pavement (b) Thin Flexible Pavement

The AASHTO LEF fitting functions for the thick flexible pavement is as follows:

Single axle: $y=8E\text{-}06x^{4.0393}$, $R^2=1$;

Tandem axle: $y=9E\text{-}07x^{3.972}$, $R^2=0.1$;

Tridem axle: $y=3E\text{-}07x^{3.8914}$, $R^2=0.99$;

Quad axle: $y=2E\text{-}07x^{3.7678}$, $R^2=0.99$.

The AASHTO LEF fitting function for the thin flexible pavement is shown below:

Single axle: $y=1E\text{-}05x^{3.8939}$, $R^2=1$;

Tandem axle: $y=2E\text{-}06x^{3.8106}$, $R^2=0.97$;

Tridem axle: $y=6E\text{-}07x^{3.7084}$, $R^2=1$;

Quad axle: $y=3E\text{-}07x^{3.6279}$, $R^2=0.99$.

Using the LEF fitting functions above, average ESAL factors were calculated using the axle load spectra at each truck classification, respectively, for thick and thin flexible pavements. The calculation results are shown in **Table 3.7** and **Table 3.8**. It should be noted that ESAL factors were underestimated if the AASHTO LEFs were used. The differences of ESAL factors vary depending on the truck classification, which has different combinations of axle configurations.

TABLE 3.7 Comparison of ESAL Factors Using AASHTO and M-E LEFs for Thick Flexible Pavement

Truck Classification	ESAL Factor from AASHTO	ESAL Factor from M-E Analysis
4	0.694	1.04
5	0.454	0.54
6	0.374	0.68
7	1.484	2.82
8	0.974	1.30
9	1.602	2.54
10	1.074	2.23
11	1.075	1.54
12	1.021	1.82
13	1.812	2.46

TABLE 3.8 Comparison of ESAL Factor Using AASHTO and M-E LEFs for Thin Flexible Pavement

Truck Classification	ESAL Factor from AASHTO	ESAL Factor from M-E Analysis
4	0.832	0.996
5	0.237	0.318
6	0.481	0.558
7	2.233	4.073
8	0.544	0.704
9	1.201	1.322
10	1.713	2.259
11	0.328	0.416
12	0.607	0.804
13	0.830	0.872

3.6 Marginal Pavement Damage Cost

For the same pavement structure, the initial construction cost is unchanged, so pavement damage cost differences occur owing to pavement life and repair frequency. The average pavement damage cost is the total maintenance cost divided by the total road usage. The marginal pavement damage cost (MPDC) is defined as a unit cost of providing pavement structure for one extra passage of a unit road usage expressed as ESAL. Compared to average damage cost, it is more realistic and practical method to calculate pavement damage cost.

According to the prior work by Ahmed (2012), linear relationship between the pavement damage costs and the logarithm of average annual ESALs to base e was developed. Pavement type (flexible pavement and rigid pavement) and pavement age range from 0 to 50 year old were the optional parameters in the final functions. Hajek et al. (1998) explored power functions to establish relationship between EUAC and the logarithm of the annual ESALs to base 10, respectively, for new pavements and in-service pavements. The regional codes for southern Ontario and north Ontario were indicator variables in the fitting functions.

In reference to the EUAC and the average annual ESALs, several alternative regression functions were investigated to build models for marginal pavement damage cost estimation. The exponent regression in **Equation 4-13** was selected based on statistical parameters:

$$EUAC = \beta_0 e^{\beta_1 \log_{10}(ESALs)} \tag{4-13}$$

Where, β_0, β_1 =Constant term and parameter estimates for model explanatory variables;

EUAC=Equivalent uniform annual cost per lane-mile over analysis period; and

ESALs=Average annual number of equivalent single axle load per lane-mile.

Average annual ESALs were estimated through dividing the total ESALs by analysis period n. The total ESALs during analysis period is computed by **Equation 4-14.**

$$ESALs = AADTT \times G \times f_d \times f_l \times 365 \times ESAL\ factor \qquad (4\text{-}14)$$

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 load factor, from **Table3.6**;

G=Growth factor $\frac{(1+r)^n - 1}{r}$

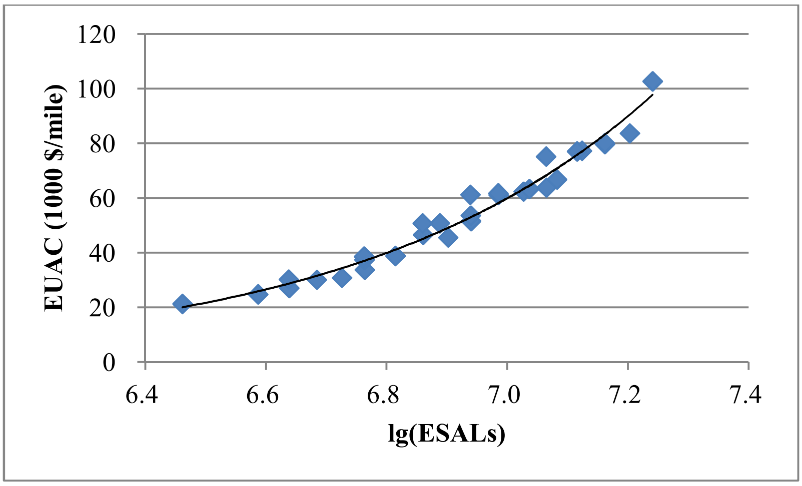
r=Growth rate (3%); and

n=Analysis period.

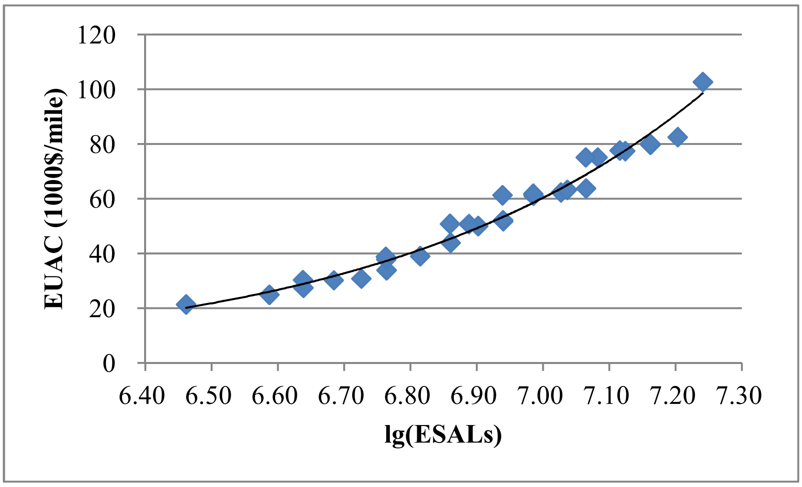
Table 3.9 shows model estimates for MPDC estimation for the four pavement structures. Variation of EUAC with ESALs is shown in **Figure 3.10** and **3.11**.

TABLE 3.9 Model Estimates for MPDC Estimation

Road Type	Pavement Structure	Coefficient	Coefficient Value	R Square
Major Road	Flexible	β_0	0.0398	0.9749
		β_1	2.032	
	Composite	β_0	0.0392	0.9759
		β_1	2.0352	
Minor Road	Flexible	β_0	0.401	0.9905
		β_1	1.933	
	Composite	β_0	0.4424	0.9708
		β_1	0.9708	

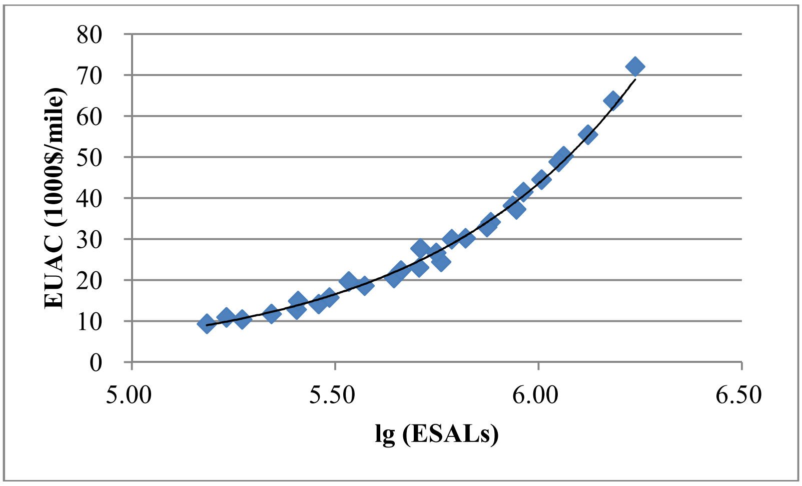


(a)

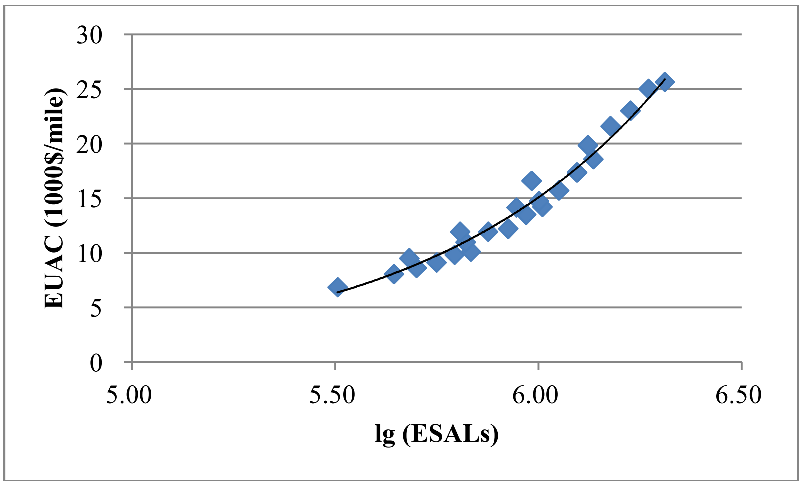


(b)

FIGURE 3.10 Variation of EUAC with ESALs for (a) Thick Flexible Pavement (b) Composite Pavement



(a)



(b)

FIGURE 3.11 Variation of EUAC with ESALs for (a) Thin Flexible Pavement (b) Composite Pavement

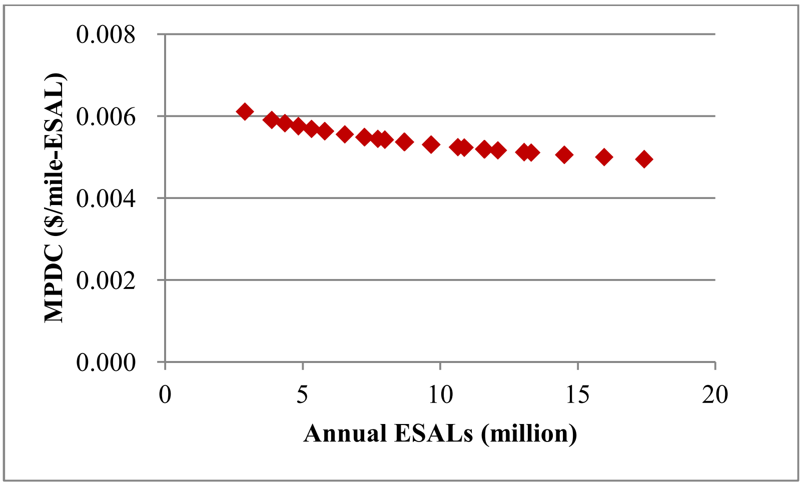
The estimated functions were differentiated with respect to average annual EASLs to obtain the marginal pavement damage costs as follows:

$$MPDC = \frac{\beta_0 \beta_1}{In(10)} (ESALs)^{\left(\frac{\beta_1}{In(10)} - 1\right)} \tag{4-15}$$

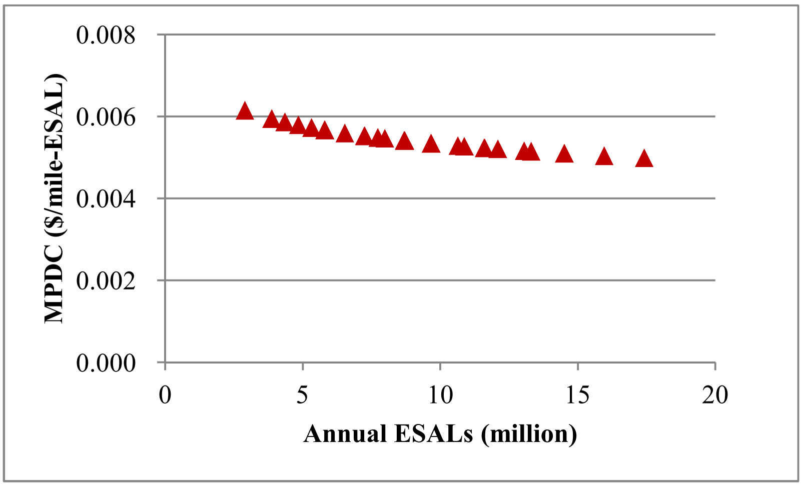
Where, MPDC= Marginal pavement damage cost ($ per ESAL-mile); and

ESALs=Average annual number of equivalent single axle load per lane-mile.

The MPDC plots in **Figure 3.12** and **Figure 3.13** were plotted using coefficient values in **Table 3.9,** respectively, for the four different pavement structures. When the traffic volume is low, fewer trucks share the pavement damage cost and the marginal pavement damage cost is higher. It should be noted that the MPDC of major road is lower than that of minor road.

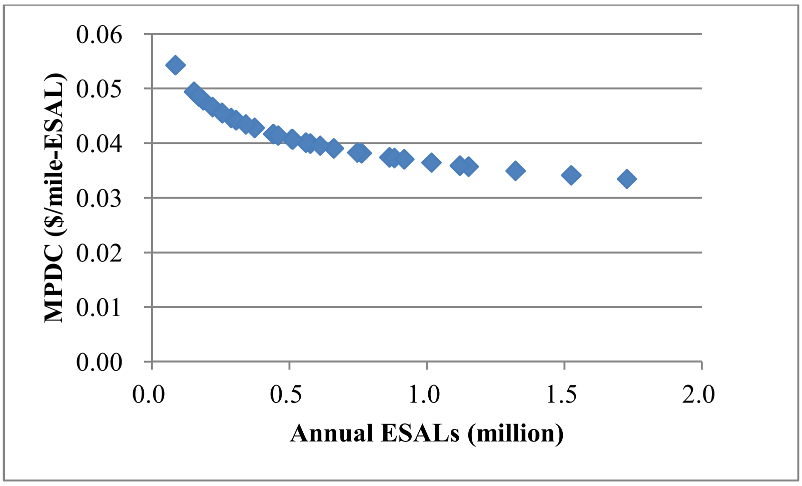


(a)

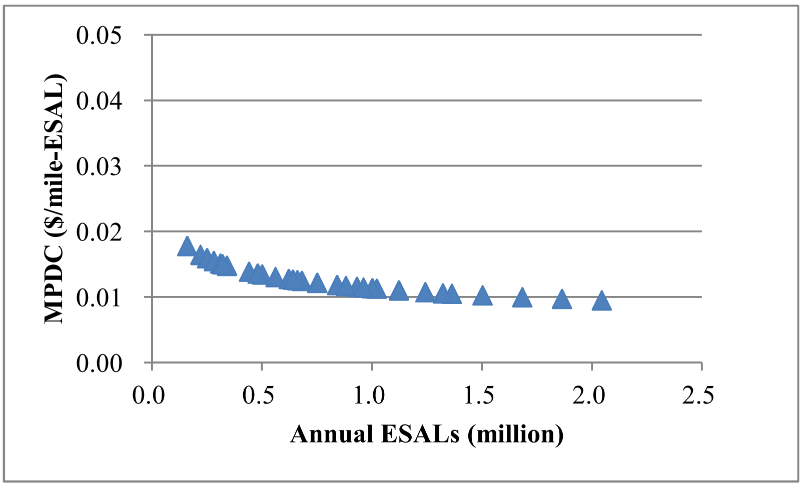


(b)

FIGURE 3.12 Variation of MPDC with ESALs for Major Road: (a) Thick Flexible Pavement (b) Composite Pavement



(a)



(b)

FIGURE 3.13 Variation of MPDC with ESALs for Minor Road: (a) Thin Flexible Pavement (b) Composite Pavement

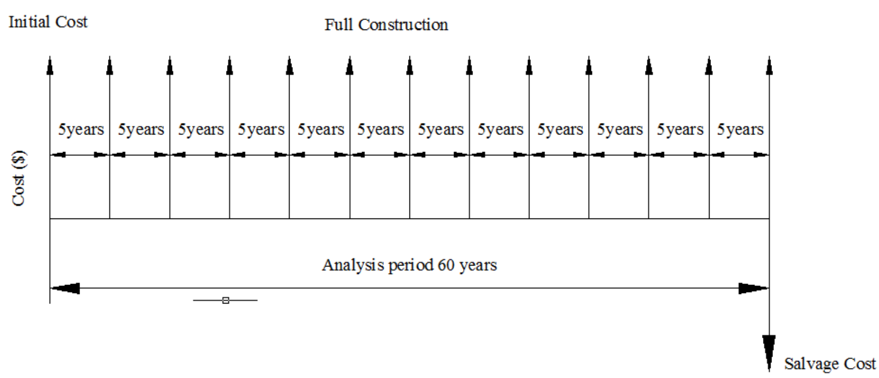
3.7 Effects of LCCA Parameters on MPDC

Sensitivity analysis was performed to evaluate the effects of LCCA parameters, such as repair strategy, discount rate, analysis period and AASHTO LEF estimates, on the marginal pavement damage cost. Sensitivity analysis can assist in selecting reasonable parameters during life-cycle cost analysis.

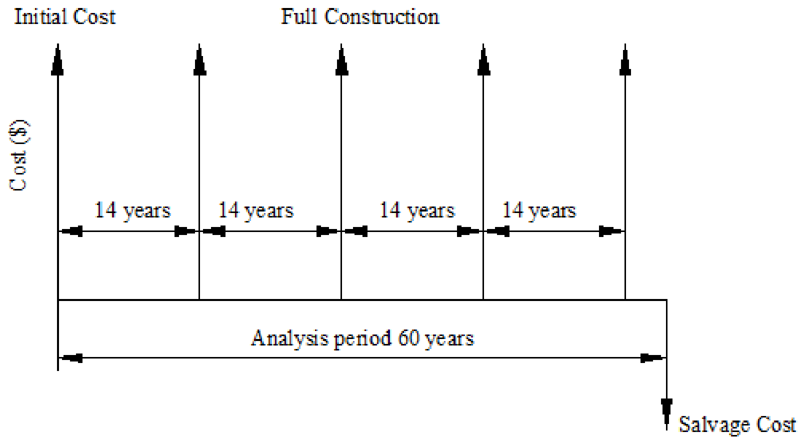
3.7.1 Effects of Maintenance Method on MPDC Estimates

The marginal pavement damage cost estimation was conducted on the basis of Mill & Overlay strategy. Reconstruction is another optional repair strategy applied in New Jersey. Repair strategy is an important factor which can lead to obvious changes of MPDC. Different from rehabilitation strategy, for full reconstruction, the pavement service life of each reconstruction is equal to the service life for the new pavements.

Figure 3.14 illustrates the activity flow in a 60-year analysis period for the flexible pavement structures, assuming reconstruction strategy. For thick flexible pavement, the non-overweight AADTT is 10,000, and the overweight percentage is 15%. The pavement life predicted using M-E approach is 5 years. For thin flexible pavement, the non-overweight AADTT is 1000 and the overweight percentage is 10%. The pavement life predicted using M-E approach is 14 years.



(a)



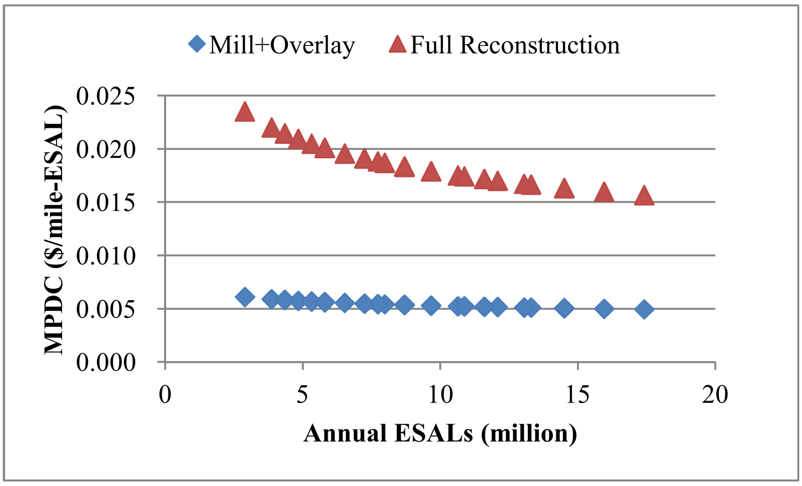
(b)

FIGURE 3.14 Activity Flow in a 60-year Analysis Period for (a) Thick Flexible Pavement (b) Thin Flexible Pavement

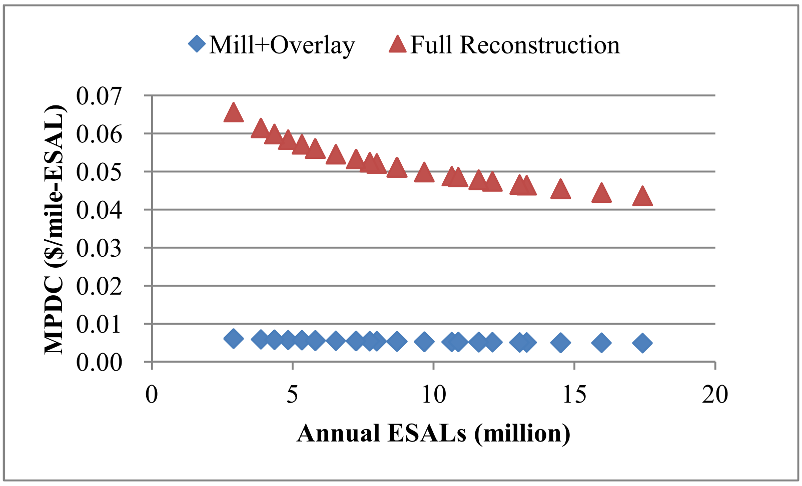
For all of the four pavement structures (thick flexible and composite pavement for major road, and thin flexible and composite pavement for minor road), pavement life-cycle cost analysis was performed using full reconstruction strategy. **Equation 4-1**, **Equation 4-5** and **Equation 4-7** were utilized to estimate NPV. According to NPV, **Equation 4-3** was used to convert NPV to EUAC. Based on EUAC using full reconstruction and average annual ESALs, regression models were developed for full reconstruction strategy (**Table 3.10**).

TABLE 3.10 Model Estimates for MPDC Estimation Using Full Reconstruction

Road Type	Pavement Structure	Coefficient	Coefficient Value	R Square
Major Road	Flexible	β_0	0.8799	0.9751
		β_1	1.7818	
	Composite	β_0	2.4988	0.9761
		β_1	1.7794	
Minor Road	Flexible	β_0	9.1257	0.9875
		β_1	1.5644	
	Composite	β_0	91.269	0.9682
		β_1	1.2602	

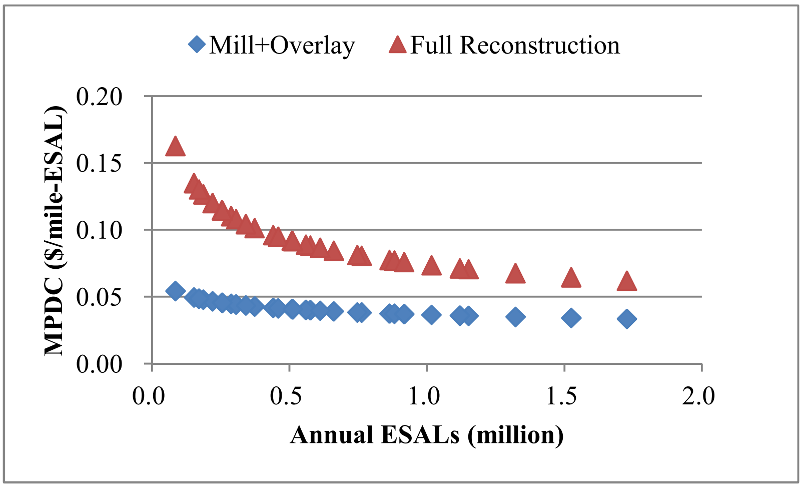


(a)

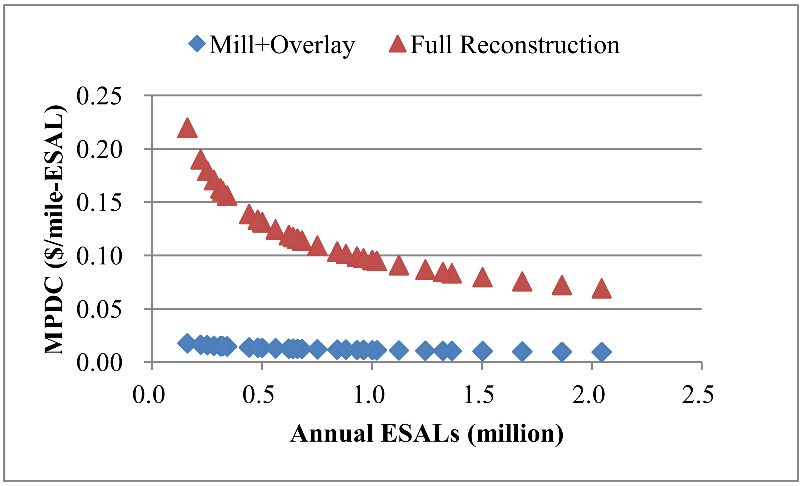


(b)

FIGURE 3.15 MPDC Comparison of Major Road between Rehabilitation and Full Reconstruction for (a) Thick Flexible Pavement (b) Composite Pavement



(a)



(b)

FIGURE 3.16 MPDC Comparison of Minor Road between Rehabilitation and Full Reconstruction (a) Thick Flexible Pavement (b) Composite Pavement

In reference to the coefficient values in the developed models, MPDC curves using full reconstruction strategy were plotted and compared with the MPDC curves using rehabilitation strategy (**Figure 3.15** and **Figure 3.16**). According to MPDC comparison, it was found that full reconstruction strategy caused MPDC's increasing. However, the impact of repair strategy on MPDC differs, depending on pavement structures.

3.7.2 Effects of Analysis Period on MPDC Estimates

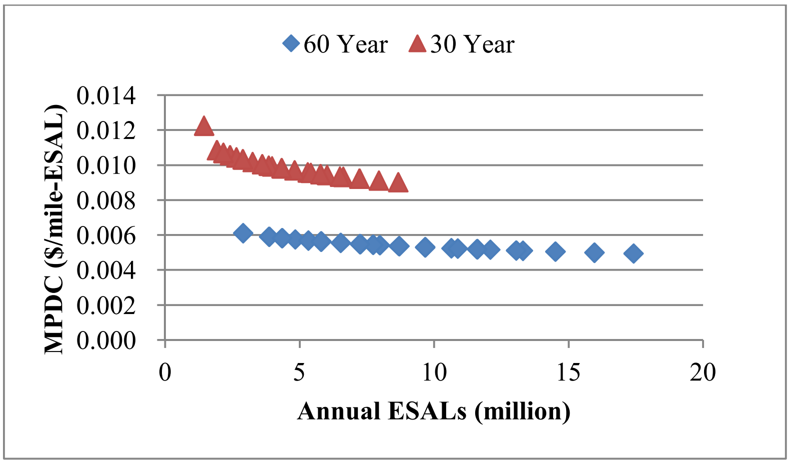
Analysis period is a critical factor affecting pavement life-cycle cost. MPDC was estimated over a 60-year analysis period. In order to study the effects of analysis period, pavement life-cycle cost analysis was conducted over 30, 40, 50 years analysis period, respectively, for the four pavement structures. **Equation 4-1**, **Equation 4-4** and **Equation 4-6** were used to estimate NPV during 30, 40, 50 years. According to NPV over various analysis periods, **Equation 4-3** was used to compute EUAC. Since average annual ESALs increase as analysis period becomes longer, average annual

ESALs for 30, 40, 50 years were recalculated based on ESAL factor included in **Tables 3.7** and **3.8**. According to average annual ESALs and EUAC during 30, 40, 50 years, separate models were developed. The coefficient values required for MPDC estimation in the developed models are summarized in **Table 3.11**.

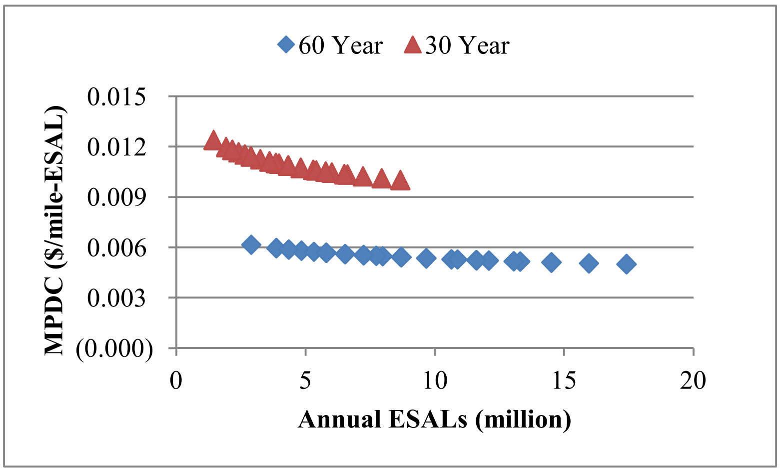
TABLE 3.11 Model Estimates over Different Analysis Period

Discount Rate	Road Type	Pavement Structure	β_0 Value	β_1 Value	R Square
30 Years	Major	Thick Flexible	0.08	2.0194	0.9749
		Composite	0.0763	2.0282	0.9764
	Minor	Thick Flexible	0.4242	2.0309	0.9824
		Composite	1.216	1.6583	0.97
40 Years	Major	Thick Flexible	0.073	2.0186	0.9747
		Composite	0.070	2.0273	0.9759
	Minor	Thick Flexible	0.6024	1.9502	0.9907
		Composite	0.8288	1.7093	0.9711
50 Years	Major	Thick Flexible	0.0638	2.0236	0.9767
		Composite	0.0581	2.039	0.9768
	Minor	Thick Flexible	0.5308	1.9557	0.9902
		Composite	0.6113	1.7461	0.9718
60 Years (Base)	Major	Thick Flexible	0.0398	2.032	0.9749
		Composite	0.0392	2.0352	0.9759
	Minor	Thick Flexible	0.401	1.922	0.9905
		Composite	0.4424	0.9708	0.9708

No obvious changing pattern could be found from the coefficient values summarized in **Table 3.11**. MPDC plots for 30-year and 60-year are shown in **Figure 3.17** and **Figure 3.18** to analyze the changes of MPDC due to analysis period. It should be noted that the MPDC during a shorter analysis period tends to be higher.

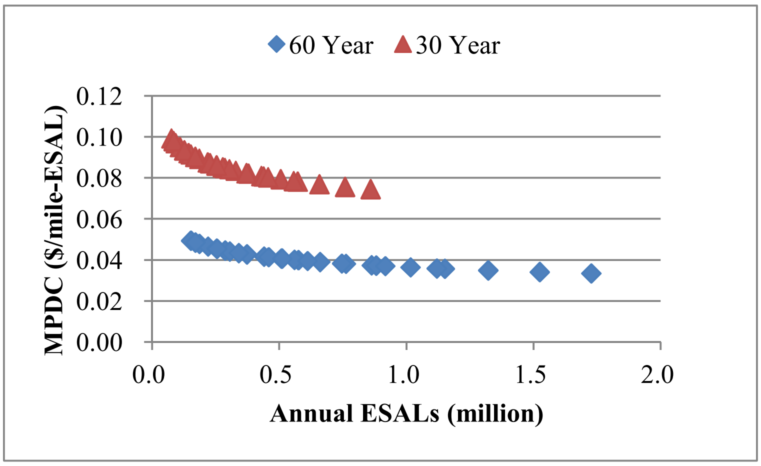


(a)

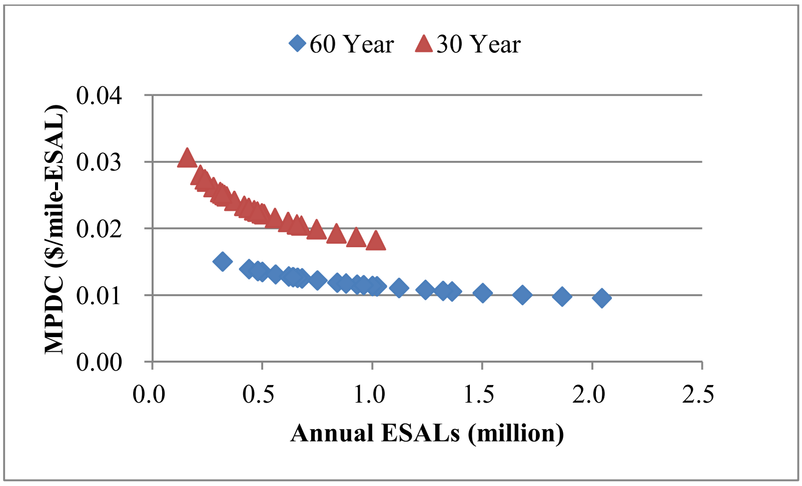


(b)

FIGURE 3.17 MPDC Comparison of Major Road during 30 and 60 years (a) Thick Flexible Pavement (b) Composite Pavement



(a)



(b)

FIGURE 3.18 MPDC Comparison of Minor Road during 30 and 60 years (a) Thin Flexible Pavement (b) Composite Pavement

3.7.3 Effects of Discount Rate on MPDC Estimates

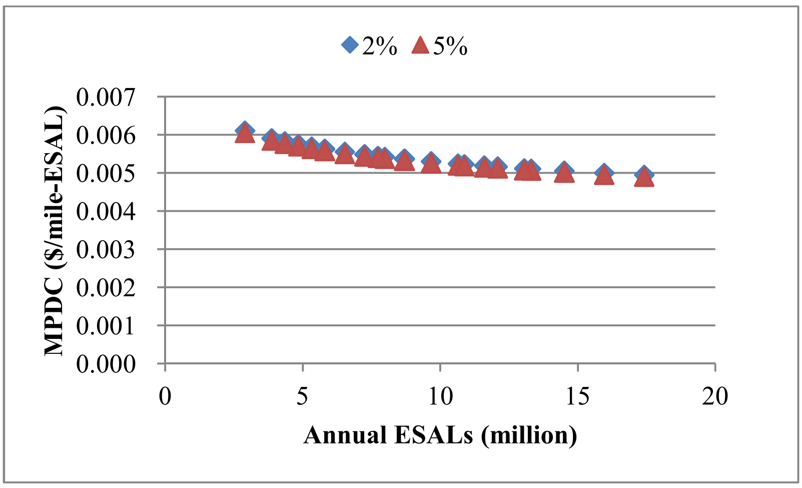
MPDC estimation is conducted based on EUAC calculation. Since EUAC is significantly affected by discount rate, EUAC is expected to decrease if lower discount rate is applied. The historically discount rates ranging from 3% to 5% were used to study the impacts of discount rate on MPDC.

For the four pavement structures, pavement life-cycle cost analysis was conducted with 3%, 4% and 5% discount rate. **Equation 4-1**, **Equation 4-4** and **Equation 4-5** were utilized to estimate NPV. According to the recalculated NPV, **Equation 4-3** was used to compute EUAC. In reference to the EUAC calculated using different discount rates, separate models were developed for 3%, 4% and 5% discount rate (**Table 3.12**).

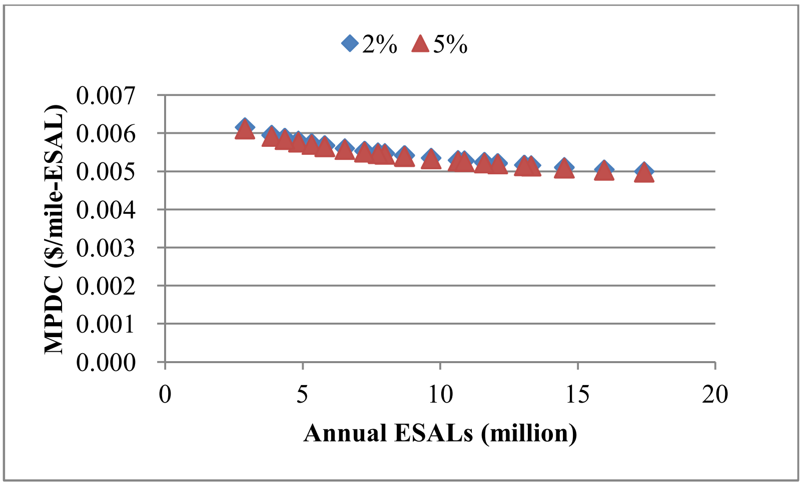
TABLE 3.12 Model Estimates for MPDC Estimation Using 3% to 5% Discount Rate

Discount Rate	Road Type	Pavement Structure	β_0 Value	β_1 Value	R Square
2% (Base)	Major	Thick Flexible	0.0398	2.032	0.9749
		Composite	0.0392	2.0352	0.9759
	Minor	Thick Flexible	0.401	1.922	0.9905
		Composite	0.4424	0.9708	0.9708
3%	Major	Thick Flexible	0.0372	2.0409	0.9748
		Composite	0.0365	2.0448	0.9758
	Minor	Thick Flexible	0.4385	1.9169	0.9897
		Composite	1.5297	1.649	0.9673
4%	Major	Thick Flexible	0.037	2.0411	0.9747
		Composite	0.0361	2.0461	0.9758
	Minor	Thick Flexible	0.5495	1.8787	0.9881
		Composite	1.6159	1.5276	0.9621
5%	Major	Thick Flexible	0.039	2.0336	0.9746
		Composite	0.0377	2.0398	0.9757
	Minor	Thick Flexible	0.7661	1.8228	0.9854
		Composite	3.7962	1.3903	0.9549

The coefficient values in **Table 3.12** were used to plot MPDC curves shown in **Figure 19** and **Figure 20**. Slight difference owning to the changes of discount rate from 2% to 5% was found. For the four pavement structures, a higher discount rate leads to a lower MPDC.

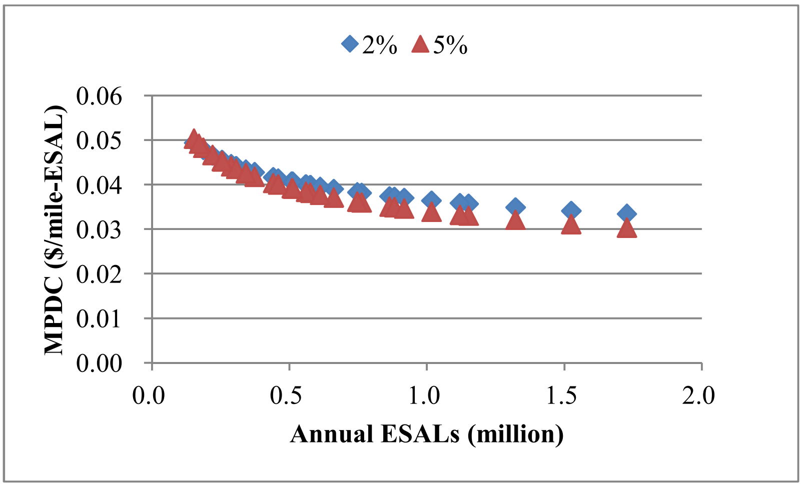


(a)

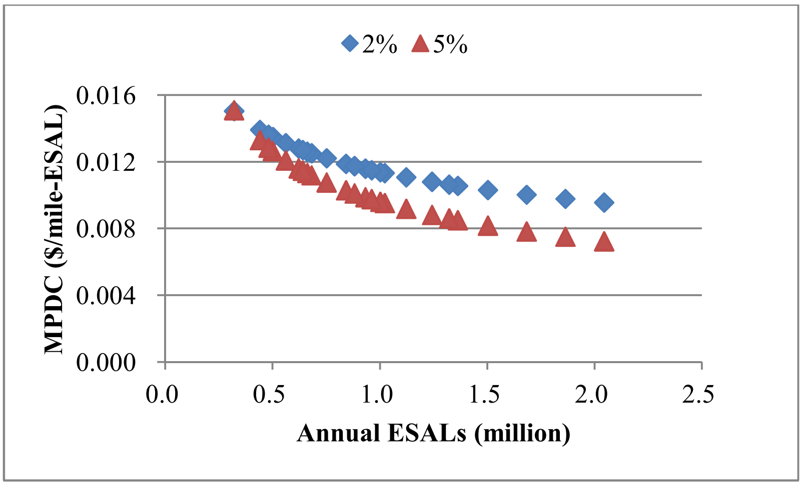


(b)

FIGURE 3.19 MPDC Comparison of Major Road with 2% and 5% Discount Rate for (a) Thick Flexible Pavement (b) Composite Pavement



(a)



(b)

FIGURE 3.20 MPDC Comparison of Minor Road with 2% and 5% Discount Rate for (a) Thin Flexible Pavement (b) Composite Pavement

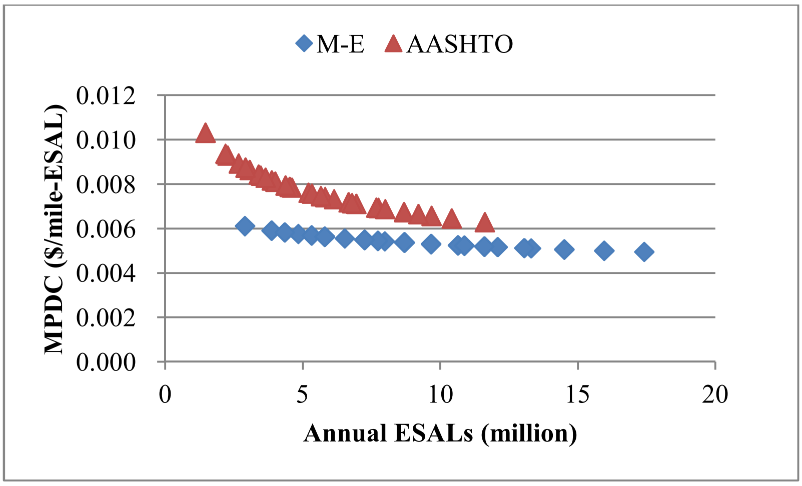
3.7.4 Effects of AASHTO LEFs on MPDC Estimates

Average annual ESALs were recalculated based on ESAL factors in (**Table 3.7** and **Table 3.8**), and new models were developed for MPDC estimation**.** The coefficient values required for MPDC estimates in the developed models are summarized in **Table 3.13**.

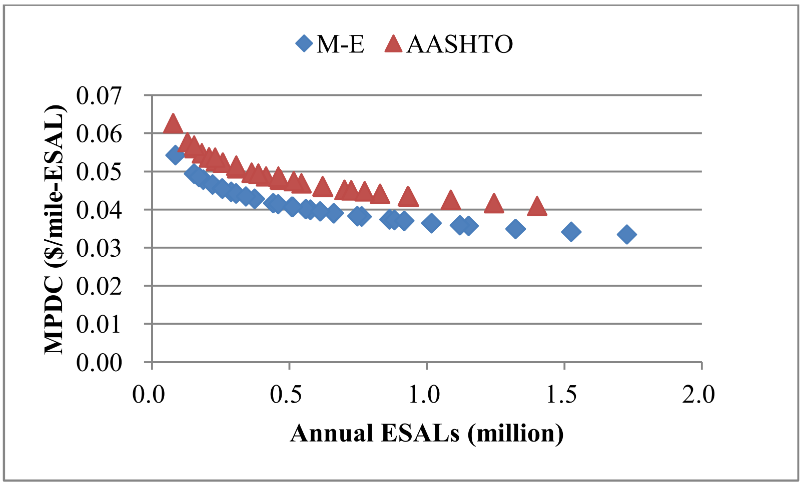
TABLE 3.13 Model Estimates for MPDC Estimation Using AASHTO LEFs

Pavement Structure	ESALs Calculation	β_0 Value	β_1 Value	R Square
Thick Flexible Pavement	M-E	0.0398	2.032	0.9749
	AASHTO	0.3965	1.7546	0.9098
Thin Flexible Pavement	M-E	0.401	1.922	0.9905
	AASHTO	0.3613	1.9781	0.9958

In reference to **Figure 3.21,** the MPDC estimated using AASHTO equations tends to greater than the MPDC estimated using M-E approach. It is supposed to be noted that a bigger gap occurs to thick flexible pavement.



(a)



(b)

FIGURE 3.21 MPDC Comparison between using M-E and AASHTO for (a) Thick Flexible Pavement (b) Thin Flexible Pavement

CHAPTER 4

DETERMINATION OF PERMIT FEE FOR OVERWEIGHT TRUCK

4.1 Conceptual Framework

Luskin et al. (2001) performed a study on a framework for the Taxes highway cost allocation. Three desirable properties: completeness, rationality, and marginality, were considered in discussing the four highway cost allocation methods. Completeness indicated that highway costs were fully charged by operating vehicle classes; rationality indicated that highway costs paid by truck class could not be more than those they would if they were part of any small alliance of truck classes; marginality indicated that sufficient highway costs were paid by operating truck classes to recover their marginal costs. According to proportional method, particular cost indicators, such as vehicle miles traveled (VMT) and ESALs, were used to allocate highway costs among vehicle classes. However, proportional method could only satisfy completeness. Researchers summarized the overall conceptual methodology of allocating pavement maintenance and rehabilitation costs. Cost components of pavement maintenance and rehabilitation were first indentified, after which, RENU3 and FPS software might be used to obtain cost equations. The ESALs per vehicle class and the percentage of each vehicle class were critical factors. Then proportional method was applied to estimate highway costs of each vehicle class. Finally, appropriate examining and changing of results were conducted.

A general framework developed for determination of permit fee for overweight trucks using marginal pavement damage cost is shown in **Figure 4.1**. It is based on proportional method, and ESAL is the critical indicator. It can be applied to the entire New Jersey highway system. The framework elements are discussed in this chapter.

The key of estimating pavement deterioration caused by overload is to define non-overweight traffic. Ohio Department of Transportation (2009) removed the overweight trucks directly from the total traffic, and compared the annual expenditure between including and excluding overweight trucks. However, additional pavement damage cost is caused by tonnage above legal limits, instead of the total weight of overweight trucks. Therefore, in this study only excessive tonnage is removed from overweight trucks.

Seven steps are summarized in this determining process.

Step 1: Collect truck configurations from WIM stations. Then axle loads and GVW of truck configurations at each truck classification for an entire year are obtained.

Step 2: Modify weight of overweight trucks in original traffic stream through removing tonnage exceeding legal weight limits, after which, overweight tonnage can be estimated.

Step 3: Based on axle load type (single, tandem, tridem or quad) and failure mechanism, select corresponding LEF (M-E or AASHTO) fitting functions to calculate the annual ESALs.

Step 4: Use EUAC regression models to determine EUAC ($/mile) of original traffic and modified traffic. Subtract EUAC ($/mile) of modified traffic from EUAC of original traffic to obtain EUAC difference ($/mile) resulted from overweight tonnage.

Step 5: Multiply vehicle miles traveled (VMT) of overweight trucks by EUAC difference ($/mile). The result represents EUAC difference ($) caused by all overweight trucks on an individual route.

Step 6: Accumulate EUAC difference ($) and the number of overweight trucks of each route in New Jersey Highway System. Divide the total EUAC difference ($) of all routes by the total number of overweight trucks.

Step 7: The overweight tonnage from **Step 2** is used to calculate weight-based permit fee.

The various items required in the general procedure are presented below:

a. Average annual ESALs over analysis period
b. EUAC fitting functions
c. AADTT and overweight truck percentage of each route
d. Average trip length

However, due to the lack of comprehensive traffic information of New Jersey highway network, accurate overweight permit fee for the entire New Jersey highway system cannot be determined. According to the obtained WIM data of Interstate Highway 78 and New Jersey state highway 55, a case study was conducted to estimate permit fee for overweight trucks which were traveling on these two routes.

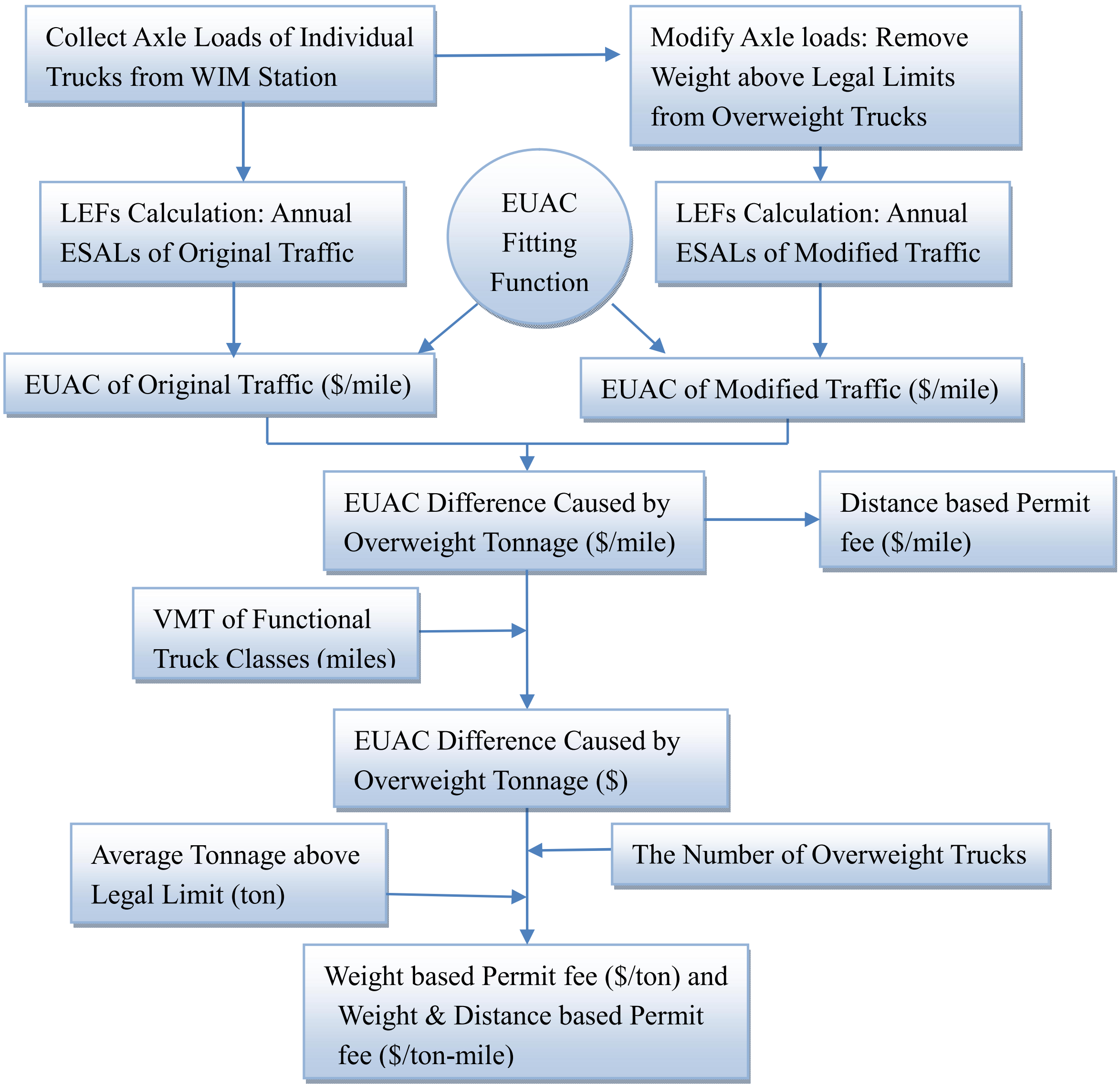


FIGURE 4.1 Framework of Determination of Permit Fee for Overweight Trucks using Marginal Pavement Damage Cost

4.2 Pavement Damage Cost Caused by Excessive Weight

4.2.1 Truck Traffic Composition

Table 4.1 provides the characteristics of Interstate Highway 78 and New Jersey state highway 55, such as pavement structure, failure mechanism, AADTT and overweight truck percentage. It should be noted that the overweight percentage of I-78 is 16.79%, and 10.64% of trucks on NJ-55 were overweight trucks.

TABLE 4.1 Characteristics of I-78 and NJ-55

Route #	I-78	NJ-55
Road Type	Major	Minor
Pavement Structure	Thick Flexible Pavement	Thin Flexible Pavement
Failure Mechanism	AC Rutting	Fatigue Cracking
Traffic Volume	11739	1348
Overweight Percentage	16.79%	10.64%

Table 4.2 presents main truck configurations and overweight truck distribution at each truck classification of Interstate Highway 78 (major road) and New Jersey state highway 55 (minor road) respectively. For major road, truck class 9 (single trailer 5-axle truck) covers 87% of the total overweight trucks. For minor road, class 9 (single trailer 5-axle truck) accounts for 53.45% of the total overweight trucks, and class 7 (single unit 4 or more axle truck) covers 29.05%. The proportion has impacts on overweight permit fee.

TABLE 4.2 Overweight Truck Distribution in Each Truck Classification on Major and Minor Road

Vehicle Class	Vehicle Class Description	Overweight Percentage	
		I-78 (Major)	NJ-55 (Minor)
4	Singe unit 2-axle truck	3.19%	0.75%
5	Singe unit 2-axle truck	1.51%	4.07%
6	Singe unit 3-axle truck	1.04%	9.52%
7	Single unit 4 or more axle truck	1.81%	29.05%
8	Single trailer 3 or 4-axle truck	1.47%	2.12%
9	Single trailer 5-axle truck	87.00%	53.45%
10	Single trailer 6 or more-axle truck	2.18%	0.88%
11	Multi-trailer 5 or less-axle truck	0.87%	0.00%
12	Multi-trailer 6-axle truck	0.52%	0.00%
13	Multi-trailer 7 or more-axle truck	0.41%	0.16%
Total		100%	100%

4.2.2 Pavement Cost Estimation Caused by Overweigh Tonnage

Modified Truck Fleet

The additional pavement damage cost was caused by tonnage exceeding legal weight limits. The overweight trucks were modified by removing the excessive weight. Thus, AADTT of original and modified case are the same, but the overweight percentage of modified case equals to 0%.

NJDOT legislates 80,000 pound as the legal GVW. The legal axle weight on a single axle is 22,400lbs, and the legal tandem axle weight is 34,000lbs. Besides, Bridge Formula weight limits are utilized to limit the maximum weight of any set of axles on a truck may carry on the Interstate highway system. In this study, overweight tonnage above GVW or axle load limits was considered. The Bridge Formula is expressed by:

$$W = 500\left[\frac{LN}{N-1} + 12N + 36\right] \tag{4-1}$$

Where, W=The overall gross weight on any group of two or more consecutive axles to the nearest 500 pounds;

L=The distance in feet between the outer axles of any group of two or more consecutive axles; and

N=The number of axles in the group under consideration.

Table 4.3 and **Table 4.4** show examples of modifying the typical overweight trucks at each truck classification. The changes of GVW and axle loads are observed. M-E LEF fitting functions for AC rutting (major road) and fatigue cracking (minor road) were used to calculate the total ESALs of each truck before and after adjustment.

The total overweight tonnage per year of major road is 1,149,352 ton, and the total overweight tonnage per year of minor road is 154,823 ton. The average overweight tonnage per truck of major road is 3.20 ton, and the average overweight tonnage per truck of minor road is 5.91 ton.

TABLE 4.3 Examples of Modifying Overweight Truck Traffic (Major Road)

Truck Class	Class 4		Class 5		Class 6		Class 7		Class 8	
Traffic	1	2	1	2	1	2	1	2	1	2
GVW (kip)	37.4	35.4	53.7	44	47.3	44.1	63.2	44.24	73.7	51.3
Single Axle (kip)	13	13	21.6	21.6	10.1	10.1	11.2	10.34	6.1	6.1
	24.4	22.4	32.1	22.4					11.2	11.2
Tandem Axle (kip)					37.2	34			56.4	34
Tridem Axle (kip)							52	33.9		
Total Equivalent ESALs	2.67	2.23	6.14	3.42	2.43	1.98	3.27	1.20	6.59	1.91
Overweight (kip)	2		9.7		3.2		18.96		22.4	
Truck Class	Class 9		Class 10		Class 11		Class 12		Class 13	
Traffic	1	2	1	2	1	2	1	2	1	2
GVW (kip)	114.8	80	86.8	80	83.6	80	105	80	134.2	80
Single Axle (kip)	17.6	12	26.2	19.4	11.2	11.2	12.7	9.1	18.2	9.8
					18.2	18.2	20.2	16.5	15.6	6.6
					18.5	18.5	17.6	14		
					15.2	15.2	17.8	6.4		
					20.5	16.9				
Tandem Axle (kip)	49.5	34	28.1	28.1			36.7	34	30.1	21.1
	47.7	34								
Tridem Axle (kip)			32.5	32.5						
Quad Axle (kip)									70.3	42.9
Total Equivalent ESALs	9.74	3.86	4.60	3.16	4.52	3.97	5.86	3.34	6.42	1.71
Overweight (kip)	34.8		6.8		3.6		25		53.8	

1.1indicates the original traffic, and 2 indicates the modified traffic.

TABLE 4.4 Examples of Modifying Overweight Truck Traffic (Minor Road)

Truck Class	Class 4		Class 5		Class 6		Class 7		Class 8	
Traffic	1	2	1	2	1	2	1	2	1	2
GVW (kip)	37.4	35.4	53.7	44	47.3	44.1	63.2	44.24	73.7	51.3
Single Axle (kip)	13	13	21.6	21.6	10.1	10.1	11.2	10.34	6.1	6.1
	24.4	22.4	32.1	22.4					11.2	11.2
Tandem Axle (kip)					37.2	34			56.4	34
Tridem Axle (kip)							52	33.9		
Total Equivalent ESALs	3.96	2.86	13.63	4.81	2.07	1.45	2.67	0.54	11.25	1.52
Overweight (kip)	2		9.7		3.2		18.96		22.4	
Truck Class	Class 9		Class 10		Class 11		Class 12		Class 13	
Traffic	1	2	1	2	1	2	1	2	1	2
GVW (kip)	114.8	80	86.8	80	83.6	80	105	80	134.2	80
Single Axle (kip)	17.6	12	26.2	19.4	11.2	11.2	12.7	9.1	18.2	9.8
					18.2	18.2	20.2	16.5	15.6	6.6
					18.5	18.5	17.6	14		
					15.2	15.2	17.8	6.4		
					20.5	16.9				
Tandem Axle (kip)	49.5	34	28.1	28.1			36.7	34	30.1	21.1
	47.7	34								
Tridem Axle (kip)			32.5	32.5						
Quad Axle (kip)									70.3	42.9
Total Equivalent ESALs	12.94	2.91	5.91	2.41	4.74	3.76	5.76	2.54	5.93	0.74
Overweight (kip)	34.8		6.8		3.6		25		54	

1. 1indicates the original traffic, and 2 indicates the modified traffic.

Average ESAL factor of original and modified traffic

The thin flexible pavement fails due to fatigue cracking, and the thick flexible pavement and composite pavement fail due to AC rutting. Annual ESALs of the modified trucks with maximum allowable weight were estimated to decide the EUAC, after which, EUAC difference between original and modified traffic can be calculated. Annual ESALs of major and minor road are included in **Table 4.4**. The reduction of annual ESALs is observed from **Figure 4.2**.

TABLE 4.5 Annual ESALs and ESAL Factor Comparison between Original Traffic and Modified Traffic of (a) Major Road (b) Minor Road

Road Type	Traffic	Original Traffic	Modified Traffic
Major Road	Annual ESALs	4588826	3957919
	ESAL Factor	2.14	1.85
Minor Road	Annual ESALs	229587	138503
	ESAL Factor	0.93	0.56

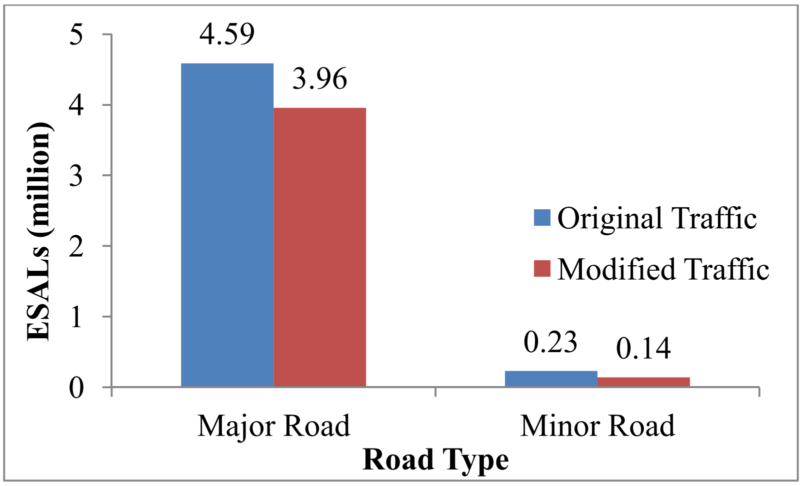
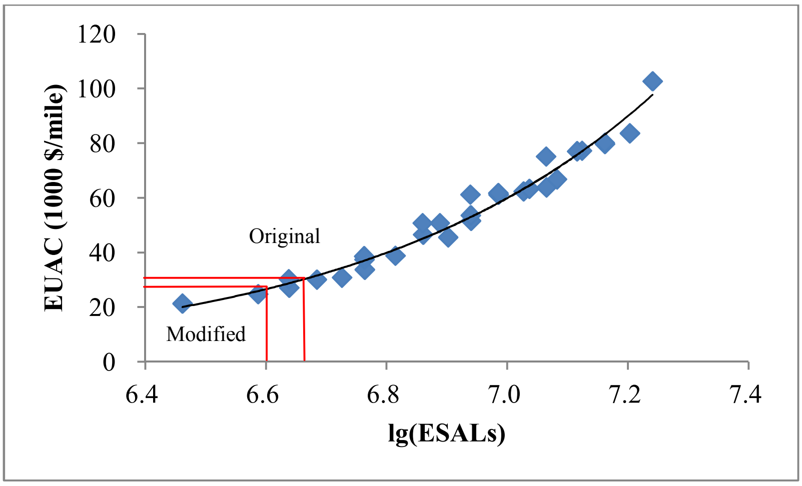


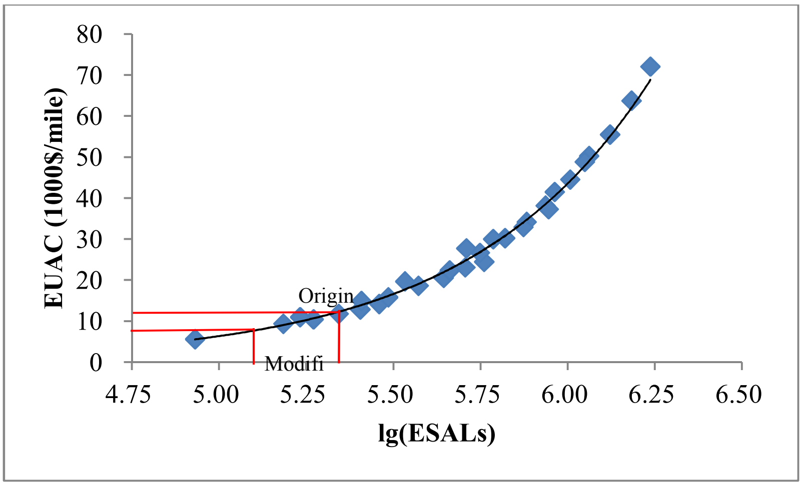
FIGURE 4.2 Annual ESALs Comparison between Original and Modified Traffic

Additional EUAC Caused by Overweight Tonnages

The EUAC regression models estimated with 2% discount rate during a 60-year analysis period using rehabilitation strategy was selected to estimate additional EUAC resulted from overweight tonnage. With the annual ESALs in **Table 4.4**, **Figure 4.3** shows the EUAC difference between original and modified traffic.



(a)



(b)

FIGURE 4.3 EUAC Differences between Original Traffic and Modified Traffic for (a) Major Road (b) Minor Road

TABLE 4.6 EUAC Difference between Original and Modified Traffic

Road Type	EUAC ($/mile)		EUAC Difference ($/mile)
	Original Traffic	Modified Traffic	
Major Road	30112	26428	3685
Minor Road	12694	8305	4389

The EUAC difference ($/mile) represents additional pavement damage cost per mile caused by overweight tonnage in one year. It provides the base of calculating overweight permit fee in various types.

4.3 Permit Fee Based on Individual Truck

Flat, weight-based permit, distance-based, and weight & distance-based permit are the four common overweight permit fee structures in the United States. These permit fee structures are used by 44 states of the 49 states, which have legislated permit fee schedule for overweight trucks.

4.3.1 Distance Based Permit Fee

Additional per mile damage cost is directly obtained through dividing EUAC difference by the number of overweight trucks as expressed by **Equation 4-2**. For major road, the distance-based permit fee is $0.0102/mile per truck, and for minor road the permit fee is $0.168/mile per truck.

$$\text{Distance base permit fee} = \frac{\Delta \text{EUAC}}{n} \tag{4-2}$$

Where, ΔEUAC= Equivalent uniform annual cost difference ($/mile); and

n=Total number of overweight trucks (**Table 4.3**).

4.3.2 Weight & Distance Based Permit Fee

Additional per ton per mile damage cost beyond the legal limit is calculated by dividing the EUAC ($/mile) by the total tonnage above the legal weight limits. Weight & distance based permit fee is computed by:

$$\text{Weight \& distance based permit fee} = \frac{\Delta \text{EUAC}}{\text{w}} \qquad (4\text{-}3)$$

Where, ΔEUAC= Equivalent uniform annual cost difference ($/mile); and

w=Total overweight tonnage exceeding legal limit (ton).

The total overweight tonnage per year of major road is 1,149,352 ton, and the total overweight tonnage per year of minor road is 154,823 ton. Thus, for major road, the weight & distance based permit fee is $0.0032/mile-ton, and for minor road, the permit fee is $0.0283/mile-ton.

4.3.3 Weight Based Permit Fee

Additional per ton damage cost beyond the legal limit is estimated by multiplying additional per ton per mile damage cost by trip length of overweight trucks. The calculation is expressed by **Equation 4-4**.

$$\text{Weight based permit fee} = \frac{\Delta \text{EUAC}}{\text{w}} \times l \qquad (4\text{-}4)$$

Where, ΔEUAC=Equivalent uniform annual cost difference ($/mile);

w=Total overweight tonnage exceeding legal limit (ton); and

l=Mileage traveled per trip.

In reference to **Equation 4-4**, weight based permit fee and miles traveled per trip by overweight trucks are coherent. Meyburg et al. (1997) calculated the loaded miles by road class through a sample of 916 trucks, which were asked operating details of individual trucks and its usage on a randomly selected day of the week. Adams et al. (2013) and Murphy et al. (2012) assumed a one-way trip of 300 miles in each state. Ohio Department of Transportation (2008) collected data and prepared a comparison between the reported and estimates and reported actual trips for 90-day hauling permit to quantify pavement damage caused by overweight trucks. In the research conducted by Chowdhury et al. (2013), it was assumed that trucks were operating five days a week and single trip per day, and the total number of trips per truck per year was 265. The same simulation was used in this study.

The average overweight truck trip length of each class was estimated through annual mileage reported in the 2002 New Jersey Economic Census (US Census, 2004). Average miles per truck per year (column 4) were determined by dividing the total mileage (column 3) by the number of trucks (column 2). The estimated truck trip length for each axle grouping (column 5) was calculated by dividing average miles per truck per year by 265. Since average trip length ranges from 46.47 mile/day to 230.6 mile/day, for major road the weight-based permit fee is in the range of $0.15/ton-$0.74/ton, and for minor road the permit fee is in the range of $1.32/ton-$6.53/ton.

According to truck configurations in **Table 4.2**, single unit 4 or more axle truck and single trailer 5-axle truck cover approximately 90% of the total overweight trucks. A majority of overweight trucks are operating 75.74 mile/day or 230.6 mile/day. Therefore, the weight based permit fee is $0.24/ton (single unit 4 or more axle truck) or $0.74/ton (single trailer 5-axle truck) for major road, and the weight based permit fee is $2.14/ton (single unit 4 or more axle truck) or $6.53/ton (single trailer 5-axle truck) for minor road.

TABLE 4.7 Estimated Truck Trip Length Using US Census Data

Truck Type	Trucks (thousands)	Millage (millions)	Average Miles per Truck (thousands)	Average Trip Length (miles)
2-axle single unit	2064.7	25016.4	12.12	46.47
3-axle single unit	13.3	273	20.53	78.73
4-axle single unit	5.2	152.9	29.40	112.78
3-axle combination	3.8	100.1	26.34	101.04
4-axle combination	13.8	272.5	19.75	75.74
5-axle combination	27.5	1653.3	60.12	230.60
6-axle combination	27.5	1653.3	60.12	230.60
7 axle combination	27.5	1653.3	60.12	230.60
8 axle combination	27.5	1653.3	60.12	230.60

In reference to distance based permit fee, pavement segments with different classification can be taken into consideration. The decided legal route in the overweight permit online application system should be recorded to determine distance based permit fee of individual trucks. The SUPERLOAD online permitting system is used by NJDOT to issue permit for overweight/oversize vehicles. Picking route segments and automatically origin/destination routing are main options of routing to determine the legal highway or local road for individual truck with various axle loads and GVW. The certain trip for the permit is determined after routing, and the trip length can be calculated.

4.3.4 Flat Permit Fee

Flat fee is estimated by multiplying additional per mile damage cost by trip length, as expressed by **Equation 4-5**.

$$\text{Flat permit fee} = \frac{\Delta \text{EUAC}}{\text{n}} \times l \qquad (4\text{-}5)$$

Where, ΔEUAC= Equivalent uniform annual cost difference ($/mile);

n=Total number of overweight trucks; and

l=Mileage traveled per trip.

For major road, the flat permit fee is in the range of \$0.48-\$2.37, and for minor road, the permit fee is in the range of \$7.80-\$38.60. Single unit 4 or more axle truck and single trailer 5-axle truck are the major truck types of class 7 and class 9. 90% of the overweight trucks need to pay \$0.77 (single unit 4 or more axle truck) or \$2.37 (single trailer 5-axle truck) for major road, and pay \$12.65 (single unit 4 or more axle truck) or \$38.60 (single trailer 5-axle truck) for minor road.

4.4 Comparison of Permit Fee Structures

Overweight permit fee, which should be charged by a particular truck at each classification, was estimated. The typical configurations at each truck class in **Table 4.3** and **Table 4.4** were used to compare different overweight permit fee structures shown in **Table 4.8** and **Table 4.9**. Only distance based and weight & distance based permit fee structures were considered, and the unit of overweight permit fee is \$/mile.

The purpose of charging overweight permit fee is to recover extra pavement damage cost caused by excessive tonnage. Extra damage cost is computed through multiplying the extra ESALs of individual overweight truck by the marginal pavement damage cost. The number of annual ESALs of major road is 4,588,826. The MPDC curve for thick flexible pavement is shown in **Figure 4.4**, and the annual ESALs of 4,588,826 is marked. According to calculation using the corresponding coefficient values, the marginal pavement damage cost is \$0.00579/mile-ESAL. The number of annual ESALs of minor road is 229,587. The MPDC curve for thin flexible pavement is shown in **Figure 4.5**, and the annual ESALs of 229,587 is marked. The marginal pavement damage cost of thin flexible pavement is \$0.0464/mile-ESAL.

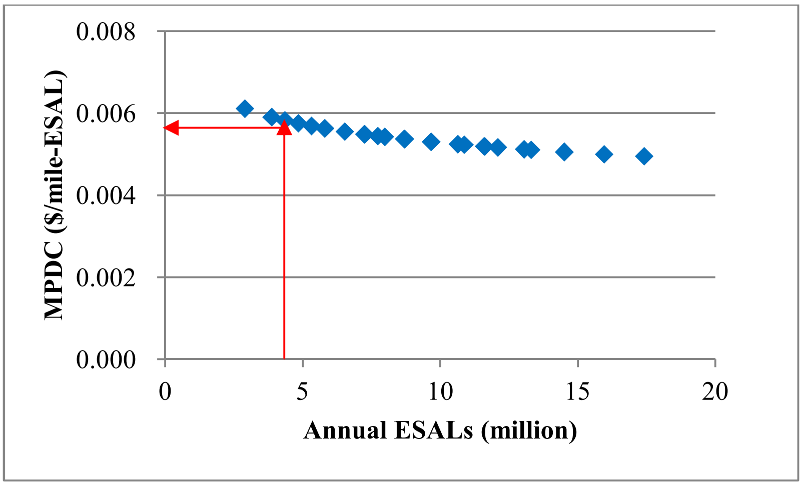


FIGURE 4.4 Variation of MPDC with ESALs for Thick Flexible Pavement

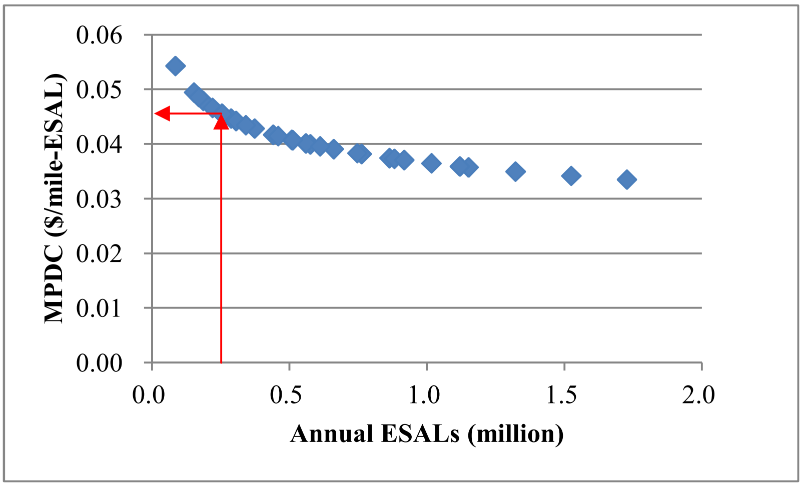


FIGURE 4.5 Variation of MPDC with ESALs for Thick Flexible Pavement

It indicates that overweight permit fees are not fair to all the trucks. Some overweight trucks have to charge permit fee which is overestimated, while the damage cost caused by some other trucks cannot by recovered by the overweight permit fees. Compared to the truck at class 5, the number of the extra ESALs of the truck at class 7 is fewer, and the excessive tonnage is more. The truck at class 7 is charged more weight & distance based permit fee than the truck at class 5.

TABLE 4.8 Comparison of Permit Fee Structures (Major Road)

Truck Class	Class 4	Class 5	Class 6	Class 7	Class 8
Extra ESALs	0.44	2.72	0.46	2.08	4.68
Overweight Tonnage	1.00	4.85	1.60	9.48	11.20
Distance Based Permit Fee ($/mile)	0.0102	0.0102	0.0102	0.0102	0.0102
Weight & Distance-Based Permit Fee ($/mile)	0.003	0.016	0.005	0.030	0.036
Extra Pavement Damage Cost ($/mile)	0.003	0.022	0.004	0.016	0.037
Truck Class	Class 9	Class 10	Class 11	Class 12	Class 13
Extra ESALs	5.88	1.44	0.56	2.52	4.71
Overweight Tonnage	17.40	3.40	1.80	12.50	26.90
Distance Based Permit Fee ($/mile)	0.0102	0.0102	0.0102	0.0102	0.0102
Weight & Distance-Based Permit Fee ($/mile)	0.056	0.011	0.006	0.040	0.086
Extra Pavement Damage Cost ($/mile)	0.047	0.011	0.004	0.020	0.037

TABLE 4.9 Comparison of Permit Fee Structures (Minor Road)

Truck Class	Class 4	Class 5	Class 6	Class 7	Class 8
Extra ESALs	0.44	2.72	0.46	2.08	4.68
Overweight Tonnage	1.00	4.85	1.60	9.48	11.20
Distance Based Permit Fee ($/mile)	0.168	0.168	0.168	0.168	0.168
Weight & Distance-Based Permit Fee ($/mile)	0.024	0.115	0.038	0.226	0.267
Extra Pavement Damage Cost ($/mile)	0.051	0.409	0.029	0.099	0.452
Truck Class	Class 9	Class 10	Class 11	Class 12	Class 13
Extra ESALs	5.88	1.44	0.56	2.52	4.71
Overweight Tonnage	17.40	3.40	1.80	12.50	26.90
Distance Based Permit Fee ($/mile)	0.168	0.168	0.168	0.168	0.168
Weight & Distance-Based Permit Fee ($/mile)	0.414	0.081	0.043	0.298	0.640
Extra Pavement Damage Cost ($/mile)	0.465	0.163	0.046	0.150	0.241

CHAPTER 5

CONCLUSIONS AND RECOMMONDATIONS

5.1 Conclusions

This study provides a methodology for developing overweight permit fees, which could be charged by highway agencies to recover additional pavement damage cost caused by overweight trucks. If complete WIM data for a whole year and miles traveled by overweight trucks are obtained, the conceptual framework developed from this study can be applied to any route in New Jersey highway system to determine overweight permit fee in distance based, weight & distance based, distance based, and flat structure.

1. According to mechanistic-empirical pavement analysis, it should be noted that thin flexible pavement fails due to fatigue cracking, while thick flexible pavement and composite pavement fail due to asphalt concrete rutting. The reflective cracking of composite pavement is not considered in this study.
2. Exponential relationship between the equivalent uniform annual cost (EUAC) and the logarithm of average annual equivalent single axle loads (ESALs) were developed, after which, exponential relationship between the marginal pavement damage cost (MPDC) and the annual ESALs were found.
3. The sensitivity analysis revealed that repair strategy, analysis period, and load equivalency factor estimates have a significant impact on marginal pavement damage cost. Slight changes were resulted from discount rate.
4. A conceptual framework reflected a considerable procedure to determine

overweight permit fee using accurate traffic data, which could be applied to New Jersey highway system.

5. Overweight permit fee is unlikely to be fair to all the overweight trucks. Overweight permit fee is determined by overweight tonnage, and pavement deterioration varies, depending on extra ESALs. However, the uncertain relationship between overweight tonnage and extra ESALs brings about the gap between overweight permit fee and pavement damage cost.

5.2 Recommendations for Future Research

Several recommendations for future research are listed as follows.

1. Local calibration of M-E pavement analysis is needed to predict pavement performance in a more practical way.
2. No matter rehabilitation or full reconstruction, the repair strategy used in the study was assumed. Real repair strategy applied in New Jersey operated by highway agency will make pavement life-cycle cost more accurate.
3. Vehicle miles traveled by overweight trucks and the total number of overweight trucks are the key elements to estimate overweight permit fee. It should be noted that, exact values of these two parameters can improve the results of the study.
4. It is not reasonable to estimate the marginal pavement damage cost only on the basis of new pavements, because pavements in highway network have different ages. Pavement ages should be considered in future work.

REFERENCES

1. Adams, T., Perry, E., Schwartz, A., Gollnik, B., Kang, M., Bittner, J., and Wagner, S. (2013). “Aligning Oversize/Overweight Fees with Agency Costs: Critical Issues.” (Report No. CFIRE 03-17)
2. Ahmed, A. (2012). “Pavement Damage Cost Estimation using Highway Agency Maintenance, Rehabilitation, and Reconstruction Strategies.” Dissertation, Purdue University
3. Barnes, G. and Langworthy, P. (2004). “Per Mile Costs of Operating Automobiles and Trucks.” *Journal of Transportation Research Board,* 1864*,* 71-77.
4. Bilal, M.K., Irfan, M., Ahmed, A., Labi, S., Sinha, K.C. (2010). “A Synthesis of Overweight Truck Permitting.” (Report No. FHWA/IN/JTRP-2010/12)
5. Boilé, M., Narayanan, P. and Ozbay, K. (2003). “Impact of Buses on Highway Infrastructure: Case Study for New Jersey State.” *Transportation Research Record*, 1841, 32-40.
6. Bruzelius, N. (2004). “Measuring the Marginal Cost of Road Use: An International Survey.” *Meddelande 963A, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.*
7. Chowdhury, M., Putman, B., Pang, W., Dunning, A., Dey, K., Chen, L. (2013). “Rate of Deterioration of Bridges and Pavements as Affected by Trucks.” (Report No. FHWA-SC-13-05)
8. Conway, A. and Walton, C.M. (2008). “Analysis and Cost-Recovery Optimization Methodology for a Fixed-Class Truck Tolling Structure.” *Journal of the Transportation Research Board,* 2066, 90-97.
9. Conway, A.J. and Walton, C.M. (2010). “A Road Pricing Methodology for

Infrastructure Cost Recovery.” (Report No. SWUTC/10/476660-00064-1)

10. Dey, K.C., Chowdhury, M., and Wiecek, M.M., (2013). “A Tradeoff Analysis for Different Damage Fee Structure for Offsetting Overweight Truck Damage Costs.” In *Transportation Research Board Annual Meeting 2014*, 14-2972.
11. Fekpe, E., Gopalakrishna, D., and Woodrooffe, J. (2006). “Performance-Based Oversize and Overweight Permitting System.” *Journal of the Transportation Research Board,* 1966, 118–125.
12. FHWA, (2010). “Freight Analysis Framework: DOT Release New Freight Transportation Data.” Federal Highway Administration, Office of Freight Management and Operations.
13. Fortowsky, J.K. and Humphreys, J. (2006). “Estimating Traffic Changes and Pavement Impacts from Freight Truck Diversion Following Changes in Interstate Truck Weight Limits.” Journal of the Transportation Research Board, 1966, 71-79.
14. Hajek, J.J., Tighe, S.L., and Hutchinson, B.G. (1998). “Allocation of Pavement Damage Due to Trucks Using a Marginal Cost Method.” Transportation Research Board, 1613, 50-56.
15. Hewitt, J., Stephens, J., Smith, K., and Menuez, N. (1999). “Infrastructure and Economic Impacts of Changes in Truck Weight Regulations in Montana.” Transportation Research Record, 1653, 42-51.
16. Hjelle, H.M. (2003). “A Foundation of Road User Charges.” Faculty of Engineering, Science and Technology, Department of Civil and Transport Engineering. Trondheim, the Norwegian University of Science and Technology (NTNU).
17. Huang, Y.H. (2004). “Pavement Analysis and Design.” 2nd ed. Pearson–Prentice

Hall, Upper Saddle River, NJ.

18. J.J. Keller & Associates (2011). "Vehicle Sizes & Weight Manual." *J.J. Keller & Associate, Inc*.
19. Jawad, D. J., and Ozbay, K. (2006). "Probabilistic Life-Cycle Cost Optimization for Pavement Management at the Project-Level." *Transportation Research Board Annual Meeting 2006*, Paper #06-1591.
20. Jawad, D.J. (2003). "Life Cycle Cost Optimization for Infrastructure Facilities." Doctoral dissertation, Rutgers University.
21. Liedtke, G. and Scholz, A.B.(2009). "Life-Cycle Cost Approach to Infrastructure Cost Calculation and Allocation." *Transportation Research Record: Journal of the Transportation Research Board,* 2121, 13–21.
22. Luskin, D.M., Garcia–Diaz, A., Lee, D., Zhang, Z., and Walton, C.M. (2001). "A Framework of Taxes Highway Cost Allocation Study." (Report No. 0-1810-1).
23. Luskin, D.M., Harrison, R., Walton, C.M., Zhang, Z., and Jamieson, J.L., Jr (2002). "Divisible-Load Permits for Overweight Trucks on Texas Highways: An Evaluation." *Transportation Research Record,* 1790, 104-109.
24. Martin, T.C. (2002). "Estimating Heavy Vehicle Road Wear Costs for Bituminous-Surfaced Arterial Roads." *Journal of Transportation Engineering,* 128(2), 103–110.
25. Meyburg, A.H., Saphores, J.M. and Schuler, R.E. (1998). "The Economic Impacts of a Divisible-Load Permit System for Heavy Vehicles." *Transpn Research-Part A,* 32*,* 115-127.
26. Mlynarski, M, Spangler, B., Rogers, H. (2013). "Review and Revision of Overload permit Classification." (Report No. RC-1589)
27. Nie, J. (2013). "Influence of Heavy Truck on Pavement Damage and Life-Cycle

Cost." Special project report for Master Degree, Rutgers University.

28. Ohio Department of Transportation (2009). "Impacts of Permitted Trucking on Ohio's Transportation System and Economy."
29. Prozzi, J., Murphy, M., Loftus-Otway, L., Banerjee, A., Kim, M., Wu, H., Prozzi, J.P., Hutchison, R., Harrison, R., Walton, C.M., Weissmann, J., Weissmann, A. (2012). "Oversize/Overweight Vehicle Permit Fee Study." (Report No. FHWA/TX-13/0-6736-2)
30. Roberts, F.L. and Djakfar, L. (1999). "Cost of Pavement Damage Due to Heavier Loads on Louisiana Highway: Preliminary Assessment." *Transportation Research Record,* 1732*,* 00-0441.
31. Sadeghi, J.M., and Fathali, M. (2007). "Deterioration Analysis of Flexible Pavements under Overweight Vehicles." *Journal of Transportation Engineering-ASCE,* 133(11), 625-633.
32. Sathaye, N., Horvath, A. and Madanat, S. (2009). "Unintended Impacts of Increased Truck Loads on Pavement Supply-Chain Emissions." *Transportation Research Part A: Policy and Practice*, 44-1, 1, 1-15.
33. Specialized Carriers & Rigging Association (2012). "*Oversize/Overweight Permit Manual*"
34. Straus, S.H. and Semmens, J. (2006). "Estimating the Cost of Overweight Vehicle Travel on Arizona Highways." (Report No. FHWA-AZ-06-528)
35. Timm, D.H., Turochy, R.E., Peters, K.D. (2007). "Correlation between Truck Weight, Highway Infrastructure Damage and Cost." (Report No.70-71-5048)
36. Titze, C. and Feese, S. (2011). "Oversize/Overweight Permitting Practices Review." (Report No. NJ-2011-002)
37. Titze, C., Feese, S., and Rivenberg, B. (2013). "Oversize/Overweight Permitting

Practices Review – Phase II." (Report No. NJ-2013-001)

38. Walls, J. and Smith, M.R. (1998). "Life-cycle Cost Analysis in Pavement Design—Interim Technical Bulletin." Federal Highway Administration, FHWA-SA-98-079.

39. Wang, H., Yang, S., Nie, J. and Wang, Z.L. (2014). "Allocation of Truck-Induced Pavement Damage Cost." *Transportation Research Board Annual Meeting 2014*, Paper #14-3567.

40. Whitford, P.K. and Moffett, D.P. (1995). "Development of Annual Permit Procedure for Overweight Trucks on Indiana Highways."(Report No. JHRP-95/5).